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Review

Spectrum sensing in cognitive vehicular network: State-of-Art, challenges and open issues

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ABSTRACT

Vehicular Ad Hoc Network (VANET) is envisaged to play an important role in the safety of drivers and passengers when moving on the roads. However, VANET still faces many challenges before it could be deployed. One such challenge is shortage of radio frequency spectrum channels. VANET has been allocated 7 channels for dedicated short range communication at 5.9 GHz band. The 7 channels are likely to get congested in high vehicle densities when many vehicles are contending for the same medium. Consequently, affecting the transmission of safety and emergency messages. To alleviate the problem of scarcity channels, dynamic spectrum access (DSA) through cognitive radio (CR) technology has been proposed. One of the core functions of a CR is to identify spectrum holes in licensed frequency bands that can be accessed by unlicensed users through spectrum sensing. In VANET, spectrum sensing is challenging because of the mobility nature of vehicles, dynamic topological changes as well as other unique characteristics not found in other networks. However, these challenges have not been fully studied and how they affect spectrum sensing in cognitive vehicular network (CVN). In this paper, we discuss challenges associated with spectrum sensing in CVN. We describe the primary system activity model used by many schemes proposed in literature. Furthermore, we present an in depth analysis of state-of-art cooperative spectrum sensing techniques for CVN from 2010 to May 2016. In addition, we present some of the open issues in spectrum sensing for CVN.

1. Introduction

Vehicular Ad Hoc Network (VANET) is envisaged to play an important role in Intelligent Transportation System (ITS). ITS applications are envisioned to reduce congestion on the road, increase the safety of drivers and provide comfort to passengers. For instance, a vehicle can get online feedback on the condition of the road such as slippery curves in order to avoid accidents. To support such applications, VANET defines two type of communication [1–3]. First is vehicle to vehicle (V2V) communication in which vehicles on the road communicate to each other in ad hoc manner. The second is vehicle to infrastructure (V2I) communication. V2I allows vehicles on the road to establish communication links with stationary road side infrastructures.

With the growing number of applications and services being developed for wireless communications, demand for bandwidth has been growing steadily. For example, it is envisioned that by 2020, there will be more than 50 billion devices connected to the Internet mostly through wireless communication [4,5]. This poses a major challenge on the already scarce radio frequency spectrum. For instance, the Federal Communications Commission (FCC) in the USA has allocated almost all the channels in the communicable frequency bands to licensed users. Free frequencies are shared among various user groups [6]. ITS applications have been allocated 75 MHz at 5.9 GHz band for dedicated short range communication (DSRC) for V2V and V2I transmission [7]. The 75 MHz is divided into 7 channels of 10 MHz each. However, these channels can get congested, especially during peak hours or accident scenarios, where the number of vehicles contending for the same channels increases [8,9]. In such situations, delivery of delay sensitive safety and emergency messages becomes difficult. Different solutions have been proposed in the literature to overcome these setbacks. One of such solution is to use protocols which guarantee

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quality of service based on priority [138]. Safety and emergency messages given high priority [10,11]. Another congestion control mechanism is to adjust contention window (CW) in the MAC layer of IEEE802.11p to accommodate increase in vehicle density [12]. For example, authors in [13] propose a reverse back-off mechanism to adjust the CW based on expiration of periodic safety messages. Nevertheless, these approaches do not perform optimal in high vehicle density and only proposed to serve safety applications[12,13]. Regardless, important service applications (e.g infotainment) may suffer from these approaches especially in high vehicle density [14].

To support the increasing demand of bandwidth to serve ITS applications, dynamic spectrum access (DSA) has been proposed [15]. DSA allows licensed channels to be used by unlicensed users provide no harmful interference is caused to the licensed users. In order to realize DSA in VANET, cognitive radio (CR) technology have been proposed [16–18]. A CR is an intelligent software defined radio (SDR) that reconfigures its network parameters based on the current network environment [19]. In addition, a CR allow for rapid and dynamic reconfiguration of a communication system [20]. This is vital in maintaining steady communication between vehicles in VANET.

It has been shown that more than 70% of licensed bands allocated to certain users are underutilized in some location and certain time of the day [21]. Therefore, vehicles can use these licensed bands through DSA whenever there is congestion in the DSRC channels. However, the licensed channels need to be identified before they can be used. The CR is used to identify the spectrum channels in licensed bands through spectrum sensing. Spectrum sensing is a key fundamental stage in any cognitive radio network system. Spectrum sensing identify spectrum bands in frequencies of licensed users or primary users (PU) that are free to be accessed by unlicensed users or secondary user(s) (SU)s. The SUs in cognitive vehicle network (CVN) are vehicles, while the PU can be any network that has exclusive rights to use licensed channels such as TV broadcasters. Spectrum sensing in CVN is a challenge due to unique characteristics of vehicles. Therefore, algorithms designed to sense the PU signals must be effective. Hence, CR plays a vital role in spectrum sensing in CVN. Some of the benefits of CR in CVN are given in the following section.

1.1. Benefit of CR in the VANET environment

The need for increased bandwidth for emerging vehicular applications has been studied in [22]. Increase in production of vehicles with VANET capabilities will lead to congesting DSRC channels defined for V2V and V2I. Therefore, a mechanism will be needed to acquire more spectrum bands to satisfy QoS need for different vehicular applications. CR is seen as enabling technology to provide extra spectrum for vehicles to communicate when the DSRC channels get congested. The major benefits of CR in VANET environment are discussed below:

- *Provision of more channels to satisfy QoS requirements:* Applications that are associated with safety need to be delivered within a short period of time. However, it is difficult to guarantee delivery of safety related messages when there is congestion in the DSRC channels. Therefore, a CR can be used to acquire additional channels in other frequency bands (e.g TV bands) through DSA that can be used for vehicular communication. The acquired channels can be used to transmit low priority messages such as infotainment applications thereby decongesting the DSRC channels. This will guarantee delivery of safety and non-safety applications.
- *Provision of common interface for heterogeneous networks:* In the near future, VANET will play a big role in the Internet of Vehicles (IoV) [23]. There are many radio technologies envisaged for IoV devices which might not operate in the same frequency range [24,25]. For example, the radio technologies anticipated for IoV include IEEE802.11p, Bluetooth, WiMAX, WiFi, etc. These radio technologies need an interface that can allow them to work together. Therefore, a CR can be used to provide that interface in order to allow interoperability of the different devices in IoV. This is because CR is based on SDR with reprogrammable capabilities and adaptation to radio frequency based on the network environment.
- *Utilization of unused licensed bands along the highway:* Experimental studies conducted in [26] indicated free and abundant TV whitespace spectrum available along the highway. Hence, a CR can exploit such spectrum opportunities through DSA and provide more channels for vehicular communication. TV bands are preferred for DSA because they use lower frequency range. Therefore, a TV signal is propagated much further compared to signal in DSRC range which is propagated only few hundred meters. Hence, TV channels can prolong the communication among vehicles and thereafter stabilizing the network.
- *Reduction of hardware upgrade:* When using a CR and SDR, the need to upgrade hardware whenever the new protocols emerge is reduced. SDR can operate across different radio spectrum range because it separate hardware and software implementation [27]. Thus, SDR is capable of reconfiguring and reprogramming using software updates without having to change the underlying hardware. This advantage will allow different versions of SDR transceivers to be deployed in different countries based on the spectrum regulation of that country.

1.2. Related work

Spectrum sensing is a well studied topic in cognitive radio networks (CRN). Surveys which have presented preliminary work in spectrum sensing for CRN are given in [28–32]. These works give the background and methodologies used to perform sensing specifically for cognitive radio network. For example, authors in [28] discuss challenges of spectrum sensing and associated methods used to overcome those challenges in CRN environment. In [29], a review of measurement methods and technologies for wideband spectrum sensing for CRN is presented. While authors in [30] give an overview of spectrum sensing techniques and compare them based on their capacity to detect the presence of primary users. The surveys presented in [33] and [34] focuses on cooperative spectrum sensing in CRN. The review in [34] concentrates on cluster based cooperative spectrum sensing in CRN. In [33], a comprehensive study of cooperative spectrum sensing in CRN is presented. They focus on cooperation methods, cooperation gain and cooperation overheard. While these surveys have given the background of spectrum sensing in CRN, they have not discussed problems of spectrum sensing associated with cognitive vehicle networks. The unique nature of vehicles as communicating nodes in VANET makes most of the proposed schemes for CRN unusable. Therefore, in this paper we have discussed the challenges associated with spectrum sensing in CVN environment. In addition we have discussed the PU activity models as they affect spectrum sensing which has not be presented by any of these previous surveys.

On the other hand, works in [35,36] and [37] presents survey related to spectrum sensing in CVN environment. In [35,36] , authors discuss issues related to spectrum sensing in CVN with emphasis on TV licensed bands. They discuss approached used in sensing awareness based on geo-location database lookup. They also discuss the influence of sensing subsystem design for CVN medium access (MAC) sublayer. However, this work does not discuss state-of-art spectrum sensing techniques in CVN but merely highlights challenges associated with geo-location database. The paper in [37] reviews studies related to spectrum sensing in CVN. It also provided existing vehicular communication standards and gives some open issues in spectrum sensing. The survey presented in [37] is what comes close to our work presented in this paper. Nevertheless, the work in [37] did not provide in depth discussion of spectrum sensing techniques proposed for CVN. Therefore, in this paper we present state-of-art cooperating spectrum sensing techniques for CVN from 2010 to May 2016. We have discussed sensing mechanisms in CVN giving advantages and disadvantages of each approach. In addition we have discussed the PU activity model considered by many spectrum sensing algorithms proposed so far. And finally we present some open issues related to spectrum sensing in CVN.

The remainder of the paper is organized as follows. In Section 2 we give a background of VANET communication while pointing out why we need CR technology. In Section 3 we discuss dynamic spectrum access as it relates to CVN. We discuss challenges associated with spectrum sensing in CVN in Section 4. Section 5 presents the PU activity models assumed by most of the sensing algorithms proposed for CVN. In Section 6 we discuss spectrum sensing while concentrating on cooperative sensing algorithms in Section 7. Section 8 presents some open issues and the paper is concluded in Section 9.

2. Background of VANET communication

Vehicular ad hoc networks define two types of communication to support ITS applications; vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. V2V communication is established in ad hoc manner between two or more vehicles moving on the road. It is mainly established in order for vehicles to exchange short messages (e.g. safety information) to their neighbors. Such information may have significance to vehicles within a short range. Therefore, the current maximum transmission range of V2V communication is approximated at 1000 m [38]. In the V2I, vehicles establish communication with road side infrastructure such as traffic light, toll gates, cellular towers etc. Vehicles use the road side infrastructures as gateways to access other services from centralized servers on the Internet. When accessing the services, communication is established between road side units (RSU) and the On Board Units (OBU) of the vehicles.

To support V2V and V2I communication, the IEEE802.11p standard have been proposed to define the physical (PHY) and medium access control (MAC) layers [39]. The IEEE802.11p is designed to accommodate the speed of vehicles up to 200 km/h on the highway [40]. The PHY layer is based on IEEE802.11a Orthogonal Frequency Division Modulation (OFDM). While the MAC layer is based on IEEE802.11e enhanced distributed channel access (EDCA) protocol to support quality of service (QoS) [41]. Four access categories are defined in EDCA based on the priority of the applications being transmitted by the vehicle [42]. The priorities as presented in [42] are concerned with emergency information such as accidents, speed information advertised by vehicles, information to seek help from other vehicles and non-safety related information such as infotainment.

Wireless access in vehicular environment (WAVE) standard combines protocols based on IEEE802.11p and IEEE 1609 family. The IEEE1609.X protocol family defines the upper layer specification related to networking, communication, application, management and security [43]. Fig. 1 shows the WAVE protocol suit defined by ITS.

The WAVE management entity (ME) specified in IEEE1609.3 standard is a set of management functions that is required to support WAVE networking services. All security concerns are handled

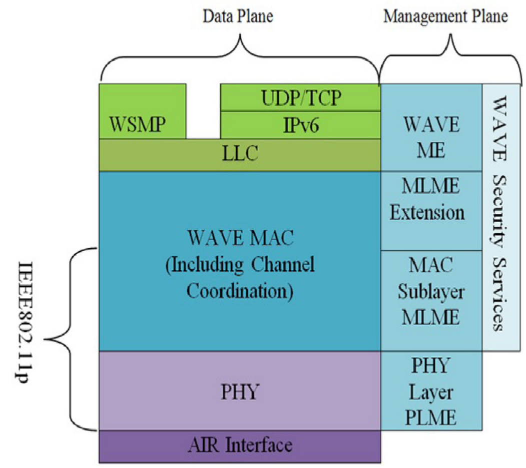

Fig. 1. WAVE protocol suit [43].

by the management plane. In addition, the management plane defines the MAC layer management entity (MLME) as well as the physical layer management entity (PLME) for MAC and PHY layers. The WAVE short message protocol (WSMP) defined in the data place is designed to support rapid exchange of messages which have strict low delay requirements such as safety messages. Other messages that do not have strict delay requirement such as infotainment are handled by UDP/IPv6 and TCP/IPv6. The link layer control (LLC) provides an interface between upper and lower layers. A comprehensive survey on VANET access technology have been presented in [44].

To support the WAVE protocols, 75 MHz radio frequency has be allocated for dedicated short range communication (DSRC) at 5.9 GHz band for VANET communication [45]. The 75 MHz DSRC frequency band is divided into *seven* channels with 10 MHz each with 5 MHz reserved as guard band. The channels consist of *six* service channels (SCH) and *one* control channel (CCH). The CCH is proposed to be used for transmitting WSMP messages related to safety applications while the SCH to be used by other applications such as infotainment.

Currently the number of vehicles with wireless capabilities is low. Therefore, demand for DSRC channels for V2V or V2I communication is also low. However, the increase in wireless enabled application that can provide safety and comfort to road users will deprive channels in use for DSRC. Many algorithms [46–48] are being proposed on how to enhance the performance of DSRC channels to support emerging technologies. For example, in [47] they propose to distinguish traffic of vehicles and implement priority based algorithms. The safety applications are given high priority while service messages are assigned low priority. However, such approaches will not guarantee delivery of safety messages in high vehicle densities due to small number of channels defined in DSRC. Furthermore, other low priority service applications can be affected from this approach.

Therefore, CR technology has been proposed to overcome the channel scarcity in VANET by providing more channels from other frequency bands. This is achieved through dynamic spectrum access (DSA) (next Section). Vehicles can utilize channels from other band (e.g. TV bands) to communicate whenever the DSRC channels are congested through DSA [49]. The adaptability and reconfigurable capabilities of CR make it more suitable in the VANET environment were the network topology changes rapidly. In addition, algorithms proposed in [50] can benefit from CR technology. A CR can act as an interface between the IEEE802.11p and cellular system based on long term evolution (LTE). Furthermore, the predictable movements of the vehicles on the road make it possible to get future spectrum occupancy based on geo-location databases [15].

3. Dynamic spectrum access in CVN

The scarcity of wireless communication channels can be alleviated through dynamic spectrum access (DSA) and CR technology [51]. DSA allow unlicensed users to access channels that have been allocated for exclusive use to licensed users. Despite many licensed frequency bands that could be used for DSA, the FCC proposed to use TV white space (TVWS) as a primary candidate for DSA especially in vehicular environment [15]. Feasibility studies [26,52] indicate 38 TV channels with bandwidth of 6 MHz each can be used for DSA by vehicles on highway. TV channels are proposed for DSA because TV broadcasters are considered to use relatively static frequency channels which do not change over time [26,53,54]. Nevertheless, the licensed users are to be protected from any harmful interference that might be caused by unlicensed users when accessing licensed channels.

In order to prevent harmful interference to PU of TV bands, authors in [55] determine detection thresholds bounds for operation of DSA devices. They performed experiments and collected results at six different locations in Northern Virginia on 13 DTV channels of Advanced Television Systems Committee (ATSC) standards. They concluded the following [55]:

- When cooperative detection is performed, the suitable approach for DSA technique to use TV bands is Listen-Before-Talk threshold-based.
- When the ATSC transmitter power level is set at −118.5 dBm, the ATSC pilot detection threshold should be set at −130 dBm when DSA systems use transmitters with power of 10mW. This will provide minimal interference to the PU and acceptable false alarm.
- However, when DSA system transmitter operate at 100 mW, the ATSC pilot detection threshold must be set at −120 dBm to minimize interference and achieve acceptable false alarm. In this case the ATSC transmitter power level is −108.5 dBm.
- The false alarm rate caused by detection of distant TV transmitters when the DSA device is located outside of the service region is significant (20%–40% using the above threshold values).

Interference is defined to be when two DSA transceivers transmit within the ATSC service region and a keep out distance of 10 km.

The protection of PU channels can also be achieved through provision of TVWS spectrum availability database for spatial and temporal use. Vehicles on the road can query the database for available channels whenever communication is needed. However, implementation of spectrum database in the vehicle environment in order to provide maximum protection to licensed users is not straight forward. The FCC [15] proposed three types of devices to access the available TV spectrum for DSA. The three types of devices in CVN correspond to vehicles that can be in mode ModeI, ModeII and sense-only as depicted in Fig. 2.

The first type of devices is called ModeII. These are vehicles equipped with geo-location capabilities like GPS. In addition, they can access the Internet through cellular infrastructure or WIFI network along the highway. Therefore, these vehicles can query the TV spectrum database to get spectrum occupancy at their location. Furthermore, ModeII vehicles are to re-check the database each time they either move 100 m or 60 s from their previous spectrum query [15]. The second type of devices is called ModeI. They involve vehicles that depend on ModeII vehicles to acquire

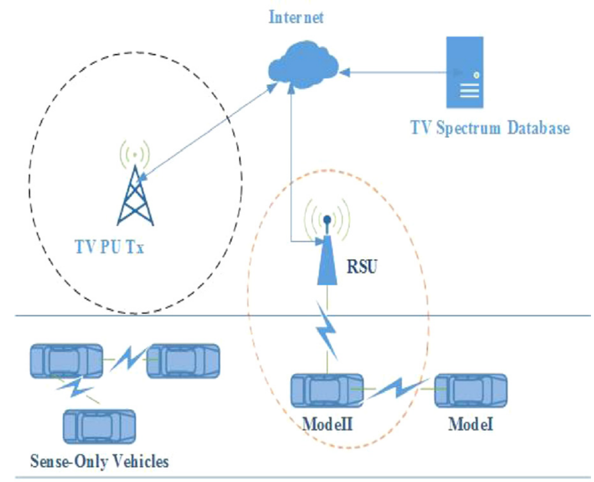

Fig. 2. Different mode of operation for CVN [56].

spectrum occupancy at their location. They use DSRC channels to communicate. The third type of devices is called Sense-only. These define vehicles which perform cooperative spectrum sensing in the absence of ModeII vehicles and any infrastructure support.

Not all vehicles are currently equipped with Internet capabilities to access the spectrum database. Hence, ModeI vehicles cannot access free TVWS when ModeII vehicles are outside communication range. Furthermore, authors in [36] demonstrate that having a GPS on a mobile device does not guarantee the device to acquire accurate position at all times. It was noted from this experiment that the accuracy of position depends on the signal strength from the Satellite, the weather at that location and surrounding environment. In addition, spectrum database results in query overhead that is generated by vehicles especially in congested scenarios and during traffic jams [57–59]. Thereby creating bottleneck to access the Internet at the RSU, denying other services that are served by RSU or cellular infrastructure.

To circumvent some of the challenges associated with spectrum database query, authors in [59–61] propose an optimal ratio between querying the spectrum database and cooperative sensing. Authors in [61] suggest a distributed protocol based on swarm-intelligence. The protocol allows vehicles to decide which type of device to use depending on the vehicular traffic condition on the road segment. The aim is to mitigate congestion problem when querying the database while guaranteeing high detection of spectrum resources. In the proposed technique, each vehicle is assumed to be equipped with three transceivers. One to communicate over TV channels using SDR, second to communicate over cellular network and last to communicate over DSRC channels. Through extensive simulation, they showed that the proposed scheme performed efficiently on deciding when to query the database or perform cooperative sensing.

Another effort to increase access to TV channels for DSA in vehicular communication is presented in [62]. Authors propose to leverage the correlation between received signal of cellular channels and TV channels to improve accuracy of local sensing among vehicles when not querying the database. They argue that at certain locations TV channels exhibit strong correlation in signal behavior with cellular spectrum. This can be attributed to common set of reflections, path loss and absorption from objects at the location of interest. Hence, they propose to use both the TV signal and cellular signals to predict any changes in the TVWS channels of interest. To reduce misdetection and false alarm, the TV channels are compared with received signal strength of cellular channels. After the PU activity is confirmed, the need to query the TV spectrum database for channels to use for DSA is eliminated.

Placement of RSU to provide channels for DSA to passing vehicles on highway is studied in [56]. Authors formulate an analytical framework that provides guidelines for placing RSUs that will provide information about spectrum availability of TVWS. In addition, they assess the cost of deploying such infrastructure along the road side and annual maintenance cost. Authors in [56] concluded that when the traffic of vehicles is low to medium, the cost to access the database through the RSU goes up. This is because vehicles will be operating in ModeII. Hence, more RSU will be needed. Conversely, increase in vehicle density result in reduction of cost to access the database. The second scenario is possible because vehicles will be in sense-only mode and performing cooperative spectrum sensing.

Techniques that propose queuing theory approach for DSA in CVN are presented in [63–65]. When a vehicle enters a region that is served by RSU, it request access to available DSA channels for communication. If any channel is available, it is assigned to a vehicle. Otherwise the request is put in the queue of waiting requests from other vehicles. The RSU process requests in the waiting queue using FIFO algorithm regardless of the traffic and requesting vehicle. This approach however causes performance degradation in the CVN network depending on the vehicle traffic condition. The authors in [65] further suggest an algorithm that utilizes multi-channel selection opposed to single-channel selection. Simulation results show that multi-channel selection algorithm performs better than single-channel selection in maintaining network connectivity.

In order to fully access the channels from TV bands for DSA in vehicular environment, maximum PU protection must be guaranteed. Consequently, understanding PU activities to avoid interfering with their communication channels is cardinal in DSA. TV spectrum database approach can provide maximum protection to PU activities. However, there are currently few RSU that could serve vehicles seeking to query the spectrum database due to deployment cost of RSU [66]. Furthermore, not all vehicles are currently equipped with GPS capabilities making it difficult to operate as ModeII devices. In addition, the queuing approach proposed in [63–65] is not optimal. This is because many vehicles could be denied access to spectrum opportunities when the vehicle traffic condition is high. Therefore, spectrum sensing is the only viable way to identify spectrum holes in TV bands that can be used for DSA. Moreover, spectrum sensing can facility discovery of idle channels in other frequency bands apart from TV bands. Hence, the research community needs to understand some of the challenges that affect spectrum sensing in CVN in order to develop algorithms to overcome the challenges.

4. Challenges of spectrum sensing in CVN

Spectrum sensing in a cognitive vehicular network environment is affected by many factors. High mobility of vehicles on the road is the main contributing factor which gives rise to other challenges. In this section, we discuss some of the challenges as they affect spectrum sensing.

4.1. Mobility and direction of vehicles

In CVN environment, vehicles as communicating nodes move with relatively high speed compared to nodes in other network environments. Therefore, spectrum opportunities should be utilized within a short period of time. In this regard, algorithms designed to detect PU activities must be quick and effective.

When a vehicle needs channels for DSA in a given region covered by PU (Fig. 3), spectrum sensing is performed for time duration S_t. After sensing, the vehicle will need time duration A_t for transmitting its data on the acquired channels. However, S_t and A_t are dependent on the transmission range (R) of the PU, the speed (v) and direction of the vehicle [67]. For a vehicle to fully utilize the spectrum opportunity and provide minimum interference to the PU activity, the following condition must hold:

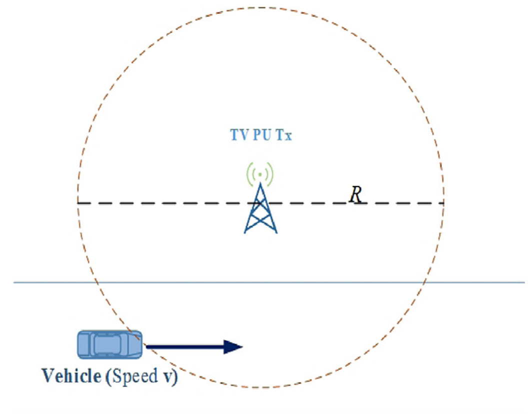

Fig. 3. PU coverage area R.

$$(S_t + A_t) < \frac{R}{v}. \tag{1}$$

The speed and direction of the vehicle determine the duration when the vehicle will be within R. When a vehicle is moving with high speed, the likelihood of being outside R are high which result in miss detection of the PU signal [67,68]. Therefore, spectrum sensing should be performed quickly in order to minimize probability of missed-detection while maximizing the probability of detection.

On the other hand, speed of the vehicle has positive impact on cooperative spectrum sensing as noted in [69,70]. The improvement in the sensing performance is caused by mobility in sensors which increase spatio-temporal diversity in the received signal strength (RSS). However, the performance depends on the direction and speed of the cooperating sensors. If vehicles cooperating in spectrum sensing are moving in the opposite direction, they are likely to experience signal fading and shadowing due to Doppler effects [71]. As a consequent, cooperative spectrum sensing is affected.

4.2. Spectrum sensing time against channel access

The high mobility of vehicles on the road has an impact on spectrum sensing time. Generally, longer sensing time entails more accurate detection of the PU signal [72]. On the other hand, quick sensing time can lead to missed detection or increased false alarm probability. Therefore, balancing the trade-off between quick sensing and fine sensing for PU occupancy activities and later accessing the identified channels is a challenge.

4.3. Variation in network density

In cognitive vehicular network, the density of vehicles in VANET is subject to change at any time and place causing fluctuation in the network. This is contrast to classic CRN where the network remains constant for a longer period of time. For example, in peak hours, there will be more vehicles communicating in urban areas opposed to suburban areas with sparse vehicles [73–75]. The variation of vehicle density affects the performance of cooperative spectrum sensing. For instance, if cluster based sensing techniques are employed, to establish the number of vehicles per cluster in

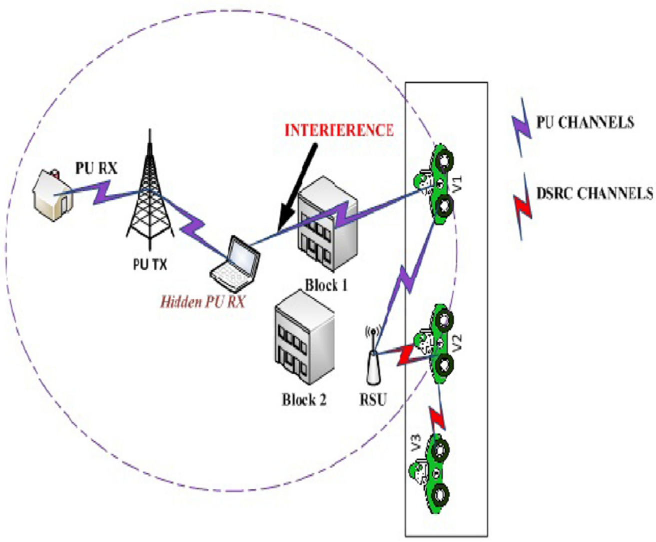

Fig. 4. Illustration of hidden PU problem.

traffic jams becomes difficult. As many vehicles will be populated within a small road segment with less or no movement. On the other hand, if cooperative sensing mechanisms are employed in suburban environment, the number of vehicles required to cooperate might not be enough. In addition, adapting the transmission power for communicating nodes is not straight forward [76]. For example, if there are many vehicles contending for the same channel, the trend is to reduce the transmission power of the transmitter to avoid interference. Conversely, if there are few vehicles in the topology, increasing transmission power enable vehicles to reach each other. Hence, the fluctuation in noise level can affect spectrum sensing based on energy detectors [77].

4.4. Modeling of PU activities in CVN environment

Performance of spectrum sensing algorithm is affected by the PU activity model assumed (see Section 5). The mobility nature of vehicles coupled with PU spectrum occupancy activities has significant effect on the probability of detection [67]. Few literature has studied the impact of PU activity model in the CVN environment [67]. Many of the algorithms reviewed in this paper assume the static ON/OFF model were the PU spectrum occupancy statistics are known in advance. In reality, PU activities are more complexity and cannot be fully modeled with ON/OFF period alone [78,79]. Therefore, new models need to be developed which will account for mobility of vehicles and the activities of the PU.

4.5. Hidden PU problem

Hidden PU problem is another issue in CVN environment [80]. An individual vehicle sensing for spectrum opportunity can experience fading and shadowing due to obstacles along the line of sight with PU transmitter (Fig. 4). Suppose vehicle ($V1$) wants to communicate with the RSU over PU channels, it will perform spectrum sensing. Since there is a building obstructing $V1$ to acquire clear sensing results, it will assume no PU receiver in the area. Therefore, when $V1$ attempt to communicate with the RSU on the acquired channels, its signal will cause interference to the PUs. Nevertheless, the hidden PU problem is eliminated by cooperative spectrum sensing. Different vehicles will have different detection levels of the same channel which they can share and determine PU occupancy thereof.

4.6. Spectrum sensing data falsification attacks

Spectrum sensing in cooperative environment can be distorted by malicious users. The attackers can introduce false data to confuse the cooperating nodes. When the false data is introduced, the sensing nodes might conclude the presence of PU when in fact the PU is absent. By so doing these malicious user can use the PU channels selfishly. These kinds of attacks are called spectrum sensing data falsification attacks (SSDF). The impact of malicious attacks on spectrum sensing has been studied in [81,82] for MANET environment. The problem of malicious users has more impact in CVN because of trust issues among nodes [83]. It becomes difficult to authenticate communicating nodes in CVN. This is because vehicles (nodes) come in contact with many other vehicles on the road some of which might have malicious intent.

5. PU activity model

A cognitive radio network works on the basis that primary network is not disrupted or interfered with. Therefore, spectrum sensing is performed to identify channels that can be used by SUs with provision of minimum interference to PUs. However, spectrum sensing is dependent on the underlying PU activity model. Different PU activity models have been proposed for CRN [78,79] which include Markov process, queuing theory, time series, and ON/OFF periods. These models capture the behavior of PU activity spectrum occupancy such as average time the PU transmission is on or off, the transition from on to off status and vice-verse. In CVN mobility nature of vehicles make it difficult to adapt some models suggested for static wireless networks. Vehicles are mobile, as a result they can move in and out of the area covered by PU in a short period of time. Therefore, many algorithms proposed for spectrum sensing in CVN assume a static PU with fixed ON/OFF periods [80]. However, this assumption is not realistic as activities of PUs are perceived to be random [84,85]. Hence, accurate PU activity models need to be derived for CVN environment.

The models based on ON/OFF are sometimes referred to as birth-death process. The ON (birth) period defines the duration when the PU network is busy or transmitting, denoted by α. On the other hand, when the PU is idle or not transmitting then the PU network will be in OFF (death) state denoted by β. SU is only allowed to transmit its data during the OFF period which represent the time duration of channel availability. The probabilities of ON periods (P_{ON}) and OFF periods (P_{OFF}) are given by [86]:

$$P_{ON} = \frac{\alpha}{\alpha + \beta} \tag{2}$$

$$P_{OFF} = \frac{\beta}{\alpha + \beta} \tag{3}$$

In [84] a model that follows the ON/OFF periods is modeled as an exponential distribution in the CR-MANET environment. Mobile SUs within transmission range of the PU learn about PU spectrum occupancy and disseminate this information to other SUs. To learn the activities of the PU, the proposed scheme switches between fine sensing and normal sensing. Fine sensing is based on maximum likelihood estimator in which the average busy and idle periods are determined. During normal sensing, the activity pattern identified in fine sensing are used to track changes in the PU ON/OFF times using mean square error (MSE) value. If any changes occur in the PU activity, the MSE will increase triggering fine sensing.

Another ON/OFF PU activity model is studied in [67] for CVN environment. They evaluate the performance of spectrum sensing for miss-detection and overlapping time. The simulation results indicated that speed of the vehicle and activities of PU have a great impact on probability of miss-detection, but not probability of false alarm. The expected overlapping time for a vehicle to cover the sensing area is affected by transmission range of the PU, initial separation distance between the PU and the sensing vehicle as well as the velocity of the vehicle. For a given PU transit activity from OFF to On, the probability of miss-detection was observed to decrease when the sensing range between the vehicle and PU increases. On the other hand, increase in vehicle speed increased the miss-detection probability for a given OFF/ON transit of the PU.

The impact of mobile PU activity model is studied in [87–89]. In [87] the SUs are assumed to be constant, while the PUs are mobile following the Random Walk Mobility model (RWM) with reflection and Random WayPoint Mobility model (RWPM). They modeled the PU traffic as two state birth-death (ON/OFF) process in which the ON state correspond to active PU while the OFF state represent inactive PU. The performance metrics were derived to measure the impact of mobility on detection probability and measure the achievable expected capacity by SUs in presence of mobile PUs. Simulation results concluded five parameters that affect the detection capability. The parameters are PU protection range, PU mobility pattern, PU coverage area, the extension of the network region and the number of PUs using the same band.

The parameters that affect the performance of spectrum sensing capacity determined in [87] have more profound effect in CVN. Vehicles move with relatively higher speed compared to nodes in MANET, therefore, a vehicle is likely to move in or out of the PU protection range quickly[67]. Therefore, a static ON/OFF model cannot capture the mobility nature of nodes in CVN. On the other hand, models described in [79] that consider time, frequency, location dimensions or mixture to model PU behavior can be used as a basis to formulate PU activity models for CVN.

6. Spectrum sensing techniques

In order to identify idle PU channels that can be used for DSA, individual vehicles have to perform spectrum sensing on those channels. The accuracy of modeling PU activity is dependent on the spectrum sensing technique employed by the vehicle. There are three main techniques proposed for spectrum sensing in literature. Among the three, the most commonly used technique is based on energy detector. Others are cyclostationary and matched filter detection. We discuss in details these three sensing techniques and their limitations.

6.1. Energy detection

Energy detector is simple to implement and prior knowledge of the PU signal is not required [81]. Thus, it is one of the most implemented sensing technique in CVN environment [90–93]. To determine the PU spectrum occupancy, the detector measures the received signal strength of PU and compares it with a predetermined threshold. Most implementation assumes the ON/OF PU activity model were ON represent PU active and OFF represent the instance when the PU is idle. Therefore, a binary hypothesis is used to model the PU status given by [68]:

$$f(x) = \begin{cases} n(x) & \text{for } H_0 \\ hs(x) + n(x) & \text{for } H_1 \end{cases} \tag{4}$$

where $f(x)$ is the received signal sample at a local SU. The signal transmitted by PU is given by $s(x)$ with amplitude signal gain between PU and SU given by h. The PU signal is distorted by noise $n(x)$ which is assumed to be Gaussian distributed with mean zero and variance σ_n^2. H_1 represent an instance when PU signal is present while H_0 represent an instance when PU signal is absent. The energy test statistics T for detector over M samples is given by [91]:

$$T = \sum_{i=0}^{M} |f(x)|^2 \tag{5}$$

To measure the performance of the energy detection algorithm, two probabilities are derived. The first is probability of detecting the true PU signal given H_1 and some threshold γ denoted by P_D. The second is probability of false alarm denoted by P_F. P_F is the probability that the detector will incorrectly decides the PU is active when it is not given H_0 and the threshold γ. The high probability of detection is desired to accurately learn the activities of the PU. The two probabilities are formulated as [92]:

$$P_D = P_r(T > \gamma | H_1) \tag{6}$$

$$P_F = P_r(T > \gamma | H_0) \tag{7}$$

Despite energy detector being widely used, its performance degrades in low SNR [94]. Furthermore, determining the detection threshold for trade-off between P_D and P_F is difficult as it is dependent on noise and PU signal power. The noise power can be estimated because it is assumed to be additive white noise and Gaussian distributed [95]. However, the PU signal power is not easy to estimate as it is dependent on the characteristics of PU transmitter and the distance between the sensing node and the PU. In practice however, the threshold is selected to attain certain false alarm rate [96]. Another disadvantage of energy based detector is failure to distinguish different signals since it is based on threshold. For example, a detector can not differentiate when the PU is transmitting from signal generated by other SUs transmissions. Hence, false alarms can be triggered frequently.

6.2. Cyclostationary detection

Cyclostationary feature detection techniques exploit the periodicity of the correlation of the received primary signal. The correlation as a function of time is usually found in modulated signal features such as sine wave carriers, spreading code, pulse trains, hopping sequences or cyclic prefixes of the primary signal [97]. Algorithms based on cyclostationary feature detection can distinguish PU signal from noise [98]. This is because a cyclic autocorrelation function (CAF) is utilized for detecting a PU signal in a given spectrum opposed to power spectral density used in the energy detector. The CAF of a received signal $f(x)$ at the SU is given by [99]:

$$R_f^{\alpha} = E[f(x+\tau) f^*(x-\tau) e^{j2\pi\alpha x}] \tag{8}$$

while the cyclic spectral density (CSD) function is given by:

$$S(y, \alpha) = \sum_{\tau=-\infty}^{\infty} R_f^{\alpha}(\tau) e^{-j2\pi y\tau}. \tag{9}$$

Where α is a cyclic frequency, * in CAF represent a complex conjugation while the quantity $E[.]$ represent the expectation operation. The peak values of the CSD are reached when α equals the fundamental frequencies of the PU transmitted signal $s(x)$ in the case for H_1. Since noise is non-cyclostationary [100, 101], the CSD function does not have any peaks under the H_0 hypothesis.

Cyclostationary feature detection method is robust to noise uncertainty. Hence it can detect a PU signal even in low SNR [102]. In addition, a detector based on feature detection can differentiate transmission from different PU systems. However, due to its implementation complexity and need for prior knowledge of the PU signal, this detection technique is not widely used. Furthermore, to acquire accurate detection results, a long sensing time is needed. In

Table 1
Comparison of spectrum sensing techniques.

Detection technique	Sensing time	Implementation complexity	PU detection accuracy	PU detection sccuracy in low SNR	Knowledge of PU signal in advance
Energy [68,90,91,94]	Medium	Low	Medium	Low	Not required
Cyclostationary [97,99,101,102]	High	Medium	Medium	High	Required
Matched Filter [27,95,103–105]	Low	High	High	Low	Required

CVN where vehicles move with high speed, performing long sensing period will result in missing the spectrum opportunities on the road. This is because a vehicle can take longer time to sense the spectrum opportunity by the time it finishes, it might have moved into another area were the sensing results might be irrelevant. Therefore, cyclostationary detection technique is less implemented in CVN.

6.3. Matched filter detection

Matched filter detection requires perfect knowledge of PU signal features before sensing the target channel [27]. These features include bandwidth of the channel, modulation scheme, frequency at which the channel operates, packet format, etc. A matched filter detector requires short sensing time to detect the PU signal because the features are known in advance [103]. Furthermore, a detector based on matched filter requires few received signal samples of the PU in order to achieve low probability of missed detection and false alarm [104]. However, techniques based on matched filter implement complex algorithm and consumption lot of energy [95]. Furthermore, different receivers have to be installed to sense different types of PU signals because each primary network will have different characteristics. In addition matched filter detector performances deteriorates with decrease in SNR [105]. Therefore matched filter detectors are seldom implemented for spectrum sensing in CVN. The summary of discussed spectrum sensing techniques are presented in Table 1.

7. Cooperative spectrum sensing in CVN

Cooperative spectrum sensing decision overcomes some of the challenges encountered in classical per device spectrum sensing discussed in the previous section. Challenges such as hidden PU problem, shadowing and multipath fading. The cooperating vehicles use spatial and temporal diversity to overcome such challenges. The impact of shadowing and fading severity on detection performance over Gamma-shadowed Nakagami-m composite fading channel for CVN is studied in [106].

In this section, we discuss cooperative spectrum sensing decision for cognitive vehicular network environment. Cooperative decision in CVN can be divided into two categories; centralized and distributed. We discuss proposed sensing schemes based on these two categories.

7.1. Centralized spectrum sensing decision

In centralized cooperative spectrum sensing decision, a node is selected to act as a fusion center (FC). The FC is responsible for deciding the overall PU occupancy. In CVN, either the RSU in V2I or a vehicle in V2V is selected to act as the FC. Different methods are used at the FC to decide PU occupancy. In this section we discuss these methods based on soft combining, hard fusion rule and others. Fig. 5 shows vehicles cooperating in sensing the PU signal and report the results to the RSU which make a final decision about the PU occupancy.

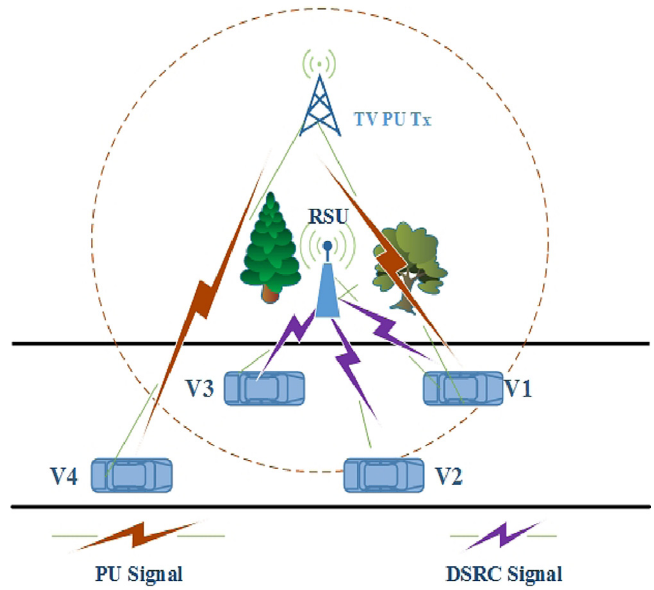

Fig. 5. Cooperating vehicles in centralized sensing.

7.1.1. Hard fusion rule

Techniques based on hard fusion combining involve each individual SU performing local sensing to detect PU signal and only send the test results to the FC. The result sent to the FC is a binary digit with 1 representing presence of PU signal and 0 absent of the PU signal [107]. The FC makes a decision on the PU spectrum occupancy based on one of the following rules; AND, OR, Majority rule or K-out-of-M. For example, in [108] a centralized cooperative spectrum sensing based on maximum likelihood ratio (MLR) is proposed for CVN. The maximum likelihood algorithm is used to estimate the average SNR. The final decision about PU occupancy is performed by the RSU based on OR fusion rule. The global probabilities of missing detection (Q_m) and false alarm (Q_fa) at the RSU is given by [108]:

$$Q_m = \prod_{k=1}^{K}[Pr_{m,k}(1 - Pr_{e,k}) + (1 - Pr_{m,k})Pr_{e,k}] \tag{10}$$

$$Q_{fa} = 1 - \prod_{k=1}^{K}[(1 - Pr_{fa,k})(1 - Pr_{e,k}) + Pr_{fa}Pr_{e,k}] \tag{11}$$

Where $Pr_{e,\ k}$ is probability of reporting error between the RSU and the k^{th} vehicle. $Pr_{m,\ k}$ and $Pr_{fa,\ k}$ are probabilities of missing detection and false alarm respectively reported by individual vehicles.

Abbassi et al. in [109] and [110] propose coordinated cooperative decision. Three vehicles are selected to actor as coordinators for spectrum sensing. In [109] one node is selected as main coordinator node and two other nodes are selected based on their geographical location. In [110] the coordinated approach is enhanced by using history of spatiotemporal and frequency pattern of sensing results to decide PU occupancy. Authors in [111] propose a cooperative spectrum sensing that addresses the problem of node selection in mobile environment. In this approach the FC makes a final decision about PU occupancy based on hard fusion rule and sends the results back to cooperating SUs.

Hard fusion rule is simple to implement because the cooperating SUs send a bit (0 or1) to the FC regardless of the local spectrum sensing results. The hard fusion rule can be used with other methods to improve decision accuracy as noted in [108]. Nevertheless, the adaptive spectrum sensing with dynamic detection threshold variations adopted in [108] underperform compared to other sensing techniques. Other issue with hard fusion rule is synchronization of sensing results. Synchronization of spectrum sensing results is difficult to keep in CVN because of high dynamic network topology and sensing overhead of synchronous cooperative action. The coordinated scheme proposed in [109,110] can introduce hidden PU problem. This is because coordinators are selected far apart. In addition, if there is no coordinator, the network topology is bound to suffer from disconnection. Furthermore, the choice of energy detector as detecting technique performs poor in low SNR. The proposed scheme lack the description of the PU activity model considered in the simulation results.

7.1.2. Soft combining method

In soft combining method, the measurement of channel energy samples obtained at the local SUs are sent to the FC. The FC combines these samples and compares the results with a predefined threshold to determine the global PU occupancy. There are three main methods based on soft combining; equal gain combining, weighted linear combining and optimal combining.

In [91] the performance of energy detector under correlated Rayleigh fading channel model is investigated. The PU occupancy is calculated using the linear global test statistic of cooperating vehicles based on equal gain combining as follows [91]:

$$E = \sum_{i=1}^{N} e_i \tag{12}$$

In Eq. 12, e_i is a received test energy statistic of i^th vehicle at the FC and N is the total number of vehicles collaborating. Another linear combining approach is presented in [112], the FC combine individual local sensing results from vehicles based on the following rule:

$$y_f = \sum_{i=1}^{M} w_i y_i \tag{13}$$

Were w_i is the weight of the local vehicle with contribution observation y_i. For equal gain combining (EGC), w_i is assumed to be 1. The authors in [113] propose a weighted average technique to identify free spectrum in the Industrial, Scientific and Medical (ISM) bands along the road. On the other hand, the authors in [114] suggest a cooperative spectrum sensing decision that exploits the advantages of hard fusion and soft combining rules. They introduce a three decision threshold to decide the PU occupancy. The three thresholds correspond to; when the SU detect the PU signal, when the SU detect the absence of the PU signal and lastly when the SU is uncertain about the decision. At local SU, spectrum sensing is performed using energy detector and a test statistics obtained is compared with two threshold levels. If the test energy level lies between the two thresholds then the SU does not transmit the test statistic or local test result to the FC. If the SU detects the PU signal, it transmits both the SNR unknown parameter and local test result. The SNR unknown parameter is used to obtain the weights for soft combining algorithm at the FC.

Another soft combining scheme based on compressive sampling technique is presented in [115]. In this approach, the PU signal is recovered from fewer measurements samples compared to traditional sampling techniques. Each vehicle equipped with a multiplier conduct the inner product operation between the stored sensing matrix vector and the PU signal to get required measurements. Once the local measurements are obtained, the vehicles send the results to RSU where the original PU signal is recovered. The RSU obtains the complete spectrum occupancy status based on the frequency domain information (f_m) and broadcast the results back to the cooperating vehicles. The signal recovery process at RSU is performed by solving the linear convex optimization problem given by [115]:

$$\hat{f}_m = arg\min_f ||f_m||_1 \text{ s.t. } y = GF^{-1} f_m + n_f \tag{14}$$

In Eq. 14 y is the sampling measurement matrix of frequency domain f_m. G is the random Gaussian measurement matrix while F is the discrete Fourier basis. The white Gaussian noise sample vector is given by n_f. The expression $F^{-1} f_m$ is the frequency domain of the received PU signal for each vehicle. The original PU signal is recovered based on the frequency domain information at RSU. Thereafter, the RSU decides PU occupancy based on the binary state vector and some threshold.

Soft combining techniques perform better than hard fusion rules when detecting the PU occupancy. Nevertheless, both soft combining and hard fusion rule are susceptible to SSDF attack. Malicious users can send distorted test statistics which can result in FC making a wrong decision about PU occupancy. Furthermore, soft combining require extra bandwidth to send the weight of local sensing results from cooperating vehicles to FC. This in turn will increase the decision time at FC as more local sensing results are sent from individual vehicles. Thus, to reduce the detection time, the work in [115] demonstrated that compressive sampling technique could be used. Hardware complexity and memory storage requirement can be greatly reduced when using compressive sampling approach as noted from the simulation. This is because vehicles only sent part of the samples for the frequency under consideration and does not sense the whole spectrum.

However, simulation results in [115] showed that detection performance is poor in low vehicle density. For example, the proposed scheme could not reach detection probability of 80% with 30 cooperating vehicles. This could pose a challenge in CVN especially in sparse environment where the density of vehicles is low. Hence, vehicles will miss the spectrum opportunities in those areas. On the other hand, the blind feature detection used in [113] to detect ISM bands perform better than energy detector. However, ISM bands are likely to experience congestion because there are many wireless technologies being developed that rely on these bands [116,117]. Therefore, ISM bands might not be the best candidate for DSA in CVN. The performance of spectrum sensing is dependent on the PU activity model assumed. However, no PU activity models are discussed in the reported work.

7.1.3. Other centralized methods

There are other centralized schemes proposed in literature not based on either soft combining or hard fusion rule. For example, a cooperative spectrum sensing decision technique based on renewal process method is proposed in [80]. A blind detection method over Nakagamin fading is investigated in [118]. The approach in [118] used blind eingenvalue based detection algorithm to detect PU signal at individual vehicle level and sent to FC for global decision. The eingenvalue spectrum sensing approach detects the PU signal based on the test statistics obtained from eingenvalues of the received covariance matrix. In [119] a cooperative coordinated spectrum sensing that mitigate the disadvantage of classical techniques approach is proposed. In this scheme, the RSU or any vehicle is selected to act as coordinating node.

Simulation results in [80] indicate the approach used in this work could achieve detection accuracy of up to 90%. However, the

Table 2
Summary of centralized cooperative spectrum sensing.

Ref	Year	Algorithm used at FC	Mobility model	PU activity model	Simulation environment	Performance metric
[119]	2010	N/A	Freeway	ON/OFF	MATLAB	Probability of detection, Temporal usage rate, Average sensing overhead.
[112]	2011	Soft combining/ Hard fusion	Unknown	Free space propagation	Unknown	Probability of mis-detection sensing time overhead
[111]	2013	Hard fusion	Gauss–Markov mobility	Unknown	OMNET++/ MiXiM	Probability of detection, probability of false alarm
[109]	2013	Hard fusion (majority rule)	Gipps model	Unknown	Microsoft C# 5.0	Probability of detection, probability of mis-detection
[115]	2013	Hard fusion (AND Rule)	Unknown	ON/OFF	MATLAB	Probability of detection, occupied fraction, processing time at RSU.
[108]	2013	Hard fusion (OR rule)	Unknown	Unknown	Unknown	Probability of detection, probability of false alarm probability of mis-detection, BER/report channel SNR
[118]	2014	Unknown	Unknown	Unknown	Unknown	Probability of detection, probability of false alarm
[91]	2014	Soft combining (EGC)	Freeway	Unknown	Unknown	Probability of mis-detection
[114]	2014	Soft combining (weighted)	Random walk process	Unknown	Unknown	Probability of Detection, Probability of Mis-Detection
[113]	2015	Weighted average	SUMO (Realistic model)	Unknown	NS2	Probability of detection probability of false alarm, overhead traffic, channel switching rate.
[80]	2015	Renewal process	Unknown	ON/OFF	Unknown	Probability of detection, probability of false alarm, average waiting time, transmission time for SU
[107]	2015	Hard fusion	Unknown	Unknown	Unknown	Probability of mis-detection
[110]	2015	Hard fusion (majority rule)	Highway	Unknown	Visual C#	Probability of false alarm, channel allocation rate, rejection to assign channel, rate to leave channel.

authors did not discuss the sensing technique used at individual vehicle level to reckon the simulation results obtained. In addition, the renewal process model is not fully discussed as the authors keep on changing the central controller of sensing operation between RSU and the PU. Furthermore, they mentioned that speed of vehicles have effect on spectrum sensing. However, no mobility model has been discussed for simulation performed. The work in [118] investigates the performance of spectrum sensing in CVN over Nakagami-m fading channel model. Simulation results showed that when the shaping factor of Nakagami-m is set to 1, the fading distribution reduces to Rayleigh fading. On the other hand, when the shaping factor is greater than 1, the fading distribution followed is Racian. The work in [118] also showed that increase in the number of sensing samples and cooperating vehicles increases the performance of detection. However, the work in [118] overlooked the impact of mobility on the sensing performance.

Table 2 gives the summary of the cooperative spectrum sensing decision based on centralized approach.

7.2. Distributed spectrum sensing decision

Distributed cooperative spectrum sensing decision involves SUs cooperating in detecting the spectrum holes in an ad hoc environment. There is no infrastructure support to act as fusion center. Therefore, each SU collaborate with its neighbors in determining the presence or absence of the PU signal for the channels of interest. In this section we discuss the proposed schemes according to the distributed algorithm used. Fig. 6 shows the concept of distributed cooperative spectrum sensing.

7.2.1. Consensus based algorithm

In [120,121] and [122] a distributed cooperative spectrum sensing based on consensus algorithm is proposed. The energy detector is used at individual SU to detect the presence or absence of the PU. Then the local estimate energy level $x_i(k)$ is exchanged with

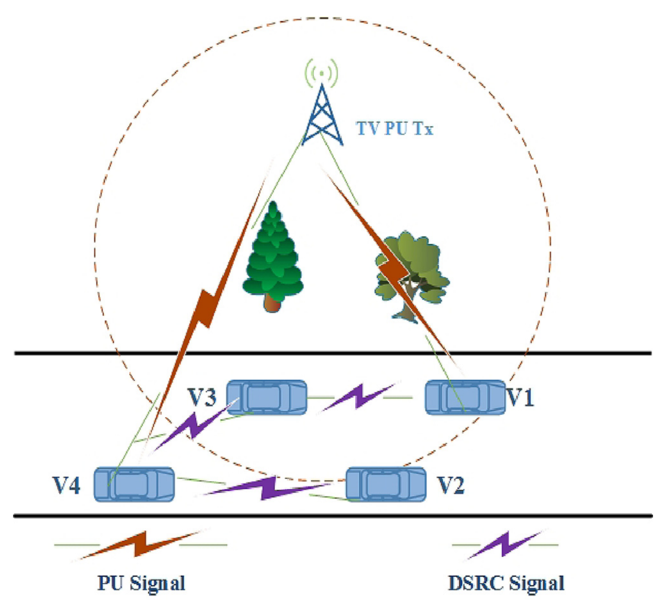

Fig. 6. Cooperating vehicles in distributed sensing.

neighbors at discrete time instant k associated with a given sampling period. In [120,122], the schemes employ maximum deviation from the mean value to identify legitimate neighbors. While in [121] weight associated with each node is used to select legitimate neighbors. This is done to prevent malicious attacks such as SSDF. Using this procedure, a subset of trusted SUs is generated whose date is used in updating the state $x_i(k+1)$. The iterations are done repetitively until all of the individual state $x_i(k)$ converge near a common value x^*. The consensus algorithm computation equation is given by [120]:

$$x_i(k+1) = x_i(k) + \epsilon \sum_i (x_j(k) - x_i(k)) \quad (15)$$

where $0 < \epsilon < 1/\Delta$, with Δ a maximum degree of the network. Each SU decide the spectrum occupancy by comparing the consensus result x^* and a predefined threshold.

The work in [120,121] and [122] study the impact of malicious user on cooperative spectrum sensing. They show that spectrum sensing results are affected by the number of malicious users in the network. In addition the consensus approach proposed out performs the hard fusion cooperative sensing with or without malicious users. However, it is difficult to determine trusted neighbors in CVN to cooperate in sensing. This is because vehicles move from one place to another where neighbors might be very different. Hence the subset of neighbors used to update the consensus state $x_i(k+1)$ is difficult to establish. In addition, the iterative approach in consensus scheme could impair the shared channel used to exchange the messages during high vehicle density. The evaluation of consensus scheme presented in [120] was performed on stationary node. While the work presented in [121] considered only ten vehicles in the simulations. Authors in [122] considered mobility in the implementation. Nevertheless, they restricted cooperating nodes in consensus sensing to 10 m which is not realistic in CVN with varying vehicle density. In addition, no PU activity model was considered in these works.

7.2.2. Belief propagation algorithm

In [123] a belief propagation scheme is proposed to identify free spectrum occupancy on highway for vehicles to use. The scheme aims to utilize spatial and temporal redundancy observed by vehicles when sensing the PU signal. Spatial redundancy is observed because neighboring vehicles share similar PU spectrum occupancy with high probability. Similarly, temporal redundancy is observed because spectrum occupancies in two consecutive time slots are believed to be alike with high probability. To limit bandwidth on the common control channel, they design simple messages (3*bits* each) for belief exchange. Vehicles send these messages in the belief propagation time slot to neighbors about existence of PU. Then each vehicle combines the belief of the neighbor and its own local observed spectral information to generate new belief. After several iterations, each vehicle computes its own belief given by [123]:

$$b_i(S_i) = c_i\phi_i(S-i)\prod_{k\neq ij} m_{ki}^M(S_i) \tag{16}$$

Where c_i is a normalization factor, ϕ_i is called local function. S_i is the state of vehicle, with $S_i = 1$ denoting the vehicle being within communicating range of the PU and $S_i = 0$ otherwise. The message sent from vehicle i to j is represented by m_{ki}^M , where M is the total number of iteration in one time slot. The belief computation $b_i(S_i)$ is used to compute the marginal probability for joint probability of vehicles.

The approach used in [123] showed performance improvement in terms of detection probability when compared to non-belief propagation approach. In addition, the proposed scheme performed better even in presence of message loss. This is vital in VANET where messages can be lost abruptly due to mobility nature of vehicles. Nevertheless, the scheme was analyzed based on three nodes. In practice, the number of vehicles to communicate on the road can increase exponentially thereafter making this approach unusable. The number of iterations needed to come to a stable belief increases with the number of vehicles. Furthermore, no mobility model of vehicles was considered when sensing is performed by vehicles. In addition the scheme only assumes the sensing vehicle is within a PU transmission region given by S_i without considering any PU activity model. The mobility of vehicles on the road and the PU activity model used play a significant part in spectrum sensing in CVN environment as discussed in previous sections. Therefore, spectrum sensing techniques proposed for CVN must consider mobility and PU activity model which is not the case for [123].

7.2.3. Weighted algorithms

Weighted algorithm is proposed in [124,139] and [125] for distributed cooperative decision. In [124] each vehicle provides energy information tagged with location and time information that is assigned weights. The weights from cooperating vehicles are used in determining the PU occupancy. In [125] the impact of mobility on spectrum sensing operations in CVN is studied. Thereafter a cooperative spectrum management scheme to alleviate the impact is proposed. The sensing scheme is based on weighted majority correlation decision making. The spectrum decision is determined by assigning weights to samples obtained from the sensing stage. The PU occupancy is determined by individual vehicle after collecting other weights from neighbor vehicles and comparing them with its own weight. The weighted majority decision is determined by [125]:

$$D^f = \begin{cases} H_0 & \text{if } \sum_{i\in Y^f} w_i^f.o_i^f \leq k \\ H_1 & \text{if } \sum_{i\in Y^f} w_i^f.o_i^f > k \end{cases} \tag{17}$$

Where Y^f is the set of observation stored for a given channel f in the database. The threshold is denoted by k with the value of 0.5 used in this work. H_1 and H_0 represent the presence and absence of the PU signal respectively.

The work in [125] presents the experimental results which show the impact of mobility on spectrum sensing. They observed that the speed of the vehicle reduces the accuracy of spectrum sensing. The scheme in [125] was evaluated under urban environment with moderate to dense traffic. On the other hand, [124] study the problem of synchronization overhead associated with cooperative spectrum sensing. In CVN, synchronizing of sensing results is difficult because of the mobility nature of vehicles. Nevertheless, in both works simulation results indicate that the performance of the schemes under sparse traffic degrades. Therefore, the schemes are not suitable to be deployed in suburban areas with sparse vehicle density. Spectrum opportunities are usually found along the highway and suburban region with sparse to moderate traffic.

7.2.4. Other distributed approach

A historical spectrum sensing data mining approach is presented in [126]. The aim is to provide vehicles on the road with spectrum channels to use in advance based on historical data mining results. The works in [82] proposes a recursive validation and clustering scheme to mitigate SSDF attacks for cooperative spectrum sensing. The aim of the scheme is to correctly identify the PU spectrum occupancy under signal fading, hidden terminal problems, byzantine device failure and in the presence of malicious users. In [127] a three state spectrum sensing model for detecting spectrum occupancy is recommended as opposed to two state sensing models. This is to ensure fairness among vehicles to compete for the identified PU channels. A three state hypothesis is proposed in which a channel is assumed to be occupied by PU (H_1), vehicle (H_2) or idle (H_0). When a channel is occupied by a vehicle, other vehicles are permitted to stay and compete for the channel. The fairness performance of each competing vehicle is measured using the Jain Index (JI) give by [127]:

$$JI(t) = \frac{[\sum_{i=1}^{N} T_i(t)]^2}{N.\sum_{i=1}^{N} T_i^2(t)} \tag{18}$$

Where N is the number of vehicles competing for the channel, $T_i(t)$ is the transmission time for ith vehicle for time t. The value of JI ranges from 0 to 1 with better transmission fairness among vehicles implied by larger JI.

Table 3
Summary of distributed spectrum sensing.

Ref	Year	Algorithm	Mobility model	PU activity model	Simulation environment	Performance metric
[120]	2010	Consensus based	Static	Unknown	Unknown	Probability of detection, probability of false alarm, probability of mis-detection.
[123]	2010	Belief propagation	Uniform distributed (highway)	Unknown	Unknown	Probability of detection, probability of false alarm
[125]	2011	Majority weighted	SUMO (realistic model)	ON/OFF	NS2 (extended)	Probability of detection, spatial vulnerability index
[122]	2012	Consensus based	Random walk	Unknown	Unknown	Probability of detection, probability of false alarm, probability of mis-detection.
[127]	2013	Likelihood	Unknown	Unknown	Unknown	Normalized throughput, Jain index
[82]	2013	ReNVaS and TMC	Random waypoint	Unknown	MATLAB	Probability of detection, measurement error, no. of recursive validation.
[124]	2014	Weighted based	Highway	ON/OFF	Unknown	Probability of detection, probability of false alarm, achievable throughput, packet transmission delay
[121]	2015	Consensus based	Unknown	Unknown	Unknown	Probability of false alarm, estimate of energy level of PU
[126]	2016	Dirichlet process, Hidden Markov Model	Highway	Continuous HMM variable	Unknown	Probability of detection, probability of false alarm, probability conflict with PU, application level delay.

The scheme in [126] showed improvement in prediction channel status based on historical sensing data and spatiotemporal correlation. Authors in [82] yet show the effect of malicious users in cooperative spectrum sensing decision. Vehicles can form virtual clusters to validate other vehicles to participate in decision making. However, the performance of the approach can degrade in urban areas and sparse vehicle density. This is because vehicles change course frequently. Furthermore, the overhead introduced by recursive validation can have a negative impact on vehicles in CVN. Spectrum opportunities in CVN environment must be utilized quickly hence minimal overhead must be observed when sensing for spectrum holes. Many algorithms proposed for spectrum sensing assume two state hypotheses; when the channel is occupied by PU (H_1) or the channel is idle (H_0). Thus spectrum opportunities are missed by vehicles when they sensed PU presence when actually the channel is occupied by other vehicles. Therefore, a three state approach proposed in [127] can improve on the fairness to use the PU channel as noted from the simulation results. However, the analysis of the simulation results in [127] was based on the assumption that the PU is absent H_0. Thus the results obtained can be considered for model of two state hypotheses (H_1 and H_0) without H_2.

Table 3 give the summary of distributed cooperative spectrum sensing in CVN and mobile environment discussed in this section.

8. Open issues for spectrum sensing in CVN

The success of DSA in CVN will greatly depend on accurate identification of primary signal to protect licensed users. It is important to bear in mind the concept of cognitive radio in VANET is relatively new. Therefore, more attention is needed to solve fundamental problems such as spectrum sensing before realizing DSA in CVN. In this section we discuss some research issues pertinent to spectrum sensing in CVN.

8.1. Impact of mobility and predictable movements

The major challenge that is faced in the implementation of VANET is mobility of vehicles as communicating nodes. Despite vehicles moving at high speed, their movements are constricted by the road trajectories. Hence, prediction algorithms can determine the future location of the vehicle given the present location and velocity. Therefore, mobility and predictable movement can help in acquiring spectrum occupancy at future location of the road. The open issue in mobility which has not been given much attention is deciding mobility parameters that affect detection performance. Vehicles moving at high speed can use spatial and temporal diversity to detect PU signal. In addition the speed of vehicles can be leveraged to acquire spectrum occupancy at future location when using geo-location spectrum database.

8.2. Variation in vehicle network density

Unlike networks in classical ad hoc networks which remain constant for a longer period of time, vehicular networks are bound to change dynamically within a short period of time. The variation in vehicle density has significant effect on cooperative spectrum sensing decision. Simulation results from many approaches reviewed in this paper suggest the number of vehicles on the road have an impact on cooperative sensing decision. Depending on the algorithm used, few vehicles can lead to poor detection performance. On the other hand, distributed cooperative sensing decision can be affect by huge number of vehicles. The common control channel used to disseminate sensing results can get congested. Nevertheless, choosing the number of vehicles to participate in cooperative sensing has not been given much attention. Adapting algorithms that use vehicle density as threshold can be used to overcome problem created by variation in network density.

8.3. Synchronization of sensing results

In the per-vehicle spectrum sensing, each vehicle perform spectrum sensing and independently transmit data. On the other hand, in cooperative sensing a global decision from cooperating vehicles has to be made before the channel of interest is accessed. Before reaching a global decision in cooperating sensing, individual vehicles has to send local results to FC in centralized approach or share among neighbors in distributed approach. Therefore, sensing results from cooperating vehicles have to be synchronized. However, synchronizing sensing results is still a challenge in cooperative spectrum sensing because of vehicle mobility. In [124], the authors suggested asynchronous cooperative sensing to over the synchronization problem.

8.4. Security in cooperative spectrum sensing

Malicious users in ad hoc networks can distort the results of cooperative spectrum sensing results by introducing false data to confuse the final sensing decision of genuine nodes. This is a challenge as it compromises the results of the cooperative spectrum sensing decision. Works in [81,82] and [120] provides means of combating the SSDF attack in mobile ad hoc networks (MANET) based on iterative or recursive exchange of messages among trusted neighbors. However, these techniques cannot be applied directly to CVN because vehicles move at relatively high speed compared to nodes in MANET. Furthermore, the network topology in VANET changes quickly with different vehicles participating in the collaboration at different times. Therefore, trust of participating vehicles is still a challenge. Privacy issues still remain a challenge in VANET as protocols developed to keep drivers communication anonymous cannot be applied in spectrum sensing since the goal is to identify legitimate collaborators. Therefore, the open questions are; how can genuine vehicles be authenticated in cooperative spectrum sensing from malicious users? How can the vehicles collaborating in the sensing be kept anonymous?

8.5. Spectrum sensing in the advent of big data

The new era of Internet of Things and big data will have an impact on the spectrum management in VANETs. Vehicles in such environment will have access to data coming from different wireless sources [128]. For example, a vehicle on the road can get data from RSU, Cellular wireless, WiMAX, Satellite communication and other wireless sources [25]. These types of communication have different physical characteristics and radio frequencies. Therefore, a cognitive radio can bridge these heterogeneous networks by forming a cognitive vehicular network. Thus, spectrum sensing in such an environment will require algorithms that will distinguish the type of communication to be established between vehicles and the source of data in a quick and timely manner considering the speed of vehicles.

8.6. Simulation environment for CVN

Cognitive vehicular network is a relative new research field in VANET environment. Due to implementation cost of VANET, validation of most proposed algorithms are conducted and verified through simulating realistic VANET models. Open source simulators such as OMNET++, NS2, NS3 [129–131] have been used in conjunction with realistic mobility traffic and road maps generators such as SUMO, Veins [132–134] to model VANET environments. However, such simulators have not been integrated with CVN capabilities like spectrum sensing, spectrum management and power spectrum density. Therefore, these simulation tools cannot be used directly to validate the proposed algorithms for spectrum sensing or cognitive functionalities for CVN. Few simulators have been used for simulation of CVN as noted in Tables 2 and 3. MATLAB proprietary software is usually used to evaluate the characteristics of physical layer communication [135]. However, it does not incorporate the mobility modules for VANET. On the other hand authors in [136] and [137] extended NS 2 and 3 respectively to include the models for simulating cognitive functionalities. Therefore, more effort is needed to develop tools that will model both the mobility nature of VANET coupled with CVN functionalities.

9. Conclusion

In this paper, we have discussed various aspects of spectrum sensing in CVN environment. Firstly, we pointed out the benefits of CR in the VANET environment in the introduction. Then we discussed the PU activity model assumed by many proposed schemes which is the ON/OFF model. The PU activity models have an effect on the probability of detection. Furthermore, we discussed the challenges associated with spectrum sensing in CVN. The performance of spectrum sensing is affect by shadowing and multipath fading especially in CVN. Therefore, cooperative spectrum sensing is preferred over individual sensing. Vehicles cooperating in sensing use spatial and temporal diversity of PU signal to overcome shadowing and multipath fading. Mobility of vehicles has been observed to have an impact on spectrum sensing especially when the sensing is performed individually. On the other hand, vehicles can utilize mobility to acquire spectrum occupancy at future locations. Many proposed algorithms mentioned the impact of mobility on spectrum sensing. However, many did not include any mobility model in their simulations as noted from Tables 2 and 3. Therefore, new algorithms that will take mobility and realistic PU activity models need to be developed for CVN. Another aspect of CVN which need attention is developing simulation tools that will combine mobility and cognitive radio functionalities.

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