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RESEARCH ARTICLE

Exploiting temporal and spatial diversities for spectrum sensing and access in cognitive vehicular networks

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ABSTRACT

In cognitive vehicular networks (CVNs), spectrum sensing and access are introduced as the promising technologies to fully exploit the underutilized licensed spectrum. Because the sensing ability of a single secondary vehicular user (SVU) is affected by high mobility, dynamic topology, and unreliable wireless environment, collaborative sensing is developed to increase the sensing accuracy and efficiency. Generally, the synchronization is required in the collaborative sensing in CVN. However, it is difficult to keep all SVUs synchronized with others for sensing under the high dynamic network topology, and the sensing overhead of the synchronous cooperative action may be significant. In this paper, we first propose an asynchronous cooperative sensing scheme in which each SVU provides an energy information (EI) that is tagged with location and time information. The sensing decision will be made on account of the EI. Considering the temporal and spatial diversities of each SVU, we assign different weights to each EI and formulate the probabilities of detection and false alarm as the optimization problems to find the optimal weight of each EI. Then, based on the asynchronous sensing, the specifications of the opportunistic spectrum access mechanism are elaborated in both centralized and decentralized CVNs for the sake of practical implementation. We analyze the system performance in terms of achievable throughput and transmission delay. Numerical results show that the proposed scheme is able to achieve substantially higher throughput and lower delay, as compared with existing schemes. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS
cognitive vehicular networks; cooperative sensing; opportunistic spectrum access

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1. INTRODUCTION

In vehicular networks, the explosive increase of vehicular devices and applications poses a serious problem of compelling need of numerous radio spectrum. In contrast, spectrum measurement shows that large portion of the licensed spectrum is unused. According to the Federal Communications Commission, 70% of the licensed spectrum in the USA is not utilized most of the time [1]. Cognitive radio (CR) [2,3], which has drawn intensive attention, is designed to enable spectrum access of these underutilized spectrum, especially for the vehicular networks [4,5]. Enabling CR technology in vehicular networks, however, is never an easy task. One major characteristic of the vehicular network is that there are multiple mobile communication nodes (vehicles) that make the entire network high dynamic mobility. As a result, how to discover and utilize the underused spectrum efficiently for the mobile vehicles emerges as the critical issue.

Based on the CR technology, the vehicles with the sensing function, which are called secondary vehicular users (SVUs), are able to solve the spectrum shortage problem by the simple and cooperative sensing. In the simple sensing, an SVU periodically monitors the licensed spectrum and identifies *spectrum opportunities* [6–14], which is defined as the licensed spectrum band for SVUs to use without interfering the primary (licensed) users' (PUs') transmission. In the cooperative sensing case, multiple SVUs are employed to collaboratively sense the spectrum to enhance the sensing performance. To guarantee the efficient discovery of spectrum opportunities, synchronization is required in the cooperative sensing in the traditional cognitive systems [15–17]. However, in a cognitive vehicular network (CVN), it is difficult to keep synchronous control for all vehicles under a high dynamic network topology.

In this paper, we first propose a new asynchronous cooperative sensing scheme (ACSS) by exploiting the temporal and spatial diversities in CVNs. The cooperative SVUs collect and store the energy information (EI), which is defined as the energy of the received signal. Any SVU who needs licensed channel information, called the *tagged SVU*, collects the EI from the cooperative SVUs and assigns relevant weight according to the EI's storing moment and location. Combining these information with local sensing result, the tagged SVU makes the final decision of the PU's presence or absence. Considering the temporal and spatial diversities of each SVU's sensing behavior, the information from different SVUs has to be assigned with different weights. We integrate the weight of EI with two important parameters in spectrum sensing: the probability of detection and the probability of false alarm. An optimization problem is formulated to find the optimal weights to maximize the detection probability and minimize the false alarm probability. Then, the specifications of the opportunistic spectrum access protocols are elaborated in both centralized and decentralized CVNs for the sake of practical implementation. By queueing theory, we evaluate the performance in terms of throughput and packet delay in multiple-user CVNs.

The objective of this paper is to propose a new ACSS for opportunistic spectrum access in CVNs. To achieve this, we have the following three major contributions in this work.

- We study and exploit the spectrum temporal and spatial dynamics and then incorporate them in a new asynchronous spectrum sensing scheme for CVNs.
- We introduce the EI concept and allow vehicles to collect them from neighboring nodes to eliminate the sensing overhead. We identify the optimal weight of each vehicle's EI by considering the spatiotemporal differences.
- An opportunistic spectrum access protocol is specified in both centralized and decentralized CR networks. An analytical model is constructed to evaluate the performance of the proposed scheme in multiple-user CVNs.

In addition, we present extensive numerical examples to demonstrate the advantages of the proposed scheme compared with the existing schemes and to show the determination of the crucial parameters. Numerical results indicate that our proposed scheme is able to achieve considerably higher throughput and lower delay, as compared with existing mechanisms.

The rest of this paper is organized as follows. The background and system model are introduced in Section 2. In Section 3, we discuss the ACSS. The opportunistic spectrum access protocol is derived under both centralized and decentralized networks in Section 4. Section 5 evaluates the performance of the proposed ACSS and opportunistic access mechanism in CVNs. Section 6 presents the numerical results of the proposed scheme in CVN. Finally, we conclude the paper in Section 7.

2. BACKGROUND INTRODUCTION AND SYSTEM MODEL

2.1. Background

Spectrum sensing is a crucial technology for CVNs in which SVUs and control node need sufficient spectrum resources to exchange information and transmit data for applications such as route planning and traffic management [18,19]. In general CR networks, many researchers have been devoted to study the efficient noncooperative sensing scheme (NCSS). However, in a vehicular network, the sensing accuracy may be limited because of radio propagation, traffic information diversity, and mobile environment complexity. In addition, the discovery of spectrum opportunities has the cost of losing transmission opportunities. This cost associated with spectrum sensing is referred to as *sensing overhead*.

In order to increase the sensing performance, collaborative sensing is employed in the CR network where multiple secondary users are allowed to cooperate to seek spectrum opportunities [22–27]. The authors in [22] and [23] studied the problem on how to determine the total sensing time and how to distribute the total sensing time to different channels in cooperative soft-decision spectrum sensing. A rigorous analytical framework for cooperative spectrum sensing with data fusion was provided in [24]. The authors in the study [25] proposed two cooperative sensing mechanisms, random sensing policy, and negotiation-based sensing policy, which use secondary users to collaboratively sense different channels to improve the sensing efficiency. In the study of [26], the authors presented a cooperative spectrum sensing using an optimal counting rule by considering both fading and sensing time constraints. In these cooperative models, the secondary users are used to operate sensing at the same time. This type of sensing is called *synchronous cooperative sensing*, in which the sensing operation of all cooperative secondary users should be synchronized so that all secondary users can detect the channel's availability.

The synchronized cooperation poses significant technical challenges and may lead to performance loss for CVNs. First, there is a high requirement on hardware in order to guarantee the precise synchronization operation among all high-speed moving SVUs. Second, each mobile SVU may have different location at any given moment. It is difficult for these SVUs to collaboratively sense the same PU (or the same set channels) at the same time. Third, the synchronous operation may cause considerable sensing overhead. When a cooperative SVU joins the cooperative sensing, its own data transmission has to be stopped, which results in the overhead in the secondary networks. In our preliminary study in this direction [27], we found that the sensing overhead cannot be omitted in the cooperative network model. These considerations motivate us to propose the asynchronous cooperation among SVUs.

There are two recent studies in the literature that have considered the asynchronous sensing [28,29]. These two studies observed that the synchronous cooperative sensing schemes (SCSSs) incur performance loss in a scenario where different SVUs may have different sensing schedules and initiate spectrum sensing at different moments [28,29]. In the study [28], the authors proposed a smart sliding-window algorithm to make use of the latest reports within an observation window for asynchronous cooperative sensing. The study [29] presented a probability-based combination scheme for asynchronous cooperative spectrum sensing, according to the Bayesian decision rule.

2.2. System model

We consider the vehicular network in which every SVU is equipped with a single antenna by which the vehicle can communicate with other vehicles and sense the PU's activities within its receiving range. The mobility model of the vehicles can be described as follows. The movement of each vehicle is restricted to its own lane, and the speed of vehicle i, at time t, $v_i(t)$ obeys $v_i(t+\Delta t) = v_i(t) + \varepsilon a_i(t)$, where ε is a random variable uniformly distributed within $[-1, 1]$, and $a_i(t)$ is the acceleration of vehicle i at time t. Also, the speed of the vehicle $v_i(t), \forall t$ is assumed to follow a truncated Gaussian distribution with parameter $(\bar{v}, \sigma_v)$. Let $f(v)$ denote the probability density function (PDF) of v_i; then, $f(v)$ can be expressed as

$$f(v) = \frac{1}{\sqrt{2\pi}\sigma_v} e^{\frac{-(v-\bar{v})^2}{2\sigma_v^2}}, \qquad v_{min} \leq v \leq v_{max} \tag{1}$$

where v_{min} and v_{max} represent the upper and lower speed limits of any vehicles, respectively. This assumption is reasonable to model the running vehicles on the freeway that has the speed restrictions [18,20].

Consider a primary system in which the licensed spectrum is divided into Ω channels. The set of the channels is denoted as $\Omega \equiv \{1, 2, \ldots, \Omega\}$ with $|\Omega| = \Omega$. In a particular region and time interval, some of the H channels might not be occupied by a PU and are available for SVUs to access. The licensed channel used by a PU alternates between state ON and state OFF, of which the OFF time is not used by PUs and hence can be exploited by SVUs. Let α denote the probability that the channel transits from state ON to state OFF. Let β denote the probability that the channel transits from state OFF to state ON. We define the channel availability as the normalized period that is available for SUs. Let p denote the channel availability. Then, we have $p = \frac{\beta}{\alpha+\beta}$.

We consider two CVN architectures: centralized networks and decentralized networks, as shown in Figure 1. In the centralized networks, we employ the infrastructure-based CR network that has a centralized base station (BS). The CR BS is installed along highways at a regular interval, which can be co-located with traffic lights, gas stations, and rest areas, as discussed and evaluated in [30]. The BS collects the sensing results from SVUs to make the final decision of the channels' availability. Then, the BS allocates the available channels to the SVUs for access. In the decentralized networks, SVUs sense the channel by their own. To coordinate with other SVUs, each SVU exchanges the control packets on the dedicated channel for channel reserving and access [31].

2.3. Sensing behavior of secondary vehicular users

We consider that each SVU has its own sensing-transmission operation on a frame-by-frame basis. Each frame has time duration T that can be divided into four parts:

- *Reservation phase*: In this phase, the SVUs reserve the channels via the BS in a centralized network or

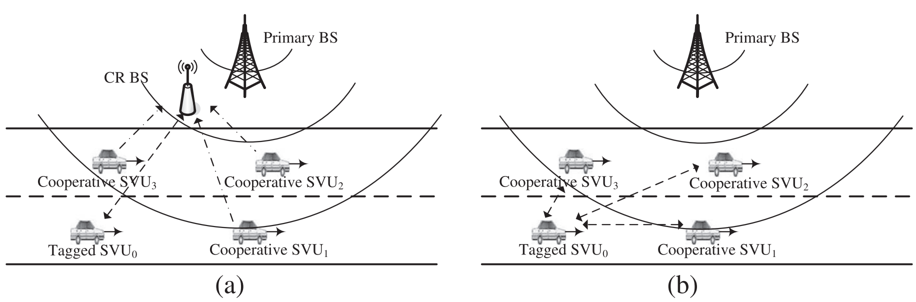

Figure 1. The vehicular network structure: (a) centralized and (b) decentralized networks. BS, base station; CR, cognitive radio; SVU, secondary vehicular user.

negotiating with other SVUs in a distributed network for the duration of T_v.

- *Sensing phase*: In this phase, SVUs sense the channel during the duration of T_s.
- *Exchanging phase*: In this phase, the tagged SVU exchanges the sensing information with the BS in a centralized network, or other SVUs in a distributed network, during the exchanging duration T_e.
- *Transmission phase*: In this phase, the tagged SVU transmits data on an available channel by using the remaining duration of the frame $T_r = T - T_v - T_s - T_e$.

3. ASYNCHRONOUS COOPERATIVE SPECTRUM SENSING

In this section, we develop the ACSS involving multiple SVUs so as to achieve sensing performance in a multiple-user asynchronous network.

In order to discuss our problem, we employ energy detection [32] for each SVU. Let t_s be the sensing time and f_s be the sample frequency during sensing time. We denote N as the number of samples in a sensing period, that is, $N = t_s f_s$. The received signal $r_i(n)$ at the nth sample and the ith SVU is given by

$$r_i(n) = \begin{cases} w_i(n), & H_0 \\ s_i(n) + w_i(n), & H_1 \end{cases}$$

where H_0 represents the hypothesis that PUs are absent, and H_1 represents the hypothesis that PUs are present. $s_i(n)$ represents the PU's transmitted signal with mean zero and variance σ_s^2. $w_i(n)$ denotes a Gaussian process with mean zero and variance σ_w^2. Then, we denote $e_i(r)$ as the ith SVU's EI, which is defined as the measured energy of the received signal $r_i(n)$ at the ith SVU. We can obtain $e_i(r)$ as

$$e_i(r) = \sum_{n=1}^{N} | r_i(n) |^2$$

As shown in Figure 1, when the appearance of a PU is detected, the tagged SVU ($\mathbf{SVU}_0$) should sense and ask for cooperative sensing. We consider that the cooperative SVUs ($\mathbf{SVU}_1$ and $\mathbf{SVU}_2$) have sensed the appointed channel and stored the EI before $\mathbf{SVU}_0$. Without forcing $\mathbf{SVU}_1$ and $\mathbf{SVU}_2$ to sense the appointed channel, $\mathbf{SVU}_0$ only collects the storing EI from $\mathbf{SVU}_1$ and $\mathbf{SVU}_2$ and makes the decision of the PU's activity on the appointed channel. By using the EI from the neighboring SVUs, we observe that such information of an identical PU has potential relationship when the cooperative SVUs operate sensing within a specified time and in a certain area. We define these features of the cooperative SVUs as *temporal diversity* and *spatial diversity*.

3.1. Temporal diversity

In our model, each SVU is able to detect an identical PU on the licensed channel following the SVU's own sensing period. Considering the variability of a PU's activity, the sensing results of a channel may not match with the channel's actual state after t seconds. However, the variation of the channel state can be estimated by using past sensing results [33]. Let $P_{I_h 0}(t)$ denote the probability that the hth $(h \in \Omega, h = 1, \cdots, \Omega)$ channel will be idle after t seconds. Here, $I_h \in \{0, 1\}$ with the interpretation that $I_h = 0$ if the hth channel is idle and $I_h = 1$ if the hth channel is occupied by a PU. According to [33], we can express this probability as

$$P_{I_h 0}(t) = \begin{cases} \frac{\beta}{\alpha+\beta} + \frac{\alpha}{\alpha+\beta} e^{-(\alpha+\beta)t}, & I_h = 0 \\ \frac{\beta}{\alpha+\beta} - \frac{\beta}{\alpha+\beta} e^{-(\alpha+\beta)t}, & I_h = 1 \end{cases} \quad (2)$$

Similarly, we define $P_{I_h 1}(t)$ as the probability that the hth channel will be occupied after t seconds.

$$P_{I_h 1}(t) = \begin{cases} \frac{\alpha}{\alpha+\beta} - \frac{\alpha}{\alpha+\beta} e^{-(\alpha+\beta)t}, & I_h = 0 \\ \frac{\alpha}{\alpha+\beta} + \frac{\beta}{\alpha+\beta} e^{-(\alpha+\beta)t}, & I_h = 1 \end{cases} \quad (3)$$

It is shown that the future channel availability can be predicted by probabilities $P_{I_h 0}(t)$ and $P_{I_h 1}(t)$ based on the latest sensing result. Hence, there is an inherent temporal connection between the current sensing result and the past sensing result discovered by an SVU. This connection also exists among the cooperative SVUs if they detect the same channel even at a different sensing moment.

We define *storing duration*, which represents the time duration from the moment sensing results obtained by the ith SVU to the moment sensing results used by the tagged SVU. Let t_i denote the length of the storing duration of the ith SVU. According to the length of the storing duration, the temporal diversity has been considered by assigning a proper weight to the cooperative SVUs' sensing results. The tagged SVU collects the weighted sensing results to make a final decision of the PU's activity. From the ith SVU perspective, the requirement from the tagged SU can be modeled as a Poisson process with arrival rate λ_{t_i}, and then, the storing duration is the random variable that follows exponential distribution. Let $f(t_i)$ denote the PDF of t_i. Then, we have$f(t_i) = \lambda_{t_i} e^{-\lambda_{t_i} t_i}$.

3.2. Spatial diversity

When the tagged SU requires the sensing results from different SVUs, the spatial diversity exists because the SVUs detected the PU's activity at different locations. Figure 2 illustrates the spatial diversity of the cooperative SVUs in CVN. Suppose that the tagged SVU requires the sensing results of an appointed channel from $\mathrm{SVU_i}$ when $\mathrm{SVU_i}$ is at place C. The $\mathrm{SVU_i}$ will send back the sensing results that are obtained and stored at place A, instead of sensing the appointed channel immediately. Hence, the tagged

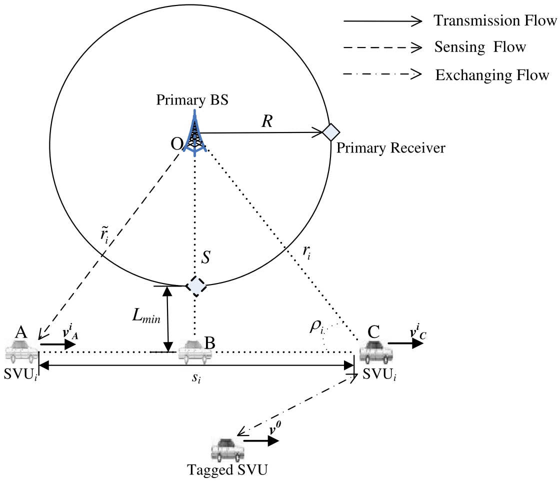

Figure 2. Spatial diversity of the cooperative secondary vehicular users (SVUs). BS, base station.

SVU should weight the sensing results, which is obtained by $\mathrm{SVU_i}$'s at place A.

Let $\bar{r}_i$ and v_A^i denote the distance from the PU's BS to the $\mathrm{SVU_i}$ and the speed of $\mathrm{SVU_i}$ at place A, respectively. Both $\bar{r}_i$ and v_B^i are random variables, and v_B^i follows the distribution $f(v)$ as shown in (1). According to Figure 2, we can obtain the distance that $\mathrm{SVU_i}$ moves from place A to place C during a random storing duration t_i as

$$s_i = v_A^i t_i + \frac{1}{2}\varepsilon a_i t_i^2$$

where a_i is the acceleration of the ith SVU, and ε follows uniform distribution within $[-1, 1]$. Then, we can obtain $\bar{r}_i$ as

$$\bar{r}_i = \sqrt{r_i^2 + s_i^2 - 2r_i s_i \cos\rho_i}$$

where r_i denotes the distance between the PU's BS and the location where the SVU_i is required to provide the stored sensing results, that is, place C. ρ_i stands for the angle between r_i and the road. Because the location of the PU's transmitter is known, the straight distance between the PU's transmitter and the road is a fix value, denoted by S. Therefore, we have

$$\bar{r}_i = \sqrt{r_i^2 + s_i^2 - 2r_i s_i \cos\arcsin\frac{S}{r_i}}$$

Because of the stochastic characteristic of the velocity of the vehicle, r_i is the random variable. Next, we will find the PDF of r_i, which is denoted by $f(r)$. Let PU_T and PU_R denote the transmitter and receiver of a PU, respectively. The transmission range of the PU's BS is within radius R in the network. In order to protect the PUs from interference, the interference range of an SVU should be properly determined. The interference range of an SVU is defined as the minimum distance from the PU's receiver at which the interference can be ignored [33]. We set a threshold δ to determine whether an SVU interferes a PU or not. If the signal-to-noise ratio (SNR) at the primary receiver is below δ, the SVU is said to cause interference to the PU. Let P_{PU} and P_{SVU} denote the transmitted power of the primary and secondary users, respectively. The interference range of the SVU, L_{min}, is then given by

$$L_{min} = \left(\frac{\delta P_{SVU}}{P_{PU} R^{-\frac{\alpha}{2}}}\right)^{\frac{2}{\alpha}} \tag{4}$$

where α is the power path loss exponent.

Moreover, we can obtain the minimum distance that SVUs should stay away from the PU's transmitter. The distance is denoted as D_{min} and given by $D_{min} = R + L_{min}$. The maximum SNR at an SVU without interfering a PU is expressed as

$$\gamma_{max} = D_{min}^{-\frac{\alpha}{2}}\gamma = \theta_{min}\gamma \tag{5}$$

where γ refers to the SNR of a PU at an SVU when $D_{min} = 1$ m.

We define the sensing range D_{max} as the maximum distance from the PU's transmitter at which an SVU is able to detect the PU's signal. Considering different practical systems (e.g., the wireless regional area network (WRAN) system [34] and the 802.11 system [35]), D_{max} can have different values. In this paper, we fix the value of D_{max} as 100 m. Then, we can obtain the SVU's distributed range with D_{min} and D_{max} as the lower and upper bounds, respectively. Within this range, the SVUs for cooperative sensing could detect the PU's signal and report the sensing results without causing interference to the PU's receiver. We assume that the cooperative SVUs are uniformly distributed with PDF

$$f(r) = \frac{2r}{D_{max}^2 - D_{min}^2}, \quad D_{min} < r < D_{max} \tag{6}$$

where r denotes the distance between the PU's transmitter and the receiver of a cooperative SVU. When an SVU is chosen for cooperative sensing, a proper weight should be assigned to the sensing result to demonstrate the spatial diversity of the cooperative SVUs.

3.3. Weight determination

Considering the case where K number of SVUs are in the CR network, our goal is to find the optimal weights $\mathbf{y} = [y_0, \ldots, y_K]$ $\left(\sum_{i=0}^{K} y_i = 1\right)$ for each SVU to maximize the detection probability or minimize the false alarm probability. The receive signal of the ith SVU at the nth sample is expressed as

$$r_i(n) = I_i\theta_i s_i(n) + w_i(n) \tag{7}$$

where $I_i = 0$ or 1. $I_i = 0$ represents the hypothesis H_0, and $I_i = 1$ represents the hypothesis H_1. $\theta_i = \int\int\int \bar{r}_i^{-\frac{\alpha}{2}} f(v)f(r)f(t_i)dvdrdt_i$ is the path loss coefficient, in which r_i denotes the distance between the PU's transmitter and the receiver of SVU$_i$. We also assume that the signal and noise power are constant over all SVUs' receivers, that is, $\sigma_{s_i}^2 = \sigma_s^2, \sigma_{w_i}^2 = \sigma_w^2$.

In our scheme, the tagged SVU collects EI from the cooperative SVUs after the tagged SVU's own sensing. After weighting the cooperative SVU's EI in terms of the temporal and spatial diversities, the tagged SVU can obtain $e(r)$ as

$$e(r) = \sum_{i=0}^{K} y_i e_i(r) \tag{8}$$

where $e_0(r)$ is the EI from the tagged SVU, $e_i(r) = \sum_{n=1}^{N} |r_i(n)|^2$ denotes the collected EI from ith SVU with the spatial diversity (θ_i), and y_i is the weight of the ith SVU's EI. By using CLT, $e(r)$ can be approximated as Gaussian distribution under hypothesis $H_i(i = 0, 1)$ with mean μ_i and variance σ_i^2 as shown in (9)

$$\begin{cases} \mu_0 = N\left(y_0\sigma_w^2 + \sum_{i=1}^{K} y_i\left(I_1\sigma_s^2 + \sigma_w^2\right)\right) & \sigma_0^2 = 2N\left(y_0^2\sigma_w^4 + \sum_{i=1}^{K} y_i^2\left(I_1\sigma_s^2 + \sigma_w^2\right)^2\right) \quad H_0 \\ \mu_1 = N\left(y_0\left(\sigma_s^2 + \sigma_w^2\right) + \sum_{i=1}^{K} y_i\left(I_1\sigma_s^2 + \sigma_w^2\right)\right) & \sigma_1^2 = 2N\left(y_0^2\left(\sigma_s^2 + \sigma_w^2\right)^2 + \sum_{i=1}^{K} y_i^2\left(I_1\sigma_s^2 + \sigma_w^2\right)^2\right) H_1 \end{cases} \tag{9}$$

Then, we can obtain the detection and false alarm probabilities without considering temporal diversity as follows:

$$[P_d]_{I_K\cdots I_1 1} = Q\left(\frac{\lambda - N\left(y_0\left(\sigma_s^2 + \sigma_w^2\right) + \sum_{i=1}^{K} y_i\left(I_i\sigma_s^2 + \sigma_w^2\right)\right)}{\sqrt{2N\left(y_0^2\left(\sigma_s^2 + \sigma_w^2\right)^2 + \sum_{i=1}^{K} y_i^2\left(I_i\sigma_s^2 + \sigma_w^2\right)^2\right)}}\right),$$

$$[P_f]_{I_K\cdots I_1 0} = Q\left(\frac{\lambda - N\left(y_0\sigma_w^2 + \sum_{i=1}^{K} y_i\left(I_i\sigma_s^2 + \sigma_w^2\right)\right)}{\sqrt{2N\left(y_0^2\sigma_w^4 + \sum_{i=1}^{K} y_i^2\left(I_i\sigma_s^2 + \sigma_w^2\right)^2\right)}}\right)$$

Let $\phi = \frac{\sigma_s^2}{\sigma_w^2}$ denote the SNR at the SVU receiver. By removing λ, we have $[P_d]_{I_K\cdots I_1 1}$ and $[P_f]_{I_K\cdots I_1 1}$ as follows:

$$[P_d]_{I_K\cdots I_1 1} = Q\left(\frac{1}{[\beta_d]_{I_K\cdots I_1 1}}\left(\beta_f Q^{-1}(P_f) - \sqrt{\frac{N}{2}}\left(y_0 + \sum_{i=1}^{K} y_i I_i\right)\phi\right)\right)$$

where $[\beta_d]_{I_K\cdots I_1 1} = \sqrt{y_0^2(\phi+1)^2 + \sum_{i=1}^{K} y_i^2\left(I_i\phi + 1\right)^2}$, $\beta_f = 1$.

$$[P_f]_{I_K\cdots I_1 0} = Q\left(\frac{1}{[\beta_f]_{I_K\cdots I_1 0}}\left(\beta_d Q^{-1}(P_d) + \sqrt{\frac{N}{2}}\left(y_0 + \sum_{i=1}^{K} y_i\ (1 - I_i)\right)\phi\right)\right)$$

where $[\beta_f]_{I_K\cdots I_1 0} = \sqrt{y_0^2 + \sum_{i=1}^{K} y_i^2\left(I_i\phi + 1\right)^2}$, $\beta_d = \phi + 1$.

Therefore, the detection and false alarm probabilities with temporal and spatial diversities in the multiple-user case are given by

$$Q_d^{(K)} = \sum_{I_K=0}^{1} \cdots \sum_{I_1=0}^{1} P_{I_K\cdots I_1 1}[P_d]_{I_K\cdots I_1 1}$$
$$Q_f^{(K)} = \sum_{I_K=0}^{1} \cdots \sum_{I_1=0}^{1} P_{I_K\cdots I_1 0}[P_f]_{I_K\cdots I_1 0}$$

where $P_{I_K\cdots I_1 1} = \prod_{i=1}^{K} \int_0^{\infty} P_{I_i 1}(t_i)\lambda_{t_i} e^{-\lambda_{t_i} t_i} dt_i$ and $P_{I_K\cdots I_1 0} = \prod_{i=1}^{K} \int_0^{\infty} P_{I_i 0}(t_i)\lambda_{t_i} e^{-\lambda_{t_i} t_i} dt_i$.

Similarly, to protect the PU, we need to design the optimal $\mathbf{y} = [y_0, \cdots, y_K]$ by maximizing Q_d for a given threshold of the false alarm probability $P_{f,Th}$, which gives

$$\begin{aligned} \max_{y_0,\ldots,y_K} \quad & Q_d^{(K)} \\ \text{s.t.} \quad & \sum_{i=0}^{K} y_i = 1, \quad P_f \le P_{f,Th} \end{aligned} \tag{10}$$

In order to find spectrum opportunities as many as possible, we need to minimize Q_f. Hence, the optimal $\mathbf{y} = [y_0, \cdots, y_K]$ should be found for a given threshold of the detection probability $P_{d,Th}$.

$$\begin{aligned} \min_{y_0,\ldots,y_K} \quad & Q_f^{(K)} \\ \text{s.t.} \quad & \sum_{i=0}^{K} y_i = 1, \quad P_d \geq P_{d,Th} \end{aligned} \tag{11}$$

The detection probability and the false alarm probability are two major performance metrics that characterize the sensing accuracy of the ACSS.

3.4. Discussion

The advantage of our proposed asynchronous cooperative sensing can also be demonstrated from sampling process perspective. Figure 3 shows the channel recovery by different sensing schemes. From Figure 3(a) and (b), we observe that the recovered channels differ greatly from the real channel in both noncooperative sensing and synchronous cooperative sensing. In our proposed ACSS as shown in Figure 3(c), the channel recovered by sensing almost fit the real channel situation. This is because the sensing is essentially a sampling procedure of the given channel [21]. The asynchronous cooperative sensing can provide more frequent sampling of the channel than the noncooperative and synchronous sensing schemes. In the proposed scheme, the sensing samples provided by different SVUs at different moments are distributed in a wide time range that may trace the real situation of the channel accurately. More importantly, the sensing overhead that exists in the synchronous sensing scheme can be largely reduced.

4. ASYNCHRONOUS SENSING-BASED OPPORTUNISTIC ACCESS MECHANISM

In this section, we present the specification of the ACSS-based opportunistic access mechanism. The access implementation is presented in two network architectures: centralized networks and decentralized networks.

4.1. Access mechanism

We consider an opportunistic access scheme for SVU to exploit the discovered spectrum opportunities by using the transmission time control. The opportunistic access schemes can be described as follows:

If an SVU has data to transmit, the SVU starts a local sensing of the appointed channel and sends the ACSS requirement to the CR BS in the centralized CVN or to the neighbor SVU in the decentralized CVN. If the sensing results from the ACSS declare the presence of PU, the SVU will cease the sensing-transmission cycle and wait for a random backoff time. After this waiting time, the SVU will resume the sensing operation. If the channel is declared as vacancy of PU, the SVU accesses the channel for transmission. The ACSS can be implemented by BS in the centralized network or by exchanging notification message with other SUs in the decentralized network as described in the following sections.

4.2. Access mechanism specifications: centralized cognitive vehicular network

We consider the infrastructure-based CVN that has a centralized CR BS. The BSs are scatteringly deployed along the roadside and allocate the available spectrum in a central manner. Under BS's dispatching, several SVUs that are running along the road may enter the transmission range of a BS. Then, these SVUs have the opportunities to access the temporarily unoccupied licensed channels. Each SVU is equipped with a single radio, which implies that the SVU cannot transmit or sense simultaneously. Considering the hardware limitation, we allow each SVU to sense a single channel at a time and send its sensing information to BS after its sensing period.

Figure 4 shows the ACSS-based opportunistic access mechanism in a centralized network architecture. More description on the major procedure is provided in the

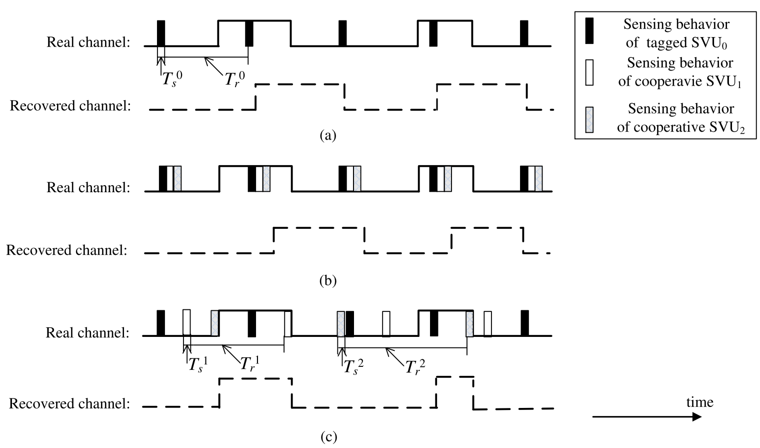

Figure 3. Channel recovery by different sensing schemes: (a) noncooperative sensing scheme, (b) synchronous cooperative sensing scheme, and (c) asynchronous cooperative sensing scheme. SVU, secondary vehicular user.

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```
Centralized CVN: code for each SVU and CR BS
Initially: e_i   % EI from ith SVU

Sensing and Reporting Phase:
        For SVU_i :
            Detect on the licensed channel and calculate the EI e_i
            Send ACSS requirement to CR BS

        For BS :
          Upon receiving local e_i from SVU_i
                Update the EI database

PU Determination Phase:
        For BS :
            Upon receiving ACSS request from SVU_i
              Calculate optimal weight of EI from SVU_i's neighboring SVUs
              Make the decision of channel's availability
              Send sensing result to SVU_i

 Channel Allocation Phase:
        For SVU_i :
          Upon receiving sensing results from CR BS
              Detect on the appointed channel
          If   appointed channel is available
              Access this channel for transmission
              else   retransmit ACSS requirement to CR BS
          end

        For BS :
              When transmission is completed
              Stop ACSS.
```

Figure 4. Asynchronous cooperative sensing scheme (ACSS)-based opportunistic access mechanism in centralized cognitive vehicular network (CVN). SVU, secondary vehicular user. CR, cognitive radio; BS, base station; EI, energy information.

following paragraphs. Each SVU periodically senses its channels and calculates EI. Then, the SVU sends the ACSS requirement and measured EI to the BS, together with the current time-stamp and location information. For the BS, upon receiving the ACSS requirement from any SVU for any appointed channel, it selects a subset of SVUs' EI of the channel and calculates optimal weights of each EI based on the spatial and temporal information. The BS will then make a decision on PU's appearance or absence and sends the decision to the SVU. If the channel is available, the SVU accesses the channel for its transmission. Otherwise, if the channel is unavailable, the SVU starts to sense a new channel and trigger a new round sensing process. Here, the expression of EI and the determination of optimal weights were developed in Section 3.3.

4.3. Access mechanism specifications: decentralized cognitive vehicular network

Figure 5 shows the ACSS-based opportunistic access mechanism in the decentralized networks. In a decentralized CVN, SVUs sense channels and make decisions independently. We allow each SVU to sense a single channel at a time and store the EI in its buffer. When an SVU has data to transmit, it sends the ACSS requirement to the neighboring SVUs. Upon receiving the ACSS requirement, the neighboring SVUs send the stored EI with the time and location information to the SVU in need. After calculating optimal weights of every EI, the SVU with transmission requirement will then make decision on PU's appearance or absence. If the channel is available, the SVU accesses the channel for its transmission. Otherwise, the SVU waits for a random backoff time and starts a new round sensing

```
Decentralized CVN: code for each SVU
Initially: e_i=0   % EI from ith SVU

Sensing and Reporting Phase:
        For SVU_i :
            Detect on the licensed channel and calculate the EI e_i
            and store the e_i in buffer
            Send ACSS requirement to the neighboring SVUs

PU Determination Phase:
        For SVU_i :
            Calculate optimal weight of e obtained by neighboring SVUs
            Make the decision of channel's availability
            Send the decision to destination SVU

Channel Allocation Phase:
        For SVU_i :
          If   appointed channel is available
              Access this channel for transmission
              Stop collecting the neighboring SVUs' EI
              else   wait for a random backoff time
                     return to Sensing and Reporting Phase
          end
```

Figure 5. Asynchronous cooperative sensing scheme (ACSS)-based opportunistic access mechanism in decentralized cognitive vehicular network (CVN). SVU, secondary vehicular user. EI, energy information.

process. Also, the expression of EI and the determination of optimal weights were developed in Section 3.3.

5. PERFORMANCE ANALYSIS

In this section, our purpose is to develop the network layer performance metrics with respect to throughput and delay. We first analyze throughput for the CVN by considering the sensing and exchanging overhead. Then, we model each licensed channel as an M/G/1 queueing system with server breakdown for the packet delay derivation.

5.1. Throughput analysis

Consider a typical scenario in which a single SVU monitors a single licensed channel. The SVU alternately senses the spectrum and transmits data with sensing time T_s and transmission time T_r, respectively. Let T_r be a random variable, and we denote L_r as the average transmission time of an SVU. For a given licensed channel, the SVU can use it to achieve the throughput of the CVN when the PU is absent. However, due to the PUs' dynamic activities, the channel state sensed by the SVUs may not remain at the same stage during the SVUs' transmission period. We let p_n denote the probability that no PU occurs during T_r when the licensed channel is detected as available and let p_m denote the probability that the PU will not be absent during T_r when the licensed channel is detected as unavailable, respectively. Then, we have $p_n = \int_{T_r}^{\infty} \mu e^{-\mu t} dt = e^{-T_r \mu}$ and $p_m = \int_{T_r}^{\infty} \lambda e^{-\lambda t} dt = e^{-T_r \lambda}$.

Let C_0 and C_1 denote the throughput of the SVU when the channel is idle and occupied by PU, respectively. The achievable throughput of an SVU can be obtained under two scenarios:

(1) When the licensed channel state is available and no false alarm is generated by the SVU, the SVU can access the available channel for transmission in the

adjacent time slot T_r. Because $\left(1 - Q_f^{(K)}\right)$ indicates the probability that there is no false alarm, we can derive the throughput of the tagged SVU in this scenario as

$$C_0 = \frac{T_r}{T} p p_n \left(1 - Q_f^{(K)}\right) B_0 \tag{12}$$

where $B_0 = \log_2(1 + \phi)$, and ϕ is the SNR of the SVU.

(2) When the licensed channel state is unavailable but the presence of a PU is not detected by the ACSS, the SVU will access in the channel for transmission. Let P_P be the interference power of a PU measured at the SVU's receiver. Then, the SNR of the PU is $\phi_{PU} = P_P/\sigma_\omega^2$. The throughput of the SVU in this scenario is

$$C_1 = \frac{T_r}{T} p p_m \left(1 - Q_d^{(K)}\right) B_1 \tag{13}$$

where $B_1 = \log_2\left(1 + \frac{\phi}{1+\phi_{PU}}\right)$.

Let C_s denote the total throughput obtained by the SVU. Then, we have

$$\begin{aligned} C_s &= C_1 + C_2 \\ &= \frac{T_r}{T} p \left(p_n \left(1 - Q_f^{(K)}\right) B_0 + p_m \left(1 - Q_d^{(K)}\right) B_1\right) \end{aligned} \tag{14}$$

Furthermore, there are three types of sensing overhead in the cooperative sensing: reserving overhead, throughput overhead, and exchange overhead. When the tagged SVU reserves the dedicated channel, it ceases the communication during the entire reserving period, thereby limiting its achievable throughput. We define the throughput loss as reserving overhead, denoted by o_r, which is given by $o_r = \frac{T_v}{T_r} C_s$. In the traditional cooperative sensing scheme, the cooperative SVUs cannot perform data transmission during the cooperative sensing time. If there are k number of the cooperative SVUs in the cooperative sensing, we define the throughput loss of these SVUs as throughput overhead that is given by $o_t^{(k)} = k \frac{T_s}{T_r} C_s$. Meantime, when the tagged SVU requires cooperative sensing, it needs to exchange information with the other SVUs. The throughput loss during this exchange process, called exchange overhead $o_e^{(k)}$, is incurred while every cooperative sensing is performed. $o_e^{(k)}$ is given by $o_e^{(k)} = k \frac{T_e}{T_r} C_s$, where T_e is the time for sensing information exchange.

To demonstrate the achieved throughput, the sensing overhead should be removed from the total throughput. We define $\mathcal{T}^{(K)}$ as *achievable throughput*, which is the difference between throughput and sensing overhead. $\mathcal{T}^{(K)}$ is given by

$$\mathcal{T}^{(K)} = C_s - o_r - o_t^{(K-1)} - o_e^{(K-1)} \tag{15}$$

where $o_r = \frac{T_v}{T_r} C_s$, $(K-1)$ represents the number of cooperative SVUs, and $o_t^{(K-1)} = (K-1) \frac{T_s}{T_r} C_s$ and $o_e^{(K-1)} = (K-1) \frac{T_e}{T_r} C_s$ represent the throughput overhead and the exchange overhead caused by $(K-1)$ number of the cooperative SVUs, respectively. In particular, throughput overhead $o_t^{(1)} = 0$ in our scheme because the cooperative SVUs do not need to stop their own transmissions.

The SVU can decide its transmission time T_r to maximize its throughput. We observe that the negative item in (15) is fixed when K is determined by (10) or (11). Hence, the achievable throughput $\mathcal{T}^{(K)}$ increases with the increasing of C_s, which is determined by the transmission time of SVU T_r. In this paper, we consider two models of transmission time: exponentially distributed T_r and fixed T_r. The investigation of different models can show the performance of the transmission time control in different scenarios.

(1) *Exponentially distributed* T_r: In this case, let $f(T_r)$ denote the PDF of T_r with parameter μ_r. Then, we have

$$f(T_r) = \frac{1}{L_r} e^{-\frac{T_r}{L_r}}$$

Following (14), we can obtain the throughput in the first scenario as

$$\begin{aligned} C_0 &= pB_0 \left(1 - Q_f^{(K)}\right) \frac{\int_0^\infty T_r e^{-t_r \mu_r} \frac{1}{L_r} e^{-\frac{T_r}{L_r}} dT_r}{\int_0^\infty T_r \frac{1}{L_r} e^{-\frac{T_r}{L_r}} dT_r + T_s} \\ &= pB_0 \left(1 - Q_f^{(K)}\right) \frac{L_r \left(\frac{1}{\mu_r}\right)^2 (L_r + T_s)}{\left(L_r + \frac{1}{\mu_r}\right)^2} \end{aligned} \tag{16}$$

Similar to (16), we have

$$C_1 = pB_1 \left(1 - Q_d^{(K)}\right) \frac{L_r \left(\frac{1}{\mu_r}\right)^2 (L_r + T_s)}{\left(L_r + \frac{1}{\mu_r}\right)^2} \tag{17}$$

Therefore, we can obtain the total throughput as follows:

$$C_s = \frac{pL_r (L_r + T_s) \left(\frac{1}{\mu_r}\right)^2}{\left(T_r + \frac{1}{\mu_r}\right)^2} \left[\left(1 - Q_f^{(K)}\right) B_0 + \left(1 - Q_d^{(K)}\right) B_1\right] \tag{18}$$

(2) *Fixed* T_r: When the transmission time of the SVU is fixed, that is, $T_r = L_r$, we have

$$C_s = \frac{L_r p}{L_r + T_s} \left(\bar{p}_n \left(1 - Q_f^{(K)}\right) B_0 + \bar{p}_m \left(1 - Q_d^{(K)}\right) B_1\right) \tag{19}$$

where $\bar{p}_n = e^{-L_r \mu}$ and $\bar{p}_m = e^{-L_r \lambda}$.

5.2. Delay analysis

After finishing the ACSS, SVUs access the selected channels to start their data transmissions. We denote that the average packet arrival rate of the ith SVU is ζ_i. Because the rate of every licensed channel is R, we have $\zeta_i = \frac{R}{L_i}$, where L_i denotes the average packet length of the ith SVU. We model the packet arrival process of the SVUs as a Poisson process. Recall that the licensed channel breaks down at rate μ_r because of the appearance of PU. In other words, the probability that a channel will be able to use for an additional time t without breaking down is $e^{-\mu_r t}$. When the channel is occupied by a PU, an SVU has to stop the transmission and search another available channel to resume transmission immediately. By letting a packet's "service time" include the time that the SVU is finding a new available channel by asynchronous sensing, the procedure is an M/G/1 queue. Let T_i denote the amount of time from when a packet first enters the transmission queue of SVU_i until it is successfully transmitted to the receiver. Then, the service time T_i is a random variable of this M/G/1 queue. The average amount of time that a packet waits in a queue, that is, the packet transmission delay of the SVU_i, is

$$W_D^i = \frac{\zeta_i E\left[T_i^2\right]}{2\left(1-\zeta_i E\left[T_i\right]\right)} \tag{20}$$

Subsequently, we need to calculate $E\left[T_i\right]$ and $E\left[T_i^2\right]$. Let X_i be the service requirement of the secondary user SVU_i. Because the false alarm probability Q_f of a channel is nonzero in the cooperative sensing, the packets will be retransmitted if they are not successfully received. Hence, the service time can be modeled as a geometric distribution [36]. Then, we have

$$\begin{cases} E\left[X_i\right] &= \frac{L_i}{R(1-Q_f)}, \\ E\left[X_i^2\right] &= \frac{L_i^2(1+Q_f)}{R^2(1-Q_f)^2} \end{cases} \tag{21}$$

Let M_i denote the number of times that SVU_i switches to other available channels. Let $S_j\,(i = 1, 2, \cdots, M_i)$ be the amount of time that SVU_i spends for waiting for the resuming transmission. Notice that the waiting time only depends on the time slot $T_s + T_e$ in our cooperative model. Hence, we have

$$\begin{cases} E[S] &= T_v + T_s + T_e, \\ E\left[S^2\right] &= (T_v + T_s + T_e)^2 \end{cases} \tag{22}$$

Finally, we can obtain the service time as $T_i = \sum_{j=1}^{M_i} S_j + X_i$. Conditioning on X_i yields

$$E[T_i|X_i = x] = E\left[\sum_{j=1}^{M_i} S_j \,\middle|\, X_j = x\right] + x,$$

$$\mathrm{Var}[T_i|X_i = x] = \mathrm{Var}\left[\sum_{j=1}^{M_i} S_j \,\middle|\, X_i = x\right]$$

Given that an SVU requires x units of service time, it follows that the number of channel breakdowns while that SVU is being served is a Poisson random variable with mean $\mu_r x$. Consequently, conditioning on $X_i = x$, the random variable $\sum_{j=1}^{M_i} S_j$ is a compound Poisson random variable with Poisson mean $\mu_r x$. Hence, we have

$$E\left[\sum_{i=1}^{M_i} S_j \,|X_i = x\right] = \mu_r x E[S],$$

$$\mathrm{Var}\left[\sum_{j=1}^{M_i} S_j \,|X_i = x\right] = \mu_r x E\left[S^2\right]$$

Therefore, we have

$$E\left[T_i|X_i = x\right] = \mu_r X_i E[S] + X_i = X_i\left(1 + \mu_r E[S]\right),$$

$$\mathrm{Var}\left[T_i|X_i = x\right] = \mu_r X_i E\left[S^2\right]$$

Thus, $E\left[T_i\right] = E\left[E\left[T_i|X_i\right]\right] = E[X_i]\left(1 + \mu_r E[S]\right)$. Similarly,

$$\begin{aligned} \mathrm{Var}[T_i] &= E\left[\mathrm{Var}\left[T_i|X_i\right]\right] + \mathrm{Var}\left[E\left[T_i|X_i\right]\right] \\ &= \mu_r E\left[X_i\right] E\left[S^2\right] + \left(1 + \mu_r E[S]\right)^2 \mathrm{Var}(X_i) \end{aligned}$$

Therefore,

$$\begin{aligned} E\left[T_i^2\right] &= \mathrm{Var}\left[T_i\right] + \left(E[T_i]\right)^2 \\ &= \mu_r E\left[X_i\right] E\left[S^2\right] + \left(1 + \mu_r E[S]\right)^2 E\left(X_i^2\right) \end{aligned}$$

Assuming that $\varphi_i E[T_i] = \zeta_i E[X_i]\left(1 + \mu_r E[S]\right) < 1$, we obtain the packet transmission delay of SVU_i as

$$\tilde{W}_D^i = \frac{\zeta_i \mu E\left[\tilde{X}_i\right] E\left[S^2\right] + \zeta_i\left(1 + \mu E[S]\right)^2 E\left[\tilde{X}_i^2\right]}{2\left(1 - \zeta_i E\left[\tilde{X}_i\right]\left(1 + \mu E[S]\right)\right)} \tag{23}$$

where $E\left[\tilde{X}_i\right] = \frac{L_i}{R\left(1-Q_f^{(K)}\right)}, E\left[\tilde{X}_i^2\right] = \frac{L_i^2\left(1+Q_f^{(K)}\right)}{R^2\left(1-Q_f^{(K)}\right)^2}$. $E[S]$ and $E\left[S^2\right]$ are given by (22).

6. NUMERICAL RESULTS

In this section, we numerically evaluate the proposed spectrum sensing and access schemes. The channel bandwidth is 1 MHz and the channel availability $p = 0.5$.

We concentrate on the low SNR situation, and the SNR threshold for a PU at the tagged SVU is $\phi = -10$ dB [27]. The licensed channels are assumed to have exponentially distributed ON/OFF periods, and the OFF period is with the parameter $\mu_r = 10$. Without loss of generality, the storing time $t_i = isec, (i = 1, 2, \cdots, K)$. The other parameters for simulation are summarized in Table I. The proposed ACSS will be compared with the NCSS [21] and SCSS [25]. In the NCSS, each SVU has to monitor a channel by itself for obtaining the knowledge of PUs' activity. When there is no PU, the SVU will use the channel to transmit data. On the contrary, the SCSS assigns the cooperative SVUs to sense the licensed channels simultaneously by ceasing their own transmissions. The comparison results clearly demonstrate that our ACSS substantially outperforms both the NCSS and SCSS.

6.1. Sensing accuracy performance: probabilities of detection and false alarm

We first investigate the probability of detection in the CVN. Figure 6 shows the comparison of the detection probability among the ACSS, NCSS, and SCSS in the two-user case and the multiple-user case, respectively. It can be seen that the ACSS can achieve a much higher detection probability than that of the NCSS. This is because the ACSS makes accurate decision of PU's activity by using other SVUs' EI. In addition, it is observed that the detection probability of the ACSS is smaller but close to that of the SCSS. That is, the ACSS uses the nonreal-time EI from other SVUs. These EI are affected by temporal and spatial diversities of the SVUs, which make the collected EI different from the realtime EI achieved by the SCSS. However, this influence is insignificant by selecting the optimal weight of EI from different SVUs as explained in our scheme, which makes the detection ability of the proposed ACSS close to that of the SCSS. We also observe that the detection probability becomes higher if the number of the cooperative SVUs becomes larger. This indicates that the number of the cooperative SVUs can influence the performance of the proposed scheme.

We obtain the numerical result of the false alarm probability in both of the two-user case and the multiple-user case as shown in Figure 7. For a fixed P_d, the false alarm probability achieved by the ACSS is lower than that by the NCSS. From Figure 7, we also observe that the false alarm probability in the ACSS is higher but very close to that in the SCSS.

Table I. The parameters of simulations.

Λ	100 bytes	The length of the data packet
T_y	1 ms	The time of reservation
T_s	2 ms	The time of spectrum sensing
T_e	1 ms	The time of information exchanging
ζ	50/100/200	Arrival rate of the data packet

6.2. Sensing efficiency performance in a two-user cognitive vehicular network

Figure 8 shows the achievable throughput in different schemes. It is shown that the throughput achieved by the ACSS outperforms that by the NCSS and SCSS, because the NCSS uses a single SVU to detect the PU's activity for seeking available channels. On the contrary, the ACSS uses another SVU's EI for cooperative sensing, which increases the sensing accuracy and leads to higher throughput. The SCSS also employs another SVU to help sense the activity of PUs. However, the cooperative SVU cannot transmit data during cooperative sensing time in the SCSS, which may cause significant sensing overhead. In the ACSS, the tagged SVU only needs the EI of another

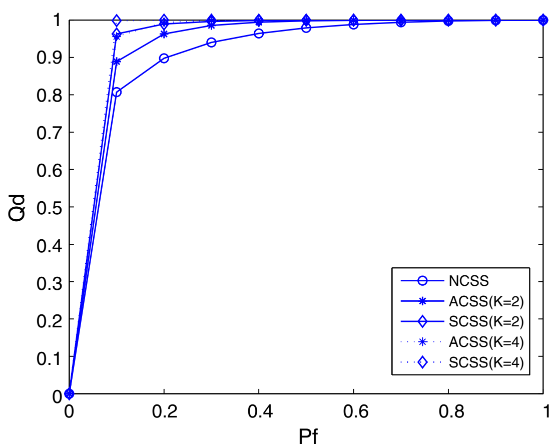

Figure 6. The detection probability Q_d in terms of the false alarm probability P_f. NCSS, noncooperative sensing scheme; ACSS, asynchronous cooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

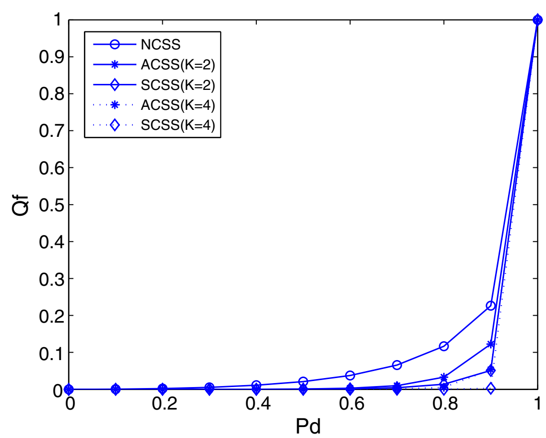

Figure 7. The false alarm probability Q_f in terms of the detection probability P_d. NCSS, noncooperative sensing scheme; ACSS, asynchronous cooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

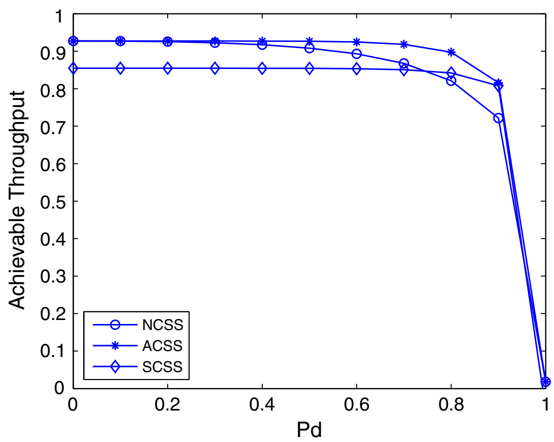

Figure 8. The achievable throughput in terms of the detection probability P_d in the two-user case. NCSS, noncooperative sensing scheme; ACSS, asynchronous cooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

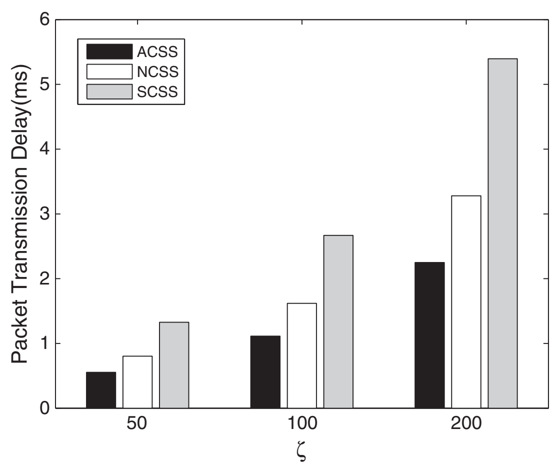

Figure 9. The packet transmission delay in terms of the packet arrival rate ζ in the two-user case. ACSS, asynchronous cooperative sensing scheme; NCSS, noncooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

SVU to make a final decision. Compared with the SCSS, the ACSS not only improves the sensing accuracy by joint decision but also reduces the sensing overhead. Both advantages make the proposed ACSS achieve higher throughput than that of the NCSS and SCSS.

Figure 9 shows the packet transmission delay in terms of the packet arrival rate ζ. It is clear that the delay in the ACSS is the lowest one, because the ACSS can make a final decision of the PU's activity without waiting for the cooperative SVUs' feedback of the sensing results. However, the waiting time for the individual sensing result is inherent in the SCSS, which results in unavoidable delay. With the help of multiple SVUs' EI, the proposed ACSS is able to save this waiting time in searching a spectrum opportunity. Compared with the NCSS, the ACSS still has shorter delay for packet transmission. That is, the NCSS has to detect the appearance of a PU by itself, which leads to the higher false alarm probability, and thus, higher delay is expected. In addition, it is observed that the packet delay increases when ζ increases. This is because more time should be used for the packet waiting for the transmission in a longer queue.

6.3. Sensing efficiency performance in a multiple-user cognitive vehicular network

Figure 10 shows the achievable throughput in multiple-user networks. Similar to the two-user case, the throughput achieved by the ACSS outperforms that by the NCSS and SCSS. That is, the NCSS has a higher false alarm probability than that of the ACSS, which is capable of finding more spectrum opportunities. The SCSS employs more than one SVUs to help sense the activity of a PU. When the number of the cooperative SVUs increases, the sensing overhead caused by the SCSS increases. Compared with the SCSS, the ACSS does not need the cooperative SVUs to stop their own transmissions. Therefore, the proposed ACSS achieves higher throughput than the NCSS and SCSS.

Figure 11 shows the packet transmission delay in terms of the packet arrival rate ζ in a multiple-user CVN. Similarly, we compare the delay among the NCSS, SCSS, and ACSS. Figure 11 shows that the packet delay in the ACSS is lower than that in the SCSS and NCSS, because the ACSS does not need to wait for the individual sensing result that is inherent in the SCSS. Compared with the NCSS, the ACSS can obtain a lower false alarm probability, which leads to lower delay. In addition, the reduction of packet delay in the ACSS is especially higher than that in the SCSS, because the service time of the packet in the SCSS includes the cooperative sensing time that increases dramatically with the increasing number of the cooperative SVUs. Comparatively, the service time in the multiple-user

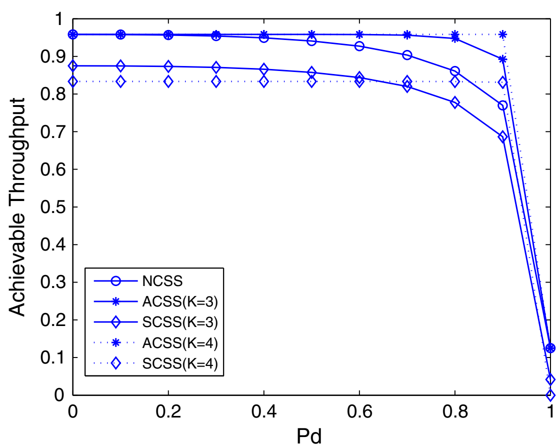

Figure 10. The achievable throughput in terms of the detection probability P_d in the multiple-user case. NCSS, noncooperative sensing scheme; ACSS, asynchronous cooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

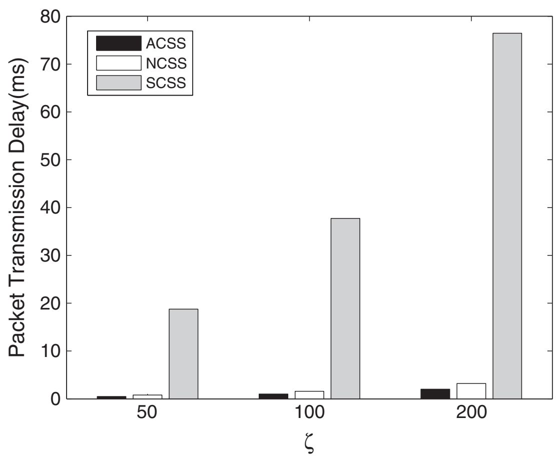

Figure 11. The packet transmission delay in terms of the packet arrival rate ζ in the multiple-user case. ACSS, asynchronous cooperative sensing scheme; NCSS, noncooperative sensing scheme; SCSS, synchronous cooperative sensing scheme.

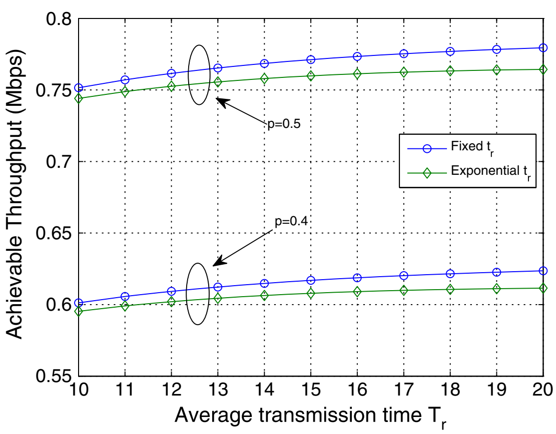

Figure 12. The throughput versus average transmission time.

case is insignificantly different from that in the two-user case because the delay in the ACSS only includes the time of local sensing and information exchanging.

Figure 12 shows the achievable throughput of the two-user case in terms of the average transmission time T_r when $p = 0.5$ and $p = 0.4$. In this case, the detection and false alarm probabilities for an SVU are set as $P_d = 0.9$ and $P_f = 0.1$, which are the important parameters used by the 802.22 standard [34]. The results are obtained for the proposed access scheme when the SVU adopts exponentially distributed and fixed length transmission time, respectively. With the increasing of T_r, the throughput becomes higher, which is intuitively expected. Again, the SVU with fixed length transmission time achieves higher throughput compared with the exponentially distributed length. In addition, we notice that it will obtain higher throughput if the channel availability p becomes larger.

7. CONCLUSION

We proposed an ACSS for opportunistic spectrum access in CVNs. In the ACSS, the final sensing decision is made by collecting the local EI of the cooperative SVUs. The temporal and spatial diversities of each SVU are considered by assigning optimal weight to different EI. Compared with the SCSS, the ACSS is able to reduce the cooperative sensing overhead. Moreover, the sensing accuracy of the ACSS is higher than that of the NCSS. Based on the ACSS, the medium access mechanism is presented in both centralized and decentralized networks. The achievable throughput and the packet transmission delay of our scheme have been also derived and discussed.

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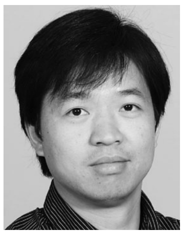

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