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Spectrum-aware Beaconless Geographical Routing Protocol for Cognitive Radio Enabled Vehicular Networks

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Abstract The FCC and ETSI have allocated spectrum in the 5.9 GHz band for intelligent transportation systems. However, this spectrum supports short-range transmissions (up to 1000 m) and limited bandwidth (up to 75 MHz), which are not enough to meet the increasing demand for in-car infotainment services. In this paper, we propose a distributed routing protocol for vehicular ad hoc networks, where cognitive radio enabled vehicles (CRVs) dynamically share the TV-band channels. In the proposed protocol, CRVs jointly select relay nodes, channels, transmission powers, and transmission rates so that their total transmission rates are maximized while meeting their rate demands and power constraints. This selection process is carefully executed so that ongoing communications between primary radios (PRs) and between other CRVs are not disrupted. Once the relay nodes are selected, they continue to relay more messages as long as they stay in a predefined forwarding area. By doing so, the overhead for selecting relay nodes can be substantially reduced. Channels, powers, and rates are changed on a per-packet and per-hop basis so that the proposed protocol can efficiently adapt to spectrum dynamics. Simulation results show that our protocol increases the end-to-end network throughput by up to 250 % and decreases the end-to-end delay by up to 400 % compared with other geographical routing protocols.

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1 Introduction

For years, a rear seat DVD player is the best solution to keep backseat passengers (mostly kids) happy mood and help drivers drive in peace for long distances. Nowadays however passengers want to use their smartphones and tablets to play video games, watch streaming videos, and post on social media. Automakers roll out Internet services for drivers such as music streaming, real-time traffic and weather updates, restaurant search, and etc.

Currently, such Internet services rely on cellular networks via smartphones tethered to head units (HU) or integrated in HU only available on a few premium models so far. LTE (or 4G) has been deployed in major cities but it is hard to imagine that it will cover all rural and suburban areas any time soon. The Federal Communications Commission (FCC) and the European Telecommunications Standards Institute (ETSI) have allocated 40 MHz of spectrum in the USA and 20 MHz of spectrum in Europe, respectively, in 5.9 GHz band for non-safety intelligent transportation services. However, the 5.9 GHz band induces significant RF attenuation and hence cannot provide wide coverage.

Recently, FCC and ETSI opened TV white spaces ranging from 54 to 698 MHz for *unlicensed* cognitive radios (CRs) [11]. CRs can communicate over TV channels currently not used by licensed users (e.g., TV broadcasters). There are many vacant TV channels in suburban and rural areas and RF signals can propagate many kilometers at these frequency bands. Future CR-enabled vehicles (CRVs) can establish multi-hop links using TV white spaces to cellular base-stations, greatly extending the coverage and capacity of cellular networks. In this paper, we propose a cross-layer routing protocol that is specially designed for this purpose.

Routing in CR-enabled vehicular ad hoc networks (CRVNs) faces unique challenges, compared with conventional mobile ad hoc networks (MANETs). In MANETs, the routing protocol is expected to adapt to node mobility and channel dynamics. In CRVNs, in addition to that, PR activities and spectrum sharing among CRVs necessitate modifying routes more quickly, according to spectrum availability. Several routing protocols have been proposed for CR networks (see the survey in [6] and the references therein). However, these protocols do not consider mobility at vehicular speeds. Most of these protocols establish the route during the route discovery phase and try to change it when messages are dropped and/or new PR activity is detected. Such an approach suffers a significant performance degradation when spectrum availability and/or node locations change faster than the rate of route updates (e.g., as in the case of vehicular ad hoc networks).

In this paper, we propose a novel routing protocol for CRVNs, called Spectrum-Aware BEaconless geographical routing (SABE). We bring the concept of beaconless geographical routing to CRVNs for the first time. The main idea in SABE is that the routing decision as well as the resource allocation strategy are made by *receivers* on a per-packet and per-hop basis. A source (or an intermediate) CRV broadcasts a *forward request* packet, and includes in it its available resources and location. Receivers calculate a link weight with consideration of their and source's available resources and locations. Then, a timer to reply to the request is set depending on the link weight. The receiver with the highest link weight replies first, establishing itself as the relay node.

Because this process is done on a per-packet and per-hop basis, SABE can efficiently adapt to spectrum dynamics and node mobility. Once the relay node is selected, it continue to relay messages as long as it remains in a predefined *forwarding area*. By doing so, the overhead for selecting a relay node can be significantly reduced. SABE is designed to exploit innovative physical-layer techniques, including non-contiguous orthogonal frequency division multiplexing (NC-OFDM) and simultaneous transmit and receive (STAR) capabilities [8, 21]. NC-OFDM capability enables a transceiver to transmit or receive over multiple non-contiguous channels.[1] STAR capability enables a transceiver to transmit and receive over different channels simultaneously. Thus, a CRVN can opportunistically exploits multiple spectrum holes using a single-transceiver radio.

[1]Non-contiguous channel access is adopted to new IEEE standards 802.11ac/af [2].

We evaluate SABE and compare its performance with GPSR and SEARCH via simulations. We completely reprogram the ns-3 components to implement NC-OFDM and STAR capabilities. Simulation results show that our protocol increases the end-to-end network throughput by up to 250 % and decreases the end-to-end delay by up to 400 % compared with other geographical routing protocols.

The rest of this paper is organized as follows. Sections 2 and 3 present related works and the problem setup, respectively. Section 4 presents the SABE protocol. Simulation results are provided in Section 5. Section 6 concludes the paper.

2 Related works

Several routing protocols for CR networks are extensions of the ad-hoc on-demand distance vector (AODV) protocol. They differ in the metric used for path selection. AODV establishes an end-to-end route by broadcasting a route request (RREQ) packet over the network. It tries to modify the route when messages are dropped [13]. In [7], the authors introduced a routing metric that depends on delay factors, such as the channel switching delay and medium access delay. The RREQ packet conveys the list of idle channels at each intermediate node. The destination selects the path and the channel for each link such that the total delay is minimized. In [25], the routing metric depends on link quality as well as delay. In [3], the *PR activity degree*, which represents how many channels are occupied by PRs, is piggybacked on the RREQ packet to minimize interference to PRs.

Several geographical routing protocols have been proposed for MANETs (see the survey in [13] and the references therein). In geographical routing, each node knows its location, e.g., using a GPS device. The greedy perimeter stateless routing (GPSR) is the best known geographical routing protocol [14]. In GPSR, a *forwarder* (a source or an intermediate node) forwards a message to the neighbor that is closest to the message's ultimate destination. Figure 1 depicts an example of the geographical routing process. Node u has a message destined to node s. By relaying the message via a neighbor v, the distance to destination s is reduced by $\mathrm{ADV}_v \stackrel{\text{def}}{=} d_u - d_v$, where for any node i, d_i denotes the Euclidean distance between nodes i and s. We refer to ADV_v as the advance due to relay node v. Let τ denote the maximum transmission range. We refer to any neighbor v with $0 \leq \mathrm{ADV}_v \leq \tau$ as a *candidate*. GPSR forwards messages to the candidate that provides the

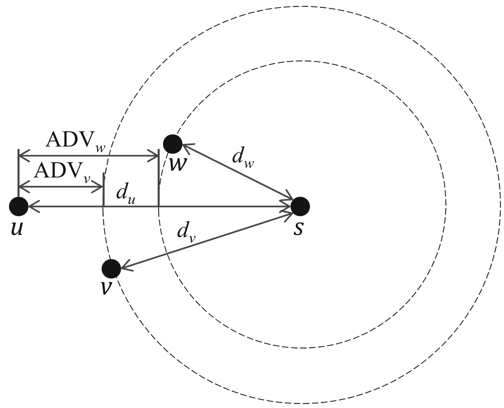


Fig. 1 Example that illustrates geographical routing

greatest advance. GPSR can lead to a *dead end*, where no candidate can be found. In this case, the message is detoured around the dead end until reaching a node that has one or more candidates.

A few geographical routing protocols have been presented for CR networks [9, 24]. In [24], nodes are assumed to know the locations of PRs. If there is no PR activity, the candidate that is closest to the destination is selected as the next relay node. When PR activity is detected, the candidate that is farthest from the destination is selected and the transmission power is adjusted so as not to disrupt PR transmissions. Nodes operate over a single channel, so opportunistic spectrum allocation is not addressed in that paper. Similar to GPSR, the spectrum-aware routing for cognitive ad-hoc networks (SEARCH) [9] forwards RREQ packets over each channel. The destination combines the routes and assigns channels for each link such that the end-to-end delay is minimized. When a dead end is encountered, SEARCH forwards a message to the closest node that is not a candidate for the current node, until a node with candidates is encountered. As network size increases, SEARCH incurs large latency and message overhead for route discovery. Moreover, it is well-known that forwarding a message to nodes outside the forwarding area often leads to a routing loop [22]. Other works related to routing in CR networks are discussed in [6].

In GPSR, every node periodically broadcasts a beacon packet to update its location. Intuitively, the rate at which beacons are generated should be high enough to maintain accurate topological information. If not, the packet drop rate can increase drastically. Beaconless geographical routing (BLR) does not require nodes to transmit beacons. The routing decision is made by the receiver [23]. In such protocols, a forwarder "broadcasts" a *request to send* (RTS), and candidates set their delay timer for the reply depending on their distance to the destination. The closer a node is to the destination, the shorter is its delay, allowing that node to be the first to reply. A drawback of this scheme is that a planar graph, used to avoid a dead end, cannot be constructed immediately, because a forwarder does not know the locations of its neighbors. To solve this problem, the authors in [22] presented the beaconless forwarder planarization (BFP) technique. In BFP, when there is no candidate, the neighbor closest to the forwarder responds to the request first and other neighbors that overhear the response check whether that neighbor satisfies the planarity condition (i.e., no edge crosses any other edge). If this condition is not satisfied, one or more neighbors send a *protest packet* to cancel the previous response.

Several routing protocols for vehicular ad hoc networks have been proposed (see the surveys [16, 17], papers [4, 10, 12], and references therein). However, most of them have focused on short-range car-to-car ad hoc communications to aid intelligent transportation systems (ITS) in urban areas. Some of them (e.g., GPCR [19] and RBVT [20]) work poorly with long transmission ranges because a relay node tends to forward frames to a node near the next road intersection where the distance between two nodes is much shorter than transmission range. Moreover, none of them considered the opportunistic spectrum access over TV white-spaces to support a fast in-car Internet access in suburban and rural areas.

An abridged version of this paper was presented in [15]. It was designed for MANETs. We carefully redesign the protocol to be more optimal for long-range vehicular communications in suburban and rural areas. We also consider important implementation issues in our design such as power limit on RF front-end and FCC regulations. The protocol design is further optimized by significantly reducing the overhead caused by the rely node selection process.

3 Problem setup

We consider a CRVN that coexists geographically with PRs (e.g., TV receivers and wireless microphones). There are one or more "CR information polls" (i.e., base stations) that have access to the Internet. They can obtain the list of available TV channels that are not occupied by PRs from the TV-band database. CRVs have to communicate with one of the information polls to receive Internet services. If the information poll is not within the CRV's transmission range, a multi-hop route should be established. We assume that CRVs know their locations. FCC regulations dictate that CRVs must incorporate a geo-location capability to use TV channels. Nowadays, more and more vehicles are equipped with GPS for navigation and car-infotainment services.

Figure 2 illustrates an OFDM-based multi-channel system for the CRVN. A set of subcarriers constitutes either a control or a data channel.[2] The control channel is selected *a priori* by the information polls (or cooperatively with other CRVs).[3] The selected control channel as well as channels adjacent to the control channel should not be occupied by PRs.

A pair of CRVs negotiate their data channel(s), transmission power(s), and transmission rate(s) by exchanging control packets over the control channel. Then, the subsequent data packet is sent over the assigned data channel(s). This data communication can be conducted over several contiguous or non-contiguous subcarriers. For example, to transmit data over TV channels 15 and 17, subcarriers over these channels are activated and subcarriers over other channels are disabled. We assume that a CRV transceiver can simultaneously transmit and receive over different channels but cannot do both over the same channel. The feasibility of this assumption has been validated in several works (e.g., [8]).

Subcarrier spacing is 15 kHz, so that the symbol duration, with the 1/2 cyclic prefix, is $(1/(15 \times 10^3) \times 1/2) \simeq 33$ us, which is similar to that of LTE [1]. As shown in Fig. 2, two pilot subcarriers are placed in each channel to aid the receiver with synchronization and channel estimation. Guard subcarriers are used to suppress the multi-access interference (MAI) from PRs and other CRVs.

According to the FCC rules, the maximum transmission powers for CRVs are set as shown in Table 2. We refer to idle channels that are not adjacent to PR-occupied channels as *clean channels*. In Fig. 2, TV channels 17 and 19 are adjacent to PR-occupied channels, so they are not clean. The information poll must check the database to get available TV channels at least once a day and it is not allowed to transmit over the adjacent channel. For CRVs, the maximum transmission power over non PR-adjacent channels is much greater if they have access to the TV-bands database (either directly or via the information poll) than otherwise. If CRVs have access to the database, they must check their location (e.g., via GPS) at least every 60 s. If they move more than 100 m from the location where they performed their last database check, they have to re-check the database. We assume that CRVs can acquire available channel lists along their path from the database so that they do not need to re-check the database too often. If CRVs do not have access to the database, they must scan the channel that they are using and its adjacent channels at least once every 60 s.

[2] We refer to an OFDM subcarrier as a subcarrier, for brevity.

[3] Several techniques have been proposed for control-channel selection. See [18] and the references therein.

4 Spectrum-aware beaconless geographical routing

Algorithm 1 When backoff counter reaches zero and queue is not empty

```
procedure A
    if Relay node is not selected or outside fast forwarding region then
        Broadcast RTF
        Set RTF timer
        if ATF is received before RTF timer is expired then
            Transmit DTF
            Prepare data transmission
            Reset RTF rebroadcast count
        else
            if RTF rebroadcast count < limit then
                Increment RTF rebroadcast count
                Goto procedure A
            else
                Reset RTF rebroadcast count
                Initiate BFP
            end if
        end if
    else
        Send RTF to relay node
    end if
end procedure
```

4.1 Protocol overview

We first provide a general overview of our routing protocol. For any source or intermediate node (say CRV u) to transfer a data packet toward its ultimate destinations, it first selects the relay node (say CRV v) and then negotiates with v the transmission parameters (e.g., data channels, transmission powers and rates). CRV u starts this process by broadcasting a *request-to-forward* (RTF) packet, containing the locations of its destination (say CRV s) and itself. Upon receiving the RTF packet, neighbors check if they are candidates for u. If so, they execute a channel/power/rate assignment algorithm and set a delay timer to reply to the RTF packet. The amount of delay depends on the distance between the destination s and CRV v as well as the link capacity between CRVs u and v. If the timer expires, CRV v transmits an *accept-to-forward* (ATF) packet to CRV u, containing the assigned channels/powers/rates. Through proper interference management, the selected transmission parameters ensure that PRs in the vicinity are not interfered with and the ongoing

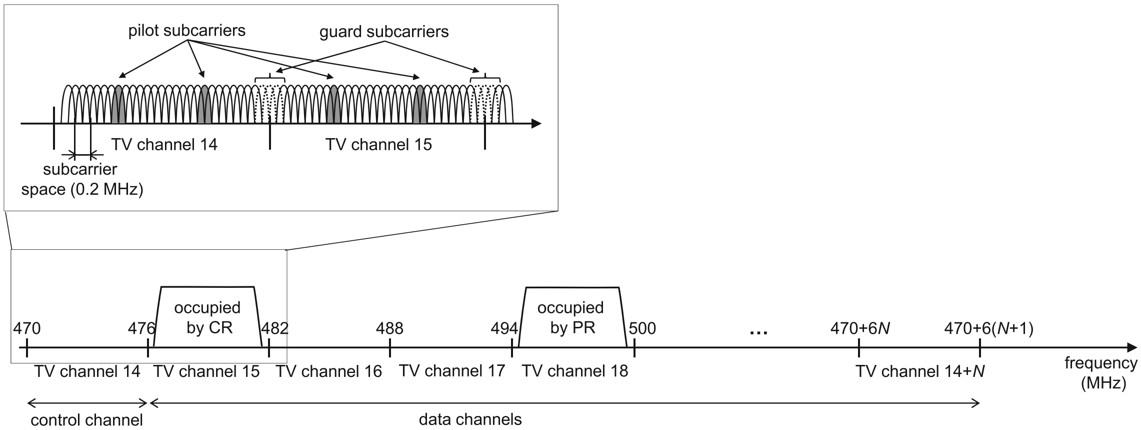


Fig. 2 Example that illustrates an OFDM-based multi-channel system for TV white spaces

communications between neighboring CRVs are not disturbed. A third control packet, called *determined-to-forward* (DTF), is then broadcasted by CRV u to inform nodes that have not received the ATF packet of the transmission parameters. Data communication then occurs over the assigned data channels. An acknowledgement (ACK) packet follows over the same data channels. For subsequent data packets destined to the same destination, CRV u transmits an RTF packet to CRV v as long as CRV v is still in the forwarding area. Otherwise, CRV u broadcasts an RTF packet to repeat the same relay node selection process.

Algorithm 2 When RTF is received

```
procedure B
    Measure channel gain
    Determine powers and rates for commonly available channels
    Select optimal channels
    Calculate link weight and set ATF timer
    if Carrier is detected before ATF timer is expired then
        Cancel ATF timer
    else
        Send ATF
    end if
end procedure
```

4.2 Transmission power and rate selection

The RTF packet is sent over the control channel at the maximum transmission power ($P_{\max}$). Upon receiving this packet, a candidate node decides the transmission powers and rates for available data channels based on its channel gain measurements. The RTF packet includes the rate demand, denoted by D, the location of the source and destination nodes, the set of available data channels (denoted by $\mathcal{A}_u$), and the allowable transmission powers, denoted by $\hat{P}_T^{(i)}$, for all $i \in \mathcal{A}_u$. The allowable transmission power for a given channel is the maximum transmission power that CRV u can use over that channel so that the ongoing communications between other CRVs in the vicinity are not disrupted. It should also conform to the FCC power masks, shown in Table 2. We later explain how to obtain $\mathcal{A}_u$ and $\hat{P}_T^{(i)}$ $\forall i \in \mathcal{A}_u$.

Upon receiving the RTF packet, a candidate (say CRV v) measures the received power over the control channel c, denoted by $P_R^{(c)}$, and estimates c's channel gain as follows [15]:

$$h^{(c)} = P_R^{(c)}/P_{\max}. \tag{1}$$

Let $\mathcal{A}$ denote the set of available data channels that are common to both nodes u and v, i.e., $\mathcal{A} = \mathcal{A}_u \cap \mathcal{A}_v$. From $h^{(c)}$, CRV v estimates the channel gains over all channels $i \in \mathcal{A}$ as follows:

$$h^{(i)} = h^{(c)} \left(\frac{f^{(c)}}{f^{(i)}} \right)^2 \tag{2}$$

where $f^{(c)}$ and $f^{(i)}$ are the center frequency of the control channel and the ith data channel, respectively.

The transmission powers and rates should be selected while considering interference. CRVs u and v may have different amounts of interference but it is reasonable to set the same transmission powers and rates for $u \to v$ data transmission and $v \to u$ ACK transmission. Let $\hat{P}^{(i)} = \min\left\{\hat{P}_u^{(i)}, \hat{P}_v^{(i)}\right\}$ denote the allowable transmission power for CRVs u and v over the ith data channel. If CRV u transmits its data over the ith data channel at power $\hat{P}^{(i)}$, the received power at CRV v over that channel is approximately $P_R^{(i)} = h^{(i)}\hat{P}^{(i)}$. Let $I_v^{(i)}$ and $\mu_v^{(i)} = P_R^{(i)}/(I_v^{(i)} + N)$ denote the total interference and the SINR at CRV v over the ith data channel, where N is the noise power.[4] We later explain how to obtain the values of $I_v^{(i)}$ for all available data channels. Let $\hat{\mu}_v^{(i)} \leq \mu_v^{(i)}$ denote the SINR threshold associated with the highest possible transmission rate for $u \rightarrow v$ data transmission over the ith data channel. Similarly, $\hat{\mu}_u^{(i)}$ is obtained for $v \rightarrow u$ ACK transmission. Then, the minimum transmission power over the ith data channel is estimated as follows:

$$P_{\min}^{(i)} = \hat{\mu}^{(i)} \frac{1}{h^{(i)}} \epsilon \tag{3}$$

where $\hat{\mu}^{(i)} = \min\left\{\hat{\mu}_u^{(i)}, \hat{\mu}_v^{(i)}\right\}$ and $\epsilon > 1$ is a inflation factor that captures channel fading.[5] Let $\rho^{(i)}$ denote the transmission rate for data channel i that is associated with $\hat{\mu}^{(i)}$ in Table 1. If $P_{\min}^{(i)} > \hat{P}^{(i)}$ due to interference, the ith data channel is excluded from $\mathcal{A}$.

4.3 Data channel selection

After computing the transmission powers and rates for all available data channels (i.e., $\forall i \in \mathcal{A}$), the candidate node selects data channels so that the sum of transmission rates over the selected data channels are maximized while meeting the rate demand and power constraints. The channel selection problem can be formally stated as follows:

$$\underset{x^{(i)}}{\text{maximize}} \sum_{i \in \mathcal{A}} \rho^{(i)} x^{(i)} \tag{4}$$

subject to

$$\sum_{i \in \mathcal{A}} \rho^{(i)} x^{(i)} \leq D \tag{5}$$

$$\sum_{i \in \mathcal{A}} W P_{\min}^{(i)} x^{(i)} \leq P_{\text{total}} \tag{6}$$

$$x^{(i)} \in \{0, 1\} \quad \forall i \in \mathcal{A}. \tag{7}$$

where $x^{(i)}$ is the indicator function, taking a value of 1 if the ith data channel is selected and zero otherwise; P_{total} is the total transmission power that is supported by the RF amplifier, and W is the frequency bandwidth of each data channel.

The above integer linear program is the 2-dimensional Knapsack problem which is known to be NP-hard. We relax this problem to the 1-dimensional Knapsack problem by replacing (5) and (6) with the following equation (as presented in [5]).

$$\sum_{i \in \mathcal{A}} \rho^{(i)} W P_{\min}^{(i)} x^{(i)} \leq D P_{\text{total}}. \tag{8}$$

[4]We assume that the noise is a stationary and ergodic random process and its statistics can be measured *a priori*.

[5]The value of ϵ should be carefully chosen to avoid fast fading effect

Table 1 Transmission rate vs. SNR table

Modulation	FEC	TX rate (Mbps)	SINR
QAM 4	1/2	3.0	3.0
QAM 4	3/4	4.0	6.0
QAM 16	1/2	5.0	12.0
QAM 16	3/4	7.0	30.0
QAM 64	1/2	9.0	70.0
QAM 64	3/4	11.0	120.0

The final problem is still NP-hard but can be solved using CPLEX with much less computations [5]. For small embedded systems, we present a heuristic algorithm to solve it. This algorithm calculates $\rho^{(i)} P_{\min}^{(i)}$ for all data channels in $\mathcal{A}$ and sorts $\mathcal{A}$ in a decreasing order of $\rho^{(i)} P_{\min}^{(i)}$. It removes the first element (i.e., data channel i) from $\mathcal{A}$ and adds i to to the set of selected data channels, denoted by $\mathcal{S}$. Then, $\rho^{(i)}$ and $W P_{\min}^{(i)}$ are subtracted from D and P_{total}, respectively. This process is repeated until $D > 0$ and $P_{\text{total}} > 0$.

Figure 3 illustrates an example of the channel selection algorithm. Note that $P_{\min}^{(i)}$ and P_{total} are in mW unit. The values of $\rho^{(i)} P_{\min}^{(i)}$ for all available data channels are indicated in the figure. With these values, the sorted $\mathcal{A}$ is $\{3, 5, 1, 8, 7, 2\}$. For $D = 10$ Mbps and $P_{\text{total}} = 0.1$ W $\times$ 20 MHz $= 2$ MW, $\mathcal{S}$ is $\{3, 5, 1\}$.

4.4 Relay node selection

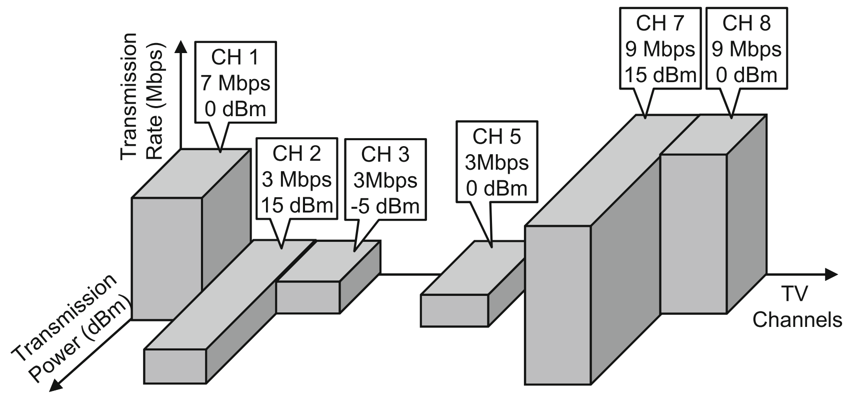
After assigning channels/powers/rates, if the rate demand is satisfied, CRV v sets its backoff timer δ before replying to the RTF packet. The value of δ is set as follows:

$$\hat{\delta} = \delta_{max} \cdot \left(1 - \frac{\text{ADV}_v \cdot \min\{R, D\}}{\tau \cdot D}\right) \tag{9}$$

$$\delta = (\hat{\delta} \bmod t_{\text{slot}}) t_{\text{slot}} + \text{uniform}\{0, B\} t_{\text{slot}} \tag{10}$$

where R is the total transmission rate, i.e., $R = \sum_{i \in S} \rho^{(i)}$, ADV_v is the advance of CRV v (i.e., $\text{ADV}_v = d_u - d_v$), $\delta_{\max}$ is the maximum delay, τ is the maximum transmission range, and t_{slot} is the slot duration. The value of $\delta_{\max}$ is set to the minimum contention window size, denoted by $\text{CW}_{\min}$, times t_{slot}. τ can be calculated a priori from the path loss formula. If several candidates are close to each other, they can have the same value of δ. Thus, a random amount of delay between 0 and $B t_{\text{slot}}$ is added to δ. Once the timer expires, CRV v transmits an ATF packet to node u.

If a candidate detects a carrier before its ATF timer expires, it cancels the timer. Because the carrier sensing range is typically larger than the transmission range, it is assumed that all candidates of a given forwarding node can sense the carrier of each other. It is possible that more than one candidate has the same delay, resulting in multiple ATF



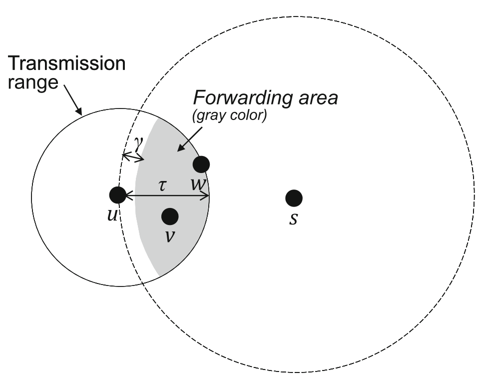
- $\rho^{(i)} P_{\min}^{(i)}$ values -

CH 1	7	CH 2	94.868	CH 3	0.948
CH 5	3	CH 7	28.46	CH 8	9

Fig. 3 Data channel selection process: Channels 1, 3, and 5 are selected to meet a rate demand of 10 Mbps

transmissions that could potentially collide at CRV u. Thus, if CRV u does not receive an ATF packet within a certain amount of time, it rebroadcasts the RTF packet.

Figure 4 illustrates the relay node selection process. Let $CW_{\min} = 32$ and $t_{\text{slot}} = 50$ us so that $\delta_{\max} = 1600$ us. We set $D = 10$ Mbps, $\tau = 8500$ m, and $B = 6$. As shown in Fig. 4, the advance of CRV w is 8,000 m, which is much greater than that of CRV v. However, because CRV w is on the edge of the maximum transmission range of CRV u, the link between CRVs u and w can only support 6 Mbps, which is lower than D. Suppose that v and w randomly choose 3 and 2, respectively, for their additional backoff delay. Then, for CRV w, the value of δ is set to $1600 \text{ us} \times (1 - 8000 \text{ m} \times 6 \text{ Mbps}/8500 \text{ m}/10 \text{ Mbps}) + 2 \times 50 \text{ us} = 797.6$ us and it is rounded off to 750 us. Similarly, CRV v sets its δ to 600 us. Thus, in this example, CRV v sends the ATF packet and CRV w cancels its delay timer.



	ADV (m)	*R* (Mbps)	δ (us)
Node v	6,000	10	600
Node w	8,000	6	750

Fig. 4 Example that illustrates the relay node selection

While waiting for an ATF packet, there are three scenarios that can happen: (1) Several candidates that satisfy D exists, (2) candidates exist but some of them do not satisfy D, and (3) no candidates exist. In the first case, the candidate that is closest to the destination sends its ATF first, and is thus selected as the relay node. In the second case, the candidate with the highest link weight is selected as the relay node. The third case occurs when a dead-end is encountered. In this case, the BFP scheme, explained in Section 2, is used. Because BFP does not take into account interference to PRs and other CRVs, we slightly modify it by excluding from the planar graph CRVs that have no available channels.

Upon receiving the ATF packet, CRV u broadcasts a DTF packet. The ATF packet conveys $\mathcal{S}$, $\rho^{(i)}$, and $P_{\min}^{(i)}$ $\forall i \in \mathcal{S}$. The DTF packet contains the same information as the ATF packet. Upon overhearing ATF or DTF packets, any neighboring node z updates its $\mathcal{A}_z$.

4.5 Data communication and fast forwarding

After transmitting the DTF packet, CRV u begins its data transmission over the selected data channel(s). Upon receiving the data packet, CRV v replies with an ACK packet, sent over the same data channel(s).

The relay node selection process incurs a delay for exchanging RTF and ATF packets. In dense networks, this delay can be substantial because of the high collision rate between ATF packets. Thus, once CRV v is selected, CRV u unicasts the RTF packet to CRV u for the data packets destined to the same destination as long as CRV v is located in the predefined *forwarding area*. Figure 4 depicts the forwarding area of u. We call this variation as *fast forwarding* (FF).

In FF, the ATF packet also contains v's position and velocity, denoted by $\mathbf{p}_v$ and $\mathbf{v}_v$, respectively. Upon receiving the ATF packet, u stores $\mathbf{p}_v$ and $\mathbf{v}_v$. For another data packet destined to the same destination, u estimates the advance of v (i.e., ADV_v) from the stored $\mathbf{p}_v$ and $\mathbf{v}_v$. If $\gamma \le \mathrm{ADV}_v \le \tau$, CRV u unicasts its RTF packet to v; otherwise, it broadcasts its RTF packet. $\gamma \ge 0$ is called the fast forwarding factor. Its impact on the end-to-end delay is evaluated in Section 5. If CRV u does not receive an ATF packet from v for k times, it broadcasts its RTF packet to select another relay node.

4.6 Estimation of allowable transmission power

The allowable transmission power for a given data channel is the maximum transmission power that can be used for that channel such that active PRs are not interfered with and the ongoing data communications between other CRVs are not disrupted. To protect PRs, the transmission powers must conform with FCC power masks, shown in Table 2. Let $\mathcal{B}_u$ denote the set of PR-adjacent channels in the vicinity of CRV u. We assume that CRVs can obtain this set from the TV-bands database or through sensing. Suppose that CRVs have access to the TV-bands database. Then, the allowable transmission powers according to the FCC rules are as follows:

$$\hat{P}^{(i)}_{\mathrm{FCC}} = \begin{cases} 20\ \mathrm{dBm}\ \text{for}\ i \in \mathcal{A}_u - \mathcal{B}_u \\ 17\ \mathrm{dBm}\ \text{for}\ i \in \mathcal{A}_u \cap \mathcal{B}_u \end{cases} \quad (11)$$

To avoid disrupting ongoing communications between other CRVs in the same vicinity, every CRV maintains a busy table (BT), as shown in Table 3, which is updated upon overhearing any ATF and DTF packets. Table 3 exemplifies the BT update procedure when the ATF and DTF are sent at times 500 msec and 700 msec, respectively. The duration of the data packet can be derived from the transmission rates and the packet size that are indicated in the ATF and DTF packets. Suppose that the durations of DTF and data packets are 10 msec and 200 msec, respectively. Then, upon overhearing the ATF packet, the transmission period for the data communication is set from $500 + 10 = 510$ msec to $510 + 200 = 710$ msec.[6] Because the ACK packet is sent with the same transmission rates and its size is fixed, the transmission period for the ACK communication can be estimated. A similar process applies upon overhearing the DTF packet. Note that upon overhearing ATF and DTF packets, the channel gain(s) from the transmitter for the assigned data channel(s) can be estimated using (1) and (2).

Suppose that CRV u wants to transmit its data packet over the ith data channel but CRV z is currently receiving over that channel. To avoid disrupting this reception, the interference from u to z has to be negligible (e.g., noise level). The

[6]In real systems, more delay factors should be considered such as the inter-frame spacing, propagation delays, etc. These are ignored in the example for simplicity.

Table 2 Transmission power mask according to FCC rules

Device Type	Database Access	PR-adjacent Channel	Maximum TX Power
Information poll	Yes	No	30 dBm
CRVs	Yes	Yes	16 dBm
	Yes	No	20 dBm
	No	Yes	17 dBm
	No	No	16 dBm

allowable transmission powers that do not harm the ongoing data receptions of other neighboring CRVs are obtained as follows:

$$\hat{P}^{(i)}_{\mathrm{CRV}} = \frac{N}{\max\limits_{z \in \mathcal{R}^{(i)}} \left\{ h^{(i)}_z \right\}} \quad (12)$$

where $h^{(i)}_z$ is the channel gain between u and z for the data channel i and $\mathcal{R}^{(i)}$ is the set of CRVs that are currently receiving over that data channel in the vicinity of u. $h^{(i)}_z$ and $\mathcal{R}^{(i)}$ for available data channels can be obtained from the BT, as shown in Table 3.

Finally, for CRV u the allowable transmission power over the ith data channel is set to $\hat{P}^{(i)}_u = \min \left\{ \hat{P}^{(i)}_{\mathrm{FCC}}, \hat{P}^{(i)}_{\mathrm{CRV}} \right\}$. If $\hat{P}^{(i)}_u > P_{\max}$, the data channel i is excluded from $\mathcal{A}_u$.

5 Experimental results

We used ns-3 simulations to evaluate the SABE and compare its performance with the GPSR and SEARCH. Hereafter, we refer to SABE without FF and SABE with FF as SABE and SABE+, respectively. For this purpose, we have completely reprogrammed the PHY/MAC/routing components of the ns-3.[7]

In our simulations, 200 CRVs are randomly distributed on grid roads over 35 km x 35 km square. Each grid road is spaced one kilometer along from the next. CRVs move according to the Manhattan mobility model with an average speed, denoted by χ, that ranges from 1 to 50 meter/second. At each intersection, a CRV chooses to keep moving in the same direction with 50 % probability or taking a left or right with 25 % probability each.

One information poll is located at the center. Five source CRVs are randomly selected and they generate 1000-byte UDP packets to the information poll. Packet generation at each source CRV follows a Poisson process with a rate λ (in packets/second). Six transmission rates are used, as listed in Table 1. The SNR values are taken from the IEEE 802.16

[7]The codes can be obtained from the authors upon request.

Table 3 Example that illustrates the busy table

Transmitter ID	Receiver ID	Data Channel ID	Transmission Duration	Transmission Power	Channel Gain from Transmitter	Channel Gain from Receiver
1	2	2	510 ~ 710 msec	5 dBm	0.6	0.3
2	1	2	710 ~ 715 msec	5 dBm	0.3	0.6
3	4	3, 4	700 ~ 800 msec	0, 3 dBm	0.8, 0.78	0.2, 0.18
4	3	3, 4	800 ~ 805 msec	0, 3 dBm	0.2, 0.18	0.8, 0.78

standard [1]. Unless indicated otherwise, the default values for the main simulation parameters are listed in Table 4.

Figure 5(a) shows the request fail rate for GPSR, SEARCH, SABE, and SABE+ as a function of χ. Hereafter, error bars represent 95% confidence intervals. The request fail rate is obtained as the number of unreturned ATF replies to the number of RTF transmissions. As the value of χ increases, the request fail rate of GPSR and SEARCH dramatically increases. If the rate of HELLO broadcasts is not high enough relative to node speeds, the sender can transmit a message to a node that is no longer in its transmission range. In contrast, in SABE and SABE+ the sender does not need the locations of neighbors and the route is decided by receivers with their up-to-date locations. Thus, the request fail rate of SABE and SABE+ does not change with χ.

Table 4 Simulation parameters

Parameter	Default value
Simulation area	35 km × 35 km
Number of information polls	1
Number of CRVs	200
Number of control channels	1
Number of data channels	15
Average CRV speed (χ)	20 m/s
Channel bandwidth	6 MHz
Center frequency of ith channel	$473 + 6i$ MHz
Traffic rate (λ)	1 packet/second
Noise power	90 dBm
Carrier sense threshold	100 dBm
Rate demand (D)	10 Mbps
Data packet size	1000 bytes
RTF unicast retransmit limit (k)	2
CW_{min}	32
CW_{max}	1024
Slot duration	50 us
Maximum transmission range for non PR-adjacent channels (τ)	8.5 km @ 17 dBm
Maximum transmission range for PR-adjacent channels	5.5 km @ 16 dBm
Fast forwarding factor (γ)	4.5 km

Figure 5(b) depicts the average end-to-end delay as a function of χ. Because a higher χ results in a higher request fail rate, the average end-to-end delay of GPSR and SEARCH decreases with χ. Likewise, the average end-to-end delay of SABE monotonically decreases as χ increases, because of the reduction in the average number of hops (see Fig. 5(d)). For SABE+, as χ increases, the average end-to-end delay monotonically increases because the likelihood of falsely estimating neighbor's location from its previous speed and velocity increases with χ.

Figure 5(c) examines the average end-to-end goodput as a function of χ. For GPSR and SEARCH, the goodput plummets as the value of χ increases. In constrast, the goodput for SABE and SABE+ is steady, implying that most of generated packets are successfully delivered to the information poll.

To study the performance when PRs are present, we assume that each TV channel is used by one PR. PRs behave as an independent ON/OFF source with an activity factor α. PR activities are homogeneous. Figures 6(a) and (b) depict the average end-to-end delay and the number of hops as a function of α. The average end-to-end delays for GPSR, SEARCH, SABE, and SABE+ are steady for $\alpha \leq 0.3$ because the number of channels not occupied by active PRs is enough to support the overall traffic demand. As α increases over 0.3, the average end-to-end delay of GPSR, SEARCH, SABE, and SABE+ increases because the number of unoccupied channels is not enough. Note that if the adjacent channel is occupied by active PRs, the maximum transmission power and range are 16 dBm and 5.5 km, respectively. Thus, a higher α means more likelihood of using a smaller transmission power and having more hops, as shown in Fig. 6(b).

Figure 7(a) examines the request fail rate as a function of traffic load λ. For GPSR, SEARCH, and SABE, as λ increases, the request fail rate increases. The request fail rate of GPSR and SEARCH is much higher than that of SABE because the rate of HELLO broadcasts is not high enough relative to node speeds (20 m/s, on average). In addition, in GPSR and SEARCH, RTF packets often collide with HELLO packets. As mentioned before, SABE suffers collisions between ATF packets sent by candidates. These ATF packets can also collide with RTF packets sent by hidden

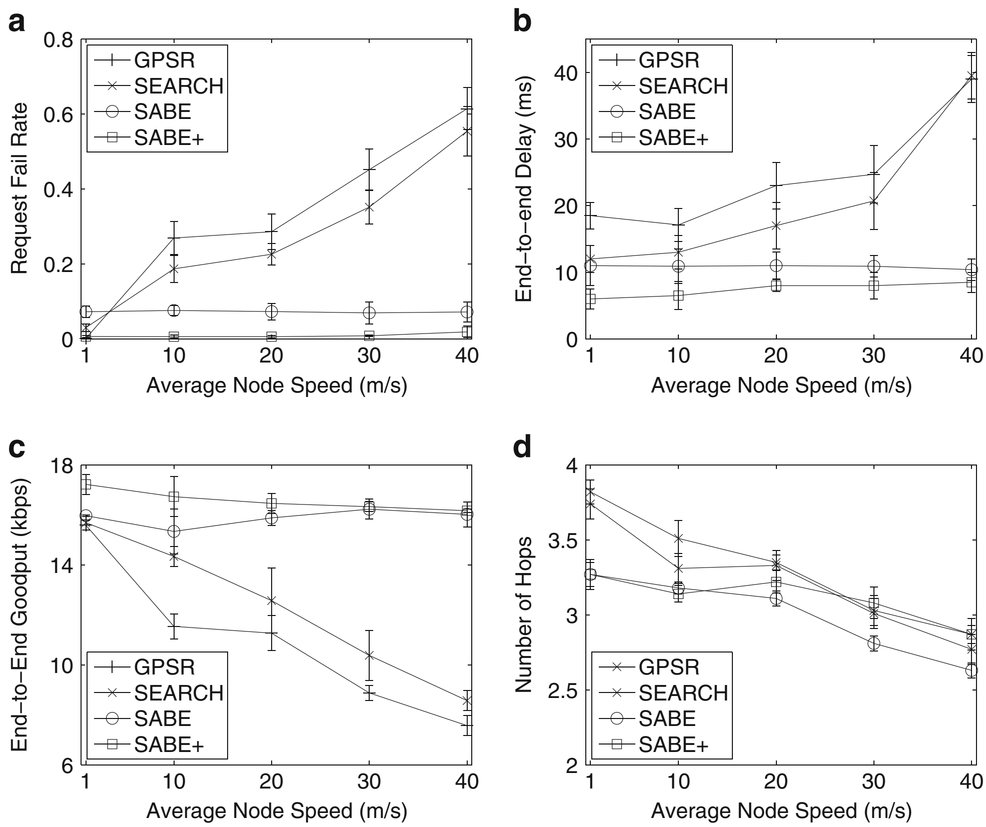


Fig. 5 Impact of node speed on performance

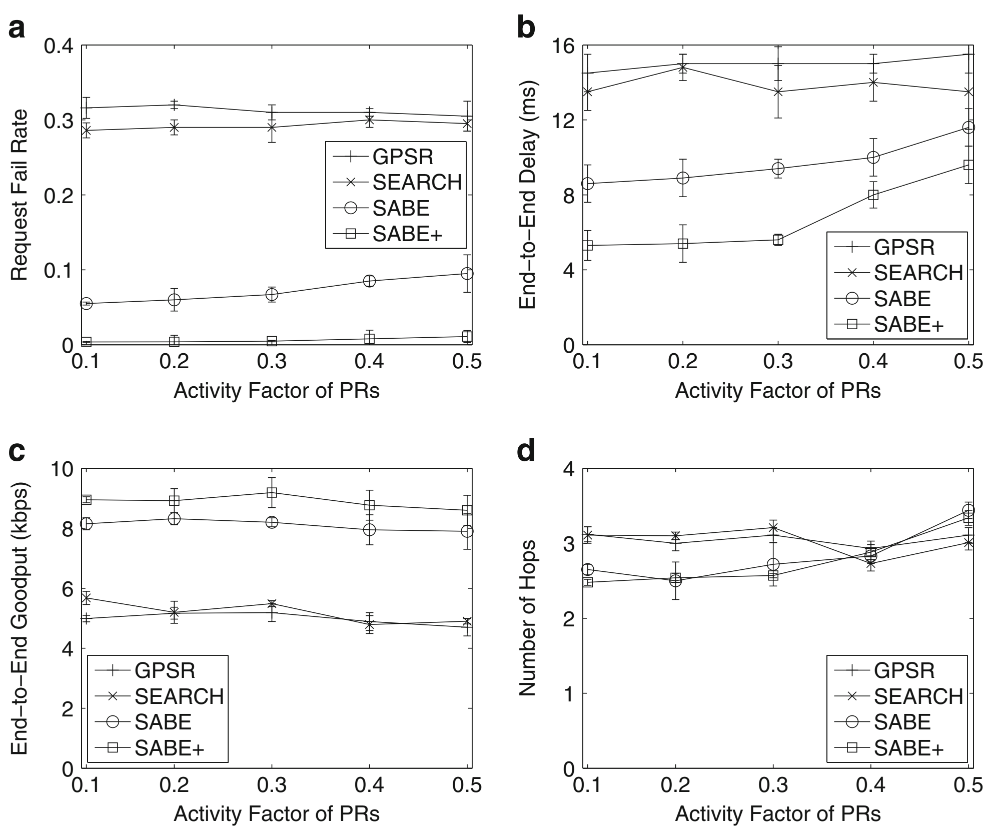
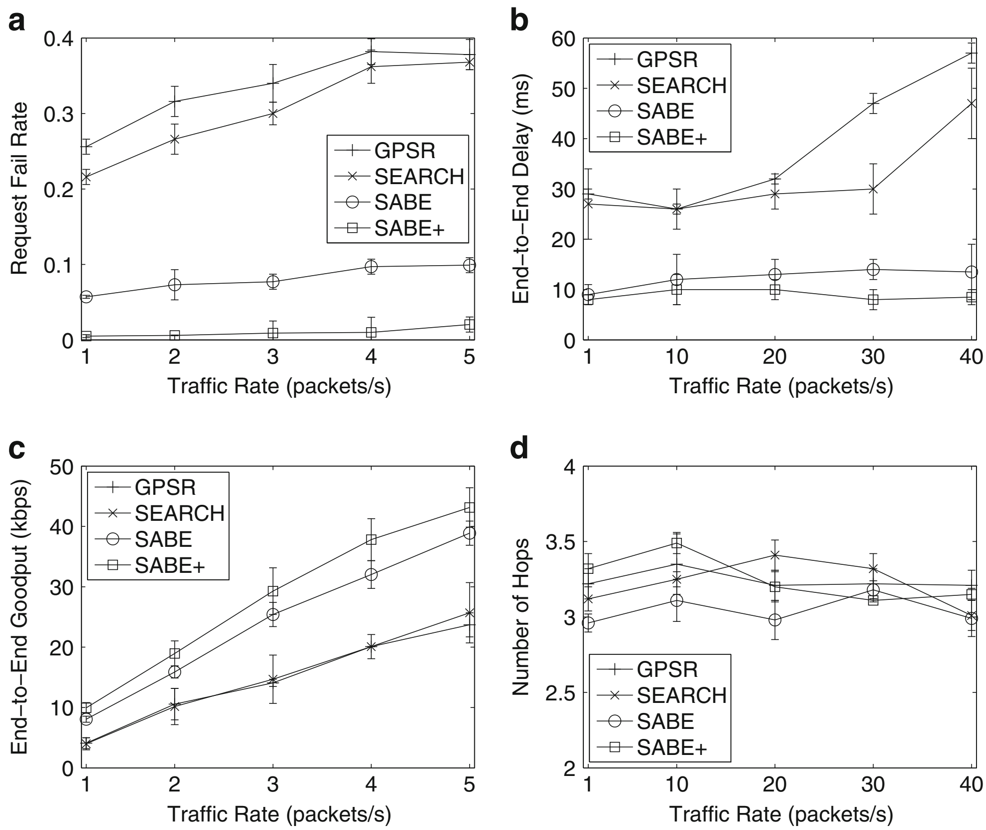


Fig. 6 Impact of PR activity on performance

Fig. 7 Impact of traffic load on performance

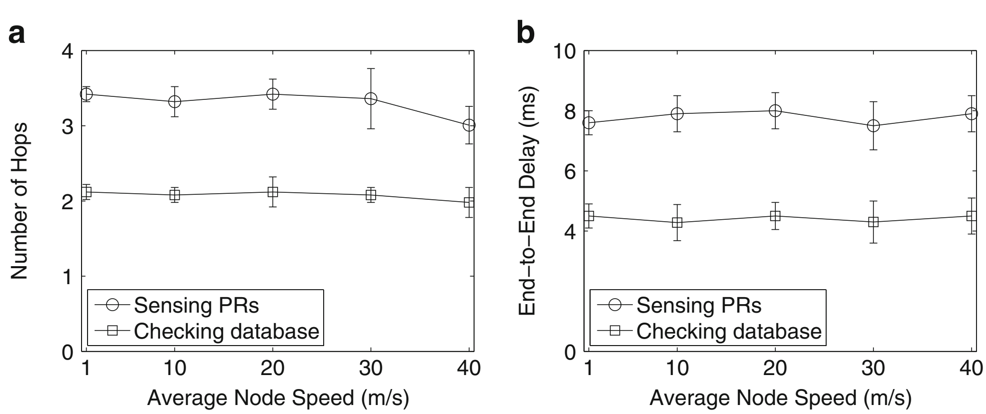


nodes. The fail rate for SABE+ is steady and much lower than that of SABE. This is because once the relay node is selected, SABE+ does not require candidates to compete again (by sending ATF packets) for several subsequent data packets.

Because of the low fail rate, SABE+ outperforms GPSR, SEARCH and SABE in terms of the end-to-end delay, as shown in Fig. 7(b). The end-to-end delay of GPSR and SEARCH is much greater than that of SABE and SABE+, and it increases dramatically with λ. Figure 7(c) depicts the end-to-end goodput as a function of λ. The end-to-end delay of GPSR and SEARCH is smaller than that of SABE and SABE+ and it does not increase linearly with λ. This means that GPSR suffers from more data losses at high values of λ. The end-to-end delay for SABE and SABE+ increases almost linearly as λ increases, meaning that SABE and SABE+ barely have data losses even though SABE suffers from some request failures. Figure 7(d) shows that the traffic load does not affect the number of hops.

According to the FCC's rules, the maximum transmission power is 20 dBm if the CRV can access the TV bands database and 17 dBm otherwise. In our simulations, the transmission ranges that correspond to these powers are 6.5 km and 8.5 km, respectively. Figure 8(a) and (b) show the the number of hops and the end-to-end delay,

Fig. 8 Impact of the use of TV-bands database on performance



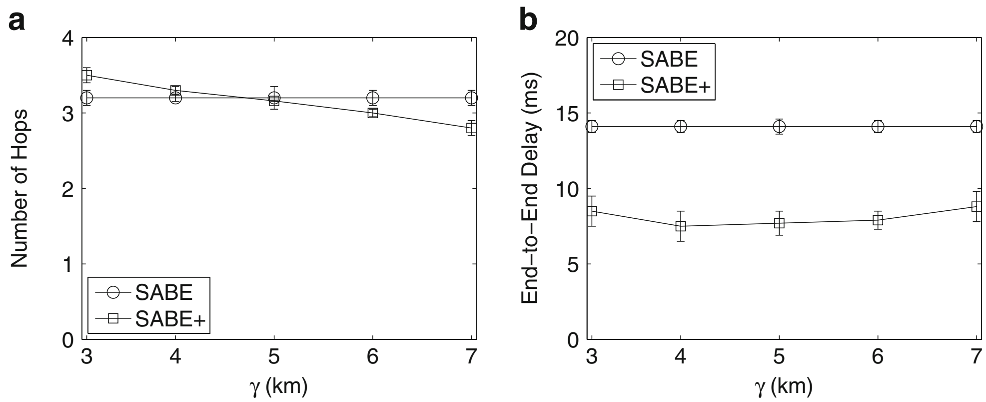


Fig. 9 Impact of fast forwarding factor (γ) on performance

respectively, versus the average node speed with different maximum transmission powers. Clearly, checking the database to obtain the available TV channels reduces the end-to-end delay and the number of hops significantly.

In SABE+, once the relay node v has been selected, it will not be changed until its expected advance is in a certain range (i.e., $\gamma \leq \text{ADV}_v \leq \tau$). Figure 9(a) and (b) depict the number of hops and the average end-to-end delay, respectively, as a function of γ. For a smaller γ, CRVs forward more messages to their selected relay nodes, reducing the overhead incurred by the relay node selection process. At the same time, each hop is likely to have a smaller ADV, increasing the number of hops. The results show that $\gamma = 5$ km provides the best performance in terms of the average end-to-end delay.

GPSR and SEARCH suffer significant packet losses because the rate of HELLO broadcasts is not high enough relative to node speeds. Figure 10(a) and (b) depict the request fail rate and end-to-end goodput as a function of HELLO interval, denoted by $\mathcal{H}$. The value of $\mathcal{H}$ is equal to the inverse of the rate of HELLO broadcasts. As $\mathcal{H}$ increases, the request fail rate decreases and the end-to-end goodput increases. When $\mathcal{H} = 10$ seconds, GPSR and SEARCH have similar request fail rates to SABE. However, its end-to-end goodput is still considerably lower than that of SABE because GPSR and SEARCH are limited to selecting only one channel for data communications. Although GPSR and SEARCH can provide good performance with a small $\mathcal{H}$, this may incur a substantial overhead for the control channel, reducing the overall network throughput.

6 Conclusions

In this paper, we proposed a routing protocol for DSA-capable vehicular ad hoc networks in which mobile CRVs opportunistically access the TV white spaces. Our protocol, called SABE, takes advantage of new physical-layer technologies such as NC-OFDM and STAR to boost network throughput using single-transceiver radios. In SABE, CRVs jointly select relay nodes, channels, transmission powers, and rates with consideration of legacy users and interference from other CRVs so that the total transmission rate is maximized while meeting rate demands and power constraints.

Because this process is done by receivers on a per-packet and per-hop basis, our protocol can efficiently adapt to spectrum dynamics and node mobility. Once the relay node is selected, it will not be changed as long as it stays in the forwarding area. In SABE, CRVs do not broadcast beacons to exchange information a priori. The most of

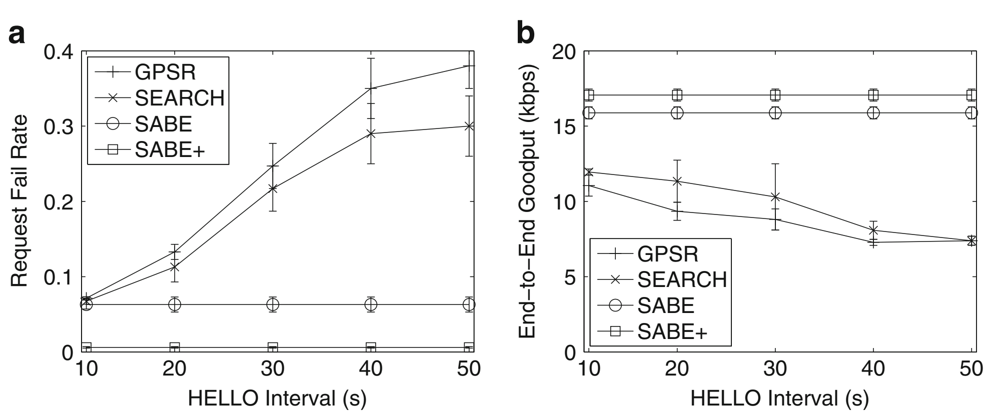


Fig. 10 Impact of HELLO interval on performance

information (required for the relay node and resource selection) is acquired during control packet exchanges and the other information is from overheard control packets. Simulation results show that our protocol outperforms GPSR and SEARCH in terms of the end-to-end delay and throughput.

Equation (2) is based on the free-space propagation model for simplicity. However, one can use more realistic models such as COST-231 model to improve the robustness of the proposed algorithm.

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