Cognitive Radio-Enabled Internet of Vehicles (IoVs): A Cooperative Spectrum Sensing and Allocation for Vehicular Communication

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Abstract: Internet of Things (IoTs) era is expected to empower all aspects of Intelligent Transportation System (ITS) to improve transport safety and reduce road accidents. US Federal Communication Commission (FCC) officially allocated 75MHz spectrum in the 5.9GHz band to support vehicular communication which many studies have found insufficient. In this paper, we studied the application of Cognitive Radio (CR) technology to IoVs in order to increase the spectrum resource opportunities available for vehicular communication, especially when the officially allocated 75MHz spectrum in 5.9GHz band is not enough due to high demands as a result of increasing number of connected vehicles as already foreseen in the near era of IoTs. We proposed a novel CR Assisted Vehicular NETwork (CRAVNET) framework which empowers CR enabled vehicles to make opportunistic usage of licensed spectrum bands on the highways. We also developed a novel co-operative three-state spectrum sensing and allocation model which makes CR vehicular secondary units (SUs) aware of additional spectrum resources opportunities on their current and future positions and applies optimal sensing node allocation algorithm to guarantee timely acquisition of the available channels within a limited sensing time. The results of the theoretical analyses and simulation experiments have demonstrated that the proposed model can significantly improve the performance of a cooperative spectrum sensing and provide vehicles with additional spectrum opportunities without harmful interference against the Primary Users (PUs) activities.

Table 1 Notation Table: List of Main Variables

$\mathbb{S}$	The state space, $\mathbb{S} = \{0, 1, 2\}$, of each radio channel.
$\mathbb{N}$	The number of cognitive road-side base stations.
$\mathbb{R}$	The number of CR vehicular SUs.
L_R	The road length of the cognitive cell (CC).
B	The block partition of the road which a given CR vehicle belongs.
d	The length of block partition of the road, which is the minimum safety distance for two adjacent CR vehicles.
$\Re_0$	The absence of any signal transmission (i.e., the presence of spectrum holes).
$\Re_{pu}$	The signal transmitted by PU transmitter.
$\Re_{su}$	The signal transmitted by a CR vehicular SU transmitter.
$\Re_*\{\cdot\}$	The real part of a complex value operation.
C_i	The non-overlapping available channels, $i = 1, 2, 3, \dots, N$.
h_c	The slow fading channel with amplitude α and phase θ, $h_c = \alpha e^{j\theta}$, (i.e. the channel impulse response).
$\mathbb{S}_{LP}$	Refers to an equivalent low-pass (LP) representation of the unknown signal.
$\mathbb{WG}_{LP}$	The equivalent LP representation of both the DTV and ATV signals, and an AWGN process with a zero mean and a known power spectral density (PSD).
f_*^i	The feature carrier frequency with $*$ indicating the type of signal.
x_{ij}	The test statistic to test H_0, H_1 and H_2 hypotheses.
N_0	Denotes the one-sided noise PSD.
$N_0 W$	The channel noise variance.
β	The chi-square distribution variance.
ω	The instantaneous signal-to-noise ratio (SNR).
$I(\cdot)$	The i^{th} first order modified Bessel function.
$\mathbb{V}_a$	The assignment vector in the N non-overlapping available channels.
$N_{k,Avail}$	The intended number of available channels to be acquired until the k^{th} sloth under the assignment vectors, $\mathbb{V}_1, \mathbb{V}_2, \dots, \mathbb{V}_k$.
$n^{\alpha}_{a,Avail}$	The expected optimal number of available channels acquired in a^{th} sloth.
$P_i(V_i, i)$	The probability that channel i is available when CR vehicular SUs V_i sense channel i.
Z_i	The total number of the CR vehicular SUs that senses channels $i, i+1, \dots, N$.
$K[Z_i, i]$	The optimal solution when Z_i CR vehicular SUs sense channels $i, i+1, \dots, N$.
V_{i,Z_i}	The corresponding optimal assignment vector.
$\delta_1^{\mathscr{k}}$	The communication range of the $\mathscr{k}^{th}$ CR vehicular SU.
$\delta_2^{\bar{\mathscr{k}}}$	The interference range (to the neighbouring CR vehicular SUs) of the $\mathscr{k}^{th}$ CR vehicular SU.
$d_{\mathscr{k},\bar{\mathscr{k}}}$	The difference in distance existing between the $\mathscr{k}^{th}$ CR vehicular SU and the $\bar{\mathscr{k}}^{th}$ CR vehicular SU.
$d_{\bar{\mathscr{k}},\mathcal{C}_n}$	The distance between the $\bar{\mathscr{k}}^{th}$ CR vehicular SU and the PU.
$d_{\mathscr{k},\mathcal{C}_n}$	the distance between the $\mathscr{k}^{th}$ CR vehicular SU and the PU.

1. Introduction

The rapid increase in the number of vehicles in most cities across the globe have led to incessant traffic congestion, road accident and air pollution. Recently, the concept of cooperative wireless communications among mobile vehicles was proposed to make the driving experience safer and more comfortable [1-2]. Vehicular networks also referred to as IoVs paradigm is a special ad-hoc network that equips vehicles with wireless communications devices to provide road safety, traffic efficiency and infotainment services. In order to mitigate social problems such as traffic congestion, road accidents, and reduce air pollution which lead to poor quality of life, the America National Highway Traffic Safety Administration (NHTSA) in its New Federal Motor Vehicle Safety Standards requires all vehicles to be equipped with such wireless communication devices in the near future. Efficient and timely exchange of current and upcoming traffic information amongst moving vehicles can reduce road accidents, minimize hours spent on the motorways due to traffic jams and reduce fuel consumption. Other applications of vehicular ad-hoc networks (VANETs) include location-based and road-side information services such as information about gas station, road-side restaurants, parking, etc. [3].

The IEEE 1609.4 [4] protocol stack which has been approved by a delegated Working Group (WG) is meant to provide mechanism for multi-channel operations in wireless access for vehicular environments (WAVE), where all the channels (i.e., control channel (CCH) and service channels (SCHs)) are periodically synchronized at intervals. The US FCC has allocated 75 MHz spectrum in the 5.9 GHz spectrum band for the WAVE system. In other words, all vehicular users will have to contend for the channel access and use it to exchange both safety and non-safety related information in the 5.9 GHz spectrum band. However, in order to realize the full potentials of IoVs, vehicles should be able to communicate with one another using vehicle-to-vehicle (V2V), vehicle-to-roadside infrastructure (V2I), and vehicle-to-other pedestrian's handheld devices (V2X) communications [5] by leveraging on the wide range of wireless spectrum and networks such as Wi-Fi networks, cellular networks, TV bands and satellite networks, depending on the availability and location of vehicles.

With the recent advances in cognitive radio (CR) technology [6-7], introduction of CR assisted IoVs will enable opportunistic spectrum sensing and hopping from one frequency to another in the entire spectrum range based on their needs and operating environment. It is imperative to point out that in designing CR assisted vehicular networks, attention must be paid to the peculiar characteristics of vehicular communication networks such as high speed of vehicles, high density in urban areas, and extremely dynamic topology which may lead to challenges of choosing suitable network, communication channel or data rate.

Recent related research studies on CR assisted VANET either used the channel selection [8], transmit power or rate adaptation approach within a given network [9]. However, these set of approaches are not directly applicable in heterogeneous wireless environment given that different networks demonstrate different features. In this paper, we propose a novel CR Assisted Vehicular NETwork (CRAVNET) framework through which we address three main contributions. First, in order to improve fairness in spectrum allocation among CR vehicular users (i.e., Secondary Users - SUs), we propose a light-weight cooperative three-state spectrum sensing model for vehicular environment, through which vehicles can exchange sensed information and detect spectrum holes along their paths as opposed to traditional two-state spectrum sensing model predominantly used in the literature. Secondly, with the advantage of vehicular mobility, we demonstrate how each vehicle can better exploit spectrum opportunities by using the received information to decide in advance the channel to use on future locations. Finally, we discuss how the proposed framework can be integrated into the existing protocol stacks for vehicular communication networks such as the multi-channel IEEE 802.11p protocol stack to achieve better channel utilization, high throughput, and fairness in spectrum sharing.

The remaining parts of the paper is arranged as follows. Section 2 contains the review of related studies. Section 3 introduces the proposed system model. Section III contains the detailed description of the proposed system model. Section 4 shows the back-off procedure adopted for packet(s) collision resolution through basic access mechanism. Section 5 contains the detailed description of the implemented architecture for allocation of CR vehicular SUs for optimal cooperative spectrum sensing and efficient allocation. The performance evaluation of the proposed CRAVNET framework is contained in Section 6. Finally, the conclusions and the future works are shown in Section 7.

2. Related Works

The act of spectrum sensing is one of the crucial roles in cognitive radio networks (CRNs) [10]. Generally, all the existing radio spectrum sensing solutions and algorithms are built to detect and identify the presence of a signal on a particular channel. In other words, the algorithms categorise the channels into either occupied (1) or idle (0) state. This scenario is referred to as a two-state spectrum sensing approach in this study. Although this two-state spectrum sensing method has been shown to work efficiently well if only one CRN is accessing a given channel, studies have shown that it can significantly restrict or hinder the potentials as well as the fairness of the available spectrum sharing especially if there are more than one CRN co-existing together [10-11]. This is due to the fact that, with the two-state spectrum sensing model, once CR vehicular SUs from one vehicular ad-hoc CRN sense spectrum hole and occupy the channel(s), CR vehicular SUs from other vehicular ad-hoc CRNs will falsely perceive that the channel(s) is/are occupied by licensed PU. Furthermore, the challenge of inefficient resource allocation arises as the other CR vehicular SUs will be starved and prohibited from accessing the available additional spectrum resource because the two-state model does not further check if the channel is actually occupied by a licensed PU or just another unlicensed CR vehicular SU [10-12].

Zhao *et al*. [12] in one of their studies, proposed a three-state sensing approach, which can classify the channel into three states such as occupied by a PU, idle, or occupied by a SU for multiple co-existing CRNs in an area. In another related study, Zhao *et al*. [13] considered a fair MAC protocol for co-existing CRNs. The authors proposed a novel MAC protocol, called Fairness-oriented Media Access Control (FMAC) protocol to address the issue of the availability of radio channels, provision of fair and efficient co-existence of multiple CRNs. The proposed FMAC protocol applied a three-state spectrum sensing mechanism to determine whether a busy radio channel is actually being occupied by a PU or a SU from an adjacent CRN. Thus, SUs from co-existing CRNs can conveniently share the additional available channel(s) together, thereby providing fair spectrum allocation and efficient co-existence of SUs from multiple CRNs. In another similar study, Gao *et al.* [14] investigated the effective capacity of the CRN as a significant parameter to measure the performance of cognitive radio systems (CRSs). Since the accuracy and efficiency of spectrum sensing and management schemes can critically affect the effective capacity of the CRS, the authors adopted a multi-channel CR model with each radio channel having three states such as idle (0), busy due to the activity of a PU (1), and busy due to the activity of a SU (2). Hence, each radio channel has the state space, $\mathbb{S} = \{0, 1, 2\}$.

Although the afore-referenced studies above showed impressive results (both numerical and simulation results) in terms of their ability to significantly improve the fairness in spectrum sharing and the efficiency of multiple CRNs co-existence, better channel utilization and transmission fairness amongst SUs, their proposed three-state spectrum sensing techniques were only applicable to conventional CRNs, as opposed to CR enabled vehicular ad-hoc networks which are known to have peculiar characteristics totally different from conventional CRNs. To the best of our knowledge, the only studies of three-state spectrum sensing and management model over CR enabled vehicular ad-hoc networks are the studies of Rawat *et al.* [15], and our own studies in [10-11]. However, the study in [15] does not show much details as the paper only presents few results generated from simulation without detailed theoretical analyses to support the simulation results.

3. System Model

We considered a cognitive network scenario of two-lane highway with two opposite vehicular movements. In the scenario depicted in Fig. 1, we used the concept of cognitive cells (CCs) which is made up of $\mathbb{N}$ number of cognitive road-side base stations (CRBS) and $\mathbb{R}$ number of CR vehicular SUs. Specifically, within a given CC, each CRBS effectively receives data from CR vehicular SUs and schedules them for efficient spectrum sensing. It is assumed that CR vehicular SUs are aware of their current location with the help of in-built Global Positioning System (GPS) receiver. It is also assumed that the road length L_R of the CC which a vehicle belongs to is partitioned into a number of blocks B of equal length d, which should be the minimum safety distance for two adjacent moving vehicles. Each road partition B can be uniquely identified through a marked road *couple*, $\langle R_{id}, B_{id}\rangle$, where R_{id} and B_{id} represent the identification coordinate of both the road R and its various partitions B, respectively. Additionally, we assumed that this identification information is incorporated into the digital road maps which the vehicles can easily obtain from the neighbouring road-side unit (RSU) to enable every vehicle to know their current road R_c and partition B_c at every point in time while on transit. We implemented this concept by creating a reference point on the road for all the mobile nodes of the scenario and assign a unique and progressive identification number to each road and its accompanying partitioned blocks B. The notation table in Table 1 presents the list of main variables.

The PU's spectrum band is divided into N non-overlapping data channels, and all channels are under

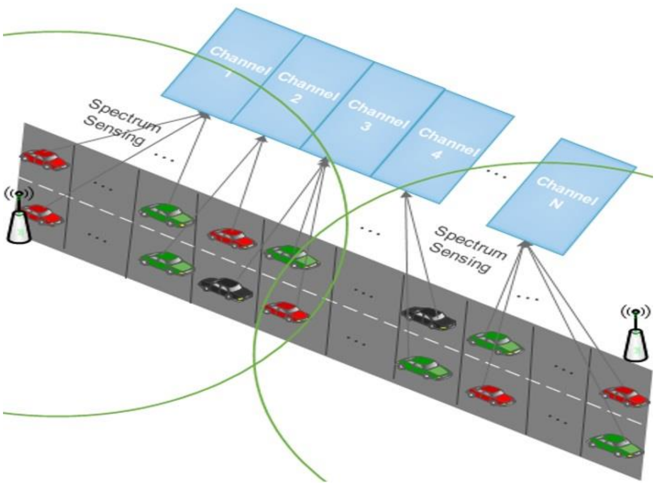

Fig. 1. *Illustration of cooperative spectrum sensing and sharing for cognitive radio assisted vehicular networks.*

Nagakami multi-path propagation fading. Though, the theoretical analyses of CRAVNET scheme applies to either low-pass (LP) or band-pass (BP) system, the objective of CRAVNET scheme spectrum sensing is to ascertain and decide between the following three hypotheses

$$r_{ij}(t) = \begin{cases} \Re_0\left\{[\mathbb{WG}_{LP}(t)]e^{j2\pi f_*^i}\right\}, & H_0 \\ \Re_{pu}\left\{[h_c\mathbb{S}_{LP}(t) + \mathbb{WG}_{LP}(t)]e^{j2\pi f_*^i}\right\}, & H_1 \\ \Re_{su}\left\{[h_c\mathbb{S}_{LP}(t) + \mathbb{WG}_{LP}(t)]e^{j2\pi f_{su}^i}\right\}, & H_2 \end{cases} \quad (1)$$

where $r_{ij}(t)$ is the signal received by the j^{th} CR vehicular SU in the i^{th} channel, with $i = 1, 2, 3, \ldots, N$ and $j = 1, 2, 3, \ldots, \mathbb{R}$. $\Re_0$, $\Re_{pu}$, and $\Re_{su}$ denote the absence of any signal transmission (i.e., the presence of spectrum holes), the signal transmitted by PU transmitter, and the signal transmitted by a CR vehicular SU transmitter, respectively. $\Re_*\{\cdot\}$ signifies the real part of a complex value operation, $h_c = \alpha e^{j\theta}$ is a slow fading channel with amplitude α and phase θ (i.e. the channel impulse response), $\mathbb{S}_{LP} = j\mathbb{S}_s(t) + \mathbb{S}_c(t)$ refers to an equivalent LP representation of the unknown signal with $\mathbb{S}_s(t)$ and $\mathbb{S}_c(t)$ signifying the quadrature (Q) and in-phase (I) components, respectively. $\mathbb{WG}_{LP}$ represents an equivalent LP representation of both the DTV and ATV signals, and an Additive White Gaussian Noise (AWGN) process with a zero mean and a known power spectral density (PSD). f_*^i refers to the feature carrier frequency with $*$ indicating the type of signal. For instance, when $* = atv$, f_{atv}^i is the signal pilot carrier frequency of ATV signal on C_i, when $* = dtv$, f_{dtv}^i is the video signal carrier frequency of DTV signals on C_i, when $* = wm$, f_{wm}^i is the wireless microphone operational signal carrier frequencies, and finally when $* = 2$, f_2^i is a SU signal pilot carrier frequency if a CR vehicles' pilot signal is used for the energy detection process.

At each CR vehicular SU, energy detector which is a simple and effective method used for the detection of unknown signals is employed to determine whether the PU is active or idle. Each received signal is fed to a BP filter of the energy detector with the bandwidth of interest (W) and the center frequency (f_c). Then, a squaring device and an integrator are used to measure the received energy and to determine the observation interval (T), respectively. When the result of spectrum sensing shows that the channel is busy, CRAVNET Scheme uses a further sensing algorithm to determine whether the busy channel is as a result of PU activity or another CR vehicular SU activity probably from another CRN. This further sensing algorithm involves the use of a two-stage detection technology as described in [16]. While the first stage of energy detection distinguishes whether a channel is busy or idle, the second stage of energy detection is used when the channel is busy to further analyse the received signal based on a distance estimation technique to distinguish whether the spectrum channel is actually occupied by a PU (H_1) or by another CR vehicular SU (H_1). Consequently, with this sensing technology approach, CR vehicular SUs can determine the state of a spectrum channel to be either H_0, H_1, or H_2. Hence, using the Nyquist theorem, a given signal should have samples $X \geq 2TW$. With the application of an ideal BP filter to pre-filter the received signal, given the observed signal $r_{ij}(t)$, for $0 \leq t \leq T$, the output of the integrator denoted by x_{ij} acts as a test statistic to test H_0, H_1 and H_2 hypotheses. Therefore, with respect to the employed sampling theorem approximation [17], and assuming a narrowband signal over H_1, x_{ij} can be represented as

$$x_{ij} \stackrel{\text{def}}{=} \frac{2}{N_0} \int_0^T r_{ij}^2(t)dt \qquad (2)$$

where N_0 denotes the one-sided noise PSD. Given that x_{ij} is a random variable with a chi-square (χ^2) distribution, the test statistics can be expressed as

$$x_{iJ} \cong \frac{1}{N_0 W} \left\{ \sum_{i=1}^{N/2} [(\alpha_c \mathbb{S}_{ci} - \alpha_s \mathbb{S}_{si} + \mathbb{WG}_{ci})^2] + \sum_{i=1}^{N/2} [(\alpha_c \mathbb{S}_{si} + \alpha_s \mathbb{S}_{ci} + \mathbb{WG}_{si})^2] \right\} \qquad (3)$$

where W denotes the signal bandwidth (i.e., the positive spectrum support), $N_0 W$ is the channel noise variance, $N/2$ denotes the number of samples per either in-phase and quadrature components, $\alpha_c = \alpha \cos\theta$, $\alpha_s = \alpha \sin\theta$, whereas $\mathbb{S}_{ci}/\mathbb{S}_{si}$ and $\mathbb{WG}_{ci}/\mathbb{WG}_{si}$ represent the i^{th} samples of the in-phase, ($\mathbb{S}_c(t)$ / $\mathbb{WG}_c(t)$) and quadrature, ($\mathbb{S}_s(t)$ / $\mathbb{WG}_s(t)$), respectively. Then, without loss of generality, it follows that x_{ij} will be central and non-central chi-square distributed under H_0, H_1 and H_2, respectively. Although x_{ij} has a chi-square distribution [18], it is asymptotically normally distributed if X is large enough [19]. Hence, the probability density function (PDF) of x_{ij} can be expressed as [18] and [9]

$$f(x_{ij}) \stackrel{\text{def}}{=} \begin{cases} \frac{1}{\beta^N 2^{N/2} \Gamma(N/2)} x_i^{(N/2)-1} f_*^i(e)^{-\frac{x_i}{2\beta^2}} & H_0 \\ \frac{1}{2}\beta^2 (x_i)^{\frac{N-2}{4}} f_*^i(e)^{-\frac{(x_i/2\omega)}{2\beta^2}} \left(\frac{\sqrt{x_i 2\omega}}{\beta^2}\right) I_{(N/2)-1} & H_1 \\ \frac{1}{2}\beta^2 (x_i)^{\frac{N-2}{4}} f_{su}^i(e)^{-\frac{(x_i/2\omega)}{2\beta^2}} \left(\frac{\sqrt{x_i 2\omega}}{\beta^2}\right) I_{(N/2)-1} & H_2 \end{cases} \qquad (4)$$

where β denotes the chi-square distribution variance, N represents degrees of freedom (DOF), $\Gamma(\cdot)$ denotes the Gamma function, ω refers to the instantaneous signal-to-noise ratio (SNR), and $I(\cdot)$ refers to the i^{th} first order modified Bessel function. In practice, Liang *et al* [20] has demonstrated that T must be large enough to guarantee low probability of a false alarm P_{fa}, and a high probability of miss-detection P_{md} (see Fig. 2). However, large observation interval T cannot satisfy the requirement of fast spectrum opportunity sensing and acquisition especially in CR enabled vehicular networks which is characterized by high mobility. Consequently, we developed a novel adaptive cooperative spectrum sensing model to ensure efficient acquisition of spectrum resource opportunities within a limited sensing time. We adopted a slot-based spectrum sensing technique, where one CR vehicular SU provides one observation on a certain channel in each slot, so that the total number of observations is equal to the total number of CR vehicular SUs that sense channels in each slot. Therefore, the main challenge to be solved is how to determine the number of CR vehicular SUs that should cooperate to detect the signals on channel i in each slot, $i = 1, 2, \ldots, N$.

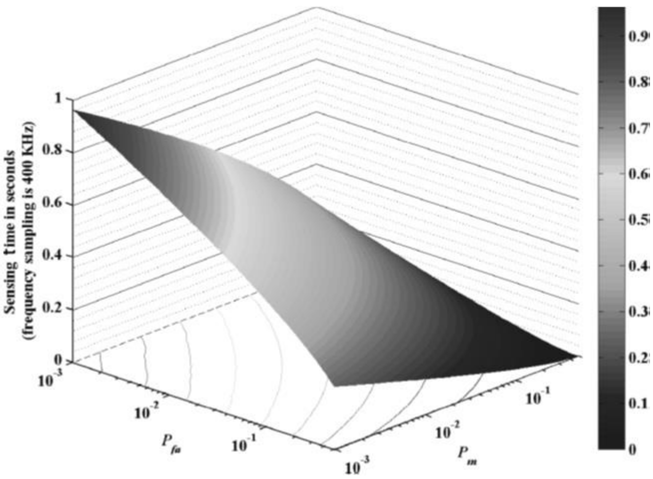

Fig. 2. *Trade-off between spectrum sensing time and detection performance.*

Based on this developed three-state spectrum sensing model, CR vehicular SUs take different actions depending on whether the outcome of the sensing and detection exercise is H_0, H_1, or H_2. When a channel is actually occupied by a licensed PU (H_1), CR vehicular SU are carefully prohibited from transmitting in such channel to avoid interference. However, a CR vehicular SU can transmit on any given channel of the PU network that is found to be idle (H_0). Likewise, if a channel is not idle (H_0), and not occupied by a licensed PU (H_1), but by a CR vehicular SU (H_2), in which case, other CR vehicular SUs are allowed to stay and contend for the channel access. When the outcome of test hypotheses is H_2 (which means that there is a presence of a spectrum resources but been used by another CR vehicular SU), any of the already existing media access control (MAC) schemes such as CSMA/CD, CSMA/CA, TDMA, FDMA, etc, can be adopted for a hitch-free access to avoid collision and improve the reliability of message broadcast in the CR vehicular secondary networks. In CRAVNET, CSMA/CA mechanism is used by CR vehicular SUs for the available channel access contention. If there occurs a collision in the process of contending for channel access, the IEEE 802.11 back-off procedure and retransmission rules are applied for collision resolution as discussed in Section IV.

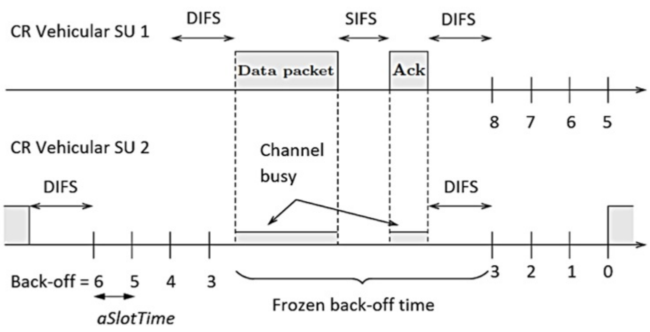

Fig. 3. A typical back-off procedure for a basic access (BA) mechanism.

4. Packet(s) Collision Resolution Through Basic Access Mechanism

If there occurs a collision in the process of contending for channel access, the legacy IEEE 802.11 back-off procedure and retransmission rules are applied for collision resolution. The proposed scheme is for CR-enabled ad-hoc networks which comprises of a number of CR Vehicular SUs communicating over a shared radio channel in a peer-to-peer fashion, without a centralized MAC protocol arbitrating requests to transmit on the wireless radio channel. Hence, the primary aim of MAC protocols for ad-hoc networks such as CR-enabled VANET is to prevent packet collision, which occurs when there are simultaneous packets transmissions on a shared channel. Although, according to the specification of the legacy IEEE 802.11 standard, each CR Vehicular SU that has packet(s) to send must monitor the shared channel prior to transmitting the packet(s), else collisions can ensue if two or more nodes are simultaneously transmitting. The adopted IEEE 802.11 standard, based on a CSMA/CA scheme, defines a Distributed Coordination Function (DCF) for this purpose. The DCF has an important feature such as the application of a randomized, slotted exponential back-off procedure, designed to break the symmetry between nodes that are retransmitting previously failed transmissions due to collision.

When the shared channel is sensed busy (i.e., the channel is not free for a duration given by the DCF Interfame Space (DIFS), the length of which depends on the physical layer), the sending CR vehicular SU enters the back-off procedure. Furthermore, there is a random choice of back-off value, that specifies the number of time periods called *slots* that must be passed through before the CR vehicular SU can begin packet transmission. The duration of each slot is given by *aSlotTime*. The duration of the *aSlotTime* is given by the sum of (i) the time taken for a CR vehicular SU to assess the shared channel and deliver its state to the MAC layer, (ii) the time taken for the receiving CR vehicular SU to switch from a receiving to a transmitting state, and (iii) the air propagation time. The back-off value will be decremented by 1 when the shared channel is sensed idle for an *aSlotTime*. However, upon detecting a transmission, the back-off value decrementing procedure will be temporarily suspended to be resumed only after the shared channel is detected idle for a DIFS. Finally, the CR vehicular SU can begin its packet(s) transmission when the back-off value reaches 0. Fig. 3 illustrates a typical back-off procedure for a BA mechanism based CSMA/CA.

Fig. 3 shows how the back-off value of CR vehicular SU 2 is frozen if the wireless channel is busy (i.e., when the packet transmission and the corresponding acknowledgement (ACK) are sent, as well as during the Short Interframe Space[1] (SIFS) that separates these transmissions. The figure also shows that the back-off count-down gets frozen during SIFS because of the timing parameters of the legacy 802.11 standard which specifies that SIFS < DIFS, and that the shared channel must be sensed idle for a DIFS before the back-off count-down can be resumed. Thus, the implementation of random selection of back-off value follows a uniform distribution over integers within the contention window (CW) range (i.e., [0, CW]). The CW is given by $CW = (2^{bc} - 1) \times (aCW_{min} + 1)$, where bc denotes a variable referred to as the back-off counter[2], and the value aCW_{min} is a constant determined by the physical layer (PHY). The back-off counter can increase to a ceiling determined by the maximum back-off (MAX BACK-OFF) counter, which is a constant usually given by the PHY.

5. Allocation of CR Vehicular SUs for Optimal Spectrum Sensing and Acquisition

Guaranteed timely acquisition of the available channels within a limited sensing time will significantly improve the efficiency of the developed three-state spectrum sensing model. This can be achieved by carefully assigning an appropriate number of CR vehicular SUs to sense channels in each slot so that the available channels are acquired before the k^{th} sloth, where $k = 1, 2, 3, \dots, \infty$. Let $\mathbb{V}_a$ represent the assignment vector in the N non-overlapping available channels, $C_i | i = 1, 2, 3, \dots, N$, $1 \le a \le k$. Now, let the intended number of available channels to be acquired until the k^{th} sloth under the assignment vectors, $\mathbb{V}_1, \mathbb{V}_2, \dots, \mathbb{V}_k$ be denoted as $N_{k,Avail}$. Consequently, we aim to obtain an optimal assignment set, $\mathbb{V}^{\alpha} = [\mathbb{V}_1, \mathbb{V}_2, \dots, \mathbb{V}_k]$, such that the corresponding $N_{k,Avail}^{\alpha}$ becomes optimal, which means that $\forall\, \mathbb{V}^{\beta} \neq \mathbb{V}^{\alpha}$, $N_{k,Avail}^{\beta} < N_{k,Avail}^{\alpha}$. However, the a^{th} column

[1] The SIFS is the time period the legacy 802.11 standard specifies that a destination CR vehicular SU must wait after successfully receiving a transmission.

[2] The back-off counter denotes the number of unsuccessful retransmissions of the pending data packet that have been made (therefore bc is initially 0).

vector (i.e. the assignment vector in a^{th} slot) in the $\mathbb{V}^{\alpha}$ is largely dependent on past spectrum sensing observation results, which in turn, relies on assignment vectors in slots $1, 2, 3, \ldots, (a-1)$. Apparently, the optimal assignment matrix cannot be achieved directly since there are correlations between the columns in $\mathbb{V}^{\alpha}$. Therefore, the optimal assignment matrix can be obtained slot-by-slot base on past spectrum sensing observation results.

Obviously, $N_{1,Avail}^{\alpha} = n_{1,Avail}^{\alpha}$ when $k = 1$, and $N_{a,Avail}^{\alpha} = n_{a,Avail}^{\alpha} + N_{(a-1),Avail}^{\alpha}$ when $k > 1$, where $n_{a,Avail}^{\alpha}$ represents the expected optimal number of available channels acquired in a^{th} sloth. Given that $N_{(a-1),Avail}^{\alpha}$ has been obtained and fixed in the a^{th}, we seek to maximize $n_{a,Avail}^{\alpha}$ in the slot a^{th} rather than $N_{a,Avail}^{\alpha}$. For the sake of brevity, the index a is ignored in the following. Hence, the expected optimal number of available channels acquired in the slot a^{th} sloth, n_{Avail} is given by

$$n_{Avail} = \sum_{i=1}^{N} P_i(V_i, i) \tag{5}$$

where $P_i(V_i, i)$ denotes the probability that channel i is available when CR vehicular SUs V_i sense channel i. Finally, we formulate the problem into an optimization problem given as

$$\max_{\mathbb{V}} \sum_{i=1}^{N} P_i(V_i, i) \tag{6}$$

Subject to

$$(i) \quad \sum_{i=1}^{N} V_i \leq \mathbb{R}$$

$$(ii) \quad 0 \leq V_i \leq \mathbb{R}$$

where $\mathbb{V} = \{V_1, \ldots, V_i, \ldots, V_N\}$. Obviously, this is a finite state variable optimization problem, which means that the optimal solution can only be obtained when $N^{\mathbb{R}}$ possible $\mathbb{V}$ which satisfy Eq. (6) have been searched. Unfortunately, assuming that the computation of $\sum_{i=1}^{N} P_i(V_i, i)$ for one $\mathbb{V}$ has the complexity of $O(1)$, then the complexity of searching $N^{\mathbb{R}}$ possible $\mathbb{V}$ will be $O(N^{\mathbb{R}})$. On the contrary, the optimal solution of the optimization problem can be obtained based on dynamic programming theory with low complexity based on the principle of optimality [21]. In fact, dynamic programming with the Viterbi algorithm avoids an exhaustive search thereby making it possible to obtain an optimal solution with very low complexity.

In order to solve the optimization problem in Eq. (6) based on dynamic programming theory, we define a variable Z_i, which represents the total number of the CR vehicular SUs that senses channels $i, i+1, \ldots, N$ and establish the dynamic programming formulation using the relationship

$$\begin{cases} Z_{i+1} = Z_i - V_i \\ V_i = \mathbb{R} \end{cases} . \tag{7}$$

Additionally, we denote the optimal solution when Z_i CR vehicular SUs sense channels $i, i+1, \ldots, N$ as $K[Z_i, i]$ and the corresponding optimal assignment vector as $V_{i,Z_i} = \{V_{i,Z_i}, V_{(i+1),Z_i}, \ldots, V_{N,Z_i}\}$. Then, we obtained the resulting recursive equation

$$\begin{aligned} K[Z_i, i] &= \max_{V_i, V_{(i+1)}, \ldots, V_N} \sum_{j=i}^{N} P_j(V_j, j) \\ &= \max_{V_i, V_{(i+1)}, \ldots, V_N} \left[P_i(V_i, i) + \sum_{j=i+1}^{N} P_j(V_j, j) \right] \\ &= \max_{V_i} \left[\max_{V_{(i+1)}, \ldots, V_N} \left(P_i(V_i, i) + \sum_{j=i+1}^{N} P_j(V_j, j) \right) \right] \\ &= \max_{V_i} \left[P_i(V_i, i) + \max_{V_{(i+1)}, \ldots, V_N} \left(\sum_{j=i+1}^{N} P_j(V_j, j) \right) \right] \\ &= \max_{V_i} [P_i(V_i, i) + K(Z_{i+1}, i+1)] \\ &= \max_{V_i} [P_i(V_i, i) + K(Z_i - V_i, i+1)] \end{aligned} \tag{8}$$

$$\mathbb{V}_{i,Z_i} = \arg \max_{V_i, V_{(i+1)}, \ldots, V_N} \sum_{j=i}^{N} P_j(V_j, j) \tag{9}$$

where the boundary conditions are

$$\begin{cases} V_N \leq Z_i \\ K(Z_N, N) = \max_{V_N = [0,1,2,\ldots,V_N]} [P_N(V_N, N)] \end{cases} \tag{10}$$

Finally, in order to solve the optimization problem in Eq. (6), we simply find $K(Z_1, 1)$ and $\mathbb{V}_{1,Z_1}$ which can easily be obtained by applying the recursive equation in Eq. (8). Furthermore, to find $K(Z_i, i)$ and $\mathbb{V}_{i,Z_i} | \, i = 2, \ldots, N$, $[(\mathbb{R}+1) * (\mathbb{R}+2)]/2$, feasible Z_i and V_i are searched. Owing to the relationship, $Z_i \geq V_i$, the search for Z_i and V_i starts from zero to $\mathbb{R}$ and from zero to Z_i, respectively. Therefore, the optimal solution has a low linear complexity of $O(\mathbb{R}^2 N)$ given that $K(Z_1, 1)$ and $\mathbb{V}_{1,Z_1}$ are obtained by searching $\mathbb{R}+1$ feasible Z_i and V_i since V_i is searched from zero to $\mathbb{R}$ because $Z_i = \mathbb{R}$. Table 2 below shows the pseudo-code followed to obtain the optimal solution based on dynamic programming.

The forward recursion of the algorithm can be described as follows:

a) Set $i = 1 : N$. For initial number of available non-overlapping channels
b) If the number of available non-overlapping channels is N $(i = N)$, then
c) when the total number of the CR vehicular SUs that senses channels $i, \ldots, N$ is between $0 : \mathbb{R}$,
d) Find the optimal solution by calculating the probability that channel N is available when CR vehicular SUs V_N sense channels using $K(Z_N, N) = \max_{V_N = 0, \ldots, Z_N} [P_N(V_N, N)]$, and

e) The corresponding optimal assignment vector using $V_{N,Z_N} = \arg\max_{V_N=0,\dots,Z_N} [P_N(V_N, N)]$
f) Else if the number of available non-overlapping channel is more than one but less than N then,
g) Set the total number of the CR vehicular SUs that senses channels $i, \dots, N$ is between $0 : \mathbb{R}$, and
h) Find the optimal solution by calculating the probability that channel N is available when CR vehicular SUs V_N sense channels using $K(Z_i, i) = \max_{V_i=0,\dots,Z_i} \left[P_i(V_i, i) + \left(K(Z_i - V_i), (i+1)\right)\right]$, and
i) The corresponding optimal assignment vector using $V_{i,Z_i} = \arg\max_{V_i=0,\dots,Z_i} \left[P_i(V_i, i) + \left(K(Z_i - V_i), (i+1)\right)\right]$.
j) Else if there is only one available channel for the CR vehicular SUs V_1 to sense, then
k) Find the optimal solution by calculating the probability that the channel is available when CR vehicular SUs V_1 senses the channel using $K(Z_1, 1) = \max_{V_1=0,\dots,M} [P_1(V_1, 1) + K(Z_2, 2)]$, and
l) The corresponding optimal assignment vector using $V_{1,Z_1} = \arg\max_{V_1=0,\dots,M} [P_1(V_1, 1) + K(Z_2, 2)]$. Then, the forward recursion is finished.

Table 2 Pseudo-code to Find the Optimal Solution

Algorithm 1: The pseudo-code used to find the optimal solution based on dynamic programming.

Procedure:

Input: maximization of the expected optimal number of the available channels acquired in a^{th} sloth

Output: Obtained optimal solution after the recursive equation in (8)

Initialization

For $i = 1 : N$
  If $i = N$
    For $Z_N = 0 : \mathbb{R}$
      $K(Z_N, N) = \max_{V_N=0,\dots,Z_N} [P_N(V_N, N)]$
      $V_{N,Z_N} = \arg\max_{V_N=0,\dots,Z_N} [P_N(V_N, N)]$
      $\mathbb{V}_{i,Z_i} = [V_{N,Z_N}]$
    End For
  Else If $1 < i < N$
    For $Z_N = 0 : \mathbb{R}$
      $K(Z_i, i) = \max_{V_i=0,\dots,Z_i} \left[P_i(V_i, i) + \left(K(Z_i - V_i), (i+1)\right)\right]$
      $V_{i,Z_i} = \arg\max_{V_i=0,\dots,Z_i} \left[P_i(V_i, i) + \left(K(Z_i - V_i), (i+1)\right)\right]$
      $\mathbb{V}_{i,Z_i} = \left[V_{i,Z_i}, \mathbb{V}_{[(i+1),(Z_i - V_{i,Z_i})]}\right]$
    End For
  Else If $i = 1$
    $K(Z_1, 1) = \max_{V_1=0,\dots,M} [P_1(V_1, 1) + K(Z_2, 2)]$
    $V_{1,Z_1} = \arg\max_{V_1=0,\dots,M} [P_1(V_1, 1) + K(Z_2, 2)]$
    $\mathbb{V}_{1,Z_1} = \left[V_{1,Z_1}, \mathbb{V}_{2,(Z_i - V_{i,Z_i})}\right]$
  End If
End For

5.1. Spectrum Holes Availability Table (SHAT)

CRAVNET framework maintains the received results of the cooperative spectrum sensing activity in SHAT, which has the following components in this particular format as given below:

$$\left\langle B \in L_R, f \in N, \overline{P_{B,f}}, n_{B,f}, O_{B,f} \right\rangle \tag{11}$$

where $B \in L_R$ denotes the particular block partition of the road length L_R of the current motor highway cognitive cell of the CR vehicular SU; $f \in N$ refers to either DTV, ATV, or wireless microphones licensed channel; $\overline{P_{B,f}}$ represents the average power (dBm) measured in the block B and channel f of the PU network; $n_{B,f}$ denotes the number of the collected native and public spectrum sensing samples which were averaged in the current estimation of $\overline{P_{B,f}}$; and $O_{B,f}$ refers to the vehicles which produced $n_{B,f}$ spectrum sensing samples for B and f. Accordingly, as each CR vehicular SU continues in movement, the content of the spectrum holes availability table is dynamically updated, and entries of B and f belonging to L_R that are outside the communication range and in the opposite direction of movement of the node are automatically deleted and replaced with B_c and f_c (i.e., the current block partitions and available channels) towards the vehicles' direction of movement. This process aids the reduction of the communication overheads and the amount of memory required to efficiently maintain the spectrum holes availability table.

5.2. Sensed Spectrum Data Aggregation

The CR vehicular secondary network under consideration in CRAVNET framework consists of randomly deployed CR vehicular SUs, labelled as $S_1, S_2, S_3, \dots, S_n$, and sparsely placed RSUs denoted as $RS_1, RS_2, RS_3, \dots, RS_n$, which also collect aggregated information of sensed spectrum data from the CR vehicular secondary network. Each CR vehicular SU broadcasts a *SENSED DATA* message on the CCH which includes the contents of its spectrum holes availability table in every T_b intervals when there are neighbouring stations with a connected logical links. A logical link exists between two SUs, S_i and S_j if and only if the Euclidean Distance between S_i and S_j which is denoted by $\|S_i - S_j\| \le r$ (where r is the transmission radius of a single or half-duplex CR communication equipment), and the secondary network represented by $Q = (S, \mathbb{E}_l)$ (where $S = \{S_1, S_2, S_3, \dots, S_n\}$ is the union of all the CR vehicular SUs, and $\mathbb{E}_l$ denotes the set of logical links existing between all the neighbouring CR vehicular SUs). When S_i receives a *SENSED DATA* packets from S_j that is within its radio transmission coverage, S_i updates the entries corresponding to block partitions in its direction of movement along L_R. Due to the spectrum sensing constraints occasioned by the limited range of radio communication, the CR vehicular SU can only sense at most N channels, which means the size of $R_i(t)$ (i.e., a set of channels available for sensing) is no more than N, (i.e., $|R_i(t)| \leq N$) and aggregates its native and the received *SENSED DATA* within CR range. Following the defined secondary network model, the aggregation of sensed spectrum data can be formalized and defined as $\mathbb{A}_t = \{\mathbb{A}_1, \mathbb{A}_2, \mathbb{A}_3, \ldots, \mathbb{A}_N\}$, a set of aggregated *SENSED DATA* from the sensed PU network channels, where $\mathbb{A}_t | (1 \leq t \leq N)$ contains the shared *SENSED DATA* packets amongst CR vehicular SU scheduled at t. Furthermore, a constraint $\forall t_i, \forall t_j \mid (1 \leq t_i,\, t_j \leq N, t_i \neq t_j)$ is applied to achieve efficient data aggregation by ensuring that each CR vehicular SU sends its aggregation result only once.

5.3. Spectrum Data Sharing Log

Each CR vehicular SU can determine the presence of additional spectrum resources in the current and future $B \in L_R$ along its direction of movement with the help of the contents of its spectrum hole availability table. The Spectrum Data Sharing Log (SDSL) is an $\mathcal{K} \times \mathcal{K} \times \mathcal{L}$ 3-dimensional (3-D) binary matrix containing $\mathcal{M}_{\ell k,\bar{\ell k}\ell}$, where $\ell k, \bar{\ell k} = 1, 2, 3, \cdots, \mathcal{K}$, and $\ell = 1, 2, 3, \cdots, \mathcal{L}$. In other words, when CR vehicular SUs established the presence of spectrum hole in the current and future $B \in L_R$ along their direction of movement, the SDSL is used to identify whether the sharing of a given channel by two or more vehicles in the current slot can result in harmful interference or not. For instance, if two CR vehicular SUs, $\mathcal{V}_{\ell k}$, and $\mathcal{V}_{\bar{\ell k}}$ say, share very close proximity, then their sharing of the same free primary channels $\mathcal{C}_n$ where $n = 1, 2, 3, \cdots, N$ will certainly result in harmful interference to one another. Hence, in order to avoid harmful interference amongst $\mathcal{V}_{\ell k}$, and $\mathcal{V}_{\bar{\ell k}}$ on $\mathcal{C}_n$, the three vehicles must not share that same channel in the current slot. Additionally, under spectral resource sharing system, the aggregated interference to the licensed PU must be put into consideration. Given that the received power is directly proportional to $d^{-\eta}$ (where d denotes the distance from the source CR vehicular SU to the destination, and η represents the path loss exponent, with $\eta = 2{\sim}4$ and $\eta = 2$ only if free space is used) when a fixed transmission power is applied. In our study, the aggregated interference is constrained by first constraining the main interference (or individual interferences from the participating CR vehicular SUs), and then ensure that the CR vehicular SUs that share the same $\mathcal{C}_n$ in the current slot do not have the same distance from the PU that owns the free (or idle) channel.

Then, let $\mathcal{M}_{\ell k,\bar{\ell k}\ell} = 0$ denotes a condition where the two CR vehicular SUs $\mathcal{V}_{\ell k}$, and $\mathcal{V}_{\bar{\ell k}}$ can successfully share $\mathcal{C}_n$ without causing harmful interference to one another, and $\mathcal{M}_{\ell k,\bar{\ell k}\ell} = 1$ denotes a condition where the two CR vehicular SUs $\mathcal{V}_{\ell k}$, and $\mathcal{V}_{\bar{\ell k}}$ cannot successfully share $\mathcal{C}_n$ without causing harmful interference to one another. Thus, the SDSL can be obtained using

$$\mathcal{M}_{\ell k,\bar{\ell k}\ell} = \begin{cases} 1, & \delta_1^{\ell k} + \delta_2^{\bar{\ell k}} > d_{\ell k,\bar{\ell k}} \ or\ \delta_1^{\bar{\ell k}} + \delta_2^{\ell k} > d_{\ell k,\bar{\ell k}} \\ & or \left| d_{\bar{\ell k},\mathcal{C}_n} - d_{\ell k,\mathcal{C}_n} \right| < d_t, \ell k \neq \bar{\ell k} \\ 0, & else \end{cases} \tag{12}$$

where $\delta_1^{\ell k}$ and $\delta_2^{\bar{\ell k}}$ denote the communication range of the ℓk^{th} CR vehicular SU and the interference range (to the neighboring CR vehicular SUs) of the ℓk^{th} CR vehicular SU, respectively. $d_{\ell k,\bar{\ell k}}$ represents the difference in distance existing between the ℓk^{th} CR vehicular SU and the $\bar{\ell k}^{th}$ CR vehicular SU. Apparently, $\mathcal{M}_{\ell k,\bar{\ell k},\ell} = \mathcal{M}_{\bar{\ell k},\ell k,\ell}$, and $\delta_1^{\ell k} + \delta_2^{\bar{\ell k}} > d_{\ell k,\bar{\ell k}}$ or $\delta_1^{\bar{\ell k}} + \delta_2^{\ell k} > d_{\ell k,\bar{\ell k}}$ indicates that the ℓk^{th} CR vehicular SU and the $\bar{\ell k}^{th}$ CR vehicular SU are too close, hence cannot share the same channel in the current slot. $d_{\bar{\ell k},\mathcal{C}_n}$ denotes the distance between the $\bar{\ell k}^{th}$ CR vehicular SU and the PU, and $d_{\ell k,\mathcal{C}_n}$ denotes the distance between the ℓk^{th} CR vehicular SU and the PU. d_t represents the distance threshold (or minimum distance that must exist between two CR vehicular SUs) to avoid harmful aggregated interference.

5.4. Evaluation Metrics

We adopted the under mentioned evaluation metrics, in addition to the metrics used in [10] to evaluate the performance of our theoretical analyses as well as the simulation experiments:

- The average *probability of detection*, P_d in the case of Nakagami channels can be expressed as

$$P_d = \eta \int_0^\infty x^{2m-1}\, e\left(-\frac{mx^2}{2\Upsilon}\right) \mathbb{Q}u\left(x, \sqrt{\delta}\right) dx, \Upsilon \geq 0 \quad (13),$$

where

$$\eta = \frac{1}{\Gamma(m) 2^{(m-1)}} \left(\frac{m}{\Upsilon}\right)^m \tag{14}$$

m denotes the Nakagami-m fading parameter, which describes the severity of fading, with $m < 1$ indicating severe fading, and $m > 1$ signifying less severe fading, Υ represents the PDF of the instantaneous SNR at the receiver node, and $\mathbb{Q}u(\cdot)$ is the generalized Marcum-Q function. Hence, solving the integral in Eq. (14) according to [11] results to a closed form expression of the P_d in Nakagami channels as:

$$P_d = \eta \left[\mathcal{F}_1 + \eta \sum_{n=1}^{d-1} \frac{\left(\delta/_2\right)}{2(n!)} \mathcal{C}_1 \left[\left(\left(\frac{\Upsilon}{m+\Upsilon} \right) \left(\frac{\delta}{2} \right) \right); n + 1; m \right] \right] \quad (15),$$

where $\mathcal{C}_1(.;.;.)$ denotes the confluent hypergeometric function, while the representations of η is given as $\eta = \Gamma(m)\left(\frac{2\Upsilon}{m+\Upsilon}\right)^m . e^{-\left(\frac{\Upsilon}{2}\right)}$ and solution of $\mathcal{F}_1$ is given by the equation $\mathcal{F}_1 = \int_0^\infty x^{2m-1}\, e\left(-\frac{mx^2}{2\Upsilon}\right) dx.$

- *Probability of Miss Detection*, P_m which complements the probability of spectral resource detection is measured by the use of receiver operating characteristics (ROC) curves as a function of the false alarm probability. It is simply expressed as

$$P_m = 1 - P_d \tag{16}$$

- *Jain Fairness Index*, $J(t)$ which is used to determine the overall level of fairness in spectral resource allocation among the participating CR vehicular SUs within the secondary network is expressed below as

$$J(t) = \left(\sum_{i=1}^{N} T_i(t)\right)^2 \Big/ \left(N \cdot \sum_{i=1}^{N} T_i^2(t)\right) \tag{17}$$

where $T_i(t)$ is the transmission time for the i^{th} CR vehicular SU during the period of time t. Note that the value of $J(t)$ ranges from 0 to 1. It follows that the higher the Jain Fairness Index the better the spectrum resource sharing/allocation fairness among the CR vehicular SUs. In ideal case, the value of $J(t)$, should be equal to 1.

- *Probability of Spectrum Sensing Conflict*, $P_{conflict}$ which is the relationship between the number of available common channels N_{Com} sensed by more than one CR vehicular SU to the total number of available channels C_i sensed by the same set of CR vehicular SUs. Hence, it is expressed as

$$P_{conflict} = N_{com} \Big/ \left(\sum_{i=1}^{n} C_i\right) \tag{18}.$$

6. Performance Evaluation

In this section, we discuss the performance evaluation of CRAVNET framework. In Subsection 6.1, we provide the model simulation parameters and performance metrics, and in Subsection 6.2, we show the discussion of the performance evaluation results.

Table 3 Performance of the Schemes

Scheme	**Description**
Benchmark (reference scheme)	Performance of the conventional two-state spectrum sensing and sharing approach in [9].
CRAVNET (Theoretical Analysis)	Theoretical performance of the proposed CRAVNET scheme through numerical calculation with (15), (16), (17), and (18).
CRAVNET (Simulation)	Performance evaluated in simulation, under the assumption that the CR vehicular SUs have *a priori* knowledge of the PU inactive period distribution

6.1. *Simulation Parameters*

We consider a multi-lane highway scenario of 15 km length divided into multiple block partitions $B \in L_R$ of equal lengths $d = 100m$. We consider a Nagakami multi-path propagation model to enable us to consider the impact of fading on PU sensing activity with the CR vehicular SUs speed randomly distributed in the range of the discrete set $v = \{(30 + 10 * i)m/s, \forall i \in [0:5]\}$ and equipped with an IEEE 802.11p radio transceiver. In the simulation, the number of licensed PU channels are assumed to be eight (8) independent channels (i.e., $N = 8$), each with radio bandwidth $bw = 10$ (MHz) with number of time slots $T = 30$ and the number of samples $M = 10$. Additionally, the channel transition probabilities P^{01} and P^{11} $\{P^{01} = 0.2, P^{11} = 0.8\}$ are also assumed. Without loss of generality, a static PU case is considered, where the PUs are always active. Eight (8) PUs transmitting up to 1 Km of distance are randomly deployed in the current scenario and located at the edge of the highways, so that: 1) the activity of a single PU can affect multiple segments of the highway, and 2) there is at least one spectrum hole available for vehicular communication on each block partition $B \in L_R$. Performance of the schemes shown in Table 3 below are simulated and compared in this Section.

6.2. *Results Discussion*

We study the ability of the proposed CRAVNET framework to provide opportunistic usage of licensed PU spectrum bands without harmful interference with the activity of the PUs. For performance evaluation, we consider four metrics such as P_d, P_m, $J(t)$, and $P_{conflict}$.

The probability of spectral resource detection is measured as a function of SNR in Fig. 4(a-b). From Fig. 4(a-b), it is clearly observed that the probability of detection rapidly improves with increasing average SNR (ϒ). In both figures, a gain of roughly one order of magnitude is achieved by the CRAVNET over the benchmark scheme for values of ϒ from 8dB to 12dB in Fig. 4(a) and from 4dB to 10dB in Fig. 4(b), respectively. This can be explained by the fact that the three-state sensing and sharing approach allows CR vehicular SUs with CRAVNET scheme to verify, discover and detect more spectral resource as opposed to traditional two-state sensing and sharing model characterised with high level of resource starvation. Furthermore, Fig. 4(b) shows an interesting improvement in spectrum detection probability even with lesser values of ϒ (between -3dB and 8dB) with an increased vehicular density from 50 to 100 CR vehicular SUs due to the increased cooperation among the sensing nodes, which eventually lead to higher probability of spectrum availability detection. Fig. 4(c-d) compare the average probability of Miss Detection P_{md} associated with the proposed cooperative three state model against the benchmark scheme as a function of P_{fa} using 50 and 100 CR vehicular SUs.

As expected, P_{md} reduces rapidly for both CRAVNET and Benchmark scheme as the number of CR vehicular SUs increases regardless of the vehicle speed. However, CRAVNET scheme shows greater magnitude of improved performance as it can be seen in both Fig. 4(c-d) that nearly one order of magnitude of discrepancy is observed between three-state CRAVNET and two-state conventional approaches which further buttress the point made in this paper. Furthermore, the fairness performance among competing CR vehicular SUs using our proposed CRAVNET empowered with the developed three-state against the benchmark two-state spectrum sensing and sharing approach in [9] is measured using Jain's Fairness Index. Two scenarios with 50 and 100 CR vehicular SUs are studied. Results are depicted

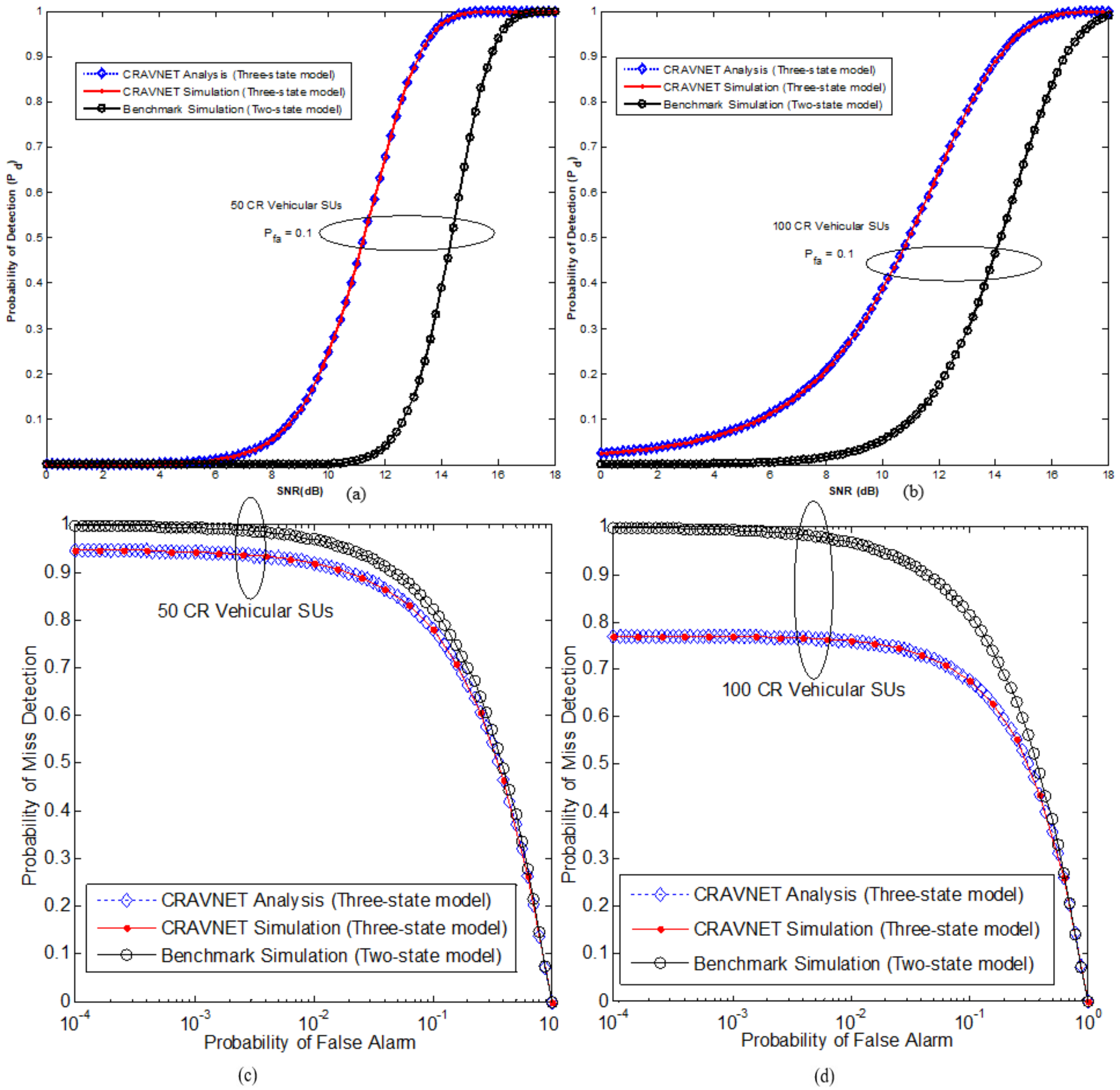

Fig. 4. *Performance comparisons between the proposed CRAVNET framework with three-state spectrum sensing and allocation model, and the traditional two-state model using 50 and 100 CR vehicular SUs using:*
(a & b) P_d measured against SNR, and (c & d) P_m versus P_{fa}.

in Fig. 5(a-b). From both Fig. 5(a) and (b), we can see that the level of fairness in spectrum resource sharing achieved with the proposed CRAVNET framework communications using the three-state spectrum sensing and allocation model is significantly improved in comparison to the result of the two-state sensing and allocation model in both scenarios. This is because all CR vehicular SUs have equal opportunities to access the channel in the three-state model as opposed to two-state where other CR vehicular SUs are denied fair share of available spectrum resource once another CR vehicular SU occupies a channel and continually transmits its own packets while others sense the channel busy (H_2) and presume that a licensed PU is currently occupying that channel. Additionally, Fig. 5(a-b) show that the number of participating CR vehicular SUs significantly impacts the fairness in resource sharing in both two-state and three-state spectrum sensing and allocation models. However, the three-state model has constantly demonstrated an improved resource sharing fairness performance in both low and high number of CR vehicular SUs scenarios.

More interestingly, the performance gap between our proposed novel CRAVNET framework and the benchmark two-state solution increased steeply when the number of participating CR vehicular SUs increased from 50 to 100.

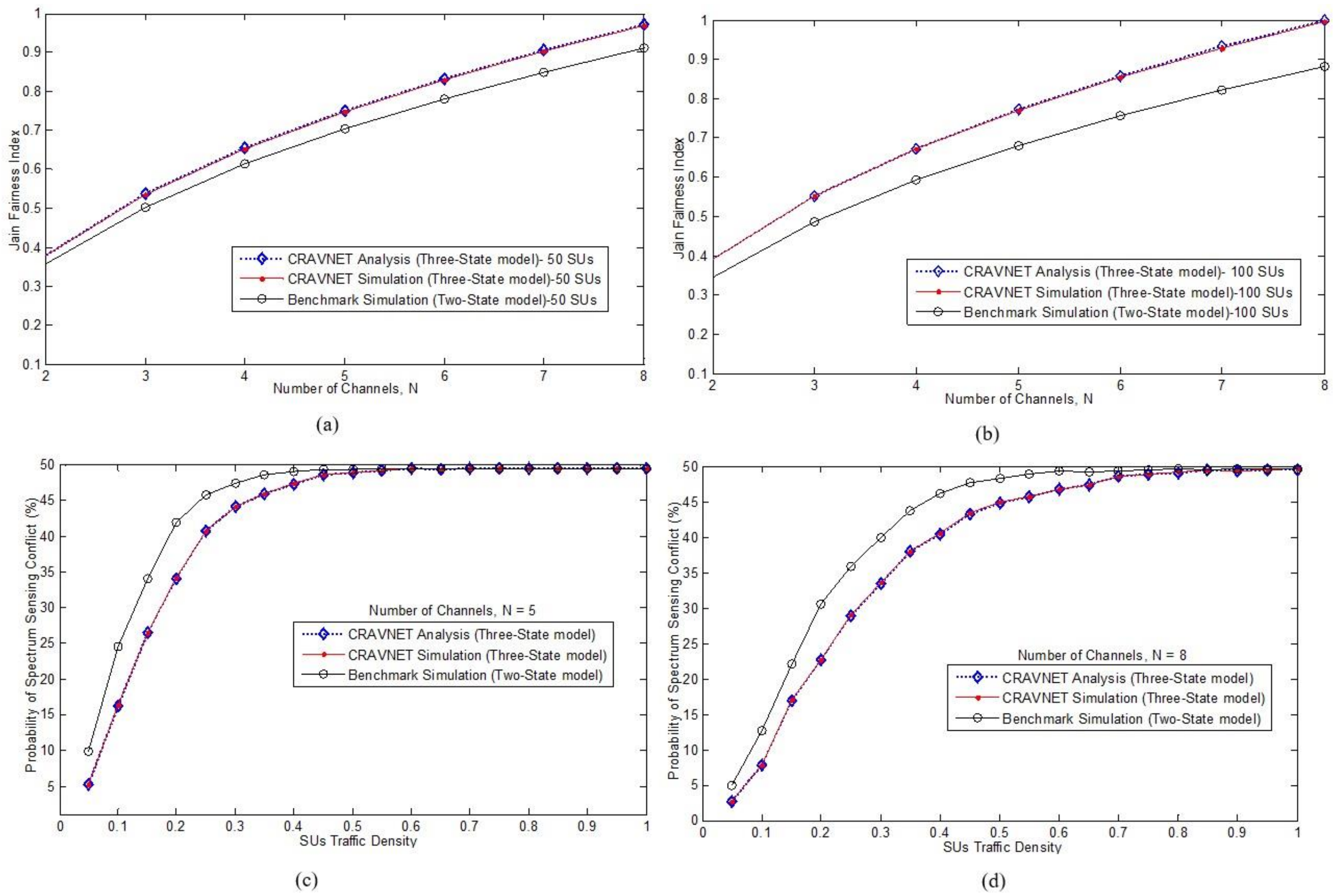

Fig. 5. *Performance comparisons between the proposed CRAVNET framework with three-state spectrum sensing and allocation model and the traditional two-state model for fair spectral resource sharing using* (a) 50 CR vehicular SUs, and (b) 100 CR vehicular SUs; and for probability of spectrum sensing conflict $P_{conflict}$ using (c) $N = 5$, and (d) $N = 8$

When the number increased to 100 CR vehicular SUs, our proposed CRAVNET framework achieved ideal Jain's Fairness Index (i.e., 1) as the total number of available sensed and shared channels increased to 8. As expected, though not only did the performance of the traditional two-state solution not improved at all, but it deteriorated when the number of available sensed and shared channels increased to 8 and drop from $J(t) = 0.9$ to $J(t) = 0.87$, (see Fig. 5(b)). This observed steep performance gap between the two solutions is as a result of the fact that in two-state spectrum sensing and allocation approach the rest of the participating CR vehicular SUs are starved and prohibited from accessing the available additional spectrum resource once a given CR vehicular SU has occupied the available channel since others would falsely perceive that the channel is actually occupied by a licensed PU.

The second set of simulation experiments evaluate the possibilities of spectrum sensing conflict in the proposed three-state spectrum sensing and sharing solution in comparison with the traditional two-state solution [9]. Probability of Spectrum Sensing Conflict is the probability that more than one CR vehicular SU identify the same available channels, thereby resulting in contention for medium access which may lead to harmful interference among the CR vehicular SUs.

In Fig. 5(c-d), the probability of spectrum sensing conflict $P_{conflict}$ in the proposed CRAVNET framework with three-state spectrum sensing and sharing approach is evaluated against the traditional two-state approach in [9] by setting the number of channels $N = 5$ and $N = 8$ in Fig. 5(c) and (d), respectively. From Fig. 5(c-d), it can be clearly seen that drastic increment of the density of CR vehicular SUs especially in the busy hours of morning and evening period can lead to high percentage of spectrum sensing conflict $P_{conflict}$ in both frameworks. However, the proposed three-state spectrum sensing approach yields smaller percentage of sensing conflict (5%) as opposed to traditional two-state sensing approach with 10% of $P_{conflict}$, both at the same 0.05 CR vehicular SUs traffic density. Notwithstanding, both approaches drastically increased as the number of CR vehicular SUs traffic density increases towards 1. The above experimentation results demonstrate the improved spectrum sensing efficiency that can be obtained by the proposed CRAVNET framework partly due to the application of the third hypothesis H_2.

7. Conclusion

In this paper, we have studied the application of CR technology to IoVs in order to increase the spectrum resource opportunities especially when the officially FCC allocated 75 MHz spectrum in 5.9 GHz band is not enough due to high demands as a result of increasing number of connected devices as already foreseen in the near era of IoTs. Hence, we have proposed a novel CRAVNET framework which empowers CR assisted vehicles to make opportunistic usage of licensed spectrum bands on the motor highways. We developed a novel distributed three-state spectrum sensing and sharing solution which enables CR vehicular SUs to be aware of additional spectrum resource opportunities on their current and future positions along their directions of movement by leveraging the cooperative spectrum sensing among them. Both the simulation and theoretical analyses have demonstrated that our solution can significantly improve the performance of a cooperative spectrum sensing and sharing schemes.

As future work, CRAVNET framework will be extended by the addition of a channel allocation scheme with novel selection metrics to ensure that the channel selected will guarantee the QoS requirements of the intended application service(s). Such novel channel selection metrics will focus on fair allocation schemes among CR vehicular SUs to avoid mutual interference and support high QoS requirements especially for time-constrained safety applications.

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