OFF-CHAIN SOLUTION FOR SCALABLE BLOCKCHAIN-BASED
VEHICULAR NETWORK

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DEDICATION

This thesis is dedicated to my mother, who taught me that even the largest tasks can be accomplished if it is done one step at a time. It is also dedicated to my late father who taught me that knowledge should be learned for oneself. I would also dedicate this thesis to my uncle, whose guidance and assistance is instrumental to me.

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ABSTRACT

Autonomous vehicles are rapidly developing a technology that has the potential to greatly impact the traditional automobile industry. The autonomous vehicle technology promises safer driving and more efficient vehicles than the current human operated vehicles. These vehicles are capable of constantly communicating information such as current position, speed and direction to other vehicles in real-time. The industry accepted model for managing communication between autonomous vehicles is by wirelessly connecting the vehicles by means of fixed roadside units via an ad hoc peer-to-peer vehicular network. As wireless networks are easily compromised, vehicular networks must be secured against any unwanted tampering. Recent research involving incorporating blockchain technology into the vehicular networks have shown promising results to secure the vehicular networks. However, conventional blockchain-based vehicular networks can suffer from performance degradation and limited scalability. One way of improving the performance and scalability of a blockchain-based vehicular network is by carrying out most of the data processing usually associated with the conventional blockchain outside of the blockchain. This study aims to show that the performance and scalability issues in a blockchain-based vehicular network can be improved by incorporating an off-chain network into the vehicular network. Simulations of vehicular network operations under different conditions were carried out to measure the network performance and scalability. Performance of the blockchain network was measured in terms of data throughput, data processing latency, and growth in data size. The results from the simulations for the conventional blockchain-based network and off-chain assisted network were compared. The simulation results showed that the off-chain assisted blockchain network performed and scaled better than the conventional blockchain network. Results of the simulations of the 80 nodes blockchain network showed that the off-chain assisted network improved the throughput by 17 times while lowering the latency by 99%, and the data size by 78% when compared to the conventional blockchain network.

ABSTRAK

Teknologi kenderaan autonomi yang sedang membangun mempunyai potensi untuk memberi kesan besar kepada industri automobil tradisional. Teknologi ini menjanjikan pemanduan yang lebih selamat serta penggunaan tenaga yang lebih efisyien berbanding kenderaan yang dipandu manusia. Kenderaan ini juga berupaya untuk sentiasa saling menghubung maklumat seperti kedudukan semasa, kelajuan dan arah dengan kenderaan lain dalam masa sebenar. Kaedah perhubungan yang diterimapakai oleh industri masakini untuk menguruskan komunikasi antara kenderaan autonomi dan unit-unit kawalan di tepi jalan adalah secara wayarles melalui rangkaian kenderaan *ad hoc* rakan ke rakan. Oleh kerana rangkaian wayarles mudah terjejas, rangkaian kenderaan perlulah dijamin selamat daripada pengubahan yang tidak dibenarkan. Penyelidikan terkini yang melibatkan penggabungan teknologi rantaian blok dengan rangkaian kenderaan telah menunjukkan hasil yang memberangsangkan untuk menjamin keselamatan rangkaian kenderaan. Walau bagaimanapun, rangkaian kenderaan berasaskan rantaian blok konvensional boleh melalui kemerosotan dalam prestasi dan skala pertumbuhan yang terhad. Salah satu cara untuk menambahbaikan prestasi dan skala pertumbuhan rangkaian kenderaan berasaskan rantaian blok adalah dengan melaksanakan pemprosesan data berkaitan rantaian blok konvensional diluar rantaian blok. Tesis ini bertujuan untuk menunjukkan prestasi dan skala pertumbuhan dalam rangkaian kenderaan berasaskan rantaian blok boleh ditambahbaikan dengan menggabungkan rangkaian *off-chain* dengan rangkaian kenderaan. Simulasi rangkaian kenderaan telah dijalankan dalam situasi yang berbeza untuk mengukur prestasi dan skala pertumbuhan rangkaian. Prestasi rantaian blok diukur mengikut keadaan daya pengeluaran data, perubahan kependaman pemprosesan dan pertumbuhan saiz data. Keputusan daripada simulasi untuk rangkaian berasaskan rantaian blok konvensional dan rangkaian dibantu *off-chain* telah dibandingkan. Hasil simulasi menunjukkan bahawa rangkaian kenderaan berasaskan rantaian blok yang dibantu *off-chain* dapat mengekalkan prestasi dan mampu menambah skala pertumbuhan berbanding rangkaian berasaskan rantaian blok konvensional. Keputusan simulasi dengan 80 nod rantaian blok telah menunjukkan rantaian blok yang dibantu *off-chain* telah menambahbaikan daya pengeluaran sebanyak 17 kali pengeluaran data manakala menurunkan kependaman pemprosesan sebanyak 99% dan juga menurunkan pertumbuhan saiz data sebanyak 78% apabila dibandingkan dengan rantaian blok konvensional.

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LIST OF ABBREVIATIONS

IoT	-	Internet of Things
VANET	-	Vehicular Ad-hoc Network
DoS	-	Denial of Service
LiDAR		Light Detection and Ranging
RSU	-	Road Side Unit
GPS	-	Global Positioning System
SAE	-	Society of Automotive Engineers
OBU	-	On Board Unit
V2V	-	Vehicle to Vehicle
V2I	-	Vehicle to Infrastructure
V2C	-	Vehicle to Cloud
BARS	-	Blockchain-based Anonymous Reputation System
VECON	-	Vehicular Edge Computing and Networks
BTQT	-	Binary Tree embedded Quad Tree
NBI	-	Northbound Interface
SDVN	-	Software-Defined Vehicular Networking
MAST	-	Merkelized Abstract Syntax Tree
PoW	-	Proof of Work
PoS	-	Proof of Stake
API	-	Application Programming Interface
MB	-	Megabyte

LIST OF SYMBOLS

t	-	Time
L	-	Latency
tx	-	Number of transactions
T	-	Throughput

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CHAPTER 1

INTRODUCTION

1.1 Background

With the mass adoption and acceptance of the Internet, more and more devices, not just computers, are connected. These "smart" devices, such as domestic appliances, security systems and agricultural machineries are connected to a network or the Internet to enable certain remote transactions such as control or automation to take place. These connected devices constitute a class on the Internet, called Internet of Things (IoT), and due to the nature of operation of these connected devices they place new requirements on the network.

Because the devices usually operate remotely, with no manual supervision, communication must be absolutely secure to ensure integrity of operation. In addition, many of these devices operate in real-time; thus, they require a very fast communication network. These two critical requirements, namely high security and fast network, pose significant challenges.

This study will look at one approach in meeting the challenges for the specific case of the communication network for autonomous vehicles. Fully autonomous vehicles can, on its own, successfully navigate through its environment, avoiding obstacles and reaching its destination without any human guidance. These vehicles rely on a variety of sensors and technologies, such as Light Detection and Ranging (LiDAR), radar, location sensors, odometer and computer vision to map their surroundings in real-time. A control system interprets the information gathered to identify optimum navigation paths while avoiding or navigating around obstacles and other vehicles.

In a scenario with many autonomous vehicles operating within the vicinity, it is necessary for the vehicles to be able to communicate with each other, exchanging vital information such as location, direction and speed in real-time to avoid collision between autonomous vehicles or with other obstacles. Communication among vehicles is carried out over a specialised vehicular network, which is the Vehicular Ad-hoc Network (VANET). Besides the requirement for real-time communication, it is also important that data integrity is maintained at all times to ensure the programmed autonomy of the vehicles are not compromised. Thus, a vehicular network must be fast and secure against threats that can disrupt data exchange within the network such as Denial of Service (DoS) attack, message tampering, wormholes attack and spread of false information (Engoulou et al., 2014).

One of the methods to ensure security against threats is to implement blockchain technology for the vehicular network. Blockchain technology provides a private and decentralized network where a transaction can only be completed upon agreement by a majority of nodes. A single entity, such as a hacker, cannot therefore easily disrupt information exchange. Despite its benefits to vehicular networks, most popular blockchain suffer from scalability issues. Most blockchain cannot handle high speed transactions and the speed of transactions degrades rapidly with an increasing number of users. Several solutions have been proposed to speed up and improve the scalability of the blockchain that can be classified into on-chain, off-chain, side-chain and inter-chain solutions (Kim et al., 2018).

In this work we will use a payment channel based off-chain solution to improve the speed and scalability of the blockchain network. The off-chain solution speeds up transaction times and improves the scalability by processing all transactions separately outside of the main blockchain by creating a temporary off-chain channel. Consequently, this off-chain solution reduces the number of transactions in the main blockchain, thus improving the data throughput of the entire network.

1.2 Problem Statement

In order to ensure the preservation of the programmed autonomy of autonomous vehicles, it is of vital importance that the vehicular network is absolutely secure and capable of handling large data exchanges in real-time. The development and implementation of vehicular networks comes with many challenges and issues. Some of these challenges include security, privacy, volatility, node mobility and scalability (Engoulou et al., 2014). Blockchain technology has been shown to provide a solution to the security vulnerabilities faced by vehicular networks (Kim et al., 2018). While a blockchain technology when implemented into a vehicular network can ensure the security and privacy of the network, the speed of transaction is usually not fast enough for use in managing a large number of autonomous vehicles. Data over the vehicular network changes dynamically and rapidly, with vehicles randomly entering and exiting the network. The scalability issue, which is the ability of the network to scale and maintain performance when the network grows in size from the increasing number of vehicles and Road Side Unit (RSU), is essential in the viability of a vehicular network. A scalable blockchain-based vehicular network must be able to handle unexpected large fluctuations in data exchange without degrading the performance of the network. Methods to speed up and improve the scalability of the network that can be easily integrated to existing open-source blockchain-based vehicular networks are preferable compared to those that require outright development of a completely new blockchain-based vehicular network.

1.3 Research Objectives

The main purpose of this research is to develop a scalable, blockchain-based vehicular network for autonomous vehicles. This research is conducted with the following objectives:

1) To investigate the scalability issue of blockchain-based vehicular networks.

2) To develop a new scalable blockchain-based vehicular network using off-chain solution with improved throughput, latency and data size compared to conventional blockchain networks.

1.4 Scope of the Study

This research focuses on the scalability issues of using blockchain-based technology in vehicular networks. Scalability of a network is defined as the ability of the network to maintain a specified performance level even with network growth, that is, when the number of roadside units (RSU) and vehicles in the network increases. We propose a blockchain-based vehicular network that uses off-chain scaling solutions to improve network scalability. In this study both the main block chain and the off-chain networks are chosen from among the most used, open-source technologies available. Because these are open-sourced and most used, stability of technology is assured and documentations are easily available. The proposed vehicular network will be simulated on the Ethereum Blockchain with the Raiden off-chain network implemented on top of the Ethereum Blockchain as the off-chain solution modification. In the simulation, each Road Side Unit (RSU) represents a node of the network and autonomous vehicles are members of the network. Simulations of transactions between members in the blockchain network are measured to evaluate the performance in terms of growth in data size, speed of data throughput and data exchange latency. The performance and scalability of the proposed Raiden off-chain network incorporated onto the Ethereum Blockchain network and the purely Ethereum Blockchain-based network are compared by simulating the growth in data size (storage requirements), speed of data throughput and data exchange latency. The simulation is conducted in a closed network to prevent any outside interference or interruptions from affecting the performance of the network. The simulation will focus solely on communications between RSU and vehicles in a vehicular network. The contribution of communication between vehicle and vehicle is ignored. This is justified in the present study because the simulation focuses on comparing the performance of the blockchain-based vehicular network in a controlled environment.

1.5 Significance of the Study

It is accepted that wireless-based networks are highly insecure and can be easily compromised. However, many devices are connected via wireless because of the flexibility afforded. The blockchain technology can provide the needed security to a wireless network but at the price of performance degradation with network growth. The aim of this study is to demonstrate that it is possible to maintain the security of the blockchain-based wireless network without performance degradation by incorporating an off-chain network onto the blockchain. The results from this study will be useful for those developing very secure wireless-based, high speed, dynamically growing networks such as for autonomous vehicles and Internet of Things.

1.6 Thesis Outline

This thesis reports the research work that has been done with the objectives mentioned. Chapter 1 introduces this work and outlines its focus. It begins with the background of research work, defines the problem statements and lays out the objectives. Chapter 2 presents an overview on vehicular network, blockchain technology, the scalability issue of blockchain based vehicular network and the proposed solution to the scalability issue. Chapter 3 describes the research methodology, covering the overall design, construction and implementation of the simulation experiments. Chapter 4 presents the results and discussion of the simulation experiments. Chapter 5 provides the discussions and conclusions of the research as well as discussions on the directions for future work.

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