VESHARE: A D2D INFRASTRUCTURE FOR REAL-TIME SOCIAL-ENABLED VEHICLE NETWORKS

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ABSTRACT

Vehicular social networks require real-time communication and are highly dynamic due to vehicle movement. In this article, we present a novel architecture, called *VeShare*, to support highly dynamic and time-sensitive social behaviors in vehicle networks. VeShare clearly separates a vehicle network into control and data planes. The control plane is managed by the cellular infrastructure. It manages the social networks over time and makes various decisions necessary for data transfer. The data plane simply forwards data, following the decision from the control plane. The clear separation of the control and data planes allows efficient social group management and data transfer. We highlight the benefits of this framework using a case study and outline a number of research challenges.

INTRODUCTION

Next generation cars are expected to be equipped with networking capabilities that enable them to cooperate with each other [1, 2]. The cooperation can lead to many benefits such as improved road safety, energy efficiency, and social activities, all contributing to make cities smarter and greener. As such, vehicle networking has become an active research area in both academia and industry in recent years [2–4].

While existing studies [2–4] have explored the mobile and ad hoc features of vehicle networking, an important property that distinguishes vehicle networking from other mobile ad hoc networks is its strong social aspect. A primary goal of vehicle networking is to serve the people who are driving or riding in the vehicles. People communicate while in vehicles often because they share common interests (e.g., information about accidents and congestion, tourist information or entertainment) on the road. Vehicles form dynamic social networks to facilitate the communication of such information. The information to be shared is, however, only of interest when people are close to each other in both time and space. Therefore, the social ties among vehicles occur and are only valid within temporal and spatial proximity.

In this article, we refer to vehicle networks that are organized by dynamic social events as social-enabled vehicle networks (SVNs).

We aim to establish a new device-to-device (D2D) framework to:

1. Achieve social event discovery among vehicles
2. Organize social-recognized vehicles
3. Enable effective and efficient communications among vehicles

This is challenging due to the following reasons.

- First, a wide range of social events need to be supported by vehicle networking. These social events have diverse quality of service (QoS) requirements. Some events (e.g., road safety) have strict real-time and reliability requirements that must be satisfied to avoid catastrophic consequences, while the requirements for some other events (e.g., entertainment) are much more relaxed.
- Second, because vehicles can move at high speed, the social networks formed by vehicles can be highly dynamic. Managing highly dynamic social networks over time and space is a challenging task.
- Finally, a vehicular social network may be of large scale, particularly in congested urban areas. Signaling among vehicles, if not managed carefully, can lead to large overhead. Similarly, data exchange among vehicles, if not managed carefully, may lead to severe congestion or interference (to both vehicle networks and other networks).

To address the above challenges, we propose a novel framework, called *VeShare*, that clearly separates vehicle networks into control and data planes. The control plane is managed by the cellular infrastructure.

Specifically, it manages the social network over time and determines efficient resource allocation and communication channels for vehicles. The data plane simply forwards data in the vehicle network following the decisions of the control plane. The clear separation of the control and data planes as well as the central management by the cellular infrastructure in the control plane allows SVNs and radio resources to be managed efficiently. We highlight the benefits of this framework using a case study, and outline a number of research challenges to be addressed to fully realize the potential of this framework.

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The rest of the article is organized as follows. We first present the design of VeShare and a case study to highlight the benefits of VeShare. We then describe the main research challenges in VeShare. We briefly review related work. Lastly, we conclude the article and present future work.

VESHARE FRAMEWORK

In this section, we first briefly describe SVN applications and the characteristics of social features in SVNs. We then describe the design of VeShare. At the end, we highlight the benefits of VeShare using a case study.

SVN APPLICATIONS AND SOCIAL FEATURES

According to the type of common interests shared among vehicles, we can roughly divide SVNs into three categories:

- *Road safety*. SVNs for road safety are formed by vehicles in situ and based on temporary social events. The applications can improve vehicle safety, such as accident avoidance and emergency alarm.
- *Road efficiency*. SVNs for road efficiency are formed because of common interests to reduce the energy consumption and exhaust emissions. For example, applications can provide effective speed and distance space between vehicles to keep the platoon-based topology [2]. They can also provide real-time road congestion information and suggestions on optimal routes.
- *Road infotainment*. SVNs for infotainment services are formed due to entertainment needs on the road, including music for driver comfort, movies for passengers, and so on.

Different from the stable relationship between human beings in online social networks (e.g., Facebook), the social behavior in SVNs has the following inherent features:

- Typically, SVNs are temporary and highly dynamic. The dynamics come from not only the instantaneous membership, but also the geographical locations and continuously changing environment. As an example, we analyzed 24 hours of GPS data collected from a car rental company for 2248 vehicles running in Beijing. Suppose that two cars encounter each other when their distance is within *d*. Figure 1 plots the average encounter time duration for any two cars when varying *d* from 10 to 500 m. We see that although the encounter duration increases with *d*, the average encounter duration is only about 20 to 25 s when *d* is from 50 to 500 m, confirming the highly dynamic nature of SVNs.
- The common interests and information shared among members are often used for event-trigged scenarios (e.g., avoiding accidents and finding the best route to a destination).
- The message exchanged on the road can be very time sensitive. For example, in the scenario where vehicles want to change lanes, in order for the vehicles to react to sudden events, messages must be transmitted among the involved vehicles in time.

How to design a reliable and real-time vehicle-to-vehicle (V2V) communication infrastructure using wireless channels to support highly dynamic and time-sensitive SVNs is a very challenging problem. VeShare is designed to resolve the above challenge.

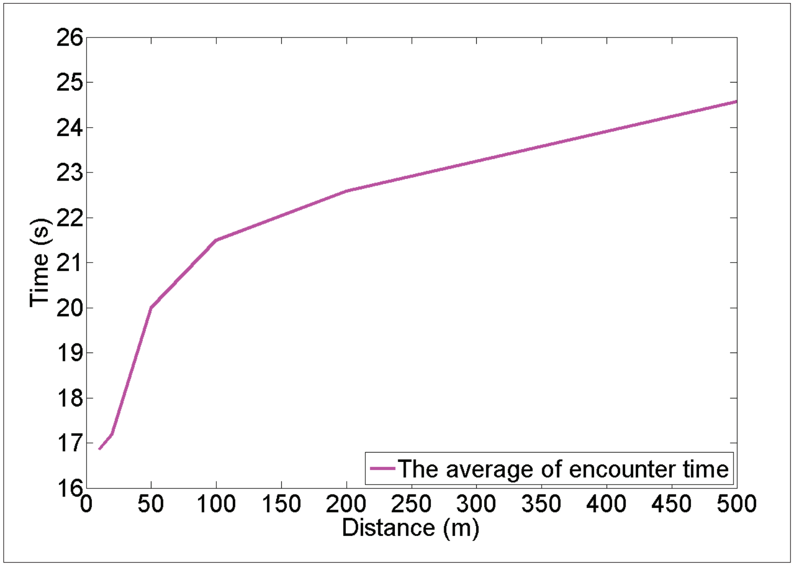

Figure 1. Average encounter duration for 2248 cars in Beijing.

We next present the design of VeShare.

VESHARE DESIGN

As shown in Fig. 2, VeShare applies a software defined networking approach. It divides SVNs into two planes, the control plane and data plane. The control plane is managed centrally by the cellular infrastructure. The data plane simply transfers data, based on the decision from the control plane. As we shall see, the clear separation of control and data planes allows efficient social group management and data transfer in SVNs. In the following, we describe the control and data planes in more detail. For ease of exposition, we refer to a vehicle as a node in a network.

Control Plane: On a high level, the control plane has two layers. One is the social layer, and the other is the decision layer, as shown in Fig. 3. The social layer supports different social applications. Specifically, it manages the SVNs, in charge of social group construction, discovery, and maintenance. The decision layer makes various decisions necessary for data transmission, such as communication mode selection, spectrum resource allocation, priority management, and routing. We next describe these two layers in detail.

Social Layer: A node uses the standard cell search procedure in cellular networks to find a nearby base station. Once finding a base station (by listening to the primary and secondary synchronization signals periodically broadcast from base stations), the node registers its interests with the base station. The base station, based on the interests and location of the node, decides which SVNs the node can join, or creates a new SVN if no suitable SVN exists for the node. Dynamics in SVNs caused by node movement can easily be handled by the cellular infrastructure. Suppose that a node connected to base station *A* performs a handover to another base station, *B*. Then base station *B* informs *A* about the node's handover; *A* then checks whether it needs to remove the

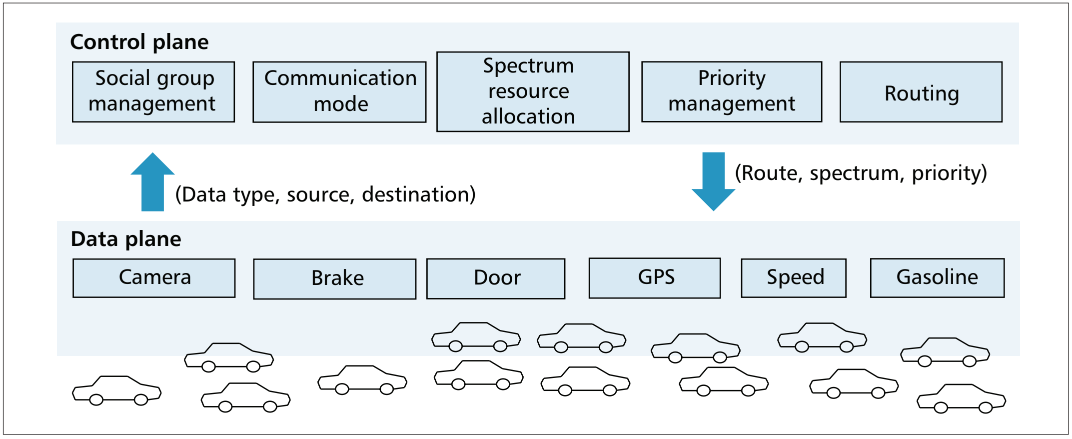

Figure 2. VeShare: Software-defined D2D infrastructure.

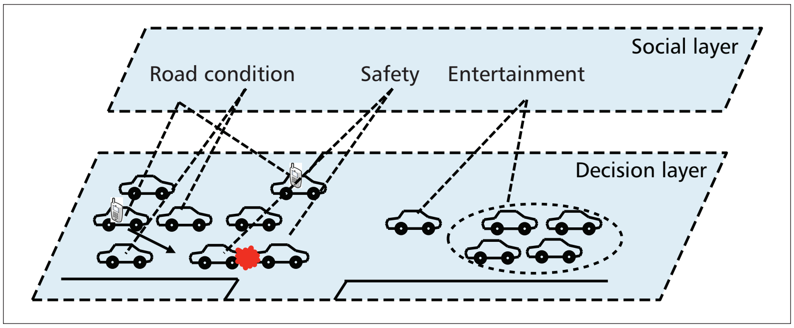

Figure 3. The two layers, social layer and decision layer, in the control plane.

node from its current SVNs (the node can still be in its current SVNs if it is in the coverage boundaries of *A* and *B*). In the meantime, *B* can find new SVNs for the node to join based on its interests and location.

Inside an SVN, when a node discovers a new event (e.g., road congestion), it informs the base station, which determines the nodes to which the information should be transmitted and how to transfer the information (through the decision layer in the control plane, described later). Similarly, when a node, *u*, needs certain information, it sends an inquiry to the base station, which in turn determines which nodes to query. Once a node, *v*, is found to have the information, the base station again determines how to transfer the information from *v* to *u* through the decision layer in the control plane.

Using the cellular infrastructure to manage SVNs has the following advantages. First, the cellular infrastructure serves as a natural coordinator to discover SVNs for a node. Without the coordination from the cellular infrastructure, nodes need to rely on themselves to discover each other and form SVNs. While peer discovery has been studied extensively in the literature, all existing schemes require nodes to send beacons at certain intervals [5] (so they can discover each other), which can be both time and energy consuming. In our architecture, nodes use the standard cell search procedure to identify a nearby base station. As such, nodes only listen to beacons from the base stations and do not need to transmit any beacon.

Second, the cellular infrastructure, knowing the location and movement of the nodes, can also naturally manage and maintain the SVNs.

Nodes register their interests with the base station, which in turn determines the SVNs for the nodes to join, leading to low latency and low energy consumption. If we do not use the cellular infrastructure, SVNs have to be managed by nodes in a distributed manner, which is very difficult in a highly dynamic environment.

The above assumes that SVNs are managed by base stations. In general, we can think that SVNs are managed by a logical entity, referred to as an *SVN controller*. Specifically, each base station can have an SVN controller, which is in charge of the SVNs in the cell; and the SVN controllers of the different base stations can communicate with each other. Or the SVN controller can be located in the cellular network. It has multiple instances (e.g., implemented using threads), each instance serving multiple base stations that are geographically close to each other. While the second approach requires additional infrastructure (for running the SVN controller), it brings an additional benefit in that vehicles in multiple nearby cells can be managed jointly by one SVN controller, which is particularly beneficial for nodes that are at the boundaries of multiple cells.

Decision Layer: The cellular infrastructure, with a global view of the SVNs and knowledge of the cellular network, is also in an ideal position to make various decisions on data transfer. We assume each vehicle is equipped with an onboard unit that has multiple radio interfaces. Specifically, we assume two types of radio interfaces are used for D2D communication: the cellular network interface and the WiFi interface. When using the cellular network interface, two nodes communicate inband (i.e., using the licensed band of the cellular network). When using the WiFi interface (e.g., WiFi Direct), two nodes communicate outband, that is, using the free unlicensed industrial, scientific and medical (ISM) radio bands. Using inband communication can provide QoS guarantee, particularly suitable for road safety related messages that require strict real-time and reliability guarantees. Using outband communication provides no QoS guarantee and can suffer from unpredictable congestion. The advantage is that it does not consume any cellular network bandwidth, and can be used for less critical applications (e.g., road infotainment) when the cellular network is already heavily utilized.

The cellular infrastructure makes various decisions on data transfer. It selects communication mode, that is, whether to utilize inband D2D or outband D2D through WiFi Direct, based on various pieces of information, including application requirements, workload of the cellular network, other data transfer in the cellular network, as well as the condition of the WiFi channel, to optimize the data transmission capacity. If inband communication is used, the cellular infrastructure allocates radio resource to D2D communication, which leads to efficient resource usage and little or no interference. In addition, the cellular infrastructure can assign different priorities to the packets so that urgent packets (e.g., those related to road safety) can be transmitted with higher priority than non-urgent packets.

In addition to single-hop D2D communication, the cellular infrastructure can also find routes for data transfer between two nodes that cannot communicate directly in an SVN. For instance, it can find the best route (i.e., a sequence of D2D communication links) so that data can be transferred from a source to a destination node. Along with the route, the cellular infrastructure can also determine the transport protocol, for example, whether to ensure end-to-end reliability or simply provide best effort service. In addition, the cellular infrastructure can also make other decisions to improve data transfer efficiency. For instance, it can decide that a node needs to cache a video clip, which will be streamed to another node to avoid bandwidth consumption from the cellular network.

Data Plane: The data plane serves as a simple fabric to collect data and transfer data. Specifically, all kinds of sensor data, such as data about the environment (e.g., CO_2, temperature), road condition, and road congestion level, can be collected by each vehicle. The data can be further processed before being transferred. The data transfer itself simply follows the decision made by the control plane.

CASE STUDY

We next use a case study to illustrate the benefits of VeShare. Consider an example of lane change. As shown in Fig. 4, three cars drive in a platoon on a campus road. They keep the safety distance and conform to the speed limit. Now suppose another car, *C*, in a neighboring lane wants to change lanes, and at the same time, a pedestrian walks across the zebra line.

Let us first assume that VeShare is not being used. The car, *C*, may choose to cut in between the second and third cars in the platoon. But just at the time it joins in, the second car stops because the first car stops to let a pedestrian walk across the zebra line. At this moment, the cut-in car has no choice but also to stop immediately. Such a sudden stop leads the third car into a difficult situation since there is no signal that warns it to slow down in advance. In the worst case, the third car may cause a severe rear-end collision, even though it is actually not at fault in this case.

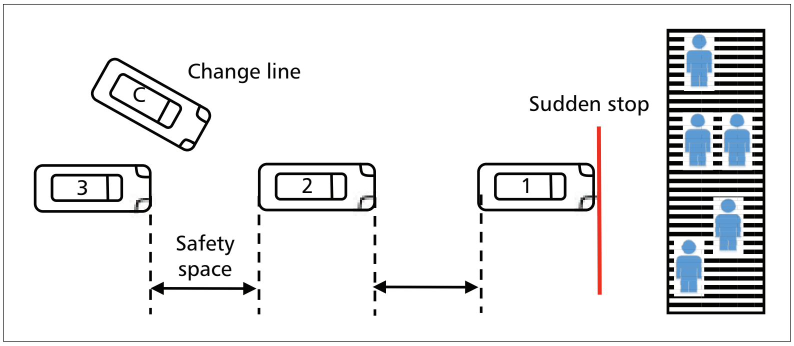

Figure 4. Lane change example.

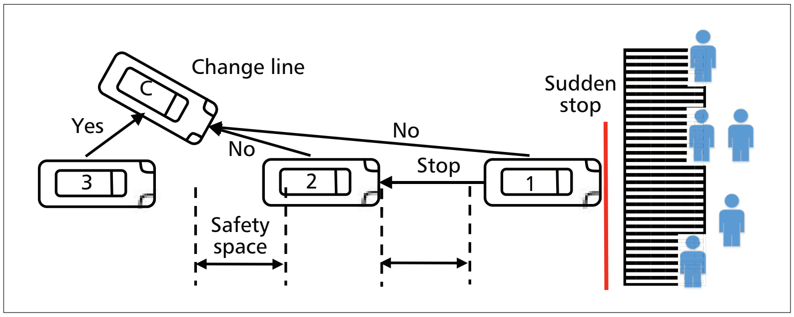

Figure 5. Safety lane change with VeShare.

We now suppose that the network is managed using VeShare. When car *C* would like to join the group, it first registers its request to the base station, and the base station finds the nearby platoon for it. Then it will use a group join-in protocol to inform the platoon that it would like to join the team. The inquiry message is then delivered to all members in the existing platoon. At this step, the application will invoke reliable networking service that is supported by inband D2D communication to ensure timely and reliable data transfer. Because the platoon application has a welcome socket, all three cars in the platoon will receive the inquiry sent by car *C*. Upon receiving such a message, each car in the platoon will check to see if it is safe at this moment to allow the join action.

Since the distance between the third and second cars in the platoon is larger than the safety distance, the third car will respond to car *C* with an OK signal. However, the first car notices a pedestrian, and hence it has to stop and immediately sends a NO signal to car *C*, and at the same time it signals its following cars to slow down to be prepared to stop. Upon receiving the signal from the leading car, the second car will choose to also send NO to car *C*. Suppose under the platoon join-in protocol, for safety reasons, a car can only join the team when it receives permissions from all members in the platoon (or at least all members within a certain distance); then car *C* cannot join the platoon in this example scenario. Therefore, no accident will happen in this case. Figure 5 illustrates the above safety lane change scenario with VeShare.

In the above scenario, the control plane finds the nearby platoon for car *C*. In addition, it determines an inband D2D communication channel for the group join-in since this application requires real-time reliable communication.

Feature name	D2D [10]	WiFi Direct [14]	DSRC [15]
Standardization	3GPP LTE-A	IEEE 802.11 a, g and n	IEEE 802.11p
Frequency band	Licensed band for LTE-A	2.4 GHz, 5 GHz	5.850 GHz to 5.925 GHz
Transmission range	Can be on the order of kilometers	200 m	Hundreds of meters
Maximum rate	1 Gb/s	250 Mb/s	6–27 Mb/s

Table 1. Characteristics of D2D with other wireless technologies.

When designing incentive strategies to encourage drivers (vehicles) to join the social group and share the information, privacy protection is another challenging problem. Some of these issues have been addressed in vehicular ad hoc networks. We believe the control plane managed by the cellular infrastructure provides new opportunities in making some of the security measures easier to achieve.

When not using any infrastructure support, finding the platoon and determining the communication channel require nodes to communicate with each other in an ad hoc manner, which may incur significant delay and overhead.

RESEARCH TOPICS IN VESHARE FRAMEWORK

The goal of VeShare is to establish a D2D paradigm to support social-aware real-time communication for vehicle networks. A number of research challenges need to be addressed to achieve this goal.

SOCIAL GROUP MANAGEMENT

While on a high level the cellular infrastructure manages the social groups based on node interests and location, a challenge is how to organize the interests and manage the social groups. In practice, nodes may have very specific interests. For instance, a node is interested in infotainment, but is only interested in tourist information, in particular Italian restaurants in the area. The interests need to be organized in a hierarchy to cover different levels of interest; the question is how to organize it to accommodate diverse interests on the fly. When the categories are too fine-grained, we may end up with many small social groups, losing the benefits of social groups; when the categories are too coarse-grained, a node may end up receiving information that is not of interest. In addition, the location estimation may not be accurate, causing some nodes to be placed in wrong groups (e.g., it cannot establish a direct communication with any node in the group). Yet another challenge is that the size of the group needs careful management. When a group is too large, it may be advantageous to divide the group into multiple smaller groups (e.g., based on clustering); and multiple groups communicate with each other through group leaders. Techniques to identify dense clusters in massive and highly dynamic graphs in real time [6] can provide a good reference for this problem.

DATA TRANSMISSION DECISIONS

Making the various decisions on data transmission, including communication mode selection, radio resource allocation, routing, and priority management, is a challenging task. In principle, the cellular infrastructure can gather the relevant information and solve a number of optimization problems (individually or jointly) to make the above decisions. In practice, gathering up-to-date information is nontrivial, particularly in a highly dynamic environment. Furthermore, the information may not be accurate due to inherent uncertainties. In addition, the solutions need to be obtained in real time and be close to the optimal solutions.

SVN CONTROLLER

As mentioned earlier, SVNs can be managed by a logical entity called an SVN controller. The SVN controller may be realized in many ways by multiple instances at multiple geographic locations. The number and placement of these instances need to be carefully planned to satisfy the dynamic loads (e.g., the amount of load can be much higher during morning and afternoon rush hours than other times) and real-time requirements of SVNs. Specifically, the SVN controllers can be located at multiple base stations, communicating with each other through the wired backbone of the cellular network. The resources to the SVN controllers need to be allocated dynamically in response to the dynamic load of the SVNs so that the real-time requirements can still be satisfied when the SVNs have heavy load.

SECURITY AND PRIVACY

Many security issues need to be considered. For instance, what if some nodes inject fake road safety messages into the network? Some messages may need to be encrypted for confidentiality, nodes may need to authenticate each other, integrity of the messages need to be checked, and so on. When designing incentive strategies to encourage drivers (vehicles) to join the social group and share the information, privacy protection is another challenging problem. Some of these issues have been addressed in vehicular ad hoc networks. We believe the control plane managed by the cellular infrastructure provides new opportunities to make some of the security measures easier to achieve.

MULTIPLE CARRIERS

Vehicles may use cellular services from different carriers. Social groups in different cellular networks, however, may have to be managed collectively to provide meaningful service. For instance, in the example earlier, if the cars that belong to a social group cannot communicate with each other because they are served by different carriers, no road safety can be achieved. How are social groups in different carrier networks to be managed? One solution is to use a third party provider that serves the multiple carrier networks simultaneously based on certain service agreements.

RELATED WORK

D2D COMMUNICATIONS

D2D communication that enables devices to communicate directly is conceived as a vital component of next generation cellular networks. It can improve spectral reuse, bring hop gains, and enhance system capacity [5, 7, 9]. Since it was first proposed for relaying purposes in cellular networks [8], to date, researchers have proposed many new applications such as content distribution and location-aware video dissemination [10–12]. It has great potential to provide better user experience and social activities in emerging mobile applications.

In general, D2D communication can occur on the cellular spectrum (i.e., inband) or unlicensed spectrum (i.e., outband) [10]. Research efforts on inband communication usually study the problem of interference mitigation between D2D and cellular communication, and optimization for resource allocation so that dedicated cellular resources will not be wasted [13]. The challenges of outband D2D communication, on the other hand, lie in the coordination of the communications over two different bands because usually D2D communication happens on a second radio interface. In addition to WiFi Direct [14], dedicated short-range communication (DSRC) [15] can also be used for outband D2D communication. Table 1 summarizes the difference of inband D2D, WiFi Direct, and DSRC. Our VeShare framework can be used for the above technologies.

NEXT GENERATION VEHICLES AND VEHICULAR SOCIAL NETWORKS

In recent years, many high-tech companies and automakers have increasingly been testing self-driving cars on public roads. Imagine that one day in the near future, many next generation vehicles, including self-driving vehicles, are on the road. Features such as autonomous driving, safety driving, social driving, electric power, and intelligence will be the most important and cutting edge technologies that should be investigated and developed today [1].

Imagine that one day in the near future, many next generation vehicles, including self-driving vehicles, are on the road. Features such as autonomous driving, safety driving, social driving, electric power, and intelligence will be the most important and cutting edge technologies that should be investigated and developed today.

The concept of vehicle social networks (VSNs), as a particular class of vehicular ad hoc networks, has been investigated in recent studies. The social features in VSNs are similar to the issues in SVNs addressed in this article. However, most recent achievements in VSN emphasize research problems in the context of data dissemination approaches, data treatment, incentive mechanisms of user involvement, and effective VSN and connectivity models. None of the studies is on using SDN and cellular infrastructure to support highly dynamic social-enabled vehicle networks as in our study.

CONCLUSIONS AND FUTURE WORK

In this article, we have presented VeShare, a software defined networking based framework for managing vehicular networks. This framework clearly separates a vehicle network into control and data planes; the control plane is managed by the cellular infrastructure, while the data plane simply forwards data to the vehicle network following the decisions of the control plane. Specifically, the cellular infrastructure ensures that a vehicle can join the right social network in a timely manner, manages the social network over time, and determines efficient resource allocation and communication channels for vehicles. The actual data communication is through the vehicle network, using a flexible set of mechanisms (e.g., either inband or outband communication). We have highlighted the benefits of this framework using a case study and outlined a number of research challenges. Our future work is centered on resolving the various challenges.

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BIOGRAPHIES

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