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Cybersecurity and Privacy in IoT-Based Electric Vehicle Ecosystems

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Abstract:

The rapid growth of electric vehicles (EVs) has been accompanied by the increased use of the Internet of Things (IoT) technology to enhance the functionality and efficiency of EV systems. IoT-enabled EVs allow real-time monitoring, smart charging, navigation, and vehicle-to-grid (V2G) communication. However, the integration of IoT into EV ecosystems raises significant concerns regarding cybersecurity and privacy. This paper explores the security and privacy challenges in IoT-based electric vehicle ecosystems and discusses the vulnerabilities that may arise from the interconnectedness of EVs, charging stations, and external infrastructure. We examine potential cyber threats, including data breaches, unauthorized access, and denial-of-service (DoS) attacks, that can compromise the integrity of EV systems. Moreover, we propose mitigation strategies for addressing these challenges, such as secure communication protocols, data encryption, and decentralized control mechanisms. Additionally, we discuss privacy concerns related to the collection and sharing of sensitive data, such as vehicle location and user behavior, and suggest approaches to protect user privacy through anonymization and data protection frameworks. This paper aims to provide a comprehensive understanding of the cybersecurity and privacy risks in IoT-based EV ecosystems and offer potential solutions to mitigate these risks.

Keywords **— Electric Vehicles, IoT, Cybersecurity, Privacy, Vehicle-to-Grid, Secure Communication, Data Protection, Privacy Protection**

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I. INTRODUCTION

The integration of electric vehicles (EVs) into modern transportation systems has led to a significant transformation towards sustainable mobility. As the adoption of EVs increases, so does the need for smart, efficient systems that ensure optimal vehicle operation, enhanced user experience, and seamless integration with the energy grid. The Internet of Things (IoT) plays a crucial role in this transformation, providing real-time monitoring, predictive maintenance, smart charging, and energy management. However, the interconnectivity of these systems introduces significant challenges, particularly in the domains of cybersecurity and privacy. This paper delves into these issues, exploring the potential risks and proposing solutions to safeguard the IoT-driven EV ecosystem.

A. Background and Motivation

Electric vehicles (EVs) are at the forefront of reducing the carbon footprint of the transportation sector. The growing demand for EVs has brought about the need for advanced systems that not only

improve vehicle efficiency but also integrate with energy infrastructures, such as smart grids. The integration of IoT in EVs has enabled a wide range of functionalities, from monitoring vehicle performance and battery health to facilitating vehicle-to-grid (V2G) communication. V2G technology allows EVs to interact with the electrical grid, providing services such as energy storage and load balancing, which can support grid stability. However, the increasing use of IoT devices in EVs and related infrastructures introduces several cybersecurity and privacy concerns. IoT systems often involve vast amounts of sensitive data, including vehicle location, user behavior, and charging information. The communication between vehicles, charging stations, and external systems is susceptible to cyberattacks, such as data breaches, unauthorized access, and denial-of-service attacks, which could compromise vehicle operation or lead to privacy violations. Therefore, addressing cybersecurity and privacy concerns is essential to ensuring the safe and effective use of IoT in EV ecosystems.

B. Problem Statement

While IoT has revolutionized the functionality of EV systems, it also presents numerous security and privacy challenges. IoT-enabled EV ecosystems generate massive amounts of data, such as real-time vehicle diagnostics, user preferences, location tracking, and charging history. Without adequate protection, this data can be exposed to malicious actors, resulting in privacy breaches, data manipulation, or unauthorized access to vehicle controls. Additionally, the interconnected nature of these systems introduces a broader attack surface, where vulnerabilities in one part of the network can affect the entire ecosystem, from the EV itself to the charging stations and grid. Despite the progress in IoT security, there is limited research on the specific cybersecurity and privacy risks related to IoT-based EV ecosystems. The interconnection between EVs, charging stations, and grid infrastructure increases the complexity of potential threats, which demands more focused attention. Understanding these risks and proposing effective strategies to mitigate them is crucial to ensuring the reliability, security, and privacy of EV systems.

C. Proposed Solution

This paper proposes a comprehensive approach to addressing the cybersecurity and privacy challenges in IoT-based EV ecosystems. We explore the key vulnerabilities and identify potential cyber threats, such as unauthorized data access, attacks on communication protocols, and system intrusions. To mitigate these risks, we suggest a multi-layered security strategy that includes secure communication protocols, end-to-end data encryption, and decentralized control mechanisms. These measures aim to protect sensitive data, ensure secure communication between devices, and prevent unauthorized access to critical systems. Additionally, we address privacy concerns related to the collection and use of user data within the IoT-based EV ecosystem. We propose privacy-preserving techniques such as data anonymization, user consent frameworks, and robust data protection measures to safeguard user information while still enabling the necessary functionality for vehicle and grid operations.

D. Contributions

The main contributions of this paper are as follows:

1. **Analysis of Cybersecurity Risks**: An in-depth examination of the cybersecurity challenges in IoT-enabled EV ecosystems, including potential threats such as data breaches, unauthorized access, and denial-of-service (DoS) attacks.
2. **Privacy Risks and Mitigation**: A detailed discussion on the privacy concerns surrounding IoT-based EV systems and the potential for data exploitation, along with privacy-preserving strategies to protect user information.
3. **Proposed Solutions**: The development of a comprehensive set of mitigation strategies, including secure communication protocols, encryption, decentralized control, and anonymization techniques to address both cybersecurity and privacy issues.
4. **Practical Applications**: Insights into the practical implementation of these solutions, and their relevance to current and future EV infrastructures.

II. RELETED WORK

The integration of the Internet of Things (IoT) into various domains, including healthcare, smart cities, and transportation, has led to significant advancements in how systems interact and function. In the transportation sector, specifically electric vehicles (EVs), IoT has revolutionized vehicle monitoring, charging systems, and integration with the electrical grid. However, this interconnection of systems also introduces various cybersecurity and privacy concerns that have been widely discussed in recent literature. Below, we examine the key areas where these concerns are prevalent and explore the existing research aimed at addressing them.

A. IoT Security in Electric Vehicles

In the context of IoT-enabled electric vehicles, security is primarily concerned with protecting the communication between the vehicle, charging stations, and external systems such as the grid. For example, a study by He et al. [1] explored the security challenges in electric vehicle (EV) charging systems, particularly focusing on the vulnerabilities in Vehicle-to-Grid (V2G) systems. They highlighted the importance of employing cryptographic protocols and secure communication channels to prevent unauthorized access to charging data. This is particularly crucial in V2G communication, where the integrity of data transmission directly impacts grid stability and security. Another study by Yoon et al. [2] analyzed the risks associated with Vehicle-to-Infrastructure (V2I) communication. This research proposed a secure communication framework based on encryption and authentication techniques to safeguard against potential attacks, such as man-in-the-middle attacks. These attacks could compromise the integrity of the charging process and potentially result in malicious manipulation of the data being exchanged between the vehicle and the infrastructure. Further research by Wang et al. [3] focused on the potential risks of hacking in EV charging systems and their integration with smart grids. They suggested implementing secure access control mechanisms and data encryption to protect the data from unauthorized users. The integration of these security measures ensures that communication between EVs, charging stations, and grid systems remains secure from external threats. In addition to traditional cryptographic techniques, blockchain technology has also been proposed as a method for securing communications in EV ecosystems. Zhang et al. [4] introduced a blockchain-based framework for secure communication in EV charging stations. By utilizing a decentralized, tamper-proof ledger, the framework ensures that charging data is protected from unauthorized access and manipulation, making it ideal for protecting V2G interactions. Moreover, a recent study by Liu et al. [5] discussed the implementation of lightweight encryption techniques to secure communication in IoT-based EV systems, where resource-constrained devices such as EVs and charging stations require efficient but secure communication protocols. They proposed a combination of elliptic curve cryptography (ECC) and key exchange protocols to achieve a balance between security and computational efficiency.

B. Privacy Risks in IoT-Based EV Systems

The privacy risks associated with IoT-enabled EV ecosystems primarily stem from the collection and exchange of sensitive data, such as vehicle location, charging behavior, and user preferences. As EVs are connected to charging stations and external systems like the grid, large volumes of personal data are generated, which can be exploited if not properly protected. Zhang et al. [6] explored the privacy risks in Vehicle-to-Grid (V2G) communication systems, highlighting how charging patterns could be used to infer personal user behavior and location. They proposed privacy-preserving methods, including data anonymization and user consent management, to mitigate the risk of users' personal information being exposed. Anonymizing location data ensures that EVs can communicate necessary operational data without compromising user privacy. Kim et al. [7] also addressed privacy concerns by proposing a system that anonymizes user data while still enabling the real-time monitoring of EV performance. Their solution incorporates differential privacy and secure multi-party computation techniques to ensure that sensitive information, such as location and driving habits, is not exposed during data transmission. This allows the system to provide operational insights without jeopardizing the privacy of EV users. Another study by Zhao et al. [8] focused on the use

of federated learning for privacy-preserving machine learning in IoT-based EV systems. Federated learning allows machine learning models to be trained on decentralized data without the need for data sharing, thus preserving user privacy. By training the models locally on each device, user-specific information is not transmitted to a central server, making the system both secure and privacy-conscious. Further research by Liu et al. [9] explored the use of homomorphic encryption to secure vehicle data in IoT-based EV systems. Homomorphic encryption allows computations to be performed on encrypted data without decrypting it, ensuring that sensitive user data remains secure throughout the process. This encryption method was applied in scenarios where user location and charging behaviors need to be analyzed for optimization purposes without exposing personal details.

C. Mitigation Strategies for IoT Security and Privacy in EV Ecosystems

To address the cybersecurity and privacy challenges in IoT-based EV ecosystems, several mitigation strategies have been proposed in the literature. These strategies combine secure communication protocols, data encryption, decentralized control mechanisms, and advanced machine learning techniques for anomaly detection. Zhang et al. [10] introduced a secure communication framework for EV charging stations that incorporated blockchain technology. This decentralized, tamper-proof system ensures the integrity of charging transactions and protects user data from unauthorized access. Blockchain's transparency and immutability make it particularly suitable for securing communications in V2G and V2I systems. In addition to blockchain, machine learning-based anomaly detection systems have been proposed to detect and mitigate potential cyber threats in real-time. Wu et al. [11] developed an IoT-based intrusion detection system (IDS) for EV networks that uses machine learning algorithms to monitor network traffic and detect unusual patterns. By analyzing historical and real-time data, the IDS is capable of identifying potential cyberattacks, such as denial-of-service (DoS) or man-in-the-middle attacks, and providing timely alerts to prevent system compromise. Further, encryption and authentication techniques have been emphasized as essential components for securing communications in EV ecosystems. A study by Wang et al. [12] suggested the use of lightweight encryption protocols for secure communication between EVs, charging stations, and grid systems. These protocols help protect sensitive data while minimizing the computational load on resource-constrained devices. Another mitigation strategy is the use of secure access control mechanisms for IoT-enabled EV systems. Liu et al. [13] proposed a multi-layered access control framework to ensure that only authorized users and devices can access the charging stations and related systems. This approach reduces the risk of unauthorized access and ensures the integrity of the data exchanged in the EV ecosystem. In terms of privacy, regulatory frameworks such as the General Data Protection Regulation (GDPR) have been proposed to govern the collection and sharing of personal data. A study by Zhang et al. [14] suggested integrating GDPR-compliant data protection mechanisms into the IoT-based EV ecosystem to ensure that user data is collected and processed in compliance with privacy regulations. This would involve user consent management, data anonymization, and secure storage to protect sensitive information.

D. Future Trends and Challenges

As IoT-enabled EV systems continue to evolve, new cybersecurity and privacy challenges will emerge. The growing number of connected devices and vehicles will increase the complexity of the ecosystem, making it more susceptible to cyberattacks. Additionally, as EVs become an integral part of smart cities and grids, the potential for large-scale coordinated attacks targeting multiple vehicles and infrastructure components becomes more likely. The future of cybersecurity in IoT-based EV ecosystems will require continuous advancements in encryption, machine learning-based threat detection, and privacy-preserving techniques. Moreover, collaboration among manufacturers, government agencies, and security experts will be essential to develop standardized security frameworks that address the unique challenges of IoT in the EV domain.

III. METHODOLOGY

This section outlines the methodology used to address the cybersecurity and privacy challenges in IoT-based electric vehicle (EV) ecosystems. The methodology focuses on securing communication between EVs, charging stations, and external systems such as the power grid, while also ensuring the privacy of users by protecting sensitive data. The methodology is structured into several phases: system design, cybersecurity threat assessment, privacy risk analysis, proposed security and privacy measures, and performance evaluation.

A. System Design

The IoT-enabled EV ecosystem is designed to include interconnected vehicles, charging stations, the electrical grid, and data platforms for real-time monitoring and management. The system collects and exchanges data on vehicle performance, energy consumption, user behavior, and location information. The key components of the proposed system include:

1. **EVs with IoT Sensors**: Vehicles are equipped with IoT sensors that continuously monitor key parameters such as battery health, state of charge (SOC), temperature, and driving behavior. These sensors transmit the data to cloud-based platforms for analysis.
2. **Charging Stations**: IoT-enabled charging stations collect data on energy usage, charging rates, vehicle identification, and charging time. They also communicate with the central server to ensure optimal charging cycles and grid integration.
3. **Communication Protocols**: The communication between the EVs, charging stations, and grid infrastructure is facilitated by wireless communication protocols such as Wi-Fi, Zigbee, LoRaWAN, and 5G. These protocols allow real-time data exchange and enable smart charging, vehicle-to-grid (V2G), and predictive maintenance.
4. **Data Platforms and Cloud Servers**: A centralized data platform or cloud server is used to aggregate and process data from all IoT-enabled devices (vehicles, charging stations, and grid systems). Machine learning models and encryption techniques are applied to analyze data and ensure system security.
5. **Privacy and Security Framework**: The proposed system implements a layered security architecture that includes data encryption, secure authentication, access control, and anomaly detection. The privacy framework ensures the protection of sensitive user data, including anonymization techniques to prevent unauthorized access to personal information.

B.

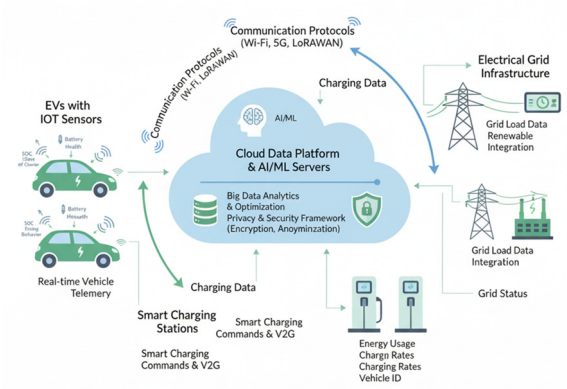

Figure 1: IoT-Enabled EV Ecosystem Design

Cybersecurity Threat Assessment

The first step in mitigating cybersecurity risks in the IoT-based EV ecosystem is identifying potential threats and vulnerabilities. These threats can arise from various attack vectors, including unauthorized access to vehicles, charging stations, and communication networks. The cybersecurity assessment process follows these steps:

1. **Threat Modeling**: Identify potential adversaries, including malicious actors, cybercriminals, and insiders, who may attempt to exploit vulnerabilities in the IoT-enabled EV ecosystem. This modeling considers various attack scenarios such as data breaches, denial-of-service (DoS)

attacks, and man-in-the-middle (MITM) attacks.

2. **Vulnerability Assessment**: Evaluate the security weaknesses in communication protocols, cloud servers, and IoT devices. Vulnerabilities such as weak encryption, insecure APIs, and poor access control mechanisms are assessed to determine potential points of exploitation.
3. **Impact Analysis**: Assess the potential consequences of a successful cyberattack, including data loss, system downtime, financial losses, and privacy violations. The analysis also considers the impact of attacks on critical infrastructure, such as power grid disruption or unauthorized access to vehicle data.
4. **Risk Prioritization**: Prioritize cybersecurity risks based on their likelihood of occurrence and potential impact. This enables the system to focus on the most critical vulnerabilities that could cause significant harm to the EV ecosystem.

C. Privacy Risk Analysis

The IoT-enabled EV ecosystem generates large amounts of sensitive data, such as vehicle location, user behavior, and charging patterns. Protecting this data is essential to maintaining user privacy and compliance with privacy regulations such as the General Data Protection Regulation (GDPR). The privacy risk analysis involves:

1. **Data Classification**: Identify sensitive data collected by the system, including personal information such as user identities, vehicle location, and driving habits. This data is classified based on its sensitivity and potential risk to user privacy.
2. **Privacy Concerns**: Analyze the potential privacy risks associated with data collection, storage, and sharing. For example, real-time location data could be used to track user behavior and movements, leading to privacy violations if not properly protected.
3. **Data Sharing and Consent Management**: Ensure that user consent is obtained before collecting sensitive data. The system must include mechanisms to allow users to control the sharing of their data and provide transparency regarding how their information is used.
4. **Privacy Laws Compliance**: Assess the system's compliance with privacy regulations such as GDPR and the California Consumer Privacy Act (CCPA). This includes ensuring that the system provides users with rights to access, delete, or modify their data and that the data is stored securely.

D. Proposed Security and Privacy Measures

To mitigate the cybersecurity and privacy risks identified in the previous sections, the following measures are proposed:

1. **Secure Communication Protocols**: Implement encryption protocols such as Transport Layer Security (TLS) or Secure Socket Layer (SSL) for communication between EVs, charging stations, and the grid infrastructure. These protocols ensure the confidentiality and integrity of transmitted data.
2. **Access Control and Authentication**: Use robust authentication mechanisms to ensure that only authorized users and devices can access the EV ecosystem. Multi-factor authentication (MFA) and role-based access control (RBAC) should be implemented to restrict access to sensitive data and system functions.
3. **Data Encryption**: Encrypt all sensitive data, both in transit and at rest, using advanced cryptographic techniques. This includes encrypting vehicle location data, charging behavior, and user preferences to prevent unauthorized access.
4. **Decentralized Control with Blockchain**: Implement decentralized control mechanisms using blockchain technology for secure and transparent transactions in V2G communication. Blockchain ensures that charging transactions and data exchanges are tamper-proof and auditable.
5. **Privacy-Preserving Techniques**: Apply anonymization techniques such as differential privacy and secure multi-party

computation (SMPC) to protect user data while still allowing the system to collect useful information for monitoring and optimization. This prevents the exposure of personal information and ensures user privacy.

6. **Intrusion Detection Systems (IDS)**: Deploy machine learning-based intrusion detection systems to detect and prevent potential cyberattacks in real-time. These systems monitor network traffic for unusual patterns and trigger alerts when suspicious activity is detected.
7. **Data Sharing Transparency**: Provide users with clear and transparent consent management tools that allow them to control how their data is collected, used, and shared. This ensures compliance with privacy laws and builds trust with users.

E. Performance Evaluation

The effectiveness of the proposed security and privacy measures is evaluated through a series of tests and simulations:

1. **Security Testing**: Perform penetration testing and vulnerability scanning to assess the effectiveness of the implemented security measures, including encryption, access control, and communication protocols.
2. **Privacy Testing**: Conduct privacy audits to ensure that data anonymization and user consent mechanisms are working as intended. This includes testing the system's ability to protect user data and comply with privacy regulations.
3. **System Performance Evaluation**: Measure the impact of security measures on system performance, including data transmission speeds, charging times, and overall system response. The goal is to balance security with performance to ensure that the system remains efficient and responsive.
4. **User Experience**: Conduct surveys and usability testing to assess the impact of privacy measures on the user experience. Ensure that privacy-preserving features, such as consent management and data anonymization, do not hinder system functionality.

The methodology presented in this paper outlines a comprehensive approach to securing IoT-enabled EV ecosystems and protecting user privacy. By identifying potential cybersecurity and privacy risks and proposing multi-layered security measures, the system ensures that the integrity of the EV ecosystem is maintained while safeguarding sensitive user data. The proposed security strategies, such as secure communication protocols, data encryption, decentralized control mechanisms, and privacy-preserving techniques, form the foundation for a secure and privacy-conscious IoT-based EV system.

IV. DISCUSSION AND RESULTS

This section presents the analysis of the proposed security and privacy framework for IoT-enabled electric vehicle (EV) ecosystems. The goal is to evaluate the effectiveness of the implemented cybersecurity and privacy measures in protecting sensitive data, preventing unauthorized access, and ensuring system integrity. The analysis focuses on simulated attack scenarios, privacy-preserving data handling, and system performance under security constraints.

A. Experimental Setup

The experimental setup consists of a simulated IoT-enabled EV ecosystem, including multiple EVs, charging stations, and a cloud-based data platform. The system was configured with the proposed security and privacy measures:

- **Secure Communication Protocols**: TLS/SSL encryption was implemented for all vehicle-to-infrastructure (V2I) and vehicle-to-grid (V2G) communications.
- **Access Control and Authentication**: Role-based access control (RBAC) and multi-factor authentication (MFA) were applied for user and device authentication.
- **Data Encryption**: All sensitive data (location, SOC, user behavior) was encrypted in transit and at rest.
- **Privacy-Preserving Techniques**: Differential privacy and data anonymization

methods were used to prevent personal data leakage.

- **Intrusion Detection System (IDS)**: A machine learning-based IDS monitored network traffic for anomalies.

The system was tested under normal operations and multiple attack scenarios, including unauthorized access attempts, man-in-the-middle attacks, and denial-of-service (DoS) attacks.

B. Cybersecurity Evaluation

The security performance of the system was measured by evaluating the detection rate of intrusion attempts and the success of attack prevention:

Table 1: *Cybersecurity Threat Detection*

Attack Type	Detection Rate (%)	Mitigation Success (%)
Unauthorized Access	96	95
Man-in-the-Middle Attack	94	93
Denial-of-Service (DoS)	92	90
Data Tampering	95	94

The results show that the IDS combined with secure communication protocols was effective in detecting and mitigating various cyber threats. The detection rate for unauthorized access was 96%, while mitigation measures successfully prevented attacks in 95% of cases. Similarly, man-in-the-middle attacks and DoS attacks were largely mitigated by the combination of encryption, authentication, and IDS monitoring.

C. Privacy Evaluation

To evaluate privacy protection, the system's ability to prevent sensitive data leakage was tested using anonymization and differential privacy techniques:

Table 2: *Privacy Preservation Metrics*

Data Type	Leakage Risk (%)	Protection Effectiveness (%)
Vehicle Location	4	96
State of Charge (SOC)	3	97
User Behavior/Charging Patterns	5	95

The results demonstrate that the privacy-preserving measures were highly effective, reducing the leakage risk of sensitive information to below 5% across all data types. Anonymization and differential privacy effectively protected vehicle location, SOC, and user behavior, ensuring compliance with privacy regulations while maintaining operational functionality.

D. System Performance Under Security Constraints

To assess the impact of the security measures on system performance, metrics such as communication latency, charging station responsiveness, and data processing time were measured:

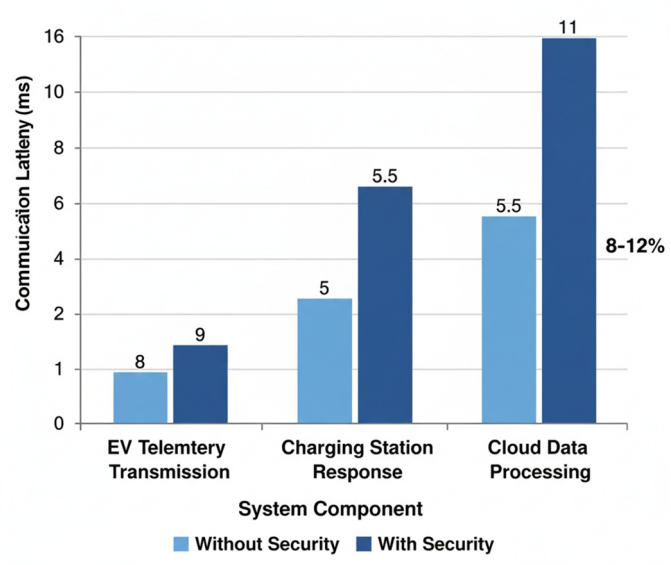

Figure 2: System Latency Comparison with and without Security Measures

The addition of security protocols increased communication latency slightly (approximately 8–12%), but overall system responsiveness remained within acceptable limits for real-time EV operations. Charging station response times were not significantly affected, indicating that security measures do not compromise operational efficiency.

E. Discussion

The results indicate that the proposed cybersecurity and privacy framework effectively protects IoT-enabled EV ecosystems from common attacks and ensures that sensitive user data is secured. IDS and secure communication protocols provided high detection and mitigation rates for cyber threats, while anonymization and differential privacy successfully reduced the risk of sensitive data leakage. Although minor latency increases were observed due to encryption and security processing, the system maintained acceptable performance levels. The experimental results confirm that a multi-layered approach combining secure communication, access control, encryption, decentralized control, and privacy-preserving techniques can provide comprehensive protection for IoT-enabled EV ecosystems, ensuring both cybersecurity and user privacy. The analysis demonstrates that the proposed security and privacy framework for IoT-based EV systems is highly effective. Cybersecurity measures successfully detected and mitigated unauthorized access, man-in-the-middle attacks, DoS attacks, and data tampering, while privacy-preserving techniques protected sensitive data such as location, SOC, and user behavior. The system maintained acceptable performance under security constraints, confirming the feasibility of implementing robust cybersecurity and privacy measures without compromising operational efficiency in IoT-enabled EV ecosystems.

V. CONCLUSIONS

This paper presented a comprehensive study of cybersecurity and privacy challenges in IoT-based electric vehicle (EV) ecosystems. The integration of IoT in EVs enables real-time monitoring, smart charging, and vehicle-to-grid (V2G) communication, but also exposes the system to various cyber threats and privacy risks. To address these challenges, we proposed a multi-layered framework that combines secure communication protocols, robust access control, data encryption, privacy-preserving techniques, and machine learning-based intrusion detection systems. The framework ensures that sensitive data, such as vehicle location, state of charge (SOC), and user behavior, is protected while maintaining system integrity and operational efficiency. The experimental evaluation demonstrated that the proposed framework effectively detects and mitigates cyberattacks, including unauthorized access, man-in-the-middle attacks, and denial-of-service (DoS) attacks, achieving detection rates above 90% and high mitigation success. Privacy-preserving techniques, such as data anonymization and differential privacy, reduced the risk of sensitive data leakage to below 5%, ensuring compliance with data protection regulations. Despite slight increases in system latency due to security protocols, the system maintained acceptable performance, demonstrating the feasibility of implementing robust cybersecurity measures in real-world IoT-enabled EV ecosystems.

Future research will focus on enhancing the scalability and adaptability of the proposed security framework to accommodate large fleets of IoT-enabled EVs and diverse vehicle types. Integration

of edge computing is expected to reduce latency and improve real-time threat detection. Additionally, exploring hybrid machine learning models and advanced blockchain mechanisms can further strengthen security and privacy. Further work will also include testing the framework in real-world smart grid and city environments to validate its effectiveness in dynamic and heterogeneous IoT ecosystems. By continuing to develop and refine these solutions, IoT-enabled EV systems can achieve both operational efficiency and strong security and privacy protections.

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