Visible Light and Reconfigurable Intelligent Surfaces for Beyond 5G V2X Communication Networks at Road Intersections

Gurinder Singh, Anand Srivastava, and Vivek Ashok Bohara

***Abstract*—Traffic safety at road intersections can be enhanced by improving opportunistic exchange of safety messages between vehicles. In urban intersection scenario, obstacles such as buildings and road side installations/signboards block the line-of-sight communication between vehicles. In order to enhance the reliability of communication link, the existing vehicular solution utilizes relay placement at road intersection. However, as the vehicular density increases, the existing vehicular-radio frequency (V-RF) communication with relaying tends to suffer from higher interference, lower packet reception rate, and longer communication delays due to channel congestion. In contrast to the existing solutions, we propose to use practical deployment strategies namely hybrid vehicular-visible light communication (V-VLC)/V-RF with relaying and reconfigurable intelligent surface (RIS) aided V-RF solutions to improve the communication range for urban vehicle-to-vehicle (V2V) communication. We present stochastic geometry based analytical framework to analyze the performance of proposed solutions in terms of outage probability, throughput and delay outage rate (DOR). Numerical results illustrate that the proposed solutions can achieve considerable performance improvement in outage, throughput while ensuring low latency as compared to conventional V-RF with relaying. These deployment strategies may also serve as a preferred alternative for Intelligent Transportation System (ITS) to meet ultra-high reliable and ultra-low latency communication for beyond 5G (B5G) vehicular networks.**

***Index Terms*—Reconfigurable Intelligent Surface, Relaying, Hybrid System, Stochastic geometry, Visible Light Communications, Intelligent Transportation System.**

I. Introduction

With advent of 5G and beyond 5G (B5G) solutions, Vehicle-to-Everything (V2X) communication aims to enhance traffic safety, while supporting higher throughput and ultra reliable low latency communication (URLLC) [1]. Even today, Intelligent Transportation System (ITS) research activities, products and standardization still rely on deployment of dedicated short range communication (DSRC) technologies and cellular-V2X (C-V2X) [2] for wireless connectivity in vehicular adhoc networks (VANETs). These aforementioned technologies tends to suffer from issues such as higher interference, longer communication delays, and lower packet reception rates, especially in higher vehicular density scenarios. Further, it is anticipated that the amount of utilized RF spectrum for V2X applications is expected to increase with increase in number of autonomous vehicles [1].

The primary objective of V2X communication is to provide relevant ITS solutions which includes opportunistic exchange of messages such as basic safety messages (BSMs), decentralized environmental notification messages (DENM) or cooperative awareness messages (CAMs) among vehicles to minimize traffic congestion as well as avoid road accidents, especially at road intersections as these critical areas are more prone to accidents. The existing vehicular-radio frequency (V-RF) solutions generally use relay placement at road intersection to enable enlarged coverage and uninterrupted connectivity for vehicles in shadowed region [3]. However, in this context, one of the main drawback that affect the performance of V2X communication is interference from neighbouring vehicles. The existing RF bands allocated for V-RF communication is limited and can suffer from considerable interference when hundreds of vehicles located in the same vicinity try to communicate concurrently. Recently, visible light communication (VLC) has been proposed to address this limitations of bandwidth congestion problem. Specifically, VLC represents a promising candidate supporting high data rate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication links.

Vehicular-VLC (V-VLC) can be visualized as a complementary potential candidate to the existing DSRC technologies by utilizing existing vehicle headlamp's light emitting diode (LED) lights as transmitter and photodetector (PD) or camera as the receivers, thereby facilitating dual utility of light: illumination and high data rate communication. Instead of viewing V-VLC as competing technology, it can be envisioned as supporting technology to V-RF technology for future ITS to meet stringent delivery rate and latency requirements for B5G vehicular networks. V-VLC can offer high data rates with very low interference in LOS scenarios, whereas V-RF can compensate for V-VLC's shortcomings, such as short communication range and inability to propagate through opaque objects. Such hybrid V-VLC and V-RF technologies have already been proposed in the literature [4], [5].

Reconfigurable Intelligent Surfaces (RIS) has also recently emerged as a promising new paradigm which can significantly enhance performance for B5G/6G vehicular communication systems. B5G-V2X can exploit the benefit of RIS in coverage limited scenarios (for instance, millimeter-wave (mmWave) or THz bands based V2X communications) or adverse propagation environment (e.g., blocked line-of-sight communication links) [1]. In urban environment, especially road intersections

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are an ideal use case scenario for deploying an RIS, wherein opportunistic exchange of safety messages between vehicles may be blocked by buildings, walls, size of surrounding vehicles and other obstructions. Specifically, vehicles in perpendicular lane may not communicate efficiently, resulting in considerable degradation of urban V2V communication performance. To mitigate the effects caused by shadowing at road intersection, RISs may be installed on the buildings surface to increase the communication range. In particular, the communication coverage of vehicles in the perpendicular lanes can be enhanced by tuning the reflection of RIS elements. In the proposed work, we show an improved V2X communication performance when compared to conventional V-RF solutions by employing V-RF with RIS and hybrid V-VLC/V-RF with relaying at road intersection. In addition, we also show that the proposed solutions experiences lower latency as compared to the existing solutions.

A. Related Works

The majority of ITS applications still rely upon the conventional V2X communication technologies, such as DSRC and C-V2X [6], [7]. However, as the vehicular density increases, the aforementioned technologies tends to suffer from higher interference, lower packet delivery rates and longer communication delay due to channel congestion (for e.g. in challenging platooning scenarios [8]) [1], [9], [10]. Compounding the issue further is the limited available RF spectrum which may not be able to suffice the growing demands for future ITS [11]. The high latency issues associated with DSRC have been discussed in [12]. In particular, at highly dense traffic scenarios, DSRC is affected by severe packet collisions, resulting in more frequent re-transmissions and high latency. Against this background, VLC can be considered as complementary solution to the existing DSRC and an economically viable candidate for B5G V2X network. Vehicular networking applications can take advantage of the LED-equipped lighting modules and transportation infrastructure to implement V-VLC [13]. Besides supporting high data rate communications [14]–[16], the V-VLC technology posses inherent advantages over DSRC technology such as lower cost, lower power consumption, less complex transceiver design, enhanced security, improved link quality, less delay and anti-electromagnetic interference [17]. Despite all the aforementioned V-VLC advantages, V-VLC also suffers from the fact that most of its applications require direct line-of-sight (LOS) communication which could increase probability of connectivity loss for long range communication. Further, the performance of V-VLC systems deteriorates in presence of adverse weather conditions and interference caused by artificial and natural light sources [18]. Therefore, recent literature has explored the feasibility of integrating V-VLC with the existing DSRC to improve the overall performance of V2X networks. V-RF can address V-VLC's shortcomings, such as low communication range and inability to propagate through opaque objects and V-VLC can offer high data transmission rates with very low interference in LOS scenarios. Such hybrid V-VLC and V-RF concepts have been proposed in literature [4], [5]. In [5], the authors proposed a radio and visible light hybrid protocol for improving the reliability of control message used in autonomous platooning systems. The authors in [4] proposed an IEEE 802.11p and VLC based hybrid security protocol for vehicular platooning applications. In addition, few reports on experimental demonstration of such hybrid V-VLC/V-RF networks are also documented in the literature [19], [20]. *Masini et al.* showed packet delivery rate improvement by considering vehicles equipped with both DSRC and VLC interfaces as compared to standalone technologies [19]. In [20], the authors investigated experimentally that complementary usage of 5G and VLC can achieve ultra-low latency upto 12 ms for vehicular communication.

Recently, RIS has also been recognized as one promising technology for the B5G ecosystem [1], [21]. The efficient integration of RISs into vehicular network brings both new opportunities as well as challenges, which deserve a dedicated investigation. RIS is specifically a re-configurable array of reflecting elements, wherein each element can independently alter the phase and/or attenuation of the incident signal [22]. Further, RISs are both energy as well as cost-efficient since they are composed of semi-passive elements and can be installed on existing infrastructure, like, building and walls. An RIS enabled vehicular communication has attracted widespread attention in enhancing wireless transmission [23]–[25]. In [23], the authors studied efficient resource allocation scheme for intelligent reflecting surface aided vehicular communications based on large-scale slowly varying channel statistics instead of instantaneous channel state information (CSI). Given the blockage and vehicle density in practical road conditions, the authors in [24] proposed to use RIS to improve the coverage and outage performance in vehicular network. An RIS enabled vehicular network is considered in [25] to improve the physical layer security. Specifically, two RIS-based vehicular network system models are proposed. One model with an RIS based access point (AP) and another model with an RIS based relay. Numerous use case scenarios for such RIS aided vehicular communication have been discussed in [26]. In particular, the authors in [26] explored potential benefits of employing reconfigurable meta-surfaces on prominent vehicular use cases, such as cooperative driving and vulnerable road users (VRUs) detection. To efficiently integrate with next generation V2X communication scenarios, RIS still needs to address fundamental challenges such as reflection optimization, optimal placement, and channel estimation in a highly dynamic vehicular environment [1].

For analytical tractability and modelling, we make use of stochastic geometry based modelling approach, which is an effective mathematical tool for modelling spatial random events based on Poisson point theory in wireless communications [27]–[31]. The authors in [32] and [33] applied stochastic geometry tools to determine successful probability in VANET whith assumption that road vehicles are spatially distributed as per linear Poisson point process (PPP). Usually, the 1D PPP model is more relevant for VANETs [33]. In our previous works [17], [18], we characterized various aspects of stochastic behavior of intervehicular interference by modeling location of road vehicles as a spatial PPP.

Road traffic safety is a major issue, and more specifically at road intersections where high percentage of road accidents generally occurs. In [3], it is shown that relaying through road side unit (RSU) can significantly improve the packet delivery ratio (PDR) performance of the vehicles at road intersection. For instance, the relaying solution through RSU at road intersection offers 68.4% improvement over without relaying case. In contrast to existing solution [3], [34], [35], this research work proposes two practical deployment strategies which can be employed at road intersection scenario where communication can be facilitated for vehicles which are not in direct LOS with transmitting vehicle. We propose to use hybrid V-VLC/V-RF with relaying and V-RF with RIS to mitigate the effects of shadowing caused by building and other obstructions at road intersection. We present stochastic geometry based analytical framework to analyze the performance of proposed solutions in terms of outage probability, throughput and delay outage rate (DOR).

B. Motivation and Contributions

Traffic safety at road intersections can be enhanced by improving opportunistic exchange of BSMs/CAMs between vehicles. There are two major causes of packet loss in vehicular communication (VC) namely: *(a) Obstruction:* As direct LOS link is blocked by obstruction such as building/obstacles, diffuse and specular scatterings may enable non-line-of-sight (NLOS) reception, however resulting in low SNR at receiver. As a consequence, inducing heavy packet drop due to the poor received signal strength at receiver. *(b) Interference/Packet collision:* The PRP at road side unit (RSU) may be heavily impacted due to interference caused from concurrent transmission from other source vehicles. Further, the hidden node problem arises due to building/obstruction at intersection scenario, where some vehicles are completely unaware about the ongoing transmission and assume the channel in idle state. This induces multiple transmissions to occur at the same time, which result in lower PRP at the receiver.

To overcome lower PRP issues at intersection, we propose to use hybrid V-VLC/V-RF with relaying and V-RF with RIS for vehicular communication system. More specifically, the novelty and major contributions of our research work are summarized below:

- We propose two different solutions namely, relayed transmission (RT) based hybrid V-VLC/V-RF and RIS assisted V-RF for establishing reliable communication between vehicles at road intersection. For an interference limited scenario, we carry out comprehensive qualitative and quantitative performance comparison of our proposed solutions with classic decode and forward relaying based V-RF communication by utilizing stochastic geometry tools.
- We show the impact of various design parameters such as access probability, delay threshold which play critical role in deciding the performance of proposed V2X solutions. Moreover, depending on distance between the vehicular nodes and number of IRS elements used, we illustrate to show trade-offs between these two proposed V2X solutions.

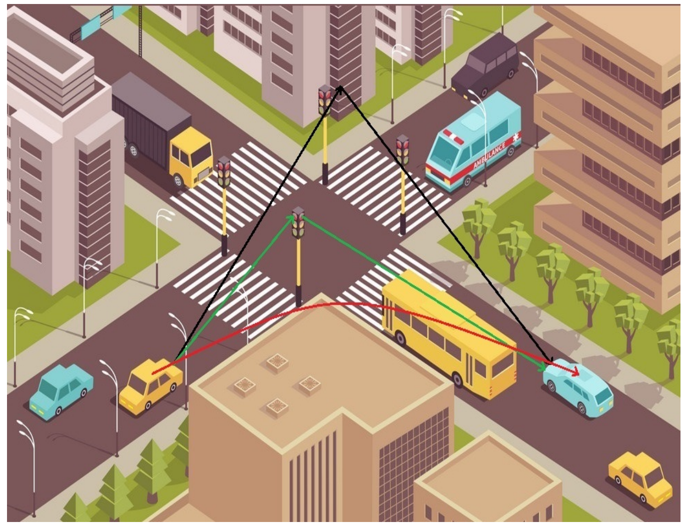


Fig. 1: Illustration of road intersection scenario where vehicles in blocked line-of-sight (solid red line) can communicate via Hybrid V-VLC/V-RF with relaying (solid green line) and V-RF with RIS (solid black line).

- We also investigate the impact of latency in terms of data oriented performance limit known as delay outage rate (DOR) for the proposed V2X solutions. For delay sensitive application, a large latency is intolerable for many safety/warning related messages. DOR serves as an statistical measure for the effective design of ultra-reliable low latency communication (URLLC) transmission schemes.

Numerical results reveal that the proposed V2X deployment strategies can achieve considerable performance improvement in terms of outage, throughput while achieving low latency as compared to traditional V-RF based V2X network.

C. Organization and Notations

This paper has been organized as follows: The system model and various deployment strategies for road intersection scenario are introduced in Section II. Section III presents detailed theoretical framework based on stochastic geometry approach to characterize the performance of conventional V-RF with relaying, hybrid V-VLC/V-RF with relaying and V-RF with RIS in terms of outage probability and DOR. In Section IV, the numerical results are presented with insightful discussion. Finally, concluding remarks are summarized in Section V.

Notations: The following notations are employed: $\mathbb{P}[\cdot]$ is the probability of an event, $\mathbb{E}_Y[\cdot]$ denotes the expectation of its argument over random variable (RV) Y and $\mathscr{L}_X(s) = \mathbb{E}_X[\exp(-sX)]$ denotes Laplace transform of pdf of RV X. $\mathcal{F}_X(\cdot)$ denotes cumulative distribution function of an RV X. $F(\alpha,\beta;\gamma;z) = \frac{1}{B(\beta,\gamma-\beta)}\int_0^1 t^{\beta-1}(1-t)^{\gamma-\beta-1}(1-tz)^{-\alpha}dt, Re\gamma > Re\beta > 0$ denotes hyper geometric function [36, Eq. 9.100], where $B(x,y) = \int_0^1 t^{x-1}(1-t)^{y-1}dt$ is the beta function.

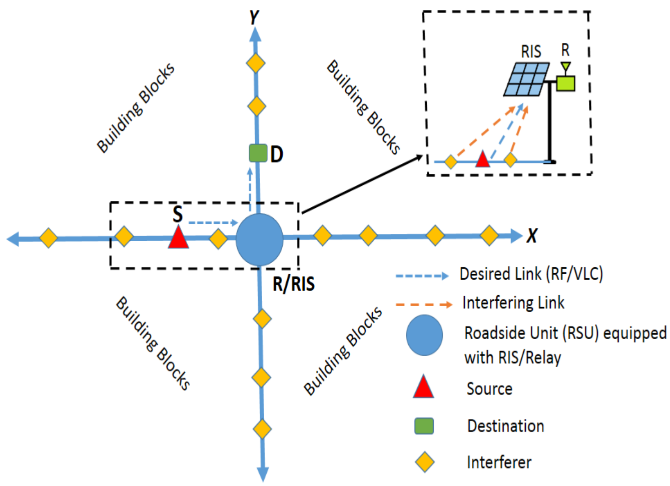


Fig. 2: Abstraction system model for vehicular communications involving a source S, relay R/RIS and a destination D in presence of one dimensional Poisson field of interference.

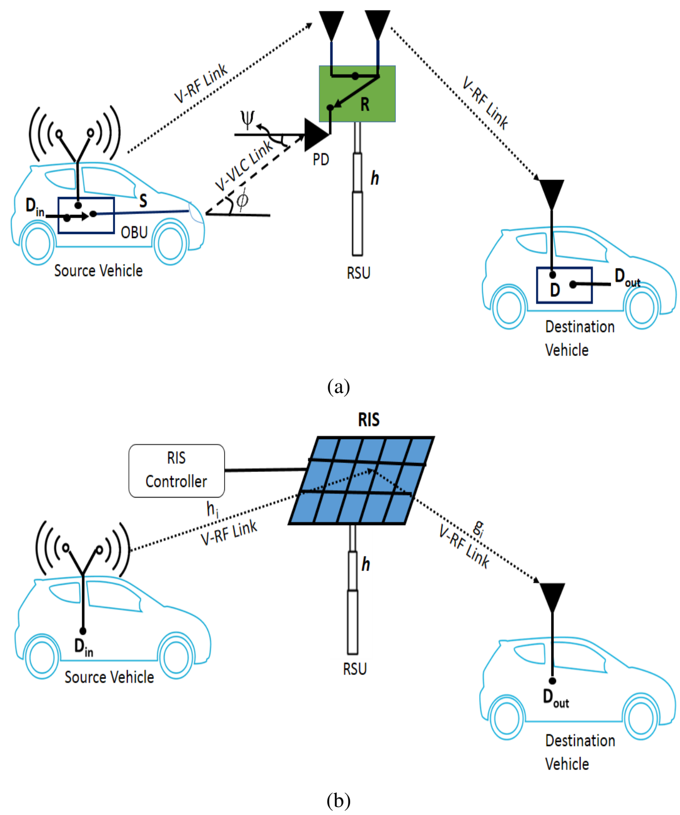


Fig. 3: Illustration of proposed V2X deployment strategies: (a) Hybrid V-VLC/V-RF scheme and (b) V-RF with RIS scheme.

II. Network Model and Preliminaries

A. Scenario Description

A typical road intersection scenario has been depicted in Fig.1. We investigate the transfer of safety messages between single source and destination node via relay/RIS in the presence of interference. The primary cause of interference are concurrent transmission caused from same lane or perpendicular lane road side vehicles[1]. It is assumed that the direct link from a vehicular node to the desired receiver is blocked by obstacles, such as buildings [41], which is indeed a realistic assumption especially when high frequency bands are considered (eg., mmWave based V2X communication). Fig. 2 portrays a simplified abstraction of the proposed intersection scenario. For relaying case, we consider a half-duplex transmission wherein transmission occurs during two phases. The duration of each phase is one time–slot. In the first phase, the source transmits the message to the relay ($S \rightarrow R$). While, in second phase, relay broadcast message to destination ($R \rightarrow D$). The transmission is subject to interference originating from a set of interfering vehicles that are located on roads. We assume that the set of interfering vehicles on axis X (Fig.2), denoted by Φ_X with traffic intensity, λ_X (respectively on axis Y, denoted by Φ_Y with traffic intensity, λ_Y) are distributed as per one-dimensional homogeneous Poisson point process (1D-HPPP). The amount of interference experienced by the receiver depends on the selection of medium access control (MAC) protocol. For a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol, a vehicle is allowed to transmit only if it has the lowest random timer within its contention region (sensing range), δ. This implies that (i) the traffic intensity depends on transmitter's location as other transmitting vehicles (interferers) in its contention region are forced to keep silent when the desired vehicle is active; (ii) the interference from the X- and Y-roads is not independent. When the desired vehicle is active and transmitting at a distance, x_{tx} from RSU, the resulting intensity of the PPPs used to approximate the PP of interferers can be expressed as [39]

$$\lambda_{MAC}^{X}(x) = \begin{cases} p_A(x)\lambda_X & \text{if } ||x - x_{tx}|| > \delta \\ 0; & \text{otherwise,} \end{cases} \quad (1)$$

$$\lambda_{MAC}^{Y}(y) = \begin{cases} p_A(y)\lambda_Y & \text{if } ||y|| > \sqrt{\delta^2 - x_{tx}^2}, \\ 0; & \text{if } ||y|| \leq \sqrt{\delta^2 - x_{tx}^2}, \end{cases} \quad (2)$$

In (1) and (2), $p_A(x)$ and $p_A(y)$ denotes the access probability of interfering vehicle from X-road and Y-road respectively. The access probability is defined as the probability that the given node has the smallest random timer in the corresponding contention region [39]. For CSMA MAC protocol, access probability is governed by [39, Eq.(12)]. Further, we consider low speed vehicular (LSV) mobility model[2] where it is assumed that interferer vehicles remain static during consecutive time slots of the transmission [40]. The theoretical framework is unified to capture the performance of desired vehicles for various deployment strategies namely:

(i) Conventional V-RF with relaying: In order to enhance the reliability of communication links between vehicles which are not in LOS at road intersection, a road side unit (RSU) is employed at the intersection-center to relay the BSMs. In

[1]A similar traffic scenario has been reported in [37]–[40], however this work also considers relay/RIS placement at the road intersection centre.

[2]This is a realistic assumption, especially at road intersections and urban scenarios where the vehicles tend to drive slowly across the junctions, intersections etc.

this case, we employ a decode–and–forward (DF) transmission scheme, i.e., the node R decodes and re-encodes the message then forwards it. Here, both source-to-relay and relay-to-destination are assumed to be an RF link. The improved communication performance by such configuration has been briefly discussed in [3], [35]. For sake of analysis, we consider communication from a single-antenna source to a single antenna destination with an aid of classic decode and forward relaying. Although relaying is not a part of conventional standardized V2X, however the relaying solutions are proposed in literature for improving performance of conventional V-RF communication near road intersection [3].

(ii) Hybrid V-VLC/V-RF with relaying: We assume that vehicles are equipped with both VLC and IEEE 802.11p transceivers. As shown in Fig.3a, SR link can be either V-VLC link or V-RF link, while relay-to-destination is an RF link. It is assumed that information is transmitted with hard-switching either V-VLC or V-RF link depending on the predefined quality of service (QoS) requirements (eg., desired SINR), i.e., only one of the links is allowed to operate at a given time instant. When SINR of V-VLC link remains above a certain threshold, the system keeps working on V-VLC. As soon as the quality of V-VLC link degrades below the predefined threshold (i.e. usually when distance of source from intersection is large), V-RF link is then activated. The SR link goes into outage when both V-VLC and V-RF link are in outage. For simplicity, it is assumed that at least one link (usually V-VLC as primary link) always remains active at a certain time and the system does not interrupt the hybrid V-VLC/V-RF link. This reduces power consumption and makes receiver design less complex with easier decoding as in [42], [43]. Further, the end-to-end system performance improves due to high SINR gain achieved by usage of V-VLC link from source-to-relay which has been later validated through simulation results.

(iii) V-RF with RIS: Fig.3b shows V-RF with RIS where an RIS composed of N reflecting elements is deployed to assist in the communication from source vehicle. The RIS reflecting elements are programmable via a RIS controller. The source vehicle, S transmits a signal to RIS over an RF link. Then, the RIS reflects the signal by using appropriate phase shifts to D. For sake of analysis, we consider a $2L$-path loss model for electrically small RIS [44], [45]. For the system considered, we assume that the CSI of all channels are known at the RIS controller such that the RIS-induced phases can be adjusted by fine tuning of RIS reflecting elements to maximize the received SNR through appropriate phase cancellations and proper alignment of reflected signals from the intelligent surface [23], [46]. Further, it is also assumed that the multipath fading induced inter symbol interference (ISI) can also be eliminated by optimizing the phase shifts at the RIS. In [47], the authors propose to use an RIS as a spatial equalizer to address the well-known multi-path fading phenomenon.

B. Channel Model for V-VLC and V-RF

For a V-VLC system, the channel DC gain between k-th vehicle and RSU can be modeled using Lambertian emission model as follows [48][3]

$$G_k^{VLC} = \frac{(m+1)A_R}{2\pi d_k^2}\cos^m(\phi_k)\cos(\Psi_k)T_s(\Psi_k)G(\Psi_k), \quad (3)$$

where, A_R, d_k, ϕ_k, and Ψ_k denote the area of PD, the distance between the k^{th} vehicle and RSU, the angle of radiance and the angle of incidence respectively. $T_s(\Psi_k)$ is defined as the gain of the optical filter at the receiver. In Eq.(3), *m* is the order of the Lambertian model which is given by $m = -\frac{\ln(2)}{\ln\left(\cos\left(\phi_{\frac{1}{2}}\right)\right)}$, where, $\phi_{\frac{1}{2}}$ is the angle of radiance at which the emitted optical power from vehicle's headlamp LED is half of that emitted with $\phi_{\frac{1}{2}}$=0, and the gain of optical concentrator at the receiver front-end can be given as $G(\Psi_k)=\frac{n^2}{\sin^2\Psi_{FOV}}$, $0 \leq \Psi_k \leq \Psi_{\text{FOV}}$, where *n* denotes the refractive index of the optical concentrator and Ψ_{FOV} is the half of the PD's FOV. Based on simple geometrical illustration shown in Fig. 3a, it can be readily verified that $\cos(\phi_k) = \cos(\Psi_k) = \frac{x_k}{\sqrt{(h^2+x_k^2)}}$ where, x_k and h denote the horizontal distance of k-th vehicle from RSU and the height of RSU respectively. Thus, (3) can be rewritten as:

$$G_k^{VLC} = \frac{(m+1)A_R}{2\pi}\frac{x_k^{(m+1)}}{(h^2+x_k^2)^{\frac{(m+3)}{2}}}T_s(\Psi_k)G(\Psi_k), \quad (4)$$

The channel power can be obtained as: $Z_k^{VLC} = (G_k^{VLC})^2$.

For V-RF communication, the channel over the links source-to-relay and relay-to-destination is modeled as Rayleigh flat fading channel with channel coefficient, h_{SR} and h_{RD} respectively. Given an RF link, the power fading coefficient is an exponential random variable with unit mean. We assume that the source and relay transmit with transmission power, P_s and P_r respectively [50]. For simplicity, we denote P_{RF} as RF transmission power at source as well as relay, P_s=P_r=P_{RF}.

III. Performance Evaluation

The outage probability is defined as the probability that the instantaneous SINR falls below than a certain SINR threshold. For a system employing DF protocol, the outage probability is given as [51]

$$\mathcal{P}_{out}^{DF} = 1 - (1-\mathcal{P}_{out,SR})(1-\mathcal{P}_{out,RD}), \quad (5)$$

where $\mathcal{P}_{out,SR}$ and $\mathcal{P}_{out,RD}$ denote the outage probability associated with SR and RD link respectively.

A. Outage Probability for V-RF with relaying

We consider a vehicular network with interferers distributed according to a PPP, Φ_{PPP} with a locally finite and diffuse intensity, λ. All interferers transmit with same transmission power, P_{RF}. Let $\Phi_i \subseteq \Phi$ denote the set of interferers that are

[3]For mathematical modelling, we consider that vehicle's LED headlamp emits an axially symmetric radiation pattern described by piecewise Lambertain model. Although this work considers the Lambertian angular distribution model, the proposed analytical framework remains valid for other models as well such as Gaussian angular distribution model, empirical model [49].

active in slot i. The interference experienced at R and D for V-RF communication are modeled by [39]

$$I_R = \underbrace{\sum_{x\in\Phi_i} P_{RF}|h_{Rx}|^2\ell_{Rx}}_{I_{Rx}} + \underbrace{\sum_{y\in\Phi_i} P_{RF}|h_{Ry}|^2\ell_{Ry}}_{I_{Ry}}, \quad (6)$$
$$I_D = \sum_{y\in\Phi_i} P_{RF}|h_{Dy}|^2\ell_{Dy},$$

where $\ell_{ab} = A_0||a-b||_2^{-\alpha}$ denotes the euclidean path loss function, $\alpha > 0$ is the the path loss index, $||\cdot||_2$ is the ℓ_2 norm and A_0 denotes a constant that depends on several factors such as antenna characteristics, propagation environment and carrier frequency [39]. In order to calculate outage probability $P_{out,RF}(\zeta)$ associated with direct DSRC V2I link, it is more convenient to express it as a function of probability of successful transmission, $P_s(\zeta)$. Mathematically,

$$\mathcal{P}_{out,RF}(\zeta) = 1 - \mathcal{P}_s(\zeta) \quad (7)$$

The probability of successful transmission, $P_{s,SR}(\zeta)$ at relay R can be calculated as

$$\begin{aligned}\mathcal{P}_{s,SR}(\zeta) &= \mathbb{P}(\mathcal{SINR} > \zeta),\\ &= \mathbb{P}\left(\frac{P_{RF}|h_{SR}|^2\ell_{SR}}{I_R+\sigma^2} > \zeta\right),\\ &= \mathbb{E}_{I_R}\left[\mathbb{P}\left(|h_{SR}|^2 > \frac{\zeta}{P_{RF}\ell_{SR}}(I_R+\sigma^2)\right)\right],\\ &\stackrel{(a)}{=} \exp\left(-\frac{\zeta\sigma^2}{P_{RF}\ell_{SR}}\right)\mathbb{E}_{I_R}\left[\exp(-\frac{\zeta I_R}{P_{RF}\ell_{SR}})\right],\\ &\stackrel{(b)}{=} \exp\left(-\frac{\zeta\sigma^2}{P_{RF}\ell_{SR}}\right)\mathscr{L}_{I_R}\left(\frac{\zeta}{P_{RF}\ell_{SR}}\right)\end{aligned} \quad (8)$$

where ζ is SINR threshold, σ^2 is noise variance at R, and $\mathscr{L}_{I_R}$ denotes the Laplace transform of the interference from X-road and Y-road at R. In (8), Step (a) follows from fact that the channel fading gain, $|h|^2 \sim \exp(1)$ due to Rayleigh fading, and Step (b) results from definition of Laplace transform. Similarly, the probability of successful transmission, $P_{s,RD}(\zeta)$ at destination D can be given as

$$\mathcal{P}_{s,RD}(\zeta) = \exp\left(-\frac{\zeta\sigma^2}{P_{RF}\ell_{RD}}\right)\mathscr{L}_{I_D}\left(\frac{\zeta}{P_{RF}\ell_{RD}}\right). \quad (9)$$

where $\mathscr{L}_{I_D}$ denotes the Laplace transform of the interference from same lane vehicles at D. The expression for Laplace transform of interference at relay R and destination D can be expressed as

$$\begin{aligned}\mathscr{L}_{I_R}(s) = \exp&\left(-\int_{-\infty}^{\infty}\frac{\lambda^X_{MAC}(x)}{1+(h^2+x^2)^{\frac{\alpha}{2}}/sP_{RF}A_0}dx\right)\\ &\times\exp\left(-\int_{-\infty}^{\infty}\frac{\lambda^Y_{MAC}(y)}{1+(h^2+y^2)^{\frac{\alpha}{2}}/sP_{RF}A_0}dy\right),\end{aligned} \quad (10)$$

$$\mathscr{L}_{I_D}(s) = \exp\left(-\int_{-\infty}^{\infty}\frac{\lambda^Y_{MAC}(y)}{1+||y||^{\alpha}/sP_{RF}A_0}dy\right). \quad (11)$$

Proof: Please refer to **Appendix A**. Note that for a general transmitter location x_{tx}, we are not able to evaluate the integrals in (10) and (11) in closed form, consequently it will be evaluated numerically. However, for sake of mathematical tractability, the closed form expressions have also been provided for high traffic density scenario assuming ALOHA protocol[4] where each interfering vehicle access the channel in each time slot independently with probability, ϱ [39].

B. Outage Probability for hybrid VLC-RF with relaying

In this subsection, we characterize the performance of the hybrid V-VLC/V-RF communication system in the presence of the aggregate interference and noise variance, N_0 in terms of outage probability. Firstly, we calculate the outage probability associated with V-VLC link using moment generating functional (MGF) based unified framework.

$$\begin{aligned}P_{out,VLC}(\zeta) &= \mathbb{P}(\mathcal{SINR} < \zeta),\\ &= \mathbb{P}\left(\frac{\mathcal{S}}{\mathcal{I}_{VLC}+N_0} < \zeta\right).\end{aligned} \quad (12)$$

The desired electrical signal power $\mathcal{S}$ from source vehicle and interference $\mathcal{I}_{VLC}$ is given given as

$$\begin{aligned}\mathcal{S} &= \mathcal{R}^2 Z_o P_{VLC},\\ \mathcal{I}_{VLC} &= \sum_{x_k\in\Phi_{PPP}} \mathcal{R}^2 Z_k^{VLC} P_{VLC}.\end{aligned} \quad (13)$$

In above, Z_o and $\mathcal{R}$ denote the channel power gain associated with source vehicle, and the responsivity of PD respectively. The electrical SINR can be represented as:

$$\mathcal{SINR} = \frac{1}{\frac{\mathcal{I_{VLC}}}{\mathcal{R}^2 Z_o P_{VLC}} + \frac{1}{\beta_0}}, \quad (14)$$

where $\beta_0 = \frac{\mathcal{R}^2 Z_o P_{VLC}}{N_0}$. From [14], the outage probability for V-VLC assuming that desired vehicle is transmitting can be given as:

$$P_{out,VLC}(\zeta) = \mathbb{P}\Big(\frac{\mathcal{I_{VLC}}}{\mathcal{R}^2 Z_o P_{VLC}} + \frac{1}{\beta_0} > \frac{1}{\zeta}\Big). \quad (15)$$

We define random variable W as

$$W = \frac{\mathcal{I_{VLC}}}{\mathcal{R}^2 Z_o P_{VLC}} + \frac{1}{\beta_0}, \quad (16)$$

Using above, Eq. (15) can be rewritten as

$$P_{out,VLC}(\zeta) = \mathbb{P}(W > \zeta^{-1}) = 1 - \mathcal{F}_W(\zeta^{-1}). \quad (17)$$

In above, a tractable solution for CDF, $\mathcal{F}_W(\zeta^{-1})$ is quite challenging to obtain. Thus, we perform numerical inversion of Laplace transform. The relationship between CDF of a rv W and the Laplace transform of $\mathcal{F}_W(w)$ is given as

$$\mathcal{F}_W(w) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty}\mathscr{L}_{\mathcal{F}_W(w)}\exp(sw)ds. \quad (18)$$

where $j \triangleq \sqrt{-1}$. The discretization of integral in (18) can be realized to get a series using the trapezoid rule and then the infinite series can be truncated to get a finite sum using the Euler summation [54]. Also, $\mathscr{L}_{\mathcal{F}_W(w)}(s) = \frac{\mathscr{L}_W(s)}{s}$. Thus,

[4]Note that the closed form Laplace transform expressions considering CSMA CA protocols are hard to obtain. In addition, [52], [53] showed that the CSMA CA performance tends to the ALOHA performance in dense networks.

we apply the MGF based numerical technique developed in [55] and after some algebraic manipulation, (17) can be approximated as [56], [57]

$$P_{out,VLC} \approx 1 - \frac{2^{-Q}e^{\frac{A}{2}}}{\zeta^{-1}} \sum_{q=0}^{Q} \binom{Q}{q} \sum_{n=0}^{N+q} \frac{(-1)^n}{D_n} Re\left\{\frac{\mathscr{L}_W(s)}{s}\right\}. \tag{19}$$

where D_0=2 and D_n=1 (n=1, 2, 3,...N+Q) and s=$\frac{A+2\pi ni}{2\zeta^{-1}}$. The triplet ($A$, Q, N) are the positive integers for the accuracy control of the estimation, where (8ln10, 11, 14) is a typical parameters choice that achieves stable numerical inversion with an estimation error of 10^{-8} [54].

The Laplace transform of random variable, W can be expressed as

$$\begin{aligned}\mathscr{L}_W(s) &= \mathbb{E}_{\mathcal{I}_{VLC}}\left[\exp\left(-s\left(\frac{\mathcal{I}_{VLC}}{\mathcal{R}^2 Z_o P_{VLC}} + \frac{1}{\beta_0}\right)\right)\right],\\ &= \mathbb{E}_{\mathcal{I}_{VLC}}\left[\exp\left(-\frac{s}{\beta_0}\right)\exp\left(-\frac{s\mathcal{I}_{VLC}}{\mathcal{R}^2 Z_o P_{VLC}}\right)\right],\\ &= \exp\left(-\frac{s}{\beta_0}\right)\\ &\quad \times \mathbb{E}_{\Phi_i}\left[\prod_{x\in\Phi_i}\exp\left(-\frac{sk' x^{2(m+1)}}{Z_o(h^2+x^2)^{(m+3)}}\right)\right].\end{aligned} \tag{20}$$

Here k':= $\left(\frac{(m+1)A_R}{2\pi}T_s(\psi)G(\psi)\right)^2$. The last expectation term in (20) can be solved using probability generating functional Laplace (PGFL) defined for a homogeneous Poisson point process over region of interest, $\mathbb{R}$ [27, Th 4.9].

$$\mathbb{E}_{\Phi_{PPP}}\left[\prod_{x\in\Phi_i}\exp\left(-\frac{sk' x^{2(m+1)}}{Z_o(h^2+x^2)^{(m+3)}}\right)\right] = \exp\left[-\int_{\mathbb{R}}\lambda_{MAC}^X(x)\left(1-\exp\left(-\frac{sk' x^{2(m+1)}}{Z_o(h^2+x^2)^{(m+3)}}\right)\right)dx\right]. \quad 0 \le \Psi_k \le \Psi_{\text{FOV}} \tag{21}$$

The Eq. (21) can be determined using numerical methods[5]

For an SR-link assuming both V-VLC and V-RF links to be independent, the outage probability is given as [42]

$$\mathcal{P}_{out,SR} = \mathcal{P}_{out,VLC}(\zeta)\mathcal{P}_{out,RF}(\zeta) \tag{22}$$

C. Outage Probability for V-RF with RIS

For an interference limited system, the received signal at D can be expressed as[6]

$$y_D = \sqrt{P_t C_t}(\sum_{i=1}^{N} h_i v_i g_i)x + \sqrt{I_D} + \sqrt{I_{RIS}}, \tag{23}$$

where x denotes the transmit signal with power, P_t, I_D and I_{RIS} are the interference from same lane's vehicles and the interference from RIS aided links at the destination D respectively, C_t is path loss function that depends on length of RIS [59], $v_i = \rho_i(\Psi_i)e^{j\Psi_i}$, ρ_i denotes the reflectance caused by the i-th reflecting surface of the RIS, and for ideal phase shifts, $\rho_i(\Psi_i)$ = 1, $\forall i$. The channel gains of the RIS-involved links are represented as h_i=$\sqrt{d'_{SR}{}^{-\varepsilon}}\alpha_i e^{-j\theta_i}$ and g_i=$\sqrt{d'_{RD}{}^{-\varepsilon}}\beta_i e^{-j\Phi_i}$, $i \in \{1,2,..,N\}$ respectively, ε is the path-loss exponent, d'_{SR}(=$\sqrt{h^2+d_{SR}^2}$) and d'_{RD}(=$\sqrt{h^2+d_{RD}^2}$) denote the distances of the links between S-RIS and RIS-D, α_i and θ_i denote the channel amplitude and phase of h_i, and β_i and Φ_i represent the channel amplitude and phase of g_i, respectively. In addition, the reconfigurable phase Ψ_i is set to $\Psi_i = \theta_i + \Phi_i$ to maximize the SIR at D [60]. The instantaneous SIR, γ_D at D can be formulated as

$$\gamma_D = \frac{P_t A^2 C_t (d'_{SR}d'_{RD})^{-\varepsilon}}{I_D + I_{RIS}}. \tag{24}$$

where $A = \sum_{i=1}^{N}\alpha_i\beta_i$. In particular, A follows distribution of sum of independent and identically distributed (i.i.d) double Rayleigh fading random vectors which aptly capture the channel characteristics of vehicular communication networks [61]–[63]. The outage probability can be expressed as[7]

$$\begin{aligned}\mathcal{P}_{out,RIS} &= 1 - \mathbb{P}(\gamma_D > \zeta),\\ &= 1 - \mathbb{E}_{I_D}\left[\mathbb{P}\left(A^2 > \frac{\zeta(I_{RIS}+I_D)}{P_t C_t (d'_{SR}d'_{RD})^{-\varepsilon}}\right)\right].\end{aligned} \tag{25}$$

Now, we make use of the boundary condition for Gamma distribution, $\mathbb{P}(A^2 < x) = (1-exp(-\beta_t x))^N$, with $\beta_t = \frac{1}{b}(a!)^{-\frac{1}{a}}$ [65]. Finally, invoking binomial expansion, (25) can be approximately expressed as

$$\begin{aligned}&\mathcal{P}_{out,RIS}\\ &\approx 1 - \sum_{k=1}^{a}(-1)^{(k+1)}\binom{a}{k}\mathbb{E}\left[exp\left(-\frac{k\beta_t\zeta(I_D+I_{RIS})}{P_t C_t (d'_{SR}d'_{RD})^{-\varepsilon}}\right)\right]\\ &\approx 1 - \sum_{k=1}^{a}(-1)^{(k+1)}\binom{a}{k}\mathscr{L}_{I_D}\left(\frac{k\beta_t\zeta}{P_t C_t (d'_{SR}d'_{RD})^{-\varepsilon}}\right)\\ &\quad \times \mathscr{L}_{I_{RIS}}\left(\frac{k\beta_t\zeta}{P_t C_t (d'_{SR}d'_{RD})^{-\varepsilon}}\right)\end{aligned} \tag{26}$$

where $\mathscr{L}_{I_{RIS}}(\cdot)$ denotes the Laplace transform of the interference from RIS aided links which can be expressed as

$$\mathscr{L}_{I_{RIS}}(s) = \exp\left(-\int_0^\infty \lambda_{MAC}^X(x)\left(1-\left(1+\frac{sP_tC_t(ud'_{RD})^{-\varepsilon}}{a}\right)^{-a}\right)dx\right). \tag{27}$$

where $u = \sqrt{h^2+x^2}$.

Proof: Please refer to **Appendix B**.

D. Data Oriented Performance: Delay Outage Rate (DOR)

In high traffic density scenarios, DSRC based V-RF communication may be affected by severe packet collisions that could

[5]The numerical methods can easily be implemented in standard mathematical software packages such as *MATLAB* and *MATHEMATICA*.

[6]For purpose of fair comparison, we assume source transmit with transmission power, P_t=$2P_{RF}$ [58].

[7]Kindly note that the distribution of A^2 also follows gamma distribution which can be verified via method of moment matching [64].

TABLE I: Simulation Parameters

Parameter	Symbol	Value
Lambertian Order	m	1 [68]
LED semi-angle	$\Phi_{\frac{1}{2}}$	70°
PD detection area	A_d	1 cm^2 [68]
Transmission power for VLC	P_{VLC}	33 dBm [18]
Responsivity of the PD	$\mathcal{R}$	0.54 A/W
Transmission power for RF	P_{RF}	23 dBm [69]
Carrier frequency	f_c	5.9 GHz
Constant	A_0	3×10^{-5} [39]
SINR Threshold	ζ	8 dB [39], [70]
Length of each RIS element[8].	$2L$	5 cm
System Bandwidth	B_s	20 MHz
Optical filter gain	$T_s(\Psi_k)$	1
Noise power spectral density	N_o	$10^{-21} A^2/Hz$
Refractive index	n	1.5
Path loss exponent	α	2
Height of RSU	h	8 m

raise latency concerns due to more frequent retransmissions [12]. Considering B5G vehicular network requirement, the proposed schemes should be able to offer URLLC among vehicles. DOR is formally defined as the probability that the minimum transmission time (MTT) needed to successfully deliver a given amount of data over a channel is more than a predefined delay threshold duration, denoted by T_{th} which can be represented as [66], [67],

$$DOR = \mathbb{P}(MTT > T_{th}), \tag{28}$$

where T_{th} is related to the delay requirement of the data to be transmitted. DOR serves as an statistical measure for the QoS experienced by individual data transmission for stringent delay requirement by a particular network. For transmitting data amount, H over a channel with bandwidth, B_s, the DOR for small data transmission within a given coherence time can be defined as [67]

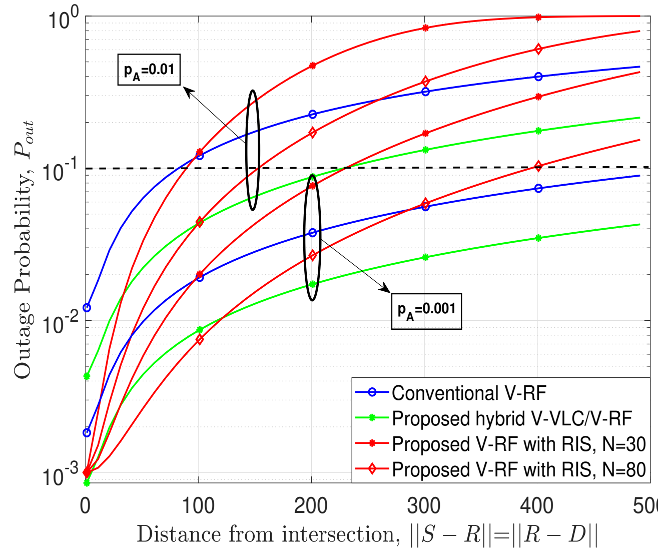
$$DOR = \mathbb{P}(SINR < 2^{\frac{H}{B_s T_{th}}} - 1). \tag{29}$$

IV. Numerical Results and analysis

This section shows the numerical as well as simulation results to show the performance of the proposed solutions. The system model parameters are adopted in accordance with practical vehicular scenario and are listed in Table I. Unless otherwise specified explicitly, we assume, for simplicity, d_{SR} = d_{RD} = d_0, i.e., the RIS/relay is located equidistantly from the source and destination. Unless otherwise stated, we assume λ_X=λ_Y=0.01. In order to corroborate the accuracy of our analytical findings, we also perform Monte Carlo (MC) simulations by averaging over 10^4 realizations of PPPs and fading channel parameters. We have considered an extreme case when the interference from same lane or perpendicular lane vehicles are originated from an infinite road segment ($\mathcal{B} = \mathbb{R}^1$).

Fig. 4 shows the impact of distance, d_0 on the outage performance of conventional V-RF, proposed hybrid V-VLC/V-RF, and RIS assisted V-RF (N=30, 80). As intuitive, the outage

[8]We consider length of each IRS element to be $\frac{\lambda}{2}$, which resembles an electrically small RIS case [44].

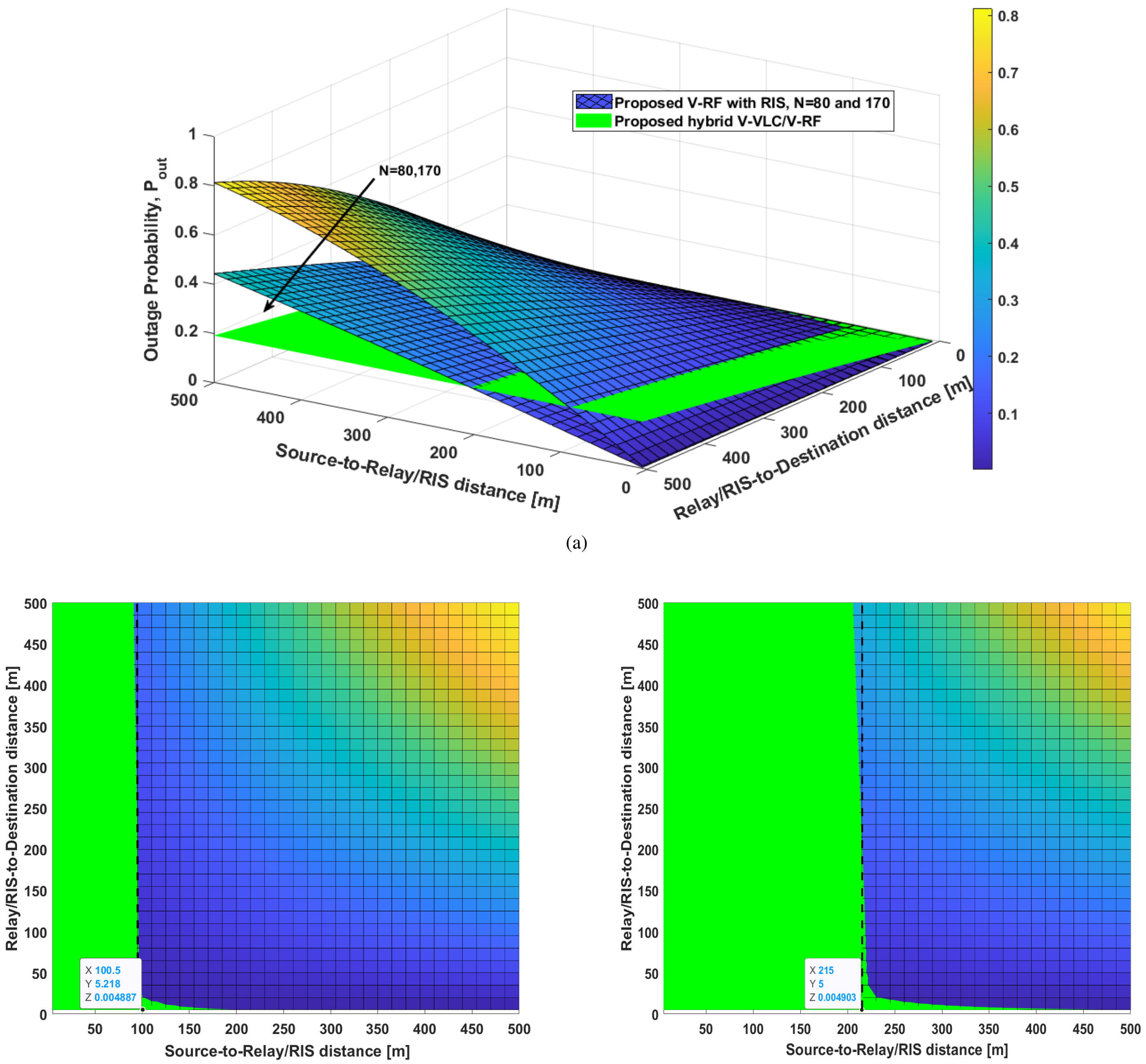


(a)

Fig. 4: Analytical (solid line) and simulation (markers) results for outage probability, $\mathcal{P}_{out}$ versus distance from intersection, i.e $||S-R||$=$||R-D||$ for conventional V-RF, proposed hybrid V-VLC/V-RF and RIS aided V-RF communication.

probability increases with increase in distance, d_0. We can observe from Fig. 4 that irrespective of any d_0 and p_A values, proposed hybrid V-VLC/V-RF scheme always outperforms conventional V-RF communication in terms of outage probability. Further, the outage performance of proposed hybrid V-VLC/V-RF scheme is better as compared to V-RF with RIS (N=80) for $d_0 > 100\,m$ and p_A=0.01. Further, with decrease in access probability, p_A, the outage performance of proposed hybrid V-VLC/V-RF as well as V-RF with RIS improves. Fig. 5a shows outage probability comparison for proposed schemes with varying distance between source and destination as $||S-R||$ and $||R-D||$. Interestingly, irrespective of relay-to-destination distance, proposed hybrid V-VLC/V-RF solution is more reliable option over proposed V-RF with RIS (N=80) when source-to-relay distance is beyond $100\,m$ and p_A=0.01 as evident from Fig. 5b. However, with increase in number of RIS elements, proposed V-RF with RIS (N=170) gives better performance while supporting source-to-relay distance upto $215\,m$ as can be verified from Fig. 5c. Since source-to-relay link is primarily a V-VLC link, the outage performance of proposed hybrid V-VLC/V-RF scheme mainly depends on source-to-relay distance. It is worth mentioning here that the outage performance of proposed schemes are sensitive to the values of vehicular density, channel access probability, source-destination distance, and number of RIS elements used for RIS aided V-RF communication.

In order to gain more insights, we next plot outage probability of proposed schemes as a function of access probability. As illustrated before, a low access probability ensures low outage probability. This is due to fact that smaller values of p_A implies probability for the vehicles to access the medium is lower, resulting in less interference, and thereby increasing the SIR



(a)

(b)

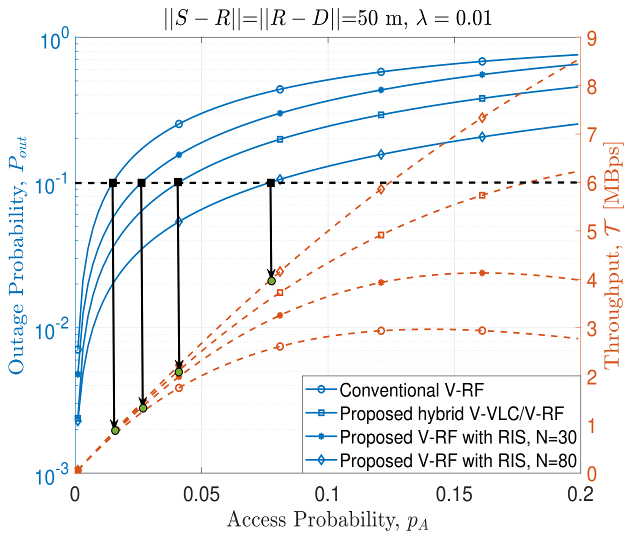
(c)

Fig. 5: Outage Probability, $\mathcal{P}_{out}$ comparison for proposed schemes with varying distance between source and destination: (a) represents 3D plot showing the impact of varying $||S-R||$ and $||R-D||$ for (λ, p_A)=(0.01, 0.01), (b) Top view illustrating 2D-distance plot for $N=80$, and (c) Top view illustrating 2D-distance plot for $N=170$.

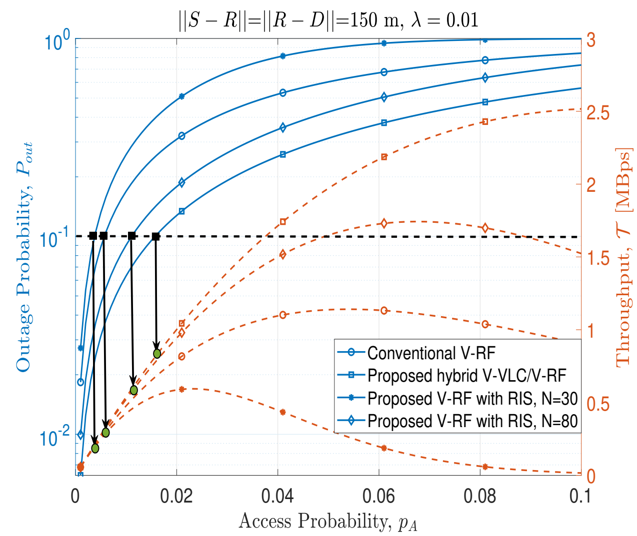
and reduce the outage. Fig. 6 shows outage probability, $\mathcal{P}_{out}$ as a function of access probability, p_A for $d_0 \in (50\,m, 150\,m)$. For $d_0 < 100\,m$, proposed V-RF with RIS ($N = 80$) is reliable option over proposed hybrid V-VLC/V-RF scheme as can be seen in Fig. 6a. However, the complementary insights can be ruled out when $d_0 > 100\,m$ as shown in Fig. 6b. From a system design perspective, the outage probability is not sufficient metric to characterize the performance, since a MAC that allows few concurrent transmissions may lead to high PRP however it will also yield low throughput [39]. Hence, we also plot the throughput as a function of p_A, where the throughput $\mathcal{T}$ is defined as follows [39]

$$\mathcal{T} = p_A(x_{tx})(1-\mathcal{P}_{out})\log_2(1+\zeta)B_s \tag{30}$$

The throughput first rises (due to active transmitter) and then declines (due to enormous amounts of interference), leading to an optimum value of p_A. However, in order to ensure a certain QoS, one must also consider a guarantee on the outage probability. For instance, to ensure an outage probability below 10% when d_0= $50\,m$, the optimal value of access probability for proposed V-RF with RIS (N=80), $p_A \approx 0.077$, results in a throughput of about 4 MBps. However, when d_0=$150\,m$, the opposite trend can be observed in Fig. 6b wherein proposed hybrid V-VLC/V-RF scheme guarantees more throughput as compared to proposed V-RF with RIS (N=80) for same outage performance. Notice that for given d_0 and p_A, the performance of proposed V-RF with RIS scheme can be improved by increasing RIS elements, N without increase in power consumption of transceiver. For sake of comparison, we



(a) d_0 = 50 m



(b) d_0 = 150 m

Fig. 6: Outage probability, $\mathcal{P}_{out}$ and throughput, $\mathcal{T}$ as a function of access probability, p_A for conventional V-RF with relaying, hybrid V-VLC/VRF with relaying, and RIS aided V-RF ($N = 30, 80$) for two different distances between the source and destination, $d_0 \in (50\,m, 150\,m)$.

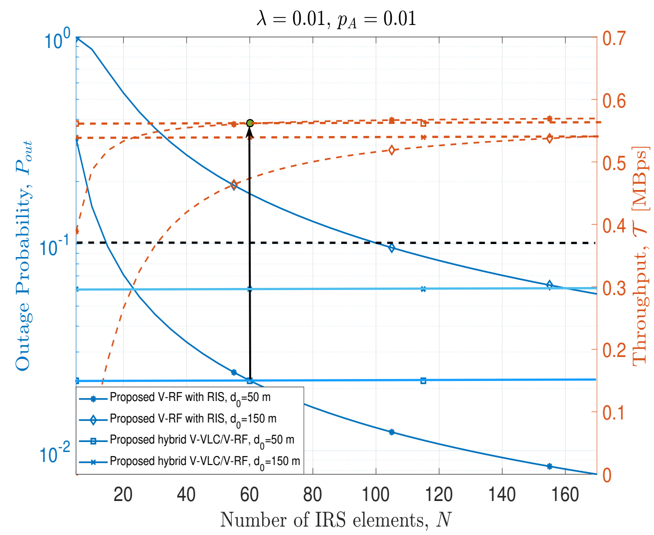
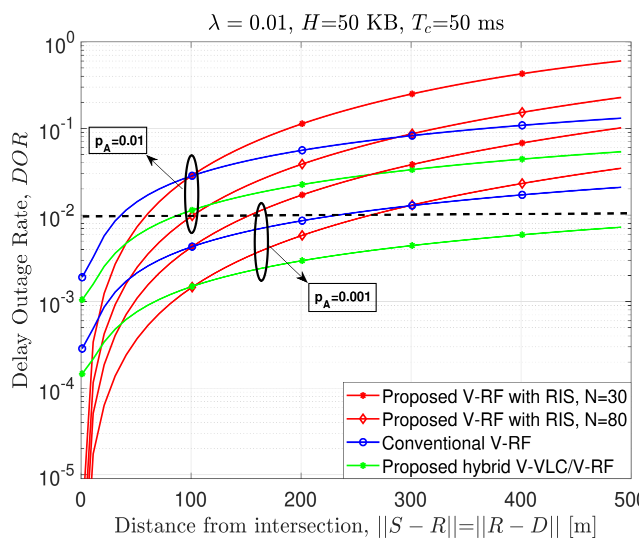


Fig. 7: Outage probability, $\mathcal{P}_{out}$ and throughput, $\mathcal{T}$ variation with increasing values of RIS elements, N for two different distances between the source and destination, $d_0 \in (50\,m, 150\,m)$.

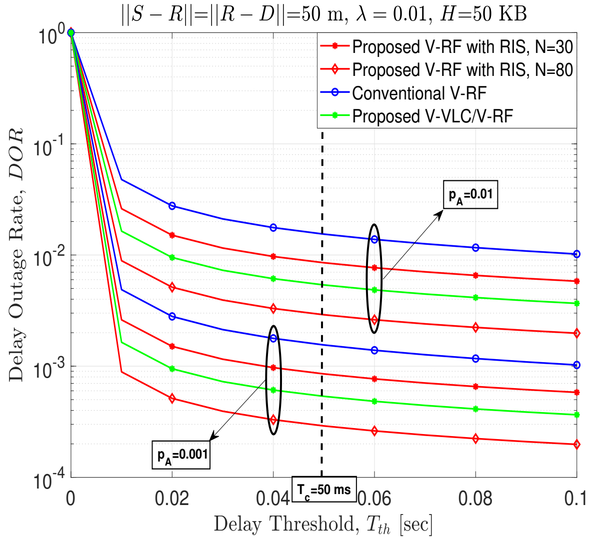


(a)

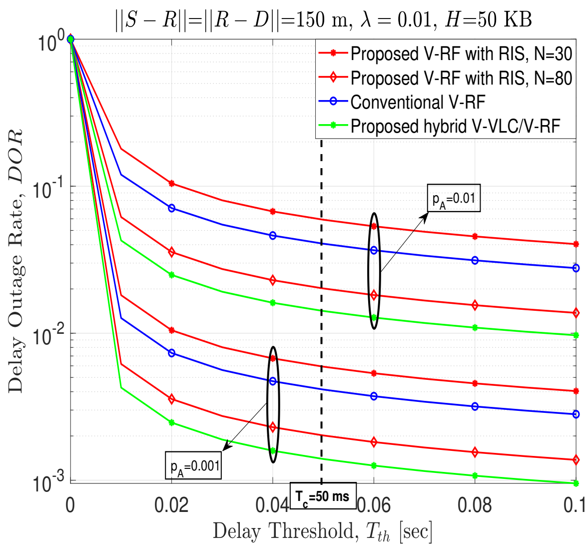
Fig. 8: Delay outage rate as a function of distance between source and destination for transmitting data amount, H=50 KB over a link ensuring a delay threshold, T_{th}=50 ms requirement.

also plot the outage performance of proposed V-RF with RIS by varying N as shown in Fig.7. It can be seen from Fig.7 that with increase in values of N, outage performance of proposed V-RF with RIS improves. Now, for d_0=50 m and p_A=0.01, proposed V-RF with RIS can outperform proposed hybrid V-VLC/V-RF solution by selecting, N>60. Undoubtedly, for sufficiently large, N, proposed V-RF with RIS will always outperform proposed hybrid V-VLC/V-RF scheme.

Fig. 8 shows relationship between DOR and distance between source and destination for conventional V-RF, proposed hybrid V-VLC/V-RF, and RIS assisted V-RF (N=30, 80) communication when distance from source to relay and relay to destination are same, i.e. $||S-R||$=$||R-D||$ for transmitting data, H=50 KB ensuring a critical delay threshold, T_c=50 ms requirement. Note that in order to improve the reaction time in critical scenarios and to obtain full situational awareness, one requires extremely low latencies (typically 50 ms in pre-crash situations) [10]. As intuitive, DOR increases with increase in distance, d_0. We can observe from Fig. 8 that irrespective of any d_0 and p_A values, proposed hybrid V-VLC/V-RF scheme always outperforms conventional V-RF communication in terms of DOR. Further, DOR performance of proposed hybrid V-VLC/V-RF scheme is better as compared to V-RF with RIS



(a) d_0 = 50 m



(b) d_0= 150 m

Fig. 9: Delay outage performance of Conventional V-RF with relaying, hybrid VLC-RF with relaying, and RIS aided V-RF ($N = 30, 80$) for two different distance between the source and destination, $d_0 \in (50\,m, 150\,m)$.

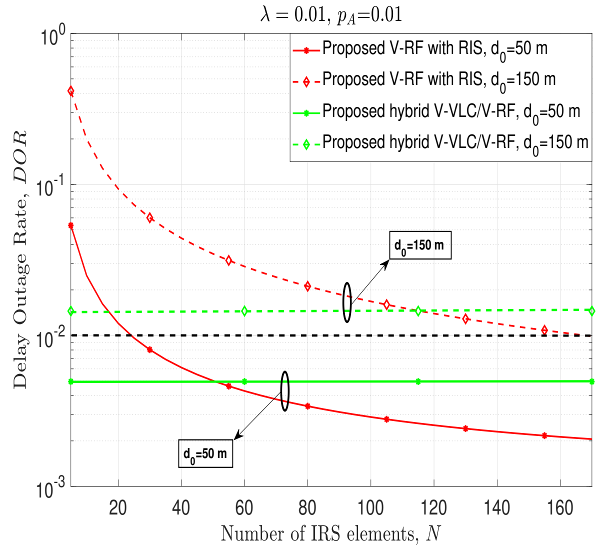


Fig. 10: Delay outage rate variation with increasing value of RIS elements, N for two different distance between the source and destination, $d_0 \in (50\,m, 150\,m)$.

scheme (N=80) for d_0>120 m and $p_A = 0.01$. Further, with decrease in access probability, p_A, the outage performance of proposed hybrid V-VLC/V-RF as well as V-RF with RIS improves.

Next, we also plot DOR performance for V2X deployment strategies ensuring different delay threshold requirement. In particular, we plot DOR performance of deployment strategies as function of the delay threshold, T_{th} for sending data amount, H=50 KB. It is interesting to note that for data traffic with stringent delay requirement, the proposed V-RF with RIS (N=80) ensures minimum delay in transmitting given amount of information from source to destination as compared to proposed hybrid V-VLC/V-RF or conventional V-RF when d_0=50 m and p_A=0.01 as can be seen from Fig 9a. We can also observe that when d_0= 150 m, there exists complementary behaviour in DOR performance of proposed schemes as evident from Fig. 9b. For sake of analysis, for given T_{th}=50 ms, we also plot the DOR performance of V-RF with RIS, by varying the number of RIS elements as shown in Fig. 10. With DOR of 1×10^{-2} as performance constraint, the proposed hybrid V-VLC/V-RF scheme are acceptable for d_0<150 m. However, V-RF with RIS requires $N > 20$ and $N > 170$ for d_0=50 m and d_0=150 m respectively in order to ensure DOR within acceptable limit.

The system design insights obtained through the simulation results can be summarized in tabular form. Table II shows the impact of access probability, p_A and distance, d_0 on outage probability, $\mathcal{P}_{out}$, throughput, $\mathcal{T}$ (Kbps) and DOR for various deployment strategies. The key inferences have been enumerated below:

- Irrespective of distance, d_0 and access probability, p_A, the proposed hybrid V-VLC/V-RF always outperforms conventional V-RF communication in terms of $\mathcal{P}_{out}$ and DOR. However, the number of RIS elements N decides the performance of proposed V-RF with RIS. The required value of N depends on distance, d_0 and p_A.
- With decrease in access probability, p_A, the outage performance and DOR performance improves for conventional V-RF, hybrid V-VLC/V-RF and V-RF with RIS. However, this improvement is achieved at the expense of compromising the throughput performance.
- Depending on distance, d_0 from source to destination and number of RIS elements, N, we can observe trade-offs between hybrid V-VLC/V-RF and V-RF with RIS.
- For sufficiently large, N, V-RF with RIS always outperforms either conventional V-RF or hybrid V-VLC/V-RF communication in terms of $\mathcal{P}_{out}$ and DOR.

p_A	d_0	Outage Probability, $\mathcal{P}_{out}$					Throughput, $\mathcal{T}$				Delay Outage Rate (DOR)				
		A	B	C	D	E	A	B	C	D	A	B	C	D	E
0.001	50 m	★★★	★★★	★★★	★★★	2	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★★	★★★	3
	100 m	★★★	★★★	★★★	★★★	6	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★★	★★★	10
	150 m	★★★	★★★	★★★	★★★	13	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★★	★★★	25
	200 m	★★★	★★★	★★★	★★★	22	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★☆	★★★	35
	250 m	★★★	★★★	★★☆	★★★	34	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★☆	★★★	55
	300 m	★★★	★★★	★★☆	★★★	49	★☆☆	★☆☆	★☆☆	★☆☆	★★★	★★★	★★☆	★★★	77
0.01	50 m	★★★	★★★	★★★	★★★	15	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★	23
	100 m	★★☆	★★★	★★☆	★★★	50	★★★	★★★	★★★	★★★	★★☆	★★★	★★☆	★★★	84
	150 m	★★☆	★★★	★★☆	★★☆	100	★★☆	★★☆	★★★	★★★	★★☆	★★☆	★★☆	★★☆	170
	200 m	★★☆	★★★	★☆☆	★★☆	170	★★☆	★★★	★★☆	★★☆	★★☆	★★☆	★★☆	★★☆	273
	250 m	★★☆	★★★	★☆☆	★★☆	255	★★☆	★★★	★☆☆	★★☆	★★☆	★★☆	★☆☆	★★☆	383
	300 m	★★☆	★★☆	★☆☆	★☆☆	360	★★☆	★★★	★☆☆	★★☆	★★☆	★★☆	★☆☆	★★☆	492

A: Conventional V-RF communication, **B**: Proposed hybrid V-VLC/V-RF, **C**: Proposed V-RF with RIS, N=30, **D**: Proposed V-RF with RIS, N=80 and **E**: Minimum number of RIS elements, N required to ensure outage probability below 10% and DOR of 0.01 at $T_{th} = 50ms$.
Rating criterion: ★★★: $\mathcal{P}_{out} < 10\%$, $\mathcal{T} > 500$ $KBps$ and $DOR < 0.01$ at T_{th} = 50ms, ★★☆: $25\% < \mathcal{P}_{out} < 10\%$, 300 $KBps< \mathcal{T} < 500$ $KBps$ and $0.1 < DOR < 0.01$ at T$_{th}$ = 50ms and ★☆☆: $\mathcal{P}_{out} > 25\%$, $\mathcal{T} < 300$ $KBps$ and $DOR > 0.1$ at T$_{th}$ = 50ms

TABLE II: Impact of access probability, p_A and distance, d_0 on outage probability, $\mathcal{P}_{out}$, throughput, $\mathcal{T}$ $(KBps)$ and DOR for various deployment strategies.

V. Concluding remarks

In this paper, we proposed hybrid V-VLC/V-RF and V-RF with RIS schemes to facilitate vehicular communication at road intersections in order to enable uninterrupted connectivity, enhanced coverage, and ultra reliable low latency communications. The obtained results show that the proposed V2X deployment strategies can achieve considerable performance improvement in outage, throughput while ensuring low latency as compared to conventional V-RF with relaying. Undoubtedly, V-RF with RIS with sufficiently large, N always outperforms either hybrid V-VLC/V-RF with relaying or V-RF with relaying. Irrespective of distance between source and destination vehicles, the proposed hybrid V-VLC/V-RF will always outperform conventional V-RF communication in terms of outage and DOR. However, the number of RIS elements, N decides the performance of proposed V-RF with RIS. The proposed solution may serve as better alternative ITS solution as compared to conventional V-RF solution to meet the ultra-high reliable and ultra low latency communication requirements for B5G vehicular networks. Further investigations will be devoted to gain more useful insights when there exists an integration of optical RIS with V-VLC technology.

Appendix A

The Laplace transform (LT) of interference at relay R can be expressed as

$$\begin{aligned}\mathscr{L}_{I_R}(s) &= \mathbb{E}[\exp(-sI_{Rx})\exp(-sI_{Ry})],\\ &= \underbrace{\mathbb{E}\left[\prod_x \exp(-sP_{RF}|h_{Rx}|^2\ell_{Rx})\right]}_{\mathscr{L}_{Rx}(s)}\\ &\quad\times \underbrace{\mathbb{E}\left[\prod_y \exp(-sP_{RF}\ell_{Ry})\right]}_{\mathscr{L}_{Ry}(s)},\end{aligned} \tag{31}$$

where $\mathscr{L}_{Rx}(\cdot)$ and $\mathscr{L}_{Ry}(\cdot)$ denote the interference from X and Y road at relay R respectively. The LT of interference from X-road at relay R can be calculated as

$$\begin{aligned}&\mathscr{L}_{Rx}(s)\\ &\overset{(a)}{=} \mathbb{E}\left[\prod_x \mathbb{E}_{|h_{Rx}|^2}\{\exp(-sP_{RF}|h_{Rx}|^2A_0(h^2+x^2)^{-\frac{\alpha}{2}}\}\right],\\ &= \mathbb{E}\left[\prod_x \frac{1}{1+sP_{RF}A_0(h^2+x^2)^{-\frac{\alpha}{2}}}\right],\\ &\overset{(b)}{=} \exp\left(-\int_{-\infty}^{\infty}\frac{\lambda^X_{MAC}(x)}{1+(h^2+x^2)^{\frac{\alpha}{2}}/sP_{RF}A_0}dx\right),\end{aligned} \tag{32}$$

In above, (a) holds due to independence of fading coefficients $|h_{Rx}|^2$, (b) uses the definition of PGFL for PPP. For slotted ALOHA case, the integral can be expressed in closed form, hence we can obtain closed form expression for LT of the interference. In this case, we can calculate the integral for $\mathcal{B} = \mathbb{R}^1$, λ_X=λ_Y=λ and $\alpha = 2$ in simplified form as

$$\mathscr{L}_{Rx}(s) = \exp\left(-\varrho\lambda\frac{\pi sP_{RF}A_0}{\sqrt{h^2+sA_0P_{RF}}}\right). \tag{33}$$

Following same steps as above, we can obtain the similar expression for $\mathscr{L}_{Ry}$ as well. Following [71, Eq. (13)], we can also express $\mathscr{L}_{I_D}$ in closed form. Now, substituting s=$\frac{\zeta}{P_{RF}\ell_{SR}}$ and ℓ_{SR}=$A_0(h^2+d_{SR}^2)^{-\frac{\alpha}{2}}$ yields the following result

$$\begin{aligned}\mathscr{L}_{I_R}\left(\frac{\zeta}{P_{RF}\ell_{SR}}\right) &= \exp\left(-2\varrho\lambda\frac{\pi\zeta(h^2+d_{SR}^2)}{\sqrt{h^2+\zeta(h^2+d_{SR}^2)}}\right),\\ \mathscr{L}_{I_D}\left(\frac{\zeta}{P_{RF}\ell_{RD}}\right) &= \exp\left(-\varrho\lambda\pi\sqrt{\zeta}\sqrt{h^2+d_{RD}^2}\right).\end{aligned} \tag{34}$$

where h, d_{SR} and d_{RD} denote the height of RSU, the horizontal distance of source and destination from RSU respectively.

APPENDIX B

The Laplace transform for the interference from RIS aided links can be expressed as

$$\begin{aligned}&\mathscr{L}_{I_{RIS}}(s)\\&=\mathbb{E}\left[\exp(-\sum_{x\in\Phi_i} sP_tC_tA^2(d'_{SR}d'_{RD})^{-\varepsilon})\right],\\&\overset{(a)}{=}\mathbb{E}\left[\prod_x\left(1+\frac{sP_tC_t(d'_{SR}d'_{RD})^{-\varepsilon}}{a}\right)^{-a}\right],\\&\overset{(b)}{=}\exp\left(-\int_0^\infty \lambda^X_{MAC}\left(1-\left(1+\frac{sP_tC_t(ud'_{RD})^{-\varepsilon}}{a}\right)^{-a}\right)dx\right)\end{aligned} \tag{35}$$

where $u=\sqrt{h^2+x^2}$, (a) follows from the properties of fading parameter, (b) utilizes the definition of PGFL for HPPP. For slotted ALOHA case, the integral can be expressed in closed form as

$$\mathscr{L}_{I_{RIS}}(s)=\exp\left(-\varrho\lambda h\left({}_2F_1(-\frac{1}{2},a;\frac{1}{2};-\frac{sP_tC_t}{a(hd'_{RD})^2})-1\right)\right). \tag{36}$$

Eq. (36) assumes ε=2 and utilizes substitution, t=$\sqrt{x^2+h^2}$, $t>>h$ and uses $\int_A^\infty\left(1-\left(1+\frac{s}{x^2}\right)^{-N}\right)dx = A\left({}_2F_1\left(-\frac{1}{2},N;\frac{1}{2};-\frac{s}{A^2}\right)-1\right)$. Note that height, h is greater than close-in distance, D_0 defined for an electrically small RIS.

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