Enhancing Power Grid Resilience With Blockchain-Enabled Vehicle-to-Vehicle Energy Trading in Renewable Energy Integration

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***Abstract*—There has been a growing penetration of renewable energy sources (RES) into power grids in recent years. As extreme weather events and cyber-attacks frequently occur, grid resilience has been an important issue. Vehicle-to-Vehicle (V2V) energy trading has great potential to improve the stability and reliability of resilient power grids integrated with high-penetrated RES. V2V energy trading is a distributed peer-to-peer (P2P) application. As a decentralized distributed ledger technology, blockchain is an ideal platform for V2V energy trading. The consensus mechanism of blockchain determines whether the V2V energy trading blockchain (ETB) can improve grid resilience. However, most studies in the ETB currently utilize conventional consensus mechanisms. Due to their substantial computational requirements and communication overhead, these consensus algorithms are not well-suited for real-time service applications like energy trading. We propose a novel BAC-SDS consensus specifically for V2V ETB, thus enabling resilient grids to maximise the use of renewable energy. We propose an Electric Vehicle (EV) leader election based on cryptography and adopt the sharding technique to enhance the system's scalability. Furthermore, our approach ensures the secure transfer of energy and value, contingent upon the condition that all EVs exhibit reasonable behavior and retain the proofs they possess. We implement the V2V ETB on Hyperledger Fabric. The experiments demonstrate (1) that V2V ETB significantly enhances the resilience of the power grid compared to traditional centralized trading models and (2) the consensus mechanism proposed in this article is better suited for V2V energy trading than existing mechanisms, exhibiting superior performance in terms of security, throughput, and scalability, thus further enhancing the resilience of the power grid.**

***Index Terms*—Blockchain, consensus, energy trading, resilience, renewable energy sources (RES), vehicle-to-vehicle (V2V).**

I. Introduction

OVER the past decade, RES, such as solar and wind, have experienced significant performance improvements and cost reductions. The grid transforms remarkably by integrating increased RES into the power system to mitigate climate change and energy shortages. [1], [2]. With the integration of RES, power grids are now facing several new challenges, including variability and uncertainty [3]. To ensure the stability and reliability of power grids, they must be designed to be resilient to these new challenges [4]. The output from RES is subject to fluctuations due to changes in weather conditions. It is difficult to predict the power available at any given time [5]. While the traditional power grid relies on large, centralized power plants, the RES power grid involves a large number of distributed power generators, leading to a significant challenge in managing the energy supply and demand [6], [7]. In addition, the intermittent nature of RES sources has resulted in significant variations in energy generation, further exacerbating the power grid's instability [1], [7].

Various approaches have been proposed to address these challenges, such as energy storage systems, demand-side management, and distributed energy resource management systems. However, these approaches have limitations, such as high costs, limited scalability, and a need for incentives for end-users to participate in energy management.

V2V energy trading has great potential to improve the stability and reliability of resilient power grids, especially those integrated with high-penetrated RES [8]. Electric Vehicles (EVs) are a valuable asset to mitigate RES integration issues and are rapidly gaining popularity among consumers.

The Internet of Electric Vehicles (IoEV) refers to the interconnected network of EVs enabled by emerging technologies

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such as communication protocols, data exchange mechanisms, and intelligent systems. Blockchain-based V2V energy trading utilizes the communication capabilities of EVs to establish a decentralized P2P energy trading system, enabling direct energy transactions between vehicles.

In V2V energy trading, EVs can buy and sell energy from and to other EVs in real time based on their energy needs and availability [9], [10]. This enables the EVs to act as distributed energy storage devices, helping to balance the supply and demand of energy in the power grid. During peak loads, EVs with excess energy can distribute the stored power to other EVs needing power (and even feed the stored energy back to the grid [11]), which can relieve the load on the centralized grid [12]. So V2V energy trading can enhance the power grid's resilience and enable it to cope better with fluctuations in electricity demand. However, energy trading between EVs is P2P, decentralized, and distributed. Existing centralized technologies are unable to facilitate the practical implementation of V2V energy trading. This requires new distributed technologies to replace the traditional centralized trading model.

Blockchain happens to be an emerging decentralized distributed ledger technology. Blockchain allows secure data storage, synchronized information sharing, and trustworthy transaction execution in P2P networks [13]. Blockchain provides a trustless platform where energy transactions can be recorded and verified without a centralized intermediary. In addition, blockchain enables the creation of smart contracts [14] (the chaincode in our experiments), which can automate the energy trading process and incentivize EV owners to participate in the energy management process. The blockchain's inherent properties provide great potential for V2V RES trading to make power grids more resilient. However, there are two critical and unresolved issues with blockchain-based V2V energy trading:

1) The consensus mechanism is blockchain's soul and core technology, the decisive factor for blockchain-based resilient power grids to operate safely and efficiently. However, the vast majority of consensus mechanisms currently used in V2V (or P2P) energy trading are either traditional consensus or improved versions based on these traditional mechanisms. These consensus mechanisms cannot be practically implemented in Internet of Things (IoT) applications such as energy trading due to the considerable computing power and communication costs. Only when this core issue is resolved can the practical implementation of V2V energy trading be facilitated, thereby enhancing grid resilience.

2) The load of EVs is challenging for distribution operators and utilities due to the unpredictable nature of EVs charging and routes [15]. The nodes in most energy trading scenarios are stationary; however, EV nodes are highly mobile [16]. In other words, nodes are not fixed in V2V ETB, and nodes can join or leave the blockchain anytime. However, the majority of consensus mechanisms currently applicable to blockchains do not support dynamic joining and removing of nodes.

Therefore, we are motivated to create a novel consensus method named BAC-SDS to address the difficulties above in V2V energy trading, thereby enabling a renewable energy-integrated power grid to be more resilient. The BAC-SDS represents the block alliance consensus mechanism with security, decentralization, and infinite scalability. This article makes the following contributions:

1) Based on the traffic volume of EVs, we propose two schemes, one for low traffic volume (low user participation) and the other for high traffic volume (high user participation).

2) We go beyond the traditional consensus framework and achieve infinite scalability (scale-out, i.e., unbounded throughput) through the sharding technique based on the properties of EVs and the IoEV.

3) Further, we break the blockchain impossibility triangle in the energy trading scenario: security, infinite scalability, and decentralization.

4) An efficient cross-shard trading commit protocol is proposed for the frequent mobility of EVs. To achieve infinite scalability without sacrificing security, a cryptography-based mechanism is designed for EV leader election.We utilize the Hashgraph instead of traditional BFT mechanisms within each shard to further improve the transaction speed.

5) We implement the V2V ETB and our BAC-SDS consensus mechanism on the Hyperledger Fabric platform. The experiments demonstrate that V2V ETB significantly enhances the resilience of the power grid compared to traditional centralized trading models. The high efficiency and security of BAC-SDS and the blockchain-based V2V energy trading platform are verified. We believe our system and consensus model are equally applicable to most energy trading scenarios and will be simpler.

The article is structured as follows: Section II provides background and related work. Section III introduces our blockchain-based energy trading model. In Section IV, we propose a detailed consensus mechanism BAC-SDS that breaks the impossible triangle of V2V ETB. The performance of our V2V ETB is presented in Section V. Finally, the last section concludes the work and outlines future research directions.

II. Background and Related Works

There were some studies about enhancing the resilience of grids integrated with RES. Energy storage technologies can be utilized to store surplus energy during peak production periods and release it during low production periods, thereby aiding in grid stability maintenance. Confrey et al. [17] optimized the architecture of the energy storage system in the context of rooftop photovoltaic power generation to facilitate timely recovery from faults caused by extreme disturbances, thereby maximizing the resilience of the power grid. Microgrids can be used to integrate RES into the grid and provide a reliable source of power in case of grid failures. Distributed generation technologies can be utilized to generate electricity close to the point of consumption, reducing the need for long-distance transmission and increasing the resilience of the grid. Baghbanzadeh et al. [18] proposed an optimal layout for distributed power generation to meet user demand in the islanded mode of a microgrid, thereby enhancing the elasticity of the distribution system. Nonetheless, these methods are not without drawbacks, including but not limited to their high expenses, limited scalability, and insufficient encouragement for end-users to engage in energy management.

The literature on the utility of blockchain technology in secure, flexible, and resilient power grids is still limited [19]. Jetley et al. [19] examined the potential of blockchain technology in facilitating smart grid deployment and identified the obstacles to implementing blockchain in smart grids. Das et al. [20] presented a comprehensive review and comparative analysis of qualitative frameworks and quantitative metrics used to study resilience in detail. Hossain et al. [21] addressed the objectives of examining grid resilience and reliability, elucidating their quantification metrics, and exploring techniques for their enhancement in a comprehensive manner. However, the aforementioned references did not provide specific solutions and methodologies.

Blockchain-based V2V energy trading offers a decentralized, flexible, transparent, scalable, and incentivized solution for energy trading that can enhance the resilience of grids integrated with high-penetrated renewable energy sources. There were several consensus methods implemented in V2V ETB. Chen et al. [22] propose a Proof-of-Solution (PoSo) using a meaningful optimization problem instead of the meaningless puzzle in Proof-of-Work (PoW). However, this approach remains in the Proof-of-X category and is limited to the energy blockchain's impossible triangle. Chen et al. [23] and Wang et al. [24] utilize the Delegated Proof of Stake (DPoS) and the directed acyclic graph (DAG) as their consensus, respectively. However, these two consensus are classic mechanisms that cannot be used in RES trading directly. Honari et al. [25] suggested the deployment of a decentralized voltage stability algorithm through blockchain-based smart contracts. Moreover, they explored sharding mechanisms to enhance the system's scalability while operating within fixed computing resources. However, the specific consensus algorithm and sharding mechanism are not described in detail.

The consensus mechanisms adopted in these studies were primarily traditional ones used in cryptocurrencies, such as PoW, PoS, DPoS, and their improved versions. There were also many studies using the Practical Byzantine Fault Tolerance (PBFT) consensus. PoW is resource-intensive and requires significant computational power, translating into high energy consumption. In the context of energy trading, where the goal is to promote energy efficiency and sustainability, using PoW can undermine the purpose by consuming excessive energy resources. While PoS is more energy-efficient than PoW, it still has limitations for P2P energy trading. PoS typically relies on participants holding a certain amount of cryptocurrency as a stake. Energy trading requires specific considerations, such as the amount of energy produced or consumed, and participants' cryptocurrency holdings may not accurately reflect their energy usage or availability. PBFT consensus requires a high degree of message exchange and communication among nodes in the network. As the number of participants increases, the communication overhead and the number of messages exchanged grow exponentially. In the context of P2P energy trading, where numerous EVs may be involved in direct trading, the scalability of the PBFT becomes a concern.

In general, there is still a considerable shortfall in the security and efficiency of the current consensus mechanisms utilized in the ETB. Therefore, enhancing the performance of the consensus mechanism is an urgent requirement for resilient grids integrated with high-penetrated RES.

III. System Overview

The main issues with blockchain are throughput and scalability caused by the present consensus methods' limitations. We break the impossible triangle: security, infinite scalability, and decentralization in V2V ETB. Here we emphasize the energy trading scenario (V2V ETB) because we sacrifice part of the decentralization. Nevertheless, it is reasonable and appropriate to sacrifice part of the decentralization in energy trading. We preserve centralization to ensure the government's macro-regulation of the energy economy. While centralized institutions may still play a role in facilitating the regulatory framework and maintaining grid stability, adopting a P2P market structure in V2V energy trading brings numerous benefits in terms of flexibility, efficiency, cost reduction, decentralization, and grid resilience.

In our V2V energy trading model, the energy transfer between EVs is facilitated through wireless power transfer (WPT) techniques. WPT allows for the wireless transmission of electrical energy from the energy provider vehicle to the energy requester vehicle without the need for physical connections or cords.

WPT enables efficient energy transfer, minimizing energy losses during transmission. By optimizing the design of the coils and the resonant frequency, the transfer efficiency can be enhanced, resulting in higher energy transfer rates and reduced energy wastage. In our V2V energy trading model, the WPT technique allows EVs to securely and efficiently trade energy among themselves. It promotes a decentralized and sustainable energy ecosystem, where surplus energy from one vehicle can be utilized by another in need. This fosters energy sharing, promotes renewable energy integration, and contributes to overall grid stability.

In V2V energy trading, individual EVs themselves act as decision-making stakeholders, autonomously engaging in direct energy transactions with other EVs. They have the freedom to negotiate prices, choose trading partners, and make decisions based on their own energy needs and preferences. The Vehicle-to-Grid (V2G) involves a more centralized approach, where a designated entity or aggregator acts as the decision-maker, managing the flow of energy between the grid and the participating EVs. Our research contributes to the field of blockchain-enabled energy trading by introducing a novel consensus mechanism specifically designed for V2V energy trading. This mechanism addresses the limitations of existing consensus mechanisms and ensures the security, scalability, and throughput required for reliable energy trading.

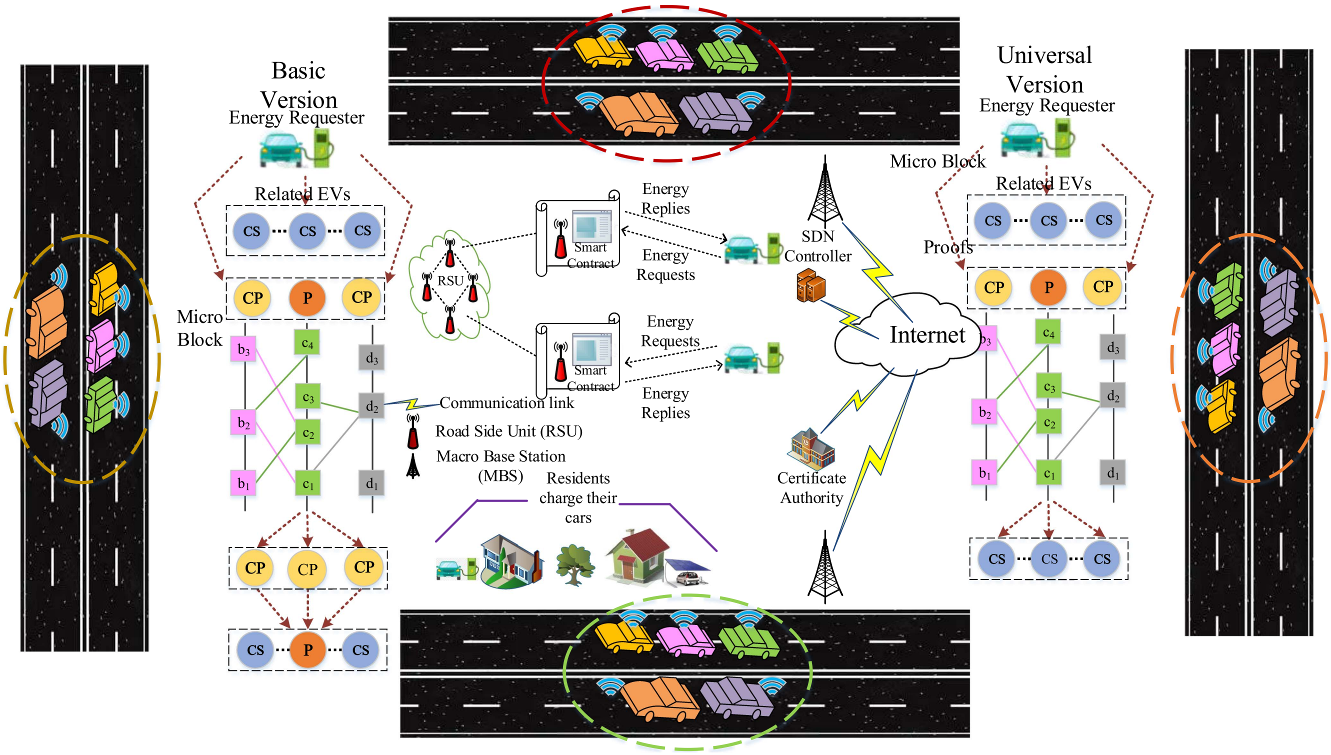


Fig. 1. V2V ETB model.

By exploring the characteristics of V2V energy trading not explored in other studies, we present a consensus method that is well-suited for V2V ETB in which the position of the nodes (EVs) is variable, and the real-time requirement is very high. Although our BAC-SDS gives up some of blockchain's decentralized features, this trade-off is perfectly justified in V2V energy trading. It may even be advantageous: retaining centralized institutions and nodes, thus ensuring the state or government will macro-regulate the energy market.

The consensus mechanisms currently employed by most ETBs are traditional methods, thus reaching three properties of the BFT model in malicious EVs less than $\lfloor \frac{N-1}{3} \rfloor$. These conventional mechanisms are generic and ignore the nature of V2V energy trading [26]. In the typical blockchain application, Bitcoin, and other digital currency systems, nodes package their transactions into the blockchain by mining themselves or giving transaction fees to the miners. The framework of our model and methodology is based on blockchain. We propose a consensus mechanism specifically designed for V2V energy trading based on this blockchain architecture. We have taken into account the frequent and high-speed movement of EVs in our model. The BAC-SDS exhibits superior performance compared to the consensus employed in P2P energy trading (or even more broadly, in consensus mechanisms applied in the Internet of Things scenarios). Fig. 1 shows the framework of V2V ETB model. In this article, we replace the resource-consuming mining approach with a random leader election based on cryptography and EVs' activity. We further define and address the characteristics of the V2V ETB:

1) The EV buyer must have sufficient funds, and the EV seller must have enough electricity. The transaction between them is carried out through the Road Side Unit (RSU). The smart contract guarantees the security of the transaction. This is used to identify the energy buyer and seller of the V2V ETB. The transaction records generated will be consensus within the shard by the BAC-SDS mechanism.

2) The rational demander broadcasts its transaction and proves its validity to validators (including energy buyers, sellers, and centralized institutional nodes).

3) Core validators (leader nodes) check the validity of all transactions and pack them into the blockchain. In contrast, regular validators merely validate the part of the transaction that relates to them and do not focus on other transactions.

4) Fast processing of cross-shard energy trading. The cross-shard here is different from the cross-shard utilized with digital currencies. Cross-shard in the digital currency means that a node in one shard transfers money to a node in another shard, and a user may also have multiple accounts in different shards. In V2V energy trading, EVs may travel quickly from one shard to another due to their excellent mobility. Additionally, one user (one EV) corresponds to only one account. Therefore, if two consecutive transactions made by a user occur in different shards, proofs must be provided by the previous shard to prohibit an EV user from engaging in double-spending.

Based on these characteristics, we propose a blockchain consensus specifically suitable for V2V energy trading. Our V2V ETB is infinitely scalable for high real-time V2V scenarios

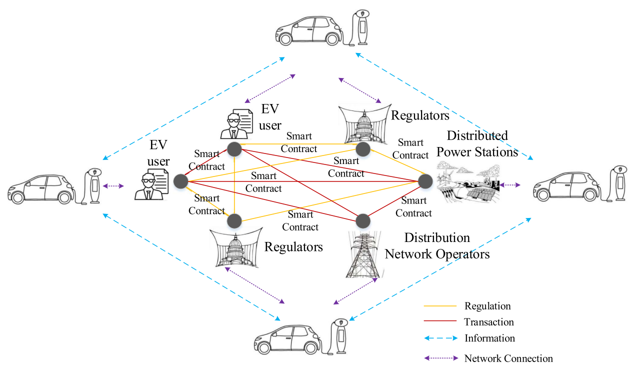


Fig. 2. Blockchain-based energy trading framework.

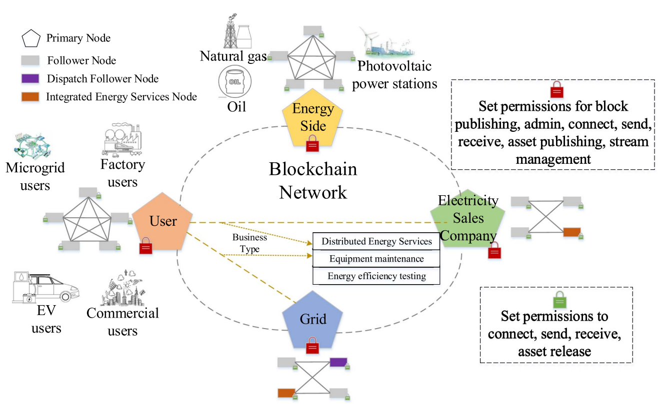


Fig. 3. Blockchain-based RES trading network.

with guaranteed security and reasonable decentralization. Our model applies to other energy trading scenarios besides V2V, as the nodes in other energy trading scenarios are primarily static.

A. Blockchain-Based V2V Energy Trading Model

The energy trading process within the V2V ETB begins with the identification of energy surplus or demand. Fig. 2 depicts the blockchain-based energy trading framework. EV users and distributed power stations can communicate their energy availability or requirements through the blockchain network [31]. Smart contracts automatically match supply with demand, considering factors such as price, proximity, and user preferences.

Once a suitable match is found, the smart contract verifies the availability of energy, validates the transaction details, and ensures compliance with regulatory requirements. Upon successful verification, the contract triggers the transfer of energy from the supplier to the buyer, either from EVs to the grid or vice versa. The transaction details, including energy quantity, price, and involved parties, are securely recorded on the blockchain, ensuring transparency and auditability.

Throughout the entire energy trading process, the blockchain network provides a decentralized and immutable ledger that all participants can access and verify. This enhances trust, eliminates the need for intermediaries, and promotes a more efficient, resilient, and sustainable energy ecosystem.

Distributed power stations, such as rooftop solar panels or wind turbines, generate renewable energy within the local vicinity. These stations contribute to the overall energy supply and can directly engage in energy trading with EV users or act as intermediaries facilitating transactions between buyers and sellers.

Distribution network operators play a critical role in managing and maintaining the electricity distribution infrastructure. In the V2V ETB, they serve as intermediaries and facilitators, ensuring the smooth flow of energy transactions between EV users, distributed power stations, and other participants.

Regulators oversee the energy market and ensure compliance with relevant regulations and policies. Their role in the EV energy trading blockchain ecosystem is to provide a regulatory framework that fosters fair and secure energy trading practices while promoting the integration of renewable energy sources.

B. Blockchain-Based RES Trading Network

The energy side focuses specifically on distributed renewable energy sources, such as solar panels, wind turbines, and other decentralized energy generation units. On the other hand, the users encompass a diverse range of stakeholders, including microgrid users, industrial users, commercial users, and electric vehicle users, who are actively involved in energy consumption and trading. Fig. 3 shows the blockchain-based RES trading network.

Within this blockchain-based renewable energy trading model, various types of business interactions are facilitated among the stakeholders. The customers and grids engage in distributed energy services, where customers can offer their surplus renewable energy to the grid or exchange energy with other users. Additionally, the customers and grids collaborate on equipment maintenance, ensuring the efficient and reliable operation of renewable energy systems. Energy efficiency testing is another aspect of the business relationship, allowing customers to validate and optimize their energy consumption patterns.

Moreover, customers and grids can engage in business representation, acting as intermediaries for energy transactions and facilitating negotiations between buyers and sellers. Data trading is another significant business opportunity, enabling the exchange of energy-related data, such as consumption patterns, production forecasts, and grid demand. This data sharing fosters transparency and enables informed decision-making in the renewable energy ecosystem.

The blockchain technology serves as the underlying infrastructure for this renewable energy trading model, offering inherent advantages such as transparency, security, and immutability. By utilizing blockchain, a decentralized ledger that records and verifies all energy transactions in a transparent and auditable manner can be established. This promotes trust among participants, eliminates the need for intermediaries, and enables seamless P2P energy trading.

C. Threat Model

1) Sybil Attack: In the context of V2V ETB, one of the potential threats is the Sybil Attack, where an attacker attempts to deceive the network by disguising a single node as multiple nodes with different identities. The attacker aims to gain control or influence over the blockchain network, disrupt message delivery, and interfere with routing. By forging multiple identities, the malicious node can manipulate the consensus process and compromise the integrity of the blockchain.

To mitigate the risk of Sybil Attacks in V2V ETB, it is essential to establish mechanisms that raise the threshold for nodes to enter the blockchain network. One effective approach is the use of consortium blockchains, where a predetermined set of trusted participants controls the network. In a consortium blockchain, any node attempting to join the network must undergo a rigorous authentication process to verify its identity and authorization.

2) Double Spending: Double spending refers to the malicious act of spending the same energy units multiple times, leading to inconsistencies and fraud within the system. To prevent double spending in the V2V ETB, the consensus mechanism must ensure that all transactions are securely and immutably recorded on the blockchain, leaving no room for tampering or manipulation. The Hashgraph consensus, with its asynchronous BFT properties, provides a robust mechanism for validating and ordering transactions, thereby mitigating the risk of double spending.

3) Denial of Service (DoS) Attack: The V2V ETB relies on a network infrastructure for communication and data exchange. Therefore, threats such as distributed denial-of-service (DDoS) attacks, packet sniffing, or man-in-the-middle attacks pose risks to the availability, confidentiality, and integrity of the system.

A DoS Attack occurs when a malicious node aims to disrupt the provision of services within the blockchain system, preventing authorized users from accessing them. In the context of V2V ETB, a malicious node can initiate requests to a target EV, consuming minimal resources on its end, while requiring the target EV to expend significant resources in processing and responding to these requests.

Resisting DoS Attacks can be challenging within traditional BFT systems due to their reliance on a precise sequence of block proposers. If a node responds with a delay, it becomes difficult for other nodes to determine whether the delay is due to network issues or if the node is under a DoS Attack. Consequently, the number of available nodes decreases, thereby compromising the system's safety.

IV. V2V ETB System and BAC-SDS

To make our V2V ETB meaningful in practice, we have developed two consensus mechanisms within the same architecture: Basic BAC-SDS and Universal BAC-SDS. The basic version is more centralized, and the typical EV is less motivated to participate. The leader nodes mainly comprise government-trusted organizations or departments and highly engaged EV users. Most general EVs are designed to achieve fairness, transparency, distributed storage, and regulation. We offer the basic version because decentralized blockchain systems are essentially composed and maintained by users. The factors not part of consensus technologies, such as incentives, are not perfect at the start of the real-life application of V2V ETB. These factors must be continuously adjusted and improved as the V2V ETB application process progresses. As a result, EV users may be reluctant to engage in the V2V ETB system at this early stage of system development. The universal version is more decentralized than the basic, and users are more motivated to participate. Ordinary EVs are highly mobile, but Byzantine Fault Tolerance (BFT)-based consensus algorithms like Hashgraph and Practical Byzantine Fault Tolerance (PBFT) do not support dynamic addition and deletion of nodes, which contradicts the V2V ETB scenario. In the universal version, each EV has its own blockchain, and all transactions commitment blockchain in the leadership committee. Both versions can coexist in real-life deployments. Users can switch between basic and universal at specified periods: such as during major festivals or specific seasons, when users may use the EV frequently (universal version) or rarely use the EV (basic version).

A. Basic BAC-SDS

There are three categories of EVs in basic version: primary (P), candidate primary (CP), and consensus nodes (CS). There no blocks and leader in the Hashgraph stage. Hashgraph belongs to the Asynchronous Byzantine Fault Tolerance (ABFT). EVs are unable to interfere with the consensus process or tamper with data within the V2V ETB. The blockchain stage is to realize distributed storage. The current Hashgraph is only available for private and consortium blockchains with a predetermined number of EVs. Dynamic node joining and leaving are not supported in Hashgraph, which contradicts the requirements of IoEV. As a result, only P and CP participate in the ABFT within BAC-SDS, creating a private environment in their shards. However, the CS EVs do not take part in the leader committee consensus, thus lacking universal consensus on transactions. To address this limitation, we continue to employ the blockchain approach, with the P publishing the block and the decentralized storage of the chain implemented in CS. Furthermore, the blockchain offers the advantage of enabling dynamic joining and leaving of EVs, which is particularly beneficial for accommodating the high mobility of EVs.

When an EV node initiates a transaction, it disseminates the transaction information to other EV nodes in the network using a gossip protocol. Through this gossip protocol, each EV node spreads the transaction to a subset of its neighboring nodes. These nodes, in turn, share the transaction with their neighbors, creating a rapidly spreading network of transaction information.

As the transaction information spreads, the EV nodes collect and store the transaction history in the form of a DAG. The DAG structure captures the causal relationships between transactions and preserves the order of events.

To determine consensus, EV nodes engage in virtual voting. Each node maintains a virtual voting algorithm that continuously runs alongside the gossip protocol [27]. EV nodes independently and asynchronously determine their votes based on the received

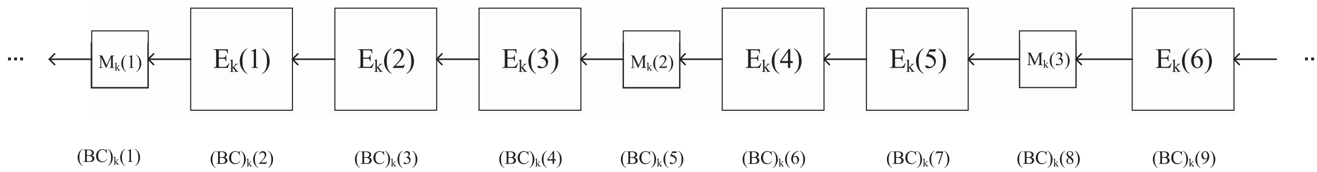


Fig. 4. Individual blockchain.

transaction information. The voting algorithm takes into account the order of transactions and the timestamps associated with them.

Through the virtual voting mechanism, the EV nodes collectively establish a consensus on the order of transactions and the validity of the transaction data. The Hashgraph consensus algorithm ensures that the majority of nodes agree on the transaction history, achieving BFT and enabling the secure and reliable operation of the V2V energy trading system.

As shown in Fig. 1, there are two types of blocks in V2V ETB: micro blocks consensused by the leader committee and energy blocks saved and supervised by regular EVs. We utilize the Hashgraph to achieve the concurrent writing of transactions solving the blockchain scalability issue. By doing this, the leader committee achieves leaderless BFT through virtual voting done locally for each committee member. Members in each committee keep up their own chains and communicate with one another using the gossip protocol. The detailed consensus in the committee and the leader election can be found in [28], [29]. The cryptography-based random leader elections could be found in Appendix A.

B. Universal BAC-SDS

We denote the a-th energy transaction from a buyer B_i to a seller S_j as $Tr(i \to j) = \langle Tr - a, i, j, O(Tr), C_p, C_s, E_p, E_s \rangle \sigma_i$. This transaction contains the energy buyer B_i and seller S_j. All buyers and sellers obtain their identification (ID) certificates $CertB_i$ and $CertS_j$ from the Certificate Authority (CA). They participate in V2V ETB with their encryption keys (public and private) pair (PK, SK) and the e-wallet address Add. Each transaction has its unique number $Tr - a$ and the origins of the a-th transaction $O(Tr)$. The $O(Tr)$ is the set of transactions sent to B_i previously. The C_p and C_s represent the B_i's present and surplus currencies, respectively. The E_p and E_s represent the B_i's present and surplus energy, respectively. All this information is encrypted with the SK_i, which is the digest (hash value) of these items.

Like the basic version, there are two types of blocks in the universal version: energy blocks and micro blocks. Energy blocks are used to store energy transactions between EV users, and micro blocks are used to reach a final consensus on the transactions. There are N nodes (EV users) in the V2V ETB. Every user has its own blockchain. Fig. 4 depicts the users' individual blockchain. These individual blockchains are denoted as $(BC)_k, k \in \{1, 2, \ldots, N\}$. The f-th energy block in the k-th node's blockchain $(BC)_k$ is represented by $E_k(f)$. An energy block $E_k(f)$ consists of a set of transaction identifications and a digest of its previous block (an energy or micro block). A transaction identification is utilized to identify a specific transaction $Tr(i \to j)$. We define a transaction identification as $(TI)_k(m, n)$, where k denotes that this transaction identification is in the k-th node's blockchain, m denotes the m-th energy block in the individual blockchain, and n denotes the n-th transaction identification in the m-th energy block. And the $(TI)_k(m, n)$ includes a specific transaction $Tr(i \to j)$. Since an energy transaction involves a buyer B_i and a seller S_j, a specific transaction will have two transaction identifications. The content of these two identifications is the same.

The micro block in the universal version is different from the basic version. The micro blocks in universal are generated by the EV users themselves and finally approved by the leadership committee. The micro blocks in the universal version are not used for storage but for consensus and do not contain transaction specifics. The f-th micro block in the k-th node's blockchain $(BC)_k$ is represented as $M_k(f)$.

The leaders committee still conducts the consensus. The result of the consensus is a global micro blockchain. The Hashgraph consensus is still used in the leaders committee. The consensus, however, is on the micro blocks delivered by EV users. The EV user B_i delivers micro blocks not only his individual blockchain but also all the information, which we call proof, that can be used to confirm the validity of the micro block.

The proof includes: (1) all the energy blocks of both nodes B_i and S_j from the last validated micro block to the current micro block to be verified. (2) the origins of $Tr(i \to j)$ until the initial balance in the genesis block, denoted by $Tr(e \to l)$. And the chain segment of $(BC)_e$ signed by node e and $(BC)_l$ signed by node l from the latest segment validated by the leader committee to the one containing $Tr(e \to l)$.

The leader nodes of the committee verify the micro block's validity:

1) Buyer's and Seller's transaction identifications: The transaction $Tr(i \to j)$ has two and only two transaction identifications $(TI)_k(m, n)$ and $(TI)_o(p, q)$. Both $(TI)_k(m, n)$ and $(TI)_o(p, q)$ have the identical transaction $Tr(i \to j)$.

2) Valid identifications: All information in the identification is correct and signed by B_i using its private key.

3) No Double Spending [26]: There no forks for the $Tr(i \to j)$. There does not exist a valid transaction $Tr'(i \to j)$ in an identification $(TI)_k(m', n')$ with $(n' < n, m' < m)$ and the $Tr'(i \to j)$'s origins $O(Tr'(i \to j)) \cap O(Tr(i \to j)) \neq \emptyset$.

4) Validated Origins [30]: All origins of the $Tr(i \to j)$ are validated.

5) Sufficient Balance: The value C_p of the $Tr(i \to j)$ plus the remaining value C_s equal to the sum of the value of all origins.

The leader nodes broadcast micro blocks in the Hashgraph in a gossip manner after their respective validations are completed. The specific process of reaching consensus on micro blocks by the leader nodes is described in the basic version. After each round, the primary in the leader committee broadcasts the consensused micro block along with its own signature $Pri[M_k(f)]$ to the corresponding node B_i. The leader committee is the centralized component of V2V ETB, but the primary has no motive to do evil. There are three ways in which the primary can do evil: (1) The primary tampers with the transaction information in $M_k(f)$. (2) The primary deliberately does not send to B_i the micro block $M_k(f)$ on which the committee has reached consensus. (3) The primary conspires with B_i node. For case (1), the primary cannot tamper with the information in the block because the $M_k(f)$ has a digital signature of the B_i with its private key SK_i. For case (2), if EV B_i does not receive the consensused $Pri[M_k(f)]$ signed by the primary within a period, it sends the $M_k(f)$ request again until it receives the valid micro block $Pri[M_k(f)]$. For case (3), collusion causes the next micro block $M_k(f+1)$ of EV B_i to fail to reach consensus because the leader committee needs to verify all origins before $M_k(f+1)$. If the next micro block $M_k(f+1)$ cannot reach consensus, then all the blocks (energy blocks and micro blocks) after $M_k(f+1)$ cannot reach consensus.

In addition to the defense against the above three primary mischief scenarios discussed above, V2V ETB has an additional assurance that it is a consortium blockchain. EVs need to be authenticated to enter the V2V ETB. And the leadership committee itself is made up of government-trusted departments and EVs with a high level of participation and honesty. This is different from Bitcoin. As a global financial system, Bitcoin is entirely decentralized and seeks to be completely open. There is no need for V2V ETB to be completely decentralized. Our goal is to minimize grid load and transaction costs while ensuring macro regulation of the energy economy by the state and government, as well as to achieve infinite scalability on this basis and break through the blockchain's impossible triangle.

The correctness of V2V ETB is that all transactions checked by the general EV users and validated by the leader committee are valid, and all transactions forged by the malicious nodes are invalid. The liveness is that the committee will eventually verify all transactions initiated by honest EV users.

Correctness: We denote a committee member z wants to verify the transaction $Tr(i \rightarrow j)$ as $V_z(Tr(i \rightarrow j))$ [30]. If $V_z(Tr(i \rightarrow j))$ is validated, it indicates that the origins of $Tr(i \rightarrow j)$ and $Tr(i \rightarrow j)$'s previous transactions are validated, then $Tr(i \rightarrow j)$ is valid. This can be proved by contradiction. Assume that there is an invalid transaction $Tr'(i \rightarrow j)$ but with valid origins is validated by an honest leader z. It indicates that the complete and correct origins, and all energy blocks prior to the latest micro block of $Tr(i \rightarrow j)$ have already been received and validated by the node z. Since the validation process of the leader committee is precisely the validity conditions of energy transactions, all the validity conditions for the $Tr'(i \rightarrow j)$ is valid. This contradicts our assumption.

Liveness: If B_i and S_j are both honest EV users, the result of the validation process by the committee for the $Tr(i \rightarrow j)$ should be either validated or abandoned before period Δ. Honest B_i and S_j will add the $Tr(i \rightarrow j)$ to their individual chains. Then the correct and complete origins and all energy blocks prior to the latest micro block of $Tr(i \rightarrow j)$ can be obtained by the honest committee since B_i and S_j are honest. It indicates that the result of the validation by the committee will not be pended.

Transferring transactions between different entities is crucial in distributed ledger technology for energy trading. Cross-shard trading is inevitable, especially in the energy trading industry. As entities involved in energy trading, such as individual customers or the power sector, are highly mobile, they may change the shards they are involved in, making secure and effective cross-shard trading essential.

To address this, we propose an innovative atomic cross-shard processing method for energy trading, as shown in Fig. 5 [31]. Our method ensures consistency between energy shards and prevents individuals or departments within a trading entity from duplicating transactions using inconsistencies across shards.

In our method, requests for cross-shard transactions are initiated by the entity itself, and the leader node of each input shard verifies the validity of the transaction. The leader EV gossips the $proof-of-validity$ and labels the transaction's input as spent if it is legitimate [32]. If the transaction is invalid, the leader rejects the cross-shard transaction request, generating $proof-of-invalidity$.

Depending on the verification result of the leader, the user can choose whether to commit or abort the transaction. If all the leader nodes prove that the transaction is valid, the user can gossip the $unblocked-commit$ message, containing the blocked transaction and all proofs of validity. Correspondingly, the leader node of each output shard verifies the transaction and adds it to the subsequent distributed ledger block.

Enabling value transfer between different shards and achieving shard interoperability requires support for secure cross-shard transactions in a sharded-ledger system. To achieve this, a novel Byzantine Shard Atomic Commit (Atomix) protocol [32] is utilized. This protocol ensures atomic processing of transactions across shards, ensuring that each transaction is either committed or eventually aborted [33]. The goal is to maintain transaction consistency between shards, prevent double spending, and avoid locking funds indefinitely [34].

In the context of V2V ETB, deploying complex atomic commit protocols becomes unnecessary due to the inherent characteristics of the shards. The shards are collectively honest and do not infinitely crash. To keep the shard logic simple and eliminate the need for direct shard-to-shard communication, the responsibility of driving the unlock process is placed on the client. Additionally, other parties such as validators or clients can step in if a transaction stalls after submission for processing.

Under the assumptions that shards are honest, do not fail, receive all messages, and reach BFT consensus, several key observations can be made. Firstly, all shards faithfully process valid transactions. Secondly, if all input shards provide a $proof-of-validity$, every output shard unlocks to commit. Thirdly, if even one input shard issues a $proof-of-invalidity$, all input shards unlock to abort. Lastly, if even one input shard

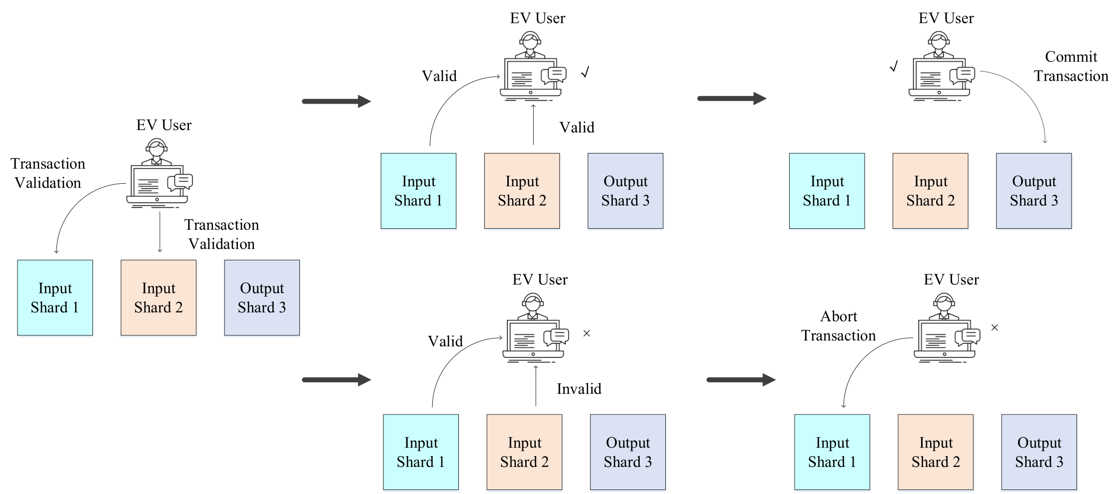


Fig. 5. Cross shard transaction.

issues a $proof-of-invalidity$, no output shard unlocks to commit. Each cross-transaction eventually either commits or aborts.

Based on these observations, each input shard returns exactly one response, either a proof-of-validity or a $proof-of-invalidity$. Therefore, if a client possesses the required number of proofs, they will either hold $proofs-of-validity$, allowing the transaction to be committed, or not, forcing the transaction to abort. Both outcomes cannot occur simultaneously.

Cross-transactions cannot be spent twice. The atomicity of cross-shard transactions ensures that they are assigned to specific shards responsible for their processing. As per the observations made, the assigned shards do not process a transaction more than once, and no other shard attempts to unlock for committing. In the event that a transaction cannot be committed, the locked funds can be reclaimed. This occurs when there is at least one $proof-of-invalidity$ issued by an input shard, thereby fulfilling the condition mentioned earlier. Once all input shards unlock to abort, the funds become available again.

V. Performance Evaluation

Although we do not conduct direct experiments on the power system, the superior performance of our proposed consensus mechanism in terms of security, scalability, and other aspects can indirectly reflect the advantages of our approach for enhancing the resilience of the power grid. A reliable and efficient consensus mechanism is critical for the successful operation of V2V energy trading, as it ensures the security and integrity of transactions while enabling efficient decision-making. Our proposed mechanism has been designed to meet these requirements, and its superior performance in terms of security and scalability can provide a strong foundation for the successful implementation of V2V energy trading. In this way, our approach can contribute to the resilience of the power grid by facilitating the reliable and efficient exchange of energy between participants.

To demonstrate the proposed BAC consensus mechanism for the ETB, we combine the VIBES blockchain simulator with a Python program [16], [37]. We compare our method with classical (PoW, PBFT, and Hashgraph [36] et al.) and recent consensus mechanisms [22], [23], [24] proposed for the renewable energy trading field. Additionally, we compare detailed data metrics such as blockchain length, average generation time per block, and system read and write performance. In contrast to current approaches, our method trades off some decentralization for additional performance benefits. Although our BAC-SDS gives up some of blockchain's decentralized features, this trade-off is perfectly justified in V2V energy trading. It may even be advantageous: retaining centralized institutions and nodes, thus ensuring the state or government will macro-regulate the energy market.

All experiments are conducted on a server with Windows 64-bit, Intel Xeon Silver 4210R CPU, 64 G RAM, two NVIDIA RTX A5000 GPUs, Java JDK Version 11.0.10, Scala Version 2.13.5, and Akka Version 2.6.14. Our simulation supports large-scale networks of thousands of EVs (nodes) with a diameter of each shard ranging from 0 to 3 km. The EVs travel at speeds of 55 to 65 miles per hour. The Euclidean distance between EV_i and EV_j varies between 5 and 100 metres. We integrate our V2V ETB system into the Hyperledger Fabric and use the Hyperledger Caliper to evaluate its performance. Energy blocks are 2.0 MB in size and have a propagation delay of 0.8 s. Energy microblocks are 0.5 MB in size and have a propagation latency of 0.5 s. [16], [38].

Table I demonstrates the comparison between different consensus mechanisms applied to V2V energy trading. PoW is a highly decentralized and secure consensus mechanism because it requires miners to perform complex mathematical calculations to validate transactions and create new blocks. However, it is also highly energy-intensive, as miners need to compete to solve mathematical puzzles, which requires a lot of computing power. As a result, PoW has scalability issues, as the more participants there are in the network, the more difficult the calculations become. PoSo (Ref. [22]) replaces meaningless puzzle in PoW with mathematical problems about the power system. However, compared to our proposed BAC-SDS, it still falls within the

TABLE I
COMPARISON OF SEVERAL CONSENSUS MECHANISMS FOR V2V ETB

Mechanisms	Decentralization	Scalability	Throughput	Latency	Computing	Security
PoW	High	Low	Low	High	High	High
PoSo (Ref. [22])	Medium	Low	Medium	Medium	Medium	High
PoS	High	Low	Low	Medium	Medium	Medium
DPoS (Ref. [23])	High	Low	Low	Medium	Medium	Medium
(Improved) PBFT (Ref. [35])	Medium	Low	Low	Medium	Low	Medium
DAG (Ref. [24])	High	Medium	High	Low	Low	Medium
Hashgraph (Ref. [36])	Medium	Medium	High	Low	Low	High
BAC-SDS	Medium	High	High	Low	Low	High

scope of PoX and does not break the impossible triangle of ETB. In PoS, validators, who own some of the cryptocurrency, are randomly selected to validate transactions and create new blocks. PoS is more scalable than PoW since it does not require miners to compete in solving mathematical puzzles. It also requires less computing power than PoW, making it more energy-efficient. DPoS is a variation of PoS that uses a voting system to select a group of block producers who are responsible for validating transactions and creating new blocks. DPoS is more scalable and energy-efficient than PoW because it does not require miners to compete in solving mathematical puzzles. PBFT uses a voting system to achieve consensus among a group of validators. PBFT is highly secure and fault-tolerant, but it is less decentralized than PoW and PoS, as it requires a pre-determined set of validators to participate in the consensus process. DAG is a consensus mechanism that is used by some blockchain networks to achieve high throughput and scalability. DAG networks use a directed acyclic graph structure instead of a linear blockchain to store transactions. Hashgraph is a consensus mechanism that uses a voting system to achieve consensus among a group of nodes. Hashgraph is designed to be highly scalable and fast, as it does not require mining or complex calculations. It is also highly secure, as it uses a unique consensus algorithm that ensures that all nodes in the network reach consensus on the same set of transactions. Table II presents the settings for the simulation and experiments.

In the following subsections, we will compare and analyze in detail the performance of different consensus mechanisms to verify their ability to enhance the resilience of the power grid.

TABLE II
LIST OF KEY ACRONYMS

Abbreviations	Descriptions
EVs	Electric Vehicles
IoEV	Internet of Electric Vehicles
P2P	Peer-to-Peer
V2V	Vehicle-to-Vehicle
V2G	Vehicle-to-Grid
ETB	Energy Trading Blockchain
BAC	Block Alliance Consensus
BFT	Byzantine Fault Tolerance
ABFT	Asynchronous Byzantine Fault Tolerance
PBFT	Practical Byzantine Fault Tolerance
PoW	Proof-of-Work
PoS	Proof-of-Stake
DPoS	Delegated Proof-of-Stake
PoSo	Proof-of-Solution
IoT	Internet of Things
WPT	Wireless Power Transfer
VRF	Verifiable Random Function
ID	Identification
CA	Certificate Authority
P	Primary
CP	Candidate Primary
CS	Consensus Node
DAG	Direct Acyclic Graph
RES	Renewable Energy Sources
RSU	Road Side Unit

A. Blockchain Length

Blockchain length refers to the number of blocks generated by a blockchain system in a given period of time. Fig. 6 demonstrates the blockchain length of different consensus methods (including the traditional central method). In the centralized approach, transactions are packaged and blocks are published only by a single EV node. Since the entire system relies on a single node to package blocks without undergoing consensus and verification by other EVs, the centralized approach can have the longest blockchain length in ideal conditions [16], [31]. However, if this centralized node fails or is subjected to malicious attacks, the entire power system will cease to operate. In this experiment, we stopped the central EV at 100, 120, and 140 nodes. From the result figure, we can see that the system no longer produces blocks under these three conditions. In addition, there is a risk of malicious behavior by the centralized node in real-world scenarios, such as arbitrary actions that allow it to manipulate transaction data and delay the publication of transaction data.

In PoW, the difficulty factor is adjusted periodically to maintain a constant block time, which is the amount of time it

TABLE III
LIST OF KEY SYMBOLS

Symbols	Meanings
B_i	The energy buyer i
S_j	The energy seller j
$Tr-a$	The a-th energy transaction
$O(Tr)$	The origins of the a-th transaction
$CertB_i$	The B_i's certificates
$CertS_j$	The S_j's certificates
PK	Public Key
SK	Private Key
Add	The e-wallet address
C_p	The EV's present currencies
C_s	The EV's surplus currencies
E_p	The EV's present energy
E_s	The EV's surplus energy
$(BC)_k$	Individual blockchains
$E_k(f)$	The f-th energy block in the k-th $(BC)_k$
$Tr(i \rightarrow j)$	A transaction identification from i to j
$(TI)_k$	The transaction identification in the k-th EV's blockchain
m	The m-th energy block
n	The n-th transaction identification
$Pri[]$	The primary's own signature

TABLE IV
EXPERIMENTAL SETTINGS

Metrics	Values
Diameter of shard	0 - 3 km
Speed of EVs	55 - 65 mph
Euclidean distance between EVs	5 - 100 m
Size of energy blocks	2.0 MB
Energy blocks' propagation delay	0.8 s
Size of energy microblocks	0.5 MB
Energy microblocks' propagation delay	0.5 s

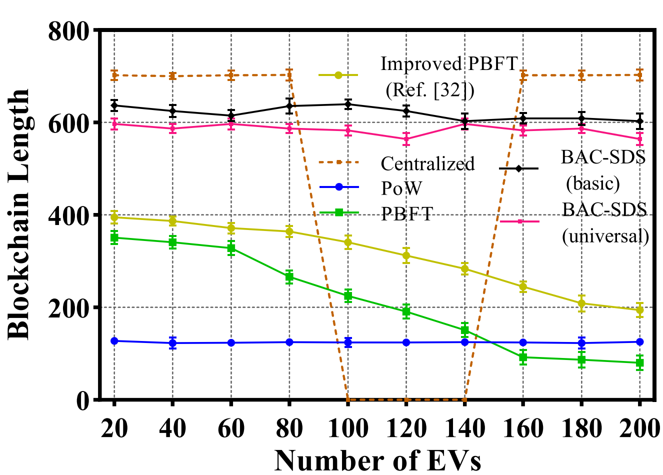


Fig. 6. Blockchain length.

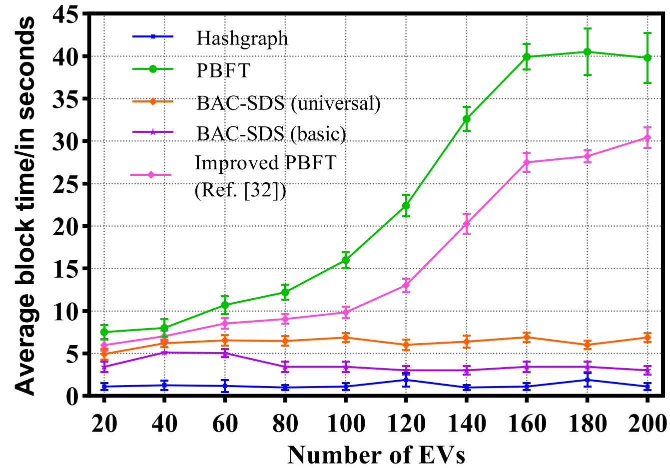


Fig. 7. Average block time - 20 to 200 EVs.

takes to generate a new block. As more nodes participate in the mining process, the difficulty level of the puzzles increases. If the previous set of blocks took longer than the target block time to generate, the difficulty factor is decreased to make it easier to generate new blocks.

When the number of nodes is small, the blockchain length of PBFT is longer than that of PoW, because nodes in PBFT do not rely on massive computing power to generate blocks. However, as the number of nodes increases, the number of blocks generated by PBFT decreases due to the high communication complexity $O(N^2)$. In addition, in PBFT, blocks are packed by the primary node. Once the primary node crashes, the system will pause processing of energy transactions. The improved PBFT in Ref. [35] has one less round of communication than PBFT, but its communication complexity is still the same as PBFT.

The blockchain length curves of BAC-SDS (universal) and BAC-SDS (basic) remain stable for up to 200 EV nodes. However, the overall blockchain length of BAC-SDS (universal) is shorter than that of BAC-SDS (basic). This is because BAC-SDS (universal) has more EV nodes participating in consensus and verification, making it a more inclusive version. As the number of nodes increases, BAC-SDS (universal) outperforms BAC-SDS (basic) due to its superior scalability (infinite scalability). We will analyze this in detail in the next section.

B. Average Block Time

The duration required for a subsequent block to be appended to the blockchain is represented by the average block time, as illustrated in Fig. 7 for the analyzed consensus mechanisms [16], [31]. The average block time is further verification of the experimental results on "blockchain length". More importantly, it reflects the scalability of consensus algorithms. PBFT's block time is influenced by the behavior and operating effectiveness of EVs, with a gradual increase observed as the number of EVs grows, and sharply increasing with over 80 EVs. On the other hand, a block in BAC requires two rounds of consensus but has a

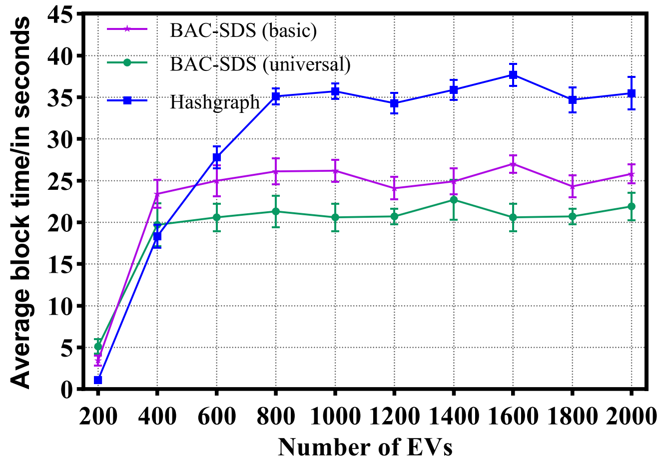


Fig. 8. Average block time - 200 to 2000 EVs.

lower average block time than PBFT due to its $O(N)$ time complexity, the benefits that become more pronounced with more than 100 EVs. Hashgraph exhibits the shortest block time among the analyzed algorithms, as EVs broadcast blocks concurrently without the need for block-by-block authentication, unlike the other algorithms.

To assess the scalability of BAC-SDS (basic), BAC-SDS (universal), and Hashgraph, we scaled the number of EVs from 200 to 2,000 [16], [31], as depicted in Fig. 8. BAC-SDS (basic) has a latency approximately five times higher than Fig. 7, but its scaling performance remains stable up to 2,000 users, indicating effective scalability. In contrast, Hashgraph's latency is roughly 18 times higher than Fig. 7, with two identifiable limitations in computational resources and bandwidth since each EV has to carry out the epidemic protocol. With more than 600 EVs, BAC-SDS (basic) surpasses Hashgraph, benefiting from most EVs implementing distributed storage. When there are more than 800 nodes, BAC-SDS (universal) performs better than BAC-SDS (basic). If BAC-SDS (basic) is scalable, then BAC-SDS (universal) is infinitely scalable. As the number of nodes in the system increases, the former can maintain stable performance, and the latter can further enhance performance on a stable basis because it requires participation of all nodes, with each node having its own "individual blockchain". This is like the horizontal scaling of distributed databases. With the increase in the number of nodes, the total computing power of the system also continuously increases.

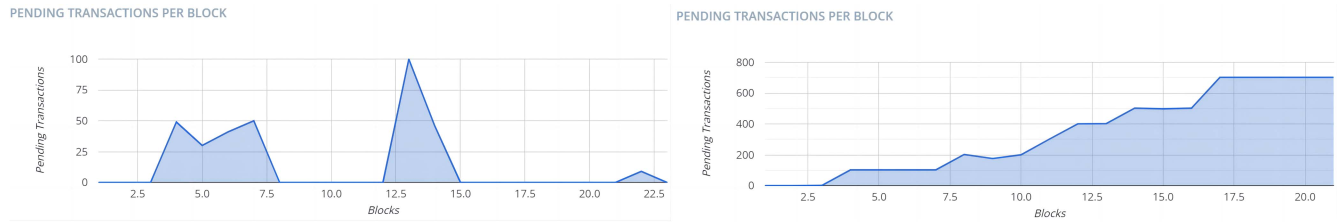
C. Pending Transactions

Pending transactions are transfer requests that are awaiting confirmation by EVs to be packaged into a block. If an EV buyer j does not have enough funds, its trading proposal will remain pending until it has adequate funds. During busy market periods, trading demands without being processed are likewise regarded as pending transactions. Fig. 9 illustrates the pending PoW and PBFT transactions [31]. To highlight the benefits of BAC-SDS over Hashgraph, we present pending transactions of BAC-SDS and Hashgraph for 2,000 EVs and 90 blocks in a single figure, as depicted in Fig. 10. The amount of transactions awaiting inclusion in a block is known as the transaction pool size for each block in the blockchain [16], [31]. PBFT tends to have the highest number of pending deals because of its heavy communication overhead and limited scalability. Hashgraph has 765 pending transactions, BAC-SDS (basic) has 442.5, and BAC-SDS (universal) has 30. PBFT is highly centralized and has poor scalability, while PoW consumes excessive resources and has inadequate network performance.

In Hashgraph, the transaction duration is unpredictable. The validation rule mandates that subsequent transactions must verify previous transactions, which results in the last transactions not being confirmed for an extended period. Hashgraph uses gossip to effectively use the idle network resources of many EVs. However, this increases the quantity of network traffic per node, without significantly enhancing overall network performance. BAC-SDS addresses this issue by implementing the sharding technique. The elected committee and leader EVs make the final decision, and the EVs that actually participate in block generation and verification are limited to a single shard. While BAC-SDS sacrifices some degree of decentralization, it performs well for the IoEV application scenario.

The pending transactions are non zero, indicating that an EV buyer j's balance may not be adequate, therefore the trading demand submitted by j is being held until it has adequate funds. Another more important reason is the ability of EV nodes to process transactions under the consensus mechanism, which, among other things, is affected by the network conditions. If the value of the vertical coordinate gradually decreases from non-zero to zero during the process of generating blocks, it indicates that the EV node has a strong and sufficient transaction processing capacity in this consensus mechanism. This means that the EVs under this consensus mechanism can fully control the volume of user-initiated transactions, and the capacity of the EVs to process transactions (total transaction volume) is greater than the total number of transaction requests received by the system over a period of time. While there may be a small number of unprocessed transactions due to network state congestion or the user's personal reasons, these pending transactions will soon be packed into blocks by the validators in the next few block times.

If the value of the vertical coordinate is always maintained at a stable level, it does not indicate that the EV node has a very poor transaction processing capability. On the contrary, it indicates that the EV node under this consensus mechanism is able to maintain the normal operation of the system, and the pending transactions of the previous block will be processed and packaged in some future block, as long as the system is not always at a transaction peak and as long as the upper limit of the node's transaction processing capability is not too lower than the peak transaction requests (which depends on the timing of the transaction peak and the performance of the consensus mechanism).



(a) (b)

Fig. 9. Pending transactions. (a) PoW. (b) PBFT.

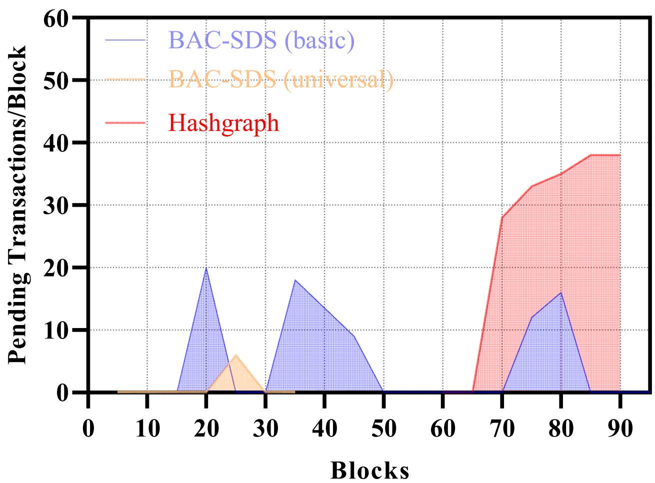


Fig. 10. Pending transactions of BAC-SDS and hashgraph.

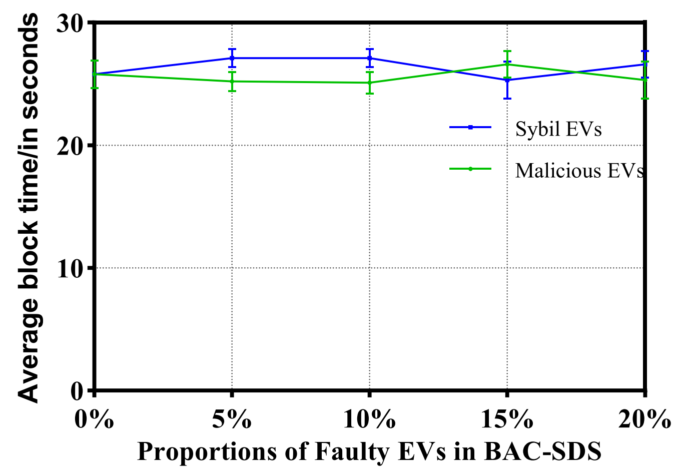


Fig. 12. Security evaluation.

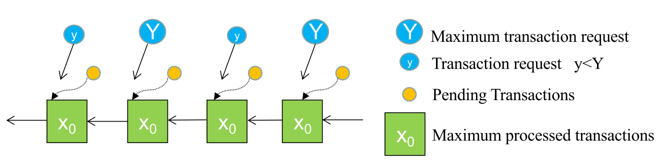


Fig. 11. Analysis of pending transactions.

D. Read and Write Performance

Our V2V ETB system is tested under different workloads, varying from 500 to 2000 TPS. In this test, 1000 users are generating proposals. Fig. 13 depicts the success rate and performance of READ and WRITE operations. The detailed analysis could be found in Ref. [16]. The pseudocode of V2V ETB performance test could be found in the supplementary material.

E. Security Evaluation

Fig. 12 illustrates the performance analysis of the ETB under different scenarios, specifically considering varying proportions of dishonest EVs and malicious EVs executing Sybil Attacks. In this evaluation, a total of 2000 EVs actively participate in the ETB [16]. One of the key strengths of ETB lies in its ABFT stage, which ensures that no EVs within the network can impede consensus or tamper with data once consensus is achieved.

The ETB offers robust security measures, theoretically comparable to the level of security provided by Bitcoin, while also delivering exceptional performance, such as high throughput. Unlike many consensus algorithms that have a maximum tolerance for message latency, ETB eliminates this assumption, allowing messages from honest EVs to be validated even if they are lost or significantly delayed. Moreover, ETB can withstand network communication failures and resist attempts by malicious EVs to disrupt the system's operation, guaranteeing the seamless functioning of V2V energy trading within the IoEV. The experimental results highlight the resilience of our ETB system, indicating that it is minimally impacted by the presence of dishonest EV behavior.

In the context of Sybil Attacks within the distributed V2V ETB, a Sybil node attempts to exploit the network by broadcasting disguised nodes throughout the entire IoEV network, aiming to gain control, deny responses, and obstruct requests. However, our ETB system implements two effective measures to defend against Sybil Attacks. Firstly, EVs joining the IoEV network undergo authentication through a Certification Authority (CA) in Hyperledger Fabric. By verifying the authenticity of each EV joining the ETB, the system prevents fake EVs from passing authentication, thereby mitigating the witch assault. The ETB employs CA as a trusted third-party organization to certify EVs, enhancing the overall security of the system.

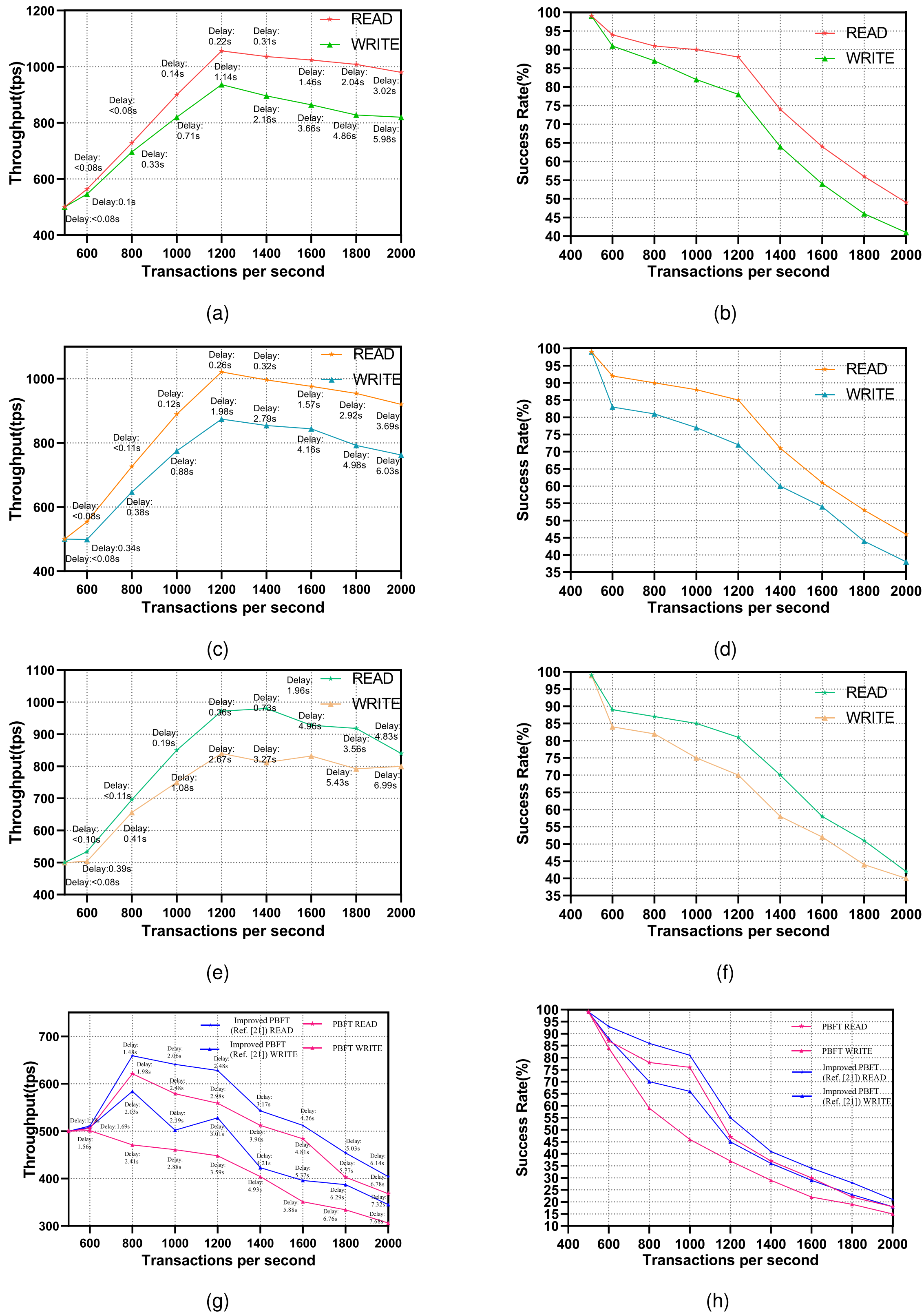


Fig. 13. Performance of READ and WRITE and success rate. (a) BAC 2.0's throughput. (b) BAC 2.0's success rate. (c) Hashgraph's throughput. (d) Hashgraph's success rate. (e) DAG (Ref. [24])'s throughput. (f) DAG (Ref. [24])'s success rate. (g) PBFT's and improved PBFT (Ref. [35])'s throughput. (h) PBFT's and improved PBFT (Ref. [35])'s success rate.

Our ETB system employs reputation incentives to make identity forgery more challenging. Committees and leaders within the ETB are elected based on the reputation scores of EV users, and EVs are assigned weights through reputation incentives. This approach deters malicious EVs from fabricating multiple identities to increase their chances of being elected or acquiring control. Additionally, regular committee re-elections are conducted to ensure power is randomly distributed among all network EVs, further reducing the likelihood of malicious nodes perpetrating malicious actions and gaining control over the V2V energy trading network. These combined measures strengthen the security and resilience of the ETB, making it highly robust against Sybil Attacks within the IoEV ecosystem.

VI. Conclusion

We propose a blockchain-based V2V RES trading model and a novel consensus for resilient power grids. We propose a novel BAC-SDS mechanism achieving infinite scalability and breaking through the blockchain impossible triangle in the IoEV. We utilize the sharding technique based on the characteristics of EVs. We also introduce an efficient cross-shard trading commit protocol for the frequent mobility of EVs. Within each shard, we utilize the Hashgraph instead of traditional BFT mechanisms to further improve the throughput. We implement our V2V ETB on the Hyperledger Fabric, and the experiments show our model and method make power grids integrated with RES more resilient.

Appendix
Random Leader Elections

The Verifiable Random Function (VRF) [39], [40] is used in leader committee election. In simple terms, given an input string a, $VRF_{sk}(a)$ produces a hash and a proof as its outcomes. By combining sk and a, the hash is uniquely defined. The proof, denoted as pf, enables other EVs (excluding EV i) to confirm that the hash value relates to a without being aware of the secret key sk.

The random leader committee election is presented in Algorithm 1, which necessitates a rl factor to differentiate among various responsibilities that an EV might be chosen for [16], [40]. An EV, for instance, might be chosen as a leader to integrate and distribute transactions and blocks in a particular phase, or as a potential leader node to verify. The estimated amount of EVs designated for P or CP is determined by the threshold θ specified by BAC-SDS.

It's important to note that EVs may be elected multiple times by the random algorithm due to their significant credit level. The election algorithm accounts for this by providing the factor η, which represents the number of times an EV has been chosen. If a supplier i possesses ϵ_i units of credit, then (i, η) with $\eta \in 1, 2, \ldots, \epsilon_i$ denotes the ηth unit of credit held by EV supplier i. EV i is chosen with a probability of $\Omega = \frac{\theta}{R}$, where R represents the total number of credit units in BAC-SDS.

A supplier i executes the election process by calculating $\langle hash, pf\rangle \leftarrow VRF_{sk}(seed||rl)$, where sk represents EV i's secret key, known exclusively to EV i. The binomial distribution describes the likelihood that precisely q out of the ϵ_i (the i's credit) units will be chosen:

$$B(q; \epsilon_i, \Omega) = C^q_{\epsilon_i} \Omega^q (1 - \Omega)^{\epsilon_i - q} \tag{1}$$

where $\sum_{q=0}^{\epsilon_i} B(q; \epsilon_i, \Omega) = 1$. The election method of BAC-SDS splits the space [0,1) into sequential intervals to decide the amount of and EV's ϵ_i units be assigned:

$$I^\eta = \left[\sum_{q=0}^{\eta} B(q; \epsilon_i, \Omega), \sum_{q=0}^{\eta+1} B(q; \epsilon_i, \Omega) \right) \tag{2}$$

where $\eta \in \{0, 1, \ldots, \epsilon_i\}$. The supplier i has precisely η chosen units (is selected eta times), if $hash/2^{hashlen}$ lies in the interval I^η.

The election method offers two crucial characteristics. The first procedure is the arbitrary allocation of EVs according to credit level. Secondly, it prevents a cyber attacker, who lacks knowledge of sk_i, from accurately guessing how frequently a supplier i is picked.

The verification process for the election is outlined in Algorithm 2 [16], [40]. If the evidence and hash do not match, additional authentication is unnecessary. The validation process outputs how many elector units there are in an EV. Additionally, BAC's election method is designed to protect the system from Sybil Attacks, where an adversary creates a single object but publishes numerous identities to the blockchain network to pose as various distinct EVs. Sybil node is the common name for these

Algorithm 1: Leader Election.

Input: sk, $seed$, θ, rl, ϵ_i, R
Output: $\langle hash, pf, \eta\rangle$

$\langle hash, pf\rangle \leftarrow VRF_{sk}(seed\|rl)$;
$\Omega \leftarrow \frac{\theta}{R}$;
$\eta \leftarrow 0$
while $\frac{hash}{2^{hashlen}} \notin \left[\sum_{k=0}^{\eta} B(k; \epsilon_i, \Omega), \sum_{k=0}^{\eta+1} B(k; \epsilon_i, \Omega)\right)$ **do**
  η ++;
  out $\leftarrow \langle hash, pf, \eta\rangle$
end
return out

Algorithm 2: Verification.

Input: pk, $seed$, $hash$, θ, pf, rl, ϵ_i, R
Output: *out*

$\Omega \leftarrow \frac{\theta}{R}$;
$\eta \leftarrow 0$
while *an EV receives i's election* **do**
  if $VRF_{pk}(pf, hash, seed\|rl)$ *fail* **then**
    return 0;
  end
end
while $\frac{hash}{2^{hashlen}} \notin \left[\sum_{q=0}^{\eta} B(q; \epsilon_i, \Omega), \sum_{q=0}^{\eta+1} B(q; \epsilon_i, \Omega)\right)$ **do**
  η ++;
  out $\leftarrow$ success
end
return out

fake accounts. However, the amount of chosen subunits that are under the authority of an EV is unaffected by the distribution of its credit among Sybils.

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