Delay Optimization-Based Joint Route Selection and Resource Allocation Algorithm for Cognitive Vehicular Ad Hoc Networks (Workshop)

Changzhu Liu(✉), Rong Chai, Shangxin Peng, and Qianbin Chen

Key Lab of Mobile Communication Technology,
Chongqing University of Posts and Telecommunications, Chongqing 400065, China
`1039410361@qq.com`, `{chairong,chenqb}@cqupt.edu.cn`,
`1585975437@qq.com`

Abstract. Cognitive vehicular ad-hoc networks (CVANETs) are expected to improve spectrum utilization efficiently and offer both infotainment and safety services for vehicles. In this paper, the joint route selection and resource allocation problem is considered for CVANETs. Taking into account the lifetime of transmission links, we first propose a candidate link selection method which selects the transmission links satisfying the link lifetime constraint. Then stressing the importance of transmission delay, we formulate the joint route selection and resource allocation problem as an end-to-end transmission delay minimization problem. As the formulated optimization problem is a complicated integer nonlinear problem, which cannot be solved conveniently, we equivalently transform the original problem into two subproblems, i.e., resource allocation subproblem for candidate links and route selection subproblem. Solving the two optimization subproblems by applying the K shortest path algorithm and the Dijkstra algorithm, respectively, we can obtain the joint route selection and resource allocation strategy. Simulation results demonstrate the effectiveness of the proposed algorithm.

Keywords: Cognitive vehicular ad hoc networks · Route selection · Resource allocation · Channel allocation · Time-frequency resource block

1 Introduction

Cognitive vehicular ad hoc networks (CVANETs) have received considerable attention from both academia and industry in recent years. In CVANETs, cognitive vehicles (CVs) equipped with onboard units are allowed to share the spectrum resource of primary vehicles (PVs) in an opportunistic manner, and transmitting both infotainment and safety related information through interacting with roadside units and other vehicles [1,2].

In CVANETs, in the case that the direct connection between one cognitive source vehicle (CSV) and cognitive destination vehicle (CDV) pair is inaccessible, multi-hop cognitive relay vehicles (CRVs) can be applied to forward the data packets for the CSV

H. Gao et al. (Eds.): ChinaCom 2019, LNICST 313, pp. 338–350, 2020.
https://doi.org/10.1007/978-3-030-41117-6_28

so that the successful information interaction between the CSV and CDV pair can be achieved. It is apparent that various route selection and resource allocation strategies may result in different user quality of service (QoS) as well as network transmission performance.

Some recent research works address the problem of route selection in CVANETs [3–5]. The authors in [3] study the route selection problem in software-defined vehicular networks and propose a cognitive routing protocol which aims to achieve the maximal end-to-end link lifetime. In [4], the authors present a software defined cognitive network framework of the Internet of vehicles and propose a reinforcement learning (RL)-based algorithm which selects the route selection strategies to maximize the rewards of the vehicles overtime. A cognitive anypath vehicular routing protocol is proposed in [5]. By jointly considering the geographical location information and the perceived channel information of various vehicles, the candidate vehicles which have available channel resources and are located close to the destination vehicles are selected as the relay vehicles.

Resource allocation problem in CVANETs is considered in [6–8]. In [6], the vehicles are categorized into primary providers (PPs) that intend to transmit safety-related messages and secondary providers (SPs) with non-safety information to be delivered. A prioritized optimal channel allocation approach is proposed to improve channel utilization and an optimal channel-hopping and channel allocation strategy is designed for the SPs to achieve the maximum throughput.

The authors in [7] study the problem of reliable adaptive resource management for CVANETs and design a distributed and adaptive resource management controller, which allows the optimal exploitation of cognitive radio and data fusion in the networks. The resource management problem is formulated as a constrained stochastic network utility maximization problem and the optimal cognitive resource manager is designed to dynamically allocate the access time windows at the serving roadside units, together with the access rates and traffic flows at the served vehicular clients. The problem of resource allocation for video streaming in CVANETs is studied in [8]. A semi-Markov decision process-based resource allocation scheme is proposed to facilitate video streaming application. By jointly considering the states of background users and vehicle users, and the availability of cognitive bands, an optimal resource allocation algorithm is proposed to improve the video streaming quality while guaranteeing the call-level performance of the background users.

Route selection problem or resource allocation problem in CVANETs has been studied independently in [3–8]. In this paper, we jointly consider route selection and resource allocation problem in CVANETs. Taking into account the link lifetime, we first propose a candidate link selection method which selects the candidate links satisfying the link lifetime constraints. Then stressing the importance of data transmission delay, we characterize the end-to-end data transmission delay of the CSV and CDV pair, and formulate the joint route selection and resource allocation problem as an end-to-end transmission delay minimization problem. Since the formulated optimization problem is a complicated nonlinear integer optimization problem which cannot be solved conveniently using traditional optimization tools, we transform the original problem into two subproblems, i.e., route selection subproblem of candidate links and resource allocation subproblem and solve the two subproblems by means of the K shortest path algorithm and the Dijkstra algorithm, respectively.

The remainder of this paper is organized as follows. Section 2 describes the system model considered in this paper. In Sect. 3, we propose a candidate link selection method. In Sect. 4, the optimization problem formulation is presented. The solution to the formulated optimization problem is described in Sect. 5 and the simulation results are described in Sect. 6. Finally, we conclude the paper in Sect. 7.

2 System Model

In this paper, we consider a CVANET consisting of L PVs and a number of CVs, where a CSV intends to transmit data packets to a CDV through a number of CRVs. For convenience, we let V_i denote the ith CRV, $1 \leq i \leq M$, where M denotes the number of the CRVs in the network, let V_0 and V_{M+1} denote respectively the CSV and the CDV. Figure 1 shows the network model considered in this paper.

We assume that each PV is allocated one licensed channel, and different licensed channels are allocated to various PVs so as to avoid the interference among the PVs. We denote the set of the licensed channels of the PVs as $C = \{C_1, C_2, ..., C_L\}$, where C_l denotes the licensed channel of the lth PV, $1 \leq l \leq L$. We further assume that the overlay spectrum sharing mode is applied between the PVs and the CVs. More specifically, the CVs are allowed to access the idle channels which are not occupied by the PVs. In the case that one PV initializes a data transmission on its allocated channel, the CVs transmitting on the channel should terminate the communications, wait on the channel or switch to other available channels in order to avoid causing interference to the PV.

In this paper, we assume that the data transmission of both the PVs and the CVs is in the unit of time slots with fixed time duration. More specifically, a number of continuous time slots are assigned to the PVs and the CVs for conducting data transmission. It is also assumed that by applying efficient spectrum prediction mechanism, the channel occupancy status of the PVs during a certain period of time can be obtained. Let $\alpha_{l,t} \in \{0, 1\}$ denote the time-frequency resource block (RB) identifier occupied by the lth PV, i.e., $\alpha_{l,t} = 1$, if the lth PV occupies the lth channel at the tth time slot, otherwise, $\alpha_{l,t} = 0$, $1 \leq l \leq L$, $1 \leq t \leq N_0$, where N_0 denotes the total number of time slots.

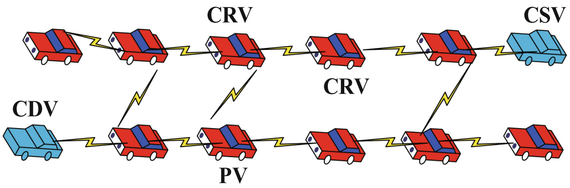

Fig. 1. System model

3 Candidate Link Selection Method

The rapid movement of the vehicles may result in communications link failure in the CVANET. To characterize the stability of transmission links connecting two vehicles, we introduce the concept of link lifetime which is defined as the time duration from connection establishment to link disconnection.

Let $L^0_{i,j}$ denote the link between V_i and V_j, x_i and y_i denote the position of V_i on horizontal direction and vertical axis, respectively, $v_{i,x}$ and $v_{i,y}$ denote the speed of V_i at the corresponding direction, D^{t}_i and D^{r}_i denote the transmission range and receiving range of V_i, respectively, and $T_{i,j}$ denote the lifetime of $L^0_{i,j}$. Denote $D^{(1)}_{i,j}$ as the distance between V_i and V_j at current time slot, we obtain

$$D^{(1)}_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}. \tag{1}$$

Assuming at current time slot, V_i is capable of transmitting data packet to V_j directly, i.e., $D^{(1)}_{i,j} \le \min\{D^{\mathrm{t}}_i, D^{\mathrm{r}}_i\}$.

Denote $D^{(2)}_{i,j}$ as the distance between V_i and V_j after time slot t, we obtain [9]

$$D^{(2)}_{i,j} = \sqrt{\Delta x^2_{i,j} + \Delta y^2_{i,j}} \tag{2}$$

where $\Delta x_{i,j}$ and $\Delta y_{i,j}$ are given by

$$\begin{aligned} \Delta x_{i,j} &= x_i + v_{i,x}t - x_j - v_{j,x}T_{i,j}, \\ \Delta y_{i,j} &= y_i + v_{i,y}t - y_j - v_{j,y}T_{i,j}. \end{aligned} \tag{3}$$

The life time of $L^0_{i,j}$ can be expressed as

$$T_{i,j} = \max\{t : D^{(2)}_{i,j} \le \min\{D^{\mathrm{t}}_i, D^{\mathrm{r}}_i\}\}. \tag{4}$$

To ensure stable transmission, we can select the transmission links of which the lifetime is larger than a given minimum lifetime threshold. Let $T^{\min}_i$ denote the minimum link lifetime of V_i, the candidate link set of V_i can be expressed as

$$\Psi_i = \left\{L^0_{i,j} | T_{i,j} \ge T^{\min}_i, 0 \le i, j \le M+1, i \ne j\right\}. \tag{5}$$

Let $L_{ij} \in \Psi_i$, $0 \le i, j \le M+1, i \ne j$ denote the candidate link of V_i, among all the candidate links of V_i, the links offering the optimal transmission performance will be selected and the corresponding optimal resource allocation strategy will be designed, as discussed in following sections.

4 Optimization Problem Formulation

In this paper, to jointly design route selection and resource allocation algorithm for CSV and CRVs in the CVANET, we examine the end-to-end transmission delay of the candidate routes between the CSV and the CDV and formulate the joint optimization problem as an end-to-end transmission delay minimization problem.

4.1 Objective Function Formulation

The end-to-end transmission delay of the candidate routes between the CSV and the CDV can be expressed as

$$D = \sum_{i=0}^{M} \sum_{j=1, j \neq i}^{M+1} \tau \beta_{i,j} N_{i,j} \tag{6}$$

where τ denotes the duration of the time slot, $\beta_{i,j}$ is the binary route selection variable, $\beta_{i,j} = 1$ indicates that $L_{i,j}$ is selected to transmit the data packets for the CSV; otherwise, $\beta_{i,j} = 0$, and $N_{i,j}$ is the minimum number of the time slots required to successfully transmit the data packets of the CSV through $L_{i,j}$. Let S denote the size of the data packets of the CSV, $N_{i,j}$ should meet the following constraints:

$$\sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}-1} \tau \delta_{i,j,l,t} R_{i,j,l} < S, \tag{7}$$

$$\sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \tau \delta_{i,j,l,t} R_{i,j,l} \geq S \tag{8}$$

where $\delta_{i,j,l,t}$ denotes the resource allocation variable of $L_{i,j}$, i.e., $\delta_{i,j,l,t} = 1$ if the lth channel is allocated to $L_{i,j}$ at the tth time slot, otherwise, $\delta_{i,j,l,t} = 0$, and $R_{i,j,l}$ denotes the data rate of $L_{i,j}$ when transmitting data packets on the lth channel, which can be expressed as

$$R_{i,j,l} = B_l \log_2 \left(1 + \frac{P_i h_{i,j,l}^2}{\sigma^2} \right) \tag{9}$$

where B_l is the bandwidth of the lth channel, P_i is the transmit power of V_i, $h_{i,j,l}$ denotes the channel gain of $L_{i,j}$ on the lth channel and σ^2 is the power of channel noise.

Let $R_{i,j}$ denote the data rate of $L_{i,j}$, we can express $R_{i,j}$ in terms of $R_{i,j,l}$ as follows

$$R_{i,j} = \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \delta_{i,j,l,t} R_{i,j,l}. \tag{10}$$

4.2 Optimization Constraints

To design the optimal joint route selection and resource allocation strategies which minimizes the total end-to-end transmission delay, we should consider a number of optimization constraints.

Flow Conservation Constraints. While the data packets of the CSV may transmit via various CRVs, route selection constraints should be satisfied at the CSV, the CDV and the CRVs, i.e.,

$$\mathrm{C1}: \sum_{j=1}^{M+1} \beta_{0,j} = 1, \tag{11}$$

$$\mathrm{C2}: \sum_{i=0}^{M} \beta_{i,M+1} = 1, \tag{12}$$

$$\mathrm{C3}: \sum_{i=0, i \neq j}^{M} \beta_{i,j} = \sum_{i'=1, i' \neq j}^{M+1} \beta_{j,i'}, 1 \leq j \leq M. \tag{13}$$

Time Slot Allocation Constraints. In the case that $L_{i,j}$ is assigned to V_i, at least one time-frequency RB should be allocated to $L_{i,j}$, hence, we obtain the following constraint:

$$\mathrm{C4}: \beta_{i,j} \leq \sum_{l=1}^{L} \delta_{i,j,l,t}. \tag{14}$$

As it is assumed that continuous time slots should be allocated to the CSV or the CRVs, we obtain

$$\mathrm{C5}: \prod_{t=1}^{t'-1} \left(\sum_{i=0}^{M} \sum_{j=1, j \neq i}^{M+1} \sum_{l=1}^{L} \delta_{i,j,l,t} \right) = 1, \text{ if } \delta_{i,j,l,t'} = 1. \tag{15}$$

To avoid causing interference to the PVs, the CSV and the CRVs are only allowed to occupy the time-frequency RBs which are not used by the PVs, i.e.,

$$\mathrm{C6}: \delta_{i,j,k,t} \leq \alpha_{k,t}. \tag{16}$$

Both the number of time slots and the resource allocation variables should meet the conditions given in (7) and (8), for convenience, we rewrite the constraints as follows

$$\mathrm{C7}: \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}-1} \tau \delta_{i,j,l,t} R_{i,j,l} < S, \tag{17}$$

$$\mathrm{C8}: \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \tau \delta_{i,j,l,t} R_{i,j,l} \geq S. \tag{18}$$

Considering the practical implementation of CVs, we assume that each CV can only send data packets to at most one neighboring CV at one time slot, and can only receive data packets from at most one neighboring CV, i.e.,

$$\mathrm{C9}: \sum_{i=0}^{M} \delta_{i,j,l,t} + \sum_{i'=1}^{M+1} \delta_{j,i',l,t} \leq 1. \tag{19}$$

Maximum Handoff Number Constraint. As frequent handoff of CSV and CRVs may cause high signaling cost and transmission performance degradation which are highly undesired. In this paper, we assume that the number of handoff on each link should subject to a maximum number of handoff, denoted by $H^{\max}$, i.e.,

$$\mathrm{C10}: \sum_{t=1}^{N_{i,j}} \sum_{l=1}^{L} \sum_{l'=1,\, l' \neq l}^{L} \delta_{i,j,l,t} \delta_{i,j,l',t+1} \leq H^{\max}. \tag{20}$$

Minimum Data Rate Constraint. We assume that the data transmission of CSV should meet a minimum data rate requirement. Let $R^{\min}$ denote the minimum data rate requirement of the CSV, the actual data rate on $L_{i,j}$, denoted by $R_{i,j}$ should meet

$$\mathrm{C11}: R_{i,j} \geq R^{\min}. \tag{21}$$

4.3 Optimization Model

According to the aforementioned optimization objective and constraints, the optimization problem can be formulated as

$$\begin{aligned} \min_{\beta_{i,j}, \delta_{i,j,l,t}} \quad & D \\ \text{s.t.} \quad & \mathrm{C1} - \mathrm{C11}. \end{aligned} \tag{22}$$

5 Solution to the Optimization Problem

The optimization problem formulated in (22) is a complicated nonlinear integer optimization problem that is difficult to be solved conveniently. However, by considering the lack of coupling between the resource allocation problem of one particular route and the route selection problem in the network, the original optimization problem can be equivalently transformed into two subproblems, namely, the resource allocation subproblem of candidate links and the route selection subproblem, and the two subproblems can then be solved successively.

5.1 Solution to the Resource Allocation Subproblem

In this subsection, we first assume that $L_{i,j}$ is allocated to the CSV for data transmission, i.e., $\beta_{i,j} = 1$, and simplify the joint route selection and resource allocation problem into the resource allocation subproblem of $L_{i,j}$, which can then be solved by applying the K shortest path algorithm [10].

Resource Allocation Subproblem Formulation. Under the assumption of $\beta_{i,j} = 1$, the transmission delay of $L_{i,j}$ can be calculated as

$$D_{i,j} = \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \tau \delta_{i,j,l,t} \frac{S}{R_{i,j,l}}, \tag{23}$$

the resource allocation subproblem of $L_{i,j}$ can be formulated as

$$\begin{aligned} &\min_{\delta_{i,j,l,t}} D_{i,j} \\ &\text{s.t } \ \mathrm{C4} - \mathrm{C11} \text{ in } (22). \end{aligned} \tag{24}$$

As both τ and S are given constants, the above optimization problem is equivalent to the following problem

$$\begin{aligned} &\min_{\delta_{i,j,l,t}} \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \delta_{i,j,l,t} \frac{1}{R_{i,j,l}} \\ &\text{s.t } \ \mathrm{C4} - \mathrm{C11} \text{ in } (22). \end{aligned} \tag{25}$$

To illustrate the resource allocation subproblem of $L_{i,j}$, we show one simple example in Table 1. Consider the case $L = 3$ and $N_{i,j} = 7$, Table I plots the unit transmission delay which is defined as the reciprocal of the data rate corresponding to particular time-frequency RBs. In Table 1, T_t denotes the tth time slot, $1 \leq t \leq 7$. Since PVs may initialize data transmission at certain time-frequency RBs, the CSV and CRVs cannot occupy these RBs for data transmission. For simplicity, we define the transmission delay of the CSV and CRVs at these time-frequency RBs as ∞. Since $N_{i,j}$ can be calculated based on (7) and (8), it is apparent that to solve the above optimization problem is equivalent to finding the combination of RBs within time interval between $t = 1$ and $N_{i,j}$, which offering the minimum transmission delay under the given conditions.

Table 1. Unit transmission delay of various time-frequency RBs

	T_1	T_2	T_3	T_4	T_5	T_6	T_7
C_1	$\frac{1}{R_{i,j,1}}$	∞	∞	$\frac{1}{R_{i,j,1}}$	$\frac{1}{R_{i,j,1}}$	$\frac{1}{R_{i,j,1}}$	∞
C_2	∞	$\frac{1}{R_{i,j,2}}$	$\frac{1}{R_{i,j,2}}$	∞	$\frac{1}{R_{i,j,2}}$	∞	$\frac{1}{R_{i,j,2}}$
C_3	$\frac{1}{R_{i,j,3}}$	$\frac{1}{R_{i,j,3}}$	$\frac{1}{R_{i,j,3}}$	$\frac{1}{R_{i,j,3}}$	∞	$\frac{1}{R_{i,j,3}}$	$\frac{1}{R_{i,j,3}}$

Graph Theory-Based Problem Formulation. In this subsection, we apply the graph theory, map the problem of resource allocation for $L_{i,j}$ into the route selection problem in a weighted graph and determine the optimal solution by means of the K shortest path algorithm [10].

Applying the graph theory to solve the resource allocation subproblem of $L_{i,j}$, we create a weighted directed graph, $G_0 = (V_0, E_0, W_0)$, where $V_0 = \{X_\mathrm{s}, X_{l,t}, X_\mathrm{d}\}$ are vertices in the graph, X_{s} and X_{d} are the introduced super source node and super destination node, respectively, $X_{l,t}, 1 \le l \le L, 1 \le t \le N_{i,j}$, denotes the time-frequency RB identifier of the lth channel at the tth time slot; $E_0 = \{E_{\mathrm{s}}, E_{\mathrm{r}}, E_{\mathrm{d}}\}$ is the set of the connected edges between channels in adjacent time slots, $E_{\mathrm{s}} = \{(X_{\mathrm{s}}, X_{l,1})\}$ denotes the set of the edges connecting X_{s} and $X_{l,1}$, $E_{\mathrm{r}} = \{(X_{l,t-1}, X_{l',t})\}$ denotes the set of edges connecting $X_{l,t-1}$ and $X_{l',t}$, $1 \le l, l' \le L, 2 \le t < N_{i,j}$, $E_{\mathrm{d}} = \{(X_{l,N_{i,j}-1}, X_{\mathrm{d}})\}$ denotes the set of edges connecting $X_{l,N_{i,j}-1}$ and X_{d}. It should be noticed that in the case of $\alpha_{l,t} = 0$, there does not exist an edge between $X_{l',t-1}$ and $X_{l,t}$, and between $X_{l,t}$ and $X_{l',t+1}$. $W_0 = \{D_{\mathrm{s},l}, D_{l_1,l_2,t}, D_{l,\mathrm{d}}\}$ is the weight set of the edges, $1 \le l_1, l_2 \le L, 1 \le t \le N_{i,j}$, where $D_{\mathrm{s},l}$ and $D_{l,\mathrm{d}}$ are constants representing the weight of the links between X_{s} and $X_{l,1}$, and the weight of the links between $X_{l,N_{i,j}}$ and X_{d}, respectively, $D_{l_1,l_2,t} = \frac{1}{R_{i,j,l_1-1}}$ is the unit transmission delay of the link between $X_{l_1,t-1}$ and $X_{l_2,t}$.

Figure 2 shows a graphical representation of resource allocation subproblem of $L_{i,j}$.

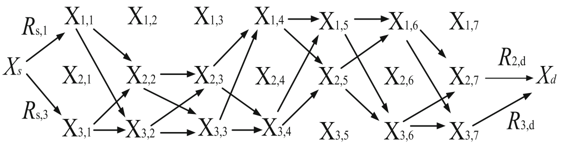

Fig. 2. Graphical representation of resource allocation subproblem.

K Shortest Path Algorithm-Based Resource Allocation Strategy. The K shortest path algorithm can be applied to find the K end-to-end routes offering the minimum weight between a source node and a destination node in a weighted directed graph.

The steps of solving the resource allocation subproblem in G_0 based on the K shortest path algorithm can be summarized as follows:

Step 1: Initialization phase
Initialize K, calculate $R_{i,j,l}$ and $T_{i,j}$ based on (7), (8) and (9).
Step 2: Find the K shortest paths
Determining the K shortest paths from X_{s} to X_{d} based on the K shortest path algorithm. Denote P_k as the kth path obtained, $1 \le k \le K$ and $\varPhi = \{P_k, 1 \le k \le K\}$ as the set of the K shortest paths.
Step 3: Check handoff number condition
Calculating the number of handoff along P_k, $1 \le k \le K$. If P_k fails to meet the constraint C11 in (22), remove P_k from $\varPhi$.
Step 4: Find the optimal path
If $\varPhi = \emptyset$, set $N_{i,j} = N_{i,j} + 1$, repeat step 1 to 3; elseif $\varPhi$ only contains one path, set the path as the optimal path; else, among all the paths in $\varPhi$, select the one with the minimum delay as the optimal path.
Step 5: Determine the optimal resource allocation strategy
For the selected optimal path, map the path strategy to the optimal resource allocation strategy. More specifically, if $(X_{\mathrm{s}}, X_{l,1})$ is contained in the optimal path, then

set $\delta^*_{i,j,l,1} = 1$; if $(X_{l,t-1}, X_{l,t})$ is contained in the optimal path, then set $\delta^*_{i,j,l,t} = 1$; similarly, if $(X_{l,N_{i,j}-1}, X_{\mathrm{d}})$ is contained in the optimal path, then $\delta^*_{i,j,l,N_{i,j}} = 1$.

According to the obtained resource allocation strategy, the transmission delay of $L_{i,j}$ can be calculated as

$$D^*_{i,j} = \sum_{l=1}^{L} \sum_{t=1}^{N_{i,j}} \tau \delta^*_{i,j,l,t} \frac{S}{R_{i,j,l}}. \tag{26}$$

5.2 Solution to the Route Selection Subproblem

For given resource allocation strategies of $L_{i,j}$, $1 \le i,j \le M, i \ne j$, we can then solve the route selection problem of the CSV. To this end, we model the CVANET as a weighted graph, and solve the optimal route selection problem between the CSV and the CDV by means of Dijkstra's Algorithm [11].

Route Selection Subproblem Formulation. Based on the obtained optimal resource allocation strategy and the minimum transmission delay of the candidate links, the corresponding end-to-end transmission delay between the CSV and the CDV can be calculated as

$$D^{\mathrm{tot}} = \sum_{i=0}^{M} \sum_{j=1, j\ne i}^{M+1} \beta_{i,j} D^*_{i,j}. \tag{27}$$

The route selection subproblem which minimizes the end-to-end transmission delay can be formulated as

$$\begin{aligned} &\min_{\beta_{i,j}} D^{\mathrm{tot}} \\ &\text{s.t } \ \mathrm{C1} - \mathrm{C4} \text{ in } (22). \end{aligned} \tag{28}$$

The optimization problem (28) is the problem of determining the shortest path between two points in a given network model. By modeling the CVANET considered in this paper as a weighted directed graph in graph theory, Dijkstra's algorithm can be used to obtain the optimal route with the minimum end-to-end transmission delay [11].

Dijkstra's Algorithm-Based Optimal Route Selection Strategy. Dijkstra's algorithm is widely used to solve the shortest path problem in a weighted directed graph. In order to apply the Dijkstra's algorithm to solve the optimization problem formulated in (28), the network topology of the CVANET is modeled as a weighted directed graph $G = (V, E, W)$, where V denotes the set of CVs, i.e., $V = \{V_0, V_1, \cdots, V_{M+1}\}$, E is the candidate link set, $E = \{L_{i,j}\}$, $W = \{D^*_{i,j}\}$ is the weight set of $L_{i,j}$.

According to the Dijkstra's algorithm, the CVs in graph G are divided into unlabeled nodes and labeled nodes. All nodes are unmarked nodes at the initialization phase.

Let U^{u} and U^{l} represent the unlabeled nodes and the labeled nodes respectively, and η_i denote the optimal transmission delay between V_0 and V_i, $1 \leq i \leq M+1$, we set $\eta_0 = 0$. Let $\Pr(V_i)$ denote the predecessor node of V_i, i.e., the last hop node of V_i along the path from the CSV to the CDV.

The steps to determine the shortest path between the CSV and the CDV based on Dijkstra's algorithm are as follows:

Step 1: Initialization phase
Let $\eta_i = \infty$, $1 \leq i \leq M+1$. If V_i and V_j are not single-hop neighbor nodes, then $D^*_{i,j} = \infty$. Let $U^{\mathrm{u}} = \{V_i,\ 1 \leq i \leq M+1\}$, $U^{\mathrm{l}} = \{V_0\}$ and $V_t = V_0$.
Step 2: Search one-hop shortest CRV of V_i
If V_i is a one-hop neighbor of V_t, calculate η_i. If $\eta_t + D^*_{t,i} < \eta_i$, then $\eta_i = \eta_t + D^*_{t,i}$. For all one-hop neighbor nodes of V_t, select the one with the shortest distance between V_t, which can be denoted as V_x, i.e.,

$$V_x = \arg\min_{L_{t,i} \in E} \{\eta_i\}, \tag{29}$$

then $\Pr(V_x) = V_t$, $U^{\mathrm{u}} = U^{\mathrm{u}} - \{V_x\}$, $U^{\mathrm{l}} = U^{\mathrm{l}} \cup \{V_x\}$, and $V_t = V_x$.
Step 3: Determine the optimal route
Repeat step 2 until $V_t = V_{M+1}$, the algorithm terminates, and the optimal route can be determined by searching $\Pr(V_x)$ in reverse order. As a result, the route with the minimum end-to-end transmission delay between the CSV and the CDV can be obtained, i.e., $\beta^*_{i,j} = \arg \min_{\beta_{i,j}} \{D^{\mathrm{tot}}\}$.

6 Simulation Results

In this section, MATLAB simulation software is used to evaluate the performance of the proposed joint route selection and resource allocation algorithm. In the simulation, it is assumed that all the CVs are randomly distributed on a $1000\,\mathrm{m} \times 15\,\mathrm{m}$ road section. Simulation parameters are shown in Table 2.

In the simulation, our proposed algorithm is compared with the route selection algorithm proposed in [3] and the random channel allocation algorithm. To examine the performance of the route selection algorithm proposed in [3], we first apply our proposed resource allocation strategy on the candidate links, and then determine the optimal route selection strategy based on the algorithm proposed in [3]. To examine the performance of the random channel allocation algorithm, we first randomly select the available channel for the CSV and the CRVs and then apply our proposed end-to-end transmission delay minimization-based route selection algorithm to obtain the optimal route selection strategy.

Figure 3 shows the end-to-end transmission delay versus the number of channels. It can be seen from the figure that as the number of channels increases, the end-to-end transmission delay gradually decreases for our proposed algorithm and the algorithm proposed in [3]. This is because the diversity of channel selection results in better transmission performance. Comparing the transmission performance obtained from three algorithms, we can see that our algorithm outperforms the other two algorithms. The

Table 2. Simulation parameter list

Parameter	Value
The maximum communication range of CSV and CRVs	300 m
Number of CRVs	40
Speed of CSV, CRVs and CDV	60–80 km/h
Packet size	1280 bits
Length of time slot	5 ms
Number of channels	3–12
Channel bandwidth	1 MHz
Transmission power of CSV and CRVs	0.1–1 W
Noise power	−136 dBm
Center frequency of channels	1 GHz

reason is that the route selection algorithm proposed in [3] aims at maximizing the transmission data rate, which may result in suboptimal end-to-end transmission delay. Furthermore, as the random channel allocation algorithm randomly selects the transmission channel, thus may offer undesired transmission performance.

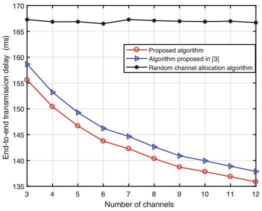

Fig. 3. End-to-end transmission delay versus the number channels.

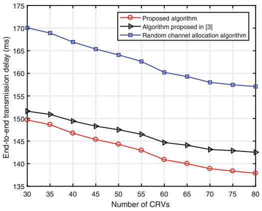

Fig. 4. End-to-end transmission delay versus the number of CRVs.

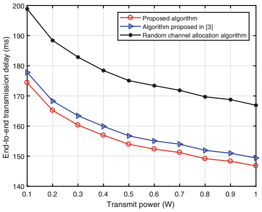

Fig. 5. End-to-end transmission delay versus the transmit power of CSV and CRVs

Figure 4 shows the end-to-end transmission delay versus the number of CRVs. From the figure we can see that as the number of CRVs increases, the end-to-end transmission delay decreases. This is because the larger number of CRVs may offer the increased number of available transmission links and transmission routes in turn, resulting in better transmission performance. It can also be observed that compared with the other two algorithms, our proposed joint optimization algorithm enjoys desired transmission performance.

Figure 5 shows the end-to-end transmission delay versus the transmit power of the CSV and the CRVs. We can see from the figure that the end-to-end transmission delay decreases as the transmit power of the CVs increases. This is because larger transmit power offers better transmission data rate and smaller transmission delay in turn. In addition, we can also observe that the proposed joint optimization algorithm achieves the smallest end-to-end transmission delay compared with the other two algorithms.

7 Conclusions

In this paper, the problem of joint route selection and resource allocation in CVANETs is addressed. We first examine the stability of the transmission links in the network and propose a candidate link selection method which selects the transmission links satisfying the link lifetime constraint. We then formulate the joint route selection and resource allocation problem as an end-to-end transmission delay minimization problem. By equivalently transforming the original problem into two subproblems, i.e., resource allocation subproblem for candidate links and route selection subproblem and solving the two optimization subproblems by applying the K shortest path algorithm and the Dijkstra's algorithm, respectively, the optimal joint route selection and resource allocation strategy can be obtained. To examine the performance of our proposed algorithm, we compare it with the route selection algorithm proposed in [3] and the random channel allocation algorithm. Simulation results demonstrate the effectiveness of the proposed algorithm.

References

1. Jiang, C., Chen, Y., Liu, K.R.: Data-driven optimal throughput analysis for route selection in cognitive vehicular networks. IEEE J. Sel. Areas Commun. **32**, 2149–2162 (2014)
2. Miao, P., Li, P., Fang, Y.: Cooperative diversity in wireless networks: efficient protocols and outage behavior. IEEE J. Sel. Areas Commun. **30**, 760–768 (2012)
3. Ghafoor, H., Koo, I.: CR-SDVN: a cognitive routing protocol for software-defined vehicular networks. IEEE Sens. J. **18**(4), 1761–1772 (2018)
4. Wang, C., Zhang, L., Li, Z., Jiang, C.: SDCoR: software defined cognitive routing for Internet of vehicles. IEEE Internet Things J. **5**, 3513–3520 (2018)
5. Kim, W., Oh, S.Y., Gerla, M., Lee, K.C.: CoRoute: a new cognitive anypath vehicular routing protocol. Wirel. Commun. Mob. Comput. **11**(12), 1588–1602 (2011)
6. Chu, J.H., Feng, K.T., Lin, J.S.: Prioritized optimal channel allocation schemes for multi-channel vehicular networks. IEEE Trans. Mob. Comput. **14**(7), 1463–1474 (2015)
7. Cordeschi, N., Amendola, D., Baccarelli, E.: Reliable adaptive resource management for cognitive cloud vehicular networks. IEEE Trans. Veh. Technol. **64**(6), 2528–2537 (2015)
8. He, H., Shan, H., Huang, A., Sun, L.: Resource allocation for video streaming in heterogeneous cognitive vehicular networks. IEEE Trans. Veh. Technol. **65**(10), 7917–7930 (2016)
9. Qian, J., Jing, T., Huo, Y., Zhou, W., Li, Z.: A next-hop selection scheme providing long path life-time in VANETs. In: IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1929–1933 (2015)
10. Liu, H., Jin, C., Yang, B., Zhou, A.: Finding top-K shortest paths with diversity. IEEE Trans. Knowl. Data Eng. **30**(3), 488–502 (2018)
11. Cormen, T.H., Leiserson, C.E., Ronald, R.L., Stein, C.: Introduction to Algorithms, 2nd edn, pp. 595–601. MIT Press and McGraw-Hill, London and New York (2001). Section 24.3: Dijkstra's Algorithm