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Towards Blockchain-based Intelligent Transportation Systems

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Abstract— **Blockchain, widely known as one of the disruptive technologies emerged in recent years, is experiencing rapid development and has the full potential of revolutionizing the increasingly centralized intelligent transportation systems (ITS) in applications. Blockchain can be utilized to establish a secured, trusted and decentralized autonomous ITS ecosystem, creating better usage of the legacy ITS infrastructure and resources, especially effective for crowdsourcing technology. This paper conducts a preliminary study of Blockchain-based ITS (B^{2}ITS). We outline an ITS-oriented, seven-layer conceptual model for blockchain, and on this basis address the key research issues in B^{2}ITS. We consider that blockchain is one of the secured and trusted architectures for building the newly developed parallel transportation management systems (PtMS) , and thereby discuss the relationship between B^{2}ITS and PtMS. Finally, we present a case study for blockchain-based realtime ride-sharing services. In our viewpoint, B^{2}ITS represents the future trend of ITS research and practice, and this paper is aimed at stimulating further effort and providing helpful guidance and reference for future research works.**

I. INTRODUCTION

With the rapid development of modern sensing, communicating, analyzing and computing techniques and devices, recent years have witnessed tremendous academic efforts and industry growth in intelligent transportation systems(ITS)[1], imposing a profound influence on every aspect of our life with smarter transport facilities and vehicles, as well as safer and more convenient transport services. Thanks to the ever-increasing uncertainty, diversity and complexity of behavior, mechanisms and strategies involved in this ecosystem, however, ITSs nowadays have demonstrated high-degree of social complexity instead of the expected intelligence, leaving many long-standing issues still unsolved or even worsened.

One critical issue is security risks caused by ITSs' evolving trend towards centralization. The fast-growing technologies including Internet-of-Things(IoT) and cloud computing make it possible for most of the data, analyses and decisions processed by centralized authorities or cloud-based platforms, which can be considered as ITSs' "Achilles' heel" and might be temporarily unavailable due to malicious attacks, performance limitations or simply improper operations. The second issue is the lack of necessary mutual trust among ITS entities. As a result, money and assets cannot "flow" from one entity to another smoothly and directly without trusted intermediaries, resulting in hierarchical structures, diversified mechanisms and increased social complexity of ITSs.

In practice, ITS practitioners typically strive to develop new resources (e.g., land, road) and smarter devices(e.g, cameras, self-driving cars). Following this practice trend, the research focus of the ITS literature[2−7] has also been witnessed to shift from transportation management and surveillance to vehicle- and vision-related topics in recent years. Generally speaking, these demand-driven solutions will certainly play a key role in improving ITSs' "intelligence", but are still far from enough to deal with such fundamental issues as security, trust and the consequent social complexity. In our viewpoint, without the underlying bases on security and trust, the high-level emerged intelligence is expected to be fake and fragile intelligence. Therefore, from a research perspective, in order to help the ITS ecosystem maintain its overall stability, profitability and effectiveness, there is a critical need to develop a secured, trusted and decentralized architecture so as to realize the smooth, intermediatory-free flow of data, money and assets among ITS entities, and thus building a healthier ITS ecosystem via creating better usage of the supply-side legacy infrastructure and resources, instead of adding new ones. However, research works in this area are almost nonexistent.

Our research is targeted at filling in this important gap. In this paper, we propose a novel blockchain-based ITS (B^{2}ITS) framework. As an emerging decentralized architecture and distributed computing paradigm underlying Bitcoin and other cryptocurrencies, blockchain is widely publisized to be a disruptive innovation that has the potential of redefining finance, economics and even the macroscopic societal systems [8,9], and has recently attracted intensive attention from governments, financial institutions, high-tech enterprises and capital markets. The key advantages of blockchain models can be summarized as decentralization, trust, security, chronological data, collective maintenance and programmability[10]. Specially, blockchain is believed by IBM to be an elegant solution to IoT, and the integrated "blockchain of things" technology can be used to collect real-world transportation data and build the physical part of the parallel transportation management system(PtTS)[2,11−13] in the literature. Furthermore, one or many artificial parts of PtMS can be established in the script space of smart contracts embedded in blockchains, in order to conduct various computational experiments[14,15]. As such, blockchain is a perfect solution to the key issues faced by ITSs, and also a potential underlying architecture for dealing with the social

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complexity via building PtMSs. To our knowledge, this paper is the first attempt in the literature to design the model and research framework, and discuss the potential applications of blockchain technology in transportation research.

This paper is organized as the following: Section II introduces the basic concepts of blockchain. Section III outlines an ITS-oriented, seven-layer conceptual model for blockchain. Section IV presents the research framework of B^2ITS and its key research issues. Section V discusses the relationship between B^2ITS and PtMS. Section VI presents a case study of B^2ITS. Section VII concludes.

II. Blockchain: Concept and Rationale

The blockchain idea originates from the foundational article entitled "Bitcoin: a peer-to-peer electronic cash system" [16], published in 2008 by a researcher with the pseudonym of "Satoshi Nakamoto" in a cryptography mail group. Technically speaking, blockchain can be narrowly defined as a kind of decentralized shared ledger that uses chronological, encrypted and chained blocks to store verifiable and synchronized data across a peer-to-peer (P2P) network. Broadly speaking, blockchain can be viewed as a novel decentralized architecture and distributed computing paradigm. It generates data with distributed consensus algorithms, stores data with encrypted chained blocks, and manipulates data with self-executed program scripts (i.e., smart contracts).

Blockchain has now become a crucial ingredient of large numbers of cryptocurrencies, among which Bitcoin is widely recognized as the first and most successful "killer use case". The underlying rationale of all blockchain systems is largely the same, with only minor variations on the consensus mechanisms. Typically, blockchain data is stored in each full-client nodes participating in a decentralized P2P network, and will be verified and recorded into blockchain using the consensus mechanism. For instance, Bitcoin uses the Proof-of-Work (PoW) mechanism (a.k.a, mining) with distributed nodes contributing their computing power to compete in a mathematical puzzle with dynamically adjusted difficulties. The node that successfully solves the puzzle wins the right to package all transaction data in a given period of time (e.g., 10mins in Bitcoin system) into a new block and append it to the main blockchain in time order. As reward, a certain amount of coins will be automatically generated and awarded to the winning node. This process is then repeated with each node starting solving a new puzzle and competing for the right to generate the next block. In this process, blockchain data will be hashed and encrypted for security.

Blockchain can solve the "Byzantine genenrals" and "double spending" problems for cryptocurrencies, which are key issues in building decentralized ITSs as well. The former problem can be depicted as "how to reach consensus and establish trusted cooperation in a distributed system without trusted central nodes", and can be solved by blockchain's digital encryption and distributed consensus algorithms. This plays a key role in promoting trusted communication and cooperation among vehicles, road-side devices, and pedestrians(smart phones) in a decentralized autonomous transportation systems. The latter problem refers to the risk of successfully spending the digital currency more than once. The consensus-based, distributed data verification mechanism guarantees a immutable, irrevocable and tracable blockchain ledger, and thus can protect against the double spending without trusted central authorities in a completely decentralized fashion. This feature helps establish an in-built monetary or financial niche system in the ITS ecosystem, thus facilitating point-to-point money transfer or digital asset exchange without intermediaries. To summarize, blockchain has the full potential of establishing a secured, trusted and decentralized ITS.

III. An ITS-Oriented Blockchain Model

This section presents an ITS-oriented, seven-layer conceptual model for characterizing and standardizing the typical architecture and major components of blockchain systems, and briefly describes its underlying key techniques. Due to space limitations, the technical details for implementation are beyond the scope of this paper and thus are omitted.

As is shown in Fig.1, similarly as the well-known open system interconnection reference model[17], the blockchain model has seven layers stacked as below.

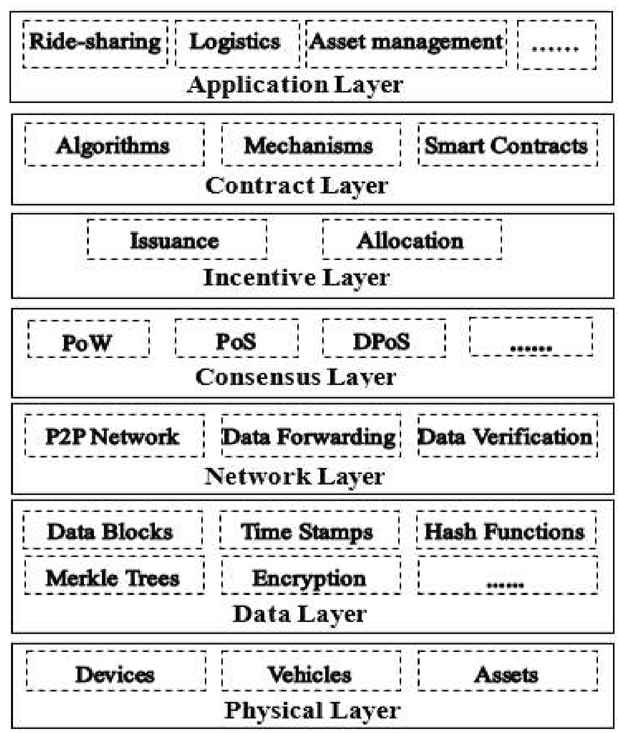

Fig. 1. An ITS-Oriented Blockchain Model

Physical Layer: The physical layer encapsulates various kinds of physical entities(e.g., devices, vehicles, assets and other environmental objects) involved in ITSs, such as traffic lights, digital cameras, cars, and so on. The key technique in this layer is IoT[18], which enjoys enhanced device security and data privacy when integrated with blockchain. Large numbers of physical entities, nowadays typically managed by central authorities in ITSs, can be in future digitalized and registered into decentralized blockchains using the so-called "blockchain of things" technique. As a first step towards this direction, specific kinds of chips have been designed and can be embedded into devices that can connect to the Internet. These chips will turn the devices into mining platforms, thereby establishing a connection to the blockchain[19]. This kind of IoT chips are expected to play a critical role in B^{2}ITSs. Once connected, ITS entities can establish a secured and trusted communication network on blockchain, and also form a self-organized, self-adaptive, and decentralized autonomous ITS ecosystem. Moreover, blockchain can be used for life-time management and surveillance of ITS devices. For instance, right from the time a car completes final assembly, it can be registered by the manufacturer into a universal blockchain, representing its beginning of life[20]. Within its lifetime, all kinds of events including maintenance, resale and traffic accidents, and all kinds of real-time data generated from its sensors, on-board units, roadside units, GPS modules and even driver's smartphones, can be securely recorded into the immutable and irrevocable ledger of blockchain, and thus forming its complete, traceable history.

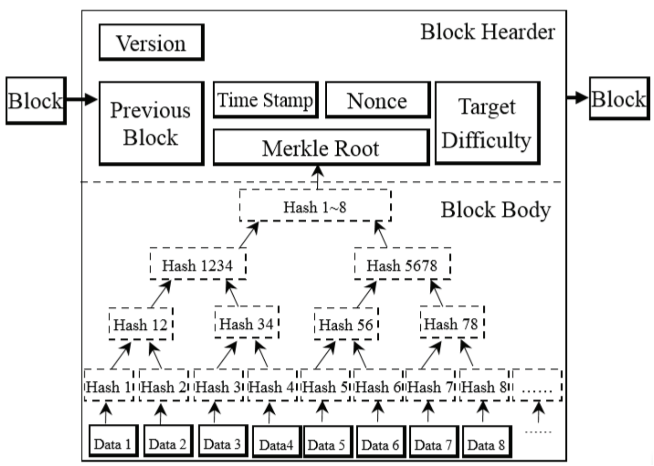

Fig. 2. The Structure of Blocks

Data Layer: This layer provides the chained data blocks, together with the related techniques including asymmetric encryption, time-stamping, hash algorithms and Merkle trees. In a blockchain system, each computing node wining the consensus competition will be empowered to create a new block, packaging all transportation-related data generated within a specific time period into a Merkle-tree-structured data block with time-stamps indicating the creating time of this block. The structure of blocks is shown in Fig.2. The header part specifies the meta-information, while the body part encapsulates all verified data, which is stored in the form of a hashed (e.g., via double SHA256 algorithm) Merkle tree with its root written in the header. The blocks are chained one by one in chronological order, forming the backbone containing the entire history from the first block(i.e., genesis block) to the newest one. In this layer, Merkle-tree-based structure and time-stamp are two key innovations. The former helps realize rapid, efficient and secured verification of the existence and integrity of blockchain data, while the latter enables the traceability and precise positioning of blockchain data. As such, blockchain is expected to be widely used in time-sensitive application scenarios in ITSs. More importantly, time-stamp has the potential of endowing transportation big data with a time dimension, and thus makes it possible to recur the past data history.

Network Layer: The network layer specifies the mechanisms of distributed networking, data forwarding and verification. Most ITS models, systems and application scenarios are composed of large numbers of distributed, autonomous, dynamic decision-making devices or vehicles, therefore a B^{2}ITS can be topologically modeled as a P2P network. Peers are equally privileged, equipotent participants without any central coordinator or hierarchical structure, and can be categorized into full-client and lightweight nodes. The former have a complete copy of all blockchain data since the genesis block, while the latter (typically smartphones, IoT devices, etc) only have a small fraction but can request the necessary data from neighboring nodes using specific protocols. Once a piece of data or a new block is created, it will be broadcast to the network, to which all nodes keep listening. Each node will verified the received data or new blocks according to predefined specifications, discard invalid ones and forward the others to neighboring nodes. This way, data or blocks passing verification from a majority of nodes will be appended into blockchain. As such, blockchain can be viewed as the next generation of "completely decentralized" big data technology. Blockchain data is stored on each and every node, and can be easily synchronized and restored even in the worst case of failure in all but one nodes. This is particularly useful in communication and interaction among ITS entities.

Consensus Layer: The consensus layer packages all possible consensus algorithms. Generally speaking, efficiently reaching consensus in decentralized systems has long been an important question in distributed computing and ITS research [21]. One of blockchain's key advantages is promoting all decentralized nodes reaching consensus on the data validity, which is the foundation of mutual trust among nodes. Various kinds of consensus algorithms have been designed. For instance, PoW-based consensus is the most widely-used algorithm that asks nodes to repeatedly run hashing functions or other client puzzles to validate the data [9]; Proof-of-Stake (PoS) consensus requires the node with larger amount of stake(e.g., coin, mileage, speed, etc) to validate the data [22]; Other algorithms include Delegated Proof-of-Stake(DPoS) [23], Proof-of-Movement, etc. Among all consensus algorithms, non-compute-intensive algorithms such as PoS and DPoS are particularly suitable for most lightweight devices and vehicles in ITS ecosystems.

Incentive Layer: This layer incorporates economic reward into blockchains, and specifies its issuance and allocation mechanisms. Once a new block is created, a certain amount of coins will be generated as reward to motivate the network continuing their efforts in data verification. These coins will be allocated to all nodes based on their contributions, according to all possible 13 kinds of allocation mechanisms[24]. The economic incentive is the main driving force for B^2ITS.

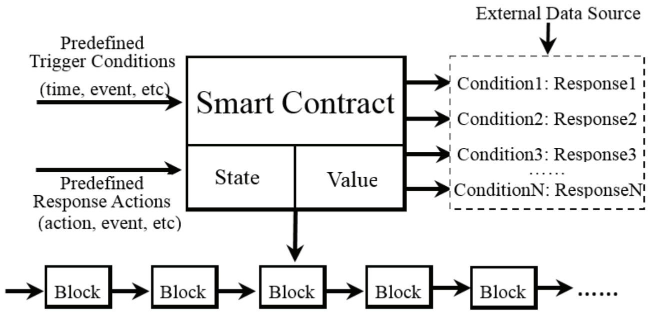

Fig. 3. The Structure of Smart Contracts

Contract Layer: This layer packages various scripts, algorithms and smart contracts, which serve as important activators to the static data, money or assets stored in blockchain. To be specific, as can be seen in Fig. 3, smart contracts are a group of self-verifying, self-executing, and self-enforcing state-response rules that is stored on and secured by the blockchain. Generally speaking, once two or more parties consent to all of the terms within the contract, they cryptographically sign the smart contract and broadcast it to the P2P network for verification [25]. When the predefined conditions are triggered, smart contracts will self-execute the stipulations of the agreement and trigger a corresponding response action without any invention of third parties. As such, smart contracts are particularly useful in the control and management of both physical and digital assets in ITSs, making them programmatic "smart properties".

Application Layer: This layer packages potential application scenarios and use cases of B^2ITS. In practice, blockchain technology is still in its infancy, especially in transportation systems. However, lots of novel business models and startup companies have been emerged in many areas including blockchain-based transportation data storage and verification, P2P trading and payment, asset management, among others. Section V presents a detailed case study of blockchain-based ride-sharing.

IV. B^2ITS and Its Key Research Issues

Blockchain has the potential to help establish a secured, trusted and decentralized ITS ecosystem. However, from a research perspective, several key research issues still need to be addressed for B^2ITS to reach its full potential. In this section, we summarize the fundamental research issues as shown in Fig.4, and briefly discuss the associated research opportunities and potential insights.

1) *Decentralized autonomous transportation systems*

Decentralized autonomous transportation has long been an active area and an "ideal" object in ITS research [26,27]. The core components of blockchain, including P2P networking, consensus-based distributed coordination, and contribution-based economic rewards, are natural ways of modeling complex transportation systems. Each computing node (e.g., IoT devices, vehicles, or other entities with computing power) can be viewed as an autonomous "agent" in this B^2ITS. Large numbers of nodes can be connected and communicate with each other via various kinds of blockchain-based decentralized Apps (Dapps), resulting in decentralized autonomous organizations (DAOs) dedicating to specific requirements or scenarios, and in the macro-level forming a decentralized autonomous system and even society (DAS). In this direction, researchers are encouraged to delve into the microscopic individual behavior and interactions among autonomous agents, and also the macroscopic system-level modeling of self-organizing, self-evolving and self-adaptive DAOs and DASs.

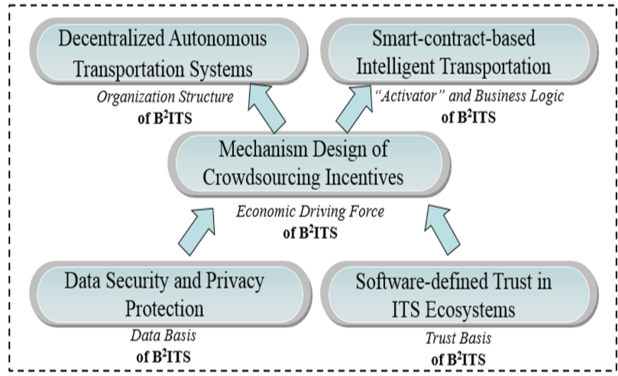

Fig. 4. Key Research Issues in B^2ITS

2) *Mechanism design of crowdsourcing incentives*

Essentially, the distributed consensus competition can be viewed as a crowdsourcing task to large numbers of ITS nodes, which contribute their computing power to verify blockchain data. These nodes are self-interested agents, so that incentive compatible crowdsourcing mechanisms must be designed to make individual behavior of revenue maximization aligned with the system-wide target of guaranteeing a secured and trusted ITS ecosystem. Equipped with such mechanisms, blockchain can be used to aggregate all possible computing resources in ITS to solve previously intractable problems, e.g., finer-grained real-time transportation management and control.

3) *Software defined trust in ITS ecosystems*

Blockchain-powered trust plays a significant role in building a decentralized and disintermediated ITS, making it possible for lots of application scenarios including point-to-point trading, payment and communication. This kind of trust is guaranteed by code, mathematics and verification from the majority, and thus can be considered as "software-defined" trust. It has the potential of greatly reducing the structural complexity and in turn social complexity of ITS, making it possible for money and asset flowing freely among ITS entities. For instance, based on the point-to-point trust, used cars can be resold and registered directly via blockchain-based Dapps, instead of centralized authorities or platforms. In this direction, the underlying rationale for trust formation, trust-based management and credit evaluation of ITS assets, are all interesting issues that await further research efforts.

4) *Smart-contract-based intelligent transportation*

Smart contract serves as an "activator" of blockchain, endowing static data with diversified algorithms (e.g., machine learning, big-data analytics, etc) and high-level business logics to build a programmatic ITS ecosystem and improve the intelligence of ITS applications. The self-executing smart contracts also significantly reduce the social complexity of ITS by lowering the importance of human factor, and can act as software agents on behalf of their creator or even themselves. Therefore, there is a critical need to study the design and implementation of specific smart contracts, as well as smart-contract-based ITS management and control.

5) *Data security and privacy protection*

Although blockchain has shown strong robustness to security risks and threats in cryptocurrencies, its asymmetric encryption framework should be further strengthened in ITS scenarios with large numbers of lightweight devices so as to protect against the possibly easier 51% attacks.

V. From B^2ITS to PtMS

In the literature, researchers have proposed the PtMS idea, which optimizes the real-world transportation system through the parallel interactions with its corresponding artificial or virtual counterparts[2]. We believe that blockchain is one of the secured and trusted architecture for a parallel transportation system, and thus B^2ITS can be viewed as an important step towards PtMS. One possible path from B^2ITS to PtMS is shown in Fig.5.

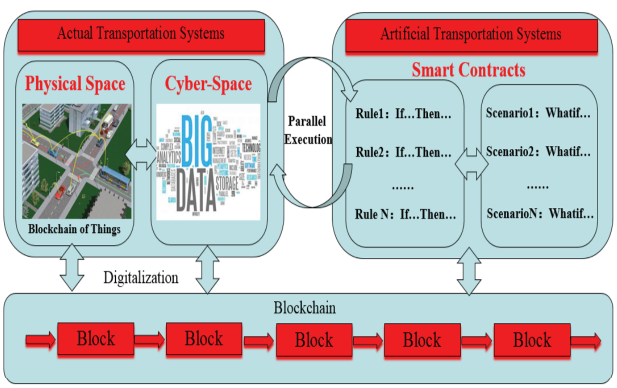

Fig. 5. Parallel Transportation Management in B^2ITS

The blockchain-based PtMS follows the research framework of ACP approach, namely Artificial societies + Computational experiments + Parallel execution[28]. In the "A" part, all ITS entities in physical space, including IoT devices, vehicles and assets, can be easily digitalized via "blockchain of things" and registered into blockchain, while online transportation big data in cyber-space can also be integrated into blockchain. This way, the real-world transportation system can be modeled as blockchain-driven DAOs or DASs. We can also establish one or more artificial transportation systems in the code space of smart contracts using the Ethereum platform[29], which offers Turing-complete and programmable scripts to support complex modeling and computing. Based on these co-evolving actual and artificial transportation systems, we can design and conduct diversified computational experiments in the "C" part to evaluate and verify specific behavior, mechanisms and strategies in ITSs(e.g., to evaluate the road network traffic conditions[30]). These experiments can be designed as "whatif" type of scenario inference and simulation, based on the predefined "if-then" rules. The optimal solution will be emerged in large numbers of computational experiments and in the "P" part feed back to actual transportation systems. This "A-C-P" step repeats infinitely, leading the actual transportation system eventually approximating its optimal artificial counterparts.

VI. A Case Study

One of the most successful application scenarios of B^2ITS, so far, is realtime ride-sharing, a leading business model in sharing economy and social transportation. La'zooz[31], widely publicized as "blockchained version of Uber", aims to build an open-source, worldwide, decentralized ride-sharing network, so as to challenge and revolutionize the established private transportation systems with large numbers of wasted empty seats and cargo space. La'zooz's Dapps of realtime ride-sharing enables private car owners to share their empty seats with others traveling the same route. It also offers a multi-hop solution for riders to switch between several vehicles on their way to destinations, targeting at increasing the number of matching rides and also creating a more robust coverage over users' transportation needs. Compared with such centralized platforms as Uber and Lyft, La'zooz takes ride-sharing to the next level of decentralized, community-owned-and-managed transportation network without unsatisfactory centralized decision-making or risks (e.g., surge pricing, privacy leaks, etc).

The underlying rationale of La'zooz basically follows our ITS-oriented blockchain model. Any device that can run La'zooz's Dapp, typically smartphones and computers of its community of users, can be registered as one of La'zooz's computing nodes called road miners (*physical layer*). The realtime data is verified and stored in a community-maintained cryptoledger, through which all ride-sharing behavior, schedules and payments are coordinated and executed(*Data layer*). Road miners are interconnected into a P2P network without any central authority(*Network layer*). Rather than the commonly-used consensus algorithms such as PoW, PoS and DPoS, La'zooz designed an innovative consensus algorithm called "proof-of-movement", which encourages road miners to drive with La'zooz's Dapp running on their smartphones or computers. This way, road miners can contribute to the community by sharing their transportation data along the way and helping La'zooz weave the local social transportation web (*Consensus layer*). As reward, La'zooz automatically generates new tokens called "zooz" to road miners, and these tokens (1 token = \$0.01USD) can be used to pay for ride-sharing and other transportation services. The longer distance they drive, the more zooz tokens they earn (*Incentive layer*). Furthermore, various algorithms are designed and integrated into La'zooz's Dapp. These algorithms can be used to make specific decisions without human intervention, e.g., detecting the usage rate of specific geographic region and activating the service in the region where the number of active users exceeds the "critical mass", and so on(*Contract layer*).

La'zooz is a decentralized, self-managed DAO. Its formal decisions are collectively made by the community according to each user's weight, which represents the user's contribution to the community and will be updated once a month via public voting process. In our viewpoint, La'zooz, together with Arcade City[32] and other companies with the similar business model, represent the future trend of social transportation and will reshape the sharing economy.

VII. CONCLUSIONS

This paper presents a preliminary study on the emerging blockchain technology and its potential applications in transportation research. We design an ITS-oriented, seven-layer conceptual model, propose the research framework of B^2ITS and discuss its key research issues. We also investigate the relationship between B^2ITS and PtMS in the literature, and point out that B^2ITS is an important step forward to PtMS.

We are now at the very beginning of the blockchain technology cycle, and it may take years for B^2ITS to come to fruition. Therefore, more research efforts are needed at this stage to explore the underlying rationale, novel business models as well as practical application scenarios of B^2ITS. The main purpose of our paper is to stimulate more detailed investigation and innovative research in this new direction.

APPENDIX

TABLE I

GLOSSARY OF SYMBOLS

Acronym	Technical Term
ACP	Artificial societies + Computational experiments + Parallel execution
B^2ITS	Blockchain-based Intelligent Transportation Systems
Dapp	Decentralized Application
DAO	Decentralized Autonomous Organization
DAS	Decentralized Autonomous System/Society
DPoS	Delegated Proof-of-Stake
IoT	Internet of Things
ITS	Intelligent Transportation Systems
P2P	Peer-to-Peer
PoS	Proof-of-Stake
PoW	Proof-of-Work
PtMS	Parallel transportation Management System

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