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Dynamic Spectrum Management with Movement Prediction in Vehicular Ad Hoc Networks

HAIPENG YAO[1,2], PENGBO SI[2,3,*], RUIZHE YANG[2,3]
AND YANHUA ZHANG[2,3]

[1]*School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China*
[2]*Beijing Advanced Innovation Center for Future Internet Technology, Beijing University of Technology, Beijing, China*
[3]*College of Electronic Information and Control Engineering, Beijing University of Technology, Beijing, China*

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Vehicular networks have been widely considered as a promising architecture to enable vehicles-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connections, and the wireless access to the Internet for the vehicles. Current sparse deployment of the roadside units (RSUs) requires multi-hop data transmission among the vehicles and the RSUs, and thus vehicular ad hoc network (VANET) has been introduced. As one of the key resources in VANETs, radio spectrum has to be carefully managed to facilitate high spectrum utilization efficiency and network throughput. In this paper, we propose a dynamic spectrum resource management scheme for VANETs, with the assistance from the movement information of the vehicles that are usually available to the network. The link status prediction is made based on the vehicle location and movement information, for optimizing the spectrum band allocation to achieve maximized system reward. The optimization problem is solved, allowing the vehicles to utilize multiple spectrum bands and make decisions in a distributed and parallel manner. Extensive simulation results are also presented to demonstrate the significant performance improvement of the proposed scheme compared to the existing scheme that ignores the spectrum management optimization with vehicle movement information.

Keywords: Vehicular network, ad hoc network, heterogeneous network, dynamic spectrum management, optimization.

* Corresponding author: E-mail: sipengbo@bjut.edu.cn

1 INTRODUCTION

In recent years, vehicular technologies have been experiencing rapid development, thanks to the increasing demands on automatic driving, traffic and weather information dissemination, infotainment data acquisition, and most importantly, safety issues. Vehicular networks, which have been proposed for real-time, reliable and secure information delivery among the vehicles and from/to the Internet, draw a lot of attention from both academia and industries [1, 2]. Wireless Local Area Networks (WLANs) [3], Bluetooth, 3G/4G/5G, dedicated short-range communication (DSRC), among other wireless techniques, are widely adopted to connect the on-board units (OBUs) and network infrastructure [4].

Connecting the vehicles to the Internet usually requires the access service provided by the base stations (BSs) and/or the roadside units (RSUs). However, BSs are built for cellular networks without specific design for vehicular communications, and RSUs are usually sparsely deployed because of the high capital expenditure (CAPEX) and operating expense (OPEX) [5]. Consequently, to access the Internet through the RSUs, which are connected to the Internet via wireless techniques or wired cables, multi-hop communication among the vehicles may need to be established to route the data for the vehicles that are out of the one-hop communication range of the RSUs. Besides, safe-driving information may require direct sharing among the vehicles that are geographically close to each other to enable real-time response. Vehicular ad hoc networks (VANETs) play an important role in these cases, allowing multi-hop and self-organized networking among the vehicles and RSUs [6].

Radio resource, especially the spectrum resource, is one of the key issues in designing wireless systems, due to that the valuable spectrum resource is almost used up, and that it becomes difficult for emerging wireless technologies to obtain sufficient spectrum [7–11]. In VANETs, we also need to design an efficient spectrum resource management scheme for wireless communications among the vehicles and the network infrastructure.

Dynamic spectrum management for ad hoc networks [12, 13] draws a lot of attention. In the scenario that ad hoc and cellular networks co-exist and cooperate, the spectrum sharing and management problem is discussed in [14], with the objective of maximizing the ad hoc transmission capacity and the constraints on the outage probability of the ad hoc network and on the throughput improvement ratio of the cellular network. Considering the energy and spectrum efficiency problem in cognitive ad hoc networks, a channel-aggregation diversity based medium access control (MAC) protocol has been proposed in [16] for joint power and channel allocation. In [17], bandwidth reservation is adopted by the primary users for improved performance under secondary user activity. And the authors of [18] propose to introduce the distributed and opportunistic access scheme for multiple-input multiple-output (MIMO) ad hoc cognitive networks based on the simple power stimuli issued by primary user transmitters. The authors of [15] study joint connection admission control and routing in wireless mesh networks. In [19], device-to-device (D2D) communications are studied in the vehicular scenarios based on both the features of D2D and the nature of vehicular networks. In 5G-enabled vehicular networks, a matrix game approach has been introduced to the optimal resource sharing problem, with the objective of maximizing the resource utilization and minimizing the power consumption [20].

Spectrum resource management has been introduced in vehicular ad hoc networks as well. In [21], cognitive radio technique has been introduced into VANETs, allowing dynamic spectrum allocation. Spectrum availability information can be shared among the vehicles to detect spectrum opportunities in the licensed band. An spectrum utilization scheme for high speed vehicle networks has been proposed in [22], where the CR-based radio resource allocation framework enables the vehicles to effectively utilize the TV white spaces. The authors of [22] also consider cognitive radio vehicular networks, and propose a queueing model to minimize both the spectrum inefficiency and spectrum scarcity issues. Several incorporating machine learning techniques in the era of dynamic spectrum access has been discussed for vehicular networks in [23], and the architecture for optimizing the performance of the network has been proposed. In [24], the authors propose to employ the cognitive radio (CR) principles in the vehicular environment to increase the spectrum opportunities for inter-vehicle communication. Besides, the spectrum allocation problem for multi-operator D2D communication is studied in [25], and vehicle-to-vehicle (V2V) communications can be considered as a special case of D2D.

Although some work has been done on spectrum management in VANETs, most focuses on coping with the problem on the highly-dynamic network topology. Indeed, the mobility of the vehicles introduces great challenge for the spectrum managing. Fortunately, the topology changing could be predictable, or at least partially predictable [26]. This is because of the availability of the information on the location as well as the moving direction and velocity of the vehicles. With this information, we can do the movement prediction, and based on this prediction, the future link status can be estimated for opportunistic spectrum scheduling. In this paper, a vehicle movement prediction based dynamic spectrum management scheme is proposed in vehicular ad hoc networks, where the link status prediction is made with the vehicle location and movement information, for optimizing the spectrum band allocation to achieve maximized throughput. The vehicles can utilize multiple spectrum bands and make decisions in a distributed and parallel manner. The specific distinct characteristics of this paper are as follows.

- We adopt the vehicle movement information to assist communications among the entities of this distributed mobile network. The movement information includes velocity, acceleration and position information, which are always available locally at the vehicles and can be utilized by the VANET. We explore its significance for predicting network topology and channel capacity in this paper.
- We take the vehicle mobility model into consideration. Advanced Manhattan model, which eliminates the fixed turning probabilities, is adopted to facilitate the analysis on the vehicle movement and to enable movement data assisted spectrum resource management.
- We propose a dynamic spectrum scheduling scheme for VANETs. The achievable data rates on the wireless channels and the costs on utilizing the spectrum bands are taken into account to achieve maximized system reward. The optimal decisions of the vehicles can be made in a distributed and parallel manner.

The rest of the paper is organized as follows. In Section 2 and 3, we present the system architecture and model, respectively. The opportunistic spectrum scheduling problem is formulated and solved in Section 4. Extensive simulation results are provided in Section 5 and Section 6 concludes this paper.

2 SYSTEM ARCHITECTURE

In this section, the system architecture of the VANET has been introduced to cope with the spectrum scheduling problem. Following the architecture overview, we study the routing and topology, system heterogeneity, and dynamic spectrum management problems.

2.1 Architecture Overview

The VANET considered in this paper is composed of entities that includes not only the vehicles, but also the roadside units (RSUs), along with the wireless data transmission links connecting the vehicles and RSUs. The onboard units (OBUs) on the vehicles and the RSUs are equipped with wireless communication tranceivers and the computing devices, to enable the Internet access for the vehicles and the distributed radio resource management.

In this system, two main types of data, emergency data and regular data, form most of the communication traffic and consume most of the radio

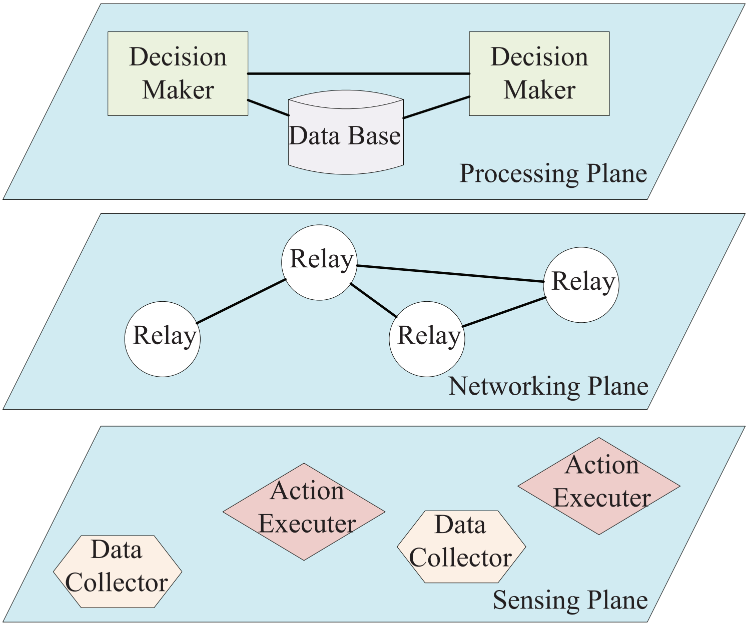

FIGURE 1
Logic architecture of the VANETs with Processing Plane, Networking Plane and Sensing Plane.

communication resources. Emergency data carries the delay-sensitive information, such as collision avoidance and traffic condition, and regular data, including infotainment and weather forecast, is delay-tolerant. In the queueing system, whenever we have emergency data waiting for transmission, it will be scheduled prior to all other regular data, and thus the delay requirements of the emergency data can be met. Besides, the system is heterogeneous. The heterogeneity exists in the transceivers, computing and storage devices embedded in the OBUs and RSUs, as well as the radio resources and data flow characteristics (data format, transmission QoS requirement, traffic priority, etc.) of the network. The current and predicted location of the vehicles can be used to determine the network topology, and further facilitate data transmission.

With this system architecture, we use Figure 1 to demonstrate the logic functions. The Sensing Plane collects wireless channel and vehicle movement information, and submits the data to the Processing Plane, which is responsible for data storage and processing, via Networking Plane that provides data connection among all entities in the system. The Sensing Plane also has action executors to response to the spectrum allocation decisions made at the decision makers (DMs) in the Processing Plane. DMs, which may reside in either vehicles or RSUs in the Processing Plane, collect data and make routing and resource management decisions independently or cooperatively. The decisions are then transmitted to the relays in the Networking Plane for network topology control, and to the Sensing Plane to execute the decisions.

2.2 Routing and Topology Control

The vehicles in VANETs can move fast, resulting in the highly dynamic network topology. This is a great challenge to design effective routing protocols and algorithms, of which the existing work mostly assumes unknown future network topology, or even current topology. Fortunately, in VANETs, the movement information of the vehicles is usually determined prior to data traffic routing decisions, allowing the network routing algorithm aware of the network topology when selecting a data flow path.

To utilize this navigation data information, a centralized routing scheme or a distributed one can be developed. In the centralized routing scheme, one of the decision makers in the processing plane collect all the channel state information (CSI) of the wireless links among the vehicles and RSUs, as well as the movement information including the vehicle velocity and planned moving path. Each vehicle or RSU always maintains a route to the DM, and submits a request along this path, enclosing the information of source, sink and quality-of-service (QoS) requirement, when data needs to be transmitted. The central routing decision maker selects a route for this request and sends the decision to the source vehicle or RSU, the sink vehicle or RSU, and all other entities that perform as routers in the selected route. In the distributed routing scheme, the data source entity makes its own route selection decision, after requesting the network topology information from the database in Processing Plane.

The vehicle always collects its own movement information, e.g., location, velocity, direction, during operation. We can use this data to determine the network topology for optimized routing and spectrum resource allocation. The dynamic nature of VANETs is considered to build the current network topology and the topology in the next timeslot based on the current location, velocity and direction.

2.3 System Heterogeneity

In our proposed system, vehicles and RSUs may have very different communication transmission power, battery or fuel capacities, computing capabilities, etc. Besides, the data transmission requirements are also heterogeneous, due to the fact that different types of data have various QoS requirments (delay, throughput, distortion, etc.). Furthermore, radio communication resources, especially the spectrum resource, can also be heterogeneous, since the system entities have different utilization capabilities for different subbands from the spectrum band allocated to the VANETs.

On one hand, such heterogeneity results in difficulties when managing the devices, since a single rule may fail in coping with the different requirements and constraints. On the other hand, this diversity can be utilized to properly allocate heterogeneous resources to improve the overall system performance and resource utilization efficiency.

Thus, in this paper, we propose to dynamically utilize the spectrum resource to achieve optimal spectrum utilization, considering the heterogeneity of communication devices, data traffic requirements and radio resources.

2.4 Dynamic Spectrum Management

Assume that a data source entity requires to select a route to a data sink entity with its QoS requirement. On receiving this request, the routing decision maker optimally selects a route between the source and the sink to optimize the system reward while satisfying the QoS requirement. The system reward could be the data rate, the delay, the number of hops, the packet loss rate, the energy consumption, among other criterions.

With the awareness of the current and future network topology along with the data traffic routing decisions, the radio spectrum management process can be simply allocating adequate spectrum subbands to the wireless links satisfying the data transmission and QoS requirements. The process can be either centralized or distributed, with the objective of achieving the maximized system reward.

In centralized dynamic radio spectrum allocation scheme, one of the decision makers performs as the central control point. In one case, the routing decision maker (RDM) and the spectrum allocation decision maker (SDM) are configured in different entities, and thus the RDM needs to submit the routing decisions to the SDM as the reference to allocate spectrum subbands. Then, the SDM analyzes the routing decision information to determine the required data rate on each wireless link, and optimally makes the spectrum allocation decision to fit all the requirements and to achieve high spectrum utilization efficiency. While in another case that the SDM and the RDM are in the same entity, submitting routing information can be simplified to a local operation.

In distributed dynamic radio spectrum allocation scheme, the transmitters of all wireless links determine the spectrum allocation cooperatively. This process can be modeled as a game or a distributed optimization problem. On receiving or determining the routing decisions, all entities that need to transmit share their transmission requirements with each other, and calculate the spectrum allocation decision separately. Several models, like cooperative game and multi-armed bandits, can be used to deal with problem.

3 SYSTEM MODEL

In this section, the network, wireless channel and vehicle movement models are presented and discussed.

3.1 Network Model

We assume that there are totally N_{V} vehicles with different characteristics such as speed, onboard devices and communication transmission power, and N_{R} roadside units with different transmission power to provide direct or relayed access to the Internet for the vehicles.

Since that we have totally $N_{\mathrm{V}} + N_{\mathrm{R}}$ communication entities, the maximum number of possible directional communication links among them is $N = (N_{\mathrm{V}} + N_{\mathrm{R}})(N_{\mathrm{V}} + N_{\mathrm{R}} - 1)$. Note that the bi-directional link between two nodes is considered as two directional links. Let $n \in \mathscr{N}$ denote the link, where $\mathscr{N}$ is the set of all the links in the network, $|\mathscr{N}| = N$.

We also assume that all the transceivers adopt OFDM-based communication schemes, which splits the whole spectrum band available in the network into subbands u, $0 \leq u \leq U - 1$, where U is the number of available subbands, $U \leq N$. Each subband allocation time line is divided into K equal-length slots, of which the beginning time point is denoted by t_k, where $0 \leq k \leq K - 1$ and $t_k - t_{k-1} = \tau$ for $1 \leq k \leq K - 1$. Here τ represents the length of a time slot. At the beginning of each time slot, the entities use subband u to share their current state information with each other one by one. Based on this information, subband u is allocated to one of these N wireless links n for $(\check{t}_k, t_{k+1})$, where $\check{t}_k$ is the subband allcoation decision time point. These U subband allocation lines make their allocation decisions independently.

Since the wireless link between two entities in the VANET is usually non-line-of-sight (NLoS), Rayleigh channel model should be adopted. Besides, the channel state information (CSI) can be estimated according to the distance between the sender and the receiver, which could be calculated and predicted by movement information.

3.2 Channel Model

Wireless channel state is one of the key factors affecting the performance of wireless communications. In VANETs, the fast movement of the vehicles induces severe Doppler shift and time-selective fast fading, and thus we adopt the assumption that the average channel state during one time slot depends on not the fading of the channel, but the link length (the distance from the transmitter to the receiver) and transmission power, i.e., only large-scale path loss is taken into account. In dynamic vehicular networks, the link length between two nodes is a random variable, which can be roughly predicted by the movement information generated by the velocity and acceleration sensors equipped on the vehicles. Let $\text{đ}_{n,u,k}$ denote the length of link n at $\check{t}_k$, and $\text{đ}_{\mathrm{E},n,u,k+1}$ denote the predicted length of link n at $\check{t}_{k+1}$. Thus, $\text{đ}_{n,u,k}$ is a known value, but $\text{đ}_{\mathrm{E},n,u,k+1}$ should be considered as a random variable at $\check{t}_k$.

Another variable $\ddot{d}_{n,u,k} = \text{đ}_{n,u,k}/\text{đ}_{\mathrm{E},n,u,k+1}$ is introduced to represent the predicted link length variation from $\text{đ}_{n,u,k}$ to $\text{đ}_{\mathrm{E},n,u,k+1}$, and a set of thresholds ϵ_m, $1 \leq m \leq M-1$, and $\epsilon_m < \epsilon_{m+1}$ for $1 \leq m \leq M-2$, is adopted to convert the continuous random variable $\ddot{d}_{n,u,k}$ to a discrete one.

$$d_{n,u,k} = \begin{cases} \tilde{d}_0, & \text{if } \ddot{d}_{n,u,k} \leq \epsilon_1, \\ \tilde{d}_m, & \text{if } \epsilon_m < \ddot{d}_{n,u,k} \leq \epsilon_{m+1}, 1 \leq m \leq M-2, \\ \tilde{d}_{M-1}, & \text{if } \ddot{d}_{n,u,k} > \epsilon_{M-1}, \end{cases} \tag{1}$$

where $\tilde{d}_m$ is a realization of $d_{n,u,k}$.

3.3 Vehicle Model

Manhattan grid model [27, 28] is adopted and further modified as the vehicle mobility model in this paper. Let u_{int} and u_{veh} represent the density of intersections and vehicles on the roads, respectively. Assume that the vehicles move at the velocity v, and only stop and wait at the intersections with the probability P_{wait}, which is the probability that the vehicle has to wait when it enters an intersection. The random waiting time at an intersection is denoted by t_{wait}, whose distribution and probability density function are $U(0, T_{\mathrm{wait}})$ and $f_{T_{\mathrm{wait}}}(t_{\mathrm{wait}}) = \frac{1}{T_{\mathrm{wait}}}$ for $t_{\mathrm{wait}} \in [0, T_{\mathrm{wait}}]$, respectively. If two vehicles A and B are moving on the road towards the same direction and within each other's one-hop communication range, B could be A's neighbor and direct connection between A and B could be established. If A waits at an intersection, other waiting vehicles at the intersection within A's communication range could be A's neighbors as well. Vehicle A does not have any other neighbor because of the inadequate time for transmitting the packets if two vehicles are moving towards different directions. Let the random variable t_{move} denote the time period from a time instance when the vehicle is moving, to the time the vehicle stops at an intersection. Then, $t_{\mathrm{move}} \sim U(0, \frac{1}{u_{\mathrm{int}} v})$, and the probability density function $f_{T_{\mathrm{move}}}(t_{\mathrm{move}}) = u_{\mathrm{int}} v$ for $t_{\mathrm{move}} \in [0, \frac{1}{u_{\mathrm{int}} v}]$.

At any time instance, the probabilities that a vehicle moves and stops can be represented as

$$P_{\mathrm{move}} = \frac{\frac{1}{u_{\mathrm{int}} v}}{\frac{1}{u_{\mathrm{int}} v} + \frac{\tau_{\mathrm{wait\_max}} P_{\mathrm{wait}}}{2}} = \frac{2}{2 + \tau_{\mathrm{wait\_max}} P_{\mathrm{wait}} u_{\mathrm{int}} v}, \tag{2}$$

and

$$P_{\mathrm{stop}} = 1 - P_{\mathrm{move}} = \frac{\tau_{\mathrm{wait\_max}} P_{\mathrm{wait}} u_{\mathrm{int}} v}{2 + \tau_{\mathrm{wait\_max}} P_{\mathrm{wait}} u_{\mathrm{int}} v}, \tag{3}$$

respectively. In Equation (2), the numerator $\frac{1}{u_{\text{int}}v}$ represents the time that a vehicle travels from one intersection to another, while the denominator $\frac{1}{u_{\text{int}}v} + \frac{T_{\text{wait\_max}}P_{\text{wait\_max}}}{2}$ is the vehicle moving time plus the stopping time. Here, $\frac{T_{\text{wait}}}{2}$ is the average waiting time at an intersection. Equation (3) denotes that $P_{\text{move}} + P_{\text{stop}} = 1$.

4 PROBLEM FORMULATION

The optimal spectrum management problem is formulated and solved in this section.

4.1 Actions

In each time slot, the subbands are allocated to the wireless links in a parallel and distributed manner. At the decision time point $\check{t}_k$, the $N_{\text{V}} + N_{\text{R}}$ communication entities makes the decisions on how their N wireless links utilize the U subbands. For each subband, the actions of each link are simply *active*, which denotes accessing the subband, or *passive*, which denotes not accessing the subband. Mathematically, the action of link n at decision time point $\check{t}_k$ for any subband is

$$a_n(k) = \begin{cases} 1, & \text{if link } n \text{ utilizes the spectrum subband in } (\check{t}_k, t_{k+1}) \\ 0, & \text{if link } n \text{ do not utilize the spectrum subband in } (\check{t}_k, t_{k+1}). \end{cases} \tag{4}$$

Let $\mathscr{A} = \{1, 0\}$ represent the set of possible actions

4.2 Optimization Objective

In this paper, we try to maximize the information transmitted while minimizing the link utilization costs. The information transmitted is defined as the average bits of data transmitted in the time slots considered,

$$\begin{aligned} R_{\text{trans}} &= \frac{1}{K}\sum_{k=1}^{K}\sum_{n=1}^{N} a_n(k) r_{\text{trans}}(n,k) \\ &= \frac{1}{K}\sum_{k=1}^{K}\sum_{n=1}^{N} a_n(k)\delta(n,k)\min[r_{\text{rate}}(n,k), l(n,k)], \end{aligned} \tag{5}$$

where $r_{\text{trans}}(n,k)$ is the data bits transmitted during (t_k, t_{k+1}) at link n, $r_{\text{rate}}(n,k)$ is the achievable data rate during (t_k, t_{k+1}) at link n, $l(n,k)$ is the queue length at t_k at link n, and $\delta(n,k)$ is the successful transmission indicator,

$$\delta(n,k) = \begin{cases} 0, & \text{if the connection is lost during } (\check{t}_k, t_{k+1}) \\ 1, & \text{otherwise.} \end{cases} \tag{6}$$

We also define the spectrum subband utilization cost as

$$C_{\text{band}} = \frac{1}{K} \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) c_{\text{band}}, \tag{7}$$

where c_{band} is the utilization cost for each spectrum subband. Thus, the average reward can be represented as

$$\begin{aligned} & W \\ = \; & R_{\text{trans}} - C_{\text{link}} \\ = \; & \frac{1}{K} \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) r_{\text{trans}}(n,k) - \frac{1}{K} \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) c_{\text{link}} \\ = \; & \frac{1}{K} \left\{ \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) \delta(n,k) \min[r_{\text{rate}}(n,k), l(n,k)] - \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) c_{\text{lin[5pt]k}} \right\} \\ = \; & \frac{1}{K} \sum_{k=1}^{K} \sum_{n=1}^{N} a_n(k) \{\delta(n,k) \min[r_{\text{rate}}(n,k), l(n,k)] - c_{\text{link}}\}. \end{aligned}$$

Note that there are totally U spectrum subbands available for allocation at t_k. Then,

$$\sum_{n=1}^{N} a_n(k) = U. \tag{8}$$

The actions $a_n(k)$ have to be carefully chosen to maximize the total system reward W, i.e., the spectrum subband allocation problem can be written as

$$\begin{aligned} & \max_{a_n(k) \in \mathscr{A}} W, \\ & \text{subject to} \sum_{n=1}^{N} a_n(k) = U. \end{aligned} \tag{9}$$

4.3 Solving the Optimization Problem

To solve this optimization problem, we need to find the optimized action $a_n(k)$ at each decision time point t_k at each link n, where $1 \leq k \leq K$ and $1 \leq n \leq N$. To maximize W, we need to allocate the U bands to the links that have the highest expected reward, which can be represented as

$$\overline{r}(n,k) = P_{\text{suc}}(n,k) \min[r_{\text{rate}}(n,k), l(n,k)] - c_{\text{link}}, \tag{10}$$

where $P_{\text{suc}}(n,k)$ is the probability of successful transmission during $(\check{t}_k, t_{k+1})$ at link n, and $P_{\text{suc}}(n,k) = \text{Prob.}(\delta(n,k) = 1)$. Besides, $\overline{r}(n,k)$ has to be greater than zero to guarantee positive reward, i.e.,

$$P_{\text{suc}}(n,k) > \frac{c_{\text{link}}}{\min[r_{\text{rate}}(n,k), l(n,k)]}. \tag{11}$$

Consequently, the optimal action at t_k for link n can be represented as

$$a_n(k) = \begin{cases} 1, & \text{if } P_{\text{suc}}(n,k) \in \mathbb{P}_{\text{suc}}(n,k,U) \text{ and } P_{\text{suc}}(n,k) > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

where $\mathbb{P}_{\text{suc}}(n,k,U)$ is the set of the highest U probabilities $P_{\text{suc}}(n,k)$ for $1 \leq n \leq N$.

However, in Equation (12), $P_{\text{suc}}(n,k)$ may not be directly available at the vehicles. Instead, we obtain the value of $P_{\text{suc}}(n,k)$ through the observation of the history of $\delta(n,k)$, based on the moving and location information of the vehicles, as well as the time slot length and wireless channel state. Specifically, $\delta(n,k)$ depends on the location and the moving direction of the vehicles at both the source and the destination of the wireless link.

Another practical way to obtain $P_{\text{suc}}(n,k)$ is through simulation results. To reduce simulation complexity, we may use τ' instead of $\tau = t_{k+1} - t_k$ when ignoring the stop time in the simulations. Here $\tau' = \tau \times P_{\text{move}}$.

5 SIMULATION RESULTS AND ANALYSIS

Extensive simulation results are presented in this section to demonstrate the performance improvement of the proposed spectrum management scheme for VANETs.

In our simulations, we consider a 1 kilometer $\times$ 1 kilometer area, where 100 vehicles move along the roads at the average velocity $v = 8.33$ m/s (30 km/h). The average distance between two adjacent intersections is 300

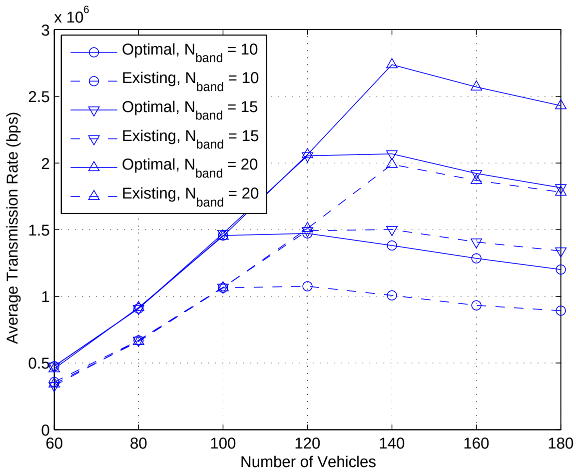

FIGURE 2
Average transmission rate comparison with different number of vehicles.

m. When a vehicle arrives at an intersection, it stops and waits with the probability $P_{\text{wait}} = 0.75$, and the maximum waiting time $T_{\text{wait}} = 120$ seconds. We assume that the data block size $B = 400$ Kbits $= 50$ KBytes. DSRC technology is adopted to enable wireless communications between connected vehicles and/or RSUs, of which the communication range $L_{\text{range}} = 200$ m and the achievable data rate $H = 1.2$ Mbps on each subband. Besides, we adopt $c_{\text{link}} = 10^6$ as the cost at utilizing a spectrum subband in one time slot, and $N_{\text{band}} \in \{10, 15, 20\}$ as the number of subband available in the network.

With these simulation parameters, we compare the system reward and QoS satisfactory probability performances of our proposed scheme and the existing one that ignores the optimization of subband management and uses static subband allocation.

We can observe from Figure 2 that the average transmission rate depends on the number of vehicles N_{V} in the network. As N_{V} increases, the average transmission data rate grows first but drops after a maximum value is achieved. This is because more vehicles in the network indicate shorter distance between the vehicles, which enables faster data rate. However, if the network is over crowded, spectrum resource may be used up and the average data rate decreases. Obviously, more available spectrum subbands enable higher data rate with large N_{V}. Besides, our proposed scheme always performs much better compared to the existing scheme that ignores the spectrum allocation optimization.

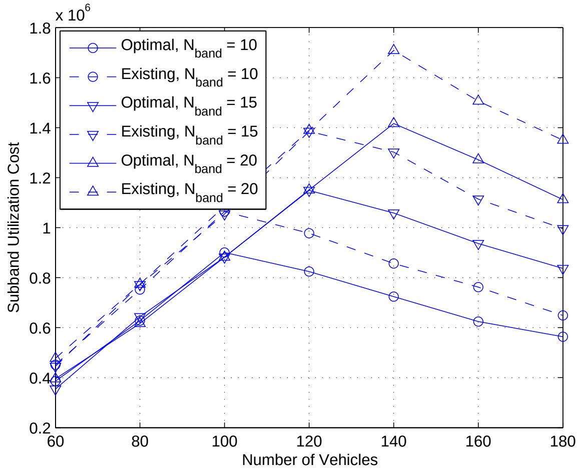

FIGURE 3
Spectrum subband utilization cost comparison with different number of vehicles.

In Figure 3, we compare the spectrum subband utilization cost with different number of vehicles in the network. Similar to Figure 2, the cost on utilizing the spectrum subbands increases first due to the fact that vehicles need more subbands when they have more neighbors to communicate. Then, the cost decreases mainly because the vehicles cannot obtain enough subbands due to the resource limitation. In any case, our proposed scheme significantly reduces the cost compared to the existing one.

The average system reward of the proposed and the existing scheme is compared in Figure 4. In this figure, the system reward is always higher with larger number of vehicles in the network. In our proposed optimal spectrum scheduling scheme, the system reward tends to be stable as the number of vehicles in the networks is larger than around 130, indicating that the network becomes saturated. We can easily observe that our scheme increases the system reward performance significantly with various simulation parameters.

We study the average transmission rate, spectrum subband utilization cost and system reward performance in Figure 5, Figure 6 and Figure 7, respectively, with different packet arriving rates. Similar conclusions can be drawn that our proposed scheme significantly increases the transmission data rate, reduces the subband utilization cost and therefore improves the system reward compared to the existing scheme, with various packet arriving rates, thanks to the optimal spectrum management with the assistance from the movement information of the vehicles.

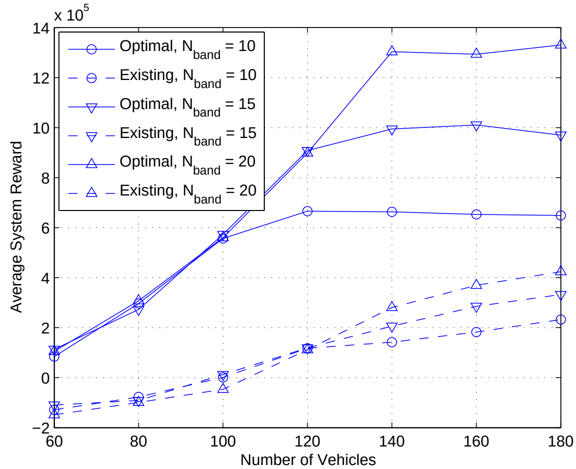

FIGURE 4
Average system reward comparison with different number of vehicles.

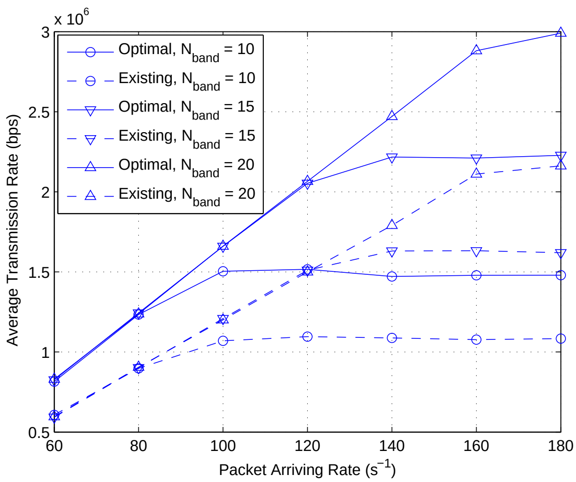

FIGURE 5
Average transmission rate comparison with different packet arriving rates.

6 CONCLUSIONS AND FUTURE WORK

In multi-hop vehicular ad hoc networks, spectrum resource management is one of the key issues to be considered to facilitate the high performance of the communications among the vehicles and the roadside units. In this paper, a

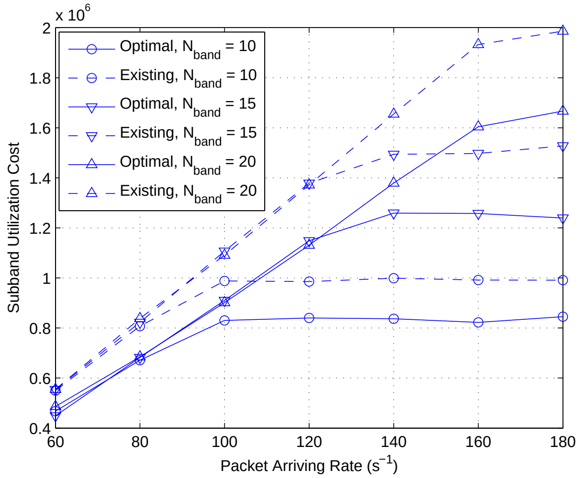

FIGURE 6
Spectrum subband utilization cost comparison with different packet arriving rates.

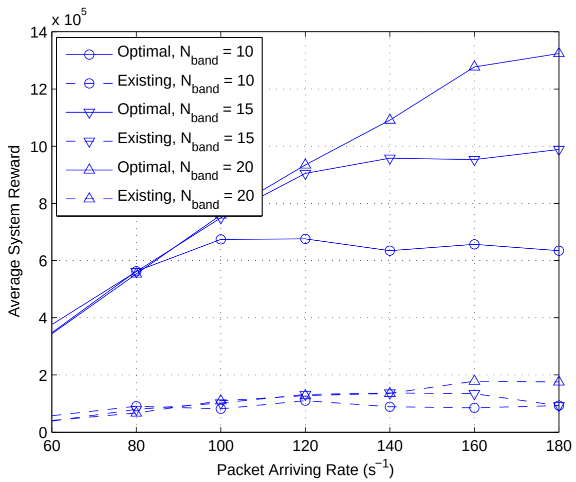

FIGURE 7
Average system reward performance comparison with different packet arriving rates.

dynamic spectrum resource management scheme has been proposed to maximize the data transmission rate while reducing the spectrum subband utilization costs. The vehicle movement information has been taken into account to predict the link status between communication entities. We formulated the optimization problem and solved it, allowing the vehicles to utilize multiple subbands and make spectrum utilization decisions in a parallel and distributed manner. Extensive simulation results have shown that our proposed scheme significantly improves the system performance compared to the existing scheme. Future work is in progress to consider wireless network virtualization [29, 30] in the proposed framework.

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REFERENCES

[1] K. Zheng, Q. Zheng, H. Yang, L. Zhao, L. Hou and P. Chatzimisios, "Reliable and efficient autonomous driving: the need for heterogeneous vehicular networks, *IEEE Communications Magazine*," vol. 53, no. 12, pp. 72–79, 2015.

[2] P. Si, Y. He, H. Yao, R. Yang and Y. Zhang, "DaVe: Offloading Delay-Tolerant Data Traffic to Connected Vehicle Networks, *IEEE Transactions on Vehicular Technology*," vol. 65, no. 6, 2016.

[3] P. Si, H. Ji, F.R. Yu, G. Yue, "IEEE 802.11 DCF PSM Model and a Novel Downlink Access Scheme, in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Las Vegas, NV, USA, Mar. 2008.

[4] M. Zhang and R.S. Wolff, "Routing protocols for vehicular Ad Hoc networks in rural areas, *IEEE Communications Magazine*," vol. 46, no. 11, pp. 126–131, 2008.

[5] O.K. Tonguz, W. Viriyasitavat, "Cars as roadside units: a self-organizing network solution, *IEEE Communications Magazine*," vol. 51, no. 12, pp. 112–120, 2013.

[6] H. Wang, R.P. Liu, W. Ni, W. Chen and I.B. Collings, "VANET modeling and clustering design under practical traffic, channel and mobility conditions, *IEEE Transactions on Communications*," vol. 63, no. 3, pp. 870–881, 2015.

[7] P. Si, F.R. Yu, H. Ji and V.C.M. Leung, "Optimal Cooperative Internetwork Spectrum Sharing for Cognitive Radio Systems with Spectrum Pooling," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 1760–1768, May 2010.

[8] P. Si, Q. Zhang, F.R. Yu and Y. Zhang, "QoS-Aware Dynamic Resource Management in Heterogeneous Mobile Cloud Computing Networks", *China Communications*, vol. 11, no. 5, pp. 144–159, 2014.

[9] R. Xie, F.R. Yu, Hong Ji, and Yi Li, "Energy-Efficient Resource Allocation for Heterogeneous Cognitive Radio Networks with Femtocells", *IEEE Transactions on Wireless Communications*, vol. 11, no. 11, pp. 3910–3920, Nov. 2012.

[10] S. Bu, F. Richard Yu, and H. Yanikomeroglu, "Interference-Aware Energy-Efficient Resource Allocation for Heterogeneous Networks with Incomplete Channel State

Information", *IEEE Transactions on Vehicular Technology*, vol. 64, no. 3, pp. 1036–1050, Mar. 2015.

[11] G. Liu, F. Richard Yu, H. Ji, and V.C.M. Leung, "Energy-Efficient Resource Allocation in Cellular Networks with Shared Full-Duplex Relaying", *IEEE Transactions on Vehicular Technology*, vol. 64, no. 8, pp. 3711–3724, Aug. 2015.

[12] H.-W. Kim and A. Kachroo, "Low Power Routing and Channel Allocation of Wireless Video Sensor Networks Using Wireless Link Utilization", *Ad Hoc & Sensor Wireless Networks*, vol. 30, no. 1–2, pp. 83–112, 2016.

[13] A. Barnawi, N. Dimitriou and A. Polydoros, "Robust Routing Under Shadow-Fading in Mobile Ad-Hoc Networks", *Ad Hoc & Sensor Wireless Networks*, vol. 29, no. 31–51, pp. 83–112, 2015.

[14] C. Zhai, W. Zhang and G. Mao, "Cooperative spectrum sharing between cellular and Ad-Hoc networks ," *IEEE Transactions on Wireless Communications*," vol. 13, no. 7, pp. 4025–4037, 2014.

[15] S. Zhang, F. Richard Yu, and V.C.M. Leung, "Joint Connection Admission Control and Routing in IEEE 802.16-Based Mesh Networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 4, pp. 1370–1379, Apr. 2010.

[16] P. Ren, Y. Wang and Q. Du, "CAD-MAC: A channel-aggregation diversity based MAC protocol for spectrum and energy efficient cognitive Ad Hoc networks," in *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, 2014.

[17] J. Alcaraz, M. Lopez-Martinez, J. Vales-Alonso and J. Garcia-Haro, "Bandwidth reservation as a coexistence strategy in opportunistic spectrum access environments," in *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 3, pp. 478–488, 2014.

[18] M. Biagi and F. Cuomo, "An opportunistic access scheme through distributed interference control for MIMO cognitive nodes," *IEEE Transactions on Communications*, vol. 12, no. 2, pp. 6500–6513, 2013.

[19] X. Cheng, L. Yang and X. Shen, "D2D for Intelligent Transportation Systems: A Feasibility Study," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 4, pp. 1784–1793, 2015.

[20] R. Yu, J. Ding, X. Huang, M. T. Zhou, S. Gjessing and Y. Zhang , "Optimal resource sharing in 5G-enabled vehicular Networks: A matrix game approach ," *IEEE Transactions on Vehicular Technology*, online, 2016.

[21] M. Di Felice, K.R. Chowdhury and L. Bononi, "Cooperative spectrum management in cognitive vehicular Ad Hoc networks," in *Proc. 2011 IEEE Vehicular Networking Conference (VNC)*, Amsterdam, Netherlands, pp. 47–54, Nov. 2011.

[22] A. Daniel, A. Paul and A. Ahmed, "Queuing model for cognitive radio vehicular network," in *Proc. 2015 International Conference on Platform Technology and Service (PlatCon)*, Singapore, pp. 9–10, Jan. 2015.

[23] S. Chen, R. Vuyyuru, Q. Altintas and A.M. Wyglinski, "Learning in vehicular dynamic spectrum access networks: Opportunities and challenges," in *Proc. 2011 International Symposium on Intelligent Signal Processing and Communications Systems (ISPACS)*, Chiang Mai, Thailand, pp. 1–6, Dec. 2011.

[24] M. Di Felice, K.R. Chowdhury, and L. Bononi, "Analyzing the potential of cooperative Cognitive Radio technology on inter-vehicle communication," in *Proc. 2010 IFIP Wireless Days (WD)*, Venice, Italy, pp. 1–6, Oct. 2010.

[25] B. Cho, K. Koufos, R. Jantti,Z. Li and M.A. Uusitalo, "Spectrum Allocation for Multi-Operator Device-to-Device Communication," in *Proc. IEEE Conference on Communications (ICC)*, London, UK, pp. 5454–5459, June 2011.

[26] D. Tian, K. Zhu, J. Zhou, Y. Wang and H. Liu, "Swarm model for cooperative multi-vehicle mobility with inter-vehicle communications," *IET Intelligent Transport Systems*, vol. 9, no. 10, pp. 887–896, 2015.

[27] S. Bandyopadhyay, E.J. Coyle, and T. Falck, "Stochastic properties of mobility models in mobile Ad Hoc networks", *IEEE Transactions on Mobile Computing*, vol. 6, no. 11, pp. 1218–1229, 2015.

[28] Y. Wang, X. Lu, Z. Ling, Y. Yang, Z. Zhang and K. Wang, "A method to calibrate vehicle-mounted cameras under urban traffic scenes ," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 6, pp. 3270–3279, 2015.

[29] C. Liang and F. Richard Yu, "Wireless Network Virtualization: A Survey, Some Research Issues and Challenges, *IEEE Comm. Surveys and Tutorials*," vol. 17, no. 1, pp. 358–380, Firstquarter 2015.

[30] C. Liang and F. Richard Yu, "Wireless Virtualization for Next Generation Mobile Cellular Networks," *IEEE Wireless Comm.*, vol. 22, no. 1, pp. 61–69, Feb. 2015.