Application of Blockchain Technology to 5G-Enabled Vehicular Networks: Survey and Future Directions

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***Abstract*—Blockchain is disrupting several sectors as it continues to grow mainstream. The attraction for Blockchain is increasing from various application domains looking to take advantage of its immutability, security, cost-saving, transparency and fast processing properties. Blockchain has empowered several sectors to upgrade their existing systems or operate an entire system architecture shift. For instance, Blockchain has enabled IoT systems to improve their quality of services while simultaneously ensuring their security requirements. Particularly, several works are applying Blockchain to manage trust in 5G-enabled autonomous vehicular systems to ensure secure vehicle authentication and handover, guarantee message integrity, and provide an irrefutable vehicle reputation record. Vehicular network systems require proper data storage management, highly secure transactions, and non-interference networks. The immutability, tamper-proof, and security by design of Blockchain make it a suitable candidate technology for 5G vehicular network systems. We present in this paper a methodical literature analysis of the application of Blockchain to 5G vehicular networks, architecture, and technical aspects. We also highlight and discuss some issues and challenges facing the application of Blockchain technology to 5G vehicular networks.**

***Index Terms*—Blockchain, 5G, Vehicular Network, VANET, IoV, V2V, V2I, Vehicular Communication, Systematic Review.**

I. Introduction

Reports by the United Nations show that 55% of the world's population lives in urban areas, and the proportion is expected to increase to 68% by 2050 [1]. This urbanisation of the world is creating major issues for both cities (which have to deal with complex and growing transportation networks) and for citizens (which use the transportation networks for their daily commutes).

With the increased embedding of computing and communication technologies in vehicles, vehicular networks (a.k.a., VANETs) stand as a viable solution for sustained urbanisation. Vehicular networks consider the creation and management of ad hoc wireless networks composed mainly of moving vehicles and also (sometimes) of a small portion of stationary communication infrastructure (a.k.a., roadside units, RSUs). VANETs enable a wide range of applications that have a direct impact on urbanisation (e.g., collision prevention, dynamic traffic routing, real-time traffic monitoring) and quality of the commute (e.g., more efficient and diverse multimedia services). In addition to the societal and economic impacts, VANETs are considered to be a billion-dollar industry on their own [2].

Historically, VANETs create their communication networks using dedicated short-range networks or by leveraging existing cell phone technologies (e.g., 4G-LTE, or its vehicular counterpart LTE-V).

5G technology has recently been defined by the Third Generation Partnership Project (3GPP) and it is starting to get deployed in various parts of the world. 5G communication technology is poised to revolutionise several application domains (particularly IoT [3]). 5G will deliver significantly improved capabilities to vehicular networks (e.g., capacity increase, latency reduction, improved connectivity) and will fulfill requirements of vehicular networks for extremely low latency, high peak data, and sustainable data rates while at the same time offering performance enhancements with regards to network reliability, security, communication cost, and efficiency of connectivity energy [4]. The 5G technology will also change the connectivity approach as we will move from vehicular networks adapting themselves to the communication technology to the communication technology adapting itself to the vehicular networks [5].

The identification of vehicular networks as one of 5G's most representative applications drew significant adopters from the vehicular networks community, creating 5G-enabled VANETs [2]. The integration of 5G technology with VANETs is likely to unlock many new services and businesses to vehicular networks. Hence, it will assist with the wide adoption and spread of VANETs in our cities, and contribute to making them smarter environments.

Given the importance of each message exchanged between vehicles in a vehicular network, it is crucial that messages are only generated by legitimate vehicles and that each of them is not tampered-with before (and when) reaching its destination [6]. Blockchain positions itself as a good solution to vehicular networks – particularly with the rising (and legitimate) concerns over privacy, security and authenticity issues in such networks [7] and other domains (e.g., healthcare [8], governance [9], smart cities [10], and Internet of Things (IoT [11]) in general.

Several works already propose the application of the Blockchain technology to vehicular networks (e.g., [12], [13]). However, these works do not consider 5G as the communication enabler. There exists several works that survey the application of Blockchain to 5G-enabled domains from IoT [14] and heterogeneous network environments [15], [16] to unmanned aerial vehicles [17] and smart-cities [18]. Mistry et al. [14] have attempted to survey Blockchain applications to encompass 5G-enabled vehicular communications, but only reported a unique work from Ortega et al. [5]. This is one of the main motivations for conducting a systematic review on this particular topic.

In our work, we survey existing works that propose to use Blockchain for 5G-enabled vehicular networks through the means of a systematic review.

The remainder of this paper is organised as follows: Section II provides a brief overview of the main technologies used in this survey study. Section III details the framework of our systematic review, whereas Section IV reports and analyses the works selected from our systematic review methodology. Finally, Section VI concludes the paper.

II. Background

In this section, we introduce the major technologies that are involved in this article.

A. Blockchain Technology

Interest in Blockchain technology has grown considerably over the last few years. Often confused with Bitcoin, Blockchain is the underlying technology used by Bitcoin to operate. Blockchain is a decentralised infrastructure and a distributed computing paradigm which uses cryptographic chained block structures to validate and store data, peer-to-peer network to communicate, and smart contracts to program and manipulate data. Blockchain is immutable (extremely hard to change), and updatable only via consensus or agreement among peers.

Nodes (devices) taking part in the Blockchain are either miners/validators (able to create new blocks) or block signers (able to validate and digitally sign the transactions). A critical decision that every Blockchain network has to make is to figure out which node will append the next block to the Blockchain. This decision is made using one a consensus mechanisms. The consensus mechanism is a protocol that makes sure all nodes that maintain the Blockchain are synchronised with each other and agree on which transactions are legitimate to be added to the Blockchain. The goal is to ensure Blockchain records are true and honest. The consensus mechanism is the backbone of a Blockchain and ensures that everyone uses the same Blockchain. There are several consensus mechanisms, out of which three are widely used (i.e., proof-of-work, proof-of-stake, and proof-of-authority) [19].

Blockchain systems are typically classified into four categories: (i) public, (ii) private, (iii) consortium and (iv) hybrid [20]. A public Blockchain is a non-restrictive, permissionless distributed ledger system. Anyone who has access to the internet can sign in on a Blockchain platform to become an authorized node and be a part of the Blockchain network, participate in the consensus process, read and send transactions, and maintain the shared ledger. Bitcoin [21] and Ethereum [22] are two representative public Blockchain systems. A private Blockchain is a restrictive or permissioned Blockchain that operates only in a closed network. Private Blockchains are usually used within an organisation or enterprise where only selected members are participants of a Blockchain network. Hyperledger projects (such as Hyperledger Fabric) [23] is the most popular private Blockchain system. A consortium Blockchain is a sub-category of private Blockchain. Unlike private Blockchain where the network is managed by only a single organisation, more than one organisation can act as a node in the consortium Blockchain and exchange information or do mining. R3 and Hyperledger are two examples of such type of Blockchain. A hybrid Blockchain is a combination of a public and a private/consortium Blockchain.

Blockchain is evolving and has already disrupted several sectors such as finance, IoT, Smart City, Healthcare, Governance and so on and it will continue to emerge to other sectors. In this paper we focus on the application of Blockchain to 5G-enabled vehicular networks.

B. 5G Telecommunication Technology

5G technology stands for the 5th generation mobile network. It is a new global wireless standard and the successor to the 4G networks. 5G and beyond 5G networks are designed to meet the very large growth in data and connectivity of today's modern society, the internet of things with billions of connected devices, and tomorrow's innovations. 5G wireless technology is meant to deliver higher multi-Gbps peak data speeds, ultra low latency, more reliability, massive network capacity, increased availability, and a more uniform user experience to more users. Higher performance and improved efficiency empower new user experiences and connect new industries [24].

C. Vehicular Networks

Vehicular networks or VANETs have emerged as a result of advancements in wireless technology, ad hoc networking, and the automobile industry. These networks are formed among moving vehicles, roadside units, and pedestrians carrying communication devices (e.g., smart phones, connected watches). Vehicular networks can be deployed in rural, urban, and highway environments. There are three main scenarios for communications in vehicular networks: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) [25].

D. 5G-Enabled Vehicular Networks

Mobile traffic has drastically increased in the recent years. This increase in the amount of data has caused vehicular networks to face challenges in both communication capacity and computing capability. Vehicular networks may have several limitations: limited spectrum resource, incapable on-board devices, and inefficient system management. To cope with the limitations of vehicular networks and improve their performance in terms of flexible resource allocation, automated network organisation, and advanced mobility management, the structure of vehicular networks is enhanced by 5G technologies such as the cloud radio access network (C-RAN) architecture and cloud computing [26], [27]. All these technologies combined improve the efficiency of the novel 5G-enabled vehicular networks and help satisfy their demand for vehicular services with heavy-data traffic or complex computing processes [28]

Figure 1 provides an overview of the different technologies used in our surveyed infrastructure from the Blockchain, to 5G telecommunications, to vehicles to roadside units. It particularly shows the 5G based vehicle-to-vehicle or vehicles-to-infrastructure communications. Furthermore, it also shows the ability of a roadside unit of a vehicle to either host a Blockchain node or to connect to the Blockchain.

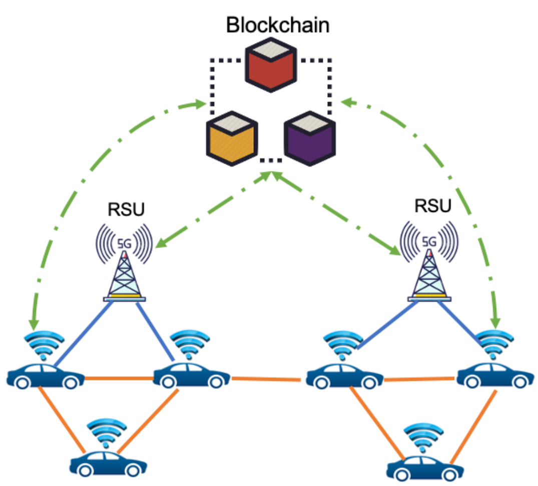

Fig. 1: An Overview of a Blockchain based 5G-enabled vehicular network. RSU: Roadside Unit. Discontinuous green lines indicate that the vehicle or the RSU either hosts a Blockchain node or connects to it. Orange lines represents vehicle-to-vehicle communications. Blue lines represent vehicle-to-infrastructure communications.

III. Review Technique

The methodical survey described in this research article has been taken from the widely accepted guidelines and process outlined in [29], [30]. Our methodical literature survey technique has three phases: (i) actively-planning, (ii) conducting and reporting the review results, and (iii) exploration of research challenges.

The remainder of this section details the research questions, the process for the identification of research, and the process of data extraction.

A. Research Questions

The following research questions have been identified for this survey:

- Q1: Are there works proposing the use of Blockchain to 5G-enabled vehicular networks? How many?
- Q2: What are the common applications of Blockchain in the context of 5G-enabled vehicular networks?
- Q3: What are the major Blockchain types and frameworks that are employed?
- Q4: What are the major environments used to validate the proposed systems?
- Q5: What are the challenges that are hindering the application of Blockchain in 5G-enabled vehicular networks?

B. Identification of Research

Research was identified from the following four electronic databases: (i) Springerlink, (ii) ScienceDirect, (iii) IEEEeXplore, and (iv) ACM Digital Library. The search string shown in Figure 2 was used to query these databases based on metadata (title, abstract, keywords). In the case of IEEEexplore, the query did not produce sufficiently accurate results. As such, the query for IEEEexplore was rerun to both metadata and full texts.

The initial search returned a total of 203 research papers related to the research topic. In line with Kitchenham [30], two researchers independently screened titles and abstracts meeting regularly to resolve differences. Title-based exclusion reduced the number of papers to 18. In the next pilot phase, we started reading papers fully. Following the pilot phase, a number of works were removed because they were outside the scope of our review, Blockchain application to 5G-enabled vehicular networks, e.g., UAV and smart grid. Additionally, we removed works that focused on the application of Blockchain to IoT and Edge/Fog in broader sense without a focus on vehicular networks.

The final inclusion and exclusion criteria are described in Table I .

Following the application of these criteria, 8 research articles were included in the final review. These are listed in Table II.

C. Data Extraction

The following data was extracted for each of the 8 papers: bibliographic data, the Blockchain purpose of application, the type and platform of Blockchain used, how the Blockchain solution is implemented, the variables or metrics under study, and the type of used validation platform. Data was extracted by two authors independently and compared. A third author cross-checked on random samples. Extracted data was stored in a shared spreadsheet and entered using a form designed for this purpose.

```
('Blockchain')
AND
('5G' OR 'fifth generation' OR '5th generation')
AND
( 'Vehicular Communication' OR 'Vehicle Communication' OR 'Vehicular Network' OR
  'Vehicle Network' OR 'Vehicular Communication Network' OR 'Vehicular Ad hoc Network'
  OR 'VANET' OR 'Vehicle Communication Network' OR 'Vehicle Ad hoc Network' OR 'IoV'
  OR 'Internet of Vehicle' OR 'V2V' OR 'Vehicle-to-Vehicle' OR 'Vehicle-to-Everything'
  OR 'V2X'
)
```

Fig. 2: Search String

TABLE I: Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Full-text	Uncompleted studies
Published at any time	Non English
Published in the above selected databases	Duplicated studies
Published in workshops, symposiums, conferences, books, and journals	Studies on UAV and smart grid
Study manuscript written in English on the topic of Blockchain application to 5G-enabled vehicular networks	Studies using Blockchain to IoT, Edge, and Fog in general

TABLE II: Final Selection of Publications

	Title	Authors	Type	Year	Venue
1	A Blockchain-SDN-Enabled Internet of Vehicles Environment for Fog Computing and 5G Networks	Gao et al. [31]	Journal	2020	IEEE Internet of Things Journal
2	B-TSCA: Blockchain assisted Trustworthiness Scalable Computation for V2I Authentication in VANETs	Wang et al. [32]	Journal	2020	IEEE Transactions on Emerging Topics in Computing
3	Blockchain-Based Energy Trading in Electric Vehicle Enabled Microgrids	Umoren et al. [33]	Journal	2020	IEEE Consumer Electronics Magazine
4	Blockchain-based mobility management for 5G	Xie et al. [34]	Journal	2020	Future Generation Computer Systems
5	Blockchain-Based Secure and Trustworthy Internet of Things in SDN-Enabled 5G-VANETs	Lee and Ma [35]	Journal	2019	IEEE Access
6	Blockchain-Enabled 5G Autonomous Vehicular Networks	Rahmadika et al. [4]	Conference	2019	International Conference on Sustainable Engineering and Creative Computing (ICSECC)
7	Towards a 5G Vehicular Architecture	Mendiboure et al. [36]	Book Section	2019	Communication Technologies for Vehicles
8	Trusted 5G Vehicular Networks: Blockchains and Content-Centric Networking	Ortega et al. [5]	Journal	2018	IEEE Vehicular Technology Magazine

IV. Review Results

In this section, we analyse the papers obtained from our systematic review. We start by reviewing their number and publication venues. Then we delve into their content and proposed approaches.

A. Preliminary Analysis

We see in Table II that the application of Blockchain technology to 5G-enabled vehicular networks is new as a field with the first recorded work in 2018. The number of works on this specific topic is not large (8 in total). However, we notice an increased number of works from a year to another (from 1, to 3, to 4 in 2018, 2019 and July 2020 respectively).

In terms of publications, the major part of the works (6 out of 8) were journal articles, whereas the two others as either conference papers (i.e., 1) or book sections (i.e., 1). Among the journal publications, 5 were published in IEEE journals and 1 was published in Elsevier. However, regardless of the publisher, it is worth noting that all the journals were published in top Q1 journals. This is an indicator that not only there exists work in the area, but it is also of a high-quality.

Table III shows results of our analysis for each paper selected from our systematic review. In order to answer our previously stated research questions, we analyse results reported in Table III in three phases: (i) Blockchain application purpose, (ii) Blockchain technologies, and (iii) validation environments.

B. Blockchain Applications to 5G-enabled Vehicular Networks

In this part, we review the reasons why blockchain is used to vehicular networks. For this, we analyse the papers on two aspects (application purpose and desired vehicular network properties). In terms of properties, we are focusing on: security, trust, anonymity, fault-tolerance, performance, and scalability.

We see from Table III that Blockchain has been used in the different papers for multiple purposes ranging from vehicle authentification, to handling handovers, to ensuring origin and authenticity of messages, to recording vehicular energy transactions. However, the Blockchain applications were majoritarily for vehicle authentification, followed by message integrity and handling handovers. The only different application of Blockchain that is reported is for an immutable storage of energy trading transactions.

TABLE III: Summary of the papers selected from the systematic review based on their application/purpose, achieved property, Blockchain technology, and validation approach. Columns Se, T, A, F, P, and Sc stand respectively for security, trust, anonymity, fault tolerance, perform, and scalabilty. We put '–' whenever the paper does not include an indication. We also put '*' for the anonymity property when it is satisfied within the Blockchain, but requires an approved third party to issue anonymous identifications.

Ref	Purpose of Application	Achieved Property						Blockchain Technology					Validation	
								Type	Platform	Implementation			Metrics	Platform
		Se	T	A	F	P	Sc			Storage	Consensus	Miners		
[31]	Vehicle authentification and communication Integrity: Enhance an immediate control of false information and prevent malicious activities	✓	✓	✓	✓	✗	✗	Consortium	Hyper-ledger	Vehicle information (signature, reputation score, and certificate expiration time), sent messages with their trust verdicts), and aggregate message verdicts	Byzantine fault-tolerance	Subset of RSUs	Transmission delay, packet delivery ratio, and block processing time	Simulation with MATLAB and NS-3
[32]	Vehicle authentication and handover: Enhance scalability and reduce time for authentication and handover re-authentification	✓	✓	✗	✗	✓	✓	Public	Bitcoin	Attributes and trustworthiness of vehicles	Proof-of-work	RSUs*	Execution time cost of approach	Security of authentication and handover proven under Computational Diffie-Hellman (CDH) assumption
[33]	Energy trading between electric vehicles in a microgrid: Verify/store energy trading transactions, and avoid double-spending or energy double-selling	✗	✓	✓	✗	✓	✗	Private	Blockchain with a cryptocurrency	Traded energy information (prosumer ID, customer ID, amount of energy, and the price), and records of payments in cryptocurrency	Byzantine fault tolerance or federated Byzantine agreement	Micro-grid control centres	Number of associated prosumers and energy trading cost	Simulation written using Java and Firebase.
[35]	User equipment handover: Enhance security and latency during handover in user equipment on board of vehicles connected to 5G base stations	✓	✗	✗	✗	✓	✗	Private	Bitcoin-like	Public-keys of base stations and user equipments	proof-of-work	All base stations covered by the same authentication server	Execution time cost + latency of the approach	Security proven using Burrows–Abadi–Needham (BAN) logic. Simulation written using JavaScript.
[34]	Trust management on vehicular messages: Detect and deal with malicious vehicles, fake and tampered messages	✓	✓	✓*	✓	✓	✓	Private	–	Vehicle identifications, shared messages, and messages trust ratings	Combination of proof-of-work and proof-of-stake	RSUs	Block processing time, detection accuracy of malicious nodes, transaction transmission delay, and execution time of encryption mechanism	Simulation with OMNeT++, Crypto++ and an in-house lightweight Blockchain scheme
[4]	Secondary authentification, handover and authentication sharing: different levels of authentication depending on the requirements of the system	✓	✓	✓*	✓	✗	✓	–	–	Authentification results	Byzantine fault tolerance or proof-of-device	–	Channel Quality Indicator when vehicles switch transmission points	Simulation written using Python
[36]	Architecture: proposed an architecture for vehicular networks which used Blockchain to improve profile management, fire-walling, intrusion detection, privacy, etc.	✓	✓	✓	✓	✓	✓	–	–	–	–	–	–	–
[5]	Vehicle authentification and message integrity	✓	✓	✓	✓	✓	✓	Private	Hyper-ledger	Vehicle and RSU identifications, and shared messages	Hyperledger friendly	Can be all components of the vehicular network	–	–

In terms of desired properties, we see from Table III that, except for [33], all the works consider security as a property that they seek to achieve/improve through their use of Blockchain. This is also similar to trust as all works except [35] are aiming to achieve it. Performance and anonymity are just behind with 6 works out of 8 considering them in their work. However, the means of measuring performance is different from a paper to another. Furthermore, the works [32], [34] assume a weaker definition for anonymity (i.e., they accept the existence of an approved third-party to issue anonymous identifications). Fault-tolerance and scalability are the properties that are the least sought, each with 3 out of 8 papers not factoring them into their work. Three works distinguish themselves as they consider all the surveyed properties (i.e., [34], [36], [5]).

C. Blockchain Technologies used for 5G-enabled Vehicular Networks

In this part, we review the blockchain technologies that have been used in the selected papers. We focus on the type of Blockchain, the name of the Blockchain platform and the way Blockchain is implemented in each of these works. In terms of implementation, we particularly review: (i) the data that is stored in the Blockchain, (ii) the consensus mechanism, and (iii) the nodes that serve as miners/validators.

We see from Table III that among the works that mention the type of Blockchain, the majority is proposing to use private Blockchains (4 out of 6), whereas two other works are proposing to use either a consortium or a public Blockchain. Using a private Blockchain brings a clear advantage in terms of improved security and simplified authentification, which makes it the preferred type. However, it is worth noting that no work has investigated/proposed an approach based on a hybrid Blockchain despite its tradeoff properties that might suit vehicular networks well.

In terms of Blockchain platforms, 3 works did not provide details of their platform, providing only a system architecture or an overview of the Blockchain implementation. Among the works that detailed their platforms, two were based on Hyperledger, two were based on Bitcoin (or a Bitcoin-like) Blockchain. A unique work (i.e., [33]) proposed using any Blockchain that includes a cryptocurrency as a payment mechanism for its energy trading market. Here as well, it is interesting (and surprising) to note that no work has proposed using Ethereum as its Blockchain, despite its fast growing notoriety and the advantages that smart-contracts bring.

With regards to Blockchain implementations, we see that each paper stores the data that are required to its application purpose, ranging from works storing only the identification of authentificated vehicles, to other works storing all the messages shared within the vehicular networks and their respective veracity scores. Therefore, there is a discrepancy in the size of the Blockchain from a work to another.

In terms of consensus mechanisms, the existing works are divided between the proof-of-work and the more light-weight Byzantine fault-tolerance (3 works each). We also notice works suggesting the use of alternative consensus mechanisms either in conjunction with proof-of-work (e.g., proof-of-stake) or independently (i.e., proof-of-device).

The implementation aspect where there is a quasi-unanimity is the nodes that serve as miners/validators. Except for [5] where any node in the vehicular network can be a miner, all other works use roadside units or base stations for that role. This is mainly because these devices are stationary, which simplifies the block propagation and Blockchain synchronisation. Furthermore, unlike vehicles, these devices are often connected to a main power source and have plenty of storage to hold the entire Blockchain (which could grow large).

D. Validation and Performance Analysis

The last aspect we look at in our survey is the set-ups that are put in place in the different papers to validate their work in terms of both metrics and validation environments.

We see in Table III that the validation approaches/environments vary between:

- Analytical, where authors provide a proof for the property that their system ensures (mostly for security).
- Simulated, where they analyse the behaviour and the performance of their system with regards to different metrics.

We note that there is no agreement between the works neither in terms of validation environment nor in terms of validation metrics as each work uses its set-up. The different works use either generic networking simulators (e.g., NS-3 or OMNeT++) or design their simulation environments in-house, and evaluate metrics of their choice. This is an indicator of the absence of a standardised and dedicated framework for the validation of such systems.

V. Issues and Challenges

We have identified from our systematic review that there is a sizable number of works applying Blockchain to 5G-enabled vehicular networks and this number is continuously growing from a year to another. However, through the study and analysis of these works, we have identified several issues and challenges that have to be addressed in the future to fulfill the objective of seeing Blockchain fully deployed and integrated to the 5G-enabled vehicular networks.

A. Blockchain Technologies Dedicated to Vehicular Environments

The majority of Blockchain applications to 5G-enabled vehicular networks define roadside units and other stationary communication devices as miners or validation nodes. This choice alleviates the need of vehicles to commission for the storage of large amounts of data and ensure their ability to satisfy the energy required by (often) energivorous Blockchain technologies. However, this choice also comes with its shortcomings as relying on roadside units reduces fault-tolerance and scalability of vehicular network systems. A move to using vehicles directly as data nodes and miners/validators would certainly require adequate and more energy friendly Blockchain consensus mechanisms. This move would also require better means for ensure Blockchain synchronisation throughout the system in a timely manner. A better integration model for the Blockchain communication technology with the 5G vehicular network would help reaching that goal.

B. Privacy vs. Anonymity

Most Blockchain deployments in vehicular networks use vehicular identification numbers as a measure for ensuring users' anonymity. While this is a move in the right direction, it is not ensuring a full privacy. Furthermore, the privacy is even less ensured when the proposed Blockchain is private and requires some third-party mapping (e.g., between the vehicle's identification number and the vehicle's registration number or the user's SIM card number).

C. Performance and Scalability of Blockchain

5G-enabled vehicular networks are expected to interconnect thousands (if not millions) of vehicles. Therefore, any technology that gets introduced into this environment should perform efficiently to meet the required quality of service levels and scale smoothly to cover the large number of devices in the network. While the drive towards using Blockchain brings trust as a major property to 5G-vehicular networks, it should not be detrimental in terms of performance and scalability. Introducing AI and Automation alongside the Blockchain will certainly help with this endeavour.

D. Standardisation

It is clear from our survey that there is no agreement within the 5G-enabled vehicular networks community regarding the most appropriate Blockchain type or platform as they choose different Blockchain technologies (which sometimes are in-house ones). While the Blockchain field is in a race towards standardisation, the vehicular networks community should take advantage of those efforts by using the most notorious and widely spread Blockchain technologies. Furthermore, the vehicular networks community should also follow on those tracks to identify, standardise and integrate the Blockchain tools that they see most fit for their domain.

E. Testing and Validation Environments

Vehicular networks is a critical domain where there is no margin for reliability and security issues. Therefore, similarly to software engineering any modification or improvement brought into vehicular network systems must be fully tested and validated to hopefully make its way out of the laboratories to the outside world. The most crucial element in that matter is the design of benchmarks and standardised testing environments, which are currently lacking in all the surveyed works.

F. Policy, Legislation and Regulation

Blockchain technologies are facing several regulatory issues in multiple countries, particularly when it comes to cryptocurrencies. In terms of vehicular networks, regulation frameworks could be introduced to enable the use of the information stored on the Blockchain to evaluate the vehicles' road behaviour and their potential responsibility when being involved in a road accident. The information could also be used as a trusted and irrefutable proof for legal or insurance purposes. Other regulation frameworks could also be defined to allow new applications involving vehicular networks such as the Blockchain based vehicle-to-vehicle energy trade or other Blockchain based vehicle entertainment services.

VI. Conclusion and Future Work

In this paper, we surveyed existing works on the application of Blockchain technologies to 5G-enabled vehicular networks. Following our systematic review, we have identified that despite being a new research field, it has attracted a sizable and increasing number of works on the matter in a yearly basis. While Blockchain has been mostly used to improve the security of vehicles' authentication/handover and the trustworthiness/integrity of messages in the system, another work proposed using Blockchain as the underlying market currency for a vehicular network application (i.e., vehicle-to-vehicle energy trade).

In our analysis of Blockchain technologies used in the surveyed papers, we found that the data storage and synchronisation responsibilities are mostly allocated to the roadside units within the network, thus alleviating the issues of vehicle storage/energy capability, and block propagation in the network. Furthermore, while the majority of the works tend to favour a private deployments of the Blockchain, they are split on the ideal consensus mechanism between the Byzantine fault-tolerance and the proof-of-work. Moreover, they are even more split on the Blockchain platform of choice. In our analysis we have also noticed an absence of common validation platforms and metrics.

Despite the sizable number of works in the area, it is clear that there is still a need for further works to cover the topic in its length and breadth. Following our analysis, we review current issues and future challenges that are facing the application of Blockchain to 5G-enabled vehicular networks. Addressing these challenges in future directions will help realise the full potential of the Blockchain application to 5G-enabled vehicular networks.

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