Performance of Hybrid Cognitive RF/VLC Systems in Vehicle-to-Vehicle Communications

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***Abstract*— Visible Light Communication is a promising ubiquitous candidate that can be leveraged to serve the rapidly growing vehicle-to-vehicle communication (V2V) networks. This high interest in visible light communication is fundamentally due to its ability to transmit secure data at a high rate with no interference to its compartments. In contrast, VLC suffers from the fact that most of its applications are mainly based on line-of-sight (LOS) components. Therefore, recent literature has focused on the possibility of integrating this technology with the existing radio frequency communication (RF) to improve the performance of the networks. In this paper, we present a decode-and-forward based hybrid underlay cognitive radio frequency/ visible light communication (CRF/VLC) cooperative system in vehicle-to-vehicle (V2V) communication networks. The system is composed of two links: direct link (DL) in parallel with a decode-and-forward based hybrid CRF/VLC cooperative link between the base station (BS) and the destination electric vehicle (EV2). The destination (EV2) employs a switching diversity technique which first selects a direct link. In case the signal quality for the direct link degrades, the destination (EV2) switches to the cooperative link in which the EV2 chooses either CRF link or VLC link based on the selection diversity technique. We further investigate the performance of the proposed system in terms of outage probability and bit error rate (BER). The closed-form analytical expression of the outage probability is derived. Our numerical and simulation results show that our system improves the performance in terms of lower outage probability and BER compared to employing the cognitive RF link stand alone. Our results show the advantage of less total transmission power allocation at the base station (BS). Finally, we study the impact of increasing the interference temperature power (Ip) on the outage probability performance.**

Keywords—Outage probability, Bit error rate, Interference temperature power

I. Introduction

Recently, vehicular communications have been gained a lot of attention as a means for facilitating the communications in vehicle-to-vehicle (V2V) and vehicle to-roadside units (V2RSU) networks [1]. For a long time, the overwhelming majority of wireless vehicular communications were mainly based on radio frequency networks (RF). However, allocating the RF communication for vehicular systems is limited since the RF network suffers from a scarcity of available resources due to the rapid growth of wireless services and adopting multiple distributed network services [2]. In addition, the RF network experiences enormous interference for high-density traffic [2]. Cooperative wireless communications have been widely considered to be an adequate technique to extend the RF coverage area in vehicular communication networks [3]. Consequently, there is a growing need for utilizing the RF spectrum by employing intelligent radio frequency namely cognitive radio frequency (CRF). Cognitive system radio frequency is an intelligent communication system that can improve the scarcity of RF resources and high mobility [4]. The cognitive radio is based fundamentally on the spectrum sharing concept between the primary users (PUs) and secondary users (SUs) in order to give relief for the congested RF spectrum [4]. Due to the complexity and vastly dynamic system of the cognitive RF, these systems experience serious challenges for reliability and transmission power consumption. Lately, visible light communications (VLC) have been shown as an effective network to overcome these issues in indoor and outdoor scenarios [5]. The superiority of VLC over conventional RF is due to the following reasons: i) it employs mainly the light-emitting diodes LEDs that are ubiquitous in all modern vehicles and street lightings; ii) it reduces the allocated power consumption; iii) it operates on unlicensed frequency spectrum; iv) it achieves high secure data transmission rates and v) it has no interference with the existing RF networks due to the fact that light operates in a different spectrum band [8]. Nevertheless, many recent studies have recognized the critical drawbacks of employing the VLC stand-alone in V2V communications. VLC is based fundamentally on the line-of-sight (LOS) components which could increase the probability of losing connectivity through long-range communications [6]. Therefore, recent studies have shown that the coexistence of RF and VLC in vehicular communications could be utilized to improve the performance of the system as well as maintain high data transmission rates. The authors in [7] studied the hybrid RF/VLC system's secrecy using a Decode-and-Forward Relaying (DFR) technique. The researchers employed a zero-force beamforming method to develop the proposed hybrid network, where security algorithms in the physical layers were utilized to prevent eavesdropping [7]. On the other hand, the researchers in [8] implemented a vehicular architecture of a hybrid VLC/RF communication. The work in [8] is slightly similar to [7] since it also focused on evaluating downlink and uplink signals in the hybrid VLC/RF scenario. However, the study in [8] implemented the downlink signal for the VLC technology and uplink transmission using RF to mitigate the overload on the RF network. The results in [8] showed that the proposed system outperformed to download high-speed data during driving using VLC links, while offered access to data services through the uplink based on RF technology. Alternatively, the scheme proposed by the researchers in [9] was diverse in the sense that the QoS exponent would affect the received data rates at the transmitter buffer, especially at the RF link which suffered from a higher impact. However, the

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proposed system in [9] employed the effective capacity for the indoor downlink hybrid RF/VLC system based on a selection process via the Access Point Controller APC. The study in [9] assumed that the destination is located within the coverage area of the VLC cell.

Nevertheless, despite the existing hybrid systems proposed in the literature to enhance the efficiency of the vehicular communication, there is still a need to improve the throughput that is affected by the resource allocation problem in RF and loss of connectivity in VLC. In this paper, we mitigate these problems by optimizing the existing solutions to achieve a considerable efficiency through the data transmission between vehicles. Through our novelty, we propose a decode-and-forward based hybrid underlay cognitive radio frequency/ visible light communication (CRF/VLC) cooperative system in vehicle-to-vehicle communications (V2V). By considering the impacts of using limited spectrum resources and the efficiency of the data transmission in a long distance, we employ the cognitive radio frequency link. (CRF) under the following manner:

- *Cooperative Communication:* we assume the electric vehicle to act as a relay, which helps to optimize the data delivery in a long-range communication.
- *Underly Spectrum Sharing:* which gives the opportunity for secondary users (SUs) to access and utilize the spectrum in parallel with the primary users (PUs) under the same frequency as well as maintaining the interference power constraints of PUs.

For the VLC link, we employ a widely used module namely, intensity modulation and direct detection (IM/DD), in case of the line- of- sight (LOS) components. Our main goal is to utilize the spectrum resources as well as enhance the data transmission by improving the outage probability and the bit error rate (BER) in vehicle-to-vehicle communications.

The following sections in the paper are structured as follows: section II, the description of the system model is presented. Performance analysis is discussed in section III. In addition, the implementation and discussion of simulation results are shown in Section IV. Finally, the conclusion and further work are discussed in Section V.

II. System Model

In this section, we present the design of our proposed system.

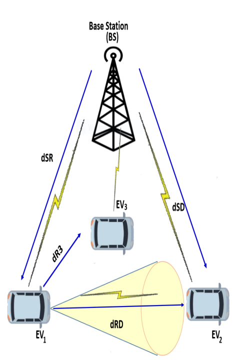

Fig.1. Schematic diagram of proposed hybrid CRF/VLC system where each of the RF node comprises of a single antenna

This work considers vehicle-to-vehicle communications (V2V) composing of a base station (BS), an electric vehicle relay (EV1,) an electric vehicle destination (EV2) and a primary receiver (EV3). The direct link between the BS and either the EV1 or EV2 uses the traditional RF network while we operate the hybrid (CRF/VLC) networks at the link between the EV1 and EV2. Hence, the proposed system employs a decode-and-forward based hybrid undelay cognitive radio frequency/visible light communication (CRF/VLC) cooperative system as shown in Fig. 1 where the destination electric vehicle (EV2) employs the switching diversity technique. In this technique, the signal from the base station (BS) is fed to the EV2 for decoding the symbol as long as the quality of that signal remains above some prescribed threshold α. When the signal quality degrades, the cooperative signal is switched in which the EV2 selects either CRF link or VLC link from a cooperative electric vehicle relay (EV1) to decode the symbol transmitted by the BS. For simplicity, we consider BS, EV1, EV2 and EV3 as S, R, D and 3 , respectively. The switching at the EV2 is done based on the instantaneous SNRs $\gamma_{SD}, \gamma_{SR}, {\gamma_{RD}}^{(1)}$ and ${\gamma_{RD}}^{(2)}$ of BS-EV2, BS-EV1, EV1(CRF)-EV2 and EV1(VLC)-EV2 links, respectively. The node EV2 chooses the direct link if $\gamma_{SD} \geq \alpha$ otherwise it switches to either the relay-cooperative CRF link or VLC link. For $\gamma_{SD} <$ α, the EV2 selects the RF link when $\gamma_{RD}^{(1)} > {\gamma_{RD}}^{(2)}$ otherwise it selects the VLC link based on the selection diversity technique. Therefore, the performance of the relay-cooperative link can be characterized by the minimum of γ_{SR} and γ_{RD}, where the $\gamma_{RD} = \max\{{\gamma_{RD}}^{(1)}, {\gamma_{RD}}^{(2)}\}$,since the end-to-end performance is dominated by the weakest link.

In this system, the end-to-end communication between the BS and EV2 comprises of two phases, the broadcast phase and the cooperative relaying phase as illustrated below:

A. The Direct Link Phase

Each node implements a single antenna with a half-duplex mode under the Rayleigh fading distribution. In this phase, the BS broadcasts the BPSK modulated symbol x with unit power i.e., $E|x|^2$= 1 to EV2 and EV1. Therefore, the received signals at the EV2 and EV1 corresponding to the transmission by the BS can be written as,

$$y_{SD} = \sqrt{P_S}\, h_{SD} x + n_{SD} \tag{1}$$

$$y_{SR} = \sqrt{P_S}\, h_{SR} x + n_{SR} \tag{2}$$

where P_S is the power at the BS and n_{SD} and n_{SR} denote the AWGN noise which is modeled as complex Gaussian with zero mean and variance N0. Both real and imaginary terms follow Gaussian distribution with zero mean and variance N0/2. The quantities $h_{SD} = \sqrt{d_{SD}^{-\beta}\,\overline{h_{SD}}}$, $h_{SR} = \sqrt{d_{SR}^{-\beta}\,\overline{h_{SR}}}$ are the channel coefficients between the BS and EV2, and the BS and EV1, respectively, where β is the path loss exponent, $\overline{h_{SD}}$, $\overline{h_{SR}}$ are modeled complex Gaussian with zero mean and variance 1, d_{SD} and d_{SR}, denote the distance between the BS and EV2, and BS and EV1, respectively.

B. *The Cooperative Relaying Phase*

In the second phase, the intermediate vehicle EV1 implements the decode-and-forward protocol in which first it decodes the symbol and re-transmits the decoded symbol to the destination vehicle EV2 over the cognitive RF or VLC link. Due to RF spectrum scarcity, the proposed system employs underlay cognitive RF. The EV1 uses the RF spectrum of the primary user where the transmit power of the EV1 is regulated such that the interference at the primary receiver (EV3) is within the specified limit. In this phase, EV2 receives the decoded symbol by one of the following links based on the selection diversity technique:

1) *Cognitive RF Link Between EV1 and EV2:*

The received RF signal at the EV2 corresponding to the transmission of decoded symbol $\hat{x}$ by the EV1 can be written as,

$$y_{RD,1} = \sqrt{P_R}\, h_{RD,1}\, \hat{x} + n_{RD,1} \tag{3}$$

where P_R is the RF transmit power of the EV1 which can be controlled as $P_R = \frac{I_P}{|h_{R3}|^2}$ to limit the interference at the primary vehicle EV3. Here Ip denotes the interference temperature power and $|h_{R3}|^2$ is the cross-channel gain between the EV1 and the EV3. The quantities $n_{RD,1}$ denote the AWGN noise and $h_{RD,1} = \sqrt{d_{RD,1}^{-\beta}\, h_{RD,1}}$ is the channel coefficient between the EV1 CRF and EV2, where $\overline{h_{RD,1}}$ is modeled complex Gaussian with zero mean and variance 1, and $d_{RD,1}$ denotes the distance between the EV1 CRF and EV2.

2) *VLC Link Between EV1 and EV2:*

This paper employs the line of sight (LOS) module of intensity modulation and direct detection (IM/DD). The VLC link has been considered between EV1 and EV2 assuming that the LEDs of both vehicles have been located at the same height from the ground. The front LED light on EV1 is employed as a transmitter while the tail light at EV2 is operated as a receiver (Photodiode PD). The LED at EV1 converts the electrical signal to the optical signal and immediately conveys the optical signal to the outdoor environment. Similarly, the PD at EV2 receives the optical signal and converts the received signal to the electrical signal. Fig.2 shows the configuration of the VLC V2V communication.

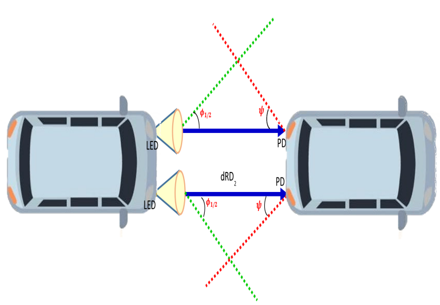

Fig.2. the VLC vehicle-to-vehicle communications between EV1 and EV2

Accordingly, the received signal is given at the photodetector considering Lambertian model by:

$$y_{RD,2} = \widetilde{x_v}\, h_{RD,2} + n_{RD,2} \tag{4}$$

where $\widetilde{x_v} \in \mathbb{R}^+$ is the emitted intensity by the LED with $E\{\widetilde{x_v}\} = P_v$ and $n_{RD,2}$ is the additive thermal noise which is modeled as a real-valued Gaussian random variable with zero mean and variance N'_0. The optical channel gain $h_{RD,2} \in \mathbb{R}^+$ at a given distance $d_l = d_{RD,2}$ is expressed as:

$$h_{RD,2} = \frac{(r+1)A}{2\pi d_1^2} \cos^r(\phi) T_s(\psi) g(\psi) \cos(\psi) rect\left(\frac{\psi}{\psi c}\right) \tag{5}$$

where A, ϕ, ψ, and ψc denote the PD physical area, the angle of irradiance, the angle of incidence with respect to the normal axis to the PD plane, and the field of view (FOV) angle of the photodetector, respectively. The optical signal propagates through the concentrator and optical filter in order to aggregate more light from the PD surface area thus improve the received gain. The parameters $T_s(\psi)$ and $g(\psi)$ are the gain of the optical filter and concentrator gain of the PD, respectively. The Lambertian index r is defined as: $r = -1/\log_2(\cos(\phi_{1/2}))$ where $\phi_{1/2}$ is the LED half intensity viewing angle. The $rect\,(\psi/\psi c)$ is an indicator function.

III. PERFORMANCE ANALYSIS

Using expressions (1), (2), and (3), the received instantaneous SNRs considering the scenario when each of the nodes is static and perfect channel knowledge is available at each receiving node can be expressed as:

$$\gamma_{SD} = \frac{P_S\,|h_{SD}|^2}{N_0}, \gamma_{SR} = \frac{P_S\,|h_{SR}|^2}{N_0}, \gamma_{RD}^{(1)} = \frac{P_R\,|h_{RD,1}|^2}{N_0}$$

Further, considering the above system model for VLC along with intensity modulation and direct detection (IMDD) technique, the instantaneous SNR at the EV2 after the optical-to-electrical conversion can be obtained using (4):

$$\gamma_{RD}^{(2)} = \frac{(\alpha' P_v\, h_{RD,2})^2}{\chi^2 N'_0} \tag{6}$$

where α' is the optical-to-electrical conversion efficiency of the photodetector and χ is the ratio between the average optical power and the average electrical power of the transmitted signal.

Let γ_{th} denotes the threshold for SNR outage at the EV2 and ϵ (γth) denotes the corresponding outage event. Therefore, the outage probability Pr (ϵ(γth)) at the EV2 can be derived as:

$$\Pr\,(\epsilon(\gamma_{th})) = \Pr\,(\epsilon(\gamma_{th}) \cap \phi) + \Pr\,(\epsilon(\gamma_{th}) \cap \bar{\phi}) \tag{7}$$

where $\Pr\,(\epsilon(\gamma_{th}) \cap \phi)$ and $\Pr\,(\epsilon(\gamma_{th}) \cap \bar{\phi}))$ denote the outage probabilities corresponding to the direct transmission and relay cooperation events respectively.

In the following sub-section the closed form analytical expressions of outage probability for each phase will be derived individually as follows:

A. *Relay Cooperative Link Outage Probability*

The analytical expression of outage probability in the cooperative link $\Pr\,(\epsilon(\gamma_{th}) \cap \bar{\phi})$ can be represented as:

$$\Pr\left(\epsilon(\gamma_{th}) \cap \bar{\phi}\right) = \Pr\left(\min\{\gamma_{SR}, \max\{\gamma_{RD}{}^{(1)}, \gamma_{RD}{}^{(2)}\}\} \leq \gamma_{th}\right) \Pr(\gamma_{SD} \leq \alpha)$$

$$= \Pr(\min\{\gamma_{SR}, \gamma_{RD}\} \leq \gamma_{th}) \Pr(\gamma_{SD} \leq \alpha) \quad (8)$$

where $\gamma_{RD} = \max\{\gamma_{RD}{}^{(1)}, \gamma_{RD}{}^{(2)}\}$. The above expression for $\Pr\left(\epsilon(\gamma_{th}) \cap \bar{\phi}\right)$ can be solved as:

$$\Pr\left(\epsilon(\gamma_{th}) \cap \bar{\phi}\right) = F_{\gamma SRD}(\gamma_{th})\, F_{\gamma SD}(\alpha) \quad (9)$$

where $F_{\gamma SRD}(\gamma_{th}) = \Pr(\min\{\gamma_{SR}, \gamma_{RD}\} \leq \gamma_{th})$ denotes the CDF of $\gamma_{SRD} = \min\{\gamma_{SR}, \gamma_{RD}\}$. The CDF of $F_{\gamma SRD}(\gamma_{th})$ can be obtained as [10,11]:

$$\begin{aligned} F_{\gamma SRD}(\gamma_{th}) &= \Pr(\min\{\gamma_{SR}, \gamma_{RD}\} \leq \gamma_{th}) \\ &= F_{\gamma SR}(\gamma_{th}) + F_{\gamma RD}(\gamma_{th}) \\ &\quad - F_{\gamma SR}(\gamma_{th})\, F_{\gamma RD}(\gamma_{th}) \end{aligned} \quad (10)$$

where $F_{\gamma RD}(\gamma_{th})$ denotes the CDF of $\gamma_{RD} = \max\{\gamma_{RD}{}^{(1)}, \gamma_{RD}{}^{(2)}\}$ and can be derived considering two different cases:

1) Case I: when VLC link is stronger than CRF link i.e., $\gamma_{RD}{}^{(2)} \geq \gamma_{RD}{}^{(1)}$, the first term contributing to the CDF $F_{\gamma RD}(\gamma_{th})$ can be derived as:

$$\begin{aligned} F_{\gamma_{RD}^{*}}(\gamma_{th}) &= \Pr(\gamma_{RD}{}^{(2)} \leq \gamma_{th} \mid \gamma_{RD}{}^{(1)} \leq \gamma_{RD}{}^{(2)}) \Pr(\gamma_{RD}{}^{(1)} \leq \gamma_{RD}{}^{(2)}) \\ &= F_{\gamma_{RD}^{(2)}}(\gamma_{th})\, F_{\gamma_{RD}^{(1)}}\left(\gamma_{RD}{}^{(2)}\right) \end{aligned} \quad (11)$$

where $F_{\gamma_{RD}^{(2)}}(\gamma_{th})$ for the deterministic VLC channel is:

$$F_{\gamma_{RD}^{(2)}}(\gamma_{th}) = \begin{cases} 1, & \gamma_{RD}{}^{(2)} \leq \gamma_{th} \\ 0, & \gamma_{RD}{}^{(2)} > \gamma_{th} \end{cases}$$

2) Case II: when RF link is stronger than VLC link i.e., $\gamma_{RD}{}^{(1)} > \gamma_{RD}{}^{(2)}$, the second term contributing to the CDF $F_{\gamma RD}(\gamma_{th})$ can be derived as:

$$\begin{aligned} F_{\gamma_{RD}^{**}}(\gamma_{th}) &= \Pr(\gamma_{RD}{}^{(1)} \leq \gamma_{th} \mid \gamma_{RD}{}^{(1)} > \gamma_{RD}{}^{(2)}) \Pr(\gamma_{RD}{}^{(1)} > \gamma_{RD}{}^{(2)}) \\ &= F_{\gamma_{RD}^{(1)}}(\gamma_{th}) - F_{\gamma_{RD}^{(1)}}(\gamma_{th})\, F_{\gamma_{RD}^{(1)}}\left(\gamma_{RD}{}^{(2)}\right) \end{aligned} \quad (12)$$

Now, using the above expressions, the closed-form expression for the CDF of $F_{\gamma RD}(\gamma_{th})$ can be written as,

$$\begin{aligned} F_{\gamma RD}(\gamma_{th}) &= F_{\gamma_{RD}^{*}}(\gamma_{th}) + F_{\gamma_{RD}^{**}}(\gamma_{th}) \\ &= F_{\gamma_{RD}^{(1)}}(\gamma_{th}) + F_{\gamma_{RD}^{(1)}}\left(\gamma_{RD}{}^{(2)}\right)\left[F_{\gamma_{RD}^{(2)}}(\gamma_{th}) - F_{\gamma_{RD}^{(1)}}(\gamma_{th})\right] \end{aligned} \quad (13)$$

Consequently, substituting the above expression in (10) and the resulting expression in (9), $\Pr\left(\epsilon(\gamma_{th}) \cap \bar{\phi}\right)$ can be written as:

$$\Bigg(F_{\gamma SR}(\gamma_{th}) + F_{\gamma_{RD}^{(1)}}(\gamma_{th}) + F_{\gamma_{RD}^{(1)}}\left(\gamma_{RD}{}^{(2)}\right)\left(F_{\gamma_{RD}^{(2)}}(\gamma_{th}) - F_{\gamma_{RD}^{(1)}}(\gamma_{th})\right) - F_{\gamma SR}(\gamma_{th}) \left\{ F_{\gamma_{RD}^{(1)}}(\gamma_{th})\, F_{\gamma_{RD}^{(1)}}\left(\gamma_{RD}{}^{(2)}\right)\left[F_{\gamma_{RD}^{(2)}}(\gamma_{th}) - F_{\gamma_{RD}^{(1)}}(\gamma_{th})\right] \right\} \Bigg) F_{\gamma SD}(\alpha) \quad (14)$$

where $F_{\gamma_{RD}^{(2)}}(\gamma_{th}) = \begin{cases} 1, & \gamma_{RD}{}^{(2)} \leq \gamma_{th} \\ 0, & \gamma_{RD}{}^{(2)} > \gamma_{th} \end{cases}$

B. Direct Link Outage Probability

The quantity outage probability $\Pr(\epsilon(\gamma_{th}) \cap \phi)$ in (7) can be derived for the direct link between the BS and EV2 considering the case when $\gamma_{SD} \geq \alpha$, $\gamma_{SD} \leq \gamma_{th}$ and $\alpha \leq \gamma_{th}$ as:

$$\begin{aligned} \Pr(\epsilon(\gamma_{th}) \cap \phi) &= \Pr(\alpha \leq \gamma_{SD} \leq \gamma_{th}) \\ &= F_{\gamma SD}(\gamma_{th}) - F_{\gamma SD}(\alpha) \end{aligned} \quad (15)$$

However, for the scenario when $\alpha \geq \gamma_{th}$, the outage probability $\Pr(\epsilon(\gamma_{th}) \cap \phi)$ in (7) would be zero.

Considering BS, EV1, EV2 and EV3 as S, R, D and 3 respectively, the CDFs $F_{\gamma ij}(x), i \in \{S\}, j \in \{R, D, 3\}$ in (10) and (15) for Rayleigh fading link between the nodes *i* and *j* can be simply derived after multiple calculations as:

$$F_{\gamma ij}(\gamma_{th}) = 1 - \exp\left(-\frac{N_0 \gamma_{th}}{P_S\, d_{ij}^{-\beta}}\right) \quad (16)$$

Using the above expressions, the closed-form expression for the CDFs of $F_{\gamma SR}(\gamma_{th})$ and $F_{\gamma SD}(\gamma_{th})$ can be written as:

$$F_{\gamma SR}(\gamma_{th}) = 1 - \exp\left(\frac{-\gamma_{th} N_0}{P_S (d_{SR})^{-\beta}}\right),$$

$$F_{\gamma SD}(\gamma_{th}) = 1 - \exp\left(\frac{-\gamma_{th}\, N_0}{P_S\, (d_{SD})^{-\beta}}\right)$$

The CDF $F_{\gamma_{RD}^{(1)}}(\gamma_{th})$ of $\gamma_{RD}{}^{(1)} = \frac{I_P |h_{RD,1}|^2}{N_0 |h_{R3}|^2}$ in (11) can be derived as:

$$F_{\gamma_{RD}^{(1)}}(\gamma_{th}) = \Pr\left(\frac{I_P |h_{RD,1}|^2}{N_0 |h_{R3}|^2} \leq \gamma_{th}\right)$$

Given $z = |h_{R3}|^2$, the above expression can be expressed as:

$$F_{\gamma_{RD}^{(1)}}(\gamma_{th}) = \int_0^\infty \Pr\left(|h_{RD,1}|^2 \leq \frac{\gamma_{th}\, N_0\, z}{I_P}\right) f_{|h_{R3}|^2}(z) dz$$

Given that $F_{h_{RD,1}}(y) = 1 - \exp\left(\frac{-y}{(d_{RD,1})^{-\beta}}\right)$, the CDF $F_{\gamma_{RD}^{(1)}}(\gamma_{th})$ can be derived as:

$$F_{\gamma_{RD}^{(1)}}(\gamma_{th}) = \int_0^\infty f_{|h_{R3}|^2}(z)dz - \int_0^\infty \exp\left(\frac{-N_0\gamma_{th}\, z}{I_P(d_{RD,1})^{-\beta}}\right) f_{|h_{R3}|^2}(z)dz$$

After multiple derivations, we sub site the above PDF in $f_{|h_{R3}|^2}(z) = \frac{1}{(d_{R3})^{-\beta}} \exp\left(\frac{-z}{(d_{R3})^{-\beta}}\right)$, the CDF $F_{\gamma_{RD}^{(1)}}(\gamma_{th})$ can be derived as:

$$F_{\gamma_{RD}^{(1)}}(\gamma_{th}) = = 1 - \frac{1}{(d_{R3})^{-\beta}} \frac{1}{\frac{N_0\gamma_{th}}{I_P(d_{RD,1})^{-\beta}} + \frac{1}{(d_{R3})^{-\beta}}} \quad (17)$$

IV. SIMULATION RESULTS

This section presents the simulation results to analyze our system performance. For simulation, the simulation parameters are depicted in Table 1. The VLC thermal noise is modeled as Gaussian random variable with variance $N'_0 = N_v B_v$ and we assume all vehicles are static at the following coordinates: EV1, BS, EV3, EV2 are set as (3,3,0), (6,6,6), (1,1,0), and (0,0,0) respectively. We set the transmit power at BS to be within the range from 0 dBm to 50 dBm. We evaluate our proposed system by the following evaluation metrics: outage probability, bit error rate (BER), varying transmit power at BS and finally increasing the temperature interference power at the primary vehicle (EV3). The results show that the proposed system improves the performance of V2V communication in terms of outage probability and bit error rate. Simultaneously, the result is compared with the cognitive RF stand-alone to investigate the achieved improvement. The numerical and simulation results have been discussed below as follows:

Table 1 Simulation Parameters

Parameter	Value	Parameter	Value
Interference temperature power, (Ip)	10 dBm	**Transmit power at LED, (Pv)**	100 watts
AWGN cognitive RF variance, (N_0)	1	**Gain of the optical filter , $T_s(\psi)$**	1
Outage probability threshold , (γ_{th})	0 dBm	**Concentrator gain , $g(\psi)$**	1
Switching diversity threshold, (α)	8 dBm	**LED half intensity viewing angle, ($\phi_{1/2}$)**	60 deg
Responsivity of photodiode, (α')	0.8 A/W	**Incidence angle at PD, (ψ)**	60 deg
Optical-to-electrical average power ratio (χ)	1	**Angle of irradiance, (ϕ)**	0 deg
Noise power spectral density, (Nv)	10^{-21} A²/Hz	**PD field of view (FOV), ψc**	85 deg
Modulation bandwidth, (Bv)	20MHz		

A. Outage Probability

Fig.3 demonstrates the performance of the proposed system in terms of outage probability and also compares the performance of the system without VLC. First, it can be seen that the analytical values obtained using the expressions derived in the previous section exactly match with the simulation, thereby validating the analytical results derived in this paper. Second, the end-to-end performance of the system improves with increasing the transmit power at the BS. Further, it can be seen that the system performance with and without VLC is identical at low transmit power at the BS. This arises because the end-to-end performance is dominated by the BS-relay link at low transmit power at BS. As transmit power at the BS increases, the performance with VLC outperforms the system without VLC. For the outage probability 4.28×10−3 at the EV2, the system with VLC requires 9.39 dBm less power at the BS as compared to the system without VLC as depicted in Fig.3.

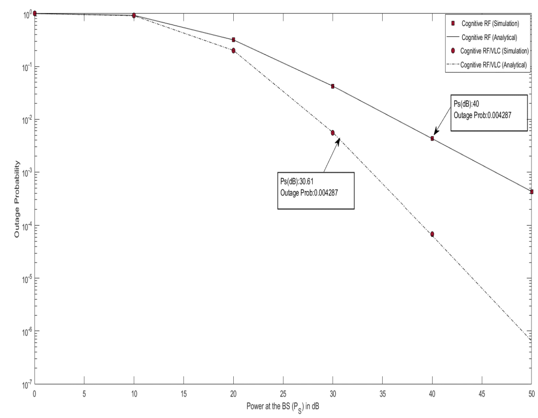

Fig. 3. Outage probability performance comparison of the proposed system with the cognitive RF

B. Bit Error Rate (BER):

Fig. 4 shows the bit error performance of the systems, where we consider the same system parameters as mentioned above.

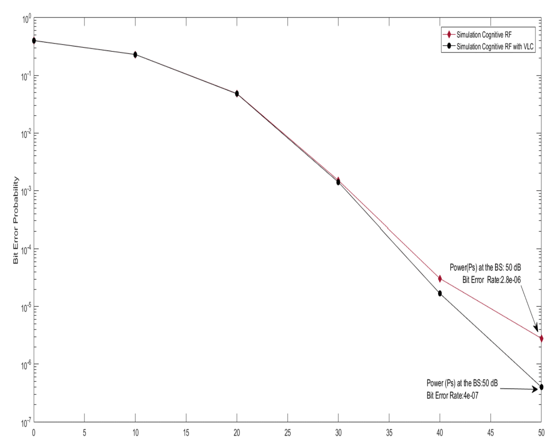

Fig.4. Bit error rate (BER) comparison of the proposed system to the Cognitive RF

Similar to SNR outage probability, the end-to-end error performance of the system improves with increasing the transmit power at the BS. When comparing the proposed system results to those in cognitive RF, it must be pointed out that our novel system is more robust to mitigate the error percentage at the received signal through data transmissions. The results demonstrate that the BER at Ps=50dbm improved from 2.8x10-6 to 4x10-7 in case of our proposed system. Further, it can be seen that the system performance with and without VLC link is identical at low transmit power at the BS. However, as *transmit power at the BS increases, the performance with VLC outperforms the system without VLC***.**

C. *Effect of Interference Temperature Power:*

Fig. 5 demonstrates the system outage performance with varying interference temperature power (Ip) regulated by the primary vehicle (EV3). Our results showed that the outage probability at EV2 decreases from 10−3 to 10−6 at Ps = 50 dBm as the value of Ip increases from 5dBm to 50 dBm. This finding proves the fact that the transmit power at the EV1 for cognitive RF transmission is proportional to interference temperature power Ip. Therefore, the increment in Ip significantly decreases the outage probability at the EV2.

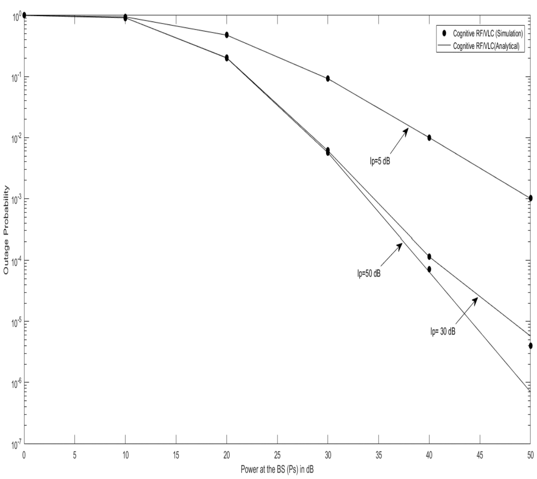

Fig. 5. outage performance of the proposed system with varying Ip

V. CONCLUSION

In this paper, we developed a decode-and-forward based hybrid underlay cognitive radio frequency with visible light communication (CRF/VLC) cooperative system in V2V environments. The EV2 selects the direct link (DL) based on the switching diversity technique. If the direct link is not satisfying the QoS constraints, then EV2 switches to the cooperative link which in turn selects either the cognitive RF or VLC channel based on the selection diversity technique.

Closed-form expressions of outage probability are derived and used to investigate the analytical results, which were compared to Monte Carlo simulations. The numerical results show that the analytical expressions of outage probability are consistent with the simulation results. Overall, our results demonstrate that a strong effect of the increasing transmit power at BS improves the end-to-end performance of the system. For the outage probability 4.28×10−3 at the EV2, the system with VLC requires 9.39 dBm less transmit power as compared to the system without VLC. These findings provide a potential mechanism for saving power allocation and minimizing the consumption of the transmit power at BS. In addition, we investigate the superiority of bit error rate (BER) for our proposed system compared to the CRF stand-alone. Finally, we discuss the impact of the interference temperature power (Ip) on the outage probability performance. We have shown that the outage probability at the EV2 decreases as the value of Ip increases.

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