An urban expressway forwarding scheme for cognitive Internet of vehicles

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Abstract
The Internet of vehicles is an essential component for building smart cities that can improve traffic safety and provide multimedia entertainment services. The cognitive radio–enabled Internet of vehicles was proposed to resolve the conflict between the increasing demand of Internet of vehicles applications and the limited spectrum resources. The multi-hop transmission is one of the most important issues in cognitive radio–enabled Internet of vehicles networks. Nevertheless, most existing forwarding solutions designed for the cognitive radio–enabled Internet of vehicles did not consider the urban expressway scenario, where primary base stations are densely installed with small coverage areas. In this case, it is difficult to ensure that the sender and the receiver of the same cognitive radio link have similar channel availability statistics, which makes cognitive radio links more likely to be interrupted. To address this challenge, we develop a multi-hop forwarding scheme to minimize the end-to-end delay for such networks. We first formulate the delay minimization problem as a non-linear integer optimization problem. Then, we propose an approach to select the relay candidates by jointly considering the high mobility of vehicles and the unique cognitive radio spectrum usage distributions in urban expressway scenarios. Finally, we propose the low-latency forwarding strategies by considering the channel availability and the delay cost of different situations of relay candidates. Simulations show the advantages of our proposed scheme, compared with state-of-art methods.

Keywords
Internet of vehicles, urban expressway, cognitive radio, end-to-end delay, forwarding scheme

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Introduction
The Internet of things (IoT) is a novel communication paradigm that connects physical objects in the world to the Internet. Nowadays, the IoT is widely applied in our social life, such as smart cities, environment monitoring, and health care.¹ The intelligent transportation system (ITS) is an essential component for building smart cities. The Internet of vehicles (IoV) enables the vehicle-to-vehicle (V2V) communication in the ITS, where the core objective is to control accidents, reduce traffic congestion, and improve driving safety in urban areas.² For example, vehicles exchange traffic or accidental information with each other. This objective has the requirement of low-latency data transmission during the V2V communication.³ Due to the plethora of applications in ITS, the high bandwidth demand to

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serve the increasing numbers of vehicles may lead to the spectrum scarcity problem in the IoV environment.

Cognitive radio (CR) technology has emerged as a potential technology to solve the spectrum scarcity problem, and it can improve the spectrum utilization efficiency in IoV networks. In CR-enabled IoV (also called cognitive IoV), the vehicle that equips with CR spectrum sensing terminals can be seen as an unlicensed user/secondary user (SU). Based on the CR-enabled roadside unit (RSU), SU can share the wireless channel along with the licensed user/primary user (PU) in an opportunistic manner. PUs will get the first priority surely, and SUs are allowed to utilize the licensed bands whenever they would not cause any interference to the PUs resulting in high spectrum utilization. When these SUs (vehicles) access the same spectrum holes or white spaces in the licensed spectrum bands, they can communicate with each other. Figure 1 gives an example of V2V communication in cognitive IoV.

Data transmission in multi-hop cognitive IoV is an important issue that affects the performance of the entire networks. Different from the traditional IoV or CR networks, forwarding in cognitive IoV has to consider the spatiotemporal variations of CR channels and high mobilities of vehicles. As vehicles move fast on roads, the spectrum sensing and handoff time may cause the channel state decision out-of-date with a certain probability. The communication links between two neighboring vehicles may be frequently interrupted by PUs’ recurrences. Thus, CR introduces great challenges for the forwarding scheme design in IoV networks.

In this article, we propose a low-latency forwarding scheme for cognitive IoV networks, by considering the special CR spectrum characteristics of urban expressway scenarios in an efficient approach. The rest of this article is organized as follows. The section “Motivation and contribution” specifies motivations and contributions of our work. The section “Related work” presents a concise review of existing related work. The section “System model and problem statement” describes the system model. The section “Relay candidate selection” evaluates the metrics to select relay candidates. The section “Low-latency forwarding scheme” proposes the urban expressway forwarding scheme (UEFS) in detail. Simulation results are presented in the section “Performance evaluation and analysis.” The final section is “Conclusion.”

Motivation and contribution

Motivation

Although some excellent works have been done to address the routing problem in the cognitive IoV, the minimum delay routing problem for the urban expressway environment is not mentioned in such a network. In the urban expressway scenario, some key features should be considered for the cognitive IoV. First, the speed of SUs (vehicles) on the urban expressway is faster than the non-expressway, which includes all types of roads with intersections and traffic lights for pedestrians. Second, two neighboring SU nodes may lie in different primary base station (BS) coverage areas with different channel usage patterns in the urban expressway cognitive IoV. Due to the high mobility of vehicles and the special CR spectrum usage distributions, existing delay-aware routing schemes are not

![Figure 1. V2V communication in cognitive IoV.](image-url)
suitable for the urban expressway scenario. Specifically, the motivation behind our work is based on the following observations.

First, in the urban expressway cognitive IoV, channel switching does occur and happens more frequently than the non-expressway scenario, which increases the channel switching delay significantly. Moreover, if two neighboring SUs do not have at least one available common channel, they have to wait for the channel to become available again or take extra costs to find alternative paths, which intrudes additional channel queuing (waiting) time. Most system models of existing delay-aware routing works only consider the transmission delay and the propagation delay, and they are not suitable for the urban expressway cognitive IoV. Therefore, a novel system model with an accurate delay estimation method is required for the urban expressway scenario, which considers additional delay factors like the channel switching delay and the queuing delay.

Second, a strict principle in cognitive IoT is that a link exists between two SUs if they are in each other’s communication range and share at least one commonly available channel. If the transmission has been established, as the sender and the receiver move fast and are with different velocities, two cases may happen and produce different types of delays for the next time period. One case is that they cannot operate in any commonly available channel for transmission. The other case is that one node moves out of the transmission range of another node. Thus, a multi-metric candidate set selection approach is required, which considers both the CR channel availabilities and the contact durations between two neighboring SUs.

Third, in the urban expressway cognitive IoV, two end nodes of the link may be covered by one BS’s coverage or different BSs’ coverage areas. Due to the inconsistent nature of the mobility speed and the channel availability of different SUs, the transmission links have heterogeneous characteristics with distinct transmission modes. However, existing solutions try to design a unified routing scheme and ignore the unique features of different transmission modes. In specific transmission modes, some complicated calculation steps of the unified scheme are not required, and thus, the computing cost can be further reduced. Moreover, most schemes choose a neighboring SU node that is the closest to the destination and with a minimum transmission delay as the optimal next-hop. Indeed, these schemes can achieve the minimum end-to-end delay for one transmission mode that two end SUs of the link are covered by one BS’s coverage. However, considering the urban expressway scenario, if the sender and the receiver are covered by different BSs’ coverage areas, these schemes cannot reach the minimum value or become unviable because it cannot guarantee that the sender and the receiver have similar channel availability statistics.

The above considerations motivate us to consider different transmission modes for the urban expressway scenario and design multiple forwarding strategies separately, considering the heterogeneous characteristics of the transmission links in cognitive IoT.

**Contribution**

The main contributions of this article include three parts:

We design a system model to study the delay characteristics in the urban expressway cognitive IoT, including the propagation delay, the transmission delay, the channel switching delay, and the queuing delay. We formulate the minimum end-to-end delay problem as a non-linear integer programming problem.

We evaluate the availability of relay candidates by two metrics. One metric is the CR channel availability, which is the idle time slot of available CR channels in adjacent primary BSs located along the urban expressway. The other metric is the contact duration between SUs, which indicates the reliability of the link between two SUs.

We separate the relay candidate set into two subsets based on the discrepancy between road segments. The relaying behaviors between two neighboring nodes are classified into three different transmission modes. We propose three forwarding strategies and analyze the end-to-end delay for these three modes. Specifically, one significant point of our contributions is considering the statuses of CR channel availabilities, which are denoted by two parameters $Z_\mu$ and $Z_{\mu+1}$. The definitions of $Z_\mu$ and $Z_{\mu+1}$ will be described in section “Relay candidates selection.” In the following, we will justify how the channel availability is to be applied in our low-latency forwarding strategies. First, the reliability of the links can be guaranteed by considering the channel availability, and thus, it can reduce the channel switching delay. Specifically, $Z_\mu$ and $Z_{\mu+1}$ can be used for the relay candidate set selection process to determine whether the candidate node and the sender node have at least one common available channel. They can also be used to determine whether the common available time slots can meet the minimum requirement for data transmissions. Second, the channel availability is required for computing the propagation time and the queuing time, which is an important part for implementing the low-latency forwarding scheme. In our scheme, we use $Z_\mu$ and $Z_{\mu+1}$ to compute equations (18)–(20), equations (22)–(24), and equations...
(27)–(29), which can ensure that the output routing solution can achieve the objective.

Related work
Forwarding schemes in IoV

From a theoretical study perspective, several studies on the multicast routing protocol, video transmission, and social-aware data dissemination in the IoV scenario were undertaken recently.

L Zhang et al.\(^9\) present a multicast data delivery scheme with random-delay lowest-cost constraint to transfer service messages on service channels. They propose a priority-aware congestion control scheme by considering differentiated priorities of beacon messages on the control channel, to cope with the congestion at the bottleneck vehicle node. M Ali et al.\(^10\) propose a dissemination scheme for delivering emergency messages in IoV, based on clustering and position-based broadcast techniques. They cluster vehicles to cope with the broadcast storm and utilize the position-based technique to reduce communication delays. D Tian et al.\(^11\) propose a multi-hop routing protocol for video transmission in IoV. They design a packet generation method for the cellular attractor selection and use an order preference to construct the candidate set for the next-hop selection. C Huang et al.\(^12\) propose a member-centric routing protocol to have cooperative video streaming services for the platoon of IoV. They consider a severity strategy and a merged strategy to disseminate data from the multiple sources to the single destination. F Lyu et al.\(^13\) propose a context-aware IoV paradigm design to enhance the V2V communication performance. They investigate the impacts of different contextual information and utilize the high-level contextual information in their design. T Qiu et al.\(^14\) present a scheme that incorporates a community-aware mechanism to propagate data packets in IoV. In their scheme, they search usable smart-phones based on a community-aware mechanism and determine a contact list of vehicles for the long-distance transmission. PY Chen et al.\(^15\) propose a global timeout scheme and an anti-packet dissemination scheme for IoV. They provide an efficient end-to-end communication for lossy and lossless data delivery, where control messages are delivered in social-based end-to-end and local-based ad hoc fashions.

Different from these researches, we focus on the CR-enabled IoV. In our forwarding scheme, the data transmission is based on the CR technology, which can alleviate the spectrum scarcity problem and increase spectrum utilization. In the high dynamic network topology of IoV, the available CR spectrum varies continuously based on the activities of PUs and SUs. In this article, we take both the availability of CR channels and the mobility of vehicles into consideration for the relay candidates’ selection.

Forwarding schemes in CR-enabled vehicular networks

Many techniques are proposed for efficient data transmission in CR-enabled vehicular networks, especially in CR vehicular ad hoc networks (CR-VANets), which is an active area of research.

W Kim et al.\(^16\) propose a cognitive VANET architecture that allows vehicle radios finding the least loaded channels. They utilize both geographical locations and sensed channel information to establish reliable and low-delay routes to the destination. J Kim and M Krunz\(^17\) propose a spectrum-aware beaconless geographical routing protocol for CR-VANETs. In their protocol, CR-enabled vehicles dynamically share TV-band channels to improve the relay selection efficiency and decrease the end-to-end delay. H Ghafoor and I Koo\(^18\) propose a spectrum-aware geographic routing protocol to decrease the end-to-end delay in CR-VANETs. They employ the Kalman filter to predict the positions of all moving vehicles and reduce the delay of the network. MK Priya et al.\(^19\) propose a spectrum and traffic-aware routing protocol to improve network efficiency. They utilize a cooperative method to collect information and to sense the spectrum holes. They measure the road weight and use it to select the relay node. Y He et al.\(^20\) adopt a common framework to enhance the security for both spectrum sensing and data transmission processes in CR-VANETs. They utilize the unified trust management scheme to protect the spectrum sensing process and apply the trust value derived from the unified trust model to enhance the security of the data transmission process. A Priyadharshini and M Sundarambal\(^21\) propose a spectrum-aware geographic routing protocol that reduces the routing delay and ranks the channel availability from end to end. In their method, the root channel is optimally selected for transmission by using an artificial fish swarm algorithm, while other channels are switched to the disabled state. We also proposed some forwarding schemes for the CR-enabled vehicular networks.\(^22,23\) These researches are focused on the non-real-time applications, with the objective of the delivery ratio maximization. The latter one applies the social characteristics of both PUs and SUs to improve the packet delivery ratio and the overhead ratio.

Different from these schemes, in this article, we focus on the urban expressway scenario for the goal of the end-to-end delay minimization. We build the system model on the characteristics of the urban expressway. Moreover, the channel heterogeneity of the urban expressway is considered in our forwarding approach that is also different from the existing works.
System model and problem statement

System model
A multi-hop V2V communication system for an urban expressway environment is shown in Figure 2. We consider a scenario with an overlay CR network. The primary network consists of a number of cellular BSs and PUs. The transmission range of each primary BS is denoted as $R_B$. Each primary BS can serve several PUs with the coverage area of $R_B$. We assume that the expressway can be divided into $M$ road segments. Each road segment is fully covered by at least one BS’s transmission range. The BS that its range can cover the road segment in the widest area will be employed for the road segment V2V transmission.

We assume that there are $K$ licensed CR channels, and the state of each channel alternates between the busy (occupied by the PU) state and the idle (unoccupied) state. We also assume the busy/idle time of PUs subject to the exponential distribution. We apply the non-stationary hidden Markov (NSHM) model\textsuperscript{24} to predict the probability of PU activities in consecutive time slots.

The secondary network consists of $N$ number of vehicles. In this system, vehicles act as SUs and can communicate with each other. As the traffic characteristics of the urban expressway, vehicles are usually driving at relatively stable velocities. Compared with traditional city roads, the density distribution of vehicles is relatively uniform. Thus, it is reasonable to assume that vehicles are uniformly distributed on the expressway in our system. We also assume that each vehicle is equipped with two transceivers and a GPS receiver for obtaining location information. One of the transceivers is used for data transmission, and the other is used for control messages. All transceivers are assumed to have the same transmission range of $R_F$.

Table 1 summarizes notations for ease of reference.

Problem statement
In the urban expressway cognitive IoV, our objective is to reduce the end-to-end delay of the multi-hop V2V communication in an efficient approach. In this multi-hop forwarding process, the SU first detects the available CR channels and then transmits packets to the one of the potential relay SUs through a selected available channel. This process may produce the propagation delay and the transmission delay. If the currently used CR channel becomes unavailable in the next time slot, the SU will switch to another available CR channel. This results in the channel switching delay. Moreover, if all CR channels are occupied by PUs, and there is no available CR channel for SUs, SUs have to wait until at least one CR channel becomes available. In this case, a queueing delay is taken into consideration.

According to the above discussions, the end-to-end delay is mainly dominated by the propagation delay, the transmission delay, the channel switching delay, and the queueing delay. We denote the end-to-end delay as $D_{end}$ and formulate our objective as follows

$$\min D_{end} = \arg\min (D_{prop} + D_{trans} + D_{sw} + D_{que}) \quad (1)$$
where $\text{d}_{\text{prop}}$ is the propagation delay, $\text{D}_{\text{trans}}$ is the transmission delay, $\text{d}_{\text{sw}}$ is the channel switching delay, and $\text{D}_{\text{que}}$ is the queueing delay.

The propagation delay depends on the idle time duration of the available CR channel that is selected by SUs. We denote $\text{d}_{\text{prop}}$ as the propagation delay. We use $d_{\text{prop}}(i, \varepsilon)$ to indicate the $\varepsilon$th-hop propagation delay of the relay node $V_i$, $i \in [1, N]$. The propagation delay of the whole route can be calculated as follows

$$D_{\text{prop}} = \sum_{\varepsilon=1}^{E(h)} \sum_{i=1}^{N} d_{\text{prop}}(i, \varepsilon)$$  \hspace{1cm} (2)

where $\varepsilon \in [1, E(h)]$, and $E(h)$ is the expected transmission hops from a source to a destination.

The transmission delay depends on the transmission rate. We utilize the expected transmission time (ETT) to estimate the one-hop transmission delay. The transmission delay over the whole route can be given as follows

$$D_{\text{trans}} = \sum_{\varepsilon=1}^{E(h)} \text{ETT}(\varepsilon) = \sum_{\varepsilon=1}^{E(h)} \frac{L_i}{(1 - P_{\text{err}}) \times f_\varepsilon}$$  \hspace{1cm} (3)

where $P_{\text{err}}$ is the false alarm probability, $L$ is the packet length, and $f$ is the data rate.

In our system, the CR channel’s switching time depends on the number and frequency bands of traversing flows.\textsuperscript{25} The switching time between channels can be expressed as

$$d_{\text{sw}} = \varphi \times |\text{Band}_k - \text{Band}_{k+1}|$$  \hspace{1cm} (4)

where $\varphi$ is a positive constant which is suggested as $10\text{ms}/10\text{MHz}$\textsuperscript{25} and $k \in [1, K]$. The notation $\text{Band}_k$ is the frequency bands of the CR channel $k$. The channel switching delay over a route can be expressed as follows

$$D_{\text{sw}} = \sum_{\varepsilon=1}^{E(h)} \sum_{\xi=1}^{J} d_{\text{sw}}(\xi, \varepsilon)$$  \hspace{1cm} (5)

where $J$ is the number of switching times and $J \geq 0$.

The queueing delay is based on the time that SUs wait for CR channels to become available. We denote the $\varepsilon$-hop queueing delay of $V_i$ as $d_{\text{que}}(i, \varepsilon)$. The queueing delay of the whole route can be formulated as follows

$$D_{\text{que}} = \sum_{\varepsilon=1}^{E(h)} \sum_{\xi=1}^{N} d_{\text{que}}(i, \varepsilon)$$  \hspace{1cm} (6)

Consequently, from equations (1)–(6), the objective of the end-to-end delay minimization problem can be specifically formulated as follows

$$\min \left\{ \sum_{\varepsilon=1}^{E(h)} \sum_{i=1}^{N} \left[ \frac{d_{\text{prop}}(i, \varepsilon) + d_{\text{que}}(i, \varepsilon)}{1 - P_{\text{err}} \times f_\varepsilon} \right] + \sum_{\xi=1}^{J} d_{\text{sw}}(\xi, \varepsilon) \right\}$$  \hspace{1cm} (7)

s.t. $\sum_{\xi=1}^{J} d_{\text{que}}(\xi, \varepsilon) \leq TH_{\text{sw}}$  \hspace{1cm} (8)

$$\sum_{i=1}^{N} d_{\text{que}}(i, \varepsilon) \leq TH_{\text{que}}$$  \hspace{1cm} (9)

$$E(h)_{i,j} \equiv |\eta(V_i) - \eta(V_j)|$$  \hspace{1cm} (10)

$$L_{i,j}^{k} + \sum L_{i,j}^{k} \geq 1, L_{i,j} \in \{0, 1\}, k \in [1, K],$$  \hspace{1cm} (11)

where $TH_{\text{sw}}$ is the threshold for one-hop channel switching time and $TH_{\text{que}}$ is the threshold for one-hop queueing time. The $\eta(V_i)$ represents the ordinal number of $V_i$. Equation (10) indicates that the expected hop from $V_i$ to $V_j$ is no more than the number of nodes between $V_i$ and $V_j$. In equation (11), $S_i$ indicates the set of relay candidates of $V_i$. We denote $L_{i,j}^{k}$ as the link status between $V_i$ and $V_j$ in channel $k$, $k \in [1, K]$. If $V_i$ is communicating with $V_j$ in channel $k$, $L_{i,j}^{k} = 1$, otherwise $L_{i,j}^{k} = 0$. The number of switching times and $J \geq 0$.

The number of channel switching times.

Table 1. Notation.

| Symbol      | Definition                                                      |
|-------------|-----------------------------------------------------------------|
| $M$         | The number of road segments                                     |
| $N$         | The number of SUs (vehicles)                                    |
| $K$         | The number of CR channels                                       |
| $\text{R}_B$ | The transmission range of BSs                                   |
| $\text{D}_{\text{end}}$ | The end-to-end delay                                           |
| $\text{D}_{\text{prop}}$ | The propagation delay                                         |
| $\text{D}_{\text{trans}}$ | The transmission delay                                       |
| $\text{D}_{\text{sw}}$ | The channel switching delay                                   |
| $\text{D}_{\text{que}}$ | The queueing delay                                             |
| $\text{V}_i$ | One of the SUs                                                   |
| $\text{f}$  | The data rate                                                   |
| $\text{P}_{\text{err}}$ | The false alarm probability                                    |
| $\varphi$   | The positive constant                                           |
| $\text{Band}_k$ | The frequency bands of CR channel $k$              |
| $\text{d}_{\text{prop}}$ | One-hop propagation delay                                      |
| $\text{d}_{\text{sw}}$ | Channel switching delay                                         |
| $\text{d}_{\text{que}}$ | One-hop queueing delay                                         |
| $\text{TH}_{\text{sw}}$ | The threshold for one-hop channel switching                    |
| $\text{TH}_{\text{que}}$ | The threshold for one-hop queueing time                        |
| $\eta(V_i)$ | The ordinal number of $V_i$                                    |
| $L_{i,j}^{k}$ | The link status between $V_i$ and $V_j$ in channel $k$         |
| $S_i$       | The relay candidates set of $V_i$                              |

CR: cognitive radio.
Relay candidate selection

In the cognitive IoV, the relay transmission requires not only the available CR channel but also the effective contact with the relay node. In this section, we propose an approach to select relay candidates taking these two metrics into account. First, we predict the CR channel availability and count the idle time slots of available CR channels in the current road segment and the next road segment. Second, we calculate the contact duration between the sender node and its neighbor nodes. Third, combining the consideration of CR channels’ availabilities and contact durations, we obtain the set of relay candidates and separate this set into two subsets based on relays’ different geographical positions on various road segments.

CR channel availability

We utilize the NSHM model to predict the PU activity and deduce the CR channel availability in the continuous time, that is

\[ P_k^0 = \frac{1}{\lambda_k^0(t)} \]  \hspace{1cm} (12)
\[ P_k^1 = \frac{1}{\lambda_k^1(t)} \]  \hspace{1cm} (13)

where \( P_k^0 \) indicates the idle time duration of the channel \( k, k \in [1, K] \) and \( P_k^1 \) means the busy time duration of the channel \( k \). The idle and the busy periods are subjected to exponential random variables \( \lambda_k^0 \) and \( \lambda_k^1 \), respectively.26

In the system model, we have described that the expressway was divided into \( M \) road segments. The statuses of CR channel availabilities in the current road segment are usually different from the statuses in the next road segment. Based on equations (12) and (13), we can obtain the idle and the busy time slots of CR channels in the current road segment and the next road segment. Figure 3 provides an example of CR channels with different time slot statuses in two adjacent road segments. The solid lines represent idle time slots, and the dotted lines express busy time slots. We count the idle and busy time slots and gather the statistics of time slots as follows

\[ Z_\mu = [X_1, X_2, \ldots, X_k] \]  \hspace{1cm} (14)
\[ Z_{\mu+1} = [Y_1, Y_2, \ldots, Y_k] \]  \hspace{1cm} (15)

where \( k \in [1, K] \). \( Z_\mu \) is the statistic of the current \( \mu \)th road segment, \( \mu \in [1, M] \). \( Z_{\mu+1} \) is the statistic of the next \( (\mu + 1) \)th road segment. The matrix \([X_1, X_2, \ldots, X_k]\) consists of the statuses of idle time slots and busy time slots of \( k \) channels in the current road segment. Similarly, the matrix \([Y_1, Y_2, \ldots, Y_k]\) contains the idle and busy time slots of the channels in the next road segment. When an SU enters into a new road segment, it will collect the current BS cell’s channel statuses and broadcast the channels’ information to SUs in the previous road segment. Considering the normalization measurement of the channel time slot, we utilize “1” to denote the idle state, “0” to denote the busy state of CR channels, and \( \tau \) to denote the time measurement of one slot. As shown in Figure 3, the statuses of channel 2 in the current road segment can be expressed by \( X_2 = [0, 1, 1, 1, 1, 1] \). The statuses of channel 2 in the next road segment can be expressed by \( Y_2 = [0, 0, 1, 1, 1, 1] \). From \( X_2 \) and \( Y_2 \), we can conclude that, for channel 2, there are four slots in the \( \mu \)th road segment and three slots in the \( (\mu + 1) \)th road segment, which can be used for the data transmission.

According to equations (14) and (15), we can select the appropriate CR channel for the data transmission between two road segments.

\[ L_{i,j} = 0. \] Here, we consider the case that other neighbor nodes of \( V_i \) will be in the non-interference status when \( V_i \) is communicating with \( V_j \). The optimization problem above is a mixed non-linear integer programming problem, which is non-deterministic polynomial (NP)-hard in general.

In the following sections, we will use the two words “SU” and “vehicle” interchangeably and the same for “packet” and “message.”
Figure 4. Contact duration between \( V_i \) and \( V_j \).

Contact duration between SUs

The link duration between two SUs not only depends on the idle time slots of CR channels but also on the contact duration between two SUs. When \( V_i \) and \( V_j \) can access to the same available CR channel, and the distance between them is within the transmission range \( R_f \), they can communicate with each other. As shown in Figure 4, \( V_i \) and \( V_j \) are moving with velocities of \( v_i \) and \( v_j \), respectively. If they do not change their velocities during the time interval \( \Delta t \), \( V_i \) could be considered as stationary and \( V_j \) would move with the relative velocity of \( v_{ij} \). When \( V_j \) moves out of the overlapping region, it cannot communicate with \( V_i \).

We assume that \( V_j \) is within the communication coverage of \( V_i \) at time \( t_c \), that is

\[
\{ \| v_{ij} t - v_i t_c^- \| > R_f \} \cap \{ \| v_{ij} t - v_i t_c^- \| = R_f \} \tag{16}
\]

where \( t_c^- \) denotes the time instance before \( t_c \). Then, the contact duration between \( V_i \) and \( V_j \) can be defined as the time period during which \( V_j \) is in contact with \( V_i \) before \( V_j \) moving out of the coverage, that is

\[
T_{V_i, V_j} = t - t_c, \min_{t\in(t_c, t)} \{ \| v_{ij} t \| > R_f \} \tag{17}
\]

where both \( t \) and \( t_c \) are in the continuous time scale. We refer \( T_{V_i, V_j} \) as a restriction of relay candidate selection. If the value of \( T_{V_i, V_j} \) is less than the sum of the propagation delay and the transmission delay between \( V_i \) and \( V_j \), we consider \( T_{V_i, V_j} \) is invalid for the data transmission between these two nodes.

relay candidate set

We denote \( S_i \) as the relay candidate set of the sender node \( V_i \). We choose the relay candidates obeying two decision rules. One rule is that on the basis of the idle time slot statistics of CR channels in the current and next road segments, the chosen candidate node and \( V_i \) should have at least one common available channel. Then, we calculate the contact durations between \( V_i \) and its neighbors in the current and next road segments. And the other decision rule is that the selected node should meet the requirement of \( T_{V_i, V_j}(d_{prop}(i, e) + ETT(e)), e \in [1, E(h)] \). This restriction implies that in the \( e \)th hop, the contact duration between \( V_i \) and \( V_j \) needs to be longer than the sum of the propagation delay and the transmission delay of \( V_i \). This requirement can ensure the effectiveness of the data forwarding process. Hence, we can guarantee that all the nodes in set \( S_i \) have two necessary characteristics for the effective data transmission in the urban expressway cognitive IoV. One is that the node in set \( S_i \) and \( V_i \) have at least one common channel during idle time slots. The other one is that the link between these two nodes can achieve valid contact durations.

The relay candidates in \( S_i \) are probably located in different road segments, for example, the \( \mu \)th road segment and the \((\mu + 1)\)th road segment. We divide \( S_i \) into two subsets, \( S_i^I \) and \( S_i^O \). Assume that \( V_j \in S_i \), then if \( V_j \) and \( V_i \) are in the same road segment, we have \( V_j \in S_i^I \), otherwise \( V_j \in S_i^O \). There exists three possible situations for \( S_i^I \) and \( S_i^O \). First, \( S_i^I \neq \emptyset \), \( S_i^O = \emptyset \); second, \( S_i^I = \emptyset \), \( S_i^O \neq \emptyset \); and third \( S_i^I \neq \emptyset \), \( S_i^O \neq \emptyset \). Different situations correspond to different forwarding strategies. In next section, we propose our low-latency forwarding scheme to cope with different situations and analyze the end-to-end delay in each situation.

Low-latency forwarding scheme

In this section, according to three different situations of relay candidates in \( S_i^I \) and \( S_i^O \), we propose different forwarding strategies. Furthermore, we also consider different available statuses of CR channels in our forwarding strategies. We theoretically analyze the end-to-end delay for each situation and select the relay nodes with the minimum delay.

The forwarding strategy for \( S_i^I \neq \emptyset \) and \( S_i^O = \emptyset \)

In this situation, the sender node \( V_i \) can only relay packets to nodes in the subset \( S_i^I \) in the current \( \mu \)th road segment. For CR channels that can be accessed by nodes in \( S_i^I \), we choose the available CR channel which has the longest idle duration for the relay transmission. Thus, the propagation time can be expressed as follows

\[
d_{prop}(i)_{\text{in}} = \tau \times \max \left( \sum \| Z_\mu \|_1 \right) \tag{18}
\]

where \( \tau \) is the time measurement of one slot. \( \sum \| Z_\mu \|_1 \) means the summation of idle time slots in \( Z_\mu \).
If the selected relay channel in the current road segment is different from the channel in the last hop, it will generate a switching time \( d_{sw} \). Otherwise, the channel switching is unnecessary for transmission, then \( d_{sw} = 0 \).

If the CR channel, for example, channel \( k \), is currently used by \( V_i \), and the channel \( k \) is still accessible in the \( \mu \)th road segment, the channel switch delay will be considered as an additional delay cost. In this situation, we evaluate the channel switch delay as an overhead of the propagation time and compare it with the idle slot time duration of the \( k \) channel. We compute them as follows and adopt the longer time as the actual propagation time

\[
T_{\text{prop}}(i)_{\text{out}} = \max \left\{ d_{\text{prop}}(i)_{\text{out}} - d_{sw}(\mu), \tau \times \sum \| Z_{\mu + 1}(k) \| \right\}
\]

(19)

In the subset \( S_i^f \), we calculate the value \( \Omega(V_i, \text{Edge}(\mu))/v_i \), \( V_i \in S_i^f \) and choose the node that will first arrive at the next road segment as the relay node. Here, the notation \( \Omega(V_i, \text{Edge}(\mu)) \) is the Euclidean distance between \( V_i \) and the edge of the cellular BS in the \( \mu \)th road segment, and \( v_i \) is the velocity of \( V_i \). Furthermore, if there is no available CR channel in \( S_i^f \) for data transmission, \( V_i \) has to wait for CR channels to become available again or carry the packet until it arrives at the next road segment. Then, the queuing time can be given as follows

\[
d_{\text{que}}(i)_{\text{in}} = \min \left\{ \tau \times \min \left( \sum \| Z_{\mu} \| \right), \frac{\Omega(V_i, \text{Edge}(\mu))}{v_i} \right\}
\]

(20)

where \( v_i \) is the velocity of \( V_i \) and \( \Omega(V_i, \text{Edge}(\mu))/v_i \) means the time duration that \( V_i \) crosses the current \( \mu \)th road segment. The bit-reversal operation can calculate busy time slots in \( Z_{\mu} \).

Thus, the one-hop delay of relaying packets to the nodes in \( S_i^f \) can be computed by

\[
D_{\text{end}}(\mu)_{\text{in}} = T_{\text{prop}}(i)_{\text{in}} + d_{\text{que}}(i)_{\text{in}} + d_{sw}(\mu) + ETT(\mu)
\]

(21)

**The forwarding strategy for** \( S_i^f = \emptyset, S_i^o \neq \emptyset \)

In this situation, the sender node \( V_i \) can only relay packets to nodes in subset \( S_i^o \) located in the next \( (\mu + 1) \)th road segment. If there is no common available CR channel between \( (\mu + 1) \)th and \( \mu \)th road segments, \( V_i \) needs to carry the packets to the \( (\mu + 1) \)th road segment and relay packets to nodes in \( S_i^o \). The queuing time can be computed as follows

\[
d_{\text{que}}(i)_{\text{out}} = \tau \times \min \left( \sum \| Z_{\mu + 1} \|, \frac{\Omega(V_i, \text{Edge}(\mu))}{v_i} \right) + \frac{\Omega(V_i, \text{Edge}(\mu))}{v_i}
\]

(22)

In the \( (\mu + 1) \)th road segment, \( V_i \) employs the available CR channel which has the longest idle state duration for data transmission. The propagation time can be expressed as follows

\[
d_{\text{prop}}(i)_{\text{out}} = \tau \times \max \left( \sum \| Z_{\mu + 1} \| \right)
\]

(23)

Similar to our last forwarding scheme, we still evaluate the channel switch delay as an overhead of the propagation time and adopt the longer time as the actual propagation time that is based on the following computation

\[
T_{\text{prop}}(i)_{\text{out}} = \max \left\{ d_{\text{prop}}(i)_{\text{out}} - d_{sw}(\mu + 1), \tau \times \sum \| Z_{\mu + 1}(k) \| \right\}
\]

(24)

In the subset \( S_i^o \), we calculate the value \( \Omega(V_i, \text{Edge}(\mu + 1))/v_i \), \( V_i \in S_i^o \), and choose the node that will first arrive at the next road segment as the relay node. Moreover, if there is no CR channel available for the nodes both in \( S_i^f \) and \( S_i^o \), \( V_i \) will store the packets and cross \( \mu \)th and \( (\mu + 1) \)th road segments. Then, the time of the crossing process can be calculated as follows

\[
T_{\text{cro}}(i)_{\text{out}} = \frac{\Omega(V_i, \text{Edge}(\mu + 1))}{v_i}
\]

(25)

Thus, the one-hop delay of relaying packets to the nodes in \( S_i^o \) is formulated as follows

\[
D_{\text{end}}(\mu)_{\text{out}} = \min \{ d_{\text{que}}(i)_{\text{out}}, T_{\text{cro}}(i)_{\text{out}} \} + T_{\text{prop}}(i)_{\text{out}} + d_{sw}(\mu + 1) + ETT(\mu + 1)
\]

(26)

If there is a common available CR channel between \( (\mu + 1) \)th and \( \mu \)th road segments, \( V_i \) will relay packets to the nodes in \( S_i^o \). It is the same process as that in **Case I** described in the next subsection. We provide the details as follows.

**The forwarding strategy for** \( S_i^f \neq \emptyset, S_i^o \neq \emptyset \)

In this situation, the sender node \( V_i \) can relay packets to nodes in the subset \( S_i^f \) or \( S_i^o \). We propose different forwarding strategies for two cases. For the first case, there exists at least one available CR channel that can be shared between these two subsets. For the second case, there is no available CR channel that can be shared between these two subsets.

**Case I.** For the sender node \( V_i \), the relay candidates in \( S_i^f \) and \( S_i^o \) can access to at least one common available
The physical meaning of $\Omega(V_i, V_j) / v_j$ is the time that $V_j$ travels to $V_i$. If the time $\Omega(V_i, V_j) / v_j$ is shorter than the summation of the propagation delay, the channel switching delay, and the queuing delay, we will choose to carry and forward packets by the traveling of SUs to decrease the one-hop end-to-end delay.

**Case 2.** For the sender node $V_i$, the relay candidates in $S_i^c$ and $S_i^O$ cannot access to at least one common available CR channel.

In this case, vehicles cannot transmit the packet over the current $\mu$th road segment. They will relay packets to nodes in $S_i^c$ or carry the packets to the $(\mu + 1)$th road segment and relay packets to nodes in $S_i^O$. The delay of relaying packets to the nodes in $S_i^c$ is different from the delay of relaying packets to the nodes in $S_i^O$. For the objective of the end-to-end delay minimization, we need to make a relay choice between $S_i^c$ and $S_i^O$, to gain a shorter one-hop delay. Accordingly, we propose proposition 1 to identify the one-hop delay differences between the $S_i^c$ and the $S_i^O$, and make an appropriate relay decision in this case.

**Proposition 1.** Given the average queuing time of $(t - 1)$ time slots as $\bar{d}_{\text{que}} = \left[ \sum_{i=1}^{E(t-1)} \sum_{i=1}^{N} d_{\text{que}}(i, e) \right] / (t - 1)$. At the time slot $t$, if $d_{\text{que}}(i)_{\text{out}} > (E(T + d_{\text{sw}} + d_{\text{que}}(i)))_{\text{in}} + \bar{d}_{\text{que}}(t) - d_{\text{sw}}$, then we have the process of relaying packets to $S_i^c$, which has a shorter one-hop delay than relaying packets to $S_i^O$.

**Proof:** If $V_i$ chooses the relay node in $S_i^O$, the delay of this hop is $D_{\text{end}}(\mu)_{\text{out}}$ in equation (26). If $V_i$ chooses the relay node in $S_i^c$, it will cause at least one additional relay transmission from the node in $S_i^c$ to the node in $S_i^O$. This transmission will result in an extra $ETT$, $d_{\text{sw}}$, and queuing delays. Here, we consider that, the one-hop $d_{\text{prop}}(i)$ approximately equals to the mean value of the sum of $d_{\text{prop}}(l)$ that can be calculated from the source to the destination. We utilize $\bar{d}_{\text{que}}(t)$ to indicate the additional queuing delay, that is $\bar{d}_{\text{que}} = \left[ \sum_{i=1}^{E(t-1)} \sum_{i=1}^{N} d_{\text{que}}(i, e) \right] / (t - 1)$. Thus, the additional delay of relaying packets to $S_i^O$ can be calculated by $ETT + d_{\text{sw}} + d_{\text{que}}(i)_{\text{in}} + \bar{d}_{\text{que}}(t)$. In order to minimize the end-to-end delay, we choose the relay node with a shorter delay. Consequently, if $d_{\text{que}}(i)_{\text{out}} > (ETT + d_{\text{sw}} + d_{\text{que}}(i))_{\text{in}} + \bar{d}_{\text{que}}(t)$, the relay node in $S_i^c$ will be chosen, and a shorter delay is caused in this hop.

According to Proposition 1, we can provide a one-hop relay process with a shorter delay. In case 2, if we choose to relay packets to nodes in $S_i^c$, the analysis of the one-hop end-to-end delay is the same as in the situation $S_i^c \neq \emptyset, S_i^O = \emptyset$. Similarly, the process of relaying to nodes in $S_i^O$ is the same as in the situation $S_i^c \neq \emptyset, S_i^O \neq \emptyset$. Here, we do not provide the repetitive analysis of these two relay processes.

The low-latency forwarding scheme works as follows. Initially, we deduce the CR channel idle time slots in the current road segment and the next road segment. Then, we calculate the contact durations between the...
sender node and its neighbor nodes. We collect the relay candidates into the set \(S_i\). It includes the nodes that can access to the same idle time slots of CR channels with the sender node and have contact durations with the sender node. After that, we separate the \(S_i\) into two subsets \(S'_i\) and \(S''_i\) on the basis of the road segment.

According to different subset situations, we propose three forwarding strategies and analyze the end-to-end delay in different CR channel available statuses. We select the relay node with the least delay in each situation. Algorithm 1 describes the low-latency forwarding scheme in detail. Steps 1 to 9 display the procedure of the situation \(S'_i \neq \emptyset, S''_i = \emptyset\). Steps 2 to 4 are used to check if there is a channel switching delay. Steps 5 to 7 provide the regulation to select relay nodes. Step 8 calculates the one-hop end-to-end delay in this situation. Steps 10 to 18 illustrate the procedure of case 1 in situation \(S'_i \neq \emptyset, S''_i \neq \emptyset\). Step 11 indicates the judgment that if the relay candidates in \(S'_i\) and \(S''_i\) have at least one common available CR channel. Step 18 calculates the one-hop end-to-end delay in this case. Steps 19 to 27 represent the procedure of the situation \(S'_i = \emptyset, S''_i \neq \emptyset\). Steps 19 to 36 express the procedure of case 2 in situation \(S'_i \neq \emptyset, S''_i \neq \emptyset\). Step 20 chooses to relay to the node in \(S'_i\) or in \(S''_i\). Steps 21 to 27 illustrate the process of relaying to nodes in \(S''_i\) without common available CR channel between \(S'_i\) and \(S''_i\). Step 27 gives the calculation of the one-hop end-to-end delay in this situation.

**Novelty analysis of the proposed scheme**

In our scheme, some steps include standard CR-enabled IoV networks between vehicles and infrastructure. However, some parts are novel from a low delay and an efficient standpoints, which are described as follows.

**Low latency.** From a low-delay standpoint, a novel multi-metric-based candidate set selection approach is proposed, which takes both the contact duration and the channel idle state duration into consideration. By using this multi-metric-based method, the probability of links’ disconnection is lower than other solutions. Therefore, the channel switching delay and the queuing delay can be reduced, and the overall end-to-end delay is also decreased.

For most cases in the urban expressway cognitive IoV, our forwarding schemes are based on the geographic routing technique, which selects a neighboring SU node that is the closest to the destination as the next-hop relay. However, this technique cannot work well in a special case when the sender and all the relay candidates cannot access to at least one common available CR channel. We have a novel conclusion for this case, which is stated in Proposition 1 of section “Low-latency forwarding scheme.” It is proved that choosing the relay node, which is not very close to the destination, can be a locally optimal solution from a low-delay standpoint.

**Efficiency.** From an efficient standpoint, our scheme can reduce the overheads caused by two special cases, which are described as follows. As the sender and the receiver move fast in the urban expressway cognitive IoV, two cases may happen for the next time period. One case is
that they cannot operate in any commonly available channel for transmission. In this case, they have to compute another routing path for retransmission and thus introduce the additional computation cost. In addition, more control messages are required to establish new links. The other case is that they have to search for another commonly available channel and switch to the new frequency. In this case, additional control messages are generated for channel switching and channel sensing procedures. Because our solutions can reduce the probability that these cases will happen and aim to reduce the number of channel switching time, they can achieve lower overheads in the urban expressway cognitive IoV.

Existing delay-aware routing techniques attempt to design a unified routing scheme and ignore the unique features of different transmission modes in the urban expressway cognitive IoV. For a specific transmission mode, some complicated calculation steps of the unified scheme are not required, and thus, the computing cost can be further reduced. From an efficient standpoint, we propose different forwarding strategies and end-to-end delay estimation methods for each transmission mode, considering the heterogeneous characteristics of the transmission links in the urban expressway cognitive IoV, which can reduce the computing cost.

Performance evaluation and analysis

Simulation setup

In the simulation, the length of the road is considered as 5 km, and the number of CR channels is five. There are 10 BSs evenly deployed along the road. We consider the transmission range of BSs as 1 km. The vehicles are acted as the SUs, and each SU is equipped with CR-based wireless communication devices. We consider the communication range of the wireless device as 150 m. SUs are distributed on the road with different densities from 10 to 60 SUs/km, which represent the relatively sparse and dense networks. They travel at their constant speeds with the range from 40 to 80 km/h, and their moving does not interact with each other. Each simulation iteration process uses the same movement pattern.

We implement the IEEE 802.11p standard for the vehicular communication scenario. The transmission pattern consists of 512 bytes packets using a constant bit rate (CBR) data bursts of 50 Kbps. The source and destination node pairs are randomly selected for repeated experiments. Simulations were repeated 20 times for each metric and each routing scheme. We adopted the 95% confidence interval for the mean of our simulation results. The simulation parameters are given in Table 2.

| Parameter                      | Value          |
|-------------------------------|----------------|
| Road length                   | 5 km           |
| Number of CR channels         | 5              |
| Number of BSs                 | 10             |
| Transmission range of BSs     | 1 km           |
| Communication range of SUs    | 150 m          |
| SU density                    | 10 – 60 SUs/km |
| SU velocity                   | 40 – 80 km/h   |
| MAC protocol                  | IEEE 802.11p   |
| Packet size                   | 512 bytes      |
| Traffic CBR                   | 50Kbps         |
| Simulation runs               | 20 times per metric |
| Confidence interval           | 95%            |

Table 2. Simulation parameters.

CR: cognitive radio; SU: scale-up; MAC: medium access control; IEEE: Institute of Electrical and Electronics Engineers; CBR: constant bit rate.

Evaluation metric and comparison object

To evaluate the performance of our proposed forwarding scheme, we utilize the average end-to-end delay, the average delivery ratio, and the routing overhead ratio as metrics. These metrics can be defined as follows.

**Average end-to-end delay.** The average time is taken for a packet to be transmitted from the source to the destination.

**Average delivery ratio.** The ratio of data packets received by the destinations to the packets generated by the sources.

**Routing overhead ratio.** The ratio of the total packet size of control packets to the total packet size of data packets delivered to the destinations.

We compare our UEFS with six forwarding schemes. We introduced four of them in the related work section. We call them SBGR, Kalman-SGR, MCTRPFS, and SADTR for short, respectively. The other two forwarding schemes are the adaptive quality-of-service-based routing for VANETs (AQRV) and the clustering-based reliable low-latency routing scheme for vehicular networks (CRLR). AQ RV is an adaptive quality-of-service (QoS)-based routing for VANETs. It selects a route that can satisfy the QoS constraints and fulfill the terms of connectivity probability, packet delivery ratio, and delay. CRLR is a clustering-based reliable low-latency multi-path routing scheme for VANETs. It computes the routes among the communicating vehicles for the improvement of reliability, end-to-end latency, throughput, and energy consumption.

Table 3 shows a comparison between the above six schemes and our proposed scheme. All the schemes involve the objective of end-to-end delay improvement except SADTR, which focuses on the packet delivery ratio and the overhead ratio improvement. All the
schemes are built for the CR spectrum scenario, excluding AQRV and CRLLR. SBGR and Kalman-SGR employ the same technique as our proposed UEFS.

Performance analysis

We evaluate the end-to-end delay, the packet delivery ratio, and the routing overhead ratio in terms of the short distance of source-to-destination node pairs, the long distance of source-to-destination node pairs, the PUs’ expected OFF time, and the SUs’ densities.

Comparisons under short source-to-destination distances

Figure 5 displays comparisons between six schemes and our proposed UEFS under different short source-to-destination distances, in terms of the end-to-end delay (Figure 5(a)), the packet delivery ratio (Figure 5(b)), and the routing overhead ratio (Figure 5(c)).

In Figure 5(a), we present the end-to-end delay of seven forwarding schemes. The end-to-end delay of UEFS is the shortest one at each distance test node. The reason is that UEFS benefits from the considerations of the CR-aware relay candidate selection and forwarding strategy. In the short-distance transmission, for example 250 m, the differences of the end-to-end delay among these seven schemes are not obvious. With the increase of source-to-destination distances, the end-to-end delay of AQRV increases rapidly. It cannot guarantee that the selected channel is with the longest idle time duration. This results in additional channel switching delays. In Figure 5(b), we compare the packet delivery ratios of forwarding schemes under the short distances of source-to-destination node pairs. The packet delivery ratios of all forwarding schemes keep growing with the increase of the source-to-destination distances. UEFS achieves a higher packet delivery ratio than other schemes except for SADTR. It is because that the forwarding strategy of UEFS can deal with different statuses of CR channel availabilities in the current road segment and the next road segment. SADTR performs best due to its social-aware strategies aiming at the packet delivery ratio improvement. Kalman-SGR performs well in the short-distance transmission because of the adaptability of the Kalman filter algorithm in the dynamic system. In Figure 5(c), all routing schemes have upward curves of routing overhead ratios with the increasing of the distance between the source and the destination. UEFS and SBGR perform well in this part. The former one benefits from its strategy that can decrease channel switching times. The later one takes advantage of its beaconless policy.

Comparisons under long source-to-destination distances

Table 3. Comparison with existing routing schemes.

| Scheme          | A1 | A2 | A3 | A4 | A5              |
|-----------------|----|----|----|----|-----------------|
| SBGR            | ✔  | ×  | ✔  | ✔  | Geographic routing |
| Kalman-SGR      | ✔  | ×  | ×  | ✔  | Geographic routing |
| MCTRPSF         | ✔  | ✔  | ×  | ×  | Artificial fish swarm optimization |
| AQRV            | ✔  | ✔  | ×  | ×  | Ant colony optimization |
| CRLLR           | ✔  | ×  | ×  | ×  | Social-aware routing |
| SADTR           | ×  | ✔  | ✔  | ✔  | Geographic routing |
| Proposed UEFS   | ✔  | ×  | ✔  | ✔  | Geographic routing |

SBGR: simple self-protected beaconless geographic routing; AQRV: adaptive quality-of-service-based routing for VANETs; CRLLR: clustering-based reliable low-latency routing; SADTR: social-aware data transmit and relay; UEFS: urban expressway forwarding scheme.

A1: Delay improvement; A2: Packet delivery ratio improvement; A3: Overhead improvement; A4: CR spectrum awareness; A5: Technique; ✗: Including; ×: Excluding.

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Table 3. Comparison with existing routing schemes.
schemes with long distances of source-to-destination node pairs. The packet delivery ratio of all forwarding schemes increased at the beginning of the test. The growth rates tend to be slow when the source-to-destination distance is long enough. UEFS achieves a higher packet delivery ratio than other schemes except for SADTR. It is the same reason as in the evaluation of short distances between sources and destinations. MCTRPFS performs well in this long-distance simulation. The reason is that the artificial fish swarm optimization works based on the population and stochastic search. Fishes show very intelligently social behaviors that help to increase the packet delivery ratio. Figure 6(c) depicts the routing overhead ratios of seven routing schemes. UEFS achieves the lowest overhead ratio than other schemes. With the increase of source-to-destination distance, UEFS can deal with different statuses of CR channel availabilities in the current road segment and the next road segment.

**Comparisons under different PUs’ expected OFF time.** Figure 7 displays comparisons between six schemes and our proposed UEFS under different PUs’ expected OFF time, in terms of the end-to-end delay (Figure 7(a)), the packet delivery ratio (Figure 7(b)), and the routing overhead ratio (Figure 7(c)).

Figure 7(a) displays the end-to-end delay with different PUs’ expected OFF time $E[T_{off}]$. UEFS has a shorter end-to-end delay than other forwarding schemes. When PUs act more frequently, the available

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**Figure 5.** Comparisons under short source-to-destination distances: (a) average end-to-end delay, (b) average packet delivery ratio, and (c) routing overhead ratio.
idle time slot of CR channels declines in numbers. This leads to an increased queuing delay that greatly increase the end-to-end delay. SBGR and Kalman-SGR do not consider the situation that there is no available CR channel in the two adjacent road segments. In this situation, the SUs in the current road segment can also be selected as relay nodes. We utilize these SUs in this situation for data transmission. Thus, the delay of our proposed UEFS is shorter than that of other forwarding schemes. Figure 7(b) expresses the results of packet delivery ratios with different PUs’ expected OFF time $E[T_{off}]$. UEFS performs better than other forwarding schemes except for SADTR. With the increase of the PUs’ expected OFF time, more idle time slots of CR channels can be used for data transmissions. UEFS chooses the available CR channel which has the longest idle duration. It means a higher probability to send data successfully and can produce a high packet delivery ratio. SBGR and Kalman-SGR perform better than AQRV and CRLLR in this part. It is because the former two schemes benefit from their spectrum-aware CR channel strategies. Figure 7(c) is a view that shows the routing overhead ratio following the different PUs’ expected OFF time $E[T_{off}]$. The routing overhead ratios of all the schemes are directly proportional to the PUs’ expected OFF time. The short PUs’ expected OFF time leads to the low availabilities of relay CR channels. It results in the low routing probability. With the increase of the PUs’ expected OFF time, UEFS performs better than other schemes.
Comparisons under different densities of SUs. Figure 8 shows comparisons between six schemes and our proposed UEFS under different densities of SUs, in terms of the end-to-end delay (Figure 8(a)), the packet delivery ratio (Figure 8(b)), and the routing overhead ratio (Figure 8(c)).

In Figure 8(a), we show the results of the end-to-end delay with different densities of SUs. The increase in the number of SUs has a positive effect on the end-to-end delay. UEFS performs better than other forwarding schemes. It always chooses the relay candidate that will reach the next road segment first. This brings an opportunity to execute the next relay process and complete the relay process quickly. SBGR and Kalman-SGR select the relays according to locations of nodes, but do not take the cross-range transmission into account. In Figure 8(b), we compare packet delivery ratios of forwarding schemes with different densities of SUs. The packet delivery ratios of all the schemes are low in sparse networks and high in dense networks. In sparse networks, fewer nodes cause fewer relay candidates and result in the low packet delivery ratio. In
UEFS, we select relay candidates considering both available CR channels and valid contact durations between SUs. This selection rule guarantees that UEFS obtains a high packet delivery ratio. CRLLR performs well in this simulation. The reason is that the positive feedback of the ant colony optimization algorithm enhances the reliability of routes from sources to destinations and thus improves the packet delivery ratio. In Figure 8(c), all routing schemes have upward curves of routing overhead ratios with the increase of the node density. It is due to the fact that more SUs cause more relay candidates and forwarding replicas. UEFS achieves the lowest routing overhead ratio in dense networks. SADTR performs well owing to its hybrid policy of reducing the overhead.

Figure 8. Comparisons under different densities of SUs: (a) average end-to-end delay, (b) average packet delivery ratio, and (c) routing overhead ratio.

Mean values of performance for relevant comparison schemes. We list the mean values of performance for relevant comparison schemes in Table 4. These mean values are calculated by considering all the simulation
results in terms of the end-to-end delay, the packet delivery ratio, and the routing overhead ratio.

Conclusion

In this article, we have studied the low-latency data forwarding problem in cognitive IoV networks. We have built a model to characterize the delay produced across a link, and we formulated the forwarding problem as a mixed non-linear integer optimization problem. We have proposed a method to determine the potential relay candidates by taking the CR channels' availabilities and the contact duration of vehicles into consideration. We have proposed three situations for the multi-hop forwarding scheme design, with jointly considered the channel availability and the delay cost of different types of relay candidates. By analyzing the end-to-end delay, we have provided low-latency forwarding strategies for each situation. With numerical simulations, we have demonstrated that the proposed scheme can achieve satisfactory end-to-end delay performance under various network parameters.

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Table 4. Mean values of performance for relevant comparison schemes.

| Scheme       | End-to-end delay (s) | Delivery ratio (%) | Overhead ratio (%) |
|--------------|----------------------|--------------------|--------------------|
| SBGR\textsuperscript{17}   | 24.1                | 67.2               | 23.9               |
| Kalman-SGR\textsuperscript{18} | 18.6                | 67.7               | 27.9               |
| MCTRPFS\textsuperscript{21}   | 20.0                | 69.0               | 25.1               |
| AQRV\textsuperscript{27}     | 23.0                | 66.6               | 27.3               |
| CRLLR\textsuperscript{28}    | 21.3                | 67.5               | 35.6               |
| SADTR\textsuperscript{23}    | 22.6                | 74.1               | 24.3               |
| Proposed UEFS           | 15.3                | 71.2               | 23.0               |

SBGR: simple self-protected beaconless geographic routing; AQRV: adaptive quality-of-service-based routing for VANETs; CRLLR: clustering-based reliable low-latency routing; SADTR: social-aware data transmit and relay; UEFS: urban expressway forwarding scheme.
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