Towards a Sustainable Ecosystem of Intelligent Transportation Systems

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***Abstract*—It is difficult to overstate how large a role Intelligent Transportation Systems (ITS) technology has played in advancing safety, mobility, and productivity in our daily lives. ITS encompasses a broad range of technologies, including information and communication technologies, transportation and communication infrastructures, connected vehicles, and emerging technologies such as Internet-of-Things (IoT). It has been studied extensively in many different disciplines, including transportation, communication, database and management communities. Unfortunately, there are still many unsolved challenges that hinder the large deployment of advanced ITS systems. Recent studies have proposed using Blockchain, an emerging technology that enables decentralized coordination, to address inherent challenges in ITS such as security and scalability. However, these studies did not address a key question: *how can we achieve a sustainable ITS ecosystem*? This paper presents our preliminary study where we first point out the limitations of prior Blockchain-based ITS systems and then outline an architecture to support a sustainable ITS ecosystem. Our main goal is to stimulate further effort and cross-disciplinary collaboration by providing guidance and reference for future studies.**

Keywords – Intelligent Transportation Systems, Blockchain, Scalability, Sustainability, Architecture

I. Introduction

Intelligent Transportation Systems (ITS) is defined as an advanced application of systems that utilize information and communication technologies to optimize decision-making in *road transportation*. Main applications of ITS include various types of systems to support efficient traffic and mobility management, yielding benefits that range from increased safety, reduced congestion (increased mobility), and fewer negative environmental externalities. Canonical examples include electronic toll collection, traffic signal coordination, cooperative intersection collision avoidance systems, and dynamic traffic light sequence, among more.

While there is understandably much excitement surrounding ITS-related research, the application of ITS itself is still an extraordinarily difficult undertaking given the myriad of institutional and technological challenges [15]. Recent research on ITS (e.g., [17], [13], [2], [10], [16], [18]) focus primarily on technological challenges such as security, scalability, and lack of trusted entity. However, they appear to overlook a key question: *how can we achieve a sustainable ITS ecosystem*?

In this paper, we answer the question by first examining recent ITS systems and identifying unsolved issues. Then, we propose a novel architecture to integrate prior systems with new components that are used to tackle the issues. Our architecture is inspired by the observations that (i) *no panacea* exists for all ITS challenges in every scenario, and (ii) there is a need for a decentralized ITS ecosystem [17] and flexible technology procurement and deployment [15]. To achieve these two intercorrelated goals, we envision an architecture that supports decentralized but connected ITS systems with different specifications, usages, guarantees, and business models. Generally speaking, our architecture aims to achieve the following goals:

- It "connects" and "coordinates" multiple ITS systems, and provides end-to-end guarantees.
- It is backward compatible and allows older vehicles without the appropriate technology to participate.
- It is self-stabilizing, i.e., it can recover from an erroneous state after some unfortunate incident(s).

The first goal is enabled by an *abstraction of consensus*, namely *Cross-System Consensus (CSC)*. Existing Blockchain-based ITS systems (e.g., [17], [13]) only rely on end-to-end guarantees on data (or packet) delivery. However, for an ecosystem of ITS, simple delivery guarantee is *not* enough, especially when some applications require interacting with multiple ITS systems. We need a stronger semantic to achieve "coordination" across multiple systems with flexible and tunable guarantees. The second goal is supported by the concept of *daemon* which executes the operations on behalf of some vehicles that do not have advanced technology. The final goal is realized by introducing a separate component that performs the *failure recovery* process asynchronously (i.e., in the background) and is able to bring the whole ecosystem back to a correct state should an incident materialize.

Contribution: In this paper, we aim to build a sustainable ITS ecosystem. We first examine prior ITS systems, particularly Blockchain-based ones, and point out unsolved challenges. Afterward, we propose a novel architecture that addresses these challenges and argue why our design supports a sustainable ITS ecosystem.

II. Preliminary

This section begins with a brief discussion on ITS's benefits as well as challenges followed by a short introduction on Blockchain. Then we argue why Blockchain might be most appropriate and innovative when paired with ITS.

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Intelligent Transportation System (ITS) ITS has been studied extensively since the directive of the European Union first defined it in 2010 as systems that utilize information and communication technologies in the field of road transportation. It received renewed interest recently due to the advancement of technologies that made such research feasible. For example, the U.S. Department of Transportation launched the Smart City Challenge in 2016, and awarded the city of Columbus, Ohio with a total of $40 million to study the deployment of ITS and ITS-related applications [14]. Such a large-scale plan is impossible without the state-of-the-art sensors and connected infrastructure and platforms that enable data sharing.

Recent articles point out that ITS research has shifted from pure transportation management and surveillance to that of vehicle-centric and/or agent-based topics (e.g., [16], [18], [17]). In other words, ITS practitioners now focus more on exploring demand-driven solutions and designs rather than on finding one holistic answer. The ultimate goal is to build a *sustainable ecosystem of ITS* that can maintain overall stability, profitability, and effectiveness. To achieve this goal, it is necessary to develop a secure, trusted, and decentralized mechanism that supports the smooth and reliable flow of data, money, and assets across different ITS systems [16], [17].

We must address institutional challenges in addition to technical ones. A report by the U.S. General Accounting Office [15] points out two main challenges: (i) the lack of funding for large-scale technology procurement and deployment and (ii) the difficulty in coordinating the exchange of data and information among technology providers, agencies, and users. Blockchain-based solutions might help alleviate the problem. However, as we point out later, Blockchain alone does *not* offer a complete solution. Particularly, there will be some scalability and performance bottlenecks.

Blockchain Interest in Blockchain technology gradually developed after Bitcoin was introduced in 2008, and has grown exponentially as Bitcoin became a household name in 2017. Categorizing its growth as "exponential" is particularly apt as Bitcoin rose one-thousand-percent in 2017 alone. In 2008, Satoshi Nakamoto published the seminal work on Bitcoin [12]. While his work eventually served as the foundation upon which Blockchain has been studied and adopted, Nakamoto's work focuses on Blockchain in the context of an alternative currency and store of value rather than in non-currency settings. Blockchain can be better thought of as an amalgamation of several existing technologies: peer-to-peer (P2P) networking, cryptographic hashing functions, trusted timestamping, and digital signatures.

Intuitively, Blockchain (or so called *distributed ledger*) is a *decentralized* database designed to enable multiple independent participants in the network to reach *consensus* about changes to the state of the shared data without needing a trusted third-party. More precisely, participants reach an agreement over transactions and records through a consensus mechanism (e.g., PoW, PoS, or PBFT), ensuring that each party's view of the shared database is consistent with that of all other parties. This eliminates the need to trust other participants who may exhibit malicious intent. Through the consensus mechanism, any tampering or improper modification of the data will be independently detected and rejected by honest participants. As a result, digital assets and records cannot be forged once they are recorded on the Blockchain, or transferred, without the participants' consent in the form of a digital signature.

Numerous non-currency use cases have been proliferating at a fast pace, including digital currency/payments, land registration, voting, identity management, and supply chain traceability. In recent years, we see an unprecedented amount of money funding Blockchain-related research. To name a few representative examples: (i) the NSF has doubled its spending on Blockchain research from 2015 to 2017, totaling $6.5 million up to date;[1] (ii) in 2017, the private sector funded approximately $4.5 billion towards Blockchain-related projects [11]; and (iii) in 2017, the Department of Homeland Security awarded $2.25 million to small businesses developing blockchain applications, up from $1.3 million in 2016.[2]

In the past three years, researchers have proposed using Blockchain for VANET (Vehicular Ad-hoc NETwork) and ITS applications. There are three main reasons:

- *Decentralization*: Blockchain is built on top of a P2P network where every entity can join it at will.[3]
- *Fault-tolerance/Security*: Blockchain is designed to tolerate malicious behavior as long as a certain threshold of participants are correct (typically the majority).
- *Integrity/Data Verification/Traceability and Revocability/Error Detection*: Blockchain's core idea is based on a chain of immutable blocks that contains important data, e.g., transaction details in Bitcoin [12].

III. Prior Systems

As mentioned earlier, there is a significant amount of research in ITS systems. In this paper, we aim to discuss those that are most relevant to our study, particularly those using Blockchain, as they generally support decentralization and are self-organizing. As a result, the technology procurement and deployment become less challenging. Multiple entities can deploy the system in a much smaller scale altogether; at the same time, the aggregate scale of the whole system is still sufficient for extensive usage.

A prior system that is closest to ours is B^2ITS [17] proposed by Yuan and Wang. They were among the first to explore the use of Blockchain to support ITS. B^2ITS is based on a seven-layer conceptual architecture that enables parallel transportation management for ITS [16]. Our architecture differs from theirs in that we focus primarily on the integration and coordination across ITS systems.

[1] Data extracted from USAspending.gov.

[2] Data extracted from grants.gov.

[3] There are permissioned and permission-less Blockchain. Since most Blockchain-based ITS is based on the permission-less design, we will not discuss permissioned system in this paper.

Additionally, Leiding et al. [6] proposed a system to provision service in a self-managed and decentralized system. Some applications include traffic regulation application and vehicle tax and insurance applications. Dorri et al. [3] proposed using a Blockchain alternative that optimizes for IoT in order to improve existing ITS applications. Singh and Kim [13] proposed a system called Trust Bit, a reward-based system that encourages intelligent vehicles to communicate truthfully. Michelin et al. [10] proposed a new Blockchain that allows connected vehicles to share data securely in a decentralized and tamper-resistant manner. These systems touched on some aspects of ITS systems such as decentralization, constrained resource and data exchange; however, these studies only dealt with a limited set of technical challenges, and did not aim to integrate multiple ITS systems together.

Most of the existing literature also proposed using Blockchain to build trusted VANET, e.g., [5], [9], [8], [7]. There are also some commercial efforts. CUBE [2] is one of the startups that is building a platform to secure connected vehicles using Blockchain. These systems have goals different from ours.

Unsolved Challenges Here, we discuss key technical issues that were *not* addressed in prior studies.

- *Efficiency and Scalability*: From a technical point of view, it is unlikely to use a *single* Blockchain to support all ITS applications due to its inherent overhead and exponential growth of ITS-related data.
- *Flexibility*: Prior studies generally assume that every vehicle uses the same Blockchain system, i.e., every entity is interacting with each other using one chain. However, real-world ITS applications are very diverse; usually different systems are deployed at different locations.
- *Backward Compatibility*: Most of the existing literature aims to build a completely new ITS system without considering how it might interact with existing ITS systems and how it can handle those vehicles without the advanced technology to participate in the new system. For example, a vehicle without the communication capability will not be able to add or read data from Blockchain-based ITS.
- *Self-Stabilizing*: ITS systems have to be reliable given a failure might cause catastrophic results, e.g., traffic accidents or heavy traffic jam. Unfortunately, no system is perfect in reality. Therefore, an ITS system requires a mechanism to recover its function from an erroneous state. Existing ones typically require human intervention to diagnose and fix the issues. Such a labor-intensive approach is *not* scalable for a large-scale ecosystem. Prior systems overlooked this issue.

IV. Our Architecture

Our goal is to address the challenges identified in Section III. Our proposed ecosystem is (i) decentralized, (ii) backward compatible, and (iii) self-stabilizing. In the end, we argue why we believe our design can support a sustainable ecosystem.

Design Overview Inspired by prior articles [16], [18], [17] and the success of the Internet, we believe that only a decentralized and open ecosystem (or a system of systems) can fully realize the potentials of ITS. The Internet is essentially the interconnection of multiple distinct network systems using a protocol stack, e.g., TCP/IP protocol suite. Analogously, our architecture aims to create an ITS ecosystem by interconnecting multiple distinct ITS systems. Each ITS system can be deployed independently at different locations by different entities, e.g., government, company, and community, among more. Moreover, an application can also interact with multiple ITS systems at the same time, namely *cross-ITS applications*. Figure 1 illustrates at a high level the data flow from one cross-ITS application to another. One novelty in our scheme is the introduction of *Cross-System Consensus (CSC)*, an abstraction of consensus that is used to coordinate multiple ITS systems *securely* in the presence of malicious and selfish behavior.

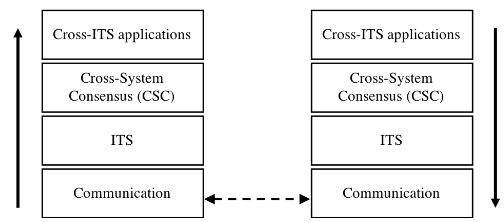

Fig. 1. Data flow from one cross-ITS application to another

Architecture A conceptual presentation of our architecture is captured in Figure 2. Its foundation is built on Blockchain-based and traditional ITS systems, topped by a CSC abstraction and daemons. We place daemons at the highest level as they solve the compatibility challenge. The component on the left hand side handles the failure recovery process, needing only direct communication with daemons and ITS systems. By design, CSC protocols have the *atomicity* property – either they successfully change the state of every ITS system involved, or the state remains unchanged. Hence, it does *not* need to recover from failures.

Our architecture is essentially an *open* platform. It is similar to TCP/IP protocol suite or OSI reference model in that it only defines the interface between components, and that any protocols that achieve the functionalities can be used. Below, we discuss some details on the design of each component.

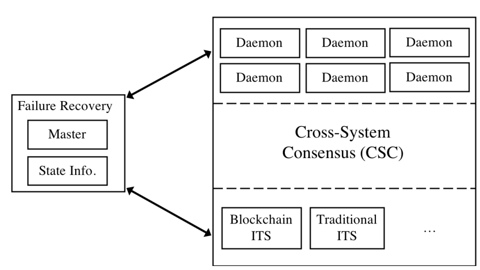

Fig. 2. Conceptual architecture of our ecosystem

1) CSC and Decentralization: To achieve decentralization, we need to connect and coordinate different ITS systems. One straightforward solution is using something similar to TCP/IP, which provides end-to-end data (or packet) delivery guarantees. When dealing with ITS systems, we need a stronger abstraction due to the complexity of interaction. Consider multiple Blockchain-based ITS systems that rely on their own "coin" (cryptocurrency) or "token." This situation may create a barrier for users attempting to interact with all the coins given that they are time-consuming to obtain, exchange, and manage. As a result, providing only delivery guarantees will make application development prohibitively difficult.

Fortunately, fundamental properties of coordination across multiple Blockchain systems are being studied recently, e.g., [4], [1]. Intuitively, these protocols allow a group of users to exchange assets (or states) that are stored in multiple Blockchains in an *atomic* fashion, and can be used in the context of ITS as well. Generally speaking, CSC protocols must have the following end-to-end guarantees: (i) if all users follow the protocol truthfully, then coordination is achieved, (ii) if some user(s) deviate from the protocol (intentionally or maliciously), then no conforming user ends up worse off, and (iii) no coalition has an incentive to deviate from the protocol.

2) Daemons and Backward Compatibility: A daemon is a standard tool in operation systems, which is a long-running background process that handles some core services for other processes. To make the ecosystem backward compatible, we need a mechanism for old vehicles (that lack the technology to participate in ITS systems). Our idea is to have multiple daemon processes running on each of the more advanced vehicles, where each daemon will interact with ITS systems on behalf of one other old vehicle.

More precisely, each old vehicle needs to register for the daemon service and buy credits using web service in advance, similar to the typical service provided by Electronic Toll Collection (ETC) in many countries. On the other hand, advanced vehicles will first use computer vision and vehicle-to-vehicle communication to identify nearby old vehicles. Afterward, such advanced vehicles can come to an agreement regarding the responsibility to each idle daemon process.

Should a case arise where there are no advanced vehicles present nor enough idle daemons, old vehicles may find themselves unable to interact with ITS systems. This leads to two consequences: (i) ITS enters an erroneous state due to unexpected behaviors and (ii) ITS uses an auxiliary way to handle these vehicles. For example, many ETC systems use cameras to identify unpaid vehicles and then proceed to send the owner a physical bill. Case (ii) is fine given we only lose efficiency. We rely on the third component to handle case (i).

3) Failure Recovery and Self-Stabilization: To make the ecosystem self-stabilizing, we need to record the state of the system and have the ability to "roll back" to the most recent correct state. We use a Blockchain-based system to store relevant state information, including states from both daemons and ITS systems. Periodically, a "master" process performs the investigation procedure. If it finds an erroneous state, it performs the following steps: (i) scan prior states and identify a snapshot that is consistent with all related ITS systems and daemons, (ii) notify them to roll back to the previous state snapshot, (iii) identify affected vehicles and perform recovery procedure, e.g., send physical bills, refund, etc., and (iv) perform "garbage collection" to throw out unnecessary state information. The master process is implemented using a long-living smart contract in the Blockchain.

Discussion We believe that our architecture is sustainable as our ecosystem not only addresses the technical challenges identified in previous studies, but also attempts to lower the friction of adoption (through the use of daemons) and lowers the operation cost (through the failure recovery component). Furthermore, similar to prior Blockchain-based systems, the decentralization feature lowers the cost of procurement, deployment, and participation.

We are in the process of evaluating suitable protocols to be integrated in each component in our architecture as well as developing daemons and the failure recovery component. We will use extensive simulations to verify the efficiency and self-stability of the process, as well as mitigate potential attacks. Another interesting line of work worth considering is a feasibility analysis to evaluate the cost of deployment, participation, and maintenance.

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