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Research paper

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QoS-aware interference management for vehicular D2D relay networks

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Abstract: Vehicular network communication technology is currently attracting a considerable amount of attention. We consider a scenario in which vehicular communication nodes share the same spectrum resources and generate interference with other nodes. Compared with traditional interference-avoiding vehicular communications, this paper aims to increase the number of accessed communication links under the premise of satisfying the required QoS. In our research, communication nodes have opportunities to select relay nodes to both help improve their data transmissions and reduce their transmit power in order to decrease interference with other links while still satisfying their QoS requirements. Based on these objectives, we propose an innovative interference management method that considers link selection, power adaption, and communication mode selection simultaneously to maximize the number of communication links with the lowest power cost. Compared with traditional link-selection and power-adaption interference management schemes, the proposed scheme improves QoS satisfaction with high energy efficiency. Simulation results demonstrate both the efficiency and the effectiveness of the proposed scheme.

Keywords: vehicular networks, interference management, link selection, power adaption, energy efficiency

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1 Introduction

As one of the most critical technologies for 5G communication networks of the future, VANETs (Vehicular Ad-hoc Networks) have gradually attracted more research interest[1-3]. Both the importance and the potential impact of VANETs have been confirmed by the rapid proliferation of consortia involving car manufacturers, various government agencies and academia[4]. Specifically, VANETs can be formed among vehicles via V2V (Vehicle-to-Vehicle) communication or between vehicles and an infrastructure via V2I (Vehicle-to-Infrastructure) communication[5-8]. However, high vehicle mobility

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results in channels instability of channels between vehicles[9,10], which causes drawbacks for VANETs, including higher probabilities of network partitioning and lower guarantees of end-to-end connectivity.

On the other hand, frequency reuse is the most direct way to satisfy the increasing system capacity demands using the limited available spectrum resources. According to Refs. [11-13], frequency reuse is the simplest and most efficient way of increasing system capacity of the four methods studied, (i.e., resource scheduling, adaptive modulation and coding, bandwidth expansion, and frequency reuse). However, the most serious problem that frequency reuse causes is interference among communications links on the same frequency band[14]. Therefore, interference management needs to be addressed urgently.

At present, there are several typical communication scenarios that consider interference management specifically. In a CDMA (Code Division Multiple Access) system, different users can access the same frequency resources and communicate by using orthogonal spreading codes[15]. Interference management is needed to reduce the impact of multiple access interference. A cognitive radio system[16] contains both primary and secondary users. For this type of network, an efficient interference management scheme has to be designed to limit the interference caused by secondary users to primary users without affecting the normal communications of primary users. In a D2D (Device-to-Device) system[17-19], D2D communication links share the same spectrum with cellular communication links. Therefore, an interference management scheme should be utilized to guarantee that the interference between the D2D and cellular users is limited to satisfy their respective QoS (Quality of Service) requirements.

In vehicular networks, when either V2V or V2I communication links require access to the networks, they can access either the idle channels, in order to avoid interference from the other links, or the channels which are occupied (i.e., they share spectrum resources with other links). The first mode is called the overlay mode and focuses on the design of the channel access mechanism, while the second mode is called the “underlay mode” and is more concerned with either satisfying the basic QoS requirements or maximizing the system capacity under interference-limited circumstances. Currently, the underlay mode is attracting much research interest because of its advantages in improving spectrum efficiency. With respect to the coexistence of V2I and V2V links in vehicular networks, this scenario can easily be compared with D2D underlaying cellular networks, in which the D2D communication mode can be used to support V2V communications in order to increase the spectrum efficiency. However, because of the existence of unique vehicular scenarios[20-22] with high-speed vehicle mobility and fast time-variant channels, the traditional D2D mode cannot be adopted directly for V2V communications. Thus, significant modifications and improvements are needed. In Ref. [23], the authors investigated a scenario in which V2V and V2I communication links are able to reuse frequency resources for the first time and use graph theory to solve the problem of maximizing system capacity. Recently, the feasibility of the use of D2D technology in VANETs was investigated comprehensively in Ref. [24] and novel and practical D2D-based vehicular communication systems were developed by using both channel prediction and interference modeling.

In this paper, we focus on the design of an interference management scheme in vehicular networks. In contrast to Refs. [23,24], the main contributions of this paper can be summarized as follows.

- A more practical scenario: In future vehicular networks, multiple types of services will co-exist. Therefore, we consider a more practical scenario in which the transmission priorities of different communication links are taken into account. We first focus on satisfying the QoS of high-priority services with a minimum power cost and then consider maximizing the QoS requirements of low-priority services. For this process, optimizing the system objective function becomes a sequencing optimization problem.
- An adaptive relay selection scheme: In a scenario in which the V2V and V2I communication links

share the same spectrum resources, their interference relationship becomes very complicated. Because of this, we propose an adaptive relay selection scheme in which the V2V and V2I links can select the relay transmission mode adaptively either to improve the transmission rate or to reduce their interference with other links when their QoS requirements have been satisfied.

• A graph theory based heuristic algorithm: Graph theory has been shown to be an efficient method for solving the resource management problem[25,26]. We propose a heuristic iterative algorithm based on graph theory that considers the link selection, power adaption, and relay mode selection together in order to satisfy the QoS requirements of as many communication links as possible, providing a sub-optimal solution. Comparisons with the schemes considered in previous works demonstrate both the efficiency and the effectiveness of our algorithm in solving the formulated problem.

The rest of this paper is organized as follows. The system model and problem formulation is presented in section 2. The details of the CLPR algorithm are given in section 3. In Section 4, the simulation results and analysis are provided. In section 5, our conclusions are presented.

2 System model and problem formulation

2.1 System description

Consider a D2D-based vehicular relay network composed of M V2V pairs and N vehicle nodes for V2I communications in which the desired channel access opportunities are controlled by the RSU (Road Side Unit), as illustrated in Figure 1. We denote the sets of V2V and V2I communication links as $\mathcal{M}$ and $\mathcal{N}$, respectively. In set $\mathcal{M}$, the source and destination nodes of each V2V communication link are denoted as S_m and D_m, respectively, with $m = 1, 2, \cdots, M$. For each V2I communication link in set $\mathcal{N}$, the source node is the RSU and the destination node is denoted as U_n for $n = 1, 2, \cdots, N$. We use $\mathcal{S}$, $\mathcal{D}$, and $\mathcal{U}$ to denote the sets of S_m, D_m, and U_n, respectively. Unlike conventional D2D cellular network communication in which the cellular users have higher transmission priorities than the D2D users, the transmission priority of each communication link depends on the urgency of its corresponding type of service in the vehicular network. For example, the safety related services have an absolute channel access advantage over the services that are unrelated to safety. We propose that there are L urgency levels for vehicular communication services and thus L corresponding transmission priority levels.

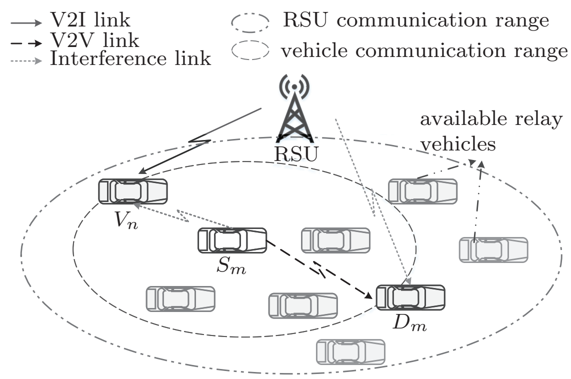

Figure 1 System model in support of V2I and V2V communications

In order to achieve a high spectrum efficiency, the V2V and V2I communications cooperate in an underlay manner. As a result, each communication link receiver experiences interference from the transmitters of the other communication links that are accessing the channel at the same time. It is not feasible to accommodate all of the links with transmission requests without limitations, since an increase in the number of links accommodated leads to higher interference. If the interference increases above a certain level, the spectrum efficiency will deteriorate and the QoS requirements for individual communications will be violated. Therefore, it is desirable to implement an interference management technique in the V2V and V2I underlay communication scenario to achieve the desired system performance while still guaranteeing the QoS requirements, especially for services with high transmission priorities. In addition to considering the two conventional interference management dimensions (i.e., scheduling and power adaption), we also consider relay technology to improve the interference management efficiency further, involving the following two transmission modes in the system:

1. DTM (the Direct Transmission Mode), in which the source node sends the data directly to the destination node without the help of intermediate nodes.

2. RTM (the Relay Transmission Mode), where the communication is completed in two transmission phases. In transmission phase 1, the source node sends the data to the relay node, which retransmits the data to the destination node with DF (Decode-and-Forward) protocol in transmission phase 2.

The set of candidate relay nodes selected for the RTM is denoted as $\mathcal{R} = \{R_1, R_2, \cdots, R_K\}$ and is composed of the available vehicles without data transmission requests. Relay technology can bring benefits in two respects: one is in reducing the interference with other communication links by splitting each long-range communication link with a high power cost into two short-range relay links with low power costs, and the other is in improving the transmission rates under certain communication scenarios. Although half of the achievable transmission rate is sacrificed due to RTMs two-phase transmission, its transmission rate can still exceed that of DTM with an equal power cost. Both analyses of performance and a comparison between DTM and RTM are presented in section 4. Mode switching between DTM and RTM as well as the power cost of each communication link are controlled by the RSU. Examples of both joint power adaption and mode selection are shown in Figure 2, in which the RSU adjusts the transmit power of the V2I communication link and the V2V communication link switches to RTM. Compared to that in Figure 1, the interference between the V2V and the V2I communications is reduced in Figure 2. In addition to pursuing throughput maximization as in conventional interference management, we choose to maximize QoS satisfaction of high transmission priority communications with a minimum power cost under a multi-priority vehicular communications network scenario. The QoS satisfaction of the communication link v_i ($v_i \in \{\mathcal{M}, \mathcal{N}\}$) is indicated by

$$Q_i = \begin{cases} r_i/\hat{r}_i, & \text{if } r_i/\hat{r}_i < 1; \\ 1, & \text{if } r_i/\hat{r}_i \geqslant 1, \end{cases} \tag{1}$$

where r_i and $\hat{r}_i$ denote the achievable and required transmission rates of v_i, respectively. Note that $\hat{r}_i$ depends on the QoS requirement of v_i, while r_i is determined by the realistic communication environment in the charge of RSU through interference management using link selection, power adaption, and mode selection together. Because the communication environment is complex, involving both power control and relay technology, we utilize the graph method to simplify the formulation of the interference management problem. The process of formulating the problem using the graph method will be described in the following subsection.

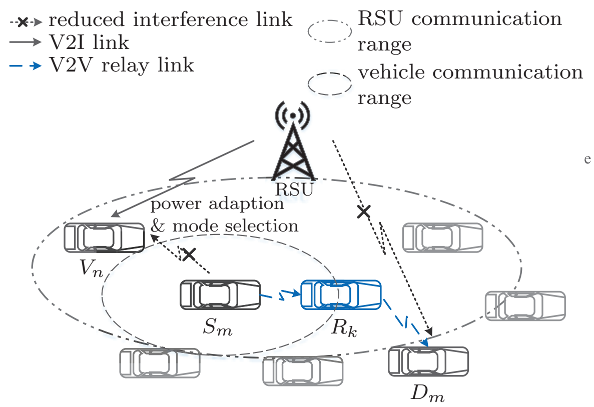

Figure 2 Example of power adaption and mode selection

2.2 Graph-based problem formulation

Because the system under consideration utilizes two-phase relay transmission, we assume that one transmission frame T allocated to each communication link is further divided into two equal subframes (i.e., $\{t_1, t_2\}$). For the communication links with DTMs, the data is sent from the source node to the corresponding destination node in both t_1 and t_2. For the communication links with RTMs, the data is first sent from the source node to the selected relay node in t_1 and then relayed to the destination node in t_2. We denote the graph constructed by the interference links among communication links as $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, which is actually a kind of digraph since the interference between any two communication links is directional. In the vertex set $\mathcal{V}$, each vertex v_i ($v_i \in \{\mathcal{M}, \mathcal{N}\}$) represents a V2V or a V2I communication link, and both the data transmitter and receiver of v_i could be time-variant depending on the transmission mode. Therefore, we specify the link between the data transmitter and the receiver of v_i in t_1 and t_2 as $v_i(t_1)$ and $v_i(t_2)$, respectively. If v_i is in the DTM, the data transmitter and the receiver of both $v_i(t_1)$ and $v_i(t_2)$ are the source and destination nodes of v_i, respectively. If v_i is in the RTM, the data transmitter and receiver of $v_i(t_1)$ are the source node and the selected relay node of v_i, respectively, and the data transmitter and the receiver of $v_i(t_2)$ are then the selected relay node and the destination node of v_i, respectively. For simplicity, we denote the source node, destination node, and relay node (if it exists) of v_i as s_i, d_i, and r_i, respectively. Thus, we have $s_i \in \{\mathcal{S}, RSU\}$, $d_i \in \{\mathcal{D}, \mathcal{U}\}$, and $r_i \in \mathcal{R}$. Accordingly, each edge $e_{ij} = \langle v_i, v_j \rangle$ ($e_{ij} \in \mathcal{E}$) characterizing the interference link between the transmitter of v_i and the receiver of v_j might also varies between t_1 and t_2 due to the transmission modes of v_i and v_j. We then use $e_{ij}(t_a) = I_{ij}(t_a)$ ($a = 1, 2$) to denote the interference from $v_i(t_a)$ on $v_j(t_a)$ in t_a. Note that the interference between any two communication links is affected by the factors of power, interference channel gain, and transmission mode. We specify the interference as that caused by the latter.

Furthermore, we consider six attributes for each vertex v_i:

1. The schedule attribute α_i.
2. The relay attribute β_{ik}.
3. The priority attribute l_i.
4. The QoS attribute q_i.
5. The QoS satisfaction attribute Q_i, which has been defined in Eq. (1).
6. The power attribute P_i.

For the schedule attribute, we have $\alpha_i = 1$ if v_i is allowed to access the channel and $\alpha_i = 0$ otherwise. With respect to the relay attribute, $\beta_{ik} = 1$ if v_i chooses the node R_k from $\mathcal{R}$ as the relay node in RTM, and otherwise, $\beta_{ik} = 0$. Therefore, the relay node r_i selected for v_i is equivalent to R_k with $\beta_{ik} = 1$. If $\sum_{k=0}^{K} \beta_{ik} = 0$ and $\alpha_i = 1$, then this indicates that the communication link v_i receives channel access and works in DTM. With respect to the priority attribute, $l_i = 1$ if the transmission priority level of v_i is l, with $l = 1, 2, \cdots, L$, and otherwise, $l_i = 0$. With respect to the QoS attribute, we consider $q_i = r_i / \hat{r}_i$, which indicates the relationship between r_i and $\hat{r}_i$. The power attribute P_i equals the total transmit power cost of v_i. Specifically, if v_i works in DTM, P_i is equal to the transmit power of source node s_i (i.e., P_{s_i}), while if v_i works in RTM, we have $P_i = P_{s_i} + P_{r_i}$, where P_{s_i} and P_{r_i} are the transmit power costs of the source node s_i in t_1 and the selected relay node r_i in t_2, respectively. To achieve fairness, the total transmit power cost should not increase when the communication mode of a link changes between RTM and DTM.

An illustrative example of the interference graph $\mathcal{G}$ in both t_1 and t_2 is shown in Fig. 3. We analyze the achieved transmission rate of v_i, (i.e., r_i), based on the interference graph $\mathcal{G}$, and the problem under consideration is formulated.

In transmission phase 1 (i.e., t_1), the link $v_i(t_1)$ suffers interference from the source nodes of other communication links that are also assigned channel access. The interference experienced at the receiver of $v_i(t_1)$ is given by

$$\begin{aligned} I_i(t_1) &= \sum_{j, j \neq i} I_{ji}(t_1) \\ &= \left(1 - \sum_{k=1}^{K} \beta_{ik}\right) \sum_{j, j \neq i} \left(P_{s_j} \left\| h_{s_j, d_i} \right\|^2 \alpha_j\right) \\ &\quad + \sum_{k=1}^{K} \beta_{ik} \sum_{j, j \neq i} \left(P_{s_j} \left\| h_{s_j, r_i} \right\|^2 \alpha_j\right), \end{aligned} \quad (2)$$

where h_{s_j, d_i} denotes the channel coefficient between s_j and d_i, and h_{s_j, r_i} denotes the channel coefficient between s_j and r_i. The first term of Eq. (2) represents the interference experienced by the destination node d_i of v_i if it works in DTM, while the second term of Eq. (2) represents the interference experienced by the relay node r_i of v_i if it works in RTM.

In transmission phase 2, (i.e., t_2), the link $v_i(t_2)$ receives interference from both the source nodes of the communication links in DTM and the relay nodes of the communication links in RTM. The interference experienced at the receiver of $v_i(t_2)$ is given by

$$\begin{aligned} I_i(t_2) &= \sum_{j,j\neq i} I_{ji}(t_2) \\ &= \sum_{j,j\neq i}\left[P_{s_j}\left\|h_{s_j,d_i}\right\|^2\alpha_j\left(1-\sum_{k=1}^{K}\beta_{jk}\right)\right] \\ &+ \sum_{j,j\neq i}\sum_{k=1}^{K}\left(P_{r_j}\left\|h_{r_j,d_i}\right\|^2\alpha_j\beta_{jk}\right), \end{aligned} \tag{3}$$

where h_{r_j,d_i} denotes the channel coefficient between r_j and d_i. Therefore, the transmission rate v_i can achieve when it works in DTM is given by

$$\begin{aligned} r_i^D = \frac{1}{2}&\left[\mathrm{lb}\left(1+\frac{P_i\|h_{s_i,d_i}\|^2}{I_i(t_1)+N_0}\right)\right. \\ &\left.+\ \mathrm{lb}\left(1+\frac{P_i\|h_{s_i,d_i}\|^2}{I_i(t_1)+N_0}\right)\right], \end{aligned} \tag{4}$$

which is the average transmission rate throughout t_1 and t_2. When v_i works in RTM, we have

$$\begin{aligned} r_i^R = \frac{1}{2}&\left[\min\left\{\mathrm{lb}\left(1+\frac{P_{s_i}\|h_{s_i,r_i}\|^2}{I_i(t_1)+N_0}\right),\right.\right. \\ &\left.\left.\mathrm{lb}\left(1+\frac{P_{r_i}\|h_{r_i,d_i}\|^2}{I_i(t_2)+N_0}\right)\right\}\right], \end{aligned} \tag{5}$$

which suffers from a rate loss because of the use of two-phase transmission. We can further merge r_i^D and r_i^R to unify the transmission rate r_i of communication link v_i as

$$r_i = \alpha_i\left[\left(1-\sum_{k=1}^{K}\beta_{ik}\right)r_i^D + \sum_{k=1}^{K}\left(\beta_{ik}r_i^R\right)\right]. \tag{6}$$

Both the QoS attribute q_i and the QoS satisfaction attribute Q_i can then be calculated with Eq. (6). The system optimization problem for maximizing the overall QoS satisfaction of high priority communication links with a minimum power cost is formulated as

$$\underset{l=1,2,\cdots,L}{\text{sort max}}\ Q_l = \sum_{i,v_i\in\{\mathcal{M},\mathcal{N}\}} l_i Q_i \tag{7}$$

$$\min\ P_T = \sum_{i,v_i\in\{\mathcal{M},\mathcal{N}\}} \alpha_i P_i \tag{8}$$

s.t.

$$0 < P_i \leqslant P_{i\max} \tag{9}$$

$$l_i,\alpha_i,\beta_{ik}\in\{0,1\},\forall i,k,l \tag{10}$$

$$\sum_{k=1}^{K}\beta_{ik}\in\{0,1\},\forall i \tag{11}$$

$$\sum_{i,v_i\in\{\mathcal{M},\mathcal{N}\}}\beta_{ik}\in\{0,1\},\forall k \tag{12}$$

$$\sum_{i,v_i\in\{\mathcal{N}\}}\alpha_i\in\{0,1\}, \tag{13}$$

under the following five constraints:

- The power cost for each link v_i is no greater than the maximum power $P_{i\max}$ described in Eq. (9).
- Because l_i, α_i, and β_{ik} are all indicators, the constraints as described in Eq. (10) apply.
- For each V2I and V2V link, the transmitter selects only one node as a relay to assist in its data transmission, as described in Eq. (11).
- Each relay node can help only one node conduct its data transmission, as described in Eq. (12).
- Only one V2I link can access the network at a time in order to avoid data overlapping at the receiver, as described in Eq. (13).

3 Heuristic combined link-selection, power-adaption and mode-selection solution

3.1 CLPR scheme introduction

The system objective function, formulated in Section 2 includes three main aspects:

- Link selection: whether communication links should access the network or not.
- Power adaption: the transmitters of different links should adapt their transmissions to improve the energy efficiency.

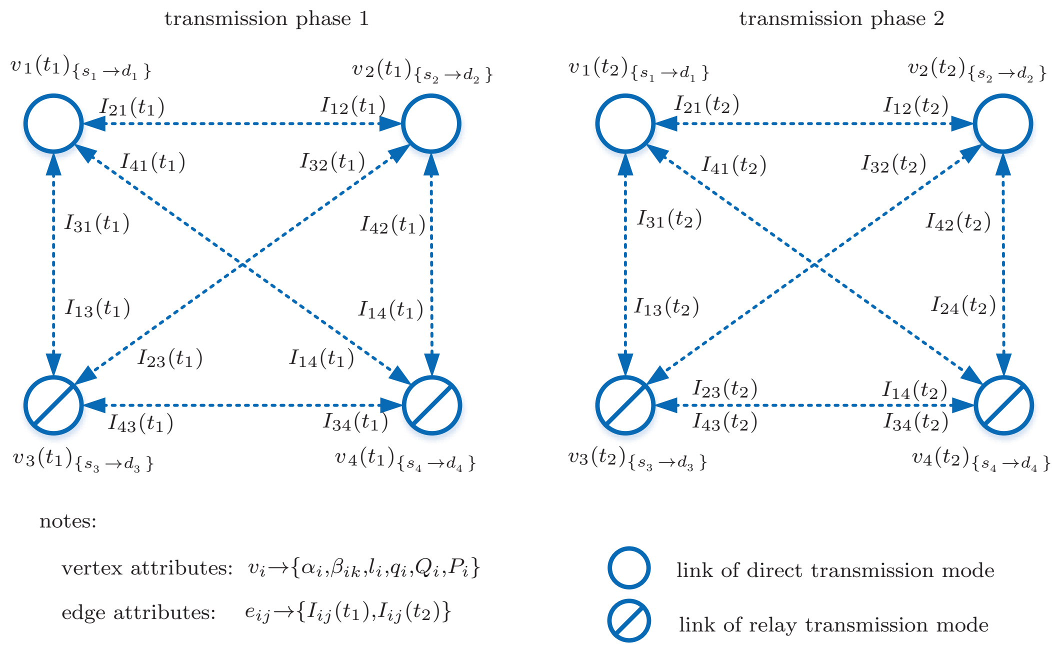

Figure 3 Communication link interference graph

• Mode selection: which means whether different links should select DTM or RTM to implement the transmission process.

Note that the optimization problem in Eqs. (7)-(13) is an NP-hard problem, which cannot be solved in polynomial time. Because of this, in Section 3, we propose a heuristic combined link-selection, power-adaption, and mode-selection (CLPR) scheme to give a near-optimal solution of the problem using a heuristic method with low computational complexity.

The basic concept of the CLPR scheme is to first select links to access the network according to their transmission priorities and then implement the joint optimization process of power-adaption and relay-mode selection. We aim to improve the QoS satisfaction of low-priority links once the QoS requirements of high-priority links have been satisfied. The details of the CLPR scheme are shown in Figure 4.

The following is a detailed discussion of each step in our proposed CLPR scheme.

Step 1: Initialization

We assume A is the set of links which access to the network. A is initialized to be an empty set, i.e., $A = \emptyset$. On the other hand, we also assume there are L sets, i.e., $B_1, B_2, \cdots, B_L$, which represent different link sets containing different service transmission priorities. Note that the links in set B_l are not accessed to the network. At the beginning of our CLPR scheme, we initialize N V2I links and M V2V links as non-accessed state, and classify the communication links with priority l into link set B_l, where $l = 1, 2, \cdots, L$.

We assume A is the set of links that have access to the network. A is initialized as an empty set (i.e., $A = \emptyset$). On the other hand, we assume that there are L sets (i.e., $B_1, B_2, \cdots, B_L$) that represent different link sets containing different service transmission priorities. Note that the links in set B_l are not accessing the network. In the initialization of our CLPR scheme, N V2I links and M V2V links are assigned non-access states, and the communication links with priority l are classified into link set B_l, where $l = 1, 2, \cdots, L$.

Step 2: The calculation and sort of priority factors

According to the objective function, the system will first consider providing access to the links in set B_l that have the highest priority levels. If there are multiple communication links in set B_l, they need to be sorted according to the following two metrics:

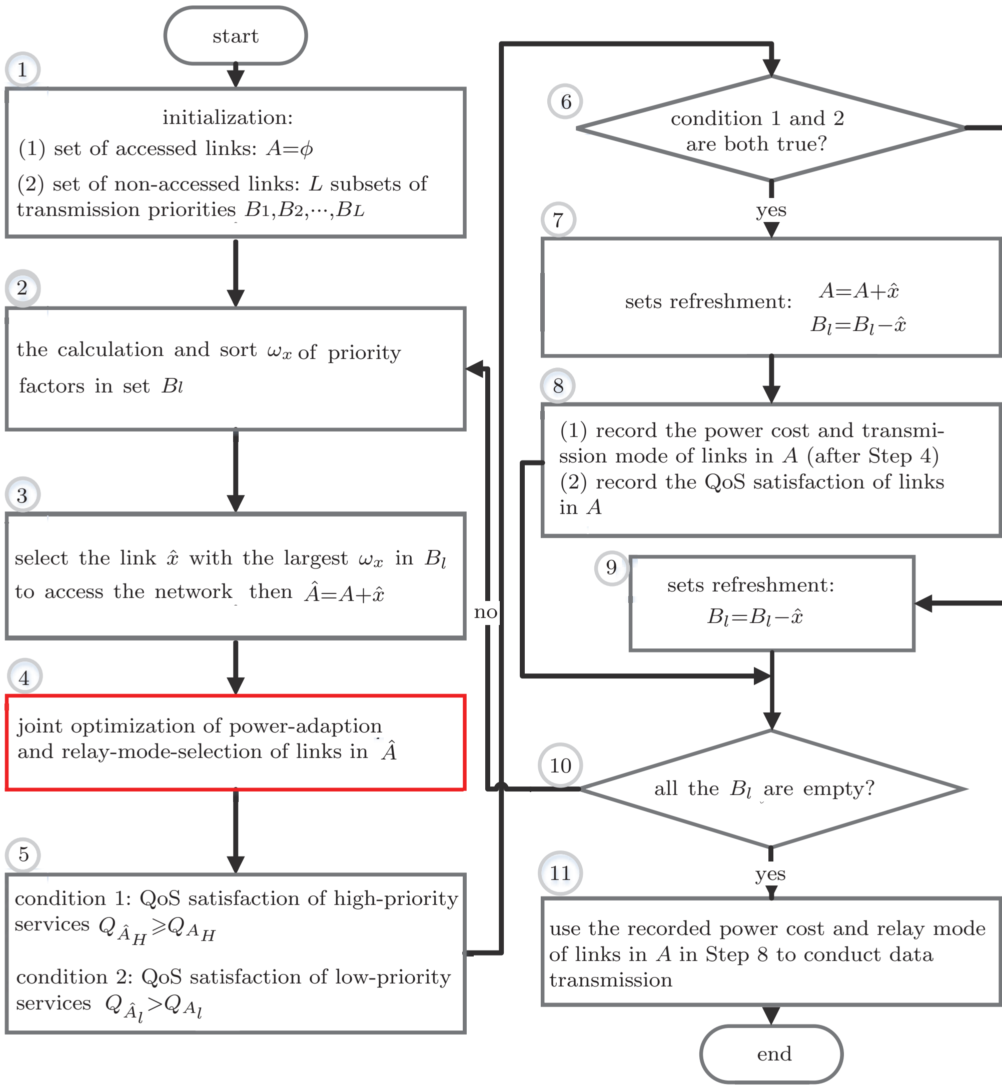

Figure 4 Flow chart for CLPR scheme

- The QoS satisfaction of the links.
- Minimal impact of network access on the QoS of the links that already have access.

Therefore, we denote the access priority factor of link x as:

$$\omega_x = \frac{r_x}{\hat{r}_x} \cdot \frac{1}{\left[1 + \sum\limits_{y \in A} (Q_y - \hat{Q}_y(x))\right]}, \tag{14}$$

where r_x represents the attainable transmission rate and $\hat{Q}_y(x)(y \in A)$ represents the QoS satisfaction factor when link x accesses the network. In Eq. (14), the first term is the unmodified QoS satisfaction factor. As its value grows, the potential for optimization grows as well. The second term in Eq. (14) represents the network impact of accessing link x . A smaller value for this term indicates a lower impact. Note that the constant value of one in the numerator is used to avoid a zero denominator when accessing link x and has no impact on the system.

The calculation of the QoS factor contains the calculations of the transmission rates of different links, (i.e., the calculations of their SINRs). During initialization, we set the transmit power of various links to the maximum transmit power and the transmission mode to DTM. Note that if there is only one link in set B_l, we do not need to calculate the priority factor.

Step 3: Access the link to the network with the highest priority factor

When there are multiple communication links in set B_l, we choose the link $\hat{x}$ with the highest priority factor in B_l to access the network, and we have $\hat{A} = A + \hat{x}$, where $\hat{A}$ represents the new set of links with access. The system selects $\hat{x}$ when there is only one link in B_l.

Note that when set A includes a V2I communication link, because the system can support only one V2I link, the V2V link with the highest priority factor in the V2V subset of B_l is selected to access the network and the other V2I links are deleted from B_l.

Step 4: Joint optimization of power adaption and relay-mode selection

The basic concept of the joint optimization process is summarized in two aspects: 1) For those links whose QoS requirements have been satisfied, the optimization process aims at reducing both the power cost and the interference with other links in order to improve their QoS satisfaction levels; 2) For those links whose QoS has not been satisfied, the process aims at improving the QoS itself. This will be discussed in more detail in the next subsection.

Steps 5-6: Judgement of link accessing condition

According to the system objective function, when the system accesses link $\hat{x}$, the link accessing principles are given by the following:

1. The QoS satisfaction cannot be smaller than when link $\hat{x}$ is not accessing the network (i.e., $Q_{\hat{A}_H} \geqslant Q_{A_H}$), where the priorities of the links in subset A_H are higher than the priority of $\hat{x}$.

2. The sum of the QoS satisfaction of links whose priorities are the same as $\hat{x}$ has to be higher than that of the non-accessing links (i.e., $Q_{\hat{A}_\ell} > Q_{A_\ell}$), where $Q_{\mathcal{A}} = \sum\limits_{x\in\mathcal{A}} Q_x$ ($\mathcal{A} = \{\hat{A}_\ell, A_\ell\}$).

When conditions (1) and (2) are both satisfied, the RSU selects link $\hat{x}$ to access the network, and goes on to steps 7-8. Otherwise, link $\hat{x}$ will not be receive access because of the decreasing impact of the high-priority links on the QoS satisfaction, and the RSU will go on to step 9 as a consequence.

Steps 7-8: Refreshing the link set that has network access and recording the system configuration

When link $\hat{x}$ is accessing the system, we have $A = A + \hat{x}$, and $B_\ell = B_\ell - \hat{x}$. After the joint optimization process in step 4, several parameters have to be recorded:

1. Both the transmit power and the transmission mode of the links in the refreshed link set A.

2. The QoS satisfaction levels of the links in A, (i.e., Q_n) when the n-th V2I link belongs to A), and Q_m when the m-th V2V link belongs to A. The records of QoS satisfaction can be used in steps 5-6 for accessing the next link.

After all of the parameters have been recorded, the RSU will continue to step 10.

Step 9: Refreshing the link set that does not have network access

When link $\hat{x}$ has accessed the system, we only need to set the link set that does not have network access B_ℓ as $B_\ell = B_\ell - \hat{x}$.

Step 10: Selecting the next link to access the network

After the processes in steps 7-8 and step 9 are complete, link $\hat{x}$ is deleted from set B_ℓ. If $B = \bigcup\limits_{l=1}^{L} B_l$ is not an empty set, the RSU will return to step 2. Otherwise, it will go on to step 11 to process the final resource allocation.

Step 11: Allocating resources

After the joint optimization of link-selection, power-adaption and relay-mode selection, the resource allocation result recorded in steps 7-8 is applied to the transmissions of the communication links that have network access.

3.2 Details of the joint optimization process

In this subsection, we discuss the critical part of the CLPR scheme, the joint optimization of power-adaption and relay-mode selection, in detail. The

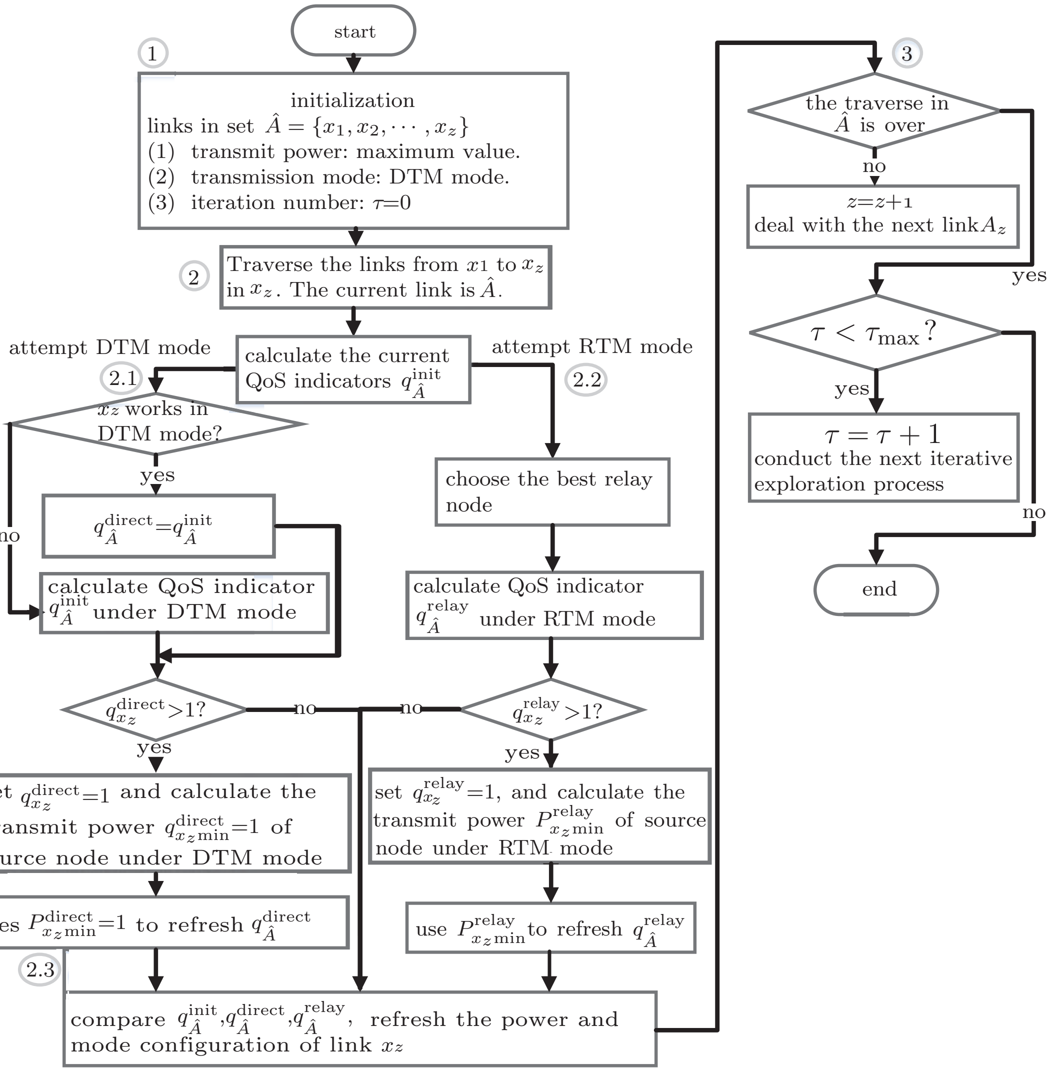

Figure 5 Flow chart of the CLPR scheme's joint optimization process

proposed algorithm adapts a heuristic method to obtain a near-optimal solution. The details of this process are shown in the flow chart in Figure 5.

Step 1: Initialization

We assume that during step 4 of the CLPR scheme, $\hat{A}=\{x_1,x_2,\cdots,x_Z\}$. Each link x_z is initialized to communication in DTM mode, and the transmit power of each link transmitter is set to the maximum value.

Step 2: Power-adaption and relay-mode selection

In this step, we traverse each link in to conduct the power-adaption and relay-mode selection process. Each link explores the best QoS satisfaction for itself iteratively under both DTM and RTM and then selects a relay mode and adjusts the transmit power. We assume the present self-adaptive link is x_z. When x_z transmits in DTM, we go on to step 3. Otherwise, we go on to step 4.

Note that link QoS indicator $q_x=r_x/\hat{r}_x$ is introduced to justify whether the QoS of link x is satisfied or not. $q_x\geqslant 1$ and $q_x<1$ represent the QoS being satisfied and not satisfied, respectively. We assume both that the initial QoS indicator vector is $q_{\hat{A}}^{\text{init}}=\{q_{x_{z'}}|x_{z'}\in\hat{A}\}$, and that the initial power vector is $P_{\hat{A}}^{\text{init}}=\{P_{x_{z'}}|x_{z'}\in\hat{A}\}$. In DTM, the total transmit power of a link is the power of its source node, while in RTM, the total power is the sum of the transmit powers of the source and relay nodes.

Step 2.1: DTM exploration

First, we calculate the QoS indicator vector $q_{\hat{A}}^{\text{direct}}$ under DTM. When link x_z works in DTM, we have $q_{\hat{A}}^{\text{direct}} = q_{\hat{A}}^{\text{init}}$, and when x_z works in RTM, we reset x_z to DTM, and refresh the vector $q_{\hat{A}}^{\text{direct}}$.

When $q_{x_z}^{\text{direct}} < 1$, there is room for x_z to reduce its transmit power further, in order to both decrease its interference with other links, and improve their QoSs. Therefore, the transmit power of x_z (i.e., $P_{x_z \min}^{\text{direct}}$) should satisfy the following formula when it works in DTM mode and when $q_{x_z}^{\text{direct}} = 1$:

$$\frac{W}{2}\left[\text{lb}\left\{\left(1+\frac{P_{x_z \min}^{\text{direct}}\left\|h_{x_z}^{\text{direct}}\right\|^2}{I_{x_z 1}^{\text{direct}}+N_0}\right)\right.\right. \cdot \left.\left.\left(1+\frac{P_{x_z \min}^{\text{direct}}\left\|h_{x_z}^{\text{direct}}\right\|^2}{I_{x_z 2}^{\text{direct}}+N_0}\right)\right\}\right] = \hat{r}_{x_z}. \quad (15)$$

In Eq. (15), $h_{x_z}^{\text{direct}}$ represents the channel between the source communication node and destination node, and $I_{x_z 1}^{\text{direct}}$ and $I_{x_z 2}^{\text{direct}}$ represent the interference from the f_1 and f_2 frequency bands, respectively.

Step 2.2: RTM exploration

First, the QoS indicator vector $q_{\hat{A}}^{\text{direct}}$ is calculated under DTM. We select the best relay node, to help the system obtain the maximum QoS satisfaction, $Q_{\hat{A}}^{\text{relay}}$, from the unoccupied relay node set. Note that $Q_{\hat{A}}^{\text{relay}} = 1$ when $q_{\hat{A}}^{\text{relay}} > 1$.

In order to reduce the computational complexity, the selected relay nodes should be located between the source node and the destination node of one link, i.e., $d_{SR} < d_{SD}$ and $d_{RD} < d_{SD}$, where d_{SR}, d_{RD} and d_{SD} represent the distances between source and relay nodes, the relay and destination nodes, and the source and destination nodes, respectively.

While exploring RTM, the transmit powers of the source and relay nodes of link x_z are represented by $P_{x_z}^S$ and $P_{x_z}^R$, respectively. Then, we have

$$\begin{cases} \dfrac{P_{x_z}^S \left\|h_{SR}(r)\right\|^2}{I_{R1}(r)+N_0} = \dfrac{P_{x_z}^R \left\|h_{RD}(r)\right\|^2}{I_{D2}(r)+N_0} \\ P_{x_z}^S + P_{x_z}^R = P_{x_z}. \end{cases} \quad (16)$$

In Eq. (16), h_{SR} and h_{RD} represent the channels between source and relay nodes and relay and destination nodes, respectively, while I_{R1} and I_{D2} represent the interference experienced in subframes t_1 and t_2, respectively. Note that P_{x_z} is the total transmit power.

The transmit power can be reduced further when the QoS indicator $q_x^{\text{relay}} > 1$. Therefore, we can use the formula below to calculate the minimum required transmit power when link x_z works in RTM mode:

$$\begin{cases} \dfrac{W}{2}\text{lb}\left(\dfrac{P_{x_z}^S \left\|h_{SR}(r)\right\|^2}{I_{R1}(r)+N_0}\right) = \hat{r}_{x_z} \\ \dfrac{W}{2}\text{lb}\left(\dfrac{P_{x_z}^R \left\|h_{RD}(r)\right\|^2}{I_{D2}(r)+N_0}\right) = \hat{r}_{x_z} \\ P_{x_z}^S + P_{x_z}^R = P_{x_z \min}^{\text{relay}}. \end{cases} \quad (17)$$

Then, the transmit powers $P_{x_z}^S$ and $P_{x_z}^R$ can both be refreshed according to Eq. (17).

Step 2.3: Self-adaptive selection of links

After steps 2.1 and 2.2, we obtain the QoS indicator vectors $q_{\hat{A}}^{\text{direct}}$ and $q_{\hat{A}}^{\text{relay}}$. x_z selects the transmission mode that both reduces its transmit power and has no impact on the QoSs of other links. The QoS satisfactions $Q_{\hat{A}}^{\text{direct}}$, $Q_{\hat{A}}^{\text{relay}}$, and $Q_{\hat{A}}^{\text{init}}$ can then be calculated. The transmission mode that leads to the largest sum of QoS satisfaction is selected.

Step 3: Further traversing and iterative exploration

After the power-adaption and relay-mode selection processes, we go back to step 2 to continue traversing other links in $\hat{A}$. When all of the links in $\hat{A}$ have been traversed, we conduct the next iterative exploration process because the interference environment has changed. The exploration process terminates when the number of iteration τ reaches the maximum number $\tau_{\max}$.

In conclusion, we proposed a CLPR scheme to solve the joint optimization problem of system link-selection, power-adaption, and relay-mode-selection.

4 Simulation results and analysis

In the investigated scenario, the range of the vehicular network is a 20 m × 1 000 m rectangular road, the RSU is located in the middle of the roadside, and vehicles are randomly distributed over the road

Table 1 Simulation parameters

parameters	value
maximum transmit power of RSU P_{0max}	40 dBm
maximum transmit power of vehicles P_{vmax}	20 dBm
large-scale fading	128.1 + 37.6 lg(d), where d represents transmission distance
small-scale fading	rayleigh fading coefficient with zero mean and unit variance
range of vehicular network	20 m × 1 000 m
number of V2V links	M
number of V2I links	N
number of relay nodes	K
priority number L	2
required transmission rate	10 Mbit/s
system bandwidth W	10 MHz
RSU position	middle of roadside
V2V communication distance	uniformly distributed from 20 to 200 m
noise power spectral density	–174 dBm/Hz

area. The simulation parameters are shown in detail in Table 1.

As listed in Table 1, services have two kinds of priorities: high and low. We choose the high and low priorities of the communication nodes randomly and with equal probability. In our proposed CLPR scheme, the system can support only one V2I communication link (otherwise the transmission data will overlap at the destination node). Therefore, we set the V2I link number N as 1, and the total number of V2I and V2V links is $U = M + N = M + 1$. Note that the number of relay nodes is $K = 4 \times (N + M)$, which means that there are K/U relay nodes distributed uniformly between each V2I and V2V link. In what follows, we conduct simulations to justify the performance of our proposed CLPR solution in four aspects: 1) the QoS satisfaction, 2) the system transmission rate, 3) the energy efficiency, and 4) the number of relay nodes. The performance comparisons include three schemes:

1. CLPR scheme: The proposed scheme that handles the three-dimensional optimization problem (i.e., combined scheduling, power-adaption, and mode-selection) in order to maximize the system QoS satisfaction with the lowest power cost.

2. CLP scheme: Because communication nodes all work in DTM, this scheme contains only two dimensions: link-selection and power-adaption.

3. Traditional frequency reusing scheme: during the scheduling process, communication nodes can access the network from high priority to low priority (i.e., we optimize the QoS of high-priority links first, followed by low-priority links).

Before conducting the simulations of our proposed CLPR scheme, we should set the maximum iteration number $\tau_{\max}$. Under circumstances of different iteration numbers, the changing process of the QoS satisfaction, i.e., the real transmission rate divided by the required transmission rate, is presented in Fig. 6. From Fig. 6 we can see that the system QoS satisfaction will converge to constant value as the iteration number increases. This is because at the beginning of the iteration process, the real transmission rate is far more higher than the required rate. As the iteration number increases, the real rate of different links gradually approaches the required rate. As shown in Fig. 6, we can set $\tau_{\max}$ as 20 to obtain the near-optimal solution of the optimizing problem.

Before conducting the simulations of our proposed CLPR scheme, we determine the value of the number of maximum iterations $\tau_{\max}$. The changing QoS satisfaction (i.e., the real transmission rate divided by the required transmission rate) is presented in Fig. 6 for different numbers of iterations. From Fig. 6, it is clear that the system QoS satisfaction converges to a constant value as the number of iterations increases. This is because at the beginning of the iteration process, the real transmission rate is far higher than the required rate. As the iteration number increases, the real rates of different links gradually approach the required rate. As shown in Fig. 6, we can set $\tau_{\max}$ as 20 to obtain a near-optimal solution for the optimization problem.

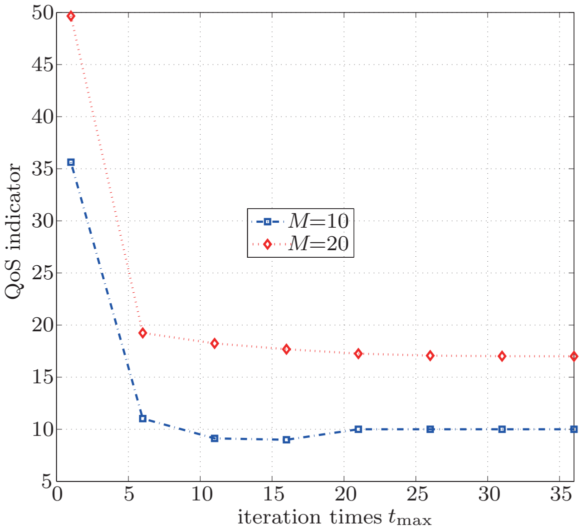

Figure 6 Impact of iteration time$\tau_{\max}$ on the QoS attribute of the proposed CLPR scheme

As stated above, the following part contains simulation results of four aspects:

1. QoS satisfaction, which represents the sum of QoS factor of each link according to Eq. (1). As shown in Fig. 7 (in which HP represents high-priority and LP represents low-priority), in terms of QoS satisfaction, the performance of the CLPR scheme exceeds that of the traditional frequency reusing scheme, and our scheme demonstrates the best performance overall. This confirms the efficiency of our scheme in improving the system QoS when the required transmission rate is satisfied. At the same time, it is clear that the QoS satisfaction of high-priority links is higher than that of low-priority links, which indicates the effectiveness of the priority factor in designing the system model. When the number of links increases, the QoS satisfaction of low-priority links gradually decreases in order to satisfy the QoS satisfaction of high-priority links.

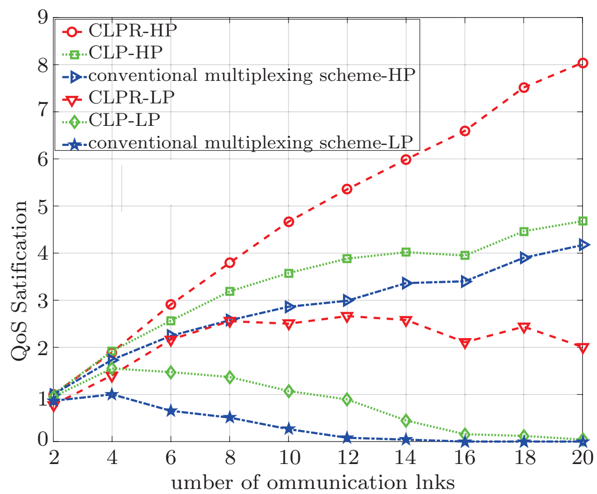

Figure 7 Comparison between proposed and conventional schemes with respect to their communication link QoS satisfaction performances

2. System transmission rate, which represents the sum transmission rate of different communication links. As shown in Figure 8, in comparison to other schemes, the system rate of the proposed scheme is lower than that of the traditional frequency reusing scheme but higher than that the CLP scheme with no relay communication nodes. We can also see that the transmission rate is far higher than the required rate, which demonstrates that there is plenty room for the optimization of both power cost reduction and reduction of interference with other links. On the other hand, the proposed CLPR scheme achieves a rate similar to the required rate. The achievable system rate increases more slowly as the total number of links grows, which illustrates that the number of links with network access gradually approaches a saturation state.

3. Energy efficiency, which represents the ratio

of the QoS satisfaction to the total power cost. The larger the ratio, the higher the energy efficiency. From Figure 9, we can see that the CLPR scheme achieves a better performance than the other two schemes do. Compared with the results shown

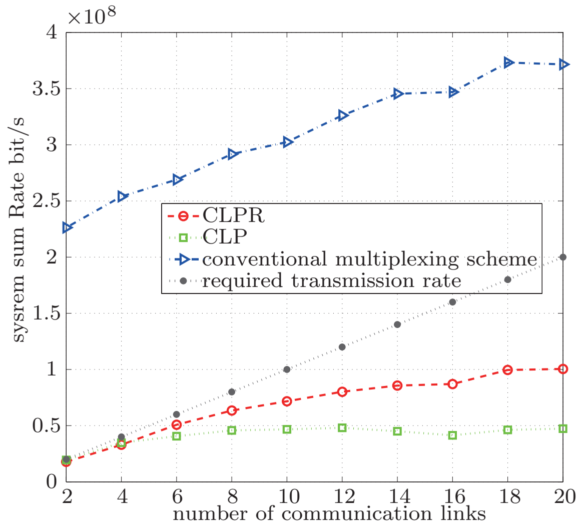

Figure 8 Comparison between proposed and conventional schemes with respect to their communication link QoS satisfaction performances

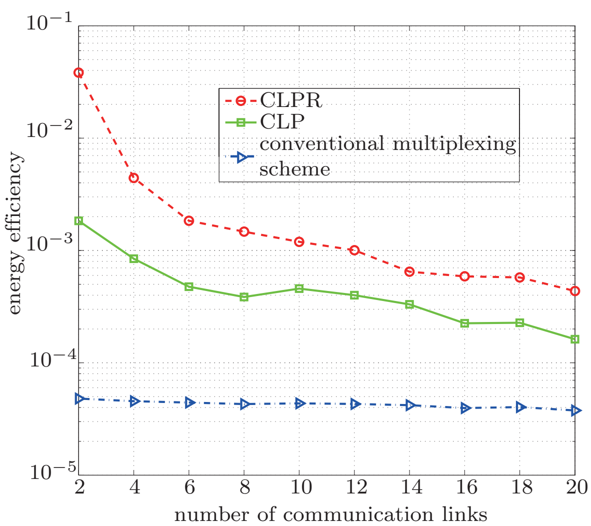

Figure 9 Comparison between proposed schemes and conventional scheme on the performance of energy efficiency

in Fig. 7, the proposed scheme satisfies the QoS of more links with a relatively low power cost, which demonstrates the effectiveness of the three-dimensional optimization method. The energy efficiency of our scheme decreases as the number of links grows. This is because the system needs to increase power costs to satisfy the QoSs of greater numbers of communication links with network access.

4. The number of relay communication nodes, which represents the average number of links that select the relay communication mode. As shown in Fig. 10, in the proposed CLPR scheme, communication links are able to select either DTM or RTM adaptively, which decreases the power cost further in order to reduce the interference with other surrounding links. The average number of links selecting the relay communication mode increases with the total number of links, which explains why the proposed CLPR scheme has better performances than the CLP scheme does in terms of both QoS satisfaction and energy efficiency.

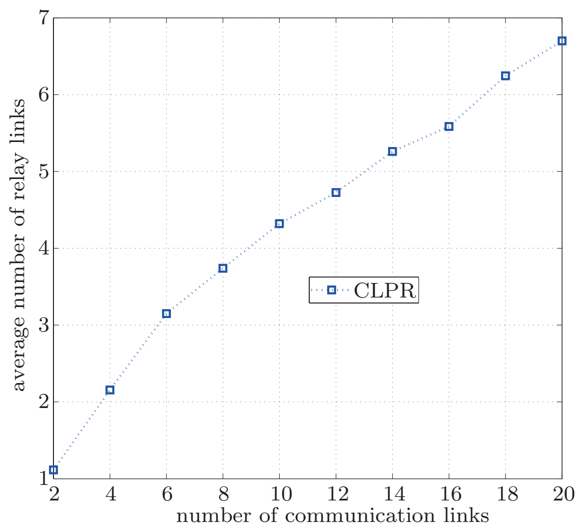

Figure 10 Average number of relay links in the proposed scheme

5 Conclusions

In this paper, we considered a scenario in which vehicular communication nodes shared the same spectrum resources and generated interference for other nodes. Graph theory was used to build a system model and formulate the QoS satisfaction optimization problem. Based on our analysis, we proposed a CLPR scheme to consider link-selection, power-adaption, and relay-mode-selection collectively to maximize the number of communication links with the lowest power cost. Simulation results verified both the efficiency and the effectiveness of the proposed scheme in improving the system QoS satisfaction and the energy efficiency.

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