Impact of Primary User Activity Statistics in Cognitive Vehicular Networks

Dhaval K. Patel, *Member, IEEE*, Sagar Kavaiya, Zhiguo Ding, *Fellow, IEEE*, Yong Liang Guan, *Senior Member, IEEE*, Sumei Sun, *Fellow, IEEE*

Abstract

Due to the scarcity of channel availability in IEEE 802.11p standard, applications related to infotainment and multimedia services can suffer from delays. Cognitive radio has the potential to overcome the issue of spectrum scarcity. By making use of the cognitive radio technology, secondary users (SU) can access a radio frequency spectrum other than 802.11p through spectrum sensing. Existing energy detection-based algorithms either consider low mobility or stationarity (no mobility) of unlicensed vehicular users. Furthermore, the joint impact of unlicensed SU mobility and primary user (PU) activity statistics has not been considered while evaluating the performance of opportunistic spectrum access. In particular, this work considers the joint impact of PU activity and vehicle mobility on spectrum sensing performance by considering single lane and double lane vehicular scenarios. We also evaluate the impact of traffic densities on sensing performance. The main contribution of this work is to show the impact of PU activity statistics on sensing performance by deriving closed form expressions for missed detection probability. These expressions are used for analysis and simulation of cognitive radio enabled vehicular communications. From our observations, it is noted that the probability of vehicle connectivity is improved when spectrum sensing employs under PU activity.

Manuscript received March XX, 2021. Authors would like to thank financial support received from DST-ASEAN (grant ref. IMRC/AISTDF/R&D/P-09/2017).

Dhaval K Patel and Sagar Kavaiya are with School of Engineering and Applied Science, Ahmedabad University, India. (Email:sagar.k@ahduni.edu.in, dhaval.patel@ahduni.edu.in).

Z. Ding is with the School of Electrical and Electronic Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom (E-mail: zhiguo.ding@manchester.ac.uk)

Yong Liang Guan is with School of Electrical and Electronics Engineering, Nanyang Technological University (NTU), Singapore. (Email:eylguan@ntu.edu.sg).

Sumei Sun is with Institute for Infocomm Research, Singapore. (Email:sunsm@i2r.a-star.edu.sg).

Index Terms

V2I Communications, primary activity statistics, medium-dense traffic, Nakagami-*m* channel

I. Introduction

A. Background

The United States Federal Communications Commission (FCC) has decided to reserve 75 MHz spectrum in the 5.9 GHz band especially for dedicated short-range communications. The National Highway Traffic Safety Administration has declared the requirement of Intelligent Transportation System in all cars by 2019 [1]. Furthermore, many research activities have been carried out with respect to vehicular networks (VANETs) to address vehicular traffic safety concerns [2]. The information exchange within a connected vehicular network includes both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. These aforementioned communications are managed via the broadcasting of control messages. Shared information, such as vehicle position, motion characteristics, and vehicle size, are used for increasing the overall environmental awareness in support of safety applications (e.g., intersection movement assist, left turn assist, do-not-pass warning sign, and light violation warning), as well as mobility applications (e.g., collision warning, road coefficient of friction, road conditions, parking management, and payment solutions). Moreover, the passengers and pedestrians as secondary users (SU) demand the infotainment and multimedia services for which sufficient bandwidth is needed [3]. The cognitive radio technology enables the quality of intelligent sharing by means of sensing the primary user (PU) band. The recent research in [4] suggests that if the sensing task is performed with the computing of the PU activity statistics, significant improvement in the detection performance is observed.

B. Literature Review

Vehicular communications in a connected environment are regarded as a backbone for ITS [5]. It helps to disseminate the traffic information to reduce traffic jams, accidents, fuel consumption to support many infotainment applications. IEEE 802.11p standard is proposed for wireless vehicular communications where, out of seven channels, one channel is used as a common control channel and six remaining channels are used for vehicular data communications. Recent studies have shown that many networks are not fully utilizing their licensed spectrum most of the time and when a massive number of vehicles are connected with each other the spectrum scarcity is expected [6], [7]. The increasing demand of infotainment and multimedia applications lead the overcrowding of band. Thus quality of service may be reduced [8]. Moreover, requirement of safety applications and high demand of infotainment applications created a spectrum scarcity in IEEE 802.11p based services [9]. Thus, there arises a need to enable the cognitive radio (CR) technology for vehicular communications. The idea of Vehicular dynamic spectrum access in the cognitive radio network is a new paradigm to enhance the spectrum utilization where unlicensed SUs sense the wireless spectrum to find spectrum opportunities for efficient communications without causing any harmful interference to licensed PUs [10]. To leverage the opportunistic communications over other channels than IEEE 802.11p channels, unlicensed vehicular users (aka SUs) in cognitive radio enabled vehicular communications employs the spectrum sensing to find idle channels (that are licensed to other users such WiMAX) to exploit the underutilized licensed spectrum opportunistically for efficient information dissemination. To avoid any harmful interference to PUs, spectrum sensing task is performed by unlicensed vehicular users to identify whether the PUs are using their licensed channels or not [11]–[13].

In [14], a variety of spectrum sensing methods have been proposed based on energy detection for vehicular networks. In the existing works, unlicensed users are assumed to be stationary while sensing the licensed spectrum and the PUs are assumed to be passive during opportunistic transmissions by unlicensed users. Out of most of the related works, SU mobility has been considered in non-cooperative spectrum sensing [15], cooperative spectrum sensing [16], spectrum sensing in the presence of PU mobility [17] and spectrum sensing using random way point model for SUs in [18] where PUs are not mobile. Further, works in [19]–[26] are mainly focused to present the impact of mobility on spectrum sensing of SU as well as PU. The activity statistics of the PUs considered in [27], [28] for the stationary environment which shows that under PU activity statistics the sensing performance can be improved. The activity statistics considered in [27], [28] include for vehicular networks, we note that none of the reported works consider the joint impact of speed of vehicles, PU statistics, PU's communication range, and SU's sensing range while evaluating the performance of spectrum sensing.

The PU activity statistics (idle and busy periods of the PUs) can be measured by deploying a fixed hardware setup from which the knowledge about time dimensional models is extracted. In [29] time dimensional models for stationary environment were proposed. It illustrates the approximation of the distributions of the estimated activity statistics over various bands. Further, by choosing the random values for probability of idle and busy period, the impact of SU mobility on spectrum sensing was shown in [30]. In cognitive vehicular networks (CVN), each vehicular client is thought to be outfitted with a wide band handset with a detecting reach to detect PU channels and a transmission range for pioneering correspondence. To maintain a strategic distance from any destructive obstruction to authorized PUs and to expand the detecting sureness, the range of the SU transmission should be more limited than or equivalent to its own detecting range. Besides, the PUs ought to have their protection range where the SUs are not permitted to utilize the authorized channels of the PUs to stay away from any unsafe impedance. At the point when a given SU and PU are reachable remotely, the SU will have the option to detect the presence of the PU. Moreover, the SU will not have the option to detect the PU signal. Besides, when the SU and PU are not versatile, their detachment distance doesn't change throughout time. In any case, when the SU is versatile, the detecting reach may or may not cover the PU after certain movement time. The speed and direction of vehicular clients decide the cover time span between vehicular clients and the PU. Besides, the ON or OFF action of the PU fundamentally impacts the range detection for CVN.

To deploy CVN effectively, accurate modelling of vehicular channels is needed for all environments and scenarios. The most important characteristic of the vehicular channel that affects the CVN operation is its inherent high mobility. Some aspects of vehicular mobility may have negative impacts on the accuracy of the sensing decisions made by cognitive radios. Static CR users may observe a PU's frequency channel to find out about its usage pattern. However, in vehicular environments, the spectrum opportunities can dynamically change since a vehicle may enter or leave a neighborhood interfered by a specific PU at different locations along the road. Thus, profiling a PU activity pattern during a dynamic environment is more complex. Therefore, it's important for a CR to detect spectrum opportunities rapidly to reduce the period of time that it may interfere a PU after entering a PU zone, or to remember of spectrum opportunities beforehand to higher utilize the whitespaces for transmission [31].

C. Motivations

The works reported in the existing literature [6], [32] are mainly focused on deriving the expression of missed detection probability when the SU is nearer to the PU. The impact of mobility of the SU was incorporated with the static function at a low speed (Approx. 10 km/h). Further, at such low velocity the impact of the activity of the PU was shown by considering the Rayleigh Fading channel. However, in real life highway scenarios, the vehicle may have a high speed up to 120 km/h for which a more suitable fading model like Nakagami-m should be considered. Moreover, for improving performance, in [6], [30], the probability of the idle and busy periods of the PU is considered which depends on the statistical parameters of the underlying distribution of the idle/busy period. However, the impact of those statistical parameters was not shown on the detection performance by finding the closed form expressions. Therefore, the goal is to develop a methodology such that the knowledge of the activity of the PUs with their underlying distributions of idle and busy periods can be utilized to show its impact through closed form expressions. In a nutshell, this paper investigates the joint impact of SU mobility and PU activity statistics for spectrum sensing in CVN.

The 3rd Generation Partnership Project has mentioned the several vehicular scenarios for small cell enhancement in its release 15 in [31] like, consideration of medium and dense traffic densities, single and double lanes of road, and distribution of distance of SU from PU. In the context of spectrum sensing in vehicular networks, existing works have not considered the aforementioned scenarios to evaluate the detection performance [14]. Therefore, motivated from the common limitations, the sensing performance should be evaluated for a mobile SU by considering the PU activity statistics under the aforementioned scenarios. Moreover, there are two types of network model are considered for the analysis.The first type considers the vehicles as SU (without mentioning the band information) [33] and the second type considers the passengers in vehicles as SU utilising the Wi-Fi/DTV band [32]. In this analysis, the second type of the network model is considered.

Due to the presence of environmental clutter and the speed of the vehicle, the sensed samples may be affected significantly by Doppler shifts, fading and shadowing, and may experience different amounts of correlation. Hence, merging these samples together to accurately identify a PU transmission is more challenging in a vehicular environment [31]. Under SU mobility, it is advantageous to have statistical knowledge of received signal-to-noise ratio (SNR) which contains the combined effect of SU mobility and small scale fading. Moreover, Nakagami-*m* is the suitable fading model for vehicular communication as it considers the shape and fading parameters in its probability distribution function (PDF). Further, to the best of our knowledge, there is no preexisting work in the literature that considers the Nakagami-*m* fading under vehicle mobility to provide the detection performance for CVN under PU activity statistics.

D. Contributions

Based on the key motivations, our key contributions are as follows:

- Mathematically, to find the missed detection probability, it is required to have the statistical knowledge of received SNR. Hence, the PDF of received SNR is obtained under vehicle mobility from the ratio of two distributions. The work differs in two ways, firstly it has considered the channel gain following the Nakagami-*m* fading for CVN. Secondly, it has considered the distribution of vehicle velocity (v) which is an integral of log-normal random variable from *0* to time *t*. We consider total four cases to be analysed according to traffic density and road lanes. $Case1$, $Case2$, $Case3$ and $Case4$ represents the scenario of single lane medium traffic, single lane dense traffic, double lane medium traffic, and double lane dense traffic respectively.
- The knowledge of PDF of received SNR is utilised to find the closed form expression of missed detection probability by considering Nakagami-*m* channel as a fading distribution under SU mobility. The closed form expressions of missed detection probability are derived by considering the four cases according to the road lanes and traffic density. These expressions suggests the detection performance of SU when inside of the PU's protection range but not having the knowledge of PU activity statistics.
- In contrast to the [6], [30], the impact of PU activity statistics on missed detection probability is shown for the aforementioned cases. Furthermore, we also show the benefit of deriving the missed detection probability with PU activity by finding the probability of connectivity. The obtained expressions significantly improves the detection performance in CVN.

The rest of the paper is organized as follows: Section II describes the complete system model. In Section III describes the analysis of received SNR for single lane and double lane. Section IV describes the analysis of missed detection probability. Section V provides the complete information on numerical results. Section VI provides the conclusion of carried research followed by the references.

II. System Model

In this section we describe the traffic network model and signal model.

TABLE I: Main notation used in this paper

Notation	Description	Notation	Description
a	Road length	m	Nakagami-m parameter
b	Road width	L	Series balancing parameter for nth term
d’	Initial distance of SU from PU	g_x	Fading distribution
d_1, d_2, d_3	Distance from PU when SU travels	v_j	velocity of jth vehicle
R	PU’s protection radius	ζ	Path loss exponent
C	speed of light	R_s	code rate
Δ	Test statistics	f_c	Carrier frequency
λ	Detection threshold	d_X	Distance distribution
α	Shape parameter	β	Scale parameter
Pr(A)	The probability of a given SU being outside of the PU’s protection radius	Pr(B)	The probability of a given SU being inside of the PU’s protection radius

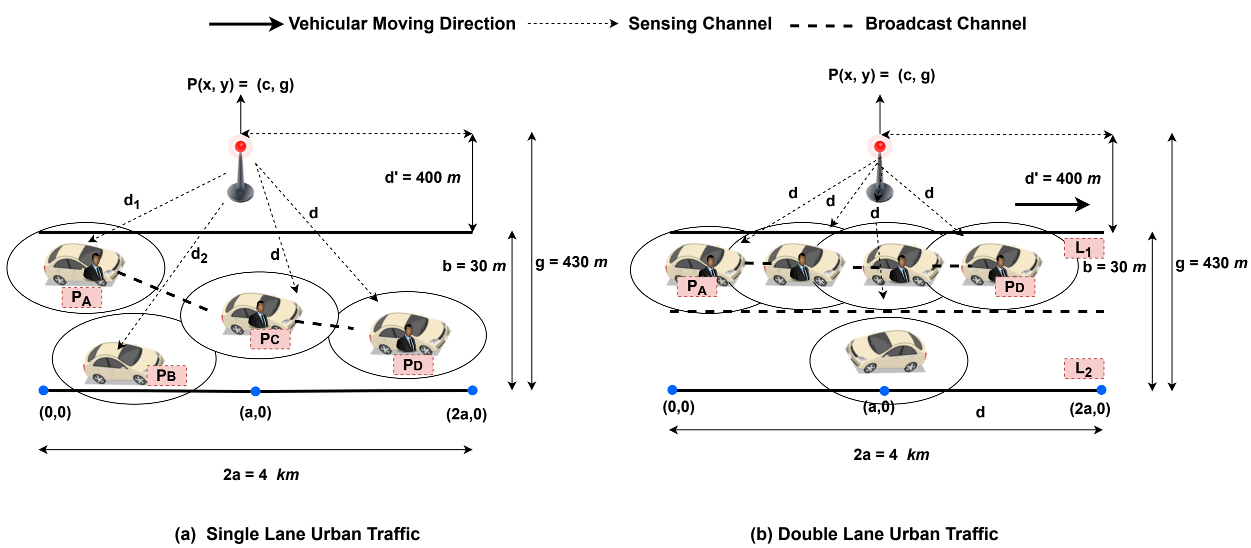

Fig. 1: A typical vehicular scenario

A. Network Model

The simplified network model is shown in Fig. 1. As per the scenarios mentioned for DSRC based communications in [9], the primary network shares the resource to secondary network. The passengers in a car or pedestrians using an unlicensed band allows to find the opportunistic access to the spectrum. Similar to the [8], [32], we assume that PUs are the licensed DSRC band holders and SUs are unlicensed Wi-Fi band holders. We also assume that the passenger in a car can access the Wi-Fi from available nearby hot spots, or travelling through bus consist of Wi-Fi. The DSRC channels are used for sharing spectrum awareness. While PUs channels are idle, SU can utilise the channels to communicate with each other. According to the wireless access in vehicular environment (WAVE) MAC Layer protocol, the control channel is used to set up the communication link. The PU's protection radius is R. In the model, a vehicular users in cognitive connected environment is mobile. In this setup, the distance between PU and SU is a function of distance between them, their relative speed, direction of travel of vehicles, PU's protection range and the sensing range of vehicular user. The notations used in the network model are defined in Table 1.

B. Signal Model

The vehicle begins its journey from point A and moving towards the point D. The vehicle is equipped with the single antenna. As a part of channel modelling for vehicular scenarios, the channel model considers all entities specific to a vehicular environment, such as multi path fading, Doppler shift, scattering, which can be mathematically expressed as [32, Eq. 1]:

$$h(\tau, t) = \sum_{k=0}^{P-1} h_k(t)\delta[\tau - \tau_k(t)], \quad (1)$$

where τ_k is the path delay of k^{th} path, t is time variable, δ is the impulse function. The Jake's correlation is utilised in order to make an impact of vehicle velocity as $\rho_j = \frac{2\pi f_c v_j}{R_s c}$ mentioned in [34, Eq. 5]. Moreover, from Fig. 1, it can be notice that when SU travels from point A to Point D, the accurate channel envelope $h_k(t)$ experiences the impact of the distance which is further explained as [35, Eq. 14] :

$$h_k(t) = \frac{g_x(t)}{\sqrt{1 + d_X^{\zeta}(t)}}, \quad (2)$$

where ζ denotes the path loss exponent, g_x is the channel gain following Nakagami-*m* distribution. d_X is the distribution of distances over dense and medium traffic. The spectrum sensing operation performs a binary hypothesis test as follows:

$$\begin{aligned} H_0 &: r(t) = \sum_{t=0}^{\infty} n_r(t) \\ H_1 &: r(t) = \sum_{t=0}^{\infty} h(\tau, t)x(t-\tau) + n_r(t), \end{aligned} \quad (3)$$

where $r(t)$ is the received signal, $x(t-\tau)$ is the transmitted signal, and $n_r(t)$ is the additive white Gaussian noise. The hypothesis of the absence and presence of the PU are H_0 and H_1, respectively. We assume single antenna at PU and SU side. Furthermore, the total effective SNR over the branches is given as [36]:

$$\gamma = \frac{E_s}{N_0}, \tag{4}$$

where, E_s is the signal power N_0 is the power of the additive white Gaussian noise.

C. Calculation of Primary Activity Statistics

When the hypothesis H_0 is true then either there is no PU within the sensing range or PU is inactive within the sensing range s. The PU 'absent' event depends on the parameter α. When a channel is used by the PU and SU detects a PU signal in a given channel (i.e., hypothesis H_1), and similarly the PU 'busy' defined on parameter β. The α and the β are the statically calculated parameters obtained from the distributions of the data acquired of idle and busy periods also called as the PU activity statistics. Without loss of generality, PUs being active and idle are exponentially distributed under the medium traffic and gamma distributed under the dense traffic with shape parameter and scale parameter (α) and (β) respectively.The probability of the PU is absent defined as $Pr(A)$. The probability of the PU is busy defined is $Pr(B)$. Note that $(Pr(A) = 1 - Pr(B))$. Then, the probabilities of PU being present/active and absent/idle are, respectively, represented by p_p and p_a and are given as:

$$p_p = \frac{\alpha}{\alpha + \beta}. \tag{5}$$

$$p_a = \frac{\beta}{\alpha + \beta}. \tag{6}$$

Similarly, the probability Pr($ON \rightarrow ON$) is used to denote the channel will be used by the PU during current sensing period t which was also active during previous sensing period. With this information, the probability Pr($OFF \rightarrow ON$) can be expressed as [4]:

$$pr(OFF \rightarrow ON) = p_p - p_p e^{-(\alpha+\beta)t}. \tag{7}$$

Similarly, the probability Pr(ON→ON) can be expressed as:

$$pr(ON \rightarrow ON) = p_p + p_p e^{-(\alpha+\beta)t}. \tag{8}$$

The probability of miss detection under the impact of primary activity statistics depends on sensing range of vehicular user, protection range of PU, velocity of vehicular user and energy detection threshold is given by [4, Eq. 16]:

$$Pr(miss)_{PAS} = Pr(\Delta \leq \lambda | H_1, B) Pr(B) pr(ON \rightarrow ON) + Pr(\Delta \leq \lambda | H_0, A) Pr(A) pr(OFF \rightarrow ON) \tag{9}$$

where $Pr(\Delta \leq \lambda|H_1, B)$ is the conditional missed detection probability over small scale fading for event B. Δ is the test statistics and λ is detection threshold. These parameters are utilized to obtain the analytical expression of miss detection probability in the medium and dense traffic. The upcoming section is illustrating the analysis of missed detection probability without the knowledge of activity statistics. The probability of the event A and B depends on the distribution function of separation distance between a fixed PU and a mobile SU. Thus, to find the missed detection over such condition, it is required to obtain statistical knowledge of the received SNR under dense and medium traffic conditions. The section III focuses on the derivation of the received SNR.

III. Analysis of Received SNR for Single and Double Lane

As per Eq. 8, it can be notice that impact of PU activity on the missed detection probability can be derived by considering the initial position of SU, and the distribution of distance between the PU and SU. However, in context of the practical highway scenarios, the initial location, and its distance are different for single and double lane. Thus, it is necessary to discriminate for both the lanes. Moreover, the traffic density on the road pays a significant impact on received SNR due to shadowing effect between SU and PU. Thus, we consider the various cases for which the knowledge of received SNR is obtained.

1) *Case 1: Single lane medium traffic*
2) *Case 2: Single lane dense traffic*
3) *Case 3: Double lane medium traffic*
4) *Case 4: Double lane dense traffic*

A. Received SNR for Case 1 and Case 2

In this section, we derive the PDF of the received SNR by considering the velocity dependent distribution. We define the case 1 as the single lane medium traffic conditions. The CDF of received SNR over Nakagami-*m* channels under vehicle mobility is expressed as follows:

$$F_Z(z) = \int_0^{\infty} \int_{-\infty}^{yz} f_{XY}(x, y) dx dy. \tag{10}$$

where, the PDF of Nakagami-*m* is given as [32]:

$$f_X(x) = g_x = \frac{2x^{Lm-1}}{\Gamma(L)} \frac{m}{\Omega}^{Lm} \left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m, Lm; m; \frac{mx^2}{\Omega}). \tag{11}$$

The distribution of distance d for single lane medium traffic is given by [33]:

$$f_Y(y) = d_X = \frac{d}{4ab}\left[\pi + 2arcsin\left(\frac{2(y^2-(b-h)^2)}{y^2}\right) - 1\right], \tag{12}$$

where a = 2km, b=30m. By substituting (10) and (11) in (9),

$$\begin{aligned} F_Z(z) = &\int_0^{\infty}\int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)}\frac{m}{\Omega}^{Lm}\left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m,m;Lm;\frac{mx^2}{\Omega}) \\ &\times \frac{d}{4ab}\left[\pi + 2arcsin\left(\frac{2(y^2-(b-h)^2)}{y^2}\right) - 1\right] dxdy. \end{aligned} \tag{13}$$

Lemma 3.1. *Under the impact of mobility, the CDF of received SNR for single lane over medium traffic is obtained as the ratio of two distributions as:*

$$F_Z(z)^{case1} = \frac{z^{2Lm}}{Lm} \times F_1(p,q;r;s) \times \frac{1}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^{Lm} \times \frac{1}{det(\Lambda)}^m. \tag{14}$$

From the properties of PDF, by differentiating of above equation,

$$f_Z(z) = \frac{\mathrm{d}}{\mathrm{d}z}F_Z(z). \tag{15}$$

$$f_Z(z) = \frac{\mathrm{d}}{\mathrm{d}z}\frac{z^{2Lm}}{Lm} \times F_1(p,q;r;s) \times \frac{1}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^{Lm} \times \frac{1}{det(\Lambda)}^m. \tag{16}$$

Proof. kindly refer Appendix A ■ □

Note that the above expression is not restricted to any fix value of the Lauricella Hypergeometric function (F_1) given in [37]. Since, the outer integral of (12) contains the limits from 0 to infinite, there exist the convergence term which is further being utilised to obtain the closed form of miss detection probability. The calculation of the convergence terms is provided in Appendix B. The impact of medium of dense traffic is justified by the separation distance between vehicle. Mathematically, the co variance matrix with the element of the separation distance is given as:

$$\Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} & \cdots & \Sigma_{1n} \\ \Sigma_{21} & \Sigma_{22} & \cdots & \Sigma_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \Sigma_{n1} & \Sigma_{n2} & \cdots & \Sigma_{nn} \end{bmatrix}_{nm \times nm}$$

$$\Sigma_{ij} = N\sigma_n^4 \mathrm{I} + 2N\sigma_n^2\sigma_s^2\xi_{ij}\begin{bmatrix} 1 & \rho_i & \cdots & \rho_i^{m-1} \\ \rho_j & \rho_j/\rho_i & \cdots & \rho_i^{m-1}/\rho_j \\ \vdots & \vdots & \ddots & \vdots \\ \rho_j^{m-1} & \rho_j^{m-1}/\rho_i & \cdots & \rho_j^{m-1}/\rho_i^{m1}. \end{bmatrix}$$

where, $\xi_{ij} = e^{-d_{ij}/d_c}$, $\rho_i = e^{-\triangle d/d_c}$. d_c is the de-correlation distance at which the vehicles are not considered in a cluster to show the impact of density. Δd is the displacement of the vehicles caused by the individual acceleration. We use the decomposition method to incorporate the impact of density co-variance matrix in the PDF [33]. Hence final expression for PDF of received SNR over Nakagami-*m* channels under vehicle mobility for single lane dense traffic by interpolation method given in [33]:

$$p_\gamma(\gamma)_{Case1} = \frac{\left(\frac{\gamma m}{\overline{\gamma}}\right)^{d(2m-1)} exp\left(\frac{-\gamma}{\overline{\gamma}\times(1-det(\Lambda))}\right) \times det(\Sigma_{ij})}{(1-det(\Lambda))^d\Gamma(Lm)}. \tag{17}$$

Similarly, the case 2 defined as the single lane dense traffic. The PDF of the received SNR is given as:

$$p_\gamma(\gamma)_{Case2} = \frac{\left(\frac{\gamma m}{\overline{\gamma}}\right)^{d(2m-1)} exp\left(\frac{1}{\overline{\gamma}\times(det(\Lambda))}\right) \times det(\Sigma_{ij})}{(det(\Lambda))^{d)}\Gamma(d'')}. \tag{18}$$

B. Received SNR for Case 3 and Case 4

We define the case 3 as double lane medium traffic conditions. In accordance with the previous section. The CDF of receiver SNR over Nakagami-*m* channels under vehicle mobility is expressed as follows:

$$F_Z(z) = \int_0^\infty \int_{-\infty}^{yz} f_{XY}(x,y)dxdy. \tag{19}$$

Here, Nakagami-*m* PDF is given by [32]:

$$f_X(x) = g_x = \frac{2x^{Lm-1}}{\Gamma(L)}\frac{m}{\Omega}^{Lm}\left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(1,m;Lm;\frac{mx^2}{\Omega}). \tag{20}$$

The distribution of distance d for the double lane is updated and given by:

$$f_Y(y) = d_X = \frac{d}{2ab}\left[\arcsin(\frac{2(d^2-{h_p}^2))}{d^2}1) - \arcsin(\frac{2(d^2-h^2))}{d^2}-1)\right]. \tag{21}$$

By substituting (22) and (21) in (20),

$$\begin{aligned} F_Z(z) = \int_0^\infty \int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)}\frac{m}{\Omega}^{Lm}\left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m,m;Lm;\frac{mx^2}{\Omega}) \\ \times \frac{d}{2ab}\left[\arcsin(\frac{2(d^2-{h_p}^2))}{d^2}1) - \arcsin(\frac{2(d^2-h^2))}{d^2}-1)\right]dxdy. \end{aligned} \tag{22}$$

Lemma 3.2. *Under the impact of mobility, the CDF of received SNR for double lane over medium traffic is obtained as the ratio of two distributions as:*

$$F_Z(z)^{Case3} = \frac{z^2}{ab} \times \frac{1}{\Gamma(m)} \times \left(\frac{1}{det(\Lambda)}\right)^m \quad \times \int_0^\infty yArcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right)y^2F_1(\cdot)dy. \tag{23}$$

By solving the above integral, the final expression of CDF is given as:

$$F_Z(z)^{case3} = \frac{z^{2Lm}}{Lm} \times F_1(p,q;r;s) \times \frac{1}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^{Lm} \times \frac{1}{det(\Lambda)}^{m}. \tag{24}$$

From the properties of PDF, by differentiating of above equation,

$$f_Z(z) = \frac{\mathrm{d}}{\mathrm{d}z} F_Z(z) \tag{25}$$

$$f_Z(z) = \frac{\mathrm{d}}{\mathrm{d}z} \frac{z^{2Lm}}{Lm} \times F_1(p,q;r;s) \times \frac{1}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^{Lm} \times \frac{1}{det(\Lambda)}^{m}. \tag{26}$$

Proof. kindly refer Appendix A □

Hence final expression for PDF of received SNR over Nakagami-*m* channels under vehicle mobility is given as:

$$p_\gamma(\gamma)_{Case3} = \frac{\left(\frac{\gamma m}{\bar{\gamma}}\right)^{d(Lm-1)} exp\left(\frac{-\gamma}{\bar{\gamma} \times (1-det(\Lambda))}\right) \times det(\Sigma_{ij})}{(1-det(\Lambda))^{d(L-1)}\Gamma(Lm)}. \tag{27}$$

Similarly, the case 4 defined as the double lane dense traffic. The PDF of the received SNR is given as:

$$p_\gamma(\gamma)_{Case4} = \frac{\left(\frac{\gamma m}{\bar{\gamma}}\right)^{d(Lm-1)} exp\left(\frac{1}{\bar{\gamma} \times (det(\Lambda))}\right) \times det(\Sigma_{ij}) L}{(det(\Lambda))^{d(L-1)}\Gamma(d'')}. \tag{28}$$

Note that there expressions are further utlised in order to incorporate the impact of velocity as per (1).

IV. Analysis of Missed Detection Probability

The vehicle per sq. km defines the density of the traffic [32]. However, the density of the traffic will not affect the underlying distributions of the PU's idle and busy periods but as per (3), it can be notice that the overall missed detection probability wii be significantly affected by the density of traffic. We consider the Nakagami-m fading as a small scale distribution of the channel gain.

A. Missed detection for Case 1 and Case 2

The detection probability describes the SU's sensing accuracy and has to be improved in order to protect the PU's data transmission. Therefore the detection probability P_d and false alarm probability P_f, is defined as P_d = $P(\Delta > \lambda | H_1)$, $P(\Delta > \lambda | H_0)$ respectively. The average probability of detection over fading channel is determined as [33]:

$$P_d = \int_0^\infty Q_u(\sqrt{2\gamma}, \sqrt{\eta}).p_\gamma(\gamma) d\gamma. \tag{29}$$

$$p_{\gamma}(\gamma)_{Case1} = \frac{\left(\frac{\gamma m}{\overline{\gamma}}\right)^{d(Lm-1)} exp\left(\frac{-\gamma}{\overline{\gamma}\times(1-det(\Lambda))}\right) \times det(\Sigma_{ij})}{(1-det(\Lambda))^{d(L-1)}\Gamma(Lm)}, \tag{30}$$

Here, $F_1(.,.;.)$ in term 1 and term 2 denotes the Lauricella hyper geometric function and is defined in [37] as

$$F_1(a1, b1 : x) = \frac{\Gamma(b_1)}{\Gamma(a_1)} \sum_{n=0}^{\infty} \frac{\Gamma(a_1+n)x^n}{\Gamma(b_1+n)n!}. \tag{31}$$

In above expression, the lauricella hyper-geometric function is a special case of generalised hyper geometric function. It illustrates the dependency between two or more variables to infinite numbers. In our case if we carefully observe the above expression then it can be noticed that the fading parameter, velocity, road length and correlation value is interconnected with the values of SNR which implies the dependency of the parameters on given SNR value in practice. Thus, to show the dependency between two or more variables we can represent it into a infinite series terms to be analytically tractable. Similarly for all diversities the Lauricella distributions can be evaluated. We use the alternative expression for Marcum-Q function in order to derive the detection probability is given as [38]:

$$Q_u(\sqrt{2\gamma}, \lambda) = 1 - e^{\frac{2\gamma+\lambda}{2}} \sum_{n=u}^{\infty} (\frac{\sqrt{\lambda}}{\sqrt{2\gamma}})^n I_n(\sqrt{2\lambda\gamma}), \tag{32}$$

The average probability of detection over fading channel is determined as [33]:

$$P_d = \int_0^{\infty} Q_u(\sqrt{2\gamma}, \sqrt{\lambda}).\frac{E}{F}\gamma^{Lm-d}e^{-C\gamma}F_1(md, La/b; G\gamma)d\gamma, \tag{33}$$

Therefore, by using the definition of PDF and by substituting (32) in (33), we obtain the average detection probability for single lane medium traffic as

$$\overline{P}_{md} \ = \ 1 - \frac{E}{F}e^{-\frac{\lambda}{2}} \sum_{n=u}^{\infty} \left(\frac{\sqrt{\lambda}}{\sqrt{2}}\right)^n \int_0^{\infty} \gamma^{L\mu-1-\frac{n}{2}}e^{-\gamma(B+1)} \ \times \ I_n(\sqrt{2\lambda\gamma})F_1(a, Lm; G\gamma)d\gamma. \tag{34}$$

Using the identity for the series representation for the Lauricella hyper geometric function, (34) becomes as:

$$\overline{P}_{md} \ = \ 1 - \frac{E\Gamma(Lm)}{F\Gamma(m)}e^{-\frac{\lambda}{2}} \sum_{n=u}^{\infty}\sum_{i=0}^{\infty} \frac{\Gamma(L+i)G^i}{\Gamma(Lm+i)} \ \times \ \int_0^{\infty} \gamma^{Lm-1-\frac{n}{2}+1}e^{-\gamma(a)}I_n(\sqrt{2\lambda\gamma})d\gamma. \tag{35}$$

For the further mathematical insights, consider the equation given below which helps the above equality to convert into a conditional closed form expressions:

$$\overline{P}_{md} = \int_0^{\infty} x^{\mu-\frac{1}{2}}e^{-\alpha x}I_{2v}(2\beta\sqrt{x})dx = \frac{\Gamma(\mu+v+\frac{1}{2})}{\Gamma(2v+1)} \times \beta^{-1}e^{\frac{\beta^2}{2\alpha}}\alpha^{-\mu}M_{-\mu,v}\left(\frac{\beta^2}{\alpha}\right), \quad \left[Re\left(\mu+v+\frac{1}{2}\right) > 0\right]. \tag{36}$$

To solve the above integral we use the special integral rule from [37, Eq. 2.742] after taking the constants outside and mapping with the appropriate variable which further defined as:

$$\int x\ arcsin\frac{x}{a}dx = \left(\frac{x^2}{2}+\frac{a^2}{4}\right)arcsin\frac{x}{a}-\frac{x}{4}\sqrt{x^2+a^2}. \tag{37}$$

The above identity is used to calculate further integral as per [37, Eq. 2.811]:

$$\int arcsin(\frac{x}{a})^n = x\sum_{k=0}^{n/2}(-1)^k\binom{n}{2k}.2k!(arcsin\ x/a)^{(n-2k)}$$

$$..\binom{n}{2k-1}.(2k-1)!(arcsin\ x/a)^{(n-2k+1)}. \tag{38}$$

The above term can be demonstrated by the hyper-geometric function (F_1) [37, Eq. 6.754] where M(.) denotes Whittaker function given by

$$M_{u,v}(z) = z^{v+\frac{1}{2}}e^{\frac{-z}{2}}F_1(v-\mu+\frac{1}{2};1+2v;z) \tag{39}$$

To proceed further, we solved the above integral by satisfying the appropriate conditions in (36) is as:

$$\overline{P}_{md} = 1-\frac{E\Gamma(Lm+\rho)}{G\Gamma(m)}e^{-\frac{\lambda}{2}}\sum_{n=u}^{\infty}\sum_{i=0}^{\infty}\left(\frac{\lambda}{2}\right)^n\frac{\Gamma(\rho)m^i}{\Gamma(n+1)(1+F)^{Lm+i}i!}F_1\left(\rho;n+1;\frac{\lambda}{2(1+F)}\right). \tag{40}$$

Corollary 4.1: *The missed detection probability for single lane medium traffic under the impact of PU activity is given by using (8):*

$$\overline{P_{mPAS1}} = \left[1-\frac{E\Gamma(Lm+\rho)}{G\Gamma(m)}e^{-\frac{\lambda}{2}}\sum_{n=u}^{\infty}\sum_{i=0}^{\infty}\left(\frac{\lambda}{2}\right)^n\frac{\Gamma(\rho)m^i}{\Gamma(n+1)(1+F)^{Lm+i}i!}F_1\left(\rho;n+1;\frac{\lambda}{2(1+F)}\right)\right] \tag{41}$$

$$\times\left[p_p+p_pe^{-(\alpha+\beta/t)}\right]+\left[Pr(\Delta\leq\lambda|H_0,A)Pr(A)\times p_p-p_pe^{-(\alpha+\beta/t)}\right] \tag{42}$$

Noticing that the expression of the missed detection probability in (40) is not bounded to integer μ or u values. The infinite series in (40) are upper bounded by the monotonically decreasing $F_1(.;.;.)$ for fixed values of m, ρ, λ, $\overline{\gamma}$, hence it converge rapidly. However, as in the vehicular scenario, the speed of the vehicle can affect the accuracy of the expression because by increasing the first parameter in monotonically decreasing function can bound the final integer value. Where E= $\frac{d}{\overline{\gamma}}^m$ $F=\frac{m}{\overline{\gamma}L}$ $G=\frac{\rho(L\rho+\rho^2)}{\overline{\gamma}(1-\rho+L\rho)}$. Similarly, the missed detection probability for dense traffic for single lane is obtained by substituting (30) in (31).

B. Missed detection for Case 3 and Case 4

By simplifying the expression of the received SNR for double lane medium traffic, we have the following expression:

$$p_{\gamma\, med}(\gamma) = \frac{1}{\Gamma(a)\, b^a}\gamma^{a-1}\, e^{-\frac{\gamma}{b}}, \quad 0 \leq \rho < 1, \tag{43}$$

where, $a = \frac{mL^2}{\delta}$, $b = \frac{\delta\bar{\gamma}}{Lm}$, $\delta = L + \frac{2\rho_2}{1-\rho_2}(L - \frac{1-\rho_2^L}{1-\rho_2})$. ρ_2 is the density parameter. where Z= $\frac{d}{\bar{\gamma}}^m$, R = $\frac{L}{\bar{\gamma}}$, S = $\frac{\rho_2(L\rho_2+\rho_2^2)}{\bar{\gamma}(1-\rho_2+L\rho_2)}$ The average detection probability is obtained by substituting (45) in (33) as:

$$P_d = \int_0^\infty Q_u(\sqrt{2\gamma}, \sqrt{\lambda}).\frac{1}{Z}\Gamma(d)e^{-R\gamma}F_1(\rho, L; S\gamma)d\gamma, \tag{44}$$

For further insight in the terms, consider the following:

$$P_d = \frac{1}{\Gamma(a)b^a}\int_0^\infty Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right)\gamma^{a-1}e^{\frac{-\gamma}{b}}d\gamma \tag{45}$$

To proceed further, let change the variable x= $\sqrt{2\gamma}$ and with some manipulation, it can be written as:

$$P_d = \frac{1}{2^{a-1}\Gamma(a)b^a}\int_0^\infty Q_u\left(x, \sqrt{\lambda}\right)x^{2a-1}e^{-\frac{x^2}{2b}}dx \tag{46}$$

By writing the above expression in terms of Nuttal integrals and then satisfying the inner condition given in [39, Eq.29] as:

$$\int_0^\infty Q_u(\alpha x, \beta)x^q e^{-\frac{p^2x^2}{2}}dx \equiv G_u$$
$$G_{u-1} + \frac{1}{2(u-1)!\frac{p^2+\alpha^2}{2}^{\frac{q+1}{2}}}\Gamma\left(\frac{q+1}{2}\right)\left(\frac{\beta^2}{2}\right)^{u-1}$$
$$\times\, e^{-\beta^2/2}F_1\left(\frac{q+1}{2}; u; \frac{\beta^2\alpha^2}{p^2+\alpha^2}\right), q > -1 \tag{47}$$

Note that, it can be solved by evaluating G_u recursively for q>-1. Note that, the above expression is conditional in which the $q > -1$ and indicates the sensitivity of the derived analytical expression to the vehicle mobility. To solve the above integral we first convert it into a hyperbolic function to discover the appropriate identity in the second integral term which is defined as [37, Eq. (2.741.1)]:

$$\int x^n\ arcsinh\frac{x}{a}dx = \frac{x^{n+1}}{n+1}arcsinh\frac{x}{a} - \frac{1}{n+1}\int\frac{x^{n+1}dx}{\sqrt{a^2-x^2}}. \tag{48}$$

The above terms will convert the integral to match with the proper identity as [37, Eq. 6.754.3]. As the integral does not converge without a conditions, we opt the conditional expression by considering the $z < 1$.

$$G_u = G_{u-1} + A_{u-1}F_u = G_{u-2} + A_{u-2}F_{u-2} + A_{u-1}F_{u-1} = G_1 + \sum_{n=1}^{u-1} A_n F_{n+1} \quad (49)$$

Where A_n and F_n can be written as:

$$A_n = \frac{1}{2(n!)\left(\frac{p^2+\alpha^2}{2}\right)^{\frac{q+1}{2}}}\Gamma\left(\frac{1+q}{2}\right)\left(\frac{\beta^2}{2}\right)^n e^{\frac{-\beta^2}{2}} \quad (50)$$

$$F_n = F_1\left(\frac{q+1}{2}; n; \frac{\beta^2\alpha^2}{2p^2\alpha^2}\right) \quad (51)$$

Corollary 4.2: *The missed detection probability for double lane medium traffic under the impact of PU activity is given by using (8) as under:*

$$\overline{P_{mPAS2}} = \left(1 - \zeta\left[G_1 + \frac{\eta}{2}\sum_{n=1}^{u-1}\left(\frac{\lambda}{2}\right)^n \frac{1}{n!} \times F_1\left(Z; n+1; \frac{\lambda b}{2(1+b)}\right)\right]\right) \times \left[p_p + p_p e^{-(\alpha+\beta/t)}\right] + \left[Pr(\Delta \leq \lambda|H_0, A)Pr(A) \times p_p - p_p e^{-(\alpha+\beta/t)}\right] \quad (52)$$

where, ζ and η are,

$$\zeta = \frac{1}{2^{a-1}\Gamma(a)} b^a \quad (53)$$

$$\eta = \Gamma(a)\left(\frac{2S}{1+b}\right)^a e^{-\frac{\lambda}{2}} \quad (54)$$

$$G_1 = \frac{2^{a-1}(a-1)!}{\frac{1}{b}^{2a}}\left(\frac{b}{1+b}\right)e^{-\frac{\lambda}{2(1+b)}} \times \left[\left(1+\frac{1}{b}\right)\left(\frac{1}{1+b}\right)^{a-1} L_{a-1}\left(\frac{-\lambda R}{2(1+b)}\right) + \sum_{n=0}^{a-2}\left(\frac{1}{b+1}\right)^n L_n\left(\frac{-\lambda b}{2(b+1)}\right)\right. \quad (55)$$

Here $L_n(.)$ denotes the Lagrangian's polynomial of n degree. The corollary 4.1 and 4.2 suggests that the missed detection probability under the impact of PU activity statistics is a function of the conditional missed detection probability. Note that under no assumption of PU activity statistics, the resultant expressions reduced to the conditional missed detection probability given in [33]. Furthermore, in comparison with the prior models in which no PU activity statistics is considered, these expressions are useful to gain insight to identify the impact of PU transmissions on missed detection probability. The prior model considers either no mobility or low mobility (up to 10 km/h) of the vehicle which may not be utilized in practice. Furthermore, the prior models provide the missed detection probability only when the SU is inside of the protection range of PU. In contrast to this, we provide the detection performance at high velocity (up to 120 km/h). Our expressions are not restricted or limited to the position of SU to PU. Moreover, it is also seen from 9 that the missed detection probability decreases with the PU activity statistics. Hence the utility of the derived expressions is proved. These expressions also suggest that at the high probability of Pr(ON $\rightarrow$ ON), the missed detection probability is also high when SU is in the protection range. Moreover, the conditional missed detection probability is the function of a fading parameter which implies that under a high fading parameter (m= 4 and above), the same performance is improved.

C. Analysis of Probability of Connectivity based on Primary Activity Statistics

This section highlights the usage of the activity statistics and determines that because of PAS and its impact on the missed detection probability, the connectivity between the vehicles in adhoc network scenario is increases. The probability of connectivity is derived as a function of missed detection probability. It has been noticed that the total time for vehicle communication depends on the sensing time, association time and information exchange time. Furthermore, if the activity statics are implied over the detection task, irrespective of the sensing time, the total communication time will be reduced. This is because the vehicle's which are not participating in the sensing, are aware of the activity pattern of the PU, and hence it can remain connect with the other vehicle user or in other way the probability of being connected with the other SU is increased. From [6], the CDF for inter vehicle distance is denoted by

$$F_L(l) = 1 - e^{\rho l} \tag{56}$$

As per the considered network model, the vehicles are said to be connected of their transmission ranges are larger than their separation distance. Moreover, the distance between any two vehicles on road is exponential with parameter ρ. Thus, while communicating over time duration t, the probability that two vehicles are connected when they are in ranges is given as [6]:

$$F_{TR}(tr) = 1 - e^{P_m TR}, \tag{57}$$

where TR denotes the transmission range, P_m denotes the missed detection considering PAS. From (60), the probability of connectivity of any j^{th} vehicle to another $j-1^{th}$ vehicle is:

$$P_{con} = 1 - e^{-\rho TRP_m} \tag{58}$$

Substituting (44) in (60), the probability of connectivity for single lane can be denoted as:

$$P_{con1} = 1 - e^{-\rho TR\left[1-\frac{E\Gamma(Lm+\rho)}{G\Gamma(m)}e^{-\frac{\lambda}{2}}\sum_{n=u}^{\infty}\sum_{i=0}^{\infty}\left(\frac{\lambda}{2}\right)^n \frac{\Gamma(\rho)m^i}{\Gamma(n+1)(1+F)^{Lm+i}i!}F_1\left(\rho;n+1;\frac{\lambda}{2(1+F)}\right)\right]}$$
$$\left[\quad \times p_p + p_p e^{-\left[\alpha+\beta/t\right)} \left[+ Pr(\Delta \le \lambda | H_0, A) Pr(A) \times p_p - p_p e^{-(\alpha+\beta/t)}\right] \tag{59}$$

Substituting (54) in (60), the probability of connectivity for single lane can be denoted as:

$$P_{con2} = 1 - e^{-\rho TR\left(1-\zeta\left[G_1+\frac{\eta}{2}\sum_{n=1}^{u-1}\left(\frac{\lambda}{2}\right)^n\frac{1}{n!}\times F_1\left(Z;n+1;\frac{\lambda b}{2(1+b)}\right)\right]\right)}$$
$$\times\left[p_p + p_p e^{-(\alpha+\beta/t)}\right] + \left[Pr(\Delta \le \lambda|H_0, A)Pr(A) \times p_p - p_p e^{-(\alpha+\beta/t)}\right] \tag{60}$$

V. Numerical Results and Discussion

This section validates the analytical expressions and provides the simulation results. The residential base stations or access points are considered to be PUs and each PU has its protection range where SUs are not permitted to use PUs' active channels. Simulations to verify the analysis was carried out. We evaluate the joint impact of PU activity and vehicle mobility under medium and dense traffic conditions. This is done by performing simulations under specific assumptions. By considering common assumptions, we set $a = 2km$, $b = 30m$, $d'' = 400m$, $R = 1\ km$ and false alarm probability P_f = 0.1. Similar to [34] the symbols are transmitted at 9.6 kbps rate (R_s) at carrier frequency (f_c) 1.9 GHz, u is bandwidth time product. Note that PU's protection range is R, within which SUs' are not allowed to use licensed frequency band if PU is present. Here d' is considered as the initial distance of SU to PU from where SU is initiating mobility.

Based on the methods provided in [29], we compute the shape and scale parameters of the distributions of the idle and busy periods. In this sections, based on the parameters, we compute the various values of ON and OFF period probabilities. This section also presents the simulation scenarios and numerical results obtained from simulations to corroborate our theoretical analysis presented in previous sections. Vehicular user (or SU) is considered to be mobile and each vehicular users has its sensing range. The residential base stations or access points are considered

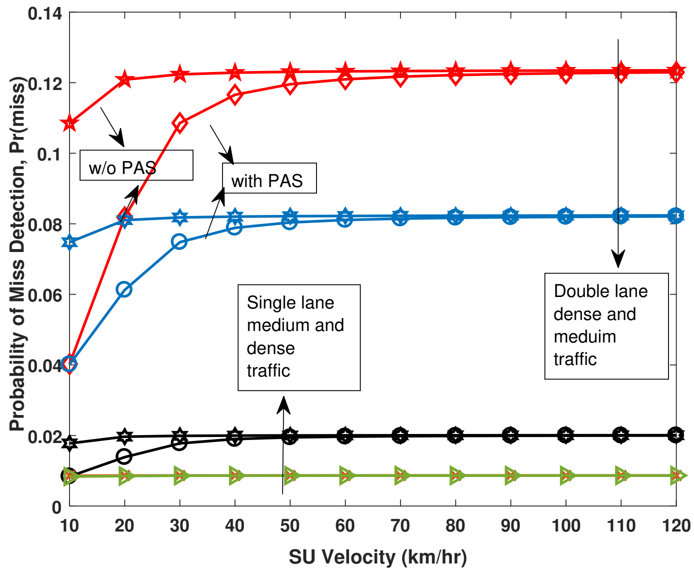

Fig. 2: Missed detection against SU velocity over various traffic (γ = 2 dB)

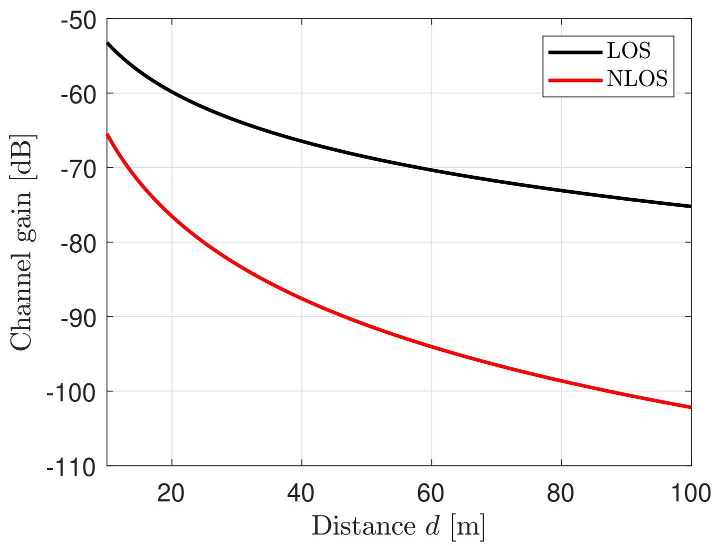

Fig. 3: Channel Gain vs Distance (No of Iterations = 10^6)

to be PUs and each PU has its protection range where SUs are not permitted to use PUs' active channels.

First, we analyse the point A for the variation of probability of missed detection for single lane and double scenario over medium and dense traffic with and without activity statistics as shown in Fig. 2. The maximum sensing range of SU is considered to be the same as the maximum range in IEEE 802.11p DSRC standard for vehicular networks as provided in [33]. We observed that

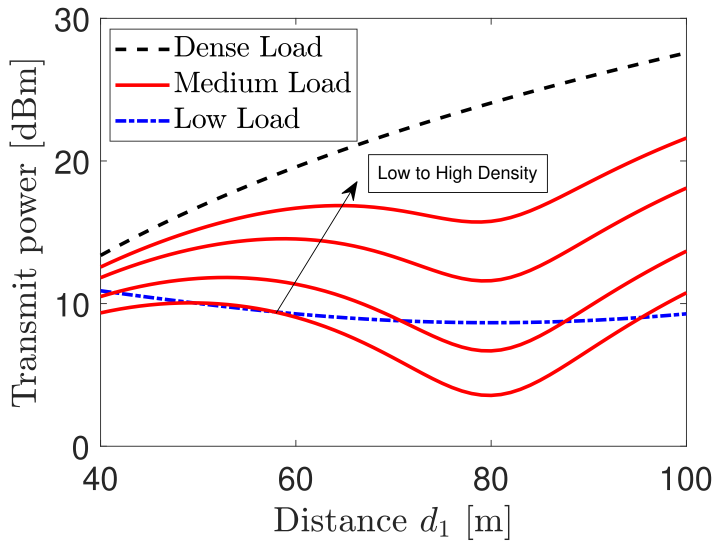

Fig. 4: Tx power requirement against distance for single lane as per IEEE 802.11p

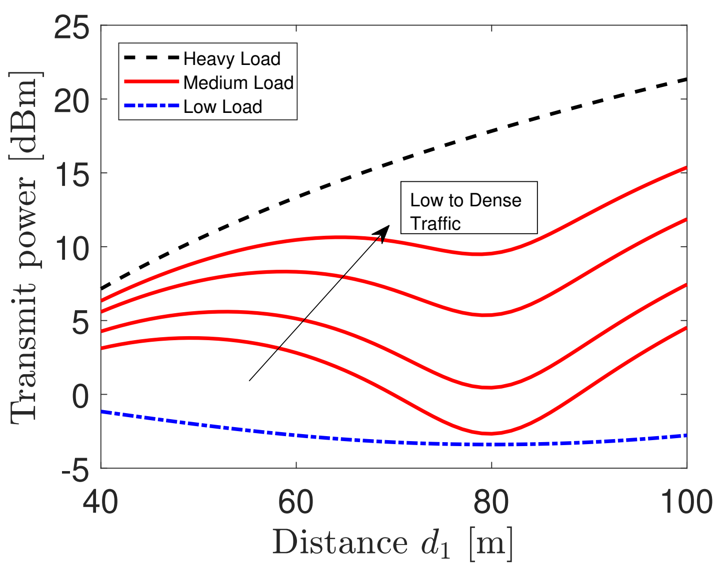

Fig. 5: Tx power requirement against distance for double lane as per IEEE 802.11p

the probability increases with the velocity as shown in Fig. 2. Then we plotted the channel gain obtained with respect to the distance of vehicle users in Fig. 3. It implies that for the LOS links the strength of the link is more than NLOS which is intuitive. In Fig. 4 and Fig. 5, according to various types of traffic load provide in [32], the requirement of transmit power against the distance of the vehicle user is plotted. It is noticeable that around 80 m distance which lies

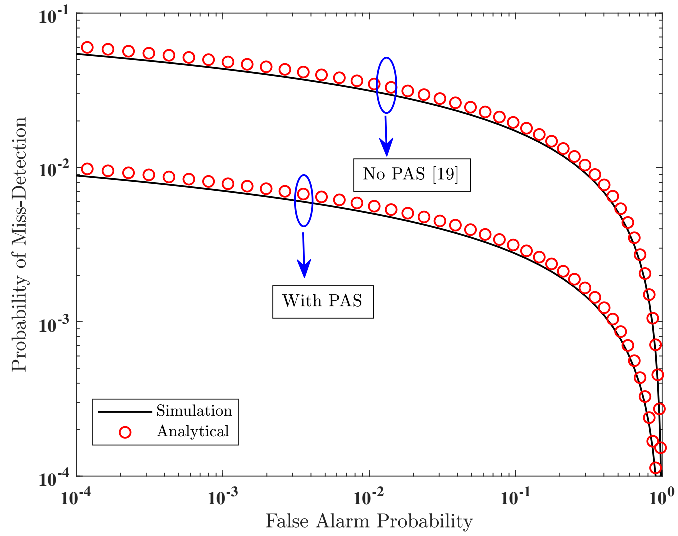

Fig. 6: Miss-detection probability against false alarm when Pr(ON) > Pr(OFF)

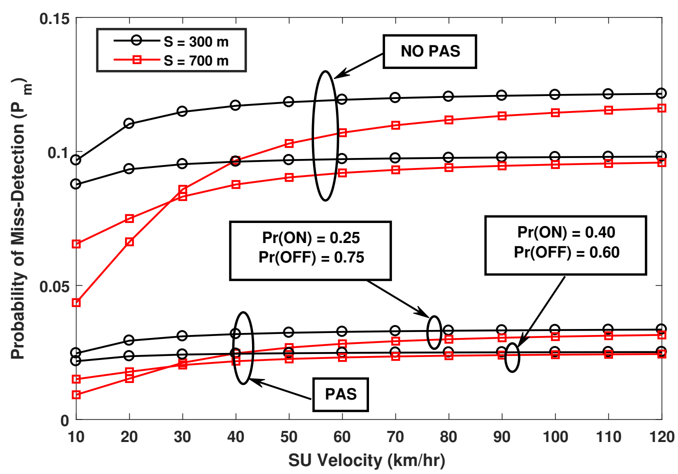

Fig. 7: Comparison of Miss-detection probabilities for different values of SU velocities with different sensing ranges for cases when Pr(OFF) > Pr(ON) for double lane - Medium (γ = 2 dB)

in the coverage of PUs, the requirement of transmit power is less for various densities. Note that, the simultaneous calculation of the activity statistics is performed in the simulation process with the interval of 1 second. In Fig. 6, to show the impact with the false alarm, the missed detection probability is plotted with and without PU activity statistics for single lane medium traffic conditions. Without PU activity statistics, the result reduced as per given in [22]. We

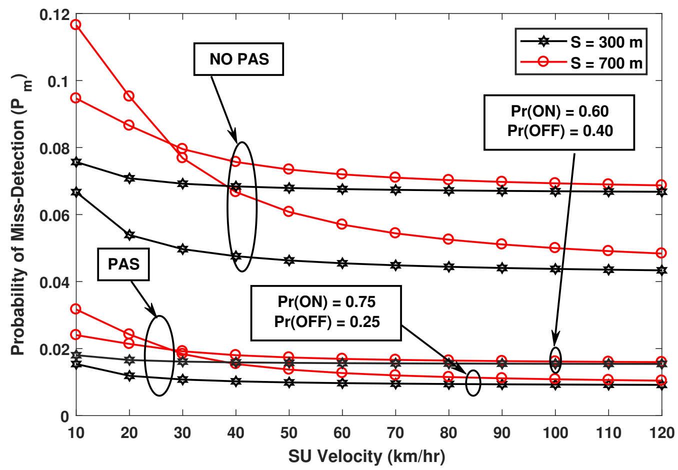

Fig. 8: Comparison of Miss-detection probabilities for different values of SU velocities with different sensing ranges for cases when Pr(ON) > Pr(OFF) for Single lane - Dense (γ = 2 dB)

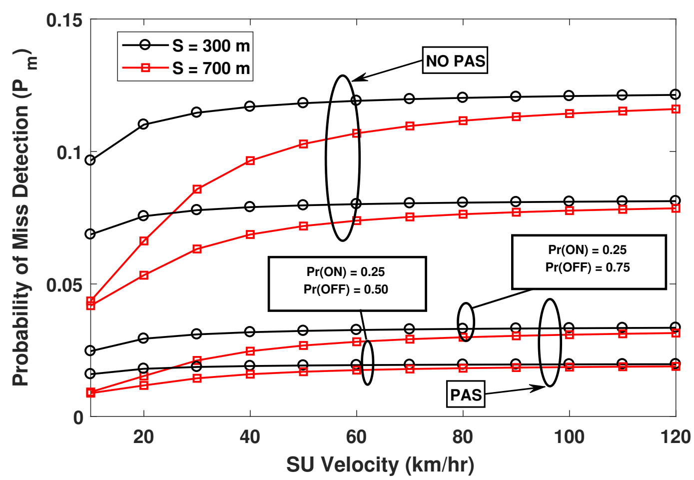

Fig. 9: Comparison of Miss-detection probabilities for different values of SU velocities with different sensing ranges for cases when Pr(OFF) > Pr(ON) for double lane dense (γ = 2 dB)

notice that the PU being active during the sensing period is increased to 0.9 and thus probability of miss detection is increased by 10 times when SU's speed is higher than 40km/hr as shown in Fig. 7. This is due to since PU was not active in previous sensing time period as expected but in actual case it is active thus results in higher missed detection probability. At the next, we choose various values of PU(ON$\rightarrow$ON), and we plot probability of miss-detection versus the velocity of SU with different sensing ranges as shown in Fig. 7. We observed that when PU(ON$\rightarrow$ON)

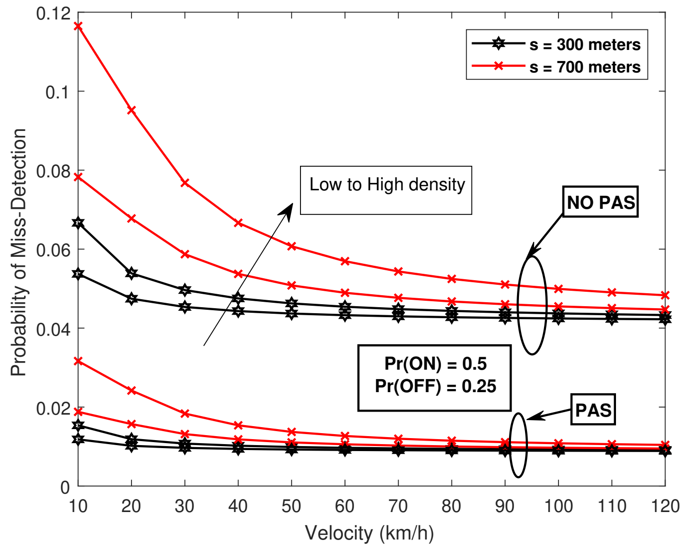

Fig. 10: Comparison of Miss-detection probabilities for different values of SU velocities with different sensing ranges for cases when Pr(ON) $>$ Pr(OFF) for single lane - Medium (γ = 2 dB)

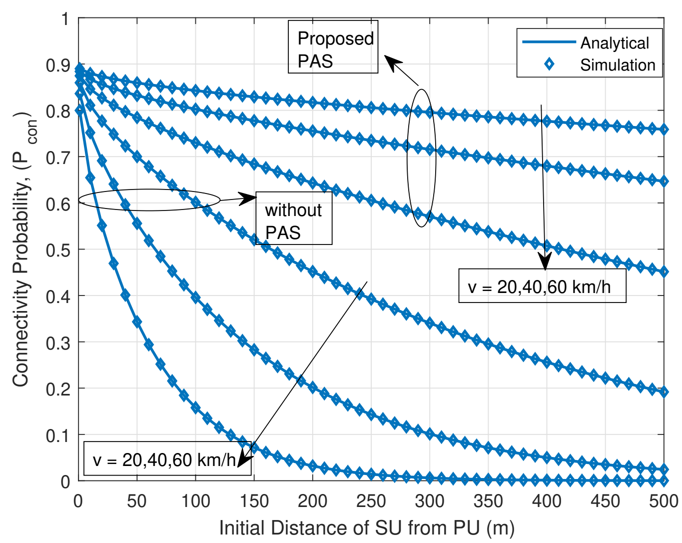

Fig. 11: Probability of Connectivity against Initial Distance of SU from PU

increased from to 0.9, the miss-detection probability increased for a given velocity as shown in Fig. 7. Moreover, when PU(ON→ON) is higher than PU(OFF →ON) , the miss-detection probability is decreasing for increasing velocity of the SU as shown in Fig. 7. Furthermore, we also observed from both Fig. 7 and Fig. 8, when probability PU(OFF →ON) is greater than or equal to the probability PU(ON→ON), the probability of miss detection increased. Then, we plotted the variation of missed detection probability of the SU's as per its speed as shown in Fig. 9. We consider that Pr(ON) is higher than Pr(OFF) to show the impact on missed detection probability due to activity statistics. Note that, for this particular scenario, we have considered the protection range of PU, r = 300 and 700 meters. The initial separation distance between PU and SU is considered as D = 200 meters but it has no significant i mpact d ue t o d ouble lane dense traffic.

In Fig. 9, the SU's sensing range was varied as s = 300 to 700 meter. In Fig. 10, we plotted the variation of probability of missed-detection Pr(miss) versus the speed of mobile SU where a given PU's protection range r = 110 meter, initial separation distance between PU and SU D = 200 meter and SU's sensing ranges ($s = 250, 500, 750\&100m$). The probability PU being ON, PU(OFF $\rightarrow$ ON) from 0.30 to 0.60 to 0.90 to see how PU's OFF to ON activity impacts the performance of miss detection. In Fig. 10 , we observed that the probability Pr(miss), decreased when the sensing range of the SU increased for a given PU(OFF $\rightarrow$ ON) value. However, the probability of miss-detection increased when the speed of the mobile SU increased for a given PU(OFF$\rightarrow$ ON) value. In Fig. 11, the probability of connectivity as a function of missed detection is plotted against the initial distance of SU from PU for single lane. It has been noted that under the PU activity, the probability of connectivity among the vehicle is higher than the idle case. It implies that the awareness regarding the PU's pattern is effectively utilised by SU and hence while performing the sensing task, the vehicle may remain connected with other vehicle. In other words, a faster speed resulted in a higher probability of missed detection as the fast speed made PU stay outside the sensing range of the SU, quickly resulting in a higher chance of missed detection of the PU's signal. We also observed that the expected missed detection for single lane increases with an increasing speed for a given sensing range and it increases with an increasing sensing range of the SU when the OFF probability is higher than the ON probability. This can be interpreted as, for a higher sensing range, the PU has a higher possibility to fall into the sensing range of the SU for a longer time duration. Furthermore, we also observed that the expected overlapping time was the highest since it assumes that the initial separation distance between the PU and the SU at the first moment of simulation is equal to the sensing range of the SU, and the PU and the SU are assumed to be within the communication range of each other at the beginning. The results give an insight of the behavior of the traffic density and its impact on the missed detection probability.

VI. Conclusion

In this paper, we have studied the combined impact of SU mobility and PU activity for opportunistic access in cognitive radio enabled vehicular networks. We derive an analytical model for the probability of missed detection for spectrum sensing, and we have shown the impact of the PU activity statistics. Performance of the proposed formal models are evaluated using numerical results obtained from Monte Carlo simulations. We found that when the speed of the vehicles increases, the probability of missed detection increases when the OFF probability is higher than the ON probability because at that time the chances of the vehicle being in the range of the PU are higher. (but no significant impact on false alarm) and for the reverse case the chances decreases. We also found that the connectivity probability is improved when PU activity is known. Opportunistic communications in cognitive connected vehicles can enhance the overall network performance by disseminating information in a timely manner.

Appendix A
The Derivation of Knowledge of Received SNR for Single Lane

In order to evaluate the missed detection over single lane and, the received SNR under the vehicle mobility can be derived by calculating the CDFs which is given as:

$$F_Z(z) = \int_0^\infty \int_{-\infty}^{yz} f_{XY}(x,y)dxdy \tag{61}$$

Since both the distributions are independent from each other and by substituting (11) and (12) in (9) we have,

$$F_Z(z) = \int_0^\infty \int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)} \frac{m}{\Omega}^{Lm} \left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m,m;Lm;\frac{mx^2}{\Omega}) \times f_Y(y)dxdy \tag{62}$$

At first integrating the inner integral with respect to dx and from [37, Eq. 6.4.1] the integral in (60) is further given by considering the appropriate identities

$$F_Z(z) = \frac{1}{ab} \times \frac{1}{\Gamma(m)} \times \left(\frac{1}{det(\Lambda)}\right)^m \times \int_0^\infty y\ Arcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2 F_1(\cdot)dy \tag{63}$$

Further to obtain final CDF, integrating again the above equation with respect to dy, by rearranging constant terms and performing some steps, (61) is further given as:

$$\begin{aligned} F_Z(z) = &\frac{yz^{mL}}{Lm}\left[\frac{2\Gamma(m-0.5)\Gamma(mL)}{2\Gamma(m)\Gamma(m)}\right] \\ &\times \int_0^\infty y\ Arcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2 F_1(\cdot)dy + yzF_1(\cdot) \\ &\times \int_0^\infty y\ Arcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2 F_1(\cdot)dy \end{aligned} \tag{64}$$

By separating the inner and outer integral we have the following arrangements. By solving the inner integral using [37], we have following term:

$$F_Z(z)^{Case1} == \int_0^{\infty} \frac{d}{4ab}\left[\pi + 2arcsin\left(\frac{2(y^2-(b-h)^2)}{y^2}\right) - 1\right] \int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)} \frac{m}{\Omega}^{Lm} \left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m, m; Lm; \frac{mx^2}{\Omega})dxdy. \tag{65}$$

The solution of inner integral is obtained by taking the identity of [12] in the section (7) of special integrals of hyper geometric function. Further we obtain:

$$F_Z(z)^{Case1} = \frac{z^2}{ab} \times \frac{1}{\Gamma(m)} \times \left(\frac{1}{det(\Lambda)}\right)^m \times \int_0^{\infty} yArcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2F_1(\cdot)dy. \tag{66}$$

Using [37, Section 6] and solving the integral by performing necessary steps, (67) is further simplified as given in (68). where, $F_1 = [\{0.5, m, m\}, \{1.5, Lm\}, yz^2]$. CDF can be expressed as:

$$G_Z(z) = \frac{z^{2LmB_k}}{Lm} \times F_1(p, q; r; s) \times \frac{1}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^{Lm} \times \frac{A_k}{det(\Lambda)}^m \tag{67}$$

where, $p = \frac{z}{2abLm}$, $q = \frac{1-det(\Lambda)}{4d}$, $r = \frac{2z}{2d^2+1}$, $s = \frac{1-det(\Lambda)}{Lm}$,$T_k = m_k\ L$ and $\lambda_k = e^{T_k}$

The above equation formed a general expression of reduced identity by performing Lagrangian polynomial for n term given in [37, Section 4, 6, 8]. At last, we get the reduced term as (21). Similarly, by substituting a respective PDFs and CDFs for exponential and arbitrarily correlation, we get the another reduced term for the same.

Appendix B
The Derivation of Knowledge of Received SNR for Double Lane

To derive the missed detection probability for both the lanes, at first, the CDF for received SNR is calculated which is given as under:

$$F_Z(z) = \int_{-\infty}^{yz} \int_0^{\infty} f_{XY}(x, y)dxdy \tag{68}$$

Both the distributions are uncorrelated thus substituting (21) and (22) in (20) we have,

$$F_Z(z) = \int_0^{\infty} \int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)} \frac{m}{\Omega}^{Lm} \left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(Lm, m; m; \frac{mx^2}{\Omega}) \times f_Y(y)dxdy \tag{69}$$

By integrating the inner integral with respect to dx and from [37], the integral in (65) is reduced to the appropriate identities,

$$F_Z(z)^{Case1} = \frac{z^2}{ab} \times \frac{1}{\Gamma(m)} \times \left(\frac{1}{det(\Lambda)}\right)^m \times \frac{d}{2ab}\left[\arcsin(\frac{2(d^2-{h_p}^2))}{d^2}1) - \arcsin(\frac{2(d^2-h^2))}{d^2}-1)\right]dy \tag{70}$$

Further to obtain final CDF, integrating again the above equation with respect to dy, by rearranging constant terms and performing some steps (66) is further given as:

$$F_Z(z)^{Case1} = \frac{yz^{Lm}}{2}\left[\frac{2\Gamma(m-0.5)\Gamma(Lm)}{2\Gamma(m)\Gamma(m)}\right] \times \int_0^\infty y\ Arcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2F_1(\cdot)dy + yzF_1(\cdot) \times \int_0^\infty y\ Arcsin\left(2y^2 - \frac{(b-h)^2}{y^2}\right) y^2F_1(\cdot)dy \tag{71}$$

By separating the inner and outer integral we have the following arrangements. By solving the inner integral using [37], we have following term.

$$F_Z(z) = \int_0^\infty \frac{d}{4ab}\left[\pi + 2arcsin\left(\frac{2(y^2-(b-h)^2)}{y^2}\right) - 1\right]\int_{-\infty}^{yz} \frac{2x^{Lm-1}}{\Gamma(L)}\frac{m}{\Omega}^{Lm}\left(\frac{1}{det(\Lambda)}\right)^m \times \Phi_2(m,m;Lm;\frac{mx^2}{\Omega})dxdy. \tag{72}$$

The solution of inner integral is obtained by taking the identity of [37] in the section (7) of special integrals of hyper geometric function. From [37], we solve the integral by performing necessary steps, (72) is further simplified as given in (73). where, $F_1 = [\{m, 0.5, m\}, \{0.5, Lm\}, yz^2]$. Similarly substituting (19) and (21) in (23), CDF for $Case\ 2$ can be expressed as:

$$F_Z(z)^{case2} = \frac{z^{mL}}{d''} \times F_1(i,k;j;l) \times \frac{1}{\Gamma(2)} \times \frac{1}{det(\Lambda)}^m \tag{73}$$

where, $i = \frac{1}{2abLm}$, $j = \frac{1-det(\Lambda)}{4d}$, $k = \frac{2z}{2d^2+1}$, $l = \frac{1-det(\Lambda)}{Lm}$. Moreover, we obtain the balance parameter for identity for the miss detection probability as:

$$L = \sum_{n=1}^{a} \lambda_i^n mz^m \frac{e^{z/ab}(1/ab)}{d^2} \tag{74}$$

References

[1] A. E. Kahn, T. J. Tardiff, and D. L. Weisman, "The telecommunications act at three years: an economic evaluation of its implementation by the federal communications commission," *Information Economics and Policy*, vol. 11, no. 4, pp. 319–365, 1999.

[2] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 ghz dsrc-based vehicular safety communication," *IEEE Wireless Commun.*, vol. 13, no. 5, pp. 36–43, 2006.

[3] S. Zeadally, R. Hunt, Y.-S. Chen, A. Irwin, and A. Hassan, "Vehicular ad hoc networks (vanets): status, results, and challenges," *Telecommunication Systems*, vol. 50, no. 4, pp. 217–241, 2012.

[4] D. B. Rawat, R. Alsabet, C. Bajracharya, and M. Song, "On the performance of cognitive internet-of-vehicles with unlicensed user-mobility and licensed user-activity," *Computer Networks*, vol. 137, pp. 98–106, 2018.

[5] A. Sładkowski and W. Pamuła, *Intelligent transportation systems-problems and perspectives*. Springer, 2016, vol. 303.

[6] D. B. Rawat, T. Amin, and M. Song, "The impact of secondary user mobility and primary user activity on spectrum sensing in cognitive vehicular networks," in *Proc. of IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2015, pp. 588–593.

[7] X. Qian and L. Hao, "Spectrum sensing with energy detection in cognitive vehicular ad hoc networks," in *Proc. of International Symposium on Wireless Vehicular Communications (WiVeC)*, 2014, pp. 1–5.

[8] K. D. Singh, P. Rawat, and J.-M. Bonnin, "Cognitive radio for vehicular ad hoc networks (cr-vanets): approaches and challenges," *EURASIP journal on wireless communications and networking*, vol. 2014, no. 1, p. 49, 2014.

[9] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 ghz dsrc-based vehicular safety communication," *IEEE wireless commun.*, vol. 13, no. 5, pp. 36–43, 2006.

[10] D. B. Rawat and C. Bajracharya, "Vehicular cyber physical systems," Springer, Tech. Rep., 2017.

[11] M. Di Felice, R. Doost-Mohammady, K. R. Chowdhury, and L. Bononi, "Smart radios for smart vehicles: Cognitive vehicular networks," *IEEE Vehicular Technol. Mag.*, vol. 7, no. 2, pp. 26–33, 2012.

[12] D. Niyato, E. Hossain, and P. Wang, "Optimal channel access management with qos support for cognitive vehicular networks," *IEEE Trans. Mobile Comput*, vol. 10, no. 4, pp. 573–591, 2010.

[13] Y. Sun and K. R. Chowdhury, "Enabling emergency communication through a cognitive radio vehicular network," *IEEE Communications Magazine*, vol. 52, no. 10, pp. 68–75, 2014.

[14] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys Tuts*, vol. 11, no. 1, pp. 116–130, 2009.

[15] A. W. Min and K. G. Shin, "Impact of mobility on spectrum sensing in cognitive radio networks," in *Proc of ACM workshop on Cognitive radio networks*, 2009, pp. 13–18.

[16] Z. Wei, F. R. Yu, and A. Boukerche, "Cooperative spectrum sensing with trust assistance for cognitive radio vehicular ad hoc networks," in *Proc. of the 5th ACM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications*, 2015, pp. 27–33.

[17] A. S. Cacciapuoti, I. F. Akyildiz, and L. Paura, "Primary-user mobility impact on spectrum sensing in cognitive radio networks," in *Proc. of IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*, 2011, pp. 451–456.

[18] K. W. Choi, E. Hossain, and D. I. Kim, "Cooperative spectrum sensing under a random geometric primary user network model," *IEEE Trans. Wireless Commun.*, vol. 10, no. 6, pp. 1932–1944, 2011.

[19] M. Di Felice, R. Doost-Mohammady, K. R. Chowdhury, and L. Bononi, "Smart radios for smart vehicles: Cognitive vehicular networks," *IEEE Vehicular Technology Magazine*, vol. 7, no. 2, pp. 26–33, 2012.

[20] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, 2014.

[21] N. Cordeschi, D. Amendola, M. Shojafar, and E. Baccarelli, "Performance evaluation of primary-secondary reliable resource-management in vehicular networks," in *Proc. of IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, 2014, pp. 959–964.

[22] A. Paul, A. Daniel, A. Ahmad, and S. Rho, “Cooperative cognitive intelligence for internet of vehicles,” *IEEE Systems Journal*, vol. 11, no. 3, pp. 1249–1258, 2015.

[23] X. Liu, Z. Zeng, C. Guo, and S. Zhu, “Performance analysis of spatial-temporal spectrum sensing for cognitive vehicular network,” in *Proceedings of the 3rd ACM workshop on mobile sensing, computing and communication*, 2016, pp. 1–6.

[24] D. K. Patel, B. Soni, and M. López-Benítez, “On the estimation of primary user activity statistics for long and short time scale models in cognitive radio,” *Wireless Networks*, vol. 25, no. 8, pp. 5099–5111, 2019.

[25] B. Soni, D. K. Patel, and M. López-Benítez, “Long short-term memory based spectrum sensing scheme for cognitive radio using primary activity statistics,” *IEEE Access*, 2020.

[26] S. Kavaiya, D. K. Patel, Y. L. Guan, S. Sun, Y. C. Chang, and J. M. Y. Lim, “Distributed spectrum sensing for cognitive vehicular networks using quasi-newton optimization,” in *Proc. of International Conference on COMmunication Systems NETworkS (COMSNETS)*, 2021, pp. 212–215.

[27] O. H. Toma, M. López-Benítez, D. K. Patel, and K. Umebayashi, “Estimation of primary channel activity statistics in cognitive radio based on imperfect spectrum sensing,” *IEEE Trans. Commun.*, vol. 68, no. 4, pp. 2016–2031, 2020.

[28] M. López-Benítez, A. Al-Tahmeesschi, D. K. Patel, J. Lehtomäki, and K. Umebayashi, “Estimation of primary channel activity statistics in cognitive radio based on periodic spectrum sensing observations,” *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 983–996, 2019.

[29] M. López-Benítez and F. Casadevall, “Time-dimension models of spectrum usage for the analysis, design, and simulation of cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 2091–2104, 2013.

[30] O. Thakkar, D. K. Patel, Y. L. Guan, S. Sun, Y. C. Chang, and J. M. Lim, “On the joint impact of su mobility and pu activity in cognitive vehicular networks with improved energy detection,” in *Proc. of IEEE 89th Vehicular Technology Conference*, 2019, pp. 1–6.

[31] B. Shang, L. Liu, H. Chen, J. C. Zhang, S. Pudlewski, E. S. Bentley, and J. D. Ashdown, “Spatial spectrum sensing in uplink two-tier user-centric deployed hetnets,” *IEEE Trans. Wireless Commun.*, 2020.

[32] B. Aygun and A. M. Wyglinski, “A voting-based distributed cooperative spectrum sensing strategy for connected vehicles,” *IEEE Trans. on Veh. technol.*, vol. 66, no. 6, pp. 5109–5121, 2016.

[33] S. Zhu, C. Guo, C. Feng, and X. Liu, “Performance analysis of cooperative spectrum sensing in cognitive vehicular networks with dense traffic,” in *Proc. VTC Spring*, 2016, pp. 1–6.

[34] L. Gahane, P. K. Sharma, N. Varshney, T. A. Tsiftsis, and P. Kumar, “An improved energy detector for mobile cognitive users over generalized fading channels,” *IEEE Trans. Commun.*, vol. 66, no. 2, pp. 534–545, Feb 2018.

[35] Y. Ai, M. Cheffena, A. Mathur, and H. Lei, “On physical layer security of double rayleigh fading channels for vehicular communications,” *IEEE Commun Lett.*, vol. 7, no. 6, pp. 1038–1041, Dec 2018.

[36] V. A. Aalo, “Performance of maximal-ratio diversity systems in a correlated nakagami-fading environment,” *IEEE Trans. Commun.*, vol. 43, no. 8, pp. 2360–2369, 1995.

[37] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*. Academic press, 2014.

[38] M. K. Simon and M. Alouini, “A unified approach to the performance analysis of digital communication over generalized fading channels,” *Proc. IEEE*, vol. 86, no. 9, pp. 1860–1877, Sep. 1998.

[39] N. Zlatanov, Z. Hadzi-Velkov, and G. K. Karagiannidis, “An efficient approximation to the correlated nakagami-m sums and its application in equal gain diversity receivers,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, 2010.