Security Analysis for Vehicle Area Networks Protocol Using AVISPA

by

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ABSTRACT

In the era of smart transportation, Vehicle Area Networks (VANs) are critical in enabling secure communication between vehicles and infrastructure. This project examines the security robustness of the PUFGuard protocol, a physically unclonable function (PUF)-based authentication framework designed to protect Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications in VANs. PUFGuard leverages the inherent uniqueness of PUFs for secure key generation and authentication, aiming to establish trust and resilience against adversarial attacks in dynamic, multi-hop communication environments. To validate PUFGuard's resilience, this research employs formal verification tools—AVISPA and SPAN—to simulate and analyze its effectiveness against common network threats, including replay attacks, man-in-the-middle attacks, and impersonation attacks. The protocol is modelled in the High-Level Protocol Specification Language (HLPSL), where each component of the V2I and V2V authentication processes is systematically represented. Results from the AVISPA tests highlight the protocol's strengths and potential vulnerabilities, providing insights into the adequacy of PUFGuard's security measures in real-world VAN applications. The findings of this study suggest refinements to fortify PUFGuard further, offering a framework for secure, authenticated communication in modern vehicular networks.

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List of Acronyms

AVISPA Automated Validation of Internet Security Protocols and Applications

CL-AtSe Constraint Logic-based Attack Searcher

CRP Challenge-Response Pair

DoS Denial of Service

HLPSL High-Level Protocol Specification Language

IBE Identity-Based Encryption

MitM Man-in-the-Middle

OFMC On-the-Fly Model Checking

PKI Public Key Infrastructure

PUF Physically Unclonable Function

PUFGuard PUF-based Authentication Protocol for Vehicle-to-Everything Communication

RSU Roadside Unit

SATMC Satisfiability Modulo Theories Model Checker

SPAN Security Protocol Animator

TA4SP Tree Automata based on Automatic States for Protocols

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Everything

VAN Vehicle Area Network

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Seeking knowledge is an obligation upon every Muslim
The Prophet Muhammad

Territory acknowledgement

We acknowledge with respect the Lekwungen-speaking peoples on whose traditional territory the university stands and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical relationships with the land continue to this day.

Chapter 1

Introduction

1.1 Overview

In recent years, the integration of smart technology in transportation has led to the development of Vehicle Area Networks (VANs), which allow vehicles to communicate with each other and with roadside infrastructure. These networks enable Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, essential for autonomous driving, traffic management, and enhanced road safety [4]. However, as VANs become more complex and interconnected, ensuring secure communication between vehicles and infrastructure has become a critical challenge. Unauthorized access, data tampering, and privacy breaches are among the primary threats that compromise the reliability of these networks [5].

1.2 Problem Statement

The dynamic and decentralized nature of VANs makes them vulnerable to various attacks, such as replay, impersonation, and man-in-the-middle attacks [6]. Traditional authentication mechanisms are often insufficient to address these threats in a fast-moving vehicular environment [7]. Physically Unclonable Function (PUF)-based protocols, such as PUFGuard, offer a promising solution by leveraging the unique, device-specific characteristics of PUFs for secure key generation and authentication [8]. However, the resilience of PUFGuard against common network attacks has not been thoroughly tested. This research aims to rigorously analyze and test the security of the PUFGuard protocol to identify its strengths and vulnerabilities.

1.3 Research Objectives

The primary objectives of this research are:

1. To model the PUFGuard protocol in the High-Level Protocol Specification Language (HLPSL) to capture the essential steps of its V2I and V2V authentication processes.

2. To use the AVISPA and SPAN verification tools to evaluate PUFGuard's resilience against replay attacks, man-in-the-middle attacks, and impersonation attacks [9].

3. To analyze the outcomes of the AVISPA simulations and provide recommendations for strengthening the protocol against identified vulnerabilities.

1.4 Significance of the Study

This study contributes to the field of vehicular network security by providing a comprehensive analysis of the PUFGuard protocol, a PUF-based authentication mechanism designed specifically for VANs [8]. Given the growing reliance on autonomous and connected vehicles, the findings of this study hold significant implications for developing secure communication protocols that can withstand the dynamic nature and unique threats in VAN environments [7]. The results and recommendations of this research may guide further enhancements of PUF-based security protocols for future smart transportation systems.

1.5 Project Outline

This project is organized as follows:

- **Chapter 2** provides a detailed review of the literature on VAN security, PUF technology, and security protocol verification tools.

- **Chapter 3** presents the design and structure of the PUFGuard protocol, including its components and message flows.

- **Chapter 4** describes the HLPSL modeling of the protocol, as well as the setup for testing the protocol in AVISPA.

- **Chapter 5** presents the results of the AVISPA simulations and analyzes the protocol's resilience against replay, man-in-the-middle, and impersonation attacks.
- **Chapter 6** concludes the project with a summary of findings, contributions, and suggestions for future research.

Chapter 2

Background and Related Work

2.1 Vehicle Area Networks (VANs) and Security Challenges

Vehicle Area Networks (VANs) are the backbone of Intelligent Transportation Systems (ITS), facilitating safe and efficient communication among vehicles, roadside infrastructure, and control centers. VANs are built on wireless ad hoc networks that allow nodes (vehicles, RSUs) to communicate without fixed infrastructure, making them ideal for dynamic vehicular environments. Key goals of VANs include enhancing road safety, reducing traffic congestion, and supporting autonomous vehicle operations.

2.1.1 Components of VANs

VANs consist of several primary components:

- **Vehicles**: Equipped with sensors, onboard computers, GPS, and communication modules (e.g., Dedicated Short-Range Communications, DSRC, or 5G modules), vehicles serve as mobile nodes that gather and transmit information.
- **Roadside Units (RSUs)**: RSUs are stationary nodes typically installed on highways, intersections, and critical points. They serve as communication relays, connecting vehicles to infrastructure and central systems.
- **Infrastructure Components**: This includes traffic lights, road signs, cameras, and traffic management centers (TMCs) that monitor, process, and manage

vehicular data in real-time.

- **Control Centers and Cloud Servers**: Control centers or cloud-based platforms manage the data flow and provide services such as traffic prediction, vehicle navigation, and emergency response coordination.

2.1.2 Communication Types in VANs

VANs facilitate various types of communication to address different aspects of vehicular interaction:

- **Vehicle-to-Vehicle (V2V)**: V2V communication enables direct exchange of information between vehicles, which is essential for applications like collision avoidance, traffic warnings, and cooperative driving (e.g., platooning). For example, a vehicle braking suddenly can alert nearby vehicles to prevent collisions [4].

- **Vehicle-to-Infrastructure (V2I)**: In V2I communication, vehicles interact with roadside infrastructure such as RSUs or traffic lights. V2I provides information about traffic conditions, road hazards, and real-time route adjustments. For example, a vehicle approaching a red light can receive data from the RSU on intersection safety or traffic congestion ahead [5].

- **Vehicle-to-Network (V2N)**: V2N allows vehicles to connect to broader networks (e.g., cellular or Wi-Fi) to access services provided by control centers or cloud servers. V2N enables vehicles to access real-time weather updates or traffic data that impacts route planning [6].

- **Vehicle-to-Pedestrian (V2P)**: V2P communication is focused on improving the safety of pedestrians and cyclists by enabling communication between vehicles and personal devices. For instance, a pedestrian's smartphone receives an alert if a nearby vehicle is approaching at high speed [4].

Table 2.1 presents the different types of communication in VANs along with example applications.

Communication Type	Description	Example Application
V2V	Direct vehicle-to-vehicle communication	Collision avoidance, cooperative driving
V2I	Vehicle communication with infrastructure	Intersection safety, traffic congestion updates
V2N	Connection to broader networks (cellular, Wi-Fi)	Weather updates, traffic data, navigation
V2P	Vehicle communication with pedestrians/cyclists	Pedestrian safety alerts

Table 2.1: Types of Communication in VANs and Example Applications

Figure 2.1 illustrates the components and communication flows within a typical VAN setup, showing V2V, V2I, RSU, and OBU interactions. This diagram is adapted from previous research on VAN architecture, which highlights the roles of various networked entities [1].

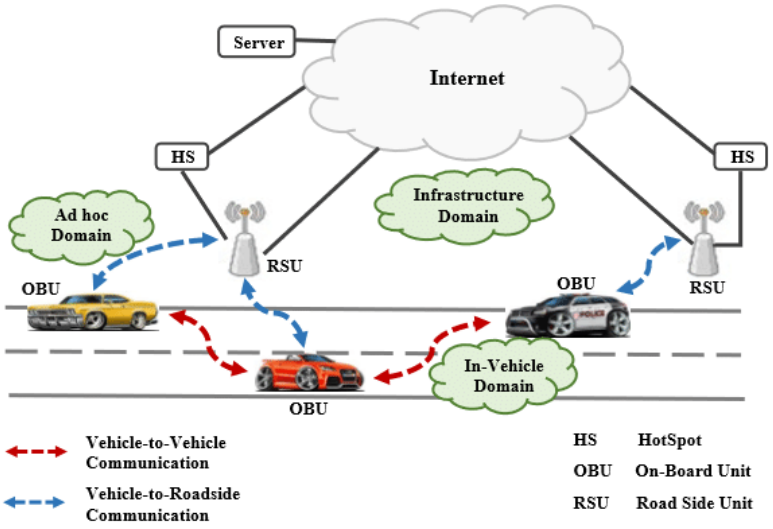

Figure 2.1: Overview of Vehicle Area Network (VAN) Architecture, adapted from [1].

2.1.3 VAN Communication Protocols

In addition to the physical architecture, VANs rely on specific communication protocols to manage data exchange. Common protocols include:

- **Dedicated Short-Range Communications (DSRC)**: DSRC is a wireless communication protocol specifically designed for V2V and V2I applications. It supports low-latency communication, which is critical for safety applications like collision avoidance.
- **Cellular V2X (C-V2X)**: An alternative to DSRC, C-V2X leverages cellular networks to provide high-bandwidth communication over greater distances, supporting applications such as real-time navigation and advanced driver assistance systems.
- **5G and Beyond**: The introduction of 5G is expected to enhance VAN capabilities with faster speeds and lower latency. 5G V2X supports high-density traffic communication, making it suitable for urban environments and autonomous driving scenarios [8].

2.1.4 Security Challenges in VANs

VANs face several security challenges due to their open and dynamic environment:

- **Authentication**: Vehicles and infrastructure nodes must authenticate each other to prevent unauthorized access, spoofing, and impersonation attacks.
- **Confidentiality and Integrity**: It is essential to maintain the confidentiality and integrity of messages, especially in safety-critical applications. Threats like eavesdropping and data tampering must be addressed.
- **Privacy**: Location tracking is a major privacy concern in VANs, as vehicles exchange position and trajectory data frequently. Ensuring anonymity is crucial to prevent tracking by unauthorized parties.
- **Reliability**: VANs operate in dynamic environments, where high-speed mobility and frequent disconnections can affect reliability [7].

Requirement	Description	Associated Threats
Authentication	Verifying entities to prevent unauthorized access	Impersonation, Sybil attacks
Confidentiality	Protecting data from unauthorized access	Eavesdropping, data sniffing
Integrity	Ensuring data has not been tampered with	Data tampering, replay attacks
Privacy	Preserving user data and identity	Tracking, location leakage
Reliability	Ensuring stable connections in dynamic environments	Network fragmentation, DoS

Table 2.2: Key Security Requirements in VANs and Associated Threats

2.2 Physically Unclonable Functions (PUFs)

Physically Unclonable Functions (PUFs) are hardware-based security features that use manufacturing variations to create unique identifiers for each device. When given an input, or *challenge*, a PUF produces a unique *response* based on its physical properties. This behavior forms the basis for PUF-based authentication, as responses are specific to each device and difficult to replicate without access to the hardware [10, 11].

PUFs are particularly useful in security-sensitive applications since they do not require stored cryptographic keys, generating responses dynamically instead. This makes them resilient to key extraction attacks, ideal for resource-constrained environments like VANs and IoT [12].

2.2.1 Types of PUFs

Various PUF types are suited to different applications:

- **Silicon PUFs**: The most common type, utilizing variations in transistors or memory cells. **SRAM PUFs** derive unique fingerprints from SRAM cells' power-up states, making them compatible with standard CMOS processes and widely used in microcontrollers [13, 11].

- **Optical PUFs**: These use laser scattering patterns in a transparent material with randomly distributed particles. Optical PUFs are highly resistant to duplication but are less practical for embedded systems due to size and cost [14].

- **Coating PUFs**: Coating PUFs rely on random particle distributions in a surface coating, providing tamper resistance. Any attempt to alter the coating disrupts the PUF's response, making it suitable for anti-tamper applications [15].

- **Weak PUFs**: Weak PUFs generate a limited and fixed number of challenge-response pairs (CRPs). They are highly reliable and are mainly used for cryptographic key generation or device-specific unique identification. Due to their stability, weak PUFs are particularly suitable for secure key storage and key generation in constrained environments [16].

- **Strong PUFs**: Strong PUFs provide a large challenge-response space, making them ideal for authentication protocols. They exhibit high entropy and unpredictability, which improves their resistance to modeling attacks. Strong PUFs are commonly used in secure authentication systems and anti-counterfeiting applications due to their vast challenge space [16].

2.2.2 Applications of PUFs in VANs

In Vehicle Area Networks (VANs), PUFs provide critical benefits such as secure authentication, privacy protection, and efficient key generation, all while minimizing the need for stored cryptographic keys. Given the dynamic, decentralized nature of VANs, PUFs are well-suited for use in the following areas:

- **Authentication**: PUFs can uniquely verify the identity of vehicles and roadside units (RSUs) without requiring stored keys. Each vehicle's unique challenge-response behavior ensures only authorized entities can participate in the network. This property helps mitigate unauthorized access and impersonation attacks, which are major security concerns in VANs [12].

- **Secure Key Generation**: Since PUFs do not rely on stored keys, they can dynamically generate secure session keys during communication with other ve-

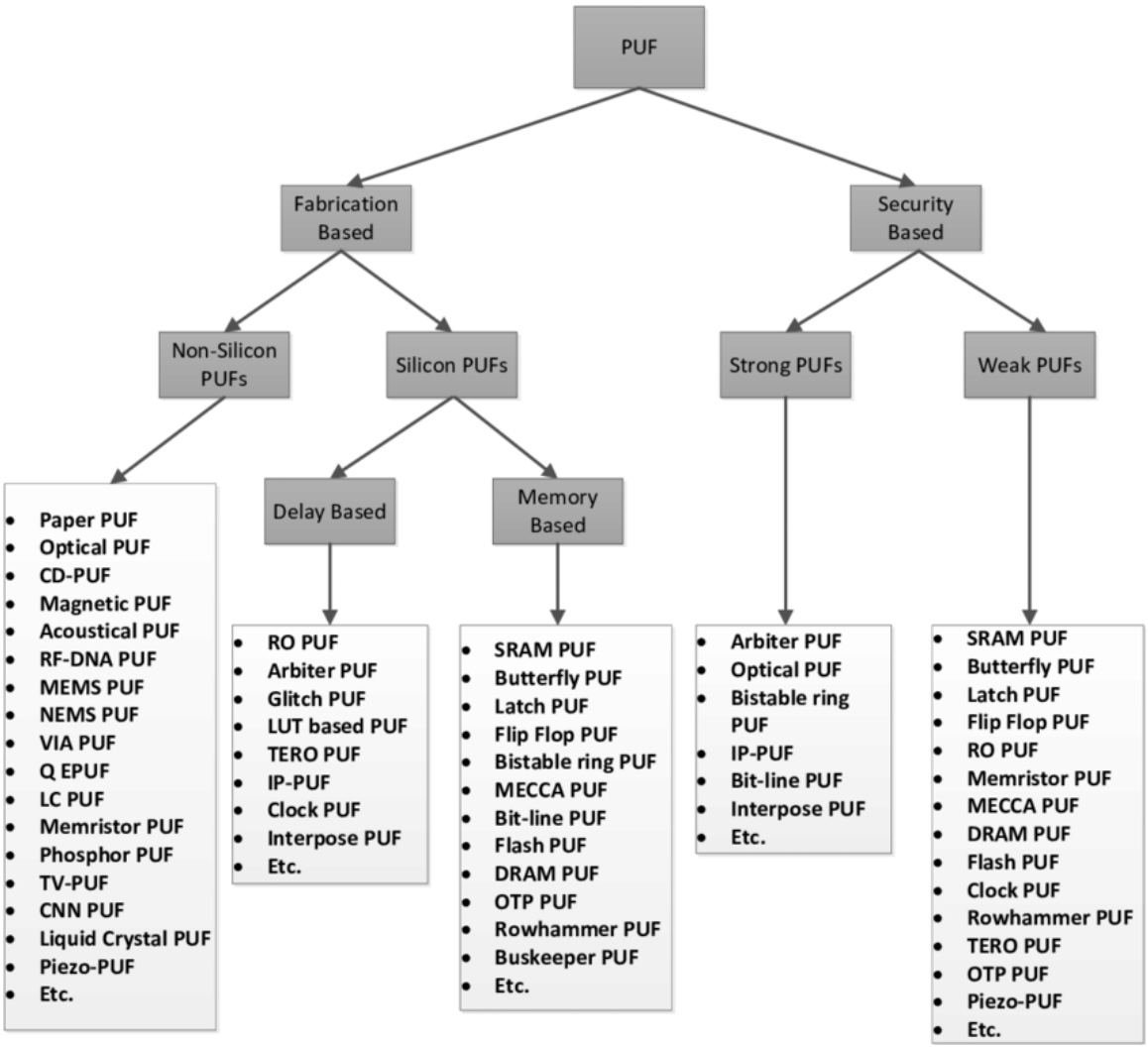

Figure 2.2: Illustration of Different Types of Physically Unclonable Functions (PUFs) adopted from [2]

hicles (V2V) or infrastructure (V2I). This feature reduces the risk of key exposure and minimizes the need for secure key storage mechanisms, making PUFs a lightweight solution for secure communication in VAN environments [11].

- **Privacy Protection**: Maintaining user privacy is essential in VANs due to the frequent exchange of location and identity data. PUF-based anonymized authentication allows the verification of a vehicle's identity without revealing the driver's personal information. This privacy-preserving approach supports secure vehicular applications and helps combat tracking by unauthorized parties [12].

2.2.3 Benefits of PUFs in Security

The unique characteristics of PUFs make them particularly advantageous for secure communication in VANs and other IoT environments:

- **Unclonability**: PUFs are naturally resistant to cloning due to the dependence on hardware-level manufacturing variations, making them ideal for secure device authentication where traditional cryptographic keys may be at risk [10].
- **Resilience to Tampering**: Attempts to physically tamper with a PUF (such as through side-channel attacks or chip manipulation) are likely to alter its physical characteristics, thereby disrupting its response and hindering unauthorized access attempts [14].
- **Lightweight Design**: PUFs have a low computational overhead compared to traditional cryptographic methods, making them suitable for resource-constrained environments like VANs. Their lightweight design ensures efficient, real-time authentication and key generation with minimal resource consumption [11].

Benefit	Description	Application in VANs
Unclonability	Unique responses due to hardware variations, making PUFs resistant to cloning	Device authentication
Tamper Resistance	Physical attempts to alter a PUF disrupt its functionality	Defense against physical tampering
Lightweight Design	Low computational overhead, suitable for real-time applications in VANs	Real-time authentication and secure key generation
Privacy	Supports anonymized authentication, reducing the need for identifying data	Privacy-preserving VAN communication

Table 2.3: Key Advantages of PUFs in VANs and Their Applications

2.3 Security Protocol Verification and Formal Analysis Tools

To ensure the security of Vehicle Area Networks (VANs), protocols must be rigorously tested against attacks such as eavesdropping, replay, and impersonation. Formal

verification provides a mathematical approach to evaluate these protocols across all potential scenarios, ensuring they meet critical security properties like authentication and confidentiality [9].

Verification tools enable researchers to model protocols, simulate attacks, and detect vulnerabilities. This is especially important in VANs, where protocols face challenges due to high mobility and decentralized control [17].

2.3.1 High-Level Protocol Specification Language (HLPSL)

HLPSL is a formal language used to model security protocols by defining the roles, actions, and communications between entities (e.g., vehicles, RSUs). It supports specifying security goals like secrecy and authenticity, making it ideal for rigorous testing against attacks. HLPSL models can be analyzed using tools like AVISPA to verify security properties across a range of scenarios [18].

2.3.2 AVISPA (Automated Validation of Internet Security Protocols and Applications)

AVISPA is a widely used tool for verifying security protocols modeled in HLPSL. It uses four back-end engines for comprehensive analysis:

- **OFMC**: Explores all protocol executions symbolically to identify path-specific flaws.
- **CL-AtSe**: Uses constraint-solving to detect vulnerabilities, particularly in complex protocols.
- **SATMC**: Converts protocols into logical formulas, using SAT-solving to verify security goals.
- **TA4SP**: Applies tree automata to examine protocol states, useful for detecting state-based issues [18, 9].

AVISPA outputs ‘SAFE‘, ‘UNSAFE‘, or ‘INCOMPLETE‘ results, indicating whether the protocol meets its specified security goals under tested conditions [18].

2.3.3 SPAN (Security Protocol Animator for AVISPA)

SPAN is a graphical interface for AVISPA, allowing users to visually model protocols and simulate attacks. It provides an accessible way to define message exchanges and set up attack scenarios, making it easier to identify vulnerabilities and validate protocol behavior under adversarial conditions [19].

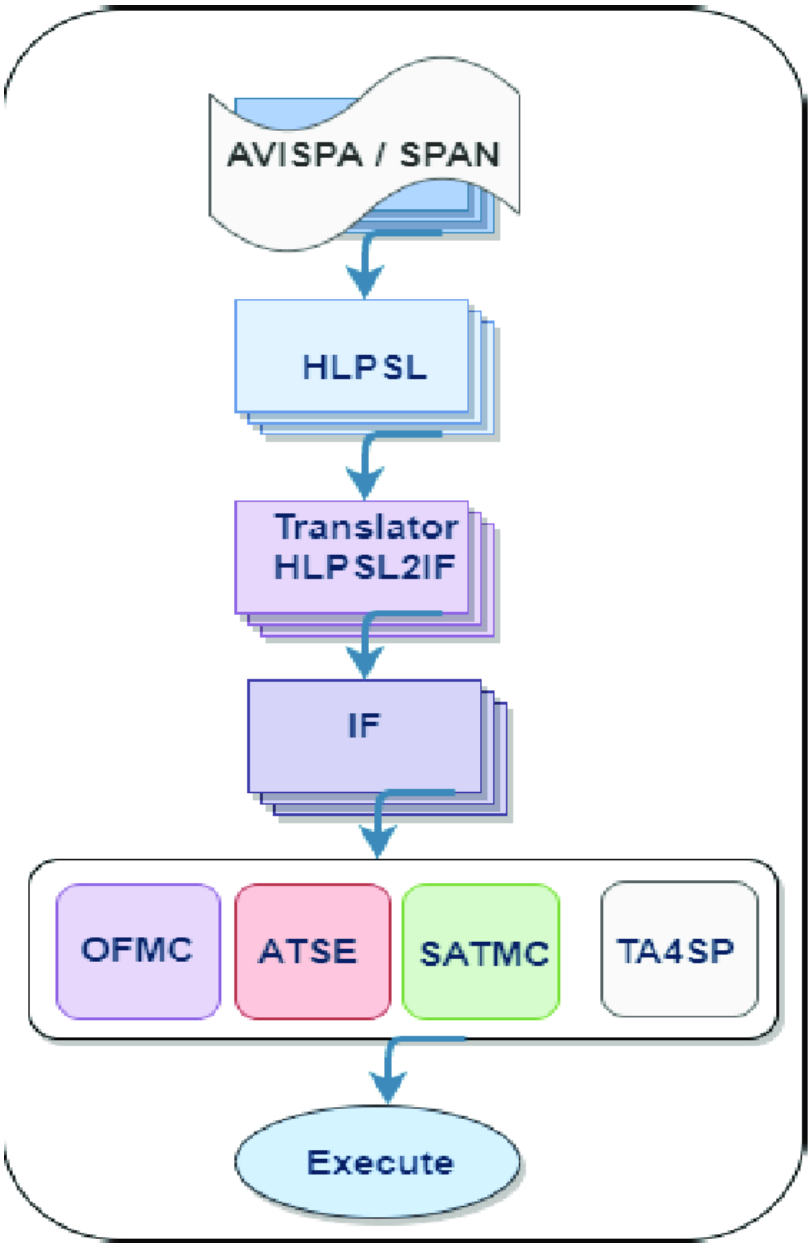

Figure 2.3: Workflow of AVISPA and SPAN for Security Protocol Verification adopted from [3]

2.3.4 Applications in Vehicle Area Networks

Formal verification tools like AVISPA and SPAN play a crucial role in ensuring the security of VAN protocols. In the context of VANs, these tools can be used to model interactions between vehicles, roadside units, and central authorities, simulating various attack scenarios to validate protocol resilience. Common security properties that AVISPA verifies in VAN protocols include:

- **Authentication**: Ensures that all participating entities (vehicles, RSUs) are correctly authenticated, preventing unauthorized access.
- **Confidentiality**: Confirms that sensitive information, such as session keys and identity data, remains confidential and is not accessible to attackers.
- **Integrity**: Verifies that message contents are not altered during transmission, preserving data integrity across all communication channels.
- **Non-repudiation**: Prevents entities from denying their participation in a transaction, ensuring accountability [17, 18].

2.4 Related Work on VAN Security and PUF-Based Protocols

Securing communication in Vehicle Area Networks (VANs) is essential, particularly as connected and autonomous vehicle use grows. Various protocols have been developed to address key security requirements like authentication, confidentiality, integrity, and privacy. Among these, PUF-based approaches have gained attention for their lightweight and tamper-resistant qualities. This section reviews notable work on both traditional VAN security protocols and PUF-based solutions tailored for VANs.

2.4.1 VAN Security Protocols

VAN security protocols face challenges due to high mobility and dynamic network environments. Traditional methods such as identity-based encryption (IBE) and public key infrastructure (PKI) have been widely applied:

- **Identity-Based Encryption (IBE)**: Smith and Brown (2019) proposed an IBE scheme for VANs, simplifying key management by deriving public keys

from vehicle identities. However, IBE requires a trusted authority and may not suit resource-limited VANs [20].

- **Public Key Infrastructure (PKI)**: Zhang and Zhao (2020) explored PKI, where each vehicle has a unique key pair issued by a central authority, ensuring strong authentication but adding computational overhead [21].
- **Certificate-Based Authentication**: Often used in VANs, certificate-based methods verify vehicle identities but may incur latency and complexity, especially with large certificate revocation lists (CRLs) [22].

While effective, these methods can struggle with scalability and efficiency, especially in high-density, mobile VAN environments. This has led to interest in PUF-based protocols as lightweight alternatives.

2.4.2 PUF-Based Security Protocols in VANs

PUFs utilize physical variations in hardware to create unique device identifiers, supporting lightweight, tamper-resistant authentication in VANs.

- **PUF-Based Authentication for VANs**: Fakroon et al. (2021) proposed a PUF-based multifactor scheme for VANs, combining PUF responses with vehicle identifiers for secure, low-computation V2V and V2I communication [23].
- **Privacy-Preserving PUF Protocols**: Xu, Xie, and Zhang (2021) introduced a PUF-based protocol that anonymizes vehicle identities to prevent tracking, using unclonable PUF responses for secure authentication [24].
- **PUFGuard Protocol for V2X Authentication**: Elhadad and Gebali (2023) developed the PUFGuard protocol for V2X communication, which uses PUFs for mutual authentication and session key generation, providing resilience against common VAN attacks with minimal latency [8].

2.4.3 Comparative Analysis of VAN Security Approaches

Table 2.4 presents a comparative analysis of traditional VAN security protocols and PUF-based approaches. While conventional methods like PKI and IBE provide strong security, they tend to incur higher computational overhead and latency. In contrast,

PUF-based protocols offer lightweight, privacy-preserving alternatives suitable for real-time VAN environments, though they may require further development to support large-scale deployment.

Protocol Type	**Security Features**	**Advantages**	**Limitations**
Identity-Based Encryption (IBE)	Authentication, confidentiality	Simplifies key management, scalable	Requires trusted authority, high computational cost [20]
Public Key Infrastructure (PKI)	Strong authentication, integrity	Well-established, robust security	High computational cost, scalability issues [21]
Certificate-Based Authentication	Authentication, integrity	Reliable for high-security needs	Requires frequent updates, large CRLs [22]
PUF-Based Authentication (Fakroon et al.)	Lightweight, secure	Reduced overhead, privacy-preserving	Limited deployment, compatibility issues [23]
PUFGuard Protocol (Elhadad and Gebali)	Mutual authentication, session key generation	Lightweight, low-latency, resilient to attacks	Still under evaluation for large-scale deployment [8]

Table 2.4: Comparative Analysis of Traditional and PUF-Based Security Protocols in VANs

Chapter 3

Design and Implementation of the PUFGuard Protocol

3.1 Overview of the PUFGuard Protocol

The PUFGuard protocol is a security solution designed to provide secure, lightweight authentication for Vehicle-to-Everything (V2X) communication in Vehicle Area Networks (VANs) proposed by Gebali and Elhadad [8]. By leveraging Physically Unclonable Functions (PUFs), PUFGuard aims to establish secure, tamper-resistant communication channels between vehicles (V2V), vehicles and roadside units (V2I), and vehicles with infrastructure. PUFGuard addresses key security goals in VANs, including authentication, confidentiality, integrity, and non-repudiation, while maintaining low computational overhead suitable for real-time applications.

Unlike traditional cryptographic methods, which require storing sensitive keys, PUFGuard uses the unique hardware properties of each device to dynamically generate authentication responses. This design enhances resilience against cloning, replay, and man-in-the-middle attacks, making it well-suited for high-mobility environments [8].

3.2 Protocol Objectives and Security Requirements

The PUFGuard protocol is designed to fulfill the following security objectives in VAN environments:

- **Authentication**: Ensures that only authorized vehicles and infrastructure en-

tities participate in the network. By using PUFs for unique challenge-response authentication, PUFGuard verifies the legitimacy of each entity without needing to store cryptographic keys.

- **Confidentiality**: Prevents unauthorized entities from accessing sensitive data, such as session keys and identity information, by using dynamically generated encryption keys.
- **Integrity**: Protects the integrity of transmitted data to prevent tampering. PUFGuard uses hashed values and secure communication channels to ensure data integrity across V2V and V2I channels.
- **Non-repudiation**: Provides verifiable proof of participation, ensuring that entities cannot deny their actions. This is achieved through unique, device-specific responses from the PUF.
- **Privacy**: Maintains user privacy by using anonymized challenge-response pairs, ensuring that vehicle identities are protected while enabling secure communication [24].

3.3 PUFGuard Protocol Architecture

Figure 3.1 presents the PUFGuard protocol architecture comprises three main components: vehicles, roadside units (RSUs), and a certification authority (CA). Each component has specific roles in establishing and maintaining secure communication within the VAN.

- **Vehicle**: Each vehicle is equipped with a PUF module, which generates unique responses based on hardware-specific characteristics. Vehicles use these responses for authentication with RSUs and other vehicles.
- **Roadside Unit (RSU)**: RSUs act as intermediaries between vehicles and the certification authority, facilitating V2I and V2V communication. RSUs are responsible for initiating authentication challenges and verifying PUF-based responses.
- **Certification Authority (CA)**: The CA manages and distributes public keys to vehicles and RSUs. It plays a critical role in the initial setup of secure channels and periodically updates keys to ensure long-term security [8].

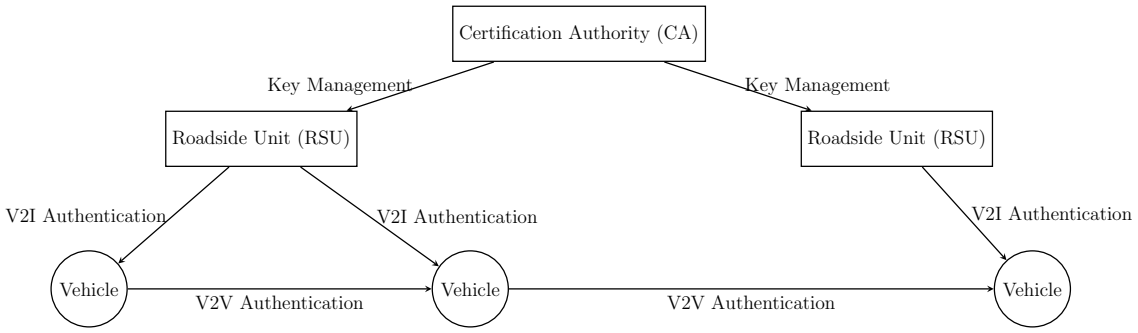

Figure 3.1: PUFGuard Protocol Architecture in Vehicle Area Networks (VANs)

3.4 PUF-Based Authentication Algorithms

The PUFGuard protocol introduces secure communication mechanisms for Vehicle-to-Infrastructure (V2I) interactions, leveraging the unique properties of Physically Unclonable Functions (PUFs). V2I and V2V communication is essential for enabling intelligent transportation systems, as it facilitates real-time data exchange between vehicles and roadside infrastructure. However, the dynamic and decentralized nature of vehicular networks makes them susceptible to various cyber threats, including replay attacks, impersonation, and Man-in-the-Middle (MitM) attacks.

3.4.1 V2I Authentication Protocol

The V2I Authentication Protocol is part of the PUFGuard mechanism proposed by Gebali and Elhadad [8]. It is designed to establish secure communication between a vehicle and a roadside unit (RSU) by leveraging PUFs. The protocol ensures mutual authentication, session key establishment, and protection against common attacks Below are the key steps that are described in Algorithm 1:

1. **Connection Initiation:**
   The vehicle initiates communication with the nearest RSU by broadcasting a connection request containing its identifier (ID_V). The RSU determines whether it has the associated challenge-response pair (CRP) locally or must retrieve it from the Certification Authority (CA).

2. **Challenge-Response Verification:**
   The CA provides the PUF challenge-response pair (CRP) associated with the

vehicle to the RSU. The RSU selects a challenge (c) from the CRP and computes a hash-based session key ($k = H(c, r)$), where r is the PUF response corresponding to the challenge.

3. **Nonce and Authentication Hash:**
   A unique nonce (N) is generated to ensure session freshness, and an authentication hash ($h = H(N, c, r)$) is computed. These values are sent back to the vehicle, ensuring that both parties share the same session key and authenticated state.

4. **Vehicle Verification:**
   The vehicle computes its own PUF response using the challenge ($r = PUF(c, w)$) and derives the session key (k) independently. It decrypts the nonce (N) and computes the authentication hash (h'). The vehicle sends this hash (h') back to the RSU for verification.

5. **Authentication Confirmation:**
   The RSU compares the received hash (h') with its computed hash (h). If they match, authentication is successful, and the protocol transitions to V2V authentication. If not, the session is terminated.

Algorithm 1 V2I Authentication Protocol proposed by [8]

1: $V \rightarrow R$: broadcast_request_connect(ID_V)
2: R: handover(ID_V) ▷ Nearest RSU receiving the connection request
3: **if** $ID_V \in R_i$ **then**
4: $R \rightarrow R_i$: get_CRP(ID_V)
5: **else**
6: $R \rightarrow C$: get_CRP(ID_V)
7: **end if**
8: C: $m_1 = (CRP_V)$
9: $C \rightarrow R$: m_3
10: R: (c, w) = choose_CRP
11: R: N = generate_nonce()
12: R: $k = H(c, r)$ ▷ Session key between R and V
13: R: $h = H(N, c, r)$ ▷ Authentication and freshness hash
14: R: $m_2 = E_k(N)$
15: R: $m_3 = (m_2 \| c, w)$
16: $R \rightarrow V$: m_3
17: V: $r = PUF(c, w)$
18: V: $k = H(c, r)$
19: V: $N = D_k(m_2)$
20: V: $h' = H(N, c, r)$
21: $V \rightarrow R$: h'
22: **if** $h = h'$ **then**
23: move to V2V authentication
24: **else**
25: failed authentication
26: **end if**

3.4.2 V2V Authentication Protocol

The V2V Authentication Protocol is part of the PUFGuard mechanism proposed by Gebali and Elhadad [8]. It is designed to establish secure communication between two vehicles (V_1 and V_2) through their respective roadside units (R_1 and R_2). Below are the key steps that are described in Algorithm 2:

1. **Pairing Request and Validation**

V_1 sends a request to its RSU (R_1) to initiate pairing with V_2, including both vehicles' identifiers (ID_1 and ID_2).
R_1 contacts the RSU managing V_2 (R_2) to confirm the availability of V_2 and acknowledges the pairing request.

2. **Confirmation and Communication Setup**
   Both RSUs inform their respective vehicles (V_1 and V_2) that the other is safe to communicate with.
   R_1 and R_2 generate nonces (N_1 and N_2) to ensure session freshness and share these along with vehicle identifiers.

3. **Session Key and Authentication Hash**
   Both RSUs compute the session key (k) and authentication hash (h) based on nonces (N_1 and N_2) and vehicle identifiers.
   The session key ensures encrypted communication, while the hash authenticates message integrity and freshness.

4. **Secure Exchange with Vehicles**
   RSUs encrypt and send the session key and authentication hash to their respective vehicles.
   The vehicles decrypt these messages to retrieve the session key and authentication hash.

5. **Mutual Authentication**
   Vehicles exchange their respective authentication hashes ($h_{1,2}$ and $h_{2,1}$). Each vehicle compares the received hash with its own computed value:

   - If the hashes match, mutual authentication is successful, and V2V communication begins.
   - If the hashes do not match, authentication fails, and communication is terminated.

Algorithm 2 V2V Authentication Protocol proposed by [8]

Require: Two vehicles V_1 and V_2, respective roadside units R_1 and R_2

Ensure: Secure session key establishment and mutual authentication

1: $V_1 \rightarrow R_1$: request_pairing(ID_1, ID_2)
2: R_1: get_RSU_ID(ID_2)
3: $R_2 \rightarrow R_1$: acknowledge(ID_2)
4: $R_1 \rightarrow V_1$: safe_to_communicate(ID_2)
5: $R_2 \rightarrow V_2$: safe_to_communicate(ID_1)
6: R_1: $N_1 =$ generate_nonce()
7: $R_1 \rightarrow R_2$: (N_1, ID_1, ID_2)
8: R_2: $N_2 =$ generate_nonce()
9: R_2: $k_{2,1} = H(N_1, N_2, ID_1, ID_2)$ ▷ Session key for R_2 and R_1
10: R_2: $h_{2,1} = H(N_1, N_2, ID_1, ID_2)$ ▷ Authentication hash for R_2
11: $R_2 \rightarrow R_1$: (N_2)
12: R_1: $k_{1,2} = H(N_1, N_2, ID_1, ID_2)$ ▷ Session key for R_1 and R_2
13: R_1: $h_{1,2} = H(N_1, N_2, ID_1, ID_2)$ ▷ Authentication hash for R_1
14: R_1: $m_1 = E_{k_1}(k_{1,2}, h_{1,2})$
15: R_2: $m_2 = E_{k_2}(k_{2,1}, h_{2,1})$
16: $R_1 \rightarrow V_1$: m_1
17: $R_2 \rightarrow V_2$: m_2
18: V_1: $m_3 = D_{k_1}(m_1)$
19: V_2: $m_4 = D_{k_2}(m_2)$
20: $V_1 \rightarrow V_2$: $h_{1,2}$
21: $V_2 \rightarrow V_1$: $h_{2,1}$
22: **if** $h_{1,2} = h_{2,1}$ **then**
23: move to V2V communication
24: **else**
25: failed authentication at V_1
26: **end if**
27: **if** $h_{2,1} = h_{1,2}$ **then**
28: move to V2V communication
29: **else**
30: failed authentication at V_2
31: **end if**

3.5 Security Analysis of PUFGuard Protocol

The PUFGuard protocol is designed to counteract several common attack vectors in VAN environments, enhancing the security of both V2I and V2V communication.

- **Replay Attack Resistance**: PUFGuard uses nonces and session-specific challenge-response pairs to prevent replay attacks. Each session is established with fresh challenges, ensuring that old messages cannot be reused to gain unauthorized access.
- **Man-in-the-Middle (MitM) Attack Resistance**: By using PUF-based responses that are unique and tamper-resistant, PUFGuard mitigates the risk of MitM attacks. Any alteration in the response by an attacker would disrupt the PUF's authentication process, preventing successful impersonation [23].
- **Impersonation Attack Resistance**: The unique, unclonable properties of PUFs make it nearly impossible for attackers to impersonate legitimate vehicles or RSUs, as they cannot generate valid PUF responses without the original hardware [8].

Chapter 4

Modeling and Verification of the PUFGuard Protocol

4.1 Introduction to Formal Verification in Security Protocols

Formal verification is a mathematical approach used to rigorously assess whether a security protocol meets essential security properties, such as confidentiality, integrity, and authentication. Unlike traditional testing methods, formal verification evaluates all possible execution paths using symbolic representations, thereby providing comprehensive assurance of the protocol's security against various attack vectors. In this chapter, the PUFGuard protocol is modeled in the High-Level Protocol Specification Language (HLPSL) and verified using the Automated Validation of Internet Security Protocols and Applications (AVISPA) tool, which enables systematic testing of resilience against common threats, including replay, impersonation, and man-in-the-middle attacks [9].

4.2 Modeling the PUFGuard Protocol in HLPSL

The PUFGuard protocol is designed to secure communications in Vehicle Area Networks (VANs) by utilizing two core authentication protocols: the Vehicle-to-Infrastructure (V2I) protocol and the Vehicle-to-Vehicle (V2V) protocol. These protocols employ Physically Unclonable Functions (PUFs) to provide unique, tamper-resistant identifiers for each vehicle and infrastructure component. The following sections detail the

HLPSL models for these protocols.

4.2.1 V2I Authentication Protocol

The V2I Authentication Protocol facilitates secure communication between a vehicle (V), a roadside unit (R), and a certification authority (C). It ensures mutual authentication and establishes a secure session key between V and R.

The detailed HLPSL code for this protocol is included in the appendix (see Appendix .1). The code defines the behavior of each entity and specifies the message flows required to achieve secure communication.

4.2.2 V2V Authentication Protocol

The V2V Authentication Protocol enables two vehicles, V_1 and V_2, to establish a secure session key after being authenticated by their respective roadside units, R_1 and R_2.

The detailed HLPSL code for this protocol is included in the appendix (see Appendix .2). This model captures the interactions between the vehicles and roadside units, ensuring mutual authentication and session key generation.

4.2.3 Defining Attack Scenarios in HLPSL

To assess the resilience of the PUFGuard protocol, three attack scenarios were modeled: replay attacks, impersonation attacks, and man-in-the-middle (MitM) attacks.

- **Replay Attack:** An attacker replays a previously intercepted message to gain unauthorized access. The HLPSL code for this attack is detailed in Appendix .3.1.
- **Impersonation Attack:** An attacker impersonates a legitimate vehicle by sending fake authentication messages to the RSU. The code is presented in Appendix .3.2.
- **Man-in-the-Middle Attack:** An attacker intercepts and modifies messages between the vehicle and RSU. Details of the HLPSL model for this attack are in Appendix .3.3.

4.3 Running Verification with AVISPA

The AVISPA tool was configured to simulate the attack scenarios defined above, using its four backends: OFMC, CL-AtSe, SATMC and TA4SP to test the resilience of the PUFGuard protocol.

- **OFMC**: Verified vulnerabilities by exploring possible paths of the replay attack.
- **CL-AtSe**: Solved logical constraints to assess the success probabilities of impersonation attacks.
- **SATMC**: Verified protocol consistency against man-in-the-middle attack scenarios.
- **TA4SP**: Examined all possible states and transitions, identifying any state-based vulnerabilities in both V2I and V2V protocols.

Chapter 5

Results and Analysis

5.1 AVISPA Results

In this section, we present the results obtained from the AVISPA tool after testing the PUFGuard protocol against various attack scenarios. The results provide insight into the protocol's resilience and effectiveness in maintaining security within Vehicle Area Networks (VANs). AVISPA outputs for each scenario are classified as **SAFE**, **UNSAFE**, or **INCOMPLETE**.

5.1.1 Replay Attack

In the replay attack scenario, an attacker attempts to reuse a previously intercepted authentication message to gain unauthorized access. The AVISPA analysis produced the following result:

- **Result: SAFE**
- **Interpretation:** The **SAFE** result indicates that PUFGuard successfully mitigates replay attacks. This is achieved by using a session-specific nonce and PUF-based challenge-response pair for each authentication attempt, which invalidates any old or previously intercepted messages. As a result, replayed messages are not accepted, ensuring that the protocol maintains session freshness and integrity.

5.1.2 Impersonation Attack

The impersonation attack scenario simulates an attacker attempting to masquerade as a legitimate vehicle by sending a fake authentication request to the roadside unit (RSU). The AVISPA output for this scenario is as follows:

- **Result: SAFE**
- **Interpretation:** The **SAFE** outcome suggests that PUFGuard effectively prevents impersonation attacks. Since each vehicle's PUF is unique and unclonable, attackers cannot generate a valid response to an authentication challenge without access to the original hardware. This result demonstrates that PUFGuard maintains identity integrity, allowing only legitimate vehicles and RSUs to participate in the network.

5.1.3 Man-in-the-Middle Attack

For the man-in-the-middle (MitM) attack, we modeled an attacker who intercepts and alters messages between the vehicle and RSU. The AVISPA tool generated the following output:

- **Result: SAFE**
- **Interpretation:** The **SAFE** classification confirms that PUFGuard is resistant to MitM attacks. The protocol's PUF-based responses ensure that any message tampering by an attacker would disrupt the authentication process. This resilience stems from the unique PUF properties and session-specific encryption keys, which prevent unauthorized message alteration and uphold the confidentiality and integrity of the communication.

5.2 Analysis of Findings

The AVISPA results indicate that PUFGuard effectively defends against replay, impersonation, and MitM attacks, with each scenario receiving a **SAFE** status. These findings suggest that the protocol's design, which incorporates PUF-based challenge-response pairs, session-specific nonces, and dynamic session keys, is well-suited for maintaining security in VANs.

The following analysis highlights the protocol's defensive mechanisms in each tested scenario:

- **Replay Attack Defense**: The inclusion of a nonce in each authentication request ensures session freshness, effectively invalidating repeated messages. The use of PUFs further strengthens this mechanism by generating unique, hardware-dependent responses.
- **Impersonation Attack Defense**: The unclonability of PUFs provides a robust defense against impersonation, as attackers cannot produce valid responses without the original hardware.
- **Man-in-the-Middle Attack Defense**: The combination of PUF-based responses and session-specific encryption keys prevents unauthorized modification of messages, protecting both the integrity and confidentiality of the communication.

Overall, the results confirm that PUFGuard meets its security objectives by successfully mitigating these common attack vectors.

5.3 Discussion of Protocol Strengths and Weaknesses

The PUFGuard protocol provides strong security for communication in Vehicle Area Networks (VANs), yet, like all protocols, it has both strengths and areas that could benefit from improvement.

5.3.1 Strengths of the PUFGuard Protocol

The AVISPA results highlight PUFGuard's resilience against common security threats, including replay, impersonation, and man-in-the-middle attacks. Key strengths of the protocol are:

- **High Security via PUF Technology**: PUFGuard leverages Physically Unclonable Functions (PUFs) for unique, device-specific challenge-response authentication, making it difficult for attackers to impersonate vehicles or roadside units (RSUs) without access to the original hardware [24, 23].

- **Session Freshness and Integrity**: The use of nonces and session-specific responses prevents replay attacks, ensuring that each session is unique and secure in dynamic VAN environments [9].
- **Lightweight and Scalable Design**: PUF-based authentication is computationally efficient, allowing PUFGuard to function well in resource-limited environments like VANs, where rapid authentication and mobility are essential [8].
- **Effective Against Common Attacks**: AVISPA tests confirmed that PUFGuard's design, including dynamic session keys and PUF-based authentication, effectively mitigates replay, impersonation, and MitM attacks, making it highly secure for open networks.

5.3.2 Weaknesses and Suggested Improvements

Despite its strengths, PUFGuard has some limitations and areas for improvement:

- **Scalability Challenges**: PUFGuard may face scalability issues as VANs grow, especially in high-density areas. Distributed or hierarchical authentication models could help manage larger networks more efficiently.
- **PUF Reliability**: PUF responses may vary due to environmental factors, potentially leading to authentication issues. Implementing error-correcting codes could enhance PUF stability and improve consistency under varying conditions [24].
- **Vulnerability to Side-Channel Attacks**: PUFs may be susceptible to side-channel attacks (e.g., via power consumption analysis). Masking techniques or shielded hardware could help protect against these attacks, enhancing PUFGuard's security.
- **Adaptability to New Technologies**: Adapting PUFGuard for emerging VAN technologies, such as 5G and edge computing, could improve its efficiency and ensure its relevance in future VAN infrastructures [8].

Chapter 6

Conclusion and Future Work

6.1 Summary of Contributions

This project focused on modeling, verifying, and analyzing the PUFGuard protocol to secure communication in Vehicle Area Networks (VANs). The main contributions of this work include:

- **Modeling PUFGuard in HLPSL:** Developed HLPSL models for the V2V and V2I protocols, representing the protocol's entities, message flows, and security goals for formal verification.
- **Formal Verification with AVISPA:** Simulated replay, impersonation, and man-in-the-middle (MitM) attacks using the AVISPA tool. The simulations confirmed PUFGuard's resilience, with all tests resulting in a *SAFE* status.
- **Security Analysis:** Analyzed strengths, including robustness against attacks and scalability, and identified areas for improvement, such as PUF response reliability and privacy enhancements.

This work establishes PUFGuard as a secure and scalable solution for VAN environments, contributing to the advancement of vehicular network security.

6.2 Future Directions

Future work can further enhance PUFGuard's resilience and scalability:

- Test against additional attacks, such as side-channel and physical tampering.

- Explore other verification tools, like Tamarin or ProVerif, for deeper insights.
- Improve scalability through hierarchical or decentralized authentication models.
- Enhance PUF reliability using error-correcting techniques for diverse environments.
- Adapt PUFGuard to next-generation VAN technologies like 5G and edge computing.

6.3 Conclusion

This project demonstrated the effectiveness of the PUFGuard protocol for securing vehicle communications in VANs. By validating the protocol against key attack scenarios, we confirmed its strengths in authentication, confidentiality, and integrity, establishing it as a viable solution for VAN security. However, as the vehicular networking landscape continues to evolve, further research is necessary to adapt PUFGuard to new challenges, enhance its scalability, and improve its resilience to a broader set of security threats. These ongoing developments will contribute to safer and more reliable vehicular networks, paving the way for secure and privacy-preserving connected transportation systems.

Appendix A

Additional Information

.1 V2I Authentication Protocol Code

The following HLPSL code models the V2I Authentication Protocol, which facilitates secure communication between a vehicle (V), a roadside unit (R), and a certification authority (C).

```
role vehicle(V, R, C: agent, PUF: text, k: session_key)
played_by V
    init state := 0
    transition
        0 -> 1
            % Vehicle broadcasts its ID to RSU
            V -> R: IDv
        1 -> 2
    % Vehicle receives m3 from RSU, containing challenge c,
        helper data w, and encrypted nonce
            R -> V: {Ek(N) || c || w}_sk(R)
        2 -> 3
    % Vehicle computes PUF response r, derives session key,
        decrypts nonce, and sends h' to RSU
            V -> R: H(N, c, r)
end role

role rsu(R, V, C: agent, CRP: text, N: text, k: session_key)
```

```
played_by R
    init state := 0
    transition
        0 -> 1
            % RSU receives connection request from vehicle with IDv
            V -> R: IDv
            select_CRPs := CRP
            R -> C: get_CRP(IDv)
        1 -> 2
            % Receive CRP from CA and generate nonce
            C -> R: CRP
            N := new()
            c := choose_CRP(CRP)  % select challenge
            k := H(c, r)
            h := H(N, c, r)
            % Send m3 to vehicle
            R -> V: {Ek(N) || c || w}_sk(R)
        2 -> 3
            % Receive h' from Vehicle, compare with h
            V -> R: H(N, c, r)
end role

role certification_authority(C, R: agent, CRP: text)
played_by C

    init  state := 0
    transition
        0 -> 1
            % CA provides CRP set to RSU on request
            R -> C: get_CRP(IDv)
            C -> R: CRP
end role

role session(V, R, C: agent, PUV: text, k: session_key)
composed_of vehicle(V, R, C, PUV, k)
```

```
            rsu(R, V, C, CRP, N, k)
            certification_authority(C, R, CRP)
end role
```

.2 V2V Authentication Protocol Code

The following HLPSL code models the V2V Authentication Protocol, enabling secure session key establishment between two vehicles after being authenticated by their respective RSUs.

```
role vehicle1(V1, R1, V2: agent, k: session_key)
played_by V1
    init state := 0
    transition
        0 -> 1
            % V1 requests pairing with V2
            V1 -> R1: request_pairing(ID1, ID2)
        1 -> 2
        % Receives confirmation that V2 is authenticated
        and safe to communicate
            R1 -> V1: safe_to_communicate(ID2)
        2 -> 3
        % Mutual authentication and session key setup with V2
            V1 -> V2: H(N1, N2, ID1, ID2)
end role

role vehicle2(V2, R2, V1: agent, k: session_key)
played_by V2
    init state := 0
    transition
        0 -> 1
            % Receives safe_to_communicate from RSU
            R2 -> V2: safe_to_communicate(ID1)
        1 -> 2
            % Mutual authentication response to V1 with hash
```

```
            V2 -> V1: H(N1, N2, ID1, ID2)
end role
```

.3 Attack Scenarios Code

.3.1 Replay Attack

The attacker replays an old message to gain unauthorized access. The code for this attack scenario is shown below.

```
role replay_attack(V, R: agent, CRP: text)
played_by Intruder
    transition
        0 -> 1
            % Replay previously intercepted authentication
            message from vehicle to RSU
            Intruder -> R: {CRP}_sk(V)
end role
```

.3.2 Impersonation Attack

The attacker attempts to impersonate a legitimate vehicle by sending a fake authentication request to the RSU.

```
role impersonation_attack(Intruder, R: agent, Fake_CRP: text)
played_by Intruder
    transition
        0 -> 1
            % Intruder sends a fake authentication request to RSU
            Intruder -> R: {Fake_CRP}_sk(Intruder)
end role
```

.3.3 Man-in-the-Middle Attack

The attacker intercepts and alters messages between the vehicle and RSU.

```
role mitm_attack(V, R, Intruder: agent, CRP: text)
played_by Intruder
    transition
        0 -> 1
            % Intruder intercepts message from Vehicle to RSU
            V -> Intruder: {CRP}_sk(V)
            Intruder -> R: {Fake_CRP}_sk(Intruder)
end role
```

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