Fortifying Smart Transportation Security through Public Blockchain

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***Abstract*—Smart vehicles-enabled intelligent transportation system (ITS) supports a wide range of applications, such as, but not limited to, traffic planning and management, collision avoidance alert system, automated road speed enforcement, electronic toll collection, and real-time parking management, to name a few. However, it suffers from various types of security and privacy issues due to insecure communication among the entities over public channels. Therefore, an efficient and lightweight security mechanism is essential to protect the data that is both at rest as well as in transit. To this direction, we propose a public blockchain-envisioned secure communication framework for ITS (in short, called PBSCF-ITS). The proposed PBSCF-ITS guarantees access control and key management among the vehicle to vehicle, vehicle to road side unit, and road side unit to cloud server. We analyze the security of PBSCF-ITS to prove its resilience against various types of possible attacks. Furthermore, the performance of PBSCF-ITS with other related competing schemes has been compared. The obtained results illustrate that PBSCF-ITS outperforms the existing ones. Additionally, the pragmatic study of PBSCF-ITS is conducted to check its influence on various network related performance parameters, like number of mined blocks and transactions per block.**

***Index Terms*—Intelligent Transportation System (ITS), vehicular network, blockchain, access control and key management, security.**

I. INTRODUCTION

Intelligent Transportation System (ITS) is a technological platform that has the capability of sensing, analysis, control, and communication to enable safe, reliable, and infotainment-enabled experience for commuters. It enables safe and secure and infotainment-rich driving experience by keeping the cyber-attackers at the bay from attacking ITS and improving the driving experience [1], [2], [3]. ITS is realized through vehicular networks and consist of smart vehicles, road-side units (RSUs), sensing units, environmental monitoring system, traffic monitoring, and surveillance system [4], [5], [6]. Vehicular networks use different communication technologies including the Dedicated Short Range Communication (DSRC), Bluetooth, WiFi, and cellular networks [7]. These technologies enable different modes of communication such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) (that includes Vehicle-to-Cloud communication). Moreover, it produces massive amount of data (referred to as Big traffic data) that needs to be stored, processed, and analysed in a secure way. The conducted analysis on this data is further helpful in predicting the important factors in transportation such as chances of road side accident, environmental conditions, driver behaviour, expected travel time, and congestion on a specific route, to name a few [8], [9].

Due to the increased number of vehicles pervading the roads, realization of ITS is essential because the ever-growing traffic surpasses the capacity of the existing infrastructure. However, such system warrants the deployment of secure data management and sharing techniques (for both data at rest and in transit) [2], [8]. Here, the mechanism of blockchain can play an important role as it is temper proof, decentralized, anonymous and robust against various types of information security related attacks [10], [11], [12]. Therefore, the use of blockchain mechanism is strongly suggested to introduce for such kind of communication environment [13]. It is worth mentioning that vehicular networks use different communication technologies that enable different modes of communication such, as V2V and Vehicle-to-Road side unit (V2RSU), Road side unit-to-cloud (RSU2C) [14], [15].

There are other applications that use the blockchain mechanism. A decoupled blockchain-based approach for the edge-envisioned ecosystem was presented by the researchers in [16]. This approach used the nearby edge devices in order to create the decoupled blocks into the blockchain. This can provide the secure exchange of healthcare data from sensors to the edge nodes [17]. The real-time processing is needed for energy trading computation, which is an important requirement of some computing environments, like Tactile Internet. Therefore, to addres such challenges, a blockchain-based secure energy trading scheme for electric vehicles (EVs) was presented by the authors in [18]. This scheme also ensures resilience against the single point of failure.

We arrange the sections of this paper in the following way. The motivation and novel contributions of the current paper are given in Section II. The literature study of related prior works is given in Section III. The network model and adversary

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model associated with the proposed PBSCF-ITS are provided in Section IV. The different phases of proposed PBSCF-ITS are elaborated in Section V. The essential security analysis of proposed PBSCF-ITS is provided in Section VI. A rigor comparative study among PBSCF-ITS and other relevant schemes is stated in Section VIII. The practical implementation of PBSCF-ITS is specified in Section VII. Finally, the work is concluded in Section IX.

II. MOTIVATION AND RESEARCH CONTRIBUTIONS

The motivation and novel contributions of the current paper are provided below.

A. Motivation

Smart vehicles-enabled Intelligent Transportation System (ITS) supports and provides a broad range of applications and services. However, communication in such an environment has security and privacy issues, and different attacks can be launched to either tamper with the data or disrupt the normal communication. The communication among the vehicles, road side units (RSUs), and cloud servers (CSs) takes place through wireless medium which is prone to a myriad of cyber-threats. For instance, an adversary may tamper with the communicated information among different parties in such a communication environment. Different potential attacks in this environment include “replay”, “man-in-the-middle”, “impersonation”, “illegal session key communication”, “credential leakage”, and other forms of data disclosure attacks. The front line of defense against most of such attacks is an effective and robust access control and key establishment mechanism. Through such a mechanism, the entities, like vehicles, RSUs and cloud servers can authenticate with each other and can then establish session keys for their secure communication. Moreover, the blockchain mechanism is essential for such kind of communication environment, because it is tamper-proof, decentralized, anonymous and robust against various types of information security related attacks [19]. Therefore, it is imperative to provide a blockchain based access control and key establishment mechanism for the smart vehicles-enabled ITS communication [15], [20], [21], [22], [23], [24]. Thus, we design a new a public blockchain-envisioned secure communication framework for ITS (PBSCF-ITS) by having an access control and key establishment scheme, where “vehicle-to-vehicle”, “vehicle-to-RSU” and “RSU-to-CS” session key establishments take place. These processes will help the entities to exchange their data in a secure way.

B. Research Contributions

Our contributions in this paper are listed below.

- We design the network and adversary models for the smart vehicles-enabled Intelligent Transportation System (ITS).
- We propose a public blockchain-envisioned secure communication framework for intelligent transportation system (in short PBSCF-ITS). The blockchain technology makes such a designed framework more secure, reliable and decentralize. The smart transportation security is fortified through the public blockchain.
- PBSCF-ITS allows access control and key management among V2V, V2RSU and RSU2C at the same time.
- A rigorous security analysis and a detailed comparative study among the proposed PBSCF-ITS and other existing state-of-art schemes show that the performance of PBSCF-ITS is better than existing schemes in terms of superior security and more functionality features, and low or comparable communication/computational overheads.
- The pragmatic blockchain-based simulation study of PBSCF-ITS shows its influence on the performance parameters, like computational time (seconds) versus “number of mined blocks” and “transactions per block”, and “transactions per second” versus “number of mined blocks”.

III. RELATED PRIOR WORKS

To date, there has been a number of papers that address authentication, access control, and key management in ITS.

A survey on the history and characteristics of big data and its role in ITS was conducted by Zhu *et al.* [1]. Furthermore, they also presented a framework for big data analytics in ITS. Several case studies of big data analytics applications in ITS such as “road traffic accidents analysis”, “road traffic flow prediction”, “public transportation service plan”, “rail transportation management and control”, etc, were also discussed. In another work, Pribyl *et al.* [2] proposed a smart city model based on ITS communication. Furthermore, some guidance for establishment of smart city architecture to overcome the system complexity was also provided.

Herrera-Quintero *et al.* [3] designed an ITS smart sensor prototype by incorporating the Internet of Things (IoT) and using the “Serverless and Microservice Architecture” for the planning of transportation system utilized in Bus Rapid Transit (BRT) systems. Similarly, Kaffash *et al.* [8] conducted a comprehensive review of the applications of ITS. They also provided a review of most of the recognized models with big data applicable in the ITS context. Yanqi Lian *et al.* [9] reviewed some studies which used big data to analyze the traffic safety in ITS and Connected/Automated Vehicles (CAV) communication environment. The focus was on topics such as crash prediction and detection and the factors, which contributed to the crash, driving behavior and so on.

Wazid *et al.* [15] proposed an authentication and key management scheme to secure the communication among vehicles, RSUs, fog, and cloud servers in the fog computing-based Internet of Vehicles (IoV) communication paradigm. Later on, Vangala *et al.* [20] proposed a blockchain-endowed authentication mechanism that is based on digital certificates to detect vehicular accidents and disseminate notification in ITS. In their scheme, each vehicle securely notifies the accident related information to its adjacent Cluster Head (CH) in case of any accident. Similarly, Liu *et al.* [21] proposed an authentication mechanism for IoV communication. They used mostly focused on security and privacy preservation through a dual authentication method for IoV communication. Egala *et al.*

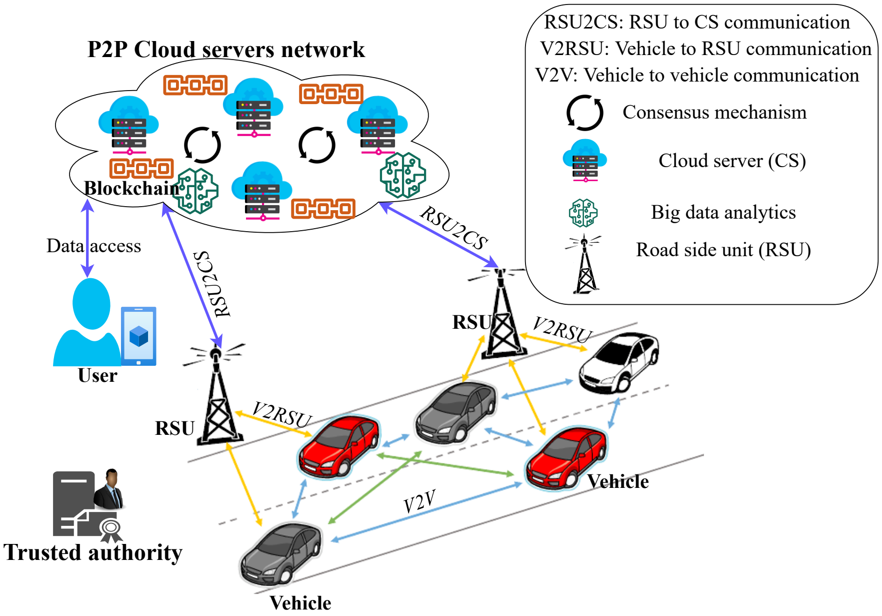


Fig. 1: Network model (adapted from [15], [20]).

[25] presented hybrid computing mechanism with blockchain-based distributed data storage system (DDSS) to overcome the drawbacks (i.e., high delay, storage cost, single point of failure) of blockchain-based cloud-centric IoMT healthcare system. Biswas *et al.* [26] presented a lightweight proof of block and trade consensus mechanism for IoT blockchain along with a integration framework. The provided mechanism allowed the validation of trades as well as blocks with less computation cost.

In another work, a mechanism for secure communication between the vehicles and RSUs through a Certificate-Less Short Signature (CLSS) method was presented by Liu *et al.* [27]. The unforgeability property of their scheme was also proven through a random oracle model. On the other hand, Cui *et al.* [22] proposed RSU-based authentication and the dissemination of authentication information to nearby vehicles to improve the efficiency of authentication. In their scheme, an RSU can authenticate vehicles, and also broadcast the authentication results to the nearby vehicles to reduce unnecessary authentication and raise the efficiency of the communication system.

Pokhrel *et al.* [28] designed a "privacy-aware automated parking model for smart autonomous vehicles". Their model is based on both differential privacy and zero-knowledge proof, where location privacy and identity privacy are addressed. Specifically, their model is able to resist multiple reservation attacks intended by the illegal users. Moreover, their model can protect user location privacy by means of applying the differential privacy schemes.

In Vehicular Cyber-Physical Systems (VCPS), both computing and physical resources are integrated in order to interact among each other as well as their nearby environment in order to improve the safety, efficiency and infotainment quality associated with the transportation. Lu *et al.* [29] suggested a scheme that can handle to mitigate data leakage in VCPS, which is based on federated learning. They also designed a random sub-gossip updating scheme for protecting the privacy during the learning procedure.

IV. MODEL OF THE PROPOSED SYSTEM

This section talks about the network and adversarial models for the proposed PBSCF-ITS.

A. *Network Model*

The network model of PBSCF-ITS is given in Fig. 1 that consists of smart vehicles, RSUs, cloud servers, users, and traffic monitoring and surveillance system. A smart vehicle can communicate with other nearby smart vehicles or RSU through DSRC or cellular networks whereas vehicles communicate with cloud servers through cellular communication networks. Furthermore, RSU can communicate with the back-end systems (such as cloud or registration authorities) through either wired or wireless networks. However, the communication between smart vehicle and cloud server may happen through some wireless communication technology such as cellular network. Similarly, RSU can communicate with the cloud server through through back-end communication, for instance either wired or wireless back-bone communication. The traffic monitoring and surveillance system is connected to the cloud server through back-end communication, like wired or wireless back-bone communication. The sensing and monitoring systems in vehicles sense the data from their surroundings and send the information to the cloud server(s) for additional processing and storage. Other network entities also generate data and send it to the cloud server. Thus, in ITS, enormous amount of data is generated by different sources and therefore termed as Big traffic data. We need some Big data analytics methods, which enable us to acquire useful information such as prediction on road and environmental condition, driver behavior, and traffic condition.

The data of ITS environment is stored in the form of a public blockchain over the peer-to-peer cloud server (P2PCS) network. The use of blockchain provides protection against some potential attacks, like the data disclosure attack and data modification attack. According to the discussed network model, following types of secure communications take place: V2V, V2RSU, and RSU2C communication, traffic monitoring and surveillance (CCTV) system to cloud server communication and User to Cloud server (U2C) communication. The entire communication happens through some wireless or wired communication technology. However, such type of communication is open to the network attackers and it can be compromised through different types of attacks as discussed earlier. The openness of wireless channel in vehicular networks inherently lure attackers to launch different attacks (discussed in the adversary model). Therefore, the use of secure blockchain based access control and key establishment scheme seems essential. Hence, to protect the communication a secure public blockchain based access control and key establishment scheme has been designed.

B. Adversary Model

We use the widely used Dolev-Yao (DY) adversary model for the proposed PBSCF-ITS. According to DY model, the communicating entities communicate over a public medium which is prone to eavesdropping and other cyber attacks. The end point entities such as smart vehicles, RSUs, and end-users are not generally untrustworthy. Therefore, the communicated messages may be delayed, updated, dropped, or modified. Moreover, the cloud server is assumed to be semi-trusted entity in ITS environment and the Trusted Authority (TA), responsible for entity registration, is considered as the fully trusted entity of network. Furthermore, we also follow the the guidelines of "Canetti and Krawczyk's (CK) adversary model [30]" that is more powerful model than the DY model and can be utilized in authentication, access control and key establishment mechanisms. According to "CK-adversary model", an adversary $\mathcal{A}$ enjoys all the facilities that are provided under the DY model including extra capabilities, such as compromise of secret credentials via session-hijacking attacks. There is also a chance that $\mathcal{A}$ may steal some of the On-Board Units OBUs of some smart vehicles as in sensor nodes [31], and later may try to acquire sensitive information from its memory with the help of advanced power analysis attacks [32]. The acquired information can be then made use of launching other attacks, such as impersonation and illegal session key computation attacks.

V. THE PROPOSED BLOCKCHAIN-BASED FRAMEWORK

In this section, we explain in detail the proposed PBSCF-ITS. After the execution of all steps of PBSCF-ITS, there will be the access control (to access data among vehicles) and key management between a vehicle and the other vehicles, vehicle to the RSU, vehicle to the cloud server, and RSU to the cloud server. The inclusion of blockchain makes this framework more secure, reliable and decentralize, which are the essential requirements of an ITS. PBSCF-ITS is divided into following phases: a) system initialization, b) registration, access control and key establishment, c) dynamic smart vehicle addition, and d) block creation, verification and addition phase, that are discussed below.

To achieve protection against strong replay attack, we assume that the clocks of the communicating entities in the network are synchronized, which is a normal supposition utilized in designing various networking environments related to authentication protocols [33], [34], [35], [15], [20], [36].

A. System Initialization Phase

In the system initialization phase, some important cryptographic primitives and parameters are selected that are needed for other phases such as "registration, access control, and key agreement". A trusted authority (TA) selects a "non-singular elliptic curve over a finite field" by picking two constants $u \in Z_q$ and $v \in Z_q$, where $Z_q = \{0, 1, \dots, q-1\}$ and $q > 3$ be a prime number such that "$4u^3 + 27v^2 \neq 0 \pmod q$", of the form: "$y^2 = x^3 + ux + v$ over $GF(q)$" having $\mathcal{O}$ as a point at infinity or zero point. Suppose G is taken as a base point in $E_q(u, v)$ having an order as big as q. Furthermore, TA selects a "one-way (collision-resistant) hash function $h(\cdot)$ (for instance, SHA-256 hashing algorithm [37])".

B. Registration Phase

The participating entities must be registered before using the network services. The TA performs registration of various entities in offline mode through a secure channel. Registration of different network entities is discussed below.

1) Registration of Smart Vehicles: The TA uses the following steps to register a smart vehicle, say V_i:

RV1: First of all, TA generates its own private key $s_{TA} \in Z_q^* = \{1, 2, \cdots, q-1\}$, and computes the respective public key as $Q_{TA} = s_{TA}.G$, where $x.G$ is the point multiplication on the specified elliptic curve and $x \in Z_q^*$. Then, TA generates a private key of smart vehicle V_i as $s_{V_i} \in Z_q^*$ and calculates the corresponding public key as $Q_{V_i} = s_{V_i}.G$.

RV2: TA selects ID_{V_i} and ID_{TA} as the identities of V_i and itself, respectively, and calculates the corresponding pseudo identity of V_i as $RID_{V_i} = h(ID_{V_i} || s_{TA})$ and its own pseudo identity as $RID_{TA} = h(ID_{TA} || s_{TA})$. TA also computes the temporal credential of V_i as $TC_{V_i} = h(ID_{V_i} || RTS_{V_i} || s_{V_i} || s_{TA} || RID_{TA})$, where RTS_{V_i} is the registration timestamp of V_i. In addition, TA generates a random secret $n_{V_i} \in Z_q^*$ to compute its corresponding public parameter $N_{V_i} = n_{V_i}.G$.

RV3: TA generates the certificate for V_i as $CT_{V_i} = s_{TA} + h(Q_{TA} || Q_{V_i}) * n_{V_i} \pmod q$, where $*$ represents a modular multiplication in Z_q^*. Note that, $n_{V_i} \in Z_q^*$ is different for different vehicles, and TA announces N_{V_i} publicly.

RV4: TA finally stores the credentials $\{RID_{V_i}, TC_{V_i}, (s_{V_i}, Q_{V_i}), CT_{V_i}, h(\cdot), E_q(u, v), G\}$ in the on-board unit OBU_{V_i} of V_i before its deployment. To protect against potential attacks, TA deletes sensitive parameters such as n_{V_i} and RTS_{V_i} from its database and makes the declaration of the public parameters publicly. The summary of registration process of smart vehicle V_i given in Fig. 2.

2) Registration of RSU: The TA uses following steps to register an RSU, say RSU_l:

RRSU1: TA first generates a private key for RSU_l as $s_{RSU_l} \in Z_q^*$ and derives the respective public key as $Q_{RSU_l} = s_{RSU_l}.G$.

RRSU2: TA selects ID_{RSU_l} as the identity of RSU_l and calculates corresponding pseudo identity of RSU_l as $RID_{RSU_l} = h(ID_{RSU_l}||s_{TA})$. TA also computes the temporal credential of RSU_l as $TC_{RSU_l} = h(ID_{RSU_l} ||RTS_{RSU_l}|| s_{RSU_l} ||s_{TA}||RID_{TA})$, where RTS_{RSU_l} is the registration timestamp of RSU_l. Furthermore, TA picks a random secret $n_{RSU_l} \in Z_q^*$ to compute its corresponding public parameter $N_{RSU_l} = n_{RSU_l}.G$.

RRSU3: TA calculates the certificate of RSU_l as $CT_{RSU_l} = s_{TA} + h(Q_{TA} ||Q_{RSU_l}) * n_{RSU_l} \pmod q$. Note that, the random secret $n_{RSU_l} \in Z_q^*$ is different for the RSUs. Further, the TA announces N_{RSU_l} publicly.

RRSU4: TA stores the credentials $\{RID_{RSU_l}, TC_{RSU_l}, (s_{RSU_l}, Q_{RSU_l}), CT_{RSU_l}, h(\cdot), E_q(u,v), G\}$ in RSU_l's memory before its stationing. TA deletes sensitive values, such as n_{RSU_l} and RTS_{RSU_l} from its database to overcome the security issues. TA publicly makes the declaration of all public parameters. The summary of registration process of road side unit RSU_l given in Fig. 3.

3) Registration of Cloud Servers: The TA also carries out the registration of a cloud server CS_k using the following steps:

RCS1: TA first generates a private key of CS_k as $s_{CS_k} \in Z_q^*$ to calculate the corresponding public key as $Q_{CS_k} = s_{CS_k}.G$. Again, TA selects CS_k's identity as ID_{CS_k}, and calculates the corresponding pseudo identity as $RID_{CS_k} = h(ID_{CS_k}||s_{TA})$ and the temporal credential of CS_k as $TC_{CS_k} = h(ID_{CS_k} ||RTS_{CS_k} ||s_{CS_k} ||s_{TA} ||RID_{TA})$, where RTS_{CS_k} is the CS_k's registration timestamp.

RCS2: TA sends the credentials RID_{CS_k}, TC_{CS_k}, (s_{CS_k}, Q_{CS_k}) to CS_k through a secure channel using a shared key K_{TA,CS_k} between them. In addition, TA also provides the registration information of the vehicles and RSUs that are located in that particular region to its corresponding cloud server CS_k through secure channel.

Registration of smart vehicle V_i	
Trusted authority (TA)	Smart vehicle (V_i)
Generate $s_{TA} \in Z_q^*$. Compute $Q_{TA} = s_{TA}.G$. Generate $s_{V_i} \in Z_q^*$. Compute $Q_{V_i} = s_{V_i}.G$. Select ID_{V_i} & ID_{TA}. Compute $RID_{V_i} = h(ID_{V_i}||s_{TA})$, $RID_{TA} = h(ID_{TA}||s_{TA})$, $TC_{V_i} = h(ID_{V_i} ||RTS_{V_i}|| s_{V_i} ||s_{TA}||RID_{TA})$, Generate $n_{V_i} \in Z_q^*$. Compute $N_{V_i} = n_{V_i}.G$, $CT_{V_i} = s_{TA} + h(Q_{TA} ||Q_{V_i}) * n_{V_i} \pmod q$. Store $\{RID_{V_i}, TC_{V_i}, (s_{V_i}, Q_{V_i}), CT_{V_i}, h(\cdot), E_q(u,v), G\}$ in OBU_{V_i}	
	V_i is deployed with OBU_{V_i} with credentials $\{RID_{V_i}, TC_{V_i}, (s_{V_i}, Q_{V_i}), CT_{V_i}, h(\cdot), E_q(u,v), G, \}$.

Fig. 2: Registration of a smart vehicle V_i

RCS3: After receiving the registration parameters from TA, CS_k stores the credentials $\{RID_{CS_k}, TC_{CS_k}, (s_{CS_k}, Q_{CS_k}), E_q(u,v), G, h(\cdot)\}$ in its secure database. CS_k publicizes its public parameters. The summary of registration process of cloud server CS_k also given in Fig. 4.

Remark 1. *Note that the TA deletes all secret information, like the private keys and registration timestamp values from its own memory. Therefore, it is not feasible for the adversary (including the privileged-insider user) to execute potential attacks, like "privileged insider attack", "unauthorized session key computation attack", and "impersonation attack". Apart from that, RSU_l and CS_k store all their secret data in the secure region of their memory for the protection of stolen verifier attack and other associated attacks.*

C. Access Control Phase

This phase is required to provide secure access control among different smart vehicles, and vehicle and its nearby road side unit (RSU). In this phase, we consider that a vehicle (V_i) can establish a secure connection with its associated cluster-

Registration of road side unit RSU_l	
Trusted authority (TA)	RSU (RSU_l)
Generate $s_{RSU_l} \in Z_q^*$. Compute $Q_{RSU_l} = s_{RSU_l}.G$. Select ID_{RSU_l} and calculate $RID_{RSU_l} = h(ID_{RSU_l}||s_{TA})$, $TC_{RSU_l} = h(ID_{RSU_l} ||RTS_{RSU_l} ||s_{RSU_l} ||s_{TA}||RID_{TA})$. Select $n_{RSU_l} \in Z_q^*$ and compute $N_{RSU_l} = n_{RSU_l}.G$, $CT_{RSU_l} = s_{TA} + h(Q_{TA} ||Q_{RSU_l}) * n_{RSU_l} \pmod q$. Store $\{RID_{RSU_l}, TC_{RSU_l}, (s_{RSU_l}, Q_{RSU_l}), h(\cdot), E_q(u,v), G\}$ in RSU_l.	
	RSU_l is deployed with $\{RID_{RSU_l}, TC_{RSU_l}, (s_{RSU_l}, Q_{RSU_l}), CT_{RSU_l}, h(\cdot), E_q(u,v), G\}$

Fig. 3: Registration of road side unit RSU_l

Registration of cloud server CS_k	
Trusted authority (TA)	Cloud server (CS_k)
Generate $s_{CS_k} \in Z_q^*$. Compute $Q_{CS_k} = s_{CS_k}.G$. Select ID_{CS_k} and compute $RID_{CS_k} = h(ID_{CS_k}||s_{TA})$, $TC_{CS_k} = h(ID_{CS_k} ||RTS_{CS_k} ||s_{CS_k} ||s_{TA} ||RID_{TA})$. $\xrightarrow{\{RID_{CS_k}, TC_{CS_k}, (s_{CS_k}, Q_{CS_k})\}}$ (through secure channel)	
	CS_k is deployed with credentials $\{RID_{CS_k}, TC_{CS_k}, (s_{CS_k}, Q_{CS_k}), E_q(u,v), G, h(\cdot)\}$.

Fig. 4: Registration of cloud server CS_k

head (V_j) to share data directly among them. Moreover, the access control can also be performed between a vehicle V_i and its related RSU_l. Both types of mechanisms are discussed below.

Access control phase between vehicles

Smart vehicle (V_i) $\{RID_{V_i}, TC_{V_i}, s_{V_i}, CT_{V_i}\}$	Smart vehicle (V_j) $\{RID_{V_j}, TC_{V_j}, s_{V_j}, CT_{V_j}\}$
Select a random nonce r_{V_i} and timestamp T_1. Compute $A_{V_i} = h(RID_{V_i}\|\| TC_{V_i} \|\|r_{V_i} \|\|T_1)$, $R_{V_i} = r_{V_i} \cdot G$, $CT^*_{V_i} = CT_{V_i} \oplus h(r_{V_i} \cdot Q_{V_j} \|\|T_1)$, $M_1 = A_{V_i} \oplus h(s_{V_i} \cdot Q_{V_j} \|\|R_{V_i} \|\|T_1)$, $M_2 = s_{V_i} + h(M_1 \|\|CT^*_{V_i}\|\| Q_{TA}\|\| Q_{V_i}) * r_{V_i} \pmod q$. $\xrightarrow{Msg_1 = \{M_1,\ M_2,\ R_{V_i},\ CT^*_{V_i},\ T_1\}}$	
	Checks if $\|T_1 - T_1^*\| \leq \Delta T$? If so, then verify $M_2 \cdot G = Q_{V_i} +$ $h(M_1 \|\|CT^*_{V_i}\|\| Q_{TA}\|\| Q_{V_i}) \cdot R_{V_i}$. If validated, generate random nonce r_{V_j} and current timestamp T_2, and compute $CT_{V_i} = CT^*_{V_i} \oplus h(r_{V_j} \cdot Q_{V_i} \|\|T_1)$. Verify if $CT_{V_i} \cdot G = Q_{TA} + h(Q_{TA} \|\|Q_{V_i}) \cdot N_{V_i}$. If so, compute $A_{V_j} = h(RID_{V_j}\|\| TC_{V_j}\|\| r_{V_j}\|\| T_2)$, $M_3 = A_{V_j} \oplus h(s_{V_j} \cdot Q_{V_i} \|\| CT_{V_j}\|\|T_1)$. Derive $A_{V_i} = M_1 \oplus h(s_{V_j} \cdot Q_{V_i} \|\|R_{V_i} \|\|T_1)$, $CT^*_{V_j} = CT_{V_j} \oplus h(r_{V_j} \cdot Q_{V_i} \|\|T_1)$, and session key SK_{V_j,V_i} $= h(A_{V_i}\|\| A_{V_j}\|\| CT_{V_i}\|\| CT_{V_j}\|\| T_1\|\| T_2)$, and session key verifier $M_4 = h(SK_{V_j,V_i} \|\|T_1 \|\|T_2)$. $\xleftarrow{Msg_2 = \{M_3,\ M_4,\ CT^*_{V_j},\ T_2\}}$
Checks if $\|T_2 - T_2^*\| \leq \Delta T$? If yes, then derive $CT_{V_j} = CT^*_{V_j} \oplus h(r_{V_i} \cdot Q_{V_j} \|\|T_1)$, $A_{V_j} = M_3 \oplus h(s_{V_i} \cdot Q_{V_j} \|\|CT_{V_j} \|\|T_1)$, and verify $CT_{V_j} \cdot G = Q_{TA} + h(Q_{TA} \|\|Q_{V_j}) \cdot N_{V_j}$. If verified, then compute $SK_{V_i,V_j} = h(A_{V_i}\|\| A_{V_j}\|\| CT_{V_i}\|\| CT_{V_j}\|\| T_1\|\| T_2)$, and check if $h(SK_{V_j,V_i}\|\| T_1\|\| T_2) = M_4$? If all successfully verified, pick timestamp T_3 and compute session key verifier as $MV_{V_i,V_j} = h(SK_{V_i,V_j}\|\| T_3)$. $\xrightarrow{Msg_3 = \{MV_{V_i,V_j},\ T_3\}}$	
	Check if $\|T_3 - T_3^*\| \leq \Delta T$? If yes, then compute $MV_{V_j,V_i} = h(SK_{V_j,V_i}\|\| T_3)$. Verify if $MV_{V_i,V_j} = MV_{V_j,V_i}$? If yes, then store the session key.

Both V_i and V_j establish the same session key SK_{V_i,V_j} $(= SK_{V_j,V_i})$.

Fig. 5: Synopsis of V2V access control and key establishment

1) Access Control between Vehicles V_i and V_j: We need to execute following steps to perform this task.

ACVV1: V_i initiates the access control process by generating a random secret $r_{V_i} \in Z_q^*$ and a current timestamp T_1, and then computing $A_{V_i} = h(RID_{V_i}|| TC_{V_i} ||r_{V_i} ||T_1)$, $R_{V_i} = r_{V_i} \cdot G$, $CT^*_{V_i} = CT_{V_i} \oplus h(r_{V_i} \cdot Q_{V_j} ||T_1)$, $M_1 = A_{V_i} \oplus h(s_{V_i} \cdot Q_{V_j} ||R_{V_i} ||T_1)$ and the ElGamal type signature as $M_2 = s_{V_i} + h(M_1 ||CT^*_{V_i}|| Q_{TA}|| Q_{V_i}) * r_{V_i} \pmod q$. After the calculations of these parameters, V_i sends the message $Msg_1 = \{M_1,\ M_2,\ R_{V_i},\ CT^*_{V_i},\ T_1\}$ to V_j through public channel.

ACVV2: Upon the arrival of Msg_1 from V_i at time T_1^*, V_j first proceeds for the verification of timeliness of T_1 through the condition: $|T_1 - T_1^*| \leq \Delta T$, given the "maximum transmission delay is ΔT". If it matches, it then verifies the signature as $M_2 \cdot G = Q_{V_i} + h(M_1 ||CT^*_{V_i}|| Q_{TA}|| Q_{V_i}) \cdot R_{V_i}$. If it is successfully verified, the next step is followed.

ACVV3: V_j proceeds for the generation of a random secret $r_{V_j} \in Z_q^*$ along with a fresh timestamp value T_2. Next, it derives $CT_{V_i} = CT^*_{V_i} \oplus h(r_{V_j} \cdot Q_{V_i} ||T_1)$, and verifies the certificate by $CT_{V_i} \cdot G = Q_{TA} + h(Q_{TA} ||Q_{V_i}) \cdot N_{V_i}$. After successfully validation, V_j computes $A_{V_j} = h(RID_{V_j}|| TC_{V_j}|| r_{V_j}|| T_2)$, $M_3 = A_{V_j} \oplus h(s_{V_j} \cdot Q_{V_i} || CT_{V_j}||T_1)$, $CT^*_{V_j} = CT_{V_j} \oplus h(r_{V_j} \cdot Q_{V_i} ||T_1)$, and $A_{V_i} = M_1 \oplus h(s_{V_j} \cdot Q_{V_i} ||R_{V_i} ||T_1)$. After that, V_j calculates a session key as $SK_{V_j,V_i} = h(A_{V_i}|| A_{V_j}|| CT_{V_i}|| CT_{V_j}|| T_1|| T_2)$, and session key verifier by $M_4 = h(SK_{V_j,V_i} ||T_1 ||T_2)$. After the calculation of these parameters, V_j sends the message $Msg_2 = \{M_3,\ M_4,\ CT^*_{V_j},\ T_2\}$ to V_i through public channel.

ACVV4: Upon the arrival of Msg_2 from V_j at time T_2^*, V_i first verifies the timeliness of T_2 by using the condition: $|T_2 - T_2^*| \leq \Delta T$, and if it matches, V_i computes $CT_{V_j} = CT^*_{V_j} \oplus h(r_{V_i} \cdot Q_{V_j} ||T_1)$, $A_{V_j} = M_3 \oplus h(s_{V_i}.Q_{V_j} ||CT_{V_j}||T_1)$ to verify the certificate of V_j as $CT_{V_j}.G = Q_{TA} + h(Q_{TA} ||Q_{V_j}).N_{V_j}$. If it holds, the received certificate is the original one. V_i again computes the session key shared with V_j as $SK_{V_i,V_j} = h(A_{V_i}|| A_{V_j}|| CT_{V_i}|| CT_{V_j}|| T_1|| T_2)$. Then, V_i computes $M_4' = h(SK_{V_i,V_j} ||T_1 ||T_2)$, and checks if $M_4' = M_4$. If it is valid, V_j is authenticated with V_i and the computed session key SK_{V_i,V_j} is correct. Next, V_i proceeds for the generation of a fresh timestamp value T_3 to estimate the session key verifier as $MV_{V_i,V_j} = h(SK_{V_i,V_j}|| T_3)$ for sending the message $Msg_3 = \{MV_{V_i,V_j},\ T_3\}$ to V_j through public channel.

ACVV5: After receiving Msg_3 from V_i at time T_3^*, V_j first verifies the timeliness of T_3 as the condition: $|T_3 - T_3^*| \leq \Delta T$. If it holds, V_j computes the session key verifier as $MV_{V_j,V_i} = h(SK_{V_j,V_i}|| T_3)$ and checks if $MV_{V_j,V_i} = MV_{V_i,V_j}$. If the values are same, V_j infers that the estimated session key by V_i is the genuine one. At the end of this phase, both V_i and V_j establish the same session key SK_{V_i,V_j} $(= SK_{V_j,V_i})$ for their secure communication. Various exchanged messages during the access control and key management phase are also summarized in Fig. 5.

2) Access Control between Vehicles V_j and RSU_l: In this phase, we discuss the access control procedure between a cluster-head V_j and a road-side unit RSU_l to share the real time road side information received from other vehicles in the network or sensed by itself. The entire process executes as follows.

VRP1: V_j proceeds for the generation of a random secret $rs_1 \in Z_q^*$ and a fresh timestamp value t_1 to compute $X_1 = h(RID_{V_j}||TC_{V_j}||r_{s_1}||s_{V_j}||t_1)$, $X_1 = h(RID_{V_j} ||TC_{V_j} ||rs_1 ||s_{V_j} ||t_1)$, $X_2 = X_1 \cdot G$, $X_3 = h(X_2 ||CT_{V_j} ||t_1)$, and $CT^*_{V_j} = CT_{V_j} \oplus h(s_{V_j} \cdot Q_{RSU_l}|| X_2|| t_1)$. V_j sends the message $MSG_1 = \{X_2,\ X_3,\ CT^*_{V_j},\ t_1\}$ to RSU_l via public channel.

VRP2: Upon the arrival of MSG_1 at time t_1^*, RSU_l first verifies timeliness of t_1 through equation: $|t_1 - t_1^*| \leq \Delta t$, where the "maximum transmission delay" is given by Δt. If it holds, RSU_l drives $CT_{V_j} = CT^*_{V_j} \oplus h(s_{RSU_l} \cdot Q_{V_j}|| X_2|| t_1)$ and verifies if $h(X_2 ||CT_{V_j} ||t_1) = X_3$. If it is valid, RSU_l verifies $CT_{V_j} \cdot G = Q_{TA} + h(Q_{TA} ||Q_{V_j}) \cdot N_{V_i}$. If this verification happens successfully, it selects a random nonce rs_2 and timestamp t_2 to compute $X_4 = h(RID_{RSU_l} ||TC_{RSU_l} ||rs_2 ||s_{RSU_l} ||t_2)$, $X_5 = X_4 \cdot G$,. RSU_l further computes the session key as $SK_{RV} = h(X_4 \cdot X_2 ||t_1 ||t_2)$ and other important parameters like $CT^*_{RSU_l} = CT_{RSU_l} \oplus h(s_{RSU_l} \cdot Q_{V_j}|| X_2|| t_2)$, $X_6 = h(X_5 ||SK_{RV} ||CT_{RSU_l} ||t_2)$. After these calculations, RSU_l sends the message $MSG_2 = \{X_5,\ X_6,\ CT^*_{RSU_l},\ t_2\}$ to V_j via public channel.

VRP3: Upon the arrival of MSG_2 at time t_2^*, V_j first verifies timeliness of t_2 with the help the condition: $|t_2 - t_2^*| \leq \Delta t$. If it holds, V_j computes $CT_{RSU_l} = CT_{RSU_l}^* \oplus h(s_{V_j} \cdot Q_{RSU_l}|| X_2|| t_2)$, and verifies the certificate of RSU_l as $CT_{RSU_l} \cdot G = Q_{TA} + h(Q_{TA} ||Q_{RSU_l}) \cdot N_{RSU_l}$. If it holds, V_j computes the session key $SK_{VR} = h(X_1 \cdot X_5 ||t_1 ||t_2)$ and verifies the session key by $h(X_5 ||SK_{VR} ||CT_{RSU_l} ||t_2) = X_6$. If it happens successfully, V_j selects a new timestamp t_3, and the session key verifier as $X_7 = h(SK_{VR} ||t_3)$. Next, V_j sends the message $MSG_3 = \{X_7, t_3\}$ to RSU_l via public channel.

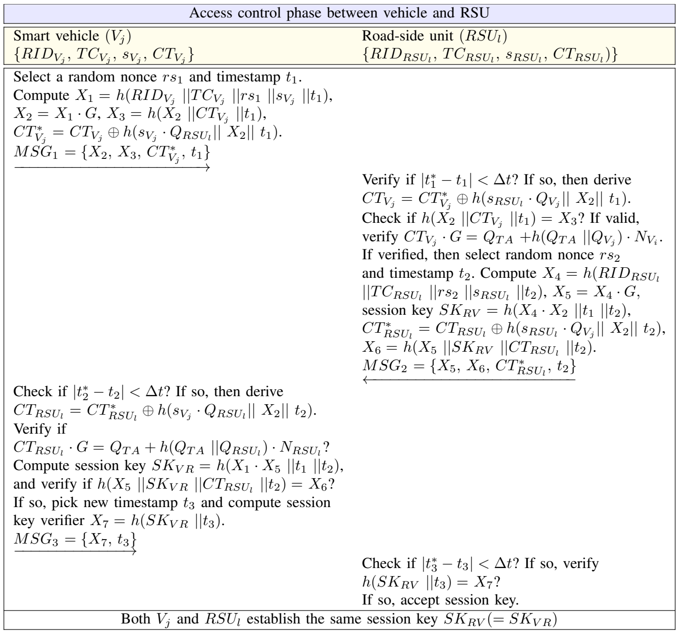
VRP4: Upon the arrival of MSG_3 at time t_3^*, RSU_l verifies timeliness of t_3 by $|t_3 - t_3^*| \leq \Delta t$. If it holds, RSU_l computes and verifies if $h(SK_{RV} ||t_3) = X_7$. The successful verification of this condition enforces RSU_l to conclude that V_j has calculated the session key correctly. If it is satisfied, both the entities will store the calculated session key $SK_{RV} (= SK_{VR})$ for their secure communication. Various exchanged messages during the access control and key management phase is also summarized in Fig. 6.

Remark 2. *It is essential to mention that RSU_l and CS_k can use their "ECC-based private-public keys pairs" for their secure communication. This is because the entities, like RSU_l and CS_k are resource-rich devices deployed in ITS.*

D. Dynamic Vehicle Addition Phase

Addition of a new vehicle to network, say V_i^{new} happens using the following steps:

DVA1: TA generates a private key of the new smart vehicle V_i^{new} as $s_{V_i}^{new} \in Z_q^*$ and computes its corresponding public key as $Q_{V_i}^{new} = s_{V_i}^{new}.G$. TA then selects $ID_{V_i}^{new}$ as the identity of V_i^{new}, and calculates corresponding pseudo identity of V_i^{new} as $RID_{V_i}^{new} = h(ID_{V_i}^{new}||s_{TA})$ and the temporal credential of V_i^{new} as $TC_{V_i}^{new} = h(ID_{V_i}^{new} ||RTS_{V_i}^{new}|| s_{V_i}^{new} ||s_{TA}||RID_{TA})$, where $RTS_{V_i}^{new}$ is the registration timestamp of V_i^{new}.



Access control phase between vehicle and RSU

Smart vehicle (V_j)
$\{RID_{V_j}, TC_{V_j}, s_{V_j}, CT_{V_j}\}$

Road-side unit (RSU_l)
$\{RID_{RSU_l}, TC_{RSU_l}, s_{RSU_l}, CT_{RSU_l})\}$

Select a random nonce rs_1 and timestamp t_1.
Compute $X_1 = h(RID_{V_j} ||TC_{V_j} ||rs_1 ||s_{V_j} ||t_1)$,
$X_2 = X_1 \cdot G$, $X_3 = h(X_2 ||CT_{V_j} ||t_1)$,
$CT_{V_j}^* = CT_{V_j} \oplus h(s_{V_j} \cdot Q_{RSU_l}|| X_2|| t_1)$.
$\xrightarrow{MSG_1 = \{X_2,\, X_3,\, CT_{V_j}^*,\, t_1\}}$

Verify if $|t_1^* - t_1| < \Delta t$? If so, then derive
$CT_{V_j} = CT_{V_j}^* \oplus h(s_{RSU_l} \cdot Q_{V_j}|| X_2|| t_1)$.
Check if $h(X_2 ||CT_{V_j} ||t_1) = X_3$? If valid,
verify $CT_{V_j} \cdot G = Q_{TA} + h(Q_{TA} ||Q_{V_j}) \cdot N_{V_i}$.
If verified, then select random nonce rs_2
and timestamp t_2. Compute $X_4 = h(RID_{RSU_l}$
$||TC_{RSU_l} ||rs_2 ||s_{RSU_l} ||t_2)$, $X_5 = X_4 \cdot G$,
session key $SK_{RV} = h(X_4 \cdot X_2 ||t_1 ||t_2)$,
$CT_{RSU_l}^* = CT_{RSU_l} \oplus h(s_{RSU_l} \cdot Q_{V_j}|| X_2|| t_2)$,
$X_6 = h(X_5 ||SK_{RV} ||CT_{RSU_l} ||t_2)$.
$\xleftarrow{MSG_2 = \{X_5,\, X_6,\, CT_{RSU_l}^*,\, t_2\}}$

Check if $|t_2^* - t_2| < \Delta t$? If so, then derive
$CT_{RSU_l} = CT_{RSU_l}^* \oplus h(s_{V_j} \cdot Q_{RSU_l}|| X_2|| t_2)$.
Verify if
$CT_{RSU_l} \cdot G = Q_{TA} + h(Q_{TA} ||Q_{RSU_l}) \cdot N_{RSU_l}$?
Compute session key $SK_{VR} = h(X_1 \cdot X_5 ||t_1 ||t_2)$,
and verify if $h(X_5 ||SK_{VR} ||CT_{RSU_l} ||t_2) = X_6$?
If so, pick new timestamp t_3 and compute session
key verifier $X_7 = h(SK_{VR} ||t_3)$.
$\xrightarrow{MSG_3 = \{X_7,\, t_3\}}$

Check if $|t_3^* - t_3| < \Delta t$? If so, verify
$h(SK_{RV} ||t_3) = X_7$?
If so, accept session key.

Both V_j and RSU_l establish the same session key $SK_{RV} (= SK_{VR})$

Fig. 6: Summary of V2RSU access control and key establishment

DVA2: TA proceeds for the generation of a random temporary identity of V_i^{new} as $TID_{V_i}^{new}$ and a random secret $n_{V_i}^{new} \in Z_q^*$ to compute its corresponding public parameter as $N_{V_i}^{new} = n_{V_i}^{new}.G$. Now, the TA calculates the certificate of V_i^{new} as $CT_{V_i}^{new} = s_{TA} + h(h(RID_{V_i}^{new} ||TC_{V_i}^{new}) ||Q_{TA} ||Q_{V_i}^{new}) * n_{V_i}^{new} \pmod q$. It is noted that $n_{V_i}^{new} \in Z_q^*$ is different for distinct vehicles. The TA also announces $N_{V_i}^{new}$ as public.

DVA3: TA stores $\{RID_{V_i}^{new},\ TC_{V_i}^{new},\ (s_{V_i}^{new},\ Q_{V_i}^{new}),\ CT_{V_i}^{new},\ E_q(u,v),\ G,\ h(\cdot)\}$ in the memory of on-board unit $OBU_{V_i}^{new}$ of V_i^{new} before its deployment. TA deletes the sensitive values, like $n_{V_i}^{new}$ and $RTS_{V_i}^{new}$ from its database, and makes the public parameters publicly available. TA also sends the registration information $\{RID_{V_i}^{new}\}$ of V_i^{new} to RSU_l securely via the pres-shared secret key K_{TA,RSU_l}.

E. Block Creation, Verification and Addition Phase

In this phase, we elaborate block creation, addition and verification phase for the proposed scheme. An RSU securely sends the data in form of transactions to cloud server network, where the cloud servers form a Peer-to-Peer (P2P) cloud server network. Once the transaction is broadcasted to the network, it can be loaded into the transactions pool which is maintained by each peer node in the network. When the transactions pool reaches to a pre-defined transactions threshold value, a leader is elected by a round-robin fashion from the network, and constructs a block as shown in Fig. 7 and executes a voting based consensus mechanism using the "Practical Byzantine Fault Tolerance (PBFT)" consensus algorithm [38]). After performing the PBFT, the proposed block will be added to the blockchain.

Timestamp	**Block generation time**
Last hash	**Hash (using SHA-256) value of previous block**
Hash	**Hash value of current block**
Data	**N_t number of transactions**
Proposer	**The creator of the block**
Merkle_hash	**Merkle tree root of all transactions**
Signature	**Signature on the block**
Sequence No.	**Sequence number of the block**
Prepare message	**A finite number of messages in prepared pool**
Commit message	**A finite number of messages in commit pool**

Fig. 7: Structure of a block to be added into blockchain (adapted from [39], [40])

The details description of a block addition with execution of the voting-based PBFT algorithm is as follows.

- Once a proposer is elected through the process of round-robin, the proposer broadcasts the generated block to the entire cloud server network.
- The follower receives the block and verifies the previous block hash, current block hash, data (also known as transactions) with their own transactions pool, Merkle_hash (Merkle hash of all the transactions in the block), and signature on the block.

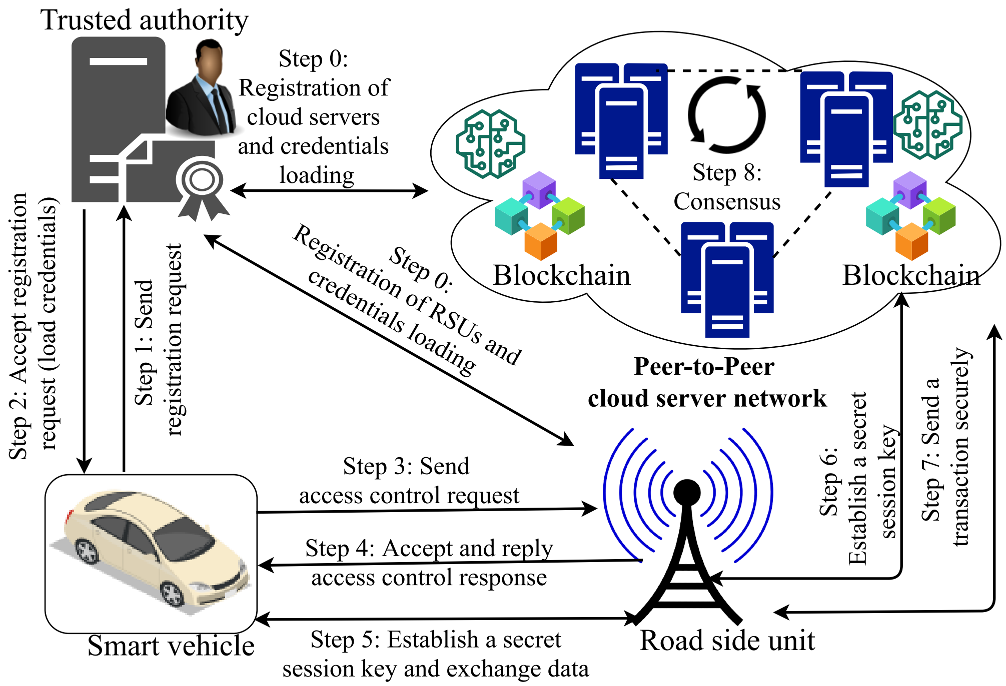


Fig. 8: Overall process diagram of the proposed framework

- If all the verifications go successfully, the followers send the validation message to each other and also to the proposer, which is stored into the prepared message pool.
- Every follower receives the validation message from others and checks their own prepared message pool maintained by themselves.
- Once the prepared message pool reaches to a pre-defined threshold value for commitment purpose, the proposer sends a commit message to other followers.
- Other followers receive the messages and maintain their own commit message pools, and if the pool reaches to the pre-defined threshold value for block addition, they can add the proposed block into their own local ledgers. After that, they broadcast the committed messages to the network.
- Finally, the block is added and the process will again starts for new block mining.

The overall process diagram of the proposed framework is given in Fig. 8. It provides a snapshot of all the above-mentioned phases, like registration, access control and key establishment, and blockchain creation. Step 0 is related to the registration of RSUs and cloud servers. Steps 1 and 2 are related to the registration of smart vehicles. After the successful registration of these entities, the respective credentials are loaded in their memory. Steps 3, 4 and 5 are used for the access control and key establishment process of a vehicle and RSU. Similar steps are used for the access control and key establishment process of a vehicle with its neighbor vehicles. Step 6 is used for the key establishment between RSU and CS. RSU sends the transactions securely to CS using Step 7. Consensus and blockchain implementation is finally performed using Step 8.

Remark 3. *The reason behind the use of the PBFT consensus mechanism, which is mostly used in the consortium blockchains over other public blockchain based Proof-of-Work (PoW) and Proof-of-Stake (PoS) consensus algorithms is that PBFT is much efficient as compared to PoW and PoS in terms of computation and ennergy. Since the PBFT can be also used for consortium blockchains, we have chosen the voting-based PBFT algorithm which is explained in Section V-E.*

Remark 4. *Since the blockchain is a resource-consuming technology, it is not good to execute blockchain related tasks at the end devices (i.e., smart vehicles). Instead of that, we use RSUs, which are resource-rich devices having high communication, computation and storage capabilities for creation of partial blocks, and then the associated miner node (i.e., cloud server) will create the full block from the received partial block. The cloud servers are also resource rich devices. Thus, the blockchain mining related tasks are performed at the P2P cloud servers (CS) network by the cloud servers. After the successful execution of all steps in the proposed scheme, the blockchain is implemented at the P2P CS network. As a result, this will not have any adverse effect on the performance of the smart vehicles. Therefore, the proposed scheme does not have any effects on the performance and working of the smart vehicles.*

Remark 5. *It is worth noticing that the public blockchain has been incorported in the proposed security framework of smart transportation. The blockchain technology makes such a designed framework more secure, reliable and decentralize. We claim that the smart transportation security is fortified through the public blockchain in the framework due to the following reason. In order to update any transactions inside a block into the blockchain, an adversary needs to update or modify the* *following contents: 1) "last hash" which is the previous block hash, 2) "Merkle tree root" which contains the hash of all the transactions put in the block, and 3) the elliptic curve digital signature on the block. Since the signature is created by the block creator's private key, it is computationally infeasible to change the signature without having the private key of the signer. All these checks will confirm the verifier that the block is genuine and no transactions are modified by the adversary. As a result, through the trasactions (information) are public in the blocks, they can not be updated, deleted or modified by the adversary. Hence, the smart transportation security is provided through the blockchain technology.*

VI. SECURITY ANALYSIS OF THE PROPOSED FRAMEWORK

We assess the robustness of the proposed PBSCF-ITS against the following attacks.

1) Replay Attack: For the access control and key management procedures, PBSCF-ITS uses three-type messages. All these messages are computed along with freshly generated timestamps and random secrets (nonces), which are also verified upon their arrival at the receiver's side. If an adversary $\mathcal{A}$ tries to replay the old messages, the malicious event can be easily detected by the receiving node by checking timestamps as ΔT is typically a small value. Hence, PBSCF-ITS prevents the replay attack against the passive adversary $\mathcal{A}$.

2) Man-in-the-Middle (MiTM) and Impersonations Attacks: Let an adversary $\mathcal{A}$ intercepts the messages Msg_1, Msg_2 and Msg_3, MSG_1, MSG_2 and MSG_3 from the public channels to launch man-in-the-middle attack. To perform this task, $\mathcal{A}$ may generate a random secret $r^a_{V_i} \in Z^*_q$ and a current timestamp T^a_1, and computes $A^a_{V_i} = h(RID_{V_i}||\ TC_{V_i}\ ||r^a_{V_i}\ ||T^a_1)$, $R^a_{V_i} = r^a_{V_i} \cdot G$, $CT^*_{V_i} = CT_{V_i} \oplus h(r^a_{V_i} \cdot Q_{V_j}\ ||T^a_1)$, $M^a_1 = A^a_{V_i} \oplus h(s_{V_i} \cdot Q_{V_j}\ ||R^a_{V_i}\ ||T^a_1)$, $M^a_2 = s_{V_i} + h(M^a_1\ ||CT^*_{V_i}||\ Q_{TA}||\ Q_{V_i}) * r^a_{V_i} \pmod q$, where $Q_{TA} = s_{TA}.G$, $Q_{V_i} = s_{V_i}.G$, $RID_{V_i} = h(ID_{V_i}||s_{TA})$, $RID_{TA} = h(ID_{TA}||s_{TA})$, $TC_{V_i} = h(ID_{V_i}\ ||RTS_{V_i}||\ s_{V_i}\ ||s_{TA}\ ||RID_{TA})$, RTS_{V_i} is the registration timestamp of V_i. However, $\mathcal{A}$ is not able to compute various components present in the messages Msg_1, Msg_2 and Msg_3 as they are based on secrets s_{TA}, s_{V_i}, s_{V_j}, n_{V_i}, n_{V_j} and pseudo identities RID_{V_i} and RID_{TA}. To determine s_{TA}, s_{V_i} and n_{V_i} from Q_{TA}, Q_{V_i} and N_{V_i} respectively, $\mathcal{A}$ needs to solve the computationally hard Elliptic Curve Discrete Logarithm Problem (ECDLP) which is not possible for $\mathcal{A}$ in polynomial time. Thus, $\mathcal{A}$ cannot modify Msg_1 or other remaining messages. In this way, in PBSCF-ITS, $\mathcal{A}$ will not be able to launch the man-in-the-middle attack. Similarly, one can also prove that PBSCF-ITS prevents the man-in-the-middle attacks during communications between V_i and RSU_l. On the other hand, $\mathcal{A}$ can not launch impersonation attacks on the proposed PBSCF-ITS on behalf of the legitimate entities, such as V_i, V_j and RSU_l because the secret credentials possessed by V_i, V_j, and RSU_l can not be obtained by the adversary $\mathcal{A}$.

3) Anonymity Preservation: In PBSCF-ITS, the secret credentials such as keys and real or pseudo identities are not exchanged in the plaintext format. Thus, $\mathcal{A}$ does not have a chance to abuse the anonymity of the exchanged messages. Moreover, each message contains the fresh timestamp and distinct random secret numbers. Hence, PBSCF-ITS preserves anonymity property.

4) Ephemeral Secret Leakage (ESL) and Privileged-Insider Attacks: The significance of the "ESL attack under the CK-adversary model" is that it tells whether a designed security scheme protects the session key or not. If the session key is computed with the help of long term secrets as well as short term secrets, it has potential to defend "ESL attack under the CK-adversary model". In the CK-adversary model, an adversary $\mathcal{A}$ has potential to steal the session states and session secret values. In the proposd PBSCF-ITS, the computed session keys (SK_{V_i,V_j} and SK_{RV}) use both long term secrets (identities and secret keys) along with short term secrets (random nonces) of different parties. However, these secret values are not known to $\mathcal{A}$. In the absence of the permanent (long term) secrets, it is infeasible for $\mathcal{A}$ to calculate the session key with having only short term secrets through session hijacking attacks.

A privileged-insider user of the TA cannot compute the session key because most of the sensitive information are deleted from the TA's database after successful registration of registered entities. Moreover, the session keys are distinct for each session. This implies that even if a session key in a specific session is compromised, the future and previous established session keys are secure. Thus, PBSCF-ITS is resilient against ESL attack and privileged-insider attack along with preservation of both forward and backward secrecy properties.

5) Stolen Verifier Attack: In proposed scheme, registration information is stored in the secure database (memory) of CS_k. Furthermore, we do not store any of the sensitive information in their memory directly. For example, RSU_l stores information $\{RID_{RSU_l}, TC_{RSU_l}, (s_{RSU_l}, Q_{RSU_l}), CT_{RSU_l}, E_q(u,v), G, h(\cdot)\}$ in its memory. CS_k stores information $RID_{CS_k}, TC_{CS_k}, (s_{CS_k}, Q_{CS_k})$ in the secured region of its database. The similar mechanism is also used in the other secure cryptosystem like the RSA or ECC based systems to thwart the attempts of stolen verifier attack. Therefore, in proposed scheme required data is not available to $\mathcal{A}$ to launch the other associated attacks, i.e., the sensitive credentials guessing, impersonation, and unauthorised session key computation. Hence, proposed scheme is able to prevent the stolen verifier attack.

6) Vehicle Physical Capture Attack: In PBSCF-ITS, OBU of a vehicle stores information $\{RID_{V_i}, TC_{V_i}, (s_{V_i}, Q_{V_i}), CT_{V_i}\}$ in its memory. $\mathcal{A}$ can steal an OBU physically to extract sensitive information from its memory through power analysis attack [32]. However, the information is distinct in every OBU. But, the credentials which are stored in other non-compromised OBUs are unique and distinct and it will not be of much help to the adversary. The extracted information from compromised OBU will not be further helpful in deriving of the session keys among other non-compromised smart vehicles as well as between the smart vehicles and their cloud servers. Hence, PBSCF-ITS is resilient against vehicle physical capture attack.

VII. PRACTICAL BLOCKCHAIN IMPLEMENTATION

The real-time blockchain simulation has been executed over a system configuration which is considered as a cloud server setting with the environment setting: "Ubuntu 18.04.3 LTS, Intel Core i5-8400 CPU @ 2.80GHz× 6, Memory 7.6 GiB, OS type 64-bit, disk size 152.6 GB". The script was written in "node.js with VS CODE 2019".

Since the blockchain technology is a distributed system, the simulation is executed over a virtually created distributed servers platform. In the system, we considered the number of distributed servers (known as distributed peer nodes) as 11, and these servers create a distributed Peer-to-Peer (P2P) cloud server network. The peer nodes can communicate or share the information by a message passing manner, where each of the cloud servers have a consistent local ledger. Each ledger has the same type of data, which is similar to each other. In this simulation time, we utilized the node.js technology for creating the distributed servers as well as the messages passing process. Here, the messages indicate the created blocks which will be added into the blockchain. In addition, for the block mining process (block verification and addition into the blockchain), we implemented the voting-based "PBFT consensus algorithm" for the distributed technology. In the blockchain technology, the blocks can be added into the blockchain and each block contains a finite number of transactions. The blockchain holds a chain of varies number of blocks. We examined three cases: 1) first case contains the varied number of blocks (where each block holds a finite number of transactions) which will be added into a blockchain and we measured the time (called as the total computational time in seconds) for mining the blocks using the voting-based "PBFT consensus algorithm", 2) second case has a varied number of transactions which are loaded into a block, and a finite number of those blocks is added into a fixed-size blockchain, and 3) third case having a varied number of mined blocks and the transactions processed per second (TPS) was then calculated. The simulations were executed under the following three scenarios:

- **Case 1:** In this case, we considered a fixed number of transactions for each block in the blockchain as 47. We then varied only the blockchain size, which means the number of blocks is varied. The simulation outcomes reported in Fig. 9 shows the "total computational time (in seconds) versus the number of blocks mined into the blockchain". The values of computational time are 9.908, 18.132, 22.306, 27.648, and 34.686 seconds, for 25, 45, 65, 85 and 105 blocks to be mined, respectively. The results clearly show that whenever the size of the chain (blockchain) increases, the computational time also increases. It is worth noticing that the computational time values increase linearly with the increasing number of mined blocks.
- **Case 2:** In this case, we considered "a fixed number of mined blocks in each blockchain as 33". The oucomes reported in Fig. 10 indicate that "the total computational time (in seconds) versus the number of transactions loaded in a block". In this case, the values of computational time are 10.433, 10.835, 12.983, 13.564, and 16.768 seconds for 30, 50, 70, 90 and 140 transactions containing in a block, respectively. Similar to Case 1, the results signify that the computational time values increase linearly when the number of transactions per block increases.

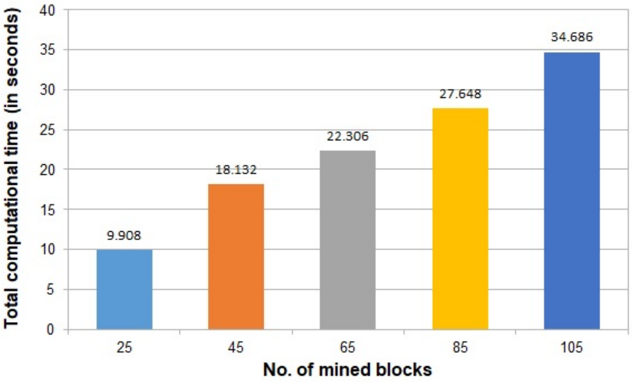


Fig. 9: Simulation results on computational time versus no. of mined blocks

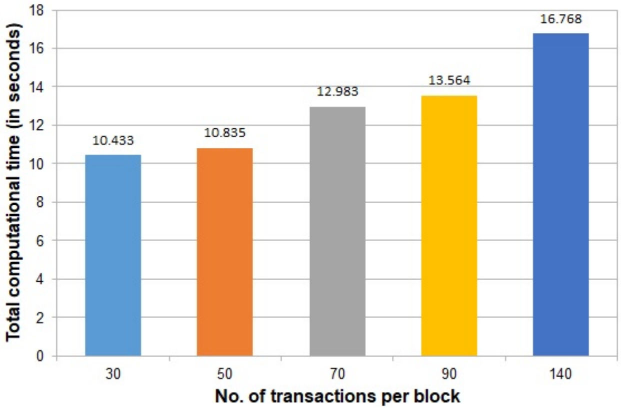


Fig. 10: Simulation results on computational time versus no. of transactions per block

- **Case 3:** In this case, we estimated the values of transactions per second (TPS) for the various number of mined blocks. The simulation outcomes reported in Fig. 11 show the values of TPS are 95, 152, 178, 219, and 276, for 25, 45, 65, 85, and 105 mined blocks, respectively. It is also observed that the values of TPS increase with the increasing number of mined blocks. This happens due to the addition of more number of blocks into the blockchain.

VIII. COMPARATIVE STUDY

In this section, we provide the details of conducted comparison among proposed scheme and other similar existing schemes. The proposed scheme is compared with the other related schemes like, Liu *et al.* [27], Jiang *et al.* [41], Moghadam *et al.* [42], Ali *et al.* [43], Ever [44] and Farooq *et al.* [45]. The details of comparisons are provided below.

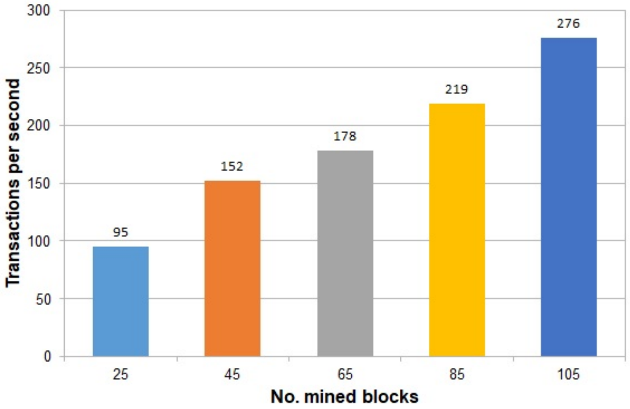


Fig. 11: Simulation results on transactions per second versus no. of mined blocks

TABLE I: Communication cost comparison with related prior works

Scheme	No. of messages	Total cost (in bits)
Liu *et al.* (2018) [27]	3	2752
Jiang *et al.* (2020) [41] (V2I initial authentication)	5	4992
Jiang *et al.* (2020) [41] (V2I handover authentication)	3	1888
Moghadam *et al.* (2020) [42]	4	3648
Ali *et al.* (2020) [43]	3	3424
Ever (2020) [44]	6	5344
Farooq*et al.* (2020) [45]	6	4032
PBSCF-ITS: Case 1	3	2208
PBSCF-ITS: Case 2	3	2016

TABLE II: Average execution time (in milliseconds) for cryptographic primitives using MIRACL

Primitive	Scenario 1: Raspberry PI (in milliseconds)	Scenario 2: Server (in milliseconds)
T_h	0.309	0.055
T_{mtp}	0.385	0.114
T_{senc}	0.018	0.003
T_{sdec}	0.014	0.003
T_{ecm}	2.288	0.674
T_{eca}	0.016	0.002
T_{bp}	32.084	4.716
T_{mul}	0.011	0.002
T_{add}	0.010	0.001
T_{exp}	0.228	0.039

A. Communication Costs Comparison

For the comparison of communication costs, we consider the sizes of different cryptographic operation as follows. We consider 256 bits, 160 bits, 160 bits, 320 bits for cryptographic one way hash function, random nonce/ secret value, various identities, ECC point multiplication, respectively. The communication costs of Liu *et al.* [27], Jiang *et al.* [41] (V2I initial authentication), Jiang *et al.* [41] (V2I handover authentication), Moghadam *et al.* [42], Ali *et al.* [43], Ever [44] and Farooq *et al.* [45] are estimated as 2752 bits, 4992 bits, 1888 bits, 3648 bits, 3424 bits, 5344 bits, 4032 bits, respectively. Moreover, the communication costs for proposed scheme are 2208 bits (for Case 1: V2V), 2016 bits (for Case 2: V2RSU), respectively. From the Table I, it is clear that proposed scheme requires less communication costs as compared to other existing schemes.

TABLE III: Computation cost comparison with related prior works

Scheme	Smart device (OBU/CH/Vehicle)	Server (RSU/CS/TA/KGC)
Liu *et al.* [27]	$7T_{ecm} + 2T_{eca}$ $+6T_h + 3T_{mul} \approx 17.935$ ms	$4T_{ecm} + 3T_{eca} + 4T_h$ $+2T_{mul} + T_{bp} \approx 7.642$ ms
Jiang *et al.* [41] (V2I initial authentication)	$8T_{ecm} + 4T_{mtp} + 6T_{bp}$ $+4T_{senc}/T_{sdec} \approx 212.412$ ms	$6T_{ecm} + 2T_{mtp} + 3T_{bp}$ $+4T_{senc}/T_{sdec} \approx 18.432$ ms
Jiang *et al.* [41] (V2I handover authentication)	$5T_{ecm} + 2T_{mtp} + 3T_{bp}+$ $2T_{senc}/T_{sdec} + 2T_{mul} + T_{add}$ ≈ 108.526 ms	$5T_{ecm} + 3T_{mtp} + 3T_{bp}$ $+2T_{senc}/T_{sdec}$ ≈ 17.866 ms
Moghadam *et al.* [42]	$5T_h + 4T_{ecm} + 2T_{senc}/T_{sdec}$ ≈ 10.729 ms	$5T_h + 2T_{ecm} + 2T_{senc}/T_{sdec}$ ≈ 1.629 ms
Ali *et al.* [43]	$18T_h + T_{fe} + T_{senc}$ ≈ 7.868 ms	$7T_h + 3T_{senc}/T_{sdec}$ ≈ 0.394 ms
Ever [44]	$9T_h + 2T_{bp}+$ $2T_{mtp} + 3T_{ecm}$ ≈ 74.583 ms	$6T_h + 3T_{bp}+$ $2T_{mtp} + 3T_{ecm}$ ≈ 16.728 ms
Farooq *et al.* [45]	$T_h + 2T_{bp} + 3T_{ecm} + T_{mul}$ ≈ 71.352 ms	$T_h + 2T_{bp} + 6T_{ecm} + T_{mul}$ $+2T_{mtp} \approx 13.761$ ms
PBSCF-ITS	$8T_h + 5T_{ecm}$ ≈ 13.912 ms	$7T_h + 5T_{ecm}$ ≈ 3.755 ms

B. Computation Costs Comparison

For the estimation of computation costs, we use the average execution time (in milliseconds) values of cryptographic primitives, which were computed through "Multiprecision Integer and Rational Arithmetic Cryptographic Library (MIRACL)" [46]. Let T_h, T_{mtp}, T_{senc}/T_{sdec}, T_{ecm}/T_{eca}, T_{bp}, T_{mul}/T_{add}, and T_{exp} signify the execution time required for one-way hash function, map-to-point, symmetric encryption/decryption, bilinear pairing, modular multiplication/addition and modular exponentiation, respectively.

The execution time of various cryptographic operations are provided in Table II. In Table II, Scenario-1 is taken for resource constrained devices i.e., sensing devices, IoT sensors, etc., under the setting: "Raspberry PI 3 B+ Rev 1.3, Ubuntu 20.04 LTS, 64- bit OS, 1.4 GHz Quad-core processor, cores 4, 1 GB RAM". On the other side, Scenario-2 is taken for resource rich devices i.e., servers, gateway nodes, etc., under the setting: "Ubuntu 18.04.4 LTS, with 7.7 GiB memory, Intel® Core™ processor- 8565U, CPU @ 1.80GHz×8, 64-bit OS type and disk size 966.1 GB". We executed each cryptographic operation for 100 times, and measured the minimum, maximum and average execution time in milliseconds.

The values of computation time for proposed scheme are 14.839 ms and 21.085 ms in Case-1 (for V2V communication) and 13.912 ms 3.755 in Case-2 (for V2RSU communication). From Table III, it is clear that proposed scheme requires less computation cost as compared to some other schemes. Though, the computation cost of the proposed scheme is higher than some of the schemes, but it can be accepted as it provides "more security and extra functionality features".

TABLE IV: Functionality & security attributes differentiation

Attribute	[27]	[41]	[42]	[43]	[44]	[45]	PBSCF-ITS
F_1	✓	✓	✓	✓	✓	×	✓
F_2	✓	✓	✓	✓	✓	✓	✓
F_3	✓	✓	✓	✓	✓	✓	✓
F_4	✓	✓	✓	✓	✓	✓	✓
F_5	✓	✓	✓	✓	✓	✓	✓
F_6	✓	✓	✓	✓	✓	✓	✓
F_7	✓	×	✓	×	×	×	✓
F_8	✓	✓	✓	✓	✓	✓	✓
F_9	×	×	×	×	×	✓	✓
F_{10}	×	×	×	×	×	×	✓
F_{11}	×	×	×	✓	×	×	✓
F_{12}	×	×	×	×	×	×	✓
F_{13}	×	×	×	✓	×	×	✓
F_{14}	✓	✓	✓	✓	✓	×	✓

F_1: "replay attack"; F_2: "man-in-the-middle attack"; F_3: "mutual authentication"; SF_4: "key agreement"; F_5: "device/vehicle impersonation attack"; F_6: "RSU/server impersonation attack"; F_7: "anonymity"; F_8: "resilience against device (vehicle) physical capture attack"; F_9: "ESL attack under the CK-adversary model"; F_{10}: "formal security verification using AVISPA tool"; F_{11}: "support dynamic node (vehicle/RSU) addition phase"; F_{12}: "support blockchain-based solution"; F_{13}: "support formal security analysis under ROR model"; F_{14}: "privileged-insider attack"
✓: "a scheme is secure or it supports an attribute"; ×: "a scheme is insecure or it does not support an attribute".

C. Comparison of Security and Functionality Features

The security and functionality features of proposed scheme and other schemes like, Liu *et al.* [27], Jiang *et al.* [41] (V2I initial authentication), Jiang *et al.* [41] (V2I handover authentication), Moghadam *et al.* [42], Ali *et al.* [43], Ever [44] and Farooq *et al.* [45] are compared in Table VIII-C. From Table VIII-C, it is clear that other existing schemes are vulnerable to various potential attacks and lack in functionality features. However, proposed scheme provides desired level of security and also supports extra functionality features. Therefore, proposed scheme seems better than the other existing schemes.

IX. CONCLUSION AND FUTURE DIRECTIONS

In this paper, we aimed to design an effective access control and key management solution for Big data analytics-endowed ITS, called PBSCF-ITS. The security analysis of PBSCF-ITS proves its resilience against various types of potential attacks. A rigor comparative study with existing related schemes reveals that PBSCF-ITS can provide more security and functionality features than the existing counterparts. Therefore, PBSCF-ITS can be a suitable mechanism for deployment in a secure communication for Big data analytics-endowed ITS.

In future, we try to include more functionality features in the proposed framework. Moreover, we also aim to include the testbed experiments of the proposed framework in a real-time environment to measure its performance with the actual settings.

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