5G Software Defined Vehicular Networks

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Abstract

With the emergence of 5G mobile communication systems and software defined networks, not only could the performance of vehicular networks be improved, but also new applications of vehicular networks are required by future vehicles (e.g., pilotless vehicles). To meet requirements of intelligent transportation systems, a new vehicular network architecture integrated with 5G mobile communication technologies and software defined networking is proposed in this article. Moreover, fog cells have been proposed to flexibly cover vehicles and avoid frequent handover between vehicles and roadside units. Based on the proposed 5G software defined vehicular networks, the transmission delay and throughput are analyzed and compared. Simulation results indicate that there is a minimum transmission delay of 5G software defined vehicular networks considering different vehicle densities. Moreover, the throughput of fog cells in 5G software defined vehicular networks is better than the throughput of traditional transportation management systems.

Introduction

Nowadays the fifth generation (5G) mobile communication systems are developed by industrial and academic researchers. With the development of millimeter-wave and massive multiple-input multiple-output (MIMO) technologies, the spectrum efficiency and energy efficiency are obviously improved for 5G wireless communications [1, 2]. With the emergence of pilotless vehicles, some rigorous requirements (e.g., the transmission delay needs to be less than 1 ms) are needed for intelligent transportation systems (ITSs) and vehicular networks [3]. To meet these rigorous requirements, 5G mobile communication technologies, cloud computing, and software defined networking (SDN) are expected to be integrated into future vehicular networks. Therefore, it is necessary to design a new network architecture for 5G vehicular networks.

Some basic issues have been investigated for vehicular networks [4–7]. Considering the drawbacks of IEEE 802.11p networks, such as poor scalability, low capacity, and intermittent connectivity, the Long Term Evolution (LTE) mobile communication technologies were proposed to support vehicular applications [4]. Moreover, the open issues of LTE vehicular networks were discussed to promote potential solutions for future vehicular networks. In [5] the basic characteristics of vehicular networks were introduced. An overview of applications and associated requirements was presented and challenges were discussed. Also, the past major ITS programs and projects in United States, Japan, and Europe were analyzed and compared. An analytical model supporting multihop relay of infrastructure-based vehicular networks was proposed to analyze uplink and downlink connectivity probabilities [6]. Simulation and experiment results revealed that there is a trade-off between the proposed performance metrics and system parameters, such as base station (BS) and vehicle densities, radio coverage, and the maximum number of hops in a path. When LTE communication technologies have been integrated into vehicular networks, the interference has cut down the performance of LTE vehicular networks [7]. To overcome this issue, the millimeter-wave transmission technology was proposed to connect users inside vehicles. On the other hand, SDN was proposed as an effective network technology, capable of supporting the dynamic nature of vehicular network functions and intelligent applications while lowering operation costs through simplified hardware, software, and management [8]. Consequently, some initial studies have been carried out to integrate SDN technology into vehicular networks [9, 10]. Utilizing SDN, an adaptive edge computing solution based on regressive admission control and fuzzy weighted queueing was proposed to monitor and react to network quality of service (QoS) changes within vehicular network scenarios [9]. Based on SDN, a cooperative data scheduling algorithm integrated at roadside units (RSUs) was developed to enhance the data dissemination performance by exploiting the synergy between infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications [10]. However, the SDN technology in [10] is limited in RSUs. When a lot of vehicles are connected to an RSU, the frequent handover problem reduces the performance of SDN [11].

To meet the high performance requirements, such as low transmission delay and high throughput, a new architecture of 5G software defined vehicular networking is proposed in this article. The main contributions of the proposed 5G software defined vehicular network are as follows:

1. Based on the basic functions and requirements of vehicular networks, an architecture of a 5G software defined vehicular network integrated with SDN, cloud computing, and fog computing technologies is proposed to form three logistical planes in network architecture (i.e., the application plane, the control plane, and the data plane). Based on three logistical planes of network architecture, the control and data functions of 5G soft-

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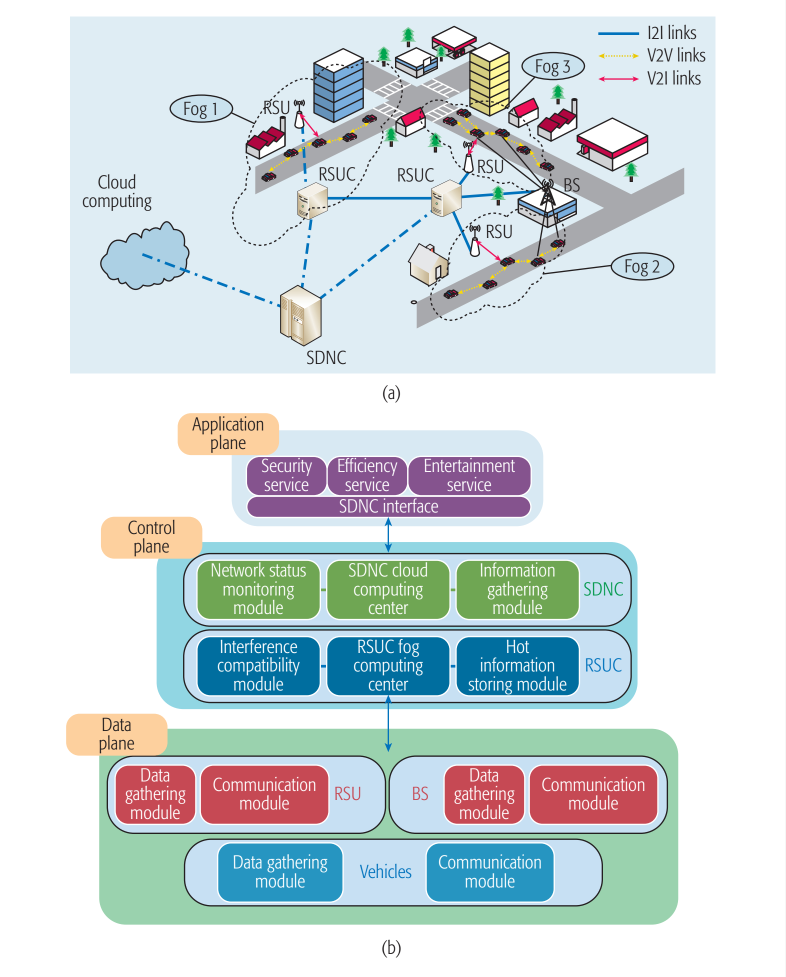

Figure 1. a) Topology structure of 5G software defined vehicular networks; b) logical structure of 5G software defined vehicular networks.

ware defined vehicular networks are separated to improve the flexibility and scalability of vehicular networks.

2. The fog cell structure is proposed and performed at the edge of 5G software defined vehicular networks. Based on the fog cell structure, frequent handover between the RSU and vehicles is avoided, and an adaptive bandwidth allocation scheme is adopted for vehicles in fog cells.

3. The transmission delay and throughput of 5G software defined vehicular networks are analyzed. Simulation results indicate that there is a minimum transmission delay of 5G software defined vehicular networks considering different vehicle densities. Moreover, the throughput of fog cells in 5G software defined vehicular networks is better than the throughput of traditional transportation management systems.

In this article we propose a new architecture of 5G software defined vehicular networks adapting the cloud computing and fog computing technologies. Moreover, the control plane and data plane are separated by the SDN technology in 5G software defined vehicular networks. To avoid frequent handover between the RSU and vehicles, the fog cell is structured, and multihop relay is adopted for vehicular communications in a fog cell. Furthermore, the transmission delay and the throughput of fog cells are simulated for 5G software defined vehicular networks. Finally, the challenges of vehicular networks are discussed, and conclusions are drawn.

5G Software Defined Vehicular Networks

Topology Structure of 5G Software Defined Vehicular Networks

The cloud computing and fog computing technologies are emerging for applications of 5G vehicular networks. Moreover, SDN is becoming a flexible approach to connect wireless access networks and cloud computing centers for 5G vehicular networks. Based on cloud computing and fog computing technologies, a 5G software defined vehicular network is proposed in this article. The topology structure of 5G software defined vehicular networks is illustrated in Fig. 1a. 5G software defined vehicular networks are composed of cloud computing centers, SDN controllers (SDNCs), RSU centers (RSUCs), RSUs, BSs, fog computing clusters, vehicles, and users. Moreover, 5G software defined vehicular networks include infrastructure-to-infrastructure (I2I) links, vehicle-to-infrastructure (V2I) links, and vehicle-to-vehicle (V2V) links. Based on 5G software defined vehicular networks, the information is shared among vehicles and users under the control of the fog computing clusters. To support prompt responses from vehicles and users, fog computing clusters are configured at the edge of 5G software defined vehicular networks. The network structure of fog computing clusters is a distributed network. Most data in the edge of 5G software defined vehicular networks is saved and processed by fog computing clusters, which include the RSUC, RSUs, BSs, vehicles, and users. The SDNCs collect and forward the state information of fog computing clusters into the cloud computing centers. Moreover, the control information is sent to fog computing clusters by SDNCs. The core of 5G software defined vehicular networks, composed of SDNCs and cloud computing centers, is adopted by a centered network structure that focuses on data forwarding and resource allocation. The detailed logical structure of 5G software defined vehicular networks is described in Fig. 1b.

Logical Structure of 5G Software Defined Vehicular Networks

In Fig. 1b, the logical structure of 5G software defined vehicular networks is composed of the data plane, the control plane, and the application plane.

The data plane includes vehicles, BSs, and RSUs. Functions of the data plane are focused on data collection, quantization, and then forwarding data into the control plane [12]. In detail, the vehicle can be configured with the following function modules.

Information collection module of vehicles: The information collection module is made up of different types of sensors in a vehicle. Utilizing sensors in the vehicle, the information on the vehicle (e.g., the speed, direction, and type of vehicle) and the environment (e.g., the number of adjacent vehicles, the users in the vehicle, and the road under the vehicle) collected for 5G software defined vehicular networks.

Position information module of vehicles: The position information of vehicles includes independent position information and dependent position information. In general, the independent position information of vehicles is obtained by the GPS, which provides the detailed location of vehicles in the longitude and latitude of the Earth. The dependent position information of vehicles is obtained by sensors of vehicles, which provide the distance between adjacent vehicles. Compared to the independent position information of vehicles, the dependent position information of vehicles can provide high location precision for 5G software defined vehicular networks.

Communications module of vehicles: The communication module includes V2I and V2V communication modules. The V2I communication module provides wireless communication between vehicles and the infrastructure along the road. The V2V communication module provides wireless communication among adjacent vehicles.

BSs can provide wireless communication for vehicles and RSUCs. In 5G software defined vehicular networks, BSs transmit wireless signals by traditional LTE frequency and provide broad coverage for vehicles. In general, vehicles first access with RSUs but then access with BSs when RSUs cannot provide enough resource for wireless access in 5G software defined vehicular networks.

In 5G software defined vehicular networks, RSUs can be configured with the following function modules.

Information collection module of RSUs: Composed of different sensors (e.g., cameras and speed measurement sensors). The information collection module of RSUs can provide the speed of vehicles, traffic status, road status, and so on.

Communication module of RSUs: Including two types of links: one is the link between RSUs and the RSUC, and the other is the link between RSUs and vehicles. The links between RSUs and the RSUC are performed by fronthaul links in 5G software defined vehicular networks.

The control plane includes RSUCs and SDNC. The RSUC is the control center of a fog cell. Considering the quick mobility of vehicles and the massive wireless traffic between the RSU and vehicles, frequent handover should be avoided for wireless communications between the RSU and vehicles. To solve this issue, the fog cell is proposed for 5G software defined vehicular networks. A fog cell is composed of vehicles and an RSU. Millimeter-wave links are adopted for wireless relay communications among vehicles, and the total bandwidth of millimeter-wave is shared by all vehicles in a fog cell. Since all vehicles move in an orderly fashion on an urban road, the total vehicle group can be assumed to be an overall communication unit within millimeter-wave links in a fog cell. When one of the vehicles in a vehicle group connects with the RSU, the whole vehicle group in the fog cell could be connected with the RSU. In this case, frequent handover can be avoided for vehicles and the RSU in a fog cell. Hence, the RSUC is configured to allocate resources and improve the transmission efficiency in a fog cell. The SDNC is the total control center for 5G software defined vehicular networks and allocates resources among fog cells. Therefore, the control plane takes charge of drawing the global information map based on the data information forwarded from the data plane and then generating the control information based on rules and strategies from the application plane. To support the above functions of the control plane, RSUCs and the SDNC are configured with the following function modules:

Information collection modules of RSUC and SDNC: Drawing the global information map based on the data information from the data plane.

Networking status module: Monitoring the link status of 5G software defined vehicular networks [13].

Computing module: Deriving the control results based on the global information map and the link status of 5G software defined vehicular networks. In general, computing modules are deployed at the cloud computing center and fog computing centers [14].

Hot caching module: saving the popular data context at RSUCs to decrease the transmission delay for vehicle applications.

The application plane directly faces different application requirements from users and vehicles. Based on application requirements from users and vehicles, rules and strategies of 5G software defined vehicular networks are generated by the application plane and forwarded to the control plane. In general, the application plane includes the security service module, the service efficiency module, and the entertainment service module.

Based on the logical structure of 5G software defined vehicular networks in Fig. 1b, the data plane takes charge of collecting data, the control plane takes charge of deriving control instructions, and the application plane takes charge of generating rules and strategies.

The SDNC is the total control center for 5G software defined vehicular networks and allocates resources among fog cells. Therefore, the control plane takes charge of drawing the global information map based on the data information forwarded from the data plane and then generating the control information based on rules and strategies from the application plane.

Transmission Delay and Throughput of 5G Software Defined Vehicular Networks

Without loss of generality, the transmission delay and throughput analysis are investigated in a fog cell of 5G software defined vehicular networks. A typical fog cell is composed of an RSU and a number of vehicles in Fig. 2. To avoid frequent handover between the RSU and vehicles in the fog cell, a vehicle (i.e., the gateway vehicle) is selected to connect with the RSU, and then other vehicles are connected with the gateway vehicle by a multihop relay method. When a gateway vehicle is located in the coverage region of the RSU, the gateway vehicle directly communicates with the RSU. When other vehicles are located in the fog cell, even if these vehicles are not directly covered by the RSU in the fog cell, they will build a multihop relay route to connect with the gateway vehicle, and then the gateway vehicle will forward those requests/data to the RSU in the fog cell. When the gateway vehicle departs from the fog cell, a vehicle in the fog cell is handed off to serve as the gateway vehicle [15]. In this way, all vehicles in the fog cell can maintain wireless communications with the RSU while moving along the road. Since the fog cell is the basic composition of the proposed 5G software defined vehicular

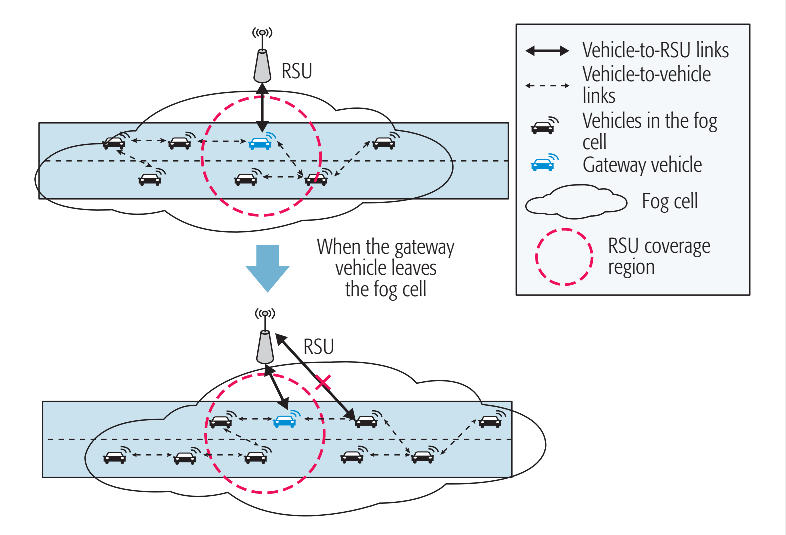

Figure 2. Vehicle communications in a typical fog cell.

networks, the transmission delay and throughput of the vehicle in a fog cell is investigated in the following sections.

Transmission Delay of 5G Software Defined Vehicular Networks

The transmission delay is one of the core metrics for 5G software defined vehicular networks. In this article, the transmission delay of the vehicle in a fog cell is analyzed for 5G software defined vehicular networks.

In Fig. 3, an RSU is located at a fog cell to serve all vehicles driving on a road of length of L. Without loss of generality, a vehicle inside a red dashed circle (i.e., VE_a) is selected to analyze the transmission delay in a fog cell of 5G software defined vehicular networks. The distance between the RSU and the vehicle VE_a is denoted as L_a. Based on the vehicle communication scheme in Fig. 2, the data packet generated from VE_a is transmitted to the RSU by a multihop vehicle relay method.

Assume that there are k hops between the RSU and the vehicle VE_a. For a data packet, the transmission delay in a fog cell of 5G software defined vehicular networks is expressed as $T = kT_{hop} + (k - 1)T_{retran}$, where T_{hop} is the average transmission delay in one hop of vehicle communications, and T_{retran} is the retransmission delay, which is the relay processing time at the relay vehicles. In a hop of vehicle communications, the wireless transmission is time slotted, and one data packet is transmitted in each time slot t_{slot}. Assume that the success transmission probability of vehicle relay communications is P_{hop}. As a consequence, the average transmission delay in one hop of vehicle communications is calculated by $T_{hop} = t_{slot}/P_{hop}$.

In this article millimeter-wave transmission is adopted for vehicle relay communications. Without loss of generality, the 60 GHz frequency spectrum is assumed to be used for vehicle relay communications. Since the wireless signals of vehicle relay communications are usually transmitted in line of sight (LOS) scenarios, the interference is ignored for the vehicle relay communications in this article. When the signal-to-noise ratio (SNR) threshold at the receiver is assumed to be θ (i.e., the data packet can be successfully received only if the SNR of receive signal is larger than the threshold θ), the success transmission probability P_{hop} is calculated by $P_{hop} = P(PL \leq P_{tx}[\text{dB}] - \theta[\text{dB}] - N_0 W_{mmWave}[\text{dB}])$, where $PL[\text{dB}](\delta) = 69.6 + 20.9\log(\delta) + \xi$, $\xi \sim (0, \sigma^2)$ is the path loss fading over millimeter-wave wireless channels, δ is the wireless transmission distance between the transmitter and receiver, P_{tx} is the transmission power of vehicles, N_0 is the noise power spectrum density, and W_{mmWave} is the bandwidth of millimeter-wave links.

To analyze the transmission delay in a fog cell of 5G software defined vehicular networks, the default parameters are configured as follows: the noise power spectrum density is $N_0 = -174$ dBm/Hz, the bandwidth of millimeter-wave links is $W_{mmWave} = 2$ GHz, the retransmission delay is $T_{retran} = 5$ μs, and one time slot is $t_{slot} = 5$ μs. Moreover, the transmission distance of millimeter-wave communications is limited to 50 m.

Figure 4 illustrates the transmission delay in a fog cell of 5G software defined vehicular networks with respect to the vehicle density considering different transmission distances L_a. When the vehicle density is fixed, the transmission delay increases with the increase of the transmission distances L_a. When the transmission distance L_a is fixed, the transmission delay first decreases with the increase of the vehicle density. However, numerical results indicate that there are turning points for vehicle densities (the turning points are 0.08, 0.09, and 0.105 for L_a = 300, 400, and 500, respectively). When the vehicle density is larger than or equal to the turning point, the transmission delay increases with the increase of vehicle density.

The numerical results in Fig. 4 show that there is a minimum value for the transmission delay in the fog cell of 5G software defined vehicular networks. The minimum transmission delay is 0.32, 0.46, and 0.63, corresponding to the transmission distance of 300, 400, and 500 m, respectively. When the vehicle density is low, the distance among adjacent vehicles is far, and thus the success transmission probability of millimeter-wave links is low. In this case, increasing vehicle density will decrease the distance among adjacent

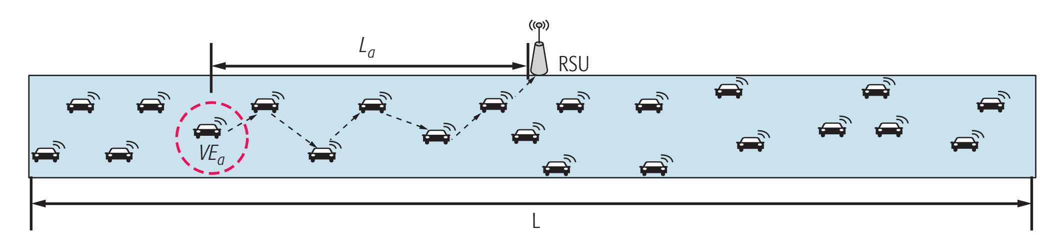

Figure 3. Transmission delay in a fog cell of 5G software defined vehicular networks..

vehicles and then increase the success transmission probability of millimeter-wave links. Hence, the transmission delay first decreases with the increase of vehicle density. When the vehicle density is larger than a threshold, the distance among adjacent vehicles is closed, and the successful transmission probability of millimeter-wave links approaches a stationary value. In this case, the transmission delay is mainly dependent on the retransmission delay in each hop of vehicle communication. In this case, increasing vehicle density will increase the number of relay hops, and then the total retransmission delay is increased. Therefore, the transmission delay increases with the increase of vehicle density.

Throughput of 5G Software Defined Vehicular Networks

In a traditional bandwidth allocation scheme, all bandwidths are averagely allocated to every vehicle in a fog cell. However, every vehicle needs different bandwidth in practical applications. Based on the control function of 5G software defined vehicular networks, which is realized at the RSUC, an adaptive bandwidth allocation scheme is proposed to optimize the throughput of fog cells in this article.

Without loss of generality, the available bandwidth in a fog cell is assumed to be B, and the maximum throughput of this fog cell is C. The average bandwidth requirement of one vehicle is B_{ave}, and the throughput of this vehicle is configured as C_{ave}. The total number of vehicles in a fog cell is assumed to be $N(N > 0)$, and the SNR at each vehicle is configured as the same. The interference is ignored in this article. Hence, in this article the throughput of a vehicle is proportional to the communication bandwidth of the vehicle. When there are N vehicles in the fog cell, the bandwidth requirement of vehicles is assumed to be governed by a uniform distribution, that is, $B_i \sim U(0,2B_{ave})$, $1 \le i \le N$. Considering the real bandwidth requirement from N vehicles, the bandwidth requirement $B_i \sim U(0,2B_{ave})$, $1 \le i \le N$ from n, $n \le B/B_{ave}$ vehicles is assumed to be less than the average bandwidth requirement B_{ave} in the fog cell. The throughput of a vehicle is C_j when the bandwidth of a vehicle is allocated by B_j. For the traditional average bandwidth allocation scheme, the maximum available bandwidth for a vehicle is B_{ave} and then the total bandwidth allocated for all vehicles in fog cell is

$$B_{tra} = \sum_{j=1}^{n} B_j + (N-n) \times B_{ave}.$$

Consequently, the throughput of the fog cell is

$$C_{tra} = \sum_{j=1}^{n} C_j + (N-n) \times C_{ave}.$$

Based on the proposed adaptive bandwidth allocation scheme, the un-occupied bandwidths of n vehicles can be reused for the other $N - n$ vehicles in the fog cell. The total requirement bandwidth of the other $N - n$ vehicles is

$$\sum_{j=n+1}^{N} B_j$$

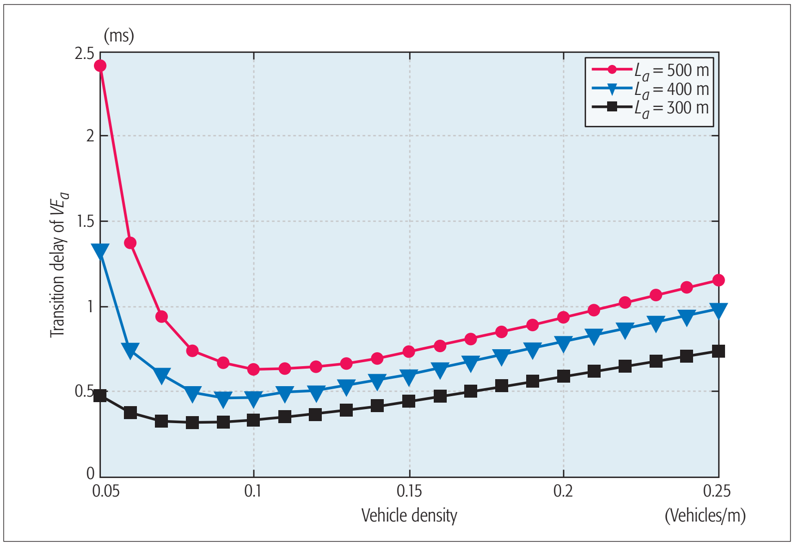

Figure 4. Transmission delay with respect to the vehicle density considering different transmission distances.

and the total available bandwidth of the other $N - n$ vehicles is

$$B - \sum_{j=1}^{n} B_j.$$

Therefore, the throughput of a fog cell adopting the adaptive bandwidth allocation scheme is

$$Min\left\{ \sum_{j=1}^{N} B_j \quad , \quad B \right\}.$$

When the parameters are configured as C = 1000 Mb/s and C_{ave} = 33 Mb/s, the throughput of a fog cell is compared to two bandwidth allocation schemes in Fig. 5. It is shown that the throughput of a fog cell with the adaptive bandwidth allocation scheme is always larger than the throughput of a fog cell with the average bandwidth allocation scheme. The reason is that the unoccupied bandwidths in the average bandwidth allocation scheme could be utilized in the adaptive bandwidth allocation scheme. When the bandwidth allocation scheme is given, the throughput of a fog cell first increases with the increase of the number of vehicles in a fog cell. When the number of vehicles is larger than 30, the throughput of a fog cell remains stationary. The reason is that all available bandwidth in a fog cell has already been allocated for vehicles. In this case, there are not any bandwidths to be allocated for additional vehicles even if the number of vehicles is larger than a specified threshold. Consequently, the throughput of a fog cell has to remain stationary when the number of vehicles is larger than a specified threshold.

Challenges of 5G Vehicular Networks

With the development of 5G mobile communication systems, high-speed wireless communications are satisfied by millimeter-wave and massive MIMO technologies. Furthermore, multimedia wireless communications are expected to be realized for 5G vehicular networks. Based on 5G high-speed wireless communications, pilot-

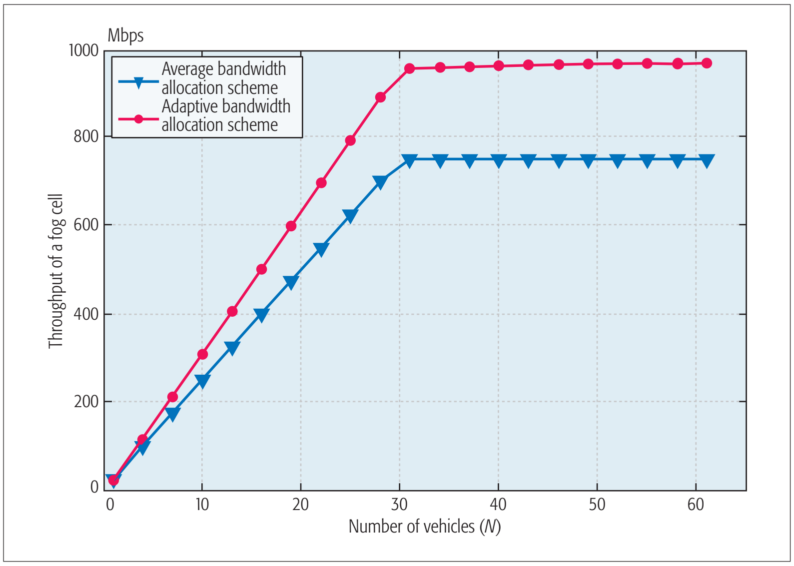

Figure 5. Throughput with respect to the number of vehicles in a fog cell.

less vehicles are emerging to change our future life. It is well known that future pilotless vehicles need to be supported by highly reliable and effective vehicular networks. However, some potential challenges and issues still need to be further investigated for 5G vehicular networks.

The low delay issues. When pilotless vehicles are deployed for city transport systems, not only traffic information but also road information should be transmitted to pilotless vehicles by vehicular networks. In general, safety message transmissions have a very low delay constraint, such as less than 1 ms. When there are many relay vehicles for a multihop relay vehicular network, the transmission delay of the warning message will be larger than a given threshold. For some extreme cases, the delay issues could cause fatal accidents. How to optimize route solution is still a key technology for 5G vehicular networks.

The frequent handover issues. In this article the fog cell is proposed to solve frequent handover between the RSU and vehicles. However, the handover among vehicles is still an issue for the multihop relay link in a fog cell. When a lot of vehicles are handed off between adjacent fog cells, the handover will be simultaneously generated for fog cells and the multihop relay links. In this case, the complexity of handover is obviously increased for 5G vehicular networks. Moreover, the propagation delay of the warning message needs to be minimized for vehicle handover in 5G vehicular networks.

The high service efficiency challenges. For future pilotless vehicles, vehicles are not only the transport tools but also entertainment centers for users. Different multimedia services need to be provided by 5G vehicular networks. Hence, massive wireless traffic is expected to increase for 5G vehicular networks. It is a great challenge to improve the service efficiency for 5G vehicular networks.

The architecture of 5G vehicular networks. To reduce the transmission delay of warning messages, a distributed network architecture is adopted for the fog cell of 5G vehicular networks. To support ITSs, the centralized network architecture is adopted for the core network of 5G vehicular networks. In this case, SDN is proposed to flexibly connect different types of network architectures. However, the scalability and compatibility of 5G vehicular networks are great challenges, especially because there are two types of network architectures in 5G vehicular networks.

Conclusions

With the development of pilotless vehicles, vehicular networks have to face rigorous performance requirements in future ITSs. 5G mobile communications, cloud computing, and SDN technologies provide potential solutions for future vehicular networks. In this article we propose a new architecture of 5G software defined vehicular networks integrating these technologies. Moreover, fog cells are established at the edge of 5G software defined vehicular networks, which utilize multihop relay networks to reduce the frequent handover between the RSU and vehicles. Simulation results indicate that there is a minimum transmission delay of 5G software defined vehicular networks considering different vehicle densities. Moreover, the throughput of fog cells in 5G software defined vehicular networks is better than the throughput of traditional transportation management systems. When the proposed challenges of 5G vehicular networks have been solved, 5G software defined vehicular networks could provide enough flexibility and compatibility to satisfy future pilotless vehicles and ITSs.

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