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Vehicle-to-Blockchain (V2B) Communication: Integrating Blockchain into V2X and IoT for Next-Generation Transportation Systems

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Abstract: As smart transportation systems evolve, secure and efficient V2X communication between vehicles and infrastructure becomes crucial. This paper introduces a Vehicle-to-Blockchain (V2B) communication architecture, leveraging blockchain technology for transparent and decentralized interactions. Our work contributes to the integration of blockchain into V2X and IoT for next-generation transportation systems. We propose several novel blockchain use cases, including a blockchain-based vehicle ownership system based on the multi-token standard, a vehicle scoring system, blockchain–IoT integration, and a decentralized ticket management system for transportation services. The architecture addresses key aspects, such as data integration, validity, and secure messaging, and introduces a decentralized payment system and marketplace for transportation in smart cities. We specifically emphasize the technical implementation of smart contracts for these use cases, underscoring their role in ensuring robust and reliable interactions. Through our decentralized approach, we pave the way for a transformative transportation ecosystem that is adaptable, resilient, and capable of meeting the evolving needs of smart cities.

Keywords: V2B; blockchain; communication; V2X; V2V; V2I; V2G; V2N; smart contracts; transportation; IoT

1. Introduction

Effective communication is a crucial aspect of enabling smart transportation systems to operate efficiently and safely. In the context of smart cities, the concept of Vehicle-to-Everything (V2X) communication has emerged as a fundamental building block for intelligent transportation networks. V2X encompasses various communication types, including Vehicle-to-Vehicle (V2V) [1], Vehicle-to-Infrastructure (V2I) [2], and Vehicle-to-Grid (V2G) [3,4], enabling seamless exchange of information between vehicles and infrastructure components. The integration of Internet of Things (IoT) sensors in this architecture further enhances its capabilities [5], making cities smarter and improving the quality of life for residents.

V2X communication in smart cities provides numerous advantages. Firstly, it enables real-time data sharing among vehicles, allowing them to exchange information about road conditions, traffic patterns, and potential hazards. This promotes proactive decision making, enhancing road safety and traffic management. Secondly, V2X communication enables vehicles to interact with infrastructure components, such as traffic signals, parking systems, and charging stations [6]. This interaction facilitates optimized routing, efficient energy management, and improved utilization of transportation resources. Moreover, the integration of IoT sensors in V2X architecture enables the collection and analysis of large-scale data, leading to intelligent insights and the provision of personalized services to city dwellers [7,8].
However, several challenges must be addressed to fully realize the potential of V2X communication. Centralization poses a significant issue as a centralized architecture may lead to single points of failure, vulnerability to cyberattacks [3], and limited scalability. Additionally, payment mechanisms for services provided within the V2X ecosystem require secure and efficient solutions to ensure fair compensation and promote widespread adoption.

To tackle these challenges and enhance communication in smart transportation systems, blockchain technology offers a promising solution. Blockchain, a decentralized and immutable ledger [9], can provide a secure and transparent platform for V2X communication. By integrating blockchain into the V2B (Vehicle-to-Blockchain) communication architecture, trust, security [10], and interoperability can be improved, ensuring the integrity of exchanged data and transactions. Furthermore, the utilization of smart contracts and tokens enables the automation and streamlined execution of various processes within the V2X ecosystem, promoting efficiency and reducing administrative overhead [6,8].

In this paper, we aim to investigate the potential and technical aspects of V2B communication in smart transportation systems. We will discuss the proposed blockchain-based architecture for V2B communication and its advantages in enabling secure and efficient data exchange. Furthermore, we will explore the technical implementation considerations, such as the use of smart contracts and tokens, and their potential applications in V2B communication. The integration of IoT sensors within the V2B architecture and their role in making cities smarter will also be examined. By examining the challenges and opportunities associated with V2B communication, we aim to contribute to the understanding of how blockchain technology can revolutionize communication in smart transportation systems, paving the way for more efficient and intelligent cities.

The research contributions of this paper are as follows:

1. Introduction of a blockchain-based vehicle ownership management system, improving the recording and verification of vehicle marks, and implementing a vehicle scoring system to encourage responsible driving behavior.
2. Development of a blockchain-based ticket management system for V2X communication, enabling secure ticket reservations, and availability checking for different transportation services, such as taxis and buses.
3. Exploration of data integration and validity in the context of blockchain technology, addressing global data integration, validity of shared data, immutability of recorded transactions, and the importance of timestamping actions.
4. Investigation of blockchain–IoT integration, focusing on penalty enforcement, validation of information, real-time monitoring, and secure messaging and communication using a blockchain covert channel.
5. Proposal of a decentralized payment system for transportation in smart cities, including the establishment of a decentralized marketplace for vehicle-related transactions.

This paper is structured as follows: Section 2 provides an overview of related work, examining previous studies on blockchain technology in transportation systems. Section 3 presents the background, covering vehicle communication, the evolution of IoT in transportation, V2X challenges, and blockchain in Web3. In Section 4, we propose a V2B approach that includes blockchain-based vehicle ownership, ticket management for V2X, data integration and validity, blockchain–IoT integration, and a decentralized payment system. Section 5 presents simulations and results for our V2B communication approach, evaluating system performance on different blockchains. Section 6 discusses the limitations and challenges of our approach. Finally, Section 7 concludes the paper, outlining future research directions in this field.

2. Related Works

This section explores the application of blockchain in IoT-enabled transportation systems, focusing on a range of topics, such as system architecture, use cases, security, privacy, and scalability. Through a comprehensive review and comparison of the existing
literature, this section highlights the unique contributions of this paper in addressing novel challenges and proposing innovative solutions for the transportation industry.

Several studies have delved into the integration of blockchain in IoT-enabled transportation systems, shedding light on its potential and providing valuable insights. Notably, these studies have laid the foundation for the concepts discussed in this paper.

Meijers et al. [6] provide a comprehensive overview of various blockchain use cases and applications in V2X communication. They explore the potential of blockchain technology in areas such as insurance and accident investigations, emission tracking, tolls and parking, ride sharing, and EV charging. Furthermore, the authors present an analysis of the specific blockchain characteristics relevant to each network type. In another study, Meijers et al. present a taxonomy of design use cases and system requirements for blockchain in V2X communication, offering insights into the design and implementation considerations [11].

In the context of V2I and V2V communication, we explore a novel approach proposed by Yixin He et al. [12]. Their study introduces a Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) collaboration framework designed to support emergency communications in the context of ABS-aided Internet of Vehicles (IoV). This framework aims to enhance communication reliability and responsiveness, particularly in critical emergency situations, by incorporating non-orthogonal multiple access (NOMA) into the ABS-aided IoV.

Dorri et al. discuss the challenges and solutions related to the integration of blockchain in the Internet of Things (IoT), including transportation systems [7]. Maskey et al. present BITS (Blockchain-based Intelligent Transportation System), which utilizes blockchain and outlier detection techniques to enhance the security and efficiency of transportation systems in smart cities [13].

Guo et al. propose a proof-of-event recording system based on blockchain for autonomous vehicles. This system ensures the integrity and immutability of event data, enabling transparent and trustworthy records of events in autonomous driving scenarios [14]. Mollah et al. provide a survey on the application of blockchain in the Internet of Vehicles (IoV) context, discussing its potential benefits, challenges, and future directions [15].

Shen et al. propose a blockchain-enabled solution for secure and scalable V2V (Vehicle-to-Vehicle) video content dissemination. Their approach ensures the authenticity and integrity of video content and enables efficient and secure sharing among vehicles [16]. Gao et al. discuss the applications of blockchain in Internet of Vehicles (IoV) scenarios, highlighting the potential benefits and challenges of blockchain technology in this context [17].

These studies significantly contribute to the understanding of blockchain’s potential in enhancing the efficiency, security, and trustworthiness of transportation systems. Building upon these foundations, this paper aims to explore and address specific challenges in the transportation industry by utilizing blockchain technology. It focuses on novel use cases, such as vehicle ownership, ticket management, IoT integration, data validity, secure V2X communication, and decentralized payment systems. Moreover, this paper goes beyond previous works by providing a detailed technical implementation and a focused analysis of the challenges faced in V2X communication and other related use cases. By emphasizing the technical aspect and presenting practical solutions, this paper adds to the existing body of knowledge in the field of blockchain-based transportation systems.

3. Background

3.1. Vehicle Communication in Smart Transportation

In the context of smart transportation, vehicle communication plays a vital role in enabling efficient and intelligent transportation systems [18]. It involves the exchange of information and data between vehicles, infrastructure, and other entities, facilitating coordination, decision making, and enhancing overall transportation performance. This subsection provides an overview of the different types of vehicle communication and their applications in the realm of smart transportation.
Vehicle communication encompasses various modes of communication, including Vehicle-to-Everything (V2X), Vehicle-to-Vehicle (V2V), and Vehicle-to-Infrastructure (V2I) communication.

- **Vehicle-to-Everything (V2X) communication** refers to the exchange of information between vehicles and their surrounding environment. It encompasses communication between vehicles, infrastructure, pedestrians, and cloud-based services. V2X communication enables vehicles to obtain real-time information about their surroundings and share their own data, fostering cooperative driving, situational awareness, and the realization of intelligent transportation systems [8,18].

- **Vehicle-to-Vehicle (V2V) communication** focuses on the direct communication between nearby vehicles. It allows vehicles to exchange critical data, such as speed, location, acceleration, and trajectory information. V2V communication enables cooperative maneuvers, such as platooning, where vehicles travel in close proximity to improve traffic flow, fuel efficiency, and safety. It also facilitates collision avoidance systems, cooperative perception, and distributed decision making among vehicles [1,18,19].

- **Vehicle-to-Infrastructure (V2I) communication** involves the exchange of information between vehicles and roadside infrastructure. This type of communication enables vehicles to interact with traffic lights, road signs, toll booths, and other infrastructure components. V2I communication supports various applications, including traffic management, signal prioritization, and intelligent transportation systems. By providing vehicles with up-to-date information from the infrastructure, V2I communication contributes to optimized routing, reduced congestion, and improved overall transportation efficiency [2,18].

- **Vehicle-to-Network (V2N) communication** involves the exchange of data between vehicles and the communication networks they are connected to. V2N communication enables vehicles to access network services and resources, facilitating connectivity to cloud platforms, Internet of Things (IoT) devices, and other online services. It allows vehicles to upload and download data, receive software updates, and utilize advanced network-based applications. V2N communication is crucial for vehicle connectivity, enabling services such as remote diagnostics, Over-the-Air (OTA) updates, and cloud-based analytics [18].

- **Vehicle-to-Grid (V2G) communication** focuses on the interaction between electric vehicles (EVs) and the power grid infrastructure. It allows EVs to communicate with the grid, enabling bidirectional energy flow. V2G communication enables EVs to not only draw power from the grid but also to inject power back into the grid. This capability opens up opportunities for Vehicle-to-Grid integration, where EVs can serve as distributed energy resources and contribute to grid stability, load balancing, and renewable energy integration. V2G communication facilitates energy management, charging coordination, and grid services, promoting a more sustainable and efficient energy ecosystem [3,4].

The integration of advanced communication technologies and protocols has opened up a wide range of applications for vehicle communication in smart transportation. These applications include real-time traffic management, congestion control, intelligent routing, collision avoidance, autonomous driving, and efficient transportation planning [18,20–22].

Overall, vehicle communication serves as the foundation for building interconnected transportation systems, allowing vehicles to communicate with each other and their environment. By enabling the seamless exchange of information, vehicle communication enhances transportation safety, efficiency, and sustainability.

### 3.2. Evolution of IoT in Transportation Systems

The evolution of IoT (Internet of Things) in transportation systems has revolutionized the way we perceive and manage urban mobility. By leveraging the capabilities of IoT technologies, transportation systems have become smarter, more efficient, and sustainable. This subsection explores the key advancements and applications of IoT in transporta-
tion systems, highlighting its role in enhancing traffic management, optimizing public transportation, and improving overall mobility.

The integration of IoT technology in transportation systems has facilitated the collection, analysis, and utilization of real-time data from various sources, including traffic lights, public transportation systems, and private vehicles. This data-driven approach has led to significant improvements in traffic management and congestion reduction strategies. Real-time traffic monitoring systems, equipped with IoT sensors and devices, enable the continuous monitoring of traffic flow, congestion hotspots, and incident detection. Such systems provide valuable insights for traffic management authorities to optimize traffic signal timings, reroute traffic, and implement dynamic congestion pricing strategies to alleviate traffic congestion.

Furthermore, IoT has played a pivotal role in optimizing public transportation systems. Smart transportation solutions powered by IoT enable the real-time tracking of buses, trains, and other modes of public transportation. This enables commuters to access accurate and up-to-date information regarding arrival times, delays, and route changes. Passengers can make informed decisions about their travel plans, reducing waiting times and enhancing the overall commuter experience. IoT-enabled ticketing systems and fare collection devices offer seamless and contactless payment options, simplifying the process for passengers and enhancing the efficiency of fare collection.

The evolution of IoT in transportation systems has also led to advancements in safety and environmental sustainability. IoT sensors and devices integrated into vehicles and infrastructure enable the collection of data on vehicle performance, road conditions, and environmental factors. These data can be used to enhance road safety by providing real-time alerts and warnings to drivers about potential hazards, such as accidents, slippery roads, or poor visibility. Additionally, IoT technology enables the monitoring of vehicle emissions, facilitating the development of eco-friendly transportation policies and promoting the adoption of electric and hybrid vehicles.

To address the challenges associated with privacy and security in IoT-enabled transportation systems, blockchain-based solutions have been proposed. Blockchain technology offers decentralized and tamper-proof transactional records, enhancing data security and privacy management in the context of social Internet of Vehicles (IoV) scenarios [23]. It also provides a scalable framework for secure transactions in IoV, ensuring the integrity and confidentiality of data exchanges [24]. Furthermore, the combination of blockchain and IoT data analytics has been explored for fine-grained transportation insurance, enabling more accurate risk assessment and personalized insurance policies [25].

The evolution of IoT in transportation systems has revolutionized urban mobility, offering improved traffic management, optimized public transportation, and enhanced overall transportation experiences. With the continued advancements in IoT technologies and the integration of emerging technologies like blockchain, transportation systems are poised to become even smarter, greener, and more efficient.

3.3. V2X Challenges

While vehicle communication offers significant benefits, it also faces several challenges that need to be addressed for effective implementation in smart transportation systems. This subsection highlights key challenges and research directions in the field of vehicle communication.

- **Trust and Security**: Establishing trust and ensuring security in vehicle communication systems are crucial. Trust is required to validate the authenticity and reliability of data exchanged between vehicles and other entities. Security measures are necessary to protect against unauthorized access, data tampering, and malicious activities that could compromise the integrity and privacy of the communication system [26].
- **Ownership Proof**: Validating ownership and proving the authenticity of data is essential in vehicle communication systems. Without a reliable mechanism to establish
ownership, the trustworthiness of the exchanged data and the identity of the communicating vehicles may be compromised.

- **Data Integration and Validity:** In smart transportation systems, data are generated and exchanged by various stakeholders, such as vehicles, traffic management systems, and infrastructure. Ensuring seamless integration and validity of data across different sources and systems is a challenge. Data integrity and consistency must be maintained to enable accurate decision making and efficient coordination between vehicles and infrastructure.

- **Global System for Vehicles Worldwide:** With the increasing connectivity of vehicles, there is a need for a global communication system that allows interoperability and seamless communication among vehicles from different manufacturers and regions. Standardizing communication protocols and ensuring compatibility across diverse systems and technologies is a complex task.

- **Payment Issues:** Efficient and secure payment systems are crucial for various services in smart transportation, such as toll collection, parking, and electric vehicle charging. Ensuring smooth and secure payment transactions while considering factors such as privacy, reliability, and interoperability presents a significant challenge.

- **Scalability and Reliability:** As the number of connected vehicles increases, the scalability and reliability of communication networks become crucial. The network infrastructure must handle the growing volume of data traffic, maintain low-latency communication, and ensure reliable connectivity even in challenging environments [21].

Addressing these challenges is vital to unlocking the full potential of vehicle communication systems in smart transportation. Solutions that leverage advanced technologies, such as blockchain, are being explored to overcome these challenges and enable more efficient and secure vehicle communication networks.

### 3.4. Blockchain Technology in Web3

The concept of blockchain technology originated with the publication of Satoshi Nakamoto’s white paper on Bitcoin, which introduced the idea of a decentralized peer-to-peer electronic cash system [27]. Since then, blockchain technology has evolved to encompass various platforms and applications beyond cryptocurrency.

Ethereum, introduced by Vitalik Buterin, expanded the capabilities of blockchain by introducing smart contracts and a decentralized application (DApp) platform [28]. Smart contracts are self-executing contracts with the terms of the agreement directly written into the code. They enable decentralized applications to operate in a transparent, tamper-proof, and trustless manner.

In the Web3 paradigm, blockchain technology provides a foundation for building decentralized applications that operate on distributed networks. These applications leverage the features of blockchain, such as immutability, transparency, and decentralized consensus, to enable new forms of digital interactions and eliminate the need for intermediaries.

Various platforms and frameworks have emerged to support the development of Web3 applications. Ethereum remains one of the most prominent platforms, providing a Turing-complete virtual machine for executing smart contracts [28,29]. Other platforms, such as Polkadot, Cardano, and Solana, offer different approaches to scalability, interoperability, and governance within the Web3 ecosystem.

Blockchain technology in Web3 extends beyond financial applications. It has the potential to disrupt industries such as supply chain management, healthcare, voting systems, and decentralized finance (DeFi). By leveraging blockchain’s inherent properties, these applications aim to enhance security, transparency, and efficiency.

Researchers have also explored privacy-preserving mechanisms for smart contracts. The Hawk protocol, proposed by Kosba et al., presents a blockchain model of cryptography that ensures privacy in smart contract execution [30]. This approach enables the execution...
of sensitive computations on public blockchains while preserving the confidentiality of the inputs and outputs.

Blockchain technology in Web3 is a rapidly evolving field, with ongoing research and development focusing on scalability, interoperability, and governance. It has the potential to transform the way we interact with digital systems, providing a decentralized and transparent foundation for a wide range of applications in the Web3 era [31].

In the context of smart transportation, blockchain technology in Web3 holds great promise for addressing the challenges in V2X communication and enabling innovative solutions. One of these applications is V2B (Vehicle-to-Blockchain) communication, which will be explored in the next section. By leveraging blockchain’s decentralized and transparent nature, V2B aims to enhance the efficiency, security, and trustworthiness of interactions between vehicles in smart transportation systems.

4. Proposed Architecture: Vehicle-to-Blockchain

In this section, we will discuss V2B (Vehicle-to-Blockchain) communication in the context of vehicle communication and IoT in smart transportation systems. V2B communication refers to the interaction between vehicles and the blockchain technology that forms the foundation of the transportation system. We will present a proposed architecture that leverages blockchain technology to facilitate secure and transparent communication between vehicles and the blockchain network.

4.1. Blockchain-Based Vehicle Ownership

The blockchain technology presents a promising solution for transforming vehicle ownership through its transparent, secure, and immutable nature. This section delves into the key aspects of blockchain-based vehicle ownership, including digitizing vehicle marks, establishing a new vehicle mark creation process, representing vehicle ownership as ERC1155 NFTs, and implementing a scoring system to track driver traffic violations.

4.1.1. Digitizing and Verifying Vehicle Marks

In the context of blockchain-based vehicle ownership, the traditional method of recording vehicle marks undergoes a revolutionary transformation through digitization. By leveraging the decentralized and immutable nature of blockchain technology, vehicle marks, such as manufacturer marks and production years, are securely digitized and stored. This process ensures the authenticity and validity of these marks, providing stakeholders with a reliable and tamper-proof source of information.

The digitization of vehicle marks fosters transparency within the ownership ecosystem. It enables stakeholders to easily verify the legitimacy of specific marks, reducing the risks associated with counterfeit or unauthorized marks. By accessing the blockchain, stakeholders can validate the origin and history of a vehicle mark, establishing trust and confidence in its authenticity.

Moreover, the blockchain assigns a unique digital identity to each vehicle, further enhancing the security and transparency of ownership information. This digital identity is recorded on the blockchain, allowing for secure and transparent tracking of ownership transfers and changes. The decentralized nature of the blockchain ensures that the ownership history of a vehicle is tamper-proof, providing a reliable and auditable record.

4.1.2. Vehicle Ownership Representation

Blockchain-based vehicle ownership utilizes ERC1155 tokens to represent ownership. Each ERC1155 NFT corresponds to a specific vehicle and contains crucial ownership information. These NFTs serve as digital certificates of ownership, providing a unique identifier for each vehicle and establishing an auditable chain of ownership history. Leveraging blockchain technology ensures that the transfer of vehicle ownership is secure, transparent, and resistant to tampering.
The ERC1155 standard offers a framework for including extensive vehicle information as attributes within the NFTs. Each ERC1155 NFT representing a vehicle can store relevant details, such as the vehicle identification number (VIN), make, model, manufacturing specifications, maintenance records, and other pertinent information. These attributes create a comprehensive and immutable record of the vehicle’s history and specifications. By utilizing the ERC1155 standard, transparency is enhanced, and trust is established among all involved parties.

### 4.1.3. Vehicle Scoring System

Integrating a scoring system into the V2B (Vehicle-to-Blockchain) systems enhances road safety and accountability. By leveraging the blockchain’s ability to record and validate data, the scoring system tracks and records traffic violations associated with each vehicle and its driver. Through this system, individual vehicles are assigned a score or rating based on their driver’s adherence to traffic rules and regulations. The scoring mechanism serves as an incentive for responsible driving behavior while enabling stakeholders, such as insurance companies or authorities, to assess the risk associated with specific vehicles or drivers.

### 4.1.4. Technical Implementation

The technical implementation of contracts in the blockchain-based vehicle ownership architecture is vital for ensuring transparent and secure vehicle ownership, standardized tokenization, responsible driving practices, and efficient insurance-related operations.

Figure 1 presents a concise overview of the architecture. It enables digitized vehicle marks, streamlined ownership representation, and additional functionalities. The figure emphasizes the relationships between key contracts, demonstrating their roles in establishing a robust and reliable vehicle ownership system.

![Blockchain-based vehicle ownership contracts](image)

**Figure 1.** Blockchain-based vehicle ownership contracts.

The following list offers a summary of each contract’s role within the architecture:

- **VehicleRegistry Contract**: The VehicleRegistry contract acts as a centralized registry for all vehicles in the system, maintaining a comprehensive record of ownership details and associated attributes. It ensures data integrity and transparency, serving as a reliable source for ownership and attribute validation.
- **VehicleFactory Contract**: The VehicleFactory contract dynamically generates unique VehicleAsset contracts for different vehicle types, automating their creation, deployment, and management. It enhances scalability and flexibility within the architecture, accommodating the addition of new vehicle types without altering the core infrastructure.
- **VehicleAsset Contract (inherits from ERC1155)**: The VehicleAsset contract represents individual vehicles as tokens on the blockchain, enabling the creation, management,
and transfer of vehicle tokens. By inheriting the ERC1155 token standard, it provides a standardized approach to handle multiple vehicle tokens and their associated attributes. This contract ensures secure and tamper-proof representation of vehicle ownership.

- ERC1155 Contract (Base Contract): The ERC1155 contract serves as the base contract for managing multi-token standards. It offers essential functionalities for creating, transferring, and managing ERC1155 tokens. This contract enables interoperability and standardized token handling across the architecture, supporting the VehicleAsset contract and ensuring compatibility with other ERC1155-based tokens and contracts.

- ScoringSystem Contract: The ScoringSystem contract tracks and manages vehicle scores based on the driver’s adherence to traffic rules and regulations. This contract promotes responsible driving practices, incentivizes safe behavior, and provides data-driven insights for stakeholders.

- InsuranceContract Contract: The InsuranceContract contract manages vehicle insurance policies within the architecture, including policy storage, coverage verification, and claims processing. It integrates insurance-related operations, ensuring seamless management of policies and enhancing transparency, efficiency, and trust in the insurance process.

4.2. Blockchain-Based Ticket Management for V2X

This section presents a blockchain-based ticket management system that enhances transparency and reliability in the travel industry. It encompasses functionalities such as ticket reservation, availability checking, and includes examples for taxi services and bus travel. The decentralized nature of the system ensures integrity and eliminates the risk of unauthorized modifications or errors in reservations.

4.2.1. Ticket Reservation and Availability Checking

In the blockchain-based ticket management system, users can reserve tickets for their desired travel dates and destinations. The reservation process is transparent and efficient, allowing users to secure their tickets hassle-free. Additionally, the system provides a real-time ticket availability checking feature. Users can easily verify the availability of tickets based on specific parameters, such as date, destination, and ticket type. This ensures that users have up-to-date information about ticket availability, enabling them to make informed booking decisions.

4.2.2. Use Cases

- Ticket Management for Taxi Services: The blockchain-based ticket management system extends its application to taxi services. The TaxiTicket contract allows for the creation, transfer, and management of taxi-specific tickets. This contract includes additional attributes such as pick-up and drop-off locations, fare details, and driver information. With the decentralized nature of the system, users can confidently reserve taxi tickets knowing that the process is secure, transparent, and free from central authority manipulation.

- Ticket Management for Bus Travel: The ticket management system also caters to bus travel through the BusTicket contract. This contract inherits functionalities from the base ticket contract and includes attributes specific to bus reservations, such as departure and arrival locations, seat numbers, and bus company details. By leveraging blockchain technology, the system ensures the transparency and immutability of bus ticket reservations, providing a reliable platform for travelers and bus operators.

4.2.3. Technical Implementation

The technical implementation of the blockchain-based ticket management system involves the utilization of smart contracts to handle the logic and operations of ticket reservations for various transportation services. At the core of the implementation is the
TicketReserve contract, which is designed to handle the reservation process for different services and use cases within the transportation industry.

The TicketReserve contract enables users to book or reserve tickets for specific dates and other relevant attributes based on the unique requirements of each transportation service. Whether it is for taxi services, bus travel, or any other mode of transportation, the TicketReserve contract provides the necessary functionality to facilitate seamless ticket reservations.

One of the key advantages of using the blockchain solution is the transparency it offers to the reservation process. The decentralized nature of the system ensures that reservations are stored on an immutable ledger, eliminating the possibility of errors or tampering with reservation details. Users can have full confidence in the integrity of their reservations, knowing that the blockchain serves as a trustless and verifiable source of truth.

By implementing the TicketReserve contract within the blockchain-based ticket management system, users can book or reserve tickets for their desired transportation services, ensuring a seamless and reliable experience. The transparency provided by the blockchain technology ensures that users can easily validate and verify their reservations, mitigating any concerns of errors or discrepancies. The technical implementation focuses on leveraging blockchain’s inherent advantages to offer a robust and trustworthy ticket reservation system for various transportation services.

4.3. Data Integration and Validity

Each block in a blockchain contains data, like transactions, and is assigned a unique hash, which acts as a digital fingerprint. The hash is generated using a cryptographic function, providing a distinct identifier for the block. Data integrity is ensured by including the hash of the previous block in the chain, creating an unbroken sequence. Any attempt to alter data within a block would necessitate recalculating the hash for that block and all subsequent blocks, resulting in hash mismatches and signaling tampering. Additionally, the blockchain employs a Merkle tree structure to verify transaction integrity within each block. This hierarchical structure combines transactions, hashes them together, and repeats the process until a single hash, known as the Merkle root, is obtained. The Merkle root represents the integrity of all the transactions in the block, allowing participants to efficiently validate individual transactions using their corresponding data and position in the tree, without the need to process the entire block’s contents.

The integration and validity of data are essential in the context of V2X communication. Blockchain technology provides robust solutions for these challenges, enabling global data integration, ensuring the validity of shared data, immutability of recorded transactions, and accurate timestamping of actions. These features contribute to the reliability and transparency of the V2X ecosystem, facilitating effective communication and collaboration between vehicles, infrastructure, and other entities.

- Global Data Integration: Blockchain technology enables the integration of V2X data on a global scale. With the decentralized nature of blockchain, data from different sources and jurisdictions can be securely shared and accessed. This global integration ensures a unified and reliable source of V2X data, facilitating effective communication and collaboration between vehicles, infrastructure, and other entities across borders.

- Validity of Shared Data: Data shared within the V2X ecosystem are verified and validated through the use of blockchain technology. The immutability of the blockchain ensures that, once data are recorded, they cannot be altered or tampered with. This feature guarantees the integrity and validity of shared data, enhancing trust among the participants in the V2X network.

- Immutability of Recorded Transactions: Transactions recorded on the blockchain, such as Vehicle-to-Vehicle communications or interactions with infrastructure, are immutable and cannot be modified. This immutability provides an auditable trail of events, ensuring the integrity and transparency of V2X transactions. It also helps in addressing disputes and verifying the sequence of events accurately.
• Timestamping Actions: Timestamping actions within the V2X ecosystem is crucial for maintaining an accurate record of events. Each action, such as data exchange or communication between vehicles and infrastructure, is timestamped and recorded on the blockchain. Timestamping ensures a chronological order of events and helps in tracing the history of interactions, providing a reliable reference for analysis, verification, and troubleshooting.

Figure 2 illustrates the integration of the blockchain layer and the application layer for V2X communication. The blockchain layer is represented as a chain of interconnected blocks, ensuring data immutability and integrity. The application layer includes various components, such as vehicles, traffic lights, radars, IoT devices, Wi-Fi, and EV charging stations, representing the diverse entities in the network. This integration facilitates real-time monitoring, coordination, and enables reliable decision making across different entities, fostering trust and ensuring the integrity of the exchanged data within the network.

4.4. Blockchain–IoT Integration

Integrating blockchain technology with IoT devices provides numerous advantages to the V2X communication system. This section explores the integration of blockchain and IoT, focusing on penalty enforcement, information validation, real-time monitoring, and secure messaging and communication between IoT sensors and vehicles.

4.4.1. Penalty Enforcement

By combining blockchain and IoT, penalty enforcement for rule violations within the V2X system can be enhanced. IoT sensors detect and capture violations, such as speeding or illegal maneuvers, while blockchain technology ensures the immutability of recorded violations. Smart contracts can be utilized to automate penalty enforcement, triggering actions such as issuing fines or deducting penalty points from drivers’ records. The transparency and integrity of the blockchain ensure that penalties are accurately enforced and recorded.

4.4.2. Validation of Information

Blockchain integration provides a reliable mechanism for validating information within the V2X ecosystem. IoT devices, such as vehicle sensors or infrastructure sensors, can collect and transmit data to the blockchain. These data undergo validation through consensus mechanisms, ensuring their accuracy and authenticity. By leveraging blockchain’s
decentralized nature and consensus protocols, the V2X system can trust the validated information, promoting data integrity and reliability.

4.4.3. Real-Time Monitoring

Blockchain and IoT integration enable real-time monitoring of various parameters in the V2X system. IoT sensors installed in vehicles and infrastructure continuously collect and transmit data, such as traffic conditions, road hazards, or weather updates, to the blockchain. These real-time data are accessible to all participants in the network, allowing for timely decision making, efficient traffic management, and enhanced situational awareness for drivers.

4.4.4. Secure Messaging and Communication

In addition to traditional secure messaging and communication methods, a blockchain covert channel [32] can be utilized to enhance the security and privacy of messages exchanged between IoT sensors and vehicles. This covert channel allows for discreet communication while leveraging the underlying blockchain technology for integrity and authentication.

The technical implementation of a blockchain covert channel involves several steps. First, the messages from IoT sensors are encoded using steganography techniques to embed them within blockchain transactions. The covert messages are then modified and embedded within the payload of these transactions, appearing normal to outside observers. A secure key exchange protocol is implemented to establish shared secret keys between the IoT sensors and vehicles, ensuring authorized access to the covert messages. On the receiving end, vehicles employ decoding algorithms to extract and decipher the covert messages from the blockchain transactions. Encryption using symmetric or asymmetric algorithms and authentication through digital signatures are employed to ensure confidentiality and integrity. Techniques to prevent steganalysis are implemented, carefully selecting encoding methods, payload placement, and transaction characteristics to maintain the covert nature of the communication.

The IoT sensors can communicate with the blockchain to retrieve the vehicle information and owner wallet address to apply a scoring system and penalties for any violations. The blockchain also allows for seamless communication between different modes of transportation and enables the addition of another layer of value to smart cities in transportation systems.

4.5. Decentralized Payment System for Transportation in Smart Cities

One of the challenges with centralized payment systems in transportation is the need for users to provide sensitive financial information, such as credit card details, when purchasing tickets or vehicles. Additionally, centralized payment systems may suffer from payment processing delays and high transaction fees. To overcome these limitations, blockchain technology offers a decentralized payment system that is more secure and efficient.

In a decentralized payment system, users can conduct transactions using cryptocurrencies and stablecoins like USDT, eliminating the reliance on traditional fiat currencies. Blockchain technology enables fast and secure payment processing with minimal transaction fees. Users maintain control over their financial information and avoid the risks associated with centralized payment systems [33].

To implement this system in smart cities, the blockchain can be integrated with existing transportation systems, allowing users to make payments in a single transaction using their wallet addresses. This requires collaboration between transportation providers and blockchain developers to establish the necessary infrastructure.
Decentralized Marketplace

One of the key features of a blockchain-based payment system in transportation is the establishment of a decentralized marketplace. This marketplace enables users to not only make payments for transportation services but also facilitates the buying and selling of vehicles within the smart city ecosystem.

By integrating the blockchain with the transportation system, users can participate in a peer-to-peer vehicle marketplace where they can purchase or sell vehicles directly without the need for intermediaries. The blockchain provides transparency, security, and immutability to the marketplace transactions, ensuring trust and eliminating the risks associated with traditional vehicle purchases.

In this decentralized marketplace, users can browse listings of available vehicles, including details such as model, price, and ownership history. Smart contracts play a crucial role in executing and automating the buying and selling process. Once a buyer and seller agree on the terms, a smart contract is created to handle the transaction. The contract verifies the authenticity of the vehicle’s information, manages the transfer of ownership, and securely holds the funds until the transaction is completed satisfactorily.

Overall, a decentralized payment system for transportation in smart cities offers numerous benefits, including enhanced security, improved efficiency, and ease of use for users. By embracing blockchain technology, smart cities can transform their transportation systems into more seamless and innovative ecosystems.

5. Simulations and Results

In this section, we present simulations and results for our Vehicle-to-Blockchain (V2B) communication approach. We evaluate system performance on Ethereum, Binance Smart Chain, Avalanche, and Polygon blockchains, examining transaction handling, gas fees, and throughput capabilities.

5.1. Simulation of Multi-Token ERC1155 Contracts for Vehicle Ownership Tracking

We conducted a comprehensive simulation of our Vehicle-to-Blockchain (V2B) architecture, involving over 30 Multi-Token ERC1155 contracts, each representing a unique vehicle model. In a network of 300 users on the Ethereum testnet, participants could purchase vehicles and become owners of corresponding vehicle tokens.

During the simulation, users utilized the integrated marketplace contract to exchange vehicles seamlessly. Our analysis revealed a consistent increase in total vehicle token transfers over time, indicating high user engagement and satisfaction. The one-transaction process for ownership transfer led to reduced fees and faster transactions compared to traditional centralized methods.

Figure 3 provides an overview of the total vehicle token transfers during the 24 h simulation. As shown in the graph, the number of vehicle token transfers steadily increased over time, indicating a growing adoption of our V2B system.

Users appreciated the transparency of blockchain, enabling them to verify vehicle ownership at any time. Positive feedback and active testing showcased the potential of blockchain-powered vehicle ownership management for future transportation systems. These results demonstrate the efficiency and promise of our V2B architecture in revolutionizing the transportation industry.
5.2. Transaction Gas Fees Comparison

We recorded the average gas fees for transactions during a 24 h period for four blockchains: Ethereum, Binance Smart Chain (BNB Chain), Avalanche, and Polygon. Our simulations encompassed all possible scenarios for our smart contracts, simulating user–vehicle communication, marketplace interactions, ticket management, and IoT sensor data recording.

Real-time gas fees were tracked for each blockchain, allowing us to evaluate their cost implications in our V2B architecture. The goal was to assess scalability and efficiency in handling V2X and IoT communications on the blockchain.

Figure 4 presents an overview of the average transaction gas fees in USD for each blockchain. As evident, Polygon stands out as the most cost-effective option, boasting lower transaction fees compared to Ethereum, BNB Chain, and Avalanche. Given the large volume of transactions we anticipate in our V2B system, scalability becomes a critical consideration, making Polygon an ideal fit for our use case.
Future work will extend the simulations to encompass other blockchain networks, providing a global perspective on transaction costs, and exploring the potential of layer2 solutions for further optimization.

5.3. Blockchain Throughput Comparison

To evaluate the capacity of different blockchains to handle transactions, we conducted stress testing simulations on Ethereum, Binance Smart Chain (BSC), Avalanche, and Polygon. Our approach requires a high level of interaction, making it essential to assess multiple blockchains.

As shown in Figure 5, the transaction throughput varies significantly between the different blockchains. Based on these results, we can conclude that Polygon stands out as the most scalable blockchain for our approach. Its high throughput capacity and low gas fees make it well-suited for handling the extensive interactions required for our Vehicle-to-Blockchain (V2B) communication system.

6. Challenges and Limitations

Implementing a V2B communication system presents several challenges and limitations that need to be addressed for successful adoption and widespread implementation. These challenges include:
• Collaboration and Partnership: Creating a blockchain-based system that encompasses all transportation system providers and members worldwide requires extensive collaboration and partnership. Overcoming the coordination challenges among diverse stakeholders and fostering cooperation is essential for the effective functioning of the system.

• User Familiarity and Wallet Addresses: Users participating in the blockchain-based transportation system need to be familiar with blockchain technology and have their own wallet addresses. This requirement may create a barrier for some individuals who are not accustomed to using cryptocurrencies or blockchain-based platforms.

• Choosing the Right Blockchain: With the existence of various blockchain platforms, selecting the most suitable blockchain for the transportation system requires careful consideration. Factors such as scalability, security, transaction speed, and governance need to be assessed to ensure optimal performance and compatibility with the system’s requirements.

• Scalability: As the blockchain-based transportation system involves a vast number of factors and users, scalability becomes a crucial concern. Ensuring that the system can handle a large volume of transactions and accommodate increasing participation is vital for its long-term viability.

• Regulatory Compliance and Privacy: Regulations and privacy concerns may pose challenges for the implementation of blockchain-based transportation systems. Anonymity is a fundamental characteristic of blockchain as users are primarily identified by their wallet addresses. However, certain regulations may require the association of names or identification with wallet addresses, raising issues of privacy and compliance.

Addressing these challenges and limitations is crucial for the successful adoption and implementation of blockchain-based transportation systems. By developing collaborative frameworks, educating users, evaluating suitable blockchain platforms, addressing scalability concerns, and considering regulatory and privacy requirements, the potential of blockchain technology can be fully harnessed to revolutionize the transportation industry.

7. Conclusions

In conclusion, the proposed V2B (Vehicle-to-Blockchain) communication architecture leveraging blockchain technology and smart contracts holds great potential for transforming the transportation industry. By utilizing blockchain’s decentralized and secure nature, coupled with smart contracts’ automation capabilities, we can create a more efficient, transparent, and secure transportation system. The integration of IoT sensors further enhances the intelligence and connectivity of the system. Moving forward, future research should focus on the practical implementation of this decentralized V2B architecture. This involves developing smart contracts and communication protocols that facilitate seamless interactions between vehicles and the blockchain network. Additionally, exploring novel approaches for integrating emerging technologies, such as artificial intelligence and machine learning, can further enhance the efficiency and effectiveness of V2B communication. By advancing the V2B communication architecture and exploring synergies with cutting-edge technologies, we can revolutionize the transportation industry and unlock new possibilities for improved efficiency, safety, and sustainability.

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Data Availability Statement: For the purpose of our study, we developed simulation models and generated smart contracts, which were subsequently deployed on various blockchain networks. Our analysis does not utilize pre-existing datasets, as we focused on creating new and specific scenarios. However, if you require access to any databases, it’s important to note that most blockchains are
publicly accessible. As an example, the Etherscan Ethereum explorer (available at https://etherscan.io/) contains comprehensive records of Ethereum transactions.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

V2B Vehicle-to-Blockchain
SC Smart Contract
V2X Vehicle-to-Everything
V2V Vehicle-to-Vehicle
V2G Vehicle-to-Grid
V2I Vehicle-to-Infrastructure
V2N Vehicle-to-Network
NFT Non-Fungible Token
IoT Internet of Things
IoV Internet-of-Vehicle
EV Electric Vehicle
VIN Vehicle Identification Number

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