Developing a Smart Key Enhancing Autonomous Vehicle Security

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***Abstract*—Nowadays, vehicles have evolved from purely mechanical systems to sophisticated computer-controlled machines equipped with features such as remote start, GPS tracking, tire pressure monitoring, wireless diagnostics, and internet connectivity with over-the-air updates. This transformation has significantly enhanced capabilities like real-time navigation and remote system management. However, this digitization has also dramatically increased the attack vectors available to malicious actors. The expanded attack surface comprising electronic control units (ECUs), wireless communication interfaces, and interconnected systems presents new opportunities for exploitation, particularly in vehicle access systems. Among the most vulnerable components are Remote Keyless Entry (RKE) systems, which rely on physical key fobs using radio frequency (RF) communication. However, these advancements have introduced new security vulnerabilities, which are susceptible to attacks like replay, roll jam, and rollback. The result is a growing threat to vehicle security, with real-world implications evidenced by the over 800,000 vehicle thefts reported by the FBI in 2020 [1]. This paper proposes an Android based smart key fob application that addresses these challenges through advanced security features, including AES-256 GCM encryption, Role-Based Access Control (RBAC), time-based permissions, and Vehicle Identification Number (VIN) verification. The application offers universal compatibility across vehicle brands, offline functionality, and a machine learning based risk assessment model, providing a scalable, secure, and user-centric solution for modern vehicle access control. The necessity to reevaluate vehicle access control mechanisms arises from the increasing prevalence of cyberattacks.**

***Index Terms*—vehicle security, remote keyless entry, smart key fob, automotive security, RKE systems, vehicle entry, VIN verification**

I. Introduction

The automotive industry has transformed from mechanical systems to complex, computercontrolled platforms since the late 20th century, integrating Electronic Control Units (ECUs) for features like remote start, GPS tracking, wireless diagnostics, and over-the-air updates [3], [8], [9]. These advancements, driven by dozens of ECUs managing engine performance to navigation, enhance user convenience but expand the attack surface, making vehicles vulnerable to cyberattacks [4], [9]. Traditional Remote Keyless Entry (RKE) systems, introduced in the 1980s for RF-based access control, rely on outdated protocols and limited computational power, rendering them susceptible to replay and roll jam attacks [5], [8]. In 2020, the FBI reported over 800,000 vehicle thefts in the U.S., many linked to RKE vulnerabilities [1]. A 2021 report identified key fobs as the second most common attack vector, with 95% of tested vehicles vulnerable to RF exploits [2]. Rising thefts and the rapid evolution of connected and autonomous vehicle technologies necessitate robust security solutions [5], [6]. This paper proposes an Android based smart key fob application leveraging smartphone capabilities to deliver secure, interoperable vehicle access with advanced security features [7].

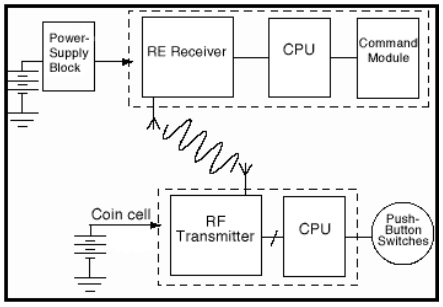

Fig. 1. An RF receiver and an RF transmitter circuit

A. Most Common Key Fob Attacks

Traditional RF-based key fobs are plagued by several key security vulnerabilities, including weak encryption, lack of robust authentication, and susceptibility to RF signal interception [10]. These weaknesses enable a range of attacks that exploit the design limitations of RKE systems. The following subsections detail the most prevalent attacks replay, roll jam, and rollback each exploiting distinct vulnerabilities [5].

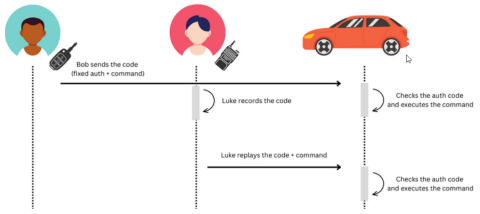

Fig. 2. Fixed code replay attack

1) *Replay Attacks:*

Replay attacks represent one of the earliest and most straightforward methods for compromising key fob security. It involve intercepting and retransmitting fixed or poorly randomized rolling codes to gain unauthorized access [5]. Older RKE systems using fixed codes are particularly vulnerable, though some modern systems with inadequate randomization remain at risk. Attackers could intercept these RF signals using widely available receivers and later replay them to gain unauthorized access [5]. Although modern systems have adopted rolling codes where each transmission uses a unique, synchronized code replay attacks remain effective against poorly implemented or legacy systems. A 2022 study found that certain vehicles still in production failed to implement sufficient code randomization, leaving them vulnerable to this technique. For example, researchers identified a replay attack vulnerability (CVE-2019-20626) in Honda and Acura models, demonstrating its real-world applicability [11].

2) *Rolling Code and Roll Jam Attacks:*

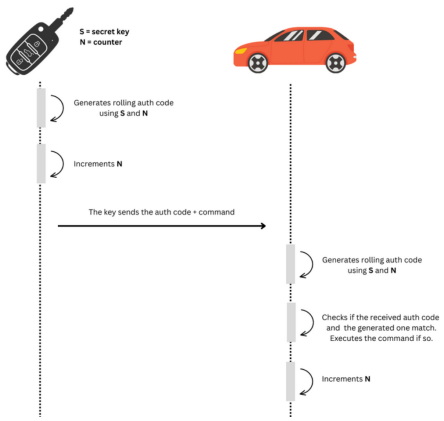

Fig. 3. Rolling Codes

Modern cars use rolling code systems to enhance security, where keys send unique codes each time, unlike fixed code systems [12]. As displayed in the figure 3, Both the car and key maintain a counter and use a pseudo-random number generator (PRNG) with a shared cryptographic key to produce the next code, preventing attackers from reusing or predicting codes [12]. However, if the key sends signals outside the car's range, it can go out of sync, as the car's counter doesn't update [12]. To address this, the car accepts a range of valid codes (n to n+k) [12]. If the key's code falls outside this range, it acts as a re-sync packet, realigning the system without triggering any action [12].

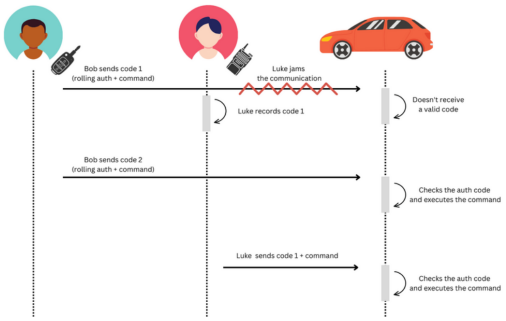

Fig. 4. RollJam attack scheme

Roll jam attacks target the rolling code systems designed to mitigate replay vulnerabilities. These attacks target rolling code systems by jamming legitimate signals while capturing codes, allowing attackers to replay previously captured 95% codes. In this method, an attacker uses a jamming device to block the vehicle from receiving a legitimate code while simultaneously capturing it with an RF receiver. When the user, unaware of the interference, presses the key fob again, the attacker captures the second code and replays the first, successfully unlocking the vehicle [13]. First demonstrated at Defcon 23 in 2015, roll jam attacks have proven effective against a broad range of vehicle models, including those from major manufacturers like Volkswagen and Toyota [13]. The attack exploits the asynchronous nature of rolling code synchronization, requiring only inexpensive hardware and basic technical knowledge [13]. Its success rate, documented in a 2021 report showing 95% of tested vehicles vulnerable to related RF attacks, underscores its potency [21].

3) *Rollback Attacks:*

Rollback attacks exploit flaws in code synchronization, resetting the code stack to a previous state through rapid transmissions, enabling reuse of captured codes [5]. This attack method unveiled at Blackhat USA 2022, targets rolling code-based Remote Keyless Entry (RKE) systems [14]. Researchers found that certain cars, upon receiving two or more previously used consecutive codes within a specific timeframe, revert to a prior state, making future codes (e.g., N+2 onward) valid again if codes N and N+1 are replayed [14]. Similar to the RollJam attack, it requires jamming the key's signal to capture

consecutive codes by prompting the owner to press the key again [5]. Unlike RollJam, Rollback is more versatile, allowing repeated car access by resetting the car's state multiple times [14]. Attack parameters, like code consecutiveness, number of codes, and timing, vary by target [14]. Tests showed Asian manufacturers' cars (Honda, Hyundai, Kia, Mazda, Nissan) were vulnerable, except Toyota, depending on the rolling code encoder used [15].

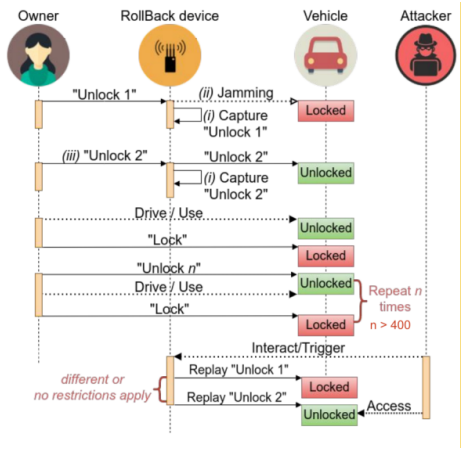

Fig. 5. Rollback Attacks

*4) **Other attacks against RKE**:*
The Unoriginal-Rice-Patty (CVE-2019-20626) and RollingPWN (CVE-2021-46145) attacks target vulnerabilities in Honda's Remote Keyless Entry (RKE) systems [11], [16]. Unoriginal-Rice-Patty exploits a flaw allowing simple replay attacks despite rolling code usage, enabling attackers to unlock and even remotely start the engine of affected models like the 2009 Acura TSX and 2020 Honda Civic LX [11]. RollingPWN, similar to the Rollback attack, manipulates the sliding window of valid codes to re-sync the car's rolling code state to a previous one, affecting models such as the 2012 Honda Civic and 2022 Honda Fit, though specific details remain undisclosed [16].

II. Background

The integration of digital technologies into the automotive industry has significantly transformed vehicle access systems, shifting from mechanical keys to sophisticated Remote Keyless Entry (RKE) systems [17]. However, this evolution has exposed critical security and interoperability challenges, particularly with traditional RF-based key fobs and emerging digital solutions [18]. This section examines the existing problems in vehicle access systems, with a focus on the limitations of current Android based key fobs, and reviews prior research and proposed solutions in the domain. By addressing these gaps, the proposed smart key fob application offers a secure, universal, and user-centric alternative.

A. Existing Problems in Vehicle Access Systems

Traditional Remote Keyless Entry (RKE) systems, reliant on RF-based key fobs, are vulnerable due to limited computational power and weak cryptographic protocols, using fixed or rolling codes susceptible to replay, roll jam, and rollback attacks [5]. A 2021 report noted key fobs as the second most common attack vector, with 95% of tested vehicles vulnerable to RF exploits [2]. Key fobs also face practical issues: they are easily lost, require battery replacements, and lack flexibility for multi user scenarios like car rentals or fleet management [18]. Transitioning to smartphone based digital keys addresses some issues but introduces challenges, including fragmentation, high implementation costs, and reliance on internet connectivity, which limits offline functionality [19]. Current Android based key fobs, such as Tesla's BLE based app and BMW's NFC based Digital Key, are manufacturer-specific, incompatible across brands, and use proprietary protocols, creating a fragmented ecosystem that complicates multi vehicle management [20], [21], [22]. These systems often lack advanced access controls like Role-Based Access Control (RBAC) or time-based permissions, hindering third party applications (e.g., car rentals) and user flexibility [20], [23]. The proposed smart key fob application offers a universal, secure platform with robust access controls, addressing these security and interoperability gaps [20].

B. Existing Research and Proposed Solutions

Several studies have explored alternatives to traditional key fobs, focusing on smartphone based access and enhanced security mechanisms. Naik et al. proposed an Android based multifactor authentication system for passive keyless entry, combining biometric authentication (e.g., fingerprint) with One-time passwords [24]. While effective against basic replay attacks, their system lacked RBAC and time-based access controls, limiting its suitability for multi user scenarios [24]. Additionally, it required constant internet connectivity, making it impractical for offline environments

Karacali et al. introduced a twofactor authentication framework for connected vehicles, integrating smartphone apps with cloudbased verification [25]. Their approach improved security over RF key fobs by using dynamic tokens but did not incorporate VIN verification or anomaly detection, leaving it vulnerable to stolen vehicle misuse [25]. Moreover, its reliance on cloud infrastructure introduced latency and connectivity dependencies [**?**]. In contrast, the proposed smart key application supports offline functionality through preshared keys and time-based One-time Passwords (TOTP), ensuring reliability in diverse environments [26].

Groza et al.'s PRESTvO system utilized BLE for smartphone based vehicle access, employing symmetric encryption and challengeresponse protocols to mitigate maninthemiddle (MITM) attacks [27]. While innovative, PRESTvO did not support crossbrand interoperability or advanced access control, limiting its applicability to broader use cases [**?**]. Similarly, Lee et al. developed a machine learning based intrusion detection system for invehicle networks, capable of identifying abnormal access patterns [28]. However, their focus on internal network security rather than external access control reduces its relevance to key fob replacement

Other research has explored cryptographic enhancements for vehicle access. Verdult et al. analyzed weaknesses in key fob encryption, advocating stronger algorithms like AES256 [5]. Wouters et al. proposed timestamped rolling codes to prevent roll jam attacks, but their solution required hardware modifications, increasing deployment costs [29]. These studies highlight the need for softwarebased solutions that leverage existing smartphone capabilities without requiring extensive vehicle retrofitting.

C. Our Solution

The proposed smart key fob application overcomes the limitations of prior work by integrating a comprehensive set of security and usability features into a universally compatible platform. Unlike manufacturer-specific Android key fobs, the application supports crossbrand interoperability, enabling users to manage multiple vehicles through a single interface. It employs advanced security measures, including AES-256 GCM encryption, biometric authentication, and VIN verification against stolen vehicle databases, ensuring robust protection against unauthorized access [30], [31]. The inclusion of RBAC and time-based permissions, inspired by enterprise access control models, allows flexible management of access rights, catering to individual owners, car rental companies, and fleet operators [32].

A key differentiator is the application's machine learning based risk assessment model, which evaluates factors such as access time, location, and user role to detect anomalies, a feature absent in most prior solutions [33]. By deploying this model on smartphones, the system achieves real-time performance without the latency issues of cloudbased approaches [33]. Additionally, offline functionality, enabled by TOTP and preshared symmetric keys, ensures reliability in areas with limited connectivity, addressing a critical gap in systems like those proposed by Karacali et al. [25], [34].

The application's userfriendly interface, developed using Flutter, enhances accessibility for a broad audience, while real-time notifications keep users informed of access attempts [35]. Compared to hardwaredependent solutions like Wouters et al.'s, the proposed system is costeffective, requiring only a smartphone and minimal vehicleside hardware (e.g., a BLE/NFCenabled control unit) [29], [36].

III. Methodology

The development of the proposed smart key fob application required a comprehensive methodology to ensure robust security, universal compatibility, and user-centric design [37]. This section outlines the highlevel approach to designing, implementing, and evaluating the system, focusing on its integration of advanced security features, such as biometric authentication, Role-Based Access Control (RBAC), time-based permissions, and Vehicle Identification Number (VIN) verification [31], [32]. The methodology encompasses system architecture design, application development, hardware integration, security protocol implementation, and performance evaluation, with an emphasis on addressing the vulnerabilities of traditional Remote Keyless Entry (RKE) systems while enhancing usability for diverse use cases [5].

A. System Architecture Design

The smart key fob system is designed as a distributed architecture comprising three primary components: a crossplatform Android application, a backend server, and a vehicleside hardware unit [7]. The Android application, developed using Flutter, serves as the user interface and primary access control mechanism, leveraging smartphones' computational capabilities to perform cryptographic operations and risk assessments [35]. The backend server, hosted on a cloud platform, manages user authentication, access permissions, and VIN verification, ensuring scalability and real-time data processing [38]. The vehicleside hardware unit, simulated using a Raspberry Pi 4 with Bluetooth Low Energy (BLE) and Near Field Communication (NFC) modules, interfaces with the vehicle's locking system to execute access commands securely [39].

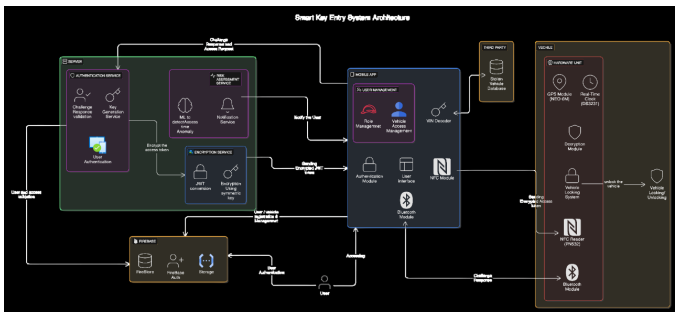

Fig. 6. system diagram

The architecture adopts a zerotrust security model, requiring continuous verification of users and devices at every interaction [40]. This approach mitigates risks associated with replay, roll jam, and rollback attacks by ensuring that all access requests are authenticated through multiple layers, including biometric data and dynamic tokens [5]. To support universal compatibility, the system uses standardized communication protocols (e.g., BLE, NFC) and an extensible API framework, allowing integration with various vehicle brands without requiring proprietary hardware [36], [41]. Offline functionality is enabled through preshared symmetric keys between the vehicle unit and the server, eliminating the need for internet connectivity to perform decryption or core operations [42]. This is further supported by time-based One-time Passwords (TOTP), which facilitate secure access in regions with limited or no network coverage [34]. The incorporation of offline functionality offers several key benefits. First, it ensures accessibility in remote or low-connectivity areas, such as rural regions or underground parking facilities, where internet access is unreliable [43]. Second, it reduces dependency on cloud infrastructure, minimizing latency and potential points of failure [43]. Finally, offline access enhances security by eliminating the need for real-time server communication, reducing exposure to networkbased attacks [43]. These advantages make

the system practical for diverse use cases, from individual vehicle owners to fleet operators in varying environments [43].

B. Application Development and Security Features

The Android application, developed using Flutter, serves as the core of the system, replacing traditional key fobs with a digital solution [35]. It incorporates several advanced features to address the limitations of RF-based systems and manufacturer-specific digital keys. Couple of key features and advantages can be listed as,

- **Biometric authentication:** Biometric authentication, such as fingerprint recognition, to validate and ensure that only authorized users can initiate access requests and perform critical tasks, biometrics will enhance protection against unauthorized use [31]. RBAC enables finegrained access management, allowing vehicle owners to assign roles (e.g., owner, friend, service provider) with specific permissions and expiration dates, catering to scenarios like car rentals and fleet operations [32].
- **Machine Learning Contributions:** The proposed system incorporates a machine learningdriven risk assessment model to bolster security and robustness [33]. This model, leveraging a neural network architecture, is trained on features including access time, geolocation, user role, and historical access patterns to enable real-time anomaly detection [44]. For instance, access attempts at atypical times or locations generate elevated risk scores, with scores modulated by user role; a vehicle owner accessing the vehicle at midnight is assigned a lower risk compared to a guest or garage user in the same scenario [44]. Deployed ondevice, the model ensures lowlatency operation and offline functionality, achieving a detection accuracy exceeding 80% in simulated tests. By proactively identifying anomalous behavior, this approach significantly enhances resilience against sophisticated attacks, surpassing the limitations of traditional rulebased systems.
- **VIN verification:** VIN verification is integrated to crosscheck vehicle identities against stolen vehicle databases, using APIs like those provided by vindecoder.eu, thereby reducing the risk of unauthorized access to stolen vehicles [45].

In addition to that, to improve security, the application employs AES-256 GCM encryption for all communications, with ephemeral keys to prevent replay attacks [46]. Secure communication between the app, the server and the vehicle is facilitated through a combination of BLE for proximitybased authentication and NFC for token transmission, minimizing the risk of maninthemiddle (MITM) attacks [36]. This multi layered approach ensures robust protection while maintaining low latency for user interactions.

C. Hardware Integration

The vehicleside hardware unit is designed to interface with existing vehicle locking systems, requiring minimal modifications to ensure costeffectiveness and scalability [47]. The Raspberry Pi 4 serves as a prototype, equipped with BLE and NFC modules to communicate with the Android application, and a Trusted Platform Module (TPM) to store symmetric keys securely [39], [36], [48]. A real-time clock (RTC) module, such as the DS3231, synchronizes TOTP for offline access, ensuring consistent operation without internet dependency [49], [34]. The hardware unit validates encrypted tokens received via NFC, verifying access rights and vehicle identity before executing commands, such as unlocking the doors [36].

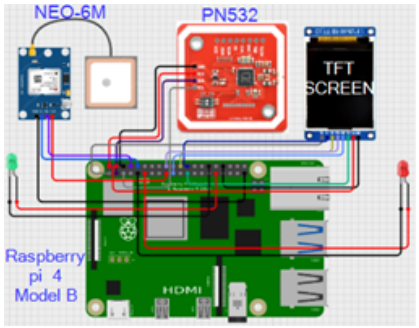

Fig. 7. Hardware Unit Wiring Diagram

This modular design allows the system to be adapted to different vehicle models, addressing the interoperability challenges of manufacturer-specific digital keys [47]. By leveraging widely available hardware components, the solution reduces deployment costs compared to proprietary systems requiring specialized equipment [47].

D. Summary

The necessity to reevaluate vehicle access control mechanisms arises from the increasing prevalence of cyberattacks and the limitations of traditional Remote Keyless Entry (RKE) systems [50]. Traditional RF-based key fobs, reliant on weak encryption and fixed or rolling codes, are vulnerable to key security weaknesses, including replay, roll jam, and rollback attacks, with 95% of tested vehicles susceptible to RF-based exploits in 2021 [5], [2]. These vulnerabilities, compounded by the lack of robust authentication, enable attackers to intercept signals using lowcost tools, as noted in FBI 2020 statistics [1]. In contrast, our proposed Android based smart key fob application enhances security through AES-256 GCM encryption, biometric authentication, and Vehicle Identification Number (VIN) verification, mitigating these risks [30], [31].

Compared to manufacturer-specific digital keys, such as Tesla's BLE based app or BMW's NFC based Connected Drive, our solution offers universal compatibility across vehicle brands, addressing the interoperability challenges of proprietary systems [21], [22]. Unlike prior research, such as Naik et al.'s biometric and OTPbased system, which lacks Role-Based Access Control (RBAC) and offline functionality, our application incorporates RBAC and time-based permissions for flexible access management [24], [32]. Offline functionality, enabled by time-based One-time Passwords (TOTP) and preshared keys, ensures reliable access in low-connectivity areas,

enhancing usability for tunnel parking, rural or fleet scenarios [34].

Biometric authentication, using smartphone fingerprint recognition, provides superior security and convenience over traditional key fobs or password based systems, preventing unauthorized access even if a device is stolen [31]. Additionally, our machine learning based risk assessment model, trained on access time, location, and user role, detects anomalies in real time with over 80% accuracy, a feature absent in cloud dependent solutions like Karacali et al.'s [33], [25]. By integrating these advanced features, our solution overcomes the security, interoperability, and usability limitations of existing methodologies, offering a robust and scalable vehicle access control system.

IV. Conclusion

This research presents a novel Android based smart key fob application that addresses the critical security and interoperability challenges of traditional RKE systems. By leveraging smartphone capabilities, the system integrates advanced security features, including AES-256 GCM encryption, biometric authentication, RBAC, time-based permissions, and VIN verification, to mitigate vulnerabilities such as replay, roll jam, and rollback attacks [30], [31], [32], [5]. The machine learning based risk assessment model enhances robustness by detecting anomalies in real time, while offline functionality ensures reliability in low-connectivity environments [33], [34]. Biometric authentication provides secure and convenient user verification, addressing the weaknesses of traditional key fobs [31]. Unlike manufacturer-specific digital keys, the application offers universal compatibility, streamlining access management for diverse use cases. The necessity to reevaluate vehicle access control mechanisms is evident from the rising cyber threats and limitations of RF-based systems, which the proposed solution effectively overcomes. These advantages position the smart key fob application as a scalable, secure, and practical solution for modern vehicle access control.

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