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TR2019-135 December 09, 2019

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IEEE Global Communications Conference (GLOBECOM)

Distributed Cyclic Delay Diversity for Cooperative Infrastructure-to-Vehicle Systems

Kyeong Jin Kim, Jianlin Guo, Jinchuan Tang, and Philip V. Orlik

***Abstract*—In this paper, a distributed cyclic delay diversity (dCDD) is proposed to the cooperative infrastructure-to-vehicle (I2V) system comprising one road side unit (RSU). At a particular time, to connect a RSU and a target vehicle outside each other's transmission range, a multiple number of vehicles located within the transmission ranges of both the RSU and the target vehicle are configured to operate as the dCDD based decode-and-forward (DF) cooperative relays. By using dCDD in the I2V system, the transmission range of the RSU is extended without the need of full channel state information of the vehicles at the RSU, and the transmit diversity gain can also be achieved. For this new preliminary setting of the I2V system, we conduct performance analysis. The simulations are conducted to verify the outage probability. The asymptotic outage diversity gain is also investigated and justified by the link level simulations.**

***Index Terms*—Distributed cyclic delay diversity, cooperative infrastructure to vehicle system, transmit diversity, outage probability, outage diversity gain.**

I. Introduction

Infrastructure-to-vehicle (I2V) has received much attention in recent years since it allows a vehicle to communicate with the infrastructure units, or road side unit (RSU) in transmission range to improve traffic safety and efficiency by sharing accident warning, position, speed, or route messages [1], [2]. Such an I2V system often relies on combining with vehicle-to-vehicle (V2V) communications, where V2V can help vehicles to communicate with nearby peers if the target vehicle is outside the transmission range of the RSU. To further reduce the infrastructure cost and flexibility in the exchange of information, the vehicles can also work as the cooperative relays so that a target vehicle can share critical information via the RSU to more vehicles covered by the RSU and the control unit in the cloud. Due to the drastic increase in road traffic, the road can be congested or populated with vehicles especially in the metropolitan areas [2]. Therefore, the diversity schemes can be applied to the distributed transceivers on many vehicles to further enhance the reliability of the link between the target vehicle and the RSU.

Since acquiring channel channel state information at the transmitting side (CSIT) is a challenging task in realizing a distributed transmit diversity scheme, a distributed cyclic delay diversity (dCDD) [3] has been proposed as a practical scheme. As the conventional cyclic delay diversity (CDD) [4]–[6], dCDD provides the same diversity benefits by enabling multiple transmissions arriving at the receiver (RX), which combines the received signals being processed by different cyclic delays. It has been verified that diversity benefits can be achieved by the receiver even when the receiver is unaware of cyclic delays introduced by the transmitter and without exact knowledge of CSIT [3]. Owing to these benefits, several types of the cyclic-prefixed single carrier (CP-SC) transmission have applied dCDD in different distributed systems, for example,

1) cooperative communication systems [3], [7];
2) physical layer secrecy (PLS) systems [8];
3) underlaying spectrum sharing systems [9], [10].

In detail, based on the original dCDD concept developed by [3], the authors of [7] investigated the performance of dCDD in the presence of spatially distributed multiple interferers. Using the benefit of dCDD which does not require CSIT, deliberate interference was designed by the authors of [8] to increase PLS performance. Due to an achievable diversity gain and non-decodable deliberate interference by the eavesdropper, a significant secrecy performance improvement can be achieved. Some benefits of dCDD were integrated into distributed underlaying spectrum sharing systems [9], which verified an improved outage probability over the systems without employing dCDD. Compared with other distributed system, dCDD converts the multiple-input and single-output (MISO) channel into an intersymbol interference (ISI)-free single-input and single-output (SISO) channel, so that the maximum transmit diversity gain can be achieved when the conditions in mitigating ISI are satisfied. In addition, in contrast to the conventional CDD [11]–[14], which applies a different cyclic delay to each of the antennas installed at the same transmitter, dCDD is applied among distributed transmitters, which are all equipped with a single antenna. Thus, unlike the conventional CDD, dCDD has the advantage of being implemented in the distributed transmitters with reduced hardware cost and power consumption.

Comparing with existing work, our main contributions are summarized as follows.

- We consider a finite-sized I2V system due to a limited number of RSU and vehicles for dCDD operation. We consider one RSU placed at a fixed location. However, there is a coverage hole, in which one target vehicle cannot receive a signal from the RSU directly. In general, the coverage hole is caused by physical obstructions such as buildings, foliage, hills, tunnels and indoor parking garages. However, this paper assumes that it is caused by a limited communication range of the RSU.
- For this system, a new cooperative communication

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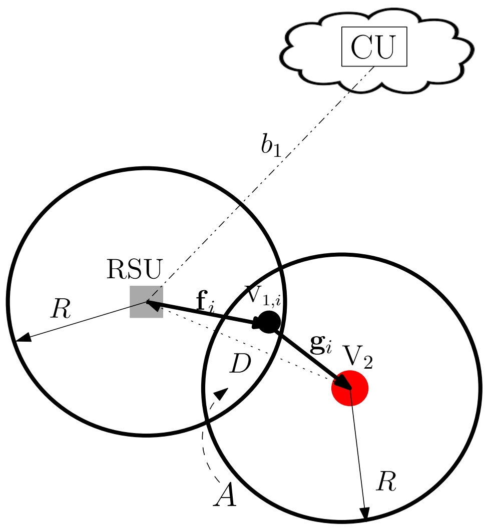

Fig. 1: Illustration of the considered dCDD-based cooperative system with one RSU. M cooperating vehicles $\{V_{1,i}, i \in [1, ..., M]\}$ are assumed to be located in the lens-shaped cooperating area, A. The RSU and target vehicle, V_2, have the same communication range, R.

method which applies a decode-and-forward (DF) relaying scheme is proposed. Each of the multiple vehicles randomly located in the lens-shaped cooperating area, overlapped by two communication ranges, decodes the source message and transmits the re-encoded message to the target vehicle. By applying dCDD, the target vehicle can achieve an improved performance even within the coverage hole.

- We firstly derive the outage probability of the considered I2V system and then show the performance with respect to different system configuration and channel parameters.

The rest of the paper is organized as follows. In Section II, we first detail the system and channel model of the dCDD-based cooperative I2V system. After defining random quantities and deriving their distributions, performance analysis of the considered system is conducted in Section III. Simulation results are presented in Section IV and conclusions are drawn in Section V.

A. Notation

$\mathbb{N}_0$ denotes the set of non-negative integers; $\mathbb{C}$ denotes the set of complex numbers; $\boldsymbol{I}_N$ is the $N \times N$ identity matrix; $\mathbf{0}$ denotes an all-zero matrix of appropriate dimensions; $\mathcal{CN}\left(\mu, \sigma^2\right)$ denotes the circularly symmetric complex Gaussian distribution with mean μ and variance σ^2; $F_\varphi(\cdot)$ and $f_\varphi(\cdot)$, respectively, denote the cumulative distribution function (CDF) and probability density function (PDF) of the random variable (RV) φ; and $\binom{n_1}{n_2} \triangleq \frac{n_1!}{n_2!(n_1-n_2)!}$ denotes the binomial coefficient. A length of a vector $\boldsymbol{a}$ is denoted by $\mathbb{L}(\boldsymbol{a})$. $K|_{i \to j}$ denotes that a variable i in K is replaced by j.

II. System and Channel Model

Illustration of the considered cooperative I2V system is provided in Fig. 1. We assume that a cooperative and distributed communication system comprising a control unit (CU) within the cloud is connected to a single antenna equipped RSU. Optical fiber is deployed from the CU to RSU as backhaul, so that backhaul connection, b_1, is assumed to be very reliable compared to the wireless backhaul [15]. The CU forms an information signal and controls the RSU to transmit the information signal. After receiving the signal from the CU, the RSU and vehicles in the lens-shaped cooperating area applies dCDD to support backhaul and wireless access to a target vehicle. To utilize the benefit of cooperative RSU transmissions, this paper assumes that RSU and vehicles are synchronized by a Global Navigation Satellite System (GNSS) (e.g., GPS, Galileo, Glonass, QZSS, etc.) [16]. A circular shaped communication range of radius R is formed around the RSU for cooperative communications. At a particular time, the communication range formed around the target vehicle, V_2, is assumed to be overlapped with the communication range formed around the RSU. In the lens-shaped cooperating area, M vehicles are assumed to be located randomly. The distance from RSU to V_2 is $D \geq R$, so that it is in the coverage hole, in which it cannot receive a signal from the RSU. Thus, it is necessary to develop the cooperative system to support transmissions from the RSU with an aid from vehicles within the lens-shaped cooperating area. Each vehicle installs a single antenna and a half-duplex transceiver, so that it is allowed to transmit or receive at any given time. For the proposed I2V system, we further assume the following channels and transmission scheme.

A. Channel from RSU to Vehicle $\mathrm{V}_{1,i}$

The channel from RSU to $\mathrm{V}_{1,i}$ is given by

$$\boldsymbol{f}_i = \sqrt{(d_{1,i})^{-\epsilon_{\mathrm{L}}}}\tilde{\boldsymbol{f}}_i \tag{1}$$

where $\tilde{\boldsymbol{f}}_i$ identifies frequency selective fading channel for the path with $N_{f,i} \triangleq \mathbb{L}(\tilde{\boldsymbol{f}}_i)$ multipath components. The distance from RSU to vehicle $\mathrm{V}_{1,i}$ is denoted by $d_{1,i}$. In addition, ϵ_{L} is denoting the path loss exponent of the path.

Proposition 1: When $D \geq R$, the PDF of $d_{1,i} \in [D-R, R]$ is given by

$$f_{d_{1,i}}(x) = \frac{2x\sin^{-1}\left(\frac{\sqrt{4D^2x^2-(D^2-R^2+x^2)^2}}{2Dx}\right)}{A} \tag{2}$$

where $A \triangleq 2R^2\cos^{-1}\left(\frac{D}{2R}\right) - \frac{D}{2}\sqrt{4R^2-D^2}$.

Proof: Having applied [17], we can readily derive (2). ■

Note that the distribution of $d_{1,i}$ is independent of the vehicle index, i.

B. Channels from Vehicle $\mathrm{V}_{1,i}$ to Vehicle V_2

The channel from vehicle $\mathrm{V}_{1,i}$ to vehicle V_2 is given by

$$\boldsymbol{g}_i = \sqrt{(d_{2,i})^{-\epsilon_{\mathrm{L}}}}\tilde{\boldsymbol{g}}_i \tag{3}$$

where $\tilde{\boldsymbol{g}}_i$ identifies frequency selective fading channel for the path with $N_{g,i} \triangleq \mathbb{L}(\tilde{\boldsymbol{g}}_i)$ multipath components, and $d_{2,i}$ is the distance between vehicle V_2 and vehicle $\mathrm{V}_{1,i}$.

C. dCDD for CP-SC Transmissions

According to multipath channels from the RSU to vehicle $\mathrm{V}_{1,i}$, we can have $N_{\max} = \max(N_{f,i}, i \in [1, M])$, so that the CP length is determined by $N_{\mathrm{CP}} = N_{\max}$, with $\max(N_{g,i}, i \in [1, M]) \leq N_{\mathrm{CP}}$. According to [3], dCDD is a transmit diversity scheme that converts the MISO channels into the SISO channels for CP-SC transmissions [3], [14]. To make an ISI-free reception at V_2, it is necessary to compute the maximum available number of the vehicles in the lens-shaped cooperating area for dCDD and its accompanying set of CDD delays, Δ_i. With N_{CP} and a linear mapping, that is, $\Delta_m = (m-1)N_{\mathrm{CP}}$, the maximum allowable number of vehicles for dCDD operation is given by [3]

$$K = \left\lfloor \frac{B}{N_{\mathrm{CP}}} \right\rfloor \tag{4}$$

where $\lfloor \cdot \rfloor$ denotes the floor function, and B denotes the block size of the transmission block symbol $\boldsymbol{s}$. In the considered system, we assume that $M \leq K$.

With an interactive handshaking, selecting the CDD delay among RSU and the vehicles within the lens-shaped cooperating area, the received signal at $\mathrm{V}_{1,i}$ is given by

$$\boldsymbol{r}_{1,i} = \sqrt{P_s}\sqrt{(d_{1,i})^{-\epsilon_{\mathrm{L}}}}\tilde{\boldsymbol{F}}_i \boldsymbol{P}_{\Delta_i}\boldsymbol{s} + \boldsymbol{z}_R \tag{5}$$

where P_s is the transmission power at the RSU, $\tilde{\boldsymbol{F}}_i$ is right circulant matrix determined by $\tilde{\boldsymbol{f}}_i$. In addition, $\boldsymbol{P}_{\Delta_i}$ denotes the $B \times B$ orthogonal permutation matrix obtained by circularly shifting down $\boldsymbol{I}_B$ by $\Delta_i \in \mathbb{N}_0$ rows. The additive noise over the desired channels is denoted by $\boldsymbol{z}_R \sim \mathcal{CN}(\boldsymbol{0}, \sigma_z^2 \boldsymbol{I}_B)$. The transmission symbol block from the CU is given by $\boldsymbol{s}$ with $E\{\boldsymbol{s}\} = \boldsymbol{0}$ and $E\{\|\boldsymbol{s}\|^2\} = \boldsymbol{I}_B$. After decoding, $\mathrm{V}_{1,i}$ forwards the encoded block symbol to V_2. Thus, the received signal at V_2 from $\mathrm{V}_{1,i}$ is given by

$$\boldsymbol{r}_{2,i} = \sqrt{P_r}\sqrt{(d_{2,i})^{-\epsilon_{\mathrm{L}}}}\tilde{\boldsymbol{G}}_i \boldsymbol{P}_{\Delta_i}\boldsymbol{s} + \boldsymbol{z}_R. \tag{6}$$

The transmission power allocated to the all vehicles is denoted by P_r. The right circulant channel determined by $\tilde{\boldsymbol{g}}_i$ is denoted by $\tilde{\boldsymbol{G}}_i$.

III. Performance Analysis

A. Analysis on the signal-to-noise ratio (SNR)

From (5) and (6), we first compute SNRs at $V_{1,i}$ and V_2 as follows:

$$\begin{aligned} \gamma_{1,i} &= \rho_s (d_{1,i})^{-\epsilon_{\mathrm{L}}} \|\tilde{\boldsymbol{f}}_i\|^2 \text{ and} \\ \gamma_{2,i} &= \rho_r (d_{2,i})^{-\epsilon_{\mathrm{L}}} \|\tilde{\boldsymbol{g}}_i\|^2 \end{aligned} \tag{7}$$

where $\rho_s \triangleq \frac{P_s}{\sigma_z^2}$ and $\rho_r \triangleq \frac{P_r}{\sigma_z^2}$. Since the SNRs defined in (7) do not consider the random locations of the vehicles in the lens-shaped cooperating area, it is necessary to compute their corresponding distributions for spatially averaged SNRs (SA-SNRs).

Proposition 2: Over the frequency selective fading channels, the distributions of the SA-SNR over the channel from RSU to $\mathrm{V}_{1,i}$ which supports dCDD is given by (8), shown at the top of the next page. In (8), $C_{n,m} \triangleq \frac{\Gamma(n+1/2)2^{-2n}(D)^{-2n-1}(D^2-R^2)^{2n+1-m}\binom{2n+1}{m}}{\sqrt{\pi}(2n+1)\Gamma(n+1)}$, and $\Gamma_u(\cdot,\cdot)$ denotes the upper incomplete gamma function. The complete gamma function is denoted by $\Gamma(\cdot)$.

Proof: See Appendix A. ■

From (8), the SA-CDF is derived as (9), shown at the top of the next page. In (9), $G_{p,q}^{m,n}\left(t \middle| \begin{matrix} (a_p) \\ (b_q) \end{matrix}\right)$ denotes the Meijer G-function [18, Eq. (9.301)]. In addition, we have defined $\mathbb{X}_c \triangleq \frac{\pi}{\rho_s \Gamma(N_{f,i})\epsilon_{\mathrm{L}} A}$, $R_1 \triangleq \frac{R^{\epsilon_{\mathrm{L}}}}{\rho_s}$, and $R_2 \triangleq \frac{(D-R)^{\epsilon_{\mathrm{L}}}}{\rho_s}$. In the derivation, we have used [19, Eq. (2.24.2.2)]. According to *Proposition 2*, the SA-PDF and SA-CDF of $\gamma_{2,i}$ can be derived as follows:

$$\begin{aligned} f_{\gamma_{2,i}}^{\mathrm{SA}}(x) &= f_{\gamma_{1,i}}^{\mathrm{SA}}(x)\big|_{N_{f,i}\to N_{g,i}, \rho_s \to \rho_r} \text{ and} \\ F_{\gamma_{2,i}}^{\mathrm{SA}}(x) &= F_{\gamma_{1,i}}^{\mathrm{SA}}(x)\big|_{N_{f,i}\to N_{g,i}, \rho_s \to \rho_r}. \end{aligned} \tag{10}$$

Due to the DF relaying protocol at $\mathrm{V}_{1,i}$, the SNR of the ith relay link, $\mathrm{RSU} \to \mathrm{V}_{1,i} \to \mathrm{V}_2$, is given by

$$\gamma_{12,i} = \min\left(\gamma_{1,i}, \gamma_{2,i}\right). \tag{11}$$

Proposition 3: According to (8) and (10), the SA-PDF and SA-CDF of the achievable SNR by the DF relaying protocol are given by

$$\begin{aligned} f_{\gamma_{12,i}}^{\mathrm{SA}}(x) &= f_{\gamma_{1,i}}^{\mathrm{SA}}(x) - f_{\gamma_{1,i}}^{\mathrm{SA}}(x)F_{\gamma_{2,i}}^{\mathrm{SA}}(x) + \\ &\quad f_{\gamma_{2,i}}^{\mathrm{SA}}(x) - f_{\gamma_{2,i}}^{\mathrm{SA}}(x)F_{\gamma_{1,i}}^{\mathrm{SA}}(x) \text{ and} \\ F_{\gamma_{12,i}}^{\mathrm{SA}}(x) &= 1 - (1 - F_{\gamma_{1,i}}^{\mathrm{SA}}(x))(1 - F_{\gamma_{2,i}}^{\mathrm{SA}}(x)). \end{aligned} \tag{12}$$

Since the expressions for the SA-PDF and SA-CDF of $\gamma_{1,i}$ and $\gamma_{2,i}$ are available, we do not provide the full expressions for $f_{\gamma_{12,i}}^{\mathrm{SA}}(x)$ and $F_{\gamma_{12,i}}^{\mathrm{SA}}(x)$.

Due to ISI-free MISO reception at the V_2, dCDD provides the V_2 with the following SNR:

$$\gamma_{\mathrm{dCDD}} = \sum_{i=1}^{M} \gamma_{12,i}. \tag{13}$$

Note that although dCDD is the transmit diversity scheme, it provides the same diversity benefits as that of maximum ratio combining (MRC) [3].

B. Analysis of the outage probability

a) Outage probability for $M = 1$: In this special case, the closed-form expression for the outage probability can be derived as follows:

$$\begin{aligned} P_{\mathrm{outage}}^{M=1}(o_{\mathrm{th}}) &= F_{\gamma_{1,1}}^{\mathrm{SA}}(o_{\mathrm{th}}) + F_{\gamma_{2,1}}^{\mathrm{SA}}(o_{\mathrm{th}}) - \\ &\quad F_{\gamma_{1,1}}^{\mathrm{SA}}(o_{\mathrm{th}})F_{\gamma_{2,1}}^{\mathrm{SA}}(o_{\mathrm{th}}) \end{aligned} \tag{14}$$

where o_{th} is a target SNR threshold that is causing outage. Upon applying (9), we can derive the closed-form expression.

Proposition 4: Over the frequency selective fading channels, the achievable diversity gain is given by $G_d^{M=1} = \min(N_{f,1}, N_{g,1})$.

$$f^{\mathrm{SA}}_{\gamma_{1,i}}(x)=\frac{\pi}{\rho_s\Gamma(N_{f,i})\epsilon_{\mathrm{L}}A}\Big(\frac{x}{\rho_s}\Big)^{-\frac{2}{\epsilon_{\mathrm{L}}}-1}\bigg(\Gamma_u\Big(N_{f,i}+\frac{2}{\epsilon_{\mathrm{L}}},\frac{x}{\rho_s}(D-R)^{\epsilon_{\mathrm{L}}}\Big)-\Gamma_u\Big(N_{f,i}+\frac{2}{\epsilon_{\mathrm{L}}},\frac{x}{\rho_s}(R)^{\epsilon_{\mathrm{L}}}\Big)\bigg)- \frac{1}{\rho_s\Gamma(N_{f,i})\epsilon_{\mathrm{L}}A}\sum_{n=0}^{\infty}\sum_{m=0}^{2n+1}C_{n,m}\Big(\frac{x}{\rho_s}\Big)^{-(2m-2n+1)/\epsilon_{\mathrm{L}}-1}\bigg(\Gamma_u\Big(N_{f,i}+\frac{(2m-2n+1)}{\epsilon_{\mathrm{L}}},\frac{x}{\rho_s}(D-R)^{\epsilon_{\mathrm{L}}}\Big)- \Gamma_u\Big(N_{f,i}+\frac{(2m-2n+1)}{\epsilon_{\mathrm{L}}},\frac{x}{\rho_s}(R)^{\epsilon_{\mathrm{L}}}\Big)\bigg). \quad (8)$$

$$F^{\mathrm{SA}}_{\gamma_{1,i}}(x)=\mathbb{X}_c\Big(\frac{1}{\rho_s}\Big)^{-\frac{2}{\epsilon_{\mathrm{L}}}-1}\bigg((R_1)^{2/\epsilon_{\mathrm{L}}}G^{1,2}_{2,3}\Big(R_1x\Big|\begin{matrix}1,1-2/\epsilon_{\mathrm{L}}\\N_{f,i},-2/\epsilon_{\mathrm{L}},0\end{matrix}\Big)-(R_2)^{2/\epsilon_{\mathrm{L}}}G^{1,2}_{2,3}\Big(R_2x\Big|\begin{matrix}1,1-2/\epsilon_{\mathrm{L}}\\N_{f,i},-2/\epsilon_{\mathrm{L}},0\end{matrix}\Big)\bigg)- \frac{\mathbb{X}_c}{\pi}\sum_{n=0}^{\infty}\sum_{m=0}^{2n+1}C_{n,m}\Big(\frac{1}{\rho_s}\Big)^{-(2m-2n+1)/\epsilon_{\mathrm{L}}-1}\bigg((R_1)^{(2m-2n+1)/\epsilon_{\mathrm{L}}}G^{1,2}_{2,3}\Big(R_1x\Big|\begin{matrix}1,1-(2m-2n+1)/\epsilon_{\mathrm{L}}\\N_{f,i},-(2m-2n+1)/\epsilon_{\mathrm{L}},0\end{matrix}\Big)- (R_2)^{(2m-2n+1)/\epsilon_{\mathrm{L}}}G^{1,2}_{2,3}\Big(R_2x\Big|\begin{matrix}1,1-(2m-2n+1)/\epsilon_{\mathrm{L}}\\N_{f,i},-(2m-2n+1)/\epsilon_{\mathrm{L}},0\end{matrix}\Big)\bigg). \quad (9)$$

Proof: The diversity gain of the proposed I2V system is determined by an asymptotic behavior either of $F^{\mathrm{SA}}_{\gamma_{1,1}}(o_{\mathrm{th}})$ or $F^{\mathrm{SA}}_{\gamma_{2,1}}(o_{\mathrm{th}})$. In addition, As $z\rightarrow 0$, $G^{m,n}_{p,q}\Big(z\Big|\begin{matrix}(a_p)\\(b_q)\end{matrix}\Big)\propto z^{\beta}$, where $\beta=\min(b_1,\ldots,b_m)$ with $(b_q)\triangleq[b_1,...,b_m,b_{m+1},...,b_q]$, [20, Section 5.4.1]. Thus, the asymptotic outage probability is given by

$$P^{M=1,\mathrm{as}}_{\mathrm{outage}}(o_{\mathrm{th}})\propto\Big(\frac{1}{\rho_s}\Big)^{N_{f,1}}\text{ or }\Big(\frac{1}{\rho_s}\Big)^{N_{g,1}}. \quad (15)$$

Thus, the diversity gain is given by $G^{M=1}_d=\min(N_{f,1},N_{g,1})$. ■

Note that $G^{M=1}_d$ is the minimum achievable diversity gain by dCDD, in which the advantage of the dCDD scheme is not fully exploited.

b) Outage probability for $M>1$: For $M>1$ vehicles working as cooperative relaying nodes in the proposed I2V system, the moment generating function (MGF) of γ_{dCDD} is given by

$$C(s)=\prod_{i=1}^{M}C_{\gamma_{12,i}}(s) \quad (16)$$

where $C_{\gamma_{12,i}}(s)$ is the MGF of $\gamma_{12,i}$. According to (9), $C_{\gamma_{12,i}}(s)$ is computed by

$$C_{\gamma_{12,i}}(s)=s\int_0^{\infty}e^{-sx}F^{\mathrm{SA}}_{\gamma_{12,i}}(x)dx. \quad (17)$$

Note that in general, the full expression for $F^{\mathrm{SA}}_{\gamma_{12,i}}(x)$ is so complex due to cross terms between $F^{\mathrm{SA}}_{\gamma_{1,i}}(x)$ and $F^{\mathrm{SA}}_{\gamma_{2,i}}(x)$ that the closed-form expression may not be feasible. Thus, we consider the MGF in the asymptotic region of ρ_s in the sequel. Depending on the asymptotic behavior of $F^{\mathrm{SA}}_{\gamma_{1,i}}(x)$ and $F^{\mathrm{SA}}_{\gamma_{2,i}}(x)$, we can have

$$C_{\gamma_{12,i}}(s)\approx s\int_0^{\infty}e^{-sx}F^{\mathrm{SA}}_{\gamma_{1,i}}(x)dx+s\int_0^{\infty}e^{-sx}F^{\mathrm{SA}}_{\gamma_{2,i}}(x)dx \propto \underbrace{s\int_0^{\infty}e^{-sx}F^{\mathrm{SA}}_{\gamma_{1,i}}(x)dx}_{J_{1,i}(s)}\text{ or } \underbrace{s\int_0^{\infty}e^{-sx}F^{\mathrm{SA}}_{\gamma_{2,i}}(x)dx}_{J_{2,i}(s)} \quad (18)$$

where $J_{1,i}(s)$ is shown at the top of the next page. In the derivation, we have used [19, Eq. (2.24.3.1)]. Similar to $J_{1,i}(s)$, $J_{2,i}(s)$ can be derived as $J_{2,i}(s)=J_{1,i}(s)\big|_{N_{f,i}\rightarrow N_{g,i},\rho_s\rightarrow\rho_r}$.

Theorem 1: The proposed cooperative I2V system can achieve the asymptotic outage diversity gain $G^{M>1}_d=\min(MN_fs,MN_gs)$, with $N_fs=N_{f,i},i\in[1,...,M]$ and $N_gs=N_{g,i},i\in[1,...,M]$, over identical frequency fading channels and by the use of M vehicles in the lens-shaped cooperating area.

Proof: Without loss of generality, we only consider the case, in which the channels from the RSU to $\{V_{1,i},i\in[1,...,M]\}$ dominate the asymptotic behavior of $F^{\mathrm{SA}}_{\gamma_{12,i}}(x)$. Thus, it is necessary to study the asymptotic behavior of $J_{1,i}(s)$ as $\rho_s\rightarrow\infty$. Utilizing [20, Section 5.4.1] again, $J_{1,i}(s)$ can expressed as $J_{1,i}(s)\propto\big(\frac{1}{\rho_s s}\big)^{N_{f,i}}$. Thus, the asymptotic $C(s)$ is given by $C^{\mathrm{as}}(s)\propto\prod_{i=1}^{M}\big(\frac{1}{\rho_s s}\big)^{N_{f,i}}=\big(\frac{1}{\rho_s}\big)^{\sum_{i=1}^{M}N_{f,i}}\big(\frac{1}{s}\big)^{\sum_{i=1}^{M}N_{f,i}}$. Applying the inverse MGF of $C^{\mathrm{as}}(s)$, the SA-PDF of γ_{dCDD} is given by

$$f^{\mathrm{as}}_{\gamma_{\mathrm{dCDD}}}(x)\propto(\rho_s)^{-\sum_{i=1}^{M}N_{f,i}}x^{\sum_{i=1}^{M}N_{f,i}-1}\frac{1}{\Gamma(\sum_{i=1}^{M}N_{f,i})} \quad (20)$$

from which the asymptotic outage probability can be derived as follows:

$$P^{M>1,\mathrm{as}}_{\mathrm{outage}}\propto\frac{1}{\Gamma\big(\sum_{i=1}^{M}N_{f,i}+1\big)}\big(\frac{\rho_s}{o_{\mathrm{th}}}\big)^{-\left(\sum_{i=1}^{M}N_{f,i}\right)} \quad (21)$$

which shows diversity gain, $G^{M>1}_d=\sum_{i=1}^{M}N_{f,i}$, at a given o_{th}. Thus, when $N_fs=N_{f,i},i\in[1,...,M]$ and $N_gs=N_{g,i},i\in[1,...,M]$, $G^{M>1}_d=\min(MN_fs,MN_gs)$. ■

$$J_{1,i}(s) = \mathbb{X}_c \Big(\frac{1}{\rho_s}\Big)^{-\frac{2}{\epsilon_{\rm L}}-1} \Bigg((R_1)^{2/\epsilon_{\rm L}} G_{3,3}^{1,3}\Big(\frac{R_1}{s}\Big|\begin{array}{c} 0, 1, 1-2/\epsilon_{\rm L} \\ N_{f,i}, -2/\epsilon_{\rm L}, 0 \end{array}\Big) - (R_2)^{2/\epsilon_{\rm L}} G_{3,3}^{1,3}\Big(\frac{R_2}{s}\Big|\begin{array}{c} 0, 1, 1-2/\epsilon_{\rm L} \\ N_{f,i}, -2/\epsilon_{\rm L}, 0 \end{array}\Big)\Bigg) - \frac{\mathbb{X}_c}{\pi} \sum_{n=0}^{\infty} \sum_{m=0}^{2n+1} C_{n,m} \Big(\frac{1}{\rho_s}\Big)^{-(2m-2n+1)/\epsilon_{\rm L}-1} \Bigg((R_1)^{(2m-2n+1)/\epsilon_{\rm L}} G_{3,3}^{1,3}\Big(\frac{R_1}{s}\Big|\begin{array}{c} 0, 1, 1-(2m-2n+1)/\epsilon_{\rm L} \\ N_{f,i}, -(2m-2n+1)/\epsilon_{\rm L}, 0 \end{array}\Big) - (R_2)^{(2m-2n+1)/\epsilon_{\rm L}} G_{3,3}^{1,3}\Big(\frac{R_2}{s}\Big|\begin{array}{c} 0, 1, 1-(2m-2n+1)/\epsilon_{\rm L} \\ N_{f,i}, -(2m-2n+1)/\epsilon_{\rm L}, 0 \end{array}\Big)\Bigg). \quad (19)$$

Note that when the ith vehicle located within the cooperating area supports dCDD, it provides the frequency selective diversity gain, $\min(N_{f,i}, N_{g,i})$. Thus, without causing ISI at the target vehicle, dCDD can provide range extension of the RSU by achieving the maximum achievable diversity gain.

IV. SIMULATION

We present the link-level simulation results to verify the performance improvement by the use of dCDD in the proposed cooperative I2V system. In the simulation, we have used the following system and transmission configuration parameters:

- $B = 64$ for CP-SC transmissions.
- The communication range is determined by a radius $R = 10$ $[m]$ for the RSU and the target vehicle V_2.
- The path-loss exponent is assumed to be $\epsilon_{\rm L} = 2.09$.
- A fixed transmission power is assigned at all the RSU and vehicles as $P_s = P_r = 1$ dB.

The curves obtained via link-level simulations are denoted by **Ex**. An analytically derived outage probability is denoted by **An**. In addition, an asymptotically derived outage probability is denoted by **As**. The target SNR threshold is fixed at $o_{\rm th} = 1$ dB.

Fig. 2 shows the outage probability for various system and channel parameters. Two different distances, $D = 12$ $[m]$ and $D = 15$ $[m]$, between the RSU and target vehicle are considered. The main purpose of this figure is to investigate the impact of the number of vehicles in the lens-shaped cooperating area on the outage probability. From Fig. 2, we can make the following observations:

- For $M = 1$, the derived closed-form expression for the outage probability provides a good accuracy. As ρ_s increases, $P_{\rm outage}^{M=1,{\rm as}}(o_{\rm th})$ approaches $P_{\rm outage}^{M=1}(o_{\rm th})$.
- As M becomes larger, a lower outage probability is achieved. Especially, the slope in $\log - \log$ domain is mainly determined by M. That is, M, the number of vehicles in the lens-shaped cooperating area, is a factor that determines the diversity gain.
- As D increases, both the average distance between the RSU and the vehicles, $V_{1,i}, \forall i$, and the average distance between the vehicles, $V_{1,i}, \forall i$ and target vehicle, V_2, increases. Thus, a higher outage probability is obtained. Path loss which is determined by the distance between two nodes is the main cause of this results. However, the slope of the curves do not change according to the value of D.

In Fig. 3, we mainly investigate the outage diversity gain. We assume a fixed distance, $D = 12$ $[m]$.

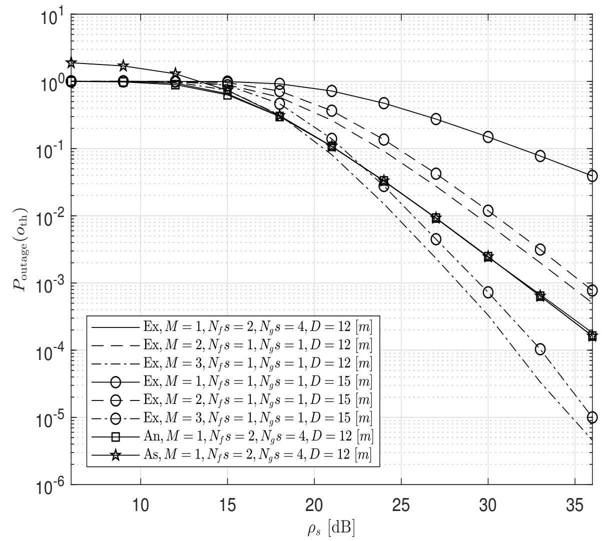

Fig. 2: Outage probability for various system and channel parameters.

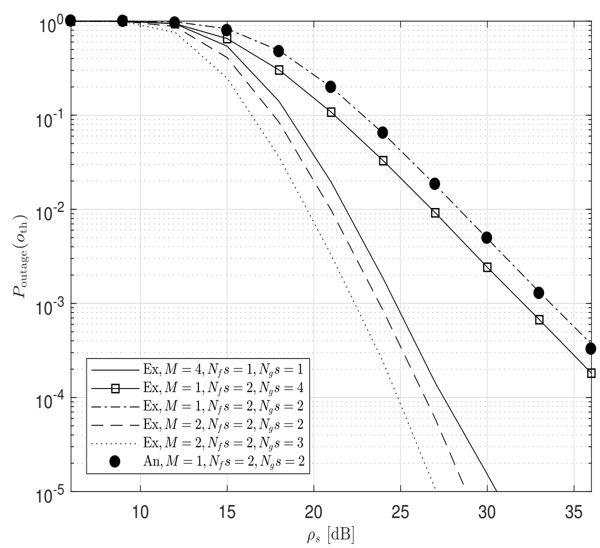

Fig. 3: Outage probability with different outage diversity gains, such as $G_d^{M=1}$, $G_d^{M=2}$, and $G_d^{M=4}$.

- Since $G_d^{M>1} = \min(MN_f s, MN_g s)$, the slope of the outage probability of the system with $(N_f s = 1, N_g s =$

1) is same as that of system with $(N_f s = 1, N_g s = 4)$. Similarly, the slope of the outage probability of the system with $(M = 2, N_f s = 2, N_g s = 2)$ is same as that of the system with $(M = 2, N_f s = 2, N_g s = 3)$. This can be justified by *Theorem 1*. However, the system with $(M = 2, N_f s = 2, N_g s = 3)$ has a lower outage probability.

- The slope of the system with $(M = 4, N_f s = 1, N_g s = 1)$, $(M = 2, N_f s = 2, N_g s = 3)$, and $(M = 2, N_f s = 2, N_g s = 2)$ has the same diversity, $G_d^{M=4} = G_d^{M=2} = 4$, which can be verified by measuring the slope of the curves in the $\log - \log$ domain.

V. Conclusions

In this paper, we have proposed a new cooperative I2V system. By employing dCDD among RSU and cooperating vehicles, the range of the RSU can be extended. By integrating the relaying protocol into dCDD, the RSU is able to provide the backhaul and wireless access to the target vehicle located in the coverage hole. As far as the total cooperating vehicles can be covered by the restriction of dCDD, the maximum achievable diversity gain can be possible in the frequency selective fading channel.

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Appendix A: Derivation of Proposition 2

We can first verify that $\frac{\sqrt{4D^2x^2-(D^2-R^2+x^2)^2}}{2Dx} \leq 1$ for $x \in [D-R, R]$. To derive a feasible expression, we use the following identical representation for $2x\sin^{-1}\left(\frac{\sqrt{4D^2x^2-(D^2-R^2+x^2)^2}}{2Dx}\right)$ as follows:

$$2x\sin^{-1}\left(\frac{\sqrt{4D^2x^2-(D^2-R^2+x^2)^2}}{2Dx}\right) = \pi x - 2x\sin^{-1}\left(\frac{D^2-R^2+x^2}{2Dx}\right). \quad (A.1)$$

Now applying Maclaurin series expansion for $\sin^{-1}(\cdot)$ and binomial expansion, (A.1) is evaluated as follows:

$$2x\sin^{-1}\left(\frac{\sqrt{4D^2x^2-(D^2-R^2+x^2)^2}}{2Dx}\right) = \pi x - \sum_{n=0}^{\infty}\sum_{m=0}^{2n+1} C_{n,m}x^{2m-2n}. \quad (A.2)$$

Thus, the PDF of $d_{1,i}$ can be expressed as follows:

$$f_{d_{1,i}}(x) = \frac{1}{A}\pi x - \frac{1}{A}\sum_{n=0}^{\infty}\sum_{m=0}^{2n+1} C_{m,n}x^{2m-2n}. \quad (A.3)$$

The SA-PDF of $\gamma_{1,i}$ is evaluated as follows:

$$f_{\gamma_{1,i}}(x) = \int_{D-R}^{R}\left(\frac{y^{\epsilon_{\rm L}}}{\rho_s}\right) f_{\|\tilde{\boldsymbol{f}}_i\|^2}\left(\frac{y^{\epsilon_{\rm L}}x}{\rho_s}\right) f_{d_{1,i}}(y)dy \quad (A.4)$$

where $f_{\|\tilde{\boldsymbol{f}}_i\|^2}(\cdot)$ denotes the PDF of $\|\tilde{\boldsymbol{f}}_i\|^2$. Based on the frequency selective fading channel assumption, we have the corresponding PDF as follows:

$$f_{\|\tilde{\boldsymbol{f}}_i\|^2}(x) = \frac{1}{\Gamma(N_{f,i})}x^{N_{f,i}-1}e^{-x}. \quad (A.5)$$

Thus, after some computations, we can have (8).