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Full Duplex AF and DF Relaying Under Channel Estimation Errors for V2V Communications

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ABSTRACT In this paper, we investigate the outage performance of full-duplex (FD) and half-duplex (HD) vehicle to vehicle (V2V) networks. We consider two vehicular communication scenarios with the assistance of roadside unit (RSU), i.e., RSU-to-vehicle-to-vehicle (RVV) and vehicle-to-RSU-to-vehicle (VRV) scenarios. In particular, we analyze the outage performance of vehicular networks with the amplify-and-forward (AF) and decode-and-forward (DF) protocols under the effect of residual loop-back-interference (LBI) and channel estimation errors. For RVV scenario, the upper bounds for the outage probability of the AF based FD and HD relaying over double Rayleigh fading channels are derived. Moreover, we derive the approximate closed form expressions for the outage probability of the DF based FD and HD relaying protocol over Rayleigh fading channels; For VRV scenario, the exact closed-form expressions for the outage probability of the AF and DF relaying protocols are presented in case of FD and HD modes. Furthermore, we derive the approximate closed-form expressions for the outage probability of hybrid FD/HD mode on AF and DF relaying protocols. The numerical and simulation results corroborate our theoretical ones and quantify the impact of the data rates, channel estimation errors and the residual LBI on the system performance.

INDEX TERMS V2V, full-duplex, half-duplex, amplify-and-forward, decode-and-forward, outage probability, channel estimation errors.

I. INTRODUCTION

Vehicular communications [1] are a key integral part of the intelligent transportation systems (ITSs) which involve the application of advanced information processing [2], D2D [3], internet of things (IOT) [4], edge computing [5], and wireless access technologies [6] that have drawn much attention in recent years. A full-duplex (FD) mode, where a node can transmit and receive on the same frequency band simultaneously, achieves up to double the spectral efficiency of a half-duplex (HD) scheme [7]–[9]. Although the FD transmission suffers from loop-back-interference (LBI), it has drawn attention due to recent advances on novel combinations of propagation-domain, analog-domain and digital-domain interference cancellations [8]–[10]. For FD system, it is crucial that the large LBI spans most of the dynamic range of the analog-to-digital converter (ADC) at the receiver. Advanced antenna isolation designs and RF-cancellation schemes can attenuate the leakage signal to a proper level to prevent the complete saturation of the receiver chain and reduce the quantization noise of the ADC. The residual nonlinear distortion of the LBI signal could be mitigated by novel digital cancellation solutions [10]–[13].

Novel cancellation solutions could be applied to mitigate the LBI, however, advanced antenna design and the energy consumption caused by analog and digital LBI suppression are still crucial for the low-cost low-cost battery-powered mobile devices. FD vehicular communications have many advantages to deal with the above issues, such as higher level of passive antenna isolation with more flexible antenna placement, stronger transceivers with unlimited power supply which can handle complex signal processing and higher-linearity analog components introducing fewer distortions and imperfections [14]. FD V2V transmission can be a potentially significant application area of full-duplex technologies.

Cooperative relay is an effective solution for achieving higher reliability and throughput required in modern wireless communication systems [15]. Relaying techniques can be classified into amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward strategies. Among those strategies, AF and DF are two commonly adopted protocols. In literature, the fundamental performance of the FD relay has recently been investigated. Zhang *et al.* [16] studied the average rate and outage probability tradeoffs of full-duplex two-way and one-way relaying under residual self-interference. In general, the results show that the DF relaying can achieve better performance than the AF one. However, there is a certain loss in the rate for DF relaying at high signal-to-noise ratio (SNR). Kwon *et al.* [17] derived the outage probability of DF relaying and investigated the conditions of full-duplex better than half-duplex mode. The research issues and challenges of FD relaying system were summarized in [18]. Reference [19] studied the switching boundary of FD and HD modes. The authors also investigated power adaptation solution to maximize the system spectrum efficiency. The analysis covers both AF and DF relaying protocols for the case of downlink and uplink systems. Kim and Paulraj [20] derived tight closed-form bounds on the outage probability expression for full-duplex AF relaying and studied the effect of the direct link and the residual LBI on the optimal duplex mode selection. According on the instantaneous channel conditions, [21] investigated an adaptive transmission scheme among direct transmission, HD relaying with maximal-ratio combining (MRC) and FD relaying with MRC at the destination. Baranwal *et al.* [22] studied the outage performance for multiple full-duplex relays cooperation system, where multiple full-duplex DF relays form a multi-hop network to forward the information. Reference [23] studied the FD relay selection for AF multiple relays cooperative networks. For the purpose of signal detection, perfect channel state information (CSI) feedback is assumed in most existing works. However, in practical cases, the CSI may only be partially obtained at the receiver [24]. Choi and Lee [25] derived the approximate closed-form expressions for the outage probability of the FD two-way AF relay with imperfect CSI. Wang *et al.* [26] studied the average end-to-end capacity for the FD AF two-way relay system. Wang *et al.* [27] investigated the performance comparison of the full-duplex and half-duplex AF two hop relaying system. For two practical relaying scenarios, the authors derived the closed form expressions of ergodic capacity with channel estimation errors, respectively.

Compared to the traditional mobile radio link, the V2V channel is much more dynamic, as the communication link is established between two mobile transceivers. For traditional mobile link, one of communicated transceivers is fixed, i.e., stationary transceiver. Some studies have suggested that double Rayleigh fading could be an appropriate small-scale fading model for V2V channels [28], [29]. Campolo *et al.* [14] investigated the design issues of full-duplex devices at the higher-layer protocols of vehicular networks and discussed the benefits full-duplex could bring with respect to half-duplex devices in some cases. Few works have focused on FD in vehicular communications, especially in full-duplex performance analysis.

In this paper, we study system performance of FD and HD V2V communications on AF and DF relaying protocols. A Roadside unit (RSU) deployed along the road supply connectivity to vehicles passing by that can exchange data [14]. We consider two vehicular communication scenarios, i.e., RSU-to-vehicle-to-vehicle (RVV) and vehicle-to-RSU-to-vehicle (VRV) scenarios. In particular, the contributions of the paper are summarized as follows:

1) By considering channel estimation errors, the expressions of the received signal-to-interference-plus-noise ratio (SINR) of the combinations of FD, HD, AF and DF modes are derived for both RVV and VRV scenarios;
2) For RVV scenario, we analyze the performance over double Rayleigh fading channel. In particular, we derive the upper bounds of outage probability for FD and HD AF modes. Moreover, the approximate closed form expressions of outage probability for FD and HD DF modes are derived, respectively;
3) For VRV scenario, we derive the closed form expressions of outage probability for all combinations duplex modes (FD or HD) and relaying protocols (AF or DF);
4) For VRV scenario, we analyze the outage performance of optimal duplex transmission. In particular, we derive an accurate approximation of outage probability for hybrid FD/HD AF relaying transmission. Furthermore, the closed form expression of outage probability for hybrid FD/HD DF relaying transmission are derived.

The paper is organized as follows. In Section II, system model is presented, including channel model, signal model and SINR model. Firstly, we investigate the outage performance for RVV scenario. A detailed derivation of the outage probabilities of FD and HD on AF and DF relaying protocols, respectively, are presented in Section III. In Section IV, we study the outage performance of FD and HD on AF and DF relaying protocols for VRV scenario. Moreover, we derive the outage probability of optimal duplex mode based on FD/HD switching. Analytical results, Monte Carlo simulations and discussions are presented in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

We consider a V2V system where two nodes exchange information though a middle node. The middle node acting as a relay with AF or DF protocols resends the received data from the source node to the target node. There are two kinds of nodes in the network, i.e., vehicle nodes a and b and a RSU r. All the nodes are equipped with single transmit and receive antennas. RSU can be seen as a infrastructure-based node to enlarge the coverage and improve the reliability of the vehicular networks.

We focus on two V2V communication scenarios, as shown in Fig. 1. For RVV scenario, the RSU r and the vehicle a exchange information with each other via the vehicle b; For VRV scenario, the vehicle a and the vehicle b exchange information with each other via the RSU r.

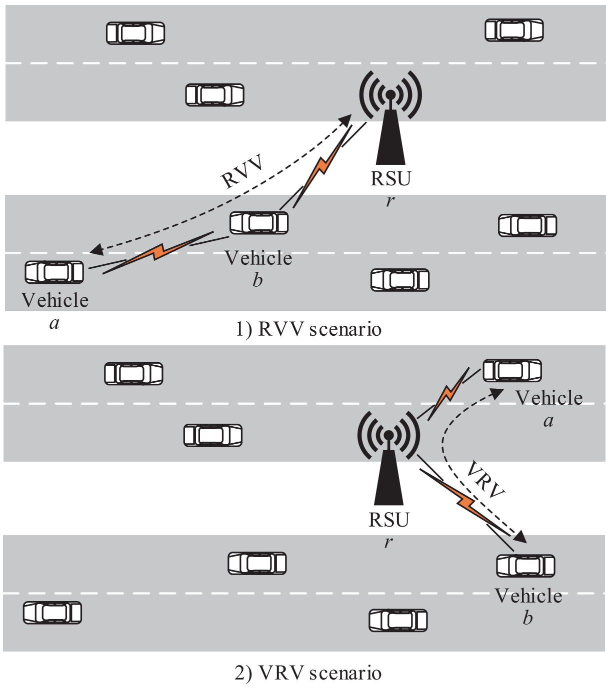

FIGURE 1. RVV scenario: RSU-to-vehicle-to-vehicle communication; VRV scenario: Vehicle-to-RSU-to-vehicle communication.

A. CHANNEL MODEL

For VRV scenario, the RSU acting as a infrastructure-based relay, the source vehicle a sends data to the destination vehicle b. The channel coefficients can be modeled as the sum of the estimate channels and the channel estimation errors. We model the channel h_{ar} and h_{rb} [27]

$$\begin{aligned} h_{ar} &= \hat{h}_{ar} + \Delta_{ar} \\ h_{rb} &= \hat{h}_{rb} + \Delta_{rb} \end{aligned} \tag{1}$$

where $h_{ar} \sim \mathcal{CN}(0, \sigma^2_{h_{ar}})$ and $h_{rb} \sim \mathcal{CN}(0, \sigma^2_{h_{rb}})$ are jointly ergodic and stationary gaussian process. Δ_{ar} and Δ_{rb} are the complex Gaussian terms with zero mean and variances $\sigma^2_{\Delta_{ar}} = \sigma^2_{h_{ar}} - \mathcal{E}(|\hat{h}_{ar}|^2)$ and $\sigma^2_{\Delta_{rb}} = \sigma^2_{h_{rb}} - \mathcal{E}(|\hat{h}_{rb}|^2)$, respectively. The orthogonality between the channel estimate and the estimation error is assumed. The similar channel model with estimation errors can also be found in [25] and [26].

For RVV scenario, the source vehicle a and RSU r exchange information with each other via the vehicle-based relay b. The channels between two vehicles a and b are modeled as the product of two independent complex Gaussian random variables, i.e., $h_{ij} = h_{ij,1}h_{ij,2}$ $(i, j \in \{a, b\}, i \neq j)$, where is $h_{ij,1}$ and $h_{ij,2}$ are the complex Gaussian random variable with zero mean and variance of $\sigma^2_{h_{ij,1}}$ and $\sigma^2_{h_{ij,2}}$. Hence, $|h_{ij}| = |h_{ij,1}||h_{ij,2}|$ follow a double Rayleigh distribution. Similar to the RSU-vehicle link, we also model the vehicle-vehicle link as

$$h_{ij,1}h_{ij,2} = \hat{h}_{ij} + \Delta_{ij} \tag{2}$$

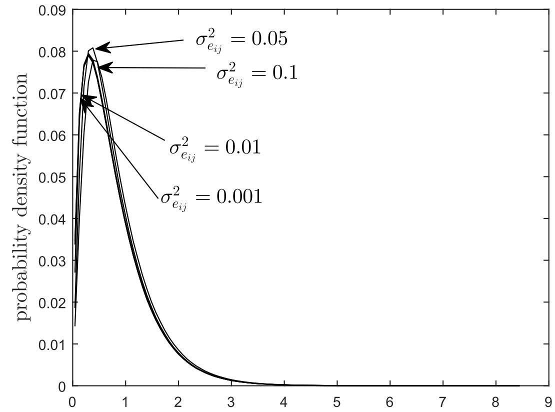

FIGURE 2. The pdfs of $|h_{ij,1}||h_{ij,2}|$ and $|\hat{h}_{ij}|$ for the case of $\sigma^2_{h_{ij,1}} = 1$, $\sigma^2_{h_{ij,1}} = 1$ and $\sigma^2_{\Delta_{ij}} = \{0.1, 0.05, 0.01, 0.001\}$.

The probability distribution function (pdf) of $|\hat{h}_{ij}|$ is hard to obtain as the presence of the estimation error term Δ_{ij}. The pdfs of $|h_{ij,1}||h_{ij,2}|$ and $|\hat{h}_{ij}|$ are plotted in the case of different variances of estimation errors, as shown in Fig.2. The channels are not reciprocal, i.e., $h_{ij} \neq h_{ji}$, since the presence of the channel estimation errors.

The cumulative distribution function (cdf) of $|h_{ij}|^2 = |h_{ij,1}|^2|h_{ij,2}|^2$ can be calculated as

$$\begin{aligned} \mathcal{F}_{|h_{ij}|^2}(s) &= 1 - \Pr\big(|h_{ij,1}|^2|h_{ij,2}|^2 > s\big) \\ &\overset{(\rho_1)}{=} 1 - \sqrt{\frac{4s}{\lambda_{ij,1}\lambda_{ij,2}}}K_1\left(\sqrt{\frac{4s}{\lambda_{ij,1}\lambda_{ij,2}}}\right) \end{aligned} \tag{3}$$

where $\lambda_{ij,1} = \sigma^2_{h_{ij,1}}$ and $\lambda_{ij,2} = \sigma^2_{h_{ij,2}}$. In (3), (ρ_1) is obtained by $\int_0^\infty e^{-\frac{a}{4s}-bs}ds = \sqrt{\frac{a}{b}}K_1(\sqrt{ab})$ in [30, eq. (3.324.1)]. $K_1(\cdot)$ is the first order modified Bessel function of the second kind [30, eq. (8.432)].

B. SIGNAL MODEL

Both RVV and VRV scenarios are one-hop relay networks, the difference between the two scenarios are channel models. Therefore, we present the common signal models for both scenarios with AF and DF relaying protocols, respectively. For VRV scenario, we will only focus on the end-to-end link of $a \to r \to b$ since analysis for the reverse link of $b \to r \to a$ is analogous. For RVV scenario, the uplink and downlink experience asymmetric channels, we consider both $r \to b \to a$ and $a \to b \to r$ links. The general signal model is described below. For RVV scenario, l denotes the vehicle b, m denotes the vehicle a or the RSU r and n denotes r or a. For VRV scenario, l denotes r, m denotes a and n denotes b.

The relay l receives the mixed signal including the signal from the source m, the LBI of the FD relay and the noise term

$$y_l[k] = \sqrt{p_m}h_{ml}x_m[k] + \sqrt{p_l}h_{l,\ell}x_l[k] + z_l[k] \tag{4}$$

where $x_m[k]$ and $x_l[k]$ are the transmit signals from the source m and the relay l with unit power; p_m and p_l are the transmit energy from the source m and the relay l; $h_{l,\ell}$ is the LBI channel between the transmit antenna and receive antenna of the relay l; $z_l[k] \sim \mathcal{CN}(0, N_0)$ is the Gaussian noise at l.

The relay exploits interference cancellation algorithm to mitigate the LBI. However, parameter estimation of the LBI and LBI cancellation solutions are beyond the scope of this paper. After LI cancellation, the residual received signal of the relay can be denoted as

$$\begin{aligned}\tilde{y}_l[k] &= y_l[k] - \sqrt{p_l}\hat{h}_{l,\ell}x_l[k] \\ &= \sqrt{p_m}h_{ml}x_m[k] + \sqrt{p_l}\Delta_{l,\ell}x_l[k] + z_l[k] \end{aligned} \tag{5}$$

where $\hat{h}_{l,\ell}$ is estimation of the LBI channel. Similar signal expression can also be found in [25]. $\Delta_{l,\ell}$ is the residual LBI after the LI cancellation. We assume that $\Delta_{l,\ell}$ is also a zero-mean complex Gaussian random variable with variance $\sigma^2_{\Delta_{l,\ell}}$.

1) AMPLIFY-AND-FORWARD

In the AF protocol, the relay amplifies the received signal by a factor G_l with a processing delay τ. The transmit signal of the relay can be denoted as

$$x_l[k] = G_l\tilde{y}_l[k-\tau] \tag{6}$$

With the help of the pilot sequence in $x_m[k]$, the relay can estimate channels and forward $\hat{h}_{ml}$ to sources. Specific estimation strategies can be found in [24]. The amplification factor with channel estimation errors can be expressed as

$$G_l = \left(p_m|\hat{h}_{ml}|^2 + p_m\sigma^2_{\Delta_{ml}} + p_l\sigma^2_{\Delta_{l,\ell}} + N_0\right)^{-\frac{1}{2}} \tag{7}$$

The received signal at the destination n is given by

$$y_n^{\text{AF}}[k] = \sqrt{p_l}h_{ln}x_l[k] + z_{ln}[k] \tag{8}$$

where $z_{ln}[k] \sim \mathcal{CN}(0, N_0)$ is independent Gaussian noise terms at n.

By ignoring the processing delay τ of relay and substituting (1), (4) and (6) into (8), the received signal with channel estimation errors at the destination n is given by

$$\begin{aligned} y_n^{\text{AF}}[k] &= G_l\sqrt{p_m}\sqrt{p_l}\hat{h}_{ml}\hat{h}_{ln}x_m[k] + G_l\sqrt{p_m}\sqrt{p_l}\hat{h}_{ln}\Delta_{ml}x_m[k] \\ &\quad + G_l\sqrt{p_l}\sqrt{p_m}\hat{h}_{ml}\Delta_{ln}x_m[k] + G_l\sqrt{p_m}\sqrt{p_l}\Delta_{ml}\Delta_{ln}x_m[k] \\ &\quad + G_l\sqrt{p_l}\sqrt{p_l}\hat{h}_{ln}\Delta_{l,\ell}x_l[k] + G_l\sqrt{p_l}\sqrt{p_l}\Delta_{ln}\Delta_{l,\ell}x_l[k] \\ &\quad + G_l\sqrt{p_l}\hat{h}_{ln}z_l[k] + G_l\sqrt{p_l}\Delta_{ln}z_l[k] + z_{ln}[k] \end{aligned} \tag{9}$$

2) DECODE-AND-FORWARD

In DF mode, the relay l decodes the received signal $\tilde{y}_l[k-\tau]$ and reencodes it to generate the transmite signal $x_l[k]$ [7]. The processing delay τ is large enough to guarantee that $x_m[k]$ and $x_l[k]$ are independent. Different from the HD relaying, the FD relay can decode the current received signal and send the last processed signal simultaneously.

The received signal at the destination n can be expressed as

$$y_n^{\text{DF}}[k] = \sqrt{p_l}h_{ln}x_l[k] + z_{ln}[k] \tag{10}$$

It should be noted that the signal $x_l[k]$ here is different from the signal in AF mode. $x_l[k]$ is the reencoded signal of the transmit signal.

By substituting the estimated channels into (10), the received signal with channel estimation errors at the destination n is given by

$$y_n^{\text{DF}}[k] = \sqrt{p_l}\hat{h}_{ln}x_l[k] + \sqrt{p_l}\Delta_{ln}x_l[k] + z_{ln}[k] \tag{11}$$

C. SIGNAL-TO-INTERFERENCE-PLUS-NOISE RATIO

To analyze the outage performance in next sections, we give the SINR for different combinations of FD, HD, AF and DF modes. For easy of expression, we denote $\gamma_a = p_a/N_0$, $\gamma_r = p_r/N_0$ and $\gamma_b = p_b/N_0$, where p_a, p_r and p_b are the transmit energy of vehicle a, RSU r and vehicle b, respectively.

1) RSU-TO-VEHICLE-TO-VEHICLE

When the vehicle b acting as a full duplex AF relay, from (9), we can obtain the effective end-to-end SINRs of the links $a \to b \to r$ and $r \to b \to a$, respectively

$$\begin{aligned} \gamma^{\text{AF}}_{\text{FD},a\to r} &= \frac{\frac{\gamma_a|\hat{h}_{ab}|^2}{\gamma_b^{\text{LI}}+\epsilon_{ab}}\frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}}}{\frac{\gamma_a|\hat{h}_{ab}|^2}{\gamma_b^{\text{LI}}+\epsilon_{ab}} + \frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}} + 1} \\ \gamma^{\text{AF}}_{\text{FD},r\to a} &= \frac{\frac{\gamma_r|\hat{h}_{rb}|^2}{\gamma_b^{\text{LI}}+\epsilon_{rb}}\frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}}}{\frac{\gamma_r|\hat{h}_{rb}|^2}{\gamma_b^{\text{LI}}+\epsilon_{rb}} + \frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}} + 1} \end{aligned} \tag{12}$$

where $\gamma_b^{\text{LI}} = \gamma_b\sigma^2_{\Delta_{b,\ell}}$, $\epsilon_{ab} = \gamma_a\sigma^2_{\Delta_{ab}} + 1$, $\epsilon_{br} = \gamma_b\sigma^2_{\Delta_{br}} + 1$, $\epsilon_{rb} = \gamma_r\sigma^2_{\Delta_{rb}} + 1$ and $\epsilon_{ba} = \gamma_b\sigma^2_{\Delta_{ba}} + 1$. For full-duplex AF relaying mode, the instantaneous end-to-end capacity of $a \to b \to r$ link is defined as $C^{\text{AF}}_{\text{FD},a\to r} = \log_2\left(1+\gamma^{\text{AF}}_{\text{FD},a\to r}\right)$. The instantaneous end-to-end capacity of $r \to b \to a$ link is defined as $C^{\text{AF}}_{\text{FD},r\to a} = \log_2\left(1+\gamma^{\text{AF}}_{\text{FD},r\to a}\right)$.

For AF based FD relaying mode, the effective end-to-end SINR of the links $a \to b \to r$ and $r \to b \to a$ are given by, respectively

$$\begin{aligned} \gamma^{\text{AF}}_{\text{HD},a\to r} &= \frac{\frac{\gamma_a|\hat{h}_{ab}|^2}{\epsilon_{ab}}\frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}}}{\frac{\gamma_a|\hat{h}_{ab}|^2}{\epsilon_{ab}} + \frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}} + 1} \\ \gamma^{\text{AF}}_{\text{HD},r\to a} &= \frac{\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}\frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}}}{\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}} + \frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}} + 1} \end{aligned} \tag{13}$$

For AF based HD relaying mode, the instantaneous end-to-end capacity of $a \to b \to r$ link is defined as $C^{\text{AF}}_{\text{HD},a\to r} = \frac{1}{2}\log_2\left(1+\gamma^{\text{AF}}_{\text{HD},a\to r}\right)$. The instantaneous end-to-end capacity of $r \to b \to a$ link is defined as $C^{\text{AF}}_{\text{HD},r\to a} = \frac{1}{2}\log_2\left(1+\gamma^{\text{AF}}_{\text{HD},r\to a}\right)$.

For DF based FD relaying mode, the effective end-to-end SINR of the links $a \to b \to r$ and $r \to b \to a$ are given by, respectively

$$\begin{aligned} \gamma^{\text{DF}}_{\text{FD},a\to r} &= \min\left(\frac{\gamma_a|\hat{h}_{ab}|^2}{\gamma_b^{\text{LI}}+\epsilon_{ab}}, \frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}}\right) \\ \gamma^{\text{DF}}_{\text{FD},r\to a} &= \min\left(\frac{\gamma_r|\hat{h}_{rb}|^2}{\gamma_b^{\text{LI}}+\epsilon_{rb}}, \frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}}\right) \end{aligned} \tag{14}$$

For DF based FD relaying mode, the instantaneous end-to-end capacity of $a \rightarrow b \rightarrow r$ link is defined as $\mathcal{C}_{\mathrm{FD},a\rightarrow r}^{\mathrm{DF}} = \log_2\left(1+\gamma_{\mathrm{FD},a\rightarrow r}^{\mathrm{DF}}\right)$. The instantaneous end-to-end capacity of $r \rightarrow b \rightarrow a$ link is defined as $\mathcal{C}_{\mathrm{FD},r\rightarrow a}^{\mathrm{DF}} = \log_2\left(1+\gamma_{\mathrm{FD},r\rightarrow a}^{\mathrm{DF}}\right)$.

For DF based HD relaying mode, the effective end-to-end SINR of the links $a \rightarrow b \rightarrow r$ and $r \rightarrow b \rightarrow a$ are given by, respectively

$$\begin{aligned}\gamma_{\mathrm{HD},a\rightarrow r}^{\mathrm{DF}} &= \min\left(\frac{\gamma_a|\hat{h}_{ab}|^2}{\epsilon_{ab}}, \frac{\gamma_b|\hat{h}_{br}|^2}{\epsilon_{br}}\right)\\ \gamma_{\mathrm{HD},r\rightarrow a}^{\mathrm{DF}} &= \min\left(\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}, \frac{\gamma_b|\hat{h}_{ba}|^2}{\epsilon_{ba}}\right)\end{aligned} \tag{15}$$

For DF based HD relaying mode, the instantaneous capacity of $a \rightarrow b \rightarrow r$ link is defined as $\mathcal{C}_{\mathrm{HD},a\rightarrow r}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1+\gamma_{\mathrm{HD},a\rightarrow r}^{\mathrm{DF}}\right)$. The instantaneous capacity of $r \rightarrow b \rightarrow a$ link is defined as $\mathcal{C}_{\mathrm{HD},r\rightarrow a}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1+\gamma_{\mathrm{HD},r\rightarrow a}^{\mathrm{DF}}\right)$.

2) VEHICLE-TO-RSU-TO-VEHICLE

When vehicle RSU r acting as a AF based FD relay, the effective end-to-end SINR of the links $a \rightarrow r \rightarrow b$ can be expressed as

$$\gamma_{\mathrm{FD},a\rightarrow b}^{\mathrm{AF}} = \frac{\frac{\gamma_a|\hat{h}_{ar}|^2}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}}{\frac{\gamma_a|\hat{h}_{ar}|^2}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}+\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}+1} \tag{16}$$

where $\gamma_r^{\mathrm{LI}} = \gamma_r\sigma_{\Delta_{r,\ell}}^2$, $\epsilon_{ar} = \gamma_a\sigma_{\Delta_{ar}}^2 + 1$, $\epsilon_{rb} = \gamma_r\sigma_{\Delta_{rb}}^2 + 1$. The instantaneous capacity is defined as $\mathcal{C}_{\mathrm{FD},a\rightarrow b}^{\mathrm{AF}} = \log_2\left(1+\gamma_{\mathrm{FD},a\rightarrow b}^{\mathrm{AF}}\right)$.

For AF based HD relaying mode, the effective end-to-end SINR of the links $a \rightarrow r \rightarrow b$ is given by

$$\gamma_{\mathrm{HD},a\rightarrow b}^{\mathrm{AF}} = \frac{\frac{\gamma_a|\hat{h}_{ar}|^2}{\epsilon_{ar}}\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}}{\frac{\gamma_a|\hat{h}_{ar}|^2}{\epsilon_{ar}}+\frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}+1} \tag{17}$$

The instantaneous capacity is defined as $\mathcal{C}_{\mathrm{HD},a\rightarrow b}^{\mathrm{AF}} = \frac{1}{2}\log_2\left(1+\gamma_{\mathrm{HD},a\rightarrow b}^{\mathrm{AF}}\right)$.

For DF based FD relaying mode, the effective end-to-end SINR of the links $a \rightarrow r \rightarrow b$ is given by

$$\gamma_{\mathrm{FD},a\rightarrow b}^{\mathrm{DF}} = \min\left(\frac{\gamma_a|\hat{h}_{ar}|^2}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}, \frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}\right) \tag{18}$$

Hence, the instantaneous end-to-end capacity is defined as $\mathcal{C}_{\mathrm{FD},a\rightarrow b}^{\mathrm{DF}} = \log_2\left(1+\gamma_{\mathrm{FD},a\rightarrow b}^{\mathrm{DF}}\right)$.

For DF based HD relaying mode, the effective end-to-end SINR of the links $a \rightarrow r \rightarrow b$ is given by

$$\gamma_{\mathrm{HD},a\rightarrow b}^{\mathrm{DF}} = \min\left(\frac{\gamma_a|\hat{h}_{ar}|^2}{\epsilon_{ar}}, \frac{\gamma_r|\hat{h}_{rb}|^2}{\epsilon_{rb}}\right) \tag{19}$$

Then, the instantaneous end-to-end capacity is defined as $\mathcal{C}_{\mathrm{HD},a\rightarrow b}^{\mathrm{DF}} = \frac{1}{2}\log_2\left(1+\gamma_{\mathrm{HD},a\rightarrow b}^{\mathrm{DF}}\right)$.

For VRV scenario, we investigate an optimal transmission scheme based on a hybrid-duplex relaying (HR) that switches between FD and HD modes. A FD/HD switching scheme has been proposed in [19] where one of uplink and downlink channels is assumed to be an non-fading channel. In this paper, both uplink and downlink channels are modeled as fading channels. To achieve the best performance, the HR RSU switches the duplex modes in terms of instantaneous end-to-end capacity. For AF based relay, the HR scheme switches the relaying mode that satisfies the following policy

$$\mathcal{C}_{\mathrm{HR},a\rightarrow b}^{\mathrm{AF}} = \max\left(\mathcal{C}_{\mathrm{FD},a\rightarrow b}^{\mathrm{AF}}, \mathcal{C}_{\mathrm{HD},a\rightarrow b}^{\mathrm{AF}}\right) \tag{20}$$

For DF based relay, the HR scheme switches the relaying mode that satisfies the following policy

$$\mathcal{C}_{\mathrm{HR},a\rightarrow b}^{\mathrm{DF}} = \max\left(\mathcal{C}_{\mathrm{FD},a\rightarrow b}^{\mathrm{DF}}, \mathcal{C}_{\mathrm{HD},a\rightarrow b}^{\mathrm{DF}}\right) \tag{21}$$

III. OUTAGE OF RSU-TO-VEHICLE-TO-VEHICLE

In this section, we analysis the outage performance with both AF and DF relaying protocols for RVV scenario. Assuming that the communication between the source and the destination targets an end-to-end data rate R. Hence, the outage threshold of the SINR for FD mode can be denoted as $\Upsilon = 2^R - 1$. The outage threshold of the SINR for HD mode can be denoted as $\Upsilon(\Upsilon + 2) = 2^{2R} - 1$. Because of the complexity of the distribution of $|\hat{h}_{ab}|$ and as a result, the complexity of $|\hat{h}_{ab}|^2$, here we approximate $|\hat{h}_{ab}|^2$ with $|h_{ab}|^2 = |h_{ab,1}|^2|h_{ab,2}|^2$. This approximation is accurate when the estimation error is relatively low, as shown in Fig. 2. For easy of expressions, we denote $\alpha_1 = |h_{ab,1}|^2$, $\alpha_2 = |h_{ab,2}|^2$ and $\beta = |\hat{h}_{br}|^2$.

A. AMPLIFY-AND-FORWARD

The outage probability of $a \rightarrow b \rightarrow r$ with AF based FD relaying protocol can be calculated as

$$\begin{aligned}\mathcal{P}_{\mathrm{FD},a\rightarrow r}^{\mathrm{AF}} &= \Pr\left\{\mathcal{C}_{\mathrm{FD},a\rightarrow r}^{\mathrm{AF}} < R\right\}\\ &= 1 - \underbrace{\Pr\left\{\frac{\frac{\gamma_a\alpha_1\alpha_2}{\gamma_b^{\mathrm{LI}}+\epsilon_{ab}}\frac{\gamma_b\beta}{\epsilon_{br}}}{\frac{\gamma_a\alpha_1\alpha_2}{\gamma_b^{\mathrm{LI}}+\epsilon_{ab}}+\frac{\gamma_b\beta}{\epsilon_{br}}+1} \geq \Upsilon\right\}}_{\mathcal{I}_{\mathrm{AF}}(\alpha_1,\alpha_2,\beta)}\end{aligned} \tag{22}$$

For given α_2, by taking the average over α_1 and β, $\mathcal{I}_{\mathrm{AF}}(\alpha_1, \beta|\alpha_2)$ is given by

$$\begin{aligned}&\mathcal{I}_{\mathrm{AF}}(\alpha_1, \beta|\alpha_2)\\ &= \int_{\frac{\Upsilon\epsilon_{br}}{\gamma_b}}^{\infty}\left\{1-\mathcal{F}_{\alpha_1}\left(\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})(\gamma_b s+\epsilon_{br})}{\gamma_a\alpha_2(\gamma_b s-\Upsilon\epsilon_{br})}\right)\right\}f_\beta(s)ds\\ &= e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})}{\lambda_{ab,1}\gamma_a\alpha_2}-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b\alpha_2}}\\ &\quad\times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b\alpha_2}}\right)\end{aligned} \tag{23}$$

where $\mathcal{F}_{\alpha_1}(s) = 1-e^{-\frac{s}{\lambda_{ab,1}}}$ is the cdf of $|h_{ab,1}|^2$. $\lambda_{br} = \sigma_{h_{br}}^2 - \sigma_{\Delta_{br}}^2$. $f_\beta(s) = \frac{1}{\bar{\gamma}_{br}}e^{-\frac{s}{\lambda_{br}}}$ is the pdf of $|\hat{\gamma}_{br}|^2$.

By taking the average over α_2, $\mathcal{I}_{\mathrm{AF}}(\alpha_1, \alpha_2, \beta)$ can be calculated as

$$\begin{aligned}
&\mathcal{I}_{\mathrm{AF}}(\alpha_1, \alpha_2, \beta)\\
&= e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}} \int_0^\infty e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})}{\lambda_{ab,1}\gamma_a s}} \sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b s}}\\
&\quad\times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b s}}\right) \frac{e^{-\frac{s}{\lambda_{ab,2}}}}{\lambda_{ab,2}} ds\\
&= e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}} \int_0^\infty e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})s}{\lambda_{ab,1}\gamma_a}} \sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} s}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b}}\\
&\quad\times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} s}{\lambda_{ab,1}\lambda_{br}\gamma_a\gamma_b}}\right) \frac{e^{-\frac{1}{\lambda_{ab,2}s}}}{\lambda_{ab,2}s^2} ds\\
&= \frac{8\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b} \int_0^\infty e^{-\frac{\lambda_{br}\gamma_b s^2}{4(\Upsilon+1)\epsilon_{br}}}\\
&\quad\times e^{-\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b s^2}} \frac{K_1(s)}{s^2} ds \qquad (24)
\end{aligned}$$

To the best of the authors' knowledge, (24) does not have a closed form solution. Although, it can be calculated numerically using tools such as Matlab, Maple or Mathematica, we still want to get a closed form expression of it. A lower bound of (24) is given by

$$\begin{aligned}
&\mathcal{I}_{\mathrm{DF}}(\alpha_1, \alpha_2, \beta)\\
&\geq \frac{8\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b} \Bigg\{\int_0^\infty \frac{K_1(s)}{s^2}\\
&\quad\times e^{-\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b s^2}} ds - \frac{\lambda_{br}\gamma_b}{4(\Upsilon+1)\epsilon_{br}}\\
&\quad\times \int_0^\infty e^{-\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b s^2}} K_1(s) ds\Bigg\}\\
&= \frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\middle| -1, 0, 0\right)\\
&\quad- \frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab}) e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\middle| 0, 0, 1\right) \qquad (25)
\end{aligned}$$

Therefore, the upper bound of the outage probability of link $a \rightarrow b \rightarrow r$ with AF based FD relaying protocol is given by

$$\begin{aligned}
\mathcal{P}_{\mathrm{FD},a\rightarrow r}^{\mathrm{AF}} &\leq 1 - \frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br} e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\middle| -1, 0, 0\right)\\
&\quad+ \frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab}) e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\middle| 0, 0, 1\right) \qquad (26)
\end{aligned}$$

Similarly, the upper bound of the outage probability of link $r \rightarrow b \rightarrow a$ with AF based FD relaying protocol is given by

$$\begin{aligned}
\mathcal{P}_{\mathrm{FD},r\rightarrow a}^{\mathrm{AF}} &\leq 1 - \frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})\epsilon_{ba} e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})}{\lambda_{rb}\gamma_r}}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_b\gamma_r}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})\epsilon_{ba}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_s\gamma_r}\middle| -1, 0, 0\right)\\
&\quad+ \frac{\Upsilon\epsilon_{ba} e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})}{\lambda_{rb}\gamma_r}}}{\lambda_{ba,1}\lambda_{ba,2}\gamma_b}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})\epsilon_{ba}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_b\gamma_r}\middle| 0, 0, 1\right) \qquad (27)
\end{aligned}$$

where $\lambda_{rb} = \sigma_{h_{rb}}^2 - \sigma_{\Delta_{rb}}^2$.

For HD mode, $\mathcal{I}(\alpha_1, \alpha_2, \beta)$ is given by

$$\begin{aligned}
&\mathcal{I}(\alpha_1, \alpha_2, \beta)\\
&= \Pr\left\{\frac{\frac{\gamma_a\alpha_1\alpha_2}{\epsilon_{ab}}\frac{\gamma_b\beta}{\epsilon_{br}}}{\frac{\gamma_a\alpha_1\alpha_2}{\epsilon_{ab}} + \frac{\gamma_b\beta}{\epsilon_{br}} + 1} \geq \Upsilon(\Upsilon+2)\right\}\\
&= \frac{8\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ab}\epsilon_{br} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b} \int_0^\infty e^{-\frac{\lambda_{br}\gamma_b s^2}{4(\Upsilon+1)^2\epsilon_{br}}}\\
&\quad\times e^{-\frac{4\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ab}\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b s^2}} \frac{K_1(s)}{s^2} ds \qquad (28)
\end{aligned}$$

The upper bound of the outage probability of link $a \rightarrow b \rightarrow r$ with AF based HD relaying protocol is given by

$$\begin{aligned}
\mathcal{P}_{\mathrm{HD},a\rightarrow r}^{\mathrm{AF}} &\leq 1 - \frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ab}\epsilon_{br} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ab}\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_s\gamma_r}\middle| -1, 0, 0\right)\\
&\quad+ \frac{\Upsilon(\Upsilon+2)\epsilon_{ab} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{br}}{\lambda_{br}\gamma_b}}}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ab}\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b}\middle| 0, 0, 1\right) \qquad (29)
\end{aligned}$$

The upper bound of the outage probability of link $r \rightarrow b \rightarrow a$ with AF based HD relaying protocol is given by

$$\begin{aligned}
\mathcal{P}_{\mathrm{HD},r\rightarrow a}^{\mathrm{AF}} &\leq 1 - \frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ba}\epsilon_{rb} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_b\gamma_r}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ba}\epsilon_{rb}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_b\gamma_r}\middle| -1, 0, 0\right)\\
&\quad+ \frac{\Upsilon(\Upsilon+2)\epsilon_{ba} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}}{\lambda_{ba,1}\lambda_{ba,2}\gamma_b}\\
&\quad\times G_{03}^{30}\left(\frac{\Upsilon(\Upsilon+2)(1+\Upsilon)^2\epsilon_{ba}\epsilon_{rb}}{\lambda_{ba,1}\lambda_{ba,2}\lambda_{rb}\gamma_b\gamma_r}\middle| 0, 0, 1\right) \qquad (30)
\end{aligned}$$

B. DECODE-AND-FORWARD

The outage probability of $a \to b \to r$ with DF based FD relaying protocol can be calculated as

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{FD},a\to r}\\
&= 1-\Pr\left\{\mathcal{C}^{\mathrm{FD}}_{\mathrm{DF},a\to r}\geq R\right\}\\
&= 1-\Pr\left\{\min\left(\frac{\gamma_a\alpha_1\alpha_2}{\gamma_b^{\mathrm{LI}}+\epsilon_{ab}},\frac{\gamma_b\beta}{\epsilon_{br}}\right)\geq\Upsilon\right\}\\
&= 1-\Pr\left\{\frac{\gamma_a\alpha_1\alpha_2}{\gamma_b^{\mathrm{LI}}+\epsilon_{ab}}\geq\Upsilon,\frac{\gamma_b\beta}{\epsilon_{br}}\geq\Upsilon\right\}\\
&= 1-e^{-\frac{\Upsilon\epsilon_{br}}{\lambda_{br}\gamma_b}}\sqrt{\frac{4\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}}K_1\left(\sqrt{\frac{4\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}}\right) \quad (31)
\end{aligned}$$

Similarly, the outage probability of $r \to b \to a$ with DF based FD relaying protocol is given by

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{FD},r\to a}\\
&\quad= 1-e^{-\frac{\Upsilon(\gamma_b^{\mathrm{LI}}+\epsilon_{rb})}{\gamma_r\lambda_{rb}}}\sqrt{\frac{4\Upsilon\epsilon_{ba}}{\gamma_b\lambda_{ba,1}\lambda_{ba,2}}}K_1\left(\sqrt{\frac{4\Upsilon\epsilon_{ba}}{\gamma_b\lambda_{ba,1}\lambda_{ba,2}}}\right)
\end{aligned} \quad (32)$$

The outage probability of $a \to b \to r$ with DF based HD relaying protocol can be calculated as

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{HD},a\to r}\\
&= 1-\Pr\left\{\mathcal{C}^{\mathrm{HD}}_{\mathrm{DF},a\to r}\geq R\right\}\\
&= 1-\Pr\left\{\min\left(\frac{\gamma_a\alpha_1\alpha_2}{\epsilon_{ab}},\frac{\gamma_b\beta}{\epsilon_{br}}\right)\geq\Upsilon(\Upsilon+2)\right\}\\
&= 1-\Pr\left\{\frac{\gamma_a\alpha_1\alpha_2}{\epsilon_{ab}}\geq\Upsilon(\Upsilon+2),\frac{\gamma_b\beta}{\epsilon_{br}}\geq\Upsilon(\Upsilon+2)\right\}\\
&= 1-e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{br}}{\lambda_{br}\gamma_b}}\sqrt{\frac{4\Upsilon(\Upsilon+2)\epsilon_{ab}}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}}K_1\left(\sqrt{\frac{4\Upsilon(\Upsilon+2)\epsilon_{ab}}{\lambda_{ab,1}\lambda_{ab,2}\gamma_a}}\right)
\end{aligned} \quad (33)$$

The outage probability of $r \to b \to a$ with DF based HD relaying protocol is given by

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{HD},r\to a}\\
&= 1-e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r\lambda_{rb}}}\sqrt{\frac{4\Upsilon(\Upsilon+2)\epsilon_{ba}}{\gamma_b\lambda_{ab,1}\lambda_{ab,2}}}K_1\left(\sqrt{\frac{4\Upsilon(\Upsilon+2)\epsilon_{ba}}{\gamma_b\lambda_{ab,1}\lambda_{ab,2}}}\right)
\end{aligned} \quad (34)$$

IV. OUTAGE OF VEHICLE-TO-RSU-TO-VEHICLE

In this section, we analysis the outage performance for both AF and DF relaying protocols for VRV scenario. Same data rate are assumed at node b, i.e., R. For easy of expression, we denote $\alpha = |\hat{h}_{ab}|^2$, $\dot{\beta} = |\hat{h}_{rb}|^2$.

A. AMPLIFY-AND-FORWARD

The outage probability of $a \to r \to b$ with AF based FD relaying protocol can be calculated as

$$\begin{aligned}
&\mathcal{P}^{\mathrm{AF}}_{\mathrm{FD},a\to b}\\
&= 1-\Pr\left\{\mathcal{C}^{\mathrm{AF}}_{\mathrm{FD},a\to b}\geq R\right\}\\
&= 1-\Pr\left\{\frac{\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}}{\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}+\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}+1}\geq\Upsilon\right\}\\
&= 1-\int_{\frac{\Upsilon\epsilon_{rb}}{\gamma_r}}^{\infty}\left\{1-\mathcal{F}_\alpha\left(\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})(\gamma_r s+\epsilon_{rb})}{\gamma_a(\gamma_r s-\Upsilon\epsilon_{rb})}\right)\right\}f_{\dot{\beta}}(s)ds\\
&= 1-\frac{1}{\lambda_{rb}}\int_{\Upsilon\epsilon_{rb}}^{\infty}e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})(\gamma_r s+\epsilon_{rb})}{\gamma_a\lambda_{ar}(\gamma_r s-\Upsilon\epsilon_{rb})}}e^{-\frac{s}{\lambda_{rb}}}ds\\
&= 1-e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\\
&\quad\times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\right)
\end{aligned} \quad (35)$$

where $\lambda_{ar} = \sigma^2_{h_{ar}} - \sigma^2_{\Delta_{ar}}$ and $\lambda_{rb} = \sigma^2_{h_{rb}} - \sigma^2_{\Delta_{rb}}$. $\mathcal{F}_\alpha(s) = 1 - e^{-\frac{s}{\lambda_{ar}}}$ is the cdf of $|\hat{h}_{ar}|^2$. $f_{\dot{\beta}}(s) = \frac{1}{\lambda_{rb}}e^{-\frac{s}{\lambda_{rb}}}$ is the pdf of $|\hat{h}_{rb}|^2$.

The outage probability of $a \to r \to b$ with AF based HD relaying protocol can be calculated as

$$\begin{aligned}
&\mathcal{P}^{\mathrm{AF}}_{\mathrm{HD},a\to b}\\
&= 1-\Pr\left\{\mathcal{C}^{\mathrm{AF}}_{\mathrm{HD},a\to b}\geq R\right\}\\
&= 1-\Pr\left\{\frac{\frac{\gamma_a\alpha}{\epsilon_{ar}}\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}}{\frac{\gamma_a\alpha}{\epsilon_{ar}}+\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}+1}\geq\Upsilon(\Upsilon+2)\right\}\\
&= 1-e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\\
&\quad\times K_1\left(\sqrt{\frac{4\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rd}\gamma_a\gamma_r}}\right)
\end{aligned} \quad (36)$$

The outage probability of HR scheme with AF relaying can be calculated as

$$\begin{aligned}
&\mathcal{P}^{\mathrm{AF}}_{\mathrm{HR},a\to b}\\
&= \Pr\left\{\mathcal{C}^{\mathrm{AF}}_{\mathrm{HR},a\to b}<R\right\}\\
&= \Pr\left\{\max\left(\mathcal{C}^{\mathrm{AF}}_{\mathrm{FD},a\to b},\mathcal{C}^{\mathrm{AF}}_{\mathrm{HD},a\to b}\right)<R\right\}\\
&= \Pr\left\{\frac{\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}}{\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}+\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}+1}<\Upsilon,\frac{\frac{\gamma_a\alpha}{\epsilon_{ar}}\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}}{\frac{\gamma_a\alpha}{\epsilon_{ar}}+\frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}+1}<\Upsilon(\Upsilon+2)\right\}
\end{aligned} \quad (37)$$

For $\gamma_r^{\mathrm{LI}} \leq (\Upsilon+1)\epsilon_{ar}$. Since $(\gamma_r^{\mathrm{LI}}+\epsilon_{ar}) \leq (\Upsilon+2)\epsilon_{ar}$. $\gamma_a\alpha\gamma_r\dot{\beta} < (\Upsilon+2)\epsilon_{ar} \leq \Upsilon(\gamma_a\alpha\epsilon_{rb}+(\Upsilon+2)\epsilon_{ar}(\dot{\beta}+\epsilon_{rb})) < \Upsilon(\Upsilon+2)(\gamma_a\alpha\epsilon_{rb}+\epsilon_{ar}(\dot{\beta}+\epsilon_{rb}))$. Therefore, $\mathcal{P}^{\mathrm{AF}}_{\mathrm{HR},a\to b} = \mathcal{P}^{\mathrm{AF}}_{\mathrm{FD},a\to b}$.

For $\gamma_r^{\mathrm{LI}} > (\Upsilon+1)\epsilon_{ar}$, $\mathcal{P}_{\mathrm{HR},a\to b}^{\mathrm{AF}}$ is given by

$$\begin{aligned}
&\mathcal{P}_{\mathrm{HR},a\to b}^{\mathrm{AF}} \\
&= 1 - \underbrace{\int_{\frac{\Upsilon(\Upsilon+2)\gamma_r^{\mathrm{LI}}\frac{\epsilon_{rb}}{\gamma_r}}{\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar}}}^{\infty}\left\{1-\mathcal{F}_\alpha\left(\frac{\Upsilon(\Upsilon+2)\frac{\epsilon_{ar}}{\gamma_a}(s+\frac{\epsilon_{rb}}{\gamma_r})}{s-\Upsilon(\Upsilon+2)\frac{\epsilon_{rb}}{\gamma_r}}\right)\right\}f_{\dot{\beta}}(s)ds}_{\mathcal{I}_1} \\
&\quad - \underbrace{\int_{\frac{\Upsilon\epsilon_{rb}}{\gamma_r}}^{\frac{\Upsilon(\Upsilon+2)\gamma_r^{\mathrm{LI}}\frac{\epsilon_{rb}}{\gamma_r}}{\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar}}}\left\{1-\mathcal{F}_\alpha\left(\frac{\Upsilon\frac{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}{\gamma_a}(s+\frac{\epsilon_{rb}}{\gamma_r})}{s-\Upsilon\frac{\epsilon_{rb}}{\gamma_r}}\right)\right\}f_{\dot{\beta}}(s)ds}_{\mathcal{I}_2}
\end{aligned} \tag{38}$$

In (38), $\mathcal{I}_1$ is given by

$$\begin{aligned}
&\mathcal{I}_1 \\
&= e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\left\{\int_{\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}^{\infty} e^{-s}\right. \\
&\quad \left.\times e^{-\frac{\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r s}}ds\right\} \\
&\overset{(\rho_2)}{\simeq} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sum_{l=0}^{L-1}\left(\frac{\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l \\
&\quad \times\frac{(-1)^l}{l!}\int_{\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}^{\infty}\frac{e^{-s}}{s^l}ds \\
&\overset{(\rho_3)}{=} e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}-\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}\sum_{l=0}^{L-1}\frac{(-1)^l}{l!} \\
&\quad \times\left(\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)^{-\frac{l}{2}} \\
&\quad \times\left(\frac{\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l \\
&\quad \times W_{-\frac{l}{2},\frac{1-l}{2}}\left(\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)
\end{aligned} \tag{39}$$

where (ρ_2) is obtained by the L-th order Taylor series approximation of the exponential function $e^{-s} \simeq \sum_{l=0}^{L}((-s)^l/l!)$; The integral in (ρ_3) can be obtained from the fact in [30, eq. (9.224)], i.e., $W_{b,1/2+b}(a) = a^{-b}e^{\frac{a}{2}}\int_a^\infty t^{2b}e^{-s}ds$. $W_{a,b}(z)$ is the Whittaker function defined in [30, eq. (9.222)]. This formulation can be easily solved by the matlab function 'whittakerW'.

In (38), $\mathcal{I}_2$ can be calculated as

$$\begin{aligned}
&\mathcal{I}_2 \\
&= e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\gamma_r\lambda_{rb}}}\left\{\int_0^{\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}} e^{-s}\right. \\
&\quad \left.\times e^{-\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\gamma_a\gamma_r\lambda_{ar}\lambda_{rb}s}}ds\right\} \\
&\simeq e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}} \\
&\quad \times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\right) \\
&\quad - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\left\{\sum_{l=0}^{L-1}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l\right. \\
&\quad \left.\times\frac{(-1)^l}{l!}\int_{\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}^{\infty}\frac{e^{-s}}{s^l}ds\right\} \\
&= e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}} \\
&\quad \times K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\right) \\
&\quad - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}-\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}\sum_{l=0}^{L-1}\frac{(-1)^l}{l!} \\
&\quad \times\left(\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)^{-\frac{l}{2}} \\
&\quad \times\left(\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l \\
&\quad \times W_{-\frac{l}{2},\frac{1-l}{2}}\left(\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)
\end{aligned} \tag{40}$$

By substituting (39) and (40) into (38), the outage probability of HR scheme with AF relaying is shown in (41), as shown at the bottom of the next page.

B. DECODE-AND-FORWARD

The outage probability of $a \to r \to b$ with DF based FD relaying protocol can be calculated as

$$\begin{aligned}
\mathcal{P}_{\mathrm{FD},a\to b}^{\mathrm{DF}} &= 1-\Pr\left\{\mathcal{C}_{\mathrm{FD},a\to b}^{\mathrm{DF}} \geq R\right\} \\
&= 1-\Pr\left\{\min\left(\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}, \frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}\right) \geq \Upsilon\right\} \\
&= 1-\Pr\left\{\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}} \geq \Upsilon, \frac{\gamma_r\dot{\beta}}{\epsilon_{rb}} \geq \Upsilon\right\} \\
&= 1-e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}
\end{aligned} \tag{42}$$

The outage probability of $a \to r \to b$ with DF based HD relaying protocol can be calculated as

$$\begin{aligned}
\mathcal{P}_{\mathrm{HD},a\to b}^{\mathrm{DF}} &= 1-\Pr\left\{\mathcal{C}_{\mathrm{HD},a\to b}^{\mathrm{DF}} \geq R\right\} \\
&= 1-e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}}
\end{aligned} \tag{43}$$

The outage probability of HR scheme with DF relaying can be calculated as

$$\begin{aligned}
\mathcal{P}_{\mathrm{HR},a\to b}^{\mathrm{DF}} &= \Pr\left\{\max\left(\mathcal{C}_{\mathrm{FD},a\to b}^{\mathrm{DF}}, \mathcal{C}_{\mathrm{HD},a\to b}^{\mathrm{DF}}\right) < R\right\} \\
&= \Pr\left\{\min\left(\frac{\gamma_a\alpha}{\gamma_r^{\mathrm{LI}}+\epsilon_{ar}}, \frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}\right) < \Upsilon,\right. \\
&\qquad \left.\min\left(\frac{\gamma_a\alpha}{\epsilon_{ar}}, \frac{\gamma_r\dot{\beta}}{\epsilon_{rb}}\right) < \Upsilon(\Upsilon+2)\right\}
\end{aligned} \tag{44}$$

For $\gamma_r^{\mathrm{LI}} \leq (\Upsilon+1)\epsilon_{ar}$, $\mathcal{P}^{\mathrm{DF}}_{\mathrm{HR},a\to b}$ is given by

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{HR},a\to b} \\
&= \int_0^{\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a}} \left\{1-\mathcal{F}_{\dot{\beta}}\left(\frac{s\gamma_a\epsilon_{rb}}{\gamma_r\epsilon_{ar}}\right)\right\} f_\alpha(s)ds \\
&\quad - \int_{\frac{\Upsilon\epsilon_{rb}}{\gamma_r}}^{\frac{\Upsilon\epsilon_{rb}(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_r\epsilon_{ar}}} \left\{1-\mathcal{F}_\alpha\left(\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\right)\right\} f_{\dot{\beta}}(s)ds \\
&\quad + \int_0^{\frac{\Upsilon\epsilon_{rb}(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_r\epsilon_{ar}}} \left\{1-\mathcal{F}_\alpha\left(\frac{s\epsilon_{ar}}{\epsilon_{rb}}\right)\right\} f_{\dot{\beta}}(s)ds \\
&= \frac{1-e^{-\left(\frac{\gamma_a\epsilon_{rb}}{\gamma_r\epsilon_{ar}\lambda_{rb}}+\frac{1}{\lambda_{ar}}\right)\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a}}}{1+\frac{\gamma_a\epsilon_{rb}\lambda_{ar}}{\gamma_r\epsilon_{ar}\lambda_{rb}}} + e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}}-\frac{\Upsilon\epsilon_{rb}(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\epsilon_{ar}\gamma_r\lambda_{rd}}} \\
&\quad - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}}-\frac{\Upsilon\epsilon_{rb}}{\gamma_r\lambda_{rb}}} + \frac{1-e^{-\left(\frac{\epsilon_{rb}\gamma_a}{\epsilon_{ar}\gamma_r\lambda_{rb}}+\frac{1}{\lambda_{ar}}\right)\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a}}}{1+\frac{\epsilon_{ar}\gamma_r\lambda_{rb}}{\epsilon_{rb}\gamma_a\lambda_{ar}}} \\
&= 1-e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}} \qquad (45)
\end{aligned}$$

For $\gamma_{\mathrm{LI}} > (\Upsilon+1)\epsilon_{ar}$, $\mathcal{P}^{\mathrm{DF}}_{\mathrm{HR},a\to b}$ is given by

$$\begin{aligned}
&\mathcal{P}^{\mathrm{DF}}_{\mathrm{HR},a\to b} \\
&= \int_0^{\frac{\Upsilon\epsilon_{ar}(\Upsilon+2)}{\gamma_a}} \left\{1-\mathcal{F}_{\dot{\beta}}\left(\frac{s\gamma_a\epsilon_{rb}}{\gamma_r\epsilon_{ar}}\right)\right\} f_\alpha(s)ds \\
&\quad + \int_0^{\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r}} \left\{1-\mathcal{F}_\alpha\left(\frac{s\gamma_r\epsilon_{ar}}{\gamma_a\epsilon_{rb}}\right)\right\} f_{\dot{\beta}}(s)ds \\
&\quad - \int_{\frac{\Upsilon\epsilon_{rb}}{\gamma_r}}^{\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r}} \left\{1-\mathcal{F}_\alpha\left(\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a}\right)\right\} f_{\dot{\beta}}(s)ds \\
&= \frac{1-e^{-\left(\frac{\gamma_a\epsilon_{rb}}{\gamma_r\epsilon_{ar}\lambda_{rb}}+\frac{1}{\lambda_{ar}}\right)\frac{\Upsilon\epsilon_{ar}(\Upsilon+2)}{\gamma_a}}}{1+\frac{\gamma_a\epsilon_{rb}\lambda_{ar}}{\gamma_r\epsilon_{ar}\lambda_{rb}}} + e^{-\frac{\Upsilon(\gamma_{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r\lambda_{rb}}} \\
&\quad - e^{-\frac{\Upsilon(\gamma_{\mathrm{LI}}+\epsilon_{ar})}{\gamma_s\lambda_{sr}}-\frac{\Upsilon\epsilon_{rd}}{\gamma_r\lambda_{rd}}} + \frac{1-e^{-\left(\frac{\gamma_r\epsilon_{ar}}{\gamma_a\epsilon_{rb}\lambda_{ar}}+\frac{1}{\lambda_{rb}}\right)\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r}}}{1+\frac{\gamma_r\epsilon_{ar}\lambda_{rb}}{\gamma_a\epsilon_{rb}\lambda_{ar}}} \\
&= 1+e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r\lambda_{rb}}} - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}}-\frac{\Upsilon\epsilon_{rb}}{\gamma_r\lambda_{rb}}} \\
&\quad - e^{-\frac{\Upsilon\epsilon_{rb}(\Upsilon+2)}{\gamma_r\lambda_{rb}}-\frac{\Upsilon\epsilon_{ar}(\Upsilon+2)}{\gamma_a\lambda_{ar}}} \qquad (46)
\end{aligned}$$

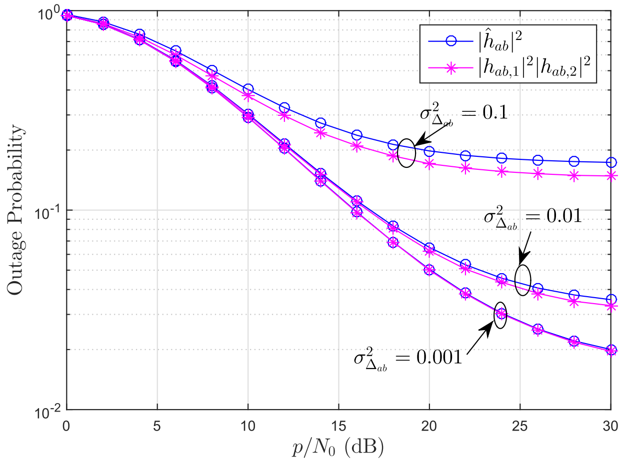

FIGURE 3. Outage probability for the case of $\sigma^2_{\Delta_{b,\ell}} = 0.01$.

Finally, the outage probability of HR scheme with DF relaying is shown in (47), as shown at the bottom of the next page.

V. SIMULATIONS AND DISCUSSION

In this section, our theoretical results will be verified through Monte-Carlo simulations. Assuming equal power allocation, i.e., $p_a = p_b = p_r = p$. Without loss of generality, same levels of channel estimation errors are assumed at the RSU and the vehicles, i.e., $\sigma^2_{e_{ar}} = \sigma^2_{e_{br}} = \sigma^2_{e_{rb}} = \sigma^2_e$. We assume $\sigma^2_{h_{ar}} = \sigma^2_{h_{br}} = \sigma^2_{h_{rb}} = \sigma^2_{h_{ab,1}} = \sigma^2_{h_{ab,2}} = \sigma^2_h$. The analytical results are generated based on expressions (26), (29), (31), (33), (35), (36), (42), (43), (41) and (47). In particular, Fig. 3,

$$\mathcal{P}^{\mathrm{AF}}_{\mathrm{HR},a\to b} = \begin{cases} 1-e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\right), & \frac{\gamma_r^{\mathrm{LI}}}{\epsilon_{ar}} \leq (\Upsilon+1) \\
1-e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}K_1\left(\sqrt{\frac{4\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}}\right) & \\
\quad -e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}-\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}\sum_{l=0}^{L-1}\frac{(-1)^l}{l!}\left(\frac{\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l & \\
\quad \times\left(\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)^{-\frac{l}{2}}W_{-\frac{l}{2},\frac{1-l}{2}}\left(\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right) & \\
\quad +e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a}-\frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}-\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}}\sum_{l=0}^{L-1}\frac{(-1)^l}{l!}\left(\frac{\Upsilon(1+\Upsilon)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r}\right)^l & \\
\quad \times\left(\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right)^{-\frac{l}{2}}W_{-\frac{l}{2},\frac{1-l}{2}}\left(\frac{\Upsilon(\Upsilon+1)(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right), & \frac{\gamma_r^{\mathrm{LI}}}{\epsilon_{ar}} > (\Upsilon+1)
\end{cases} \qquad (41)$$

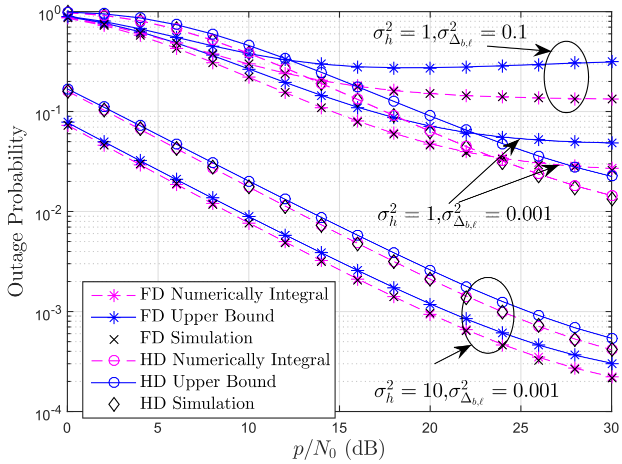

FIGURE 4. Outage probability of RVV scenario. Comparison of FD and HD AF relaying for the case of $\sigma^2_{\Delta e} = 0.001$.

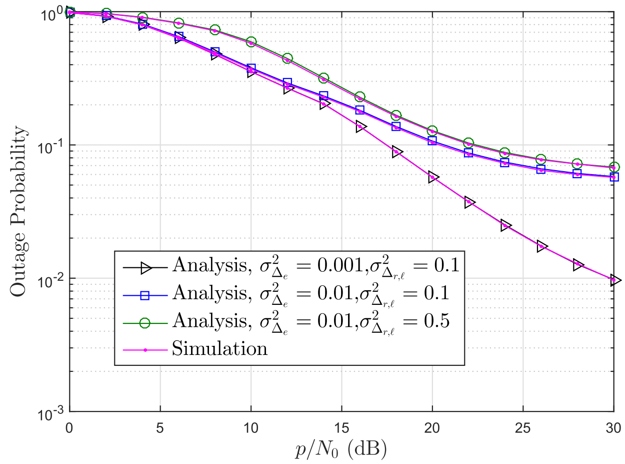

FIGURE 6. Outage probability of VRV scenario. Approximate accuracy verification of HR AF relaying for different $\sigma^2_{\Delta e}$ and $\sigma^2_{\Delta_{r,\ell}}$. $L = 2$.

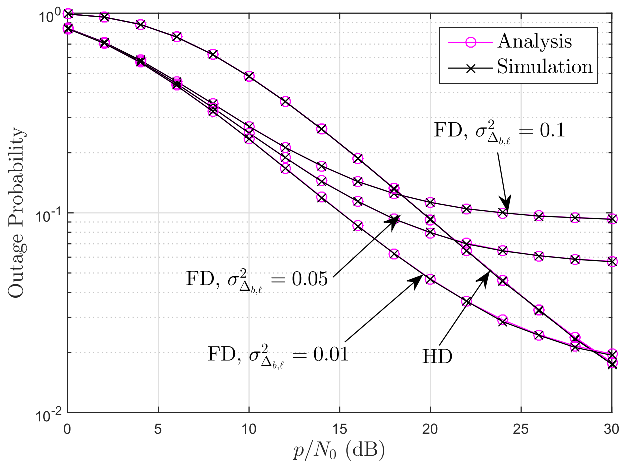

FIGURE 5. Outage probability of RVV scenario. Comparison of FD and HD DF relaying for the case of $\sigma^2_{\Delta e} = 0.001$.

Fig. 4 and Fig. 5 are plotted for RVV scenario, while Fig. 6 and Fig. 7 are plotted for VRV scenario. And Fig. 4 is for both RVV and VRV scenarios.

As the complexity of the distribution of $|\hat{h}_{ab}|$, we approximate $|\hat{h}_{ab}|^2$ with $|h_{ab,1}|^2|h_{ab,2}|^2$. Fig. 3 shows the effect of channel estimation errors on the accuracy of approximations for the case of $\sigma^2_{h_{ab,1}} = \sigma^2_{h_{ab,1}}$ and $\sigma^2_{\Delta_{b,\ell}} = 0.01$. It is quite obvious that the errors of approximations decrease as the channel estimation errors decrease. When $\sigma^2_{\Delta_e} = 0.001$, the approximate results are accurate enough to match the practical ones. For the same duplex modes, it can be observed that the outage probability of the DF relaying always outperforms AF relaying.

Fig. 4 shows the theoretical upper bound of outage probability for FD and HD AF transmission modes. The integral expressions in (24) and (28) are also plotted as the benchmarks. When the channel estimation error is low, i.e., $\sigma^2_{\Delta_e} = 0.001$, the integral results are perfectly matched with the simulation results. The upper bound results are close to the integral ones as the residual LBI decreases and the channel gains increase. The reason is that e^{-x} can be approximate by $1 - x$ as $x \to 0$. Hence, $\frac{4\Upsilon(1+\Upsilon)(\gamma_b^{\mathrm{LI}}+\epsilon_{ab})\epsilon_{br}}{\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}\gamma_a\gamma_b s^2} \to 0$ as γ_b^{LI} is small and $\lambda_{ab,1}\lambda_{ab,2}\lambda_{br}$ is relative big. Fig. 5 shows the approximate closed form expressions of outage probability for FD and HD DF transmission modes. For fixed estimation error $\sigma^2_{\Delta_e} = 0.001$, the LBI $\sigma^2_{\Delta_{r,\ell}}$ changes from 0.01 to 0.1. It can be seen that the high LBI will deteriorate the outage performance. For low LBI, the the FD relaying mode outperforms the HD mode for most SNR. For $\sigma^2_{\Delta_{b,\ell}} = 0.05$ and $\sigma^2_{\Delta_{b,\ell}} = 0.1$, as the SNR is above a certain threshold, the HD mode is superior to the FD mode. This is because that the SINRs are dominated by high LBI as SNR increases.

For the result in (41), very small values of L, i.e., $L = 2$ can achieve sufficient accuracy. From the Fig. 6, it can be seen that all the analytical results are perfect matched with the simulation ones. Actually, the accuracy of approximations is sufficient even for $L = 1$, i.e., (39) is simplified as

$$e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a} - \frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r} - \frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}} \times W_{0,\frac{1}{2}}\left(\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}\right) \tag{48}$$

$$\mathcal{P}^{\mathrm{DF}}_{\mathrm{HR},a\to b} = \begin{cases} 1 - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\lambda_{ar}\gamma_a} - \frac{\Upsilon\epsilon_{rb}}{\lambda_{rb}\gamma_r}}, & \frac{\gamma_r^{\mathrm{LI}}}{\epsilon_{ar}} \le (\Upsilon+1) \\ 1 - e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}} - \frac{\Upsilon\epsilon_{rb}}{\gamma_r\lambda_{rb}}} - e^{-\frac{\Upsilon\epsilon_{rb}(\Upsilon+2)}{\gamma_r\lambda_{rb}} - \frac{\Upsilon\epsilon_{ar}(\Upsilon+2)}{\gamma_a\lambda_{ar}}} + e^{-\frac{\Upsilon(\gamma_r^{\mathrm{LI}}+\epsilon_{ar})}{\gamma_a\lambda_{ar}} - \frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\gamma_r\lambda_{rb}}}, & \frac{\gamma_r^{\mathrm{LI}}}{\epsilon_{ar}} > (\Upsilon+1) \end{cases} \tag{47}$$

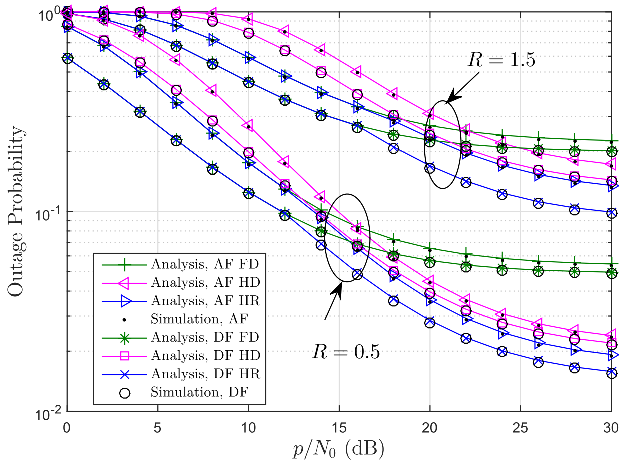

FIGURE 7. Outage probability of VRV scenario. Comparison of FD/HD/HR AF and DF relaying for different data rates. $L = 2$. $\sigma_h^2 = 1$.

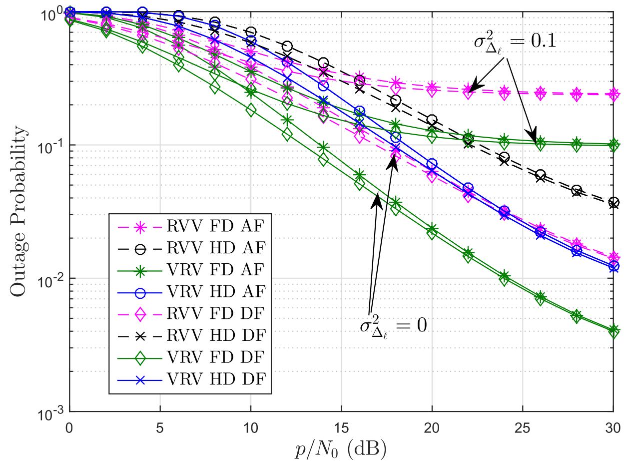

FIGURE 8. Comparison of RVV and VRV scenarios.

This is different from the case of $\exp\left(-\frac{\Upsilon(2+\Upsilon)(1+\Upsilon)^2\epsilon_{ar}\epsilon_{rb}}{\lambda_{ar}\lambda_{rb}\gamma_a\gamma_r s}\right)$ is approximated by 0-th order Taylor series, i.e. 1. At this time, $\mathcal{I}_1$ is given by

$$e^{-\frac{\Upsilon(\Upsilon+2)\epsilon_{ar}}{\lambda_{ar}\gamma_a}-\frac{\Upsilon(\Upsilon+2)\epsilon_{rb}}{\lambda_{rb}\gamma_r}-\frac{\Upsilon(\Upsilon+2)(\Upsilon+1)\epsilon_{ar}\epsilon_{rb}}{2(\gamma_r^{\mathrm{LI}}-(\Upsilon+1)\epsilon_{ar})\gamma_r\lambda_{rb}}} \tag{49}$$

The expression (48) is much more accurate than (48). Hence, we can obtain a simple version of (41) by $L = 1$. It can be seen from the Fig. 6 that high channel estimation errors will lead to a floor when p/N_0 is in high-SNR area.

In Fig. 7, for fixed estimation error $\sigma^2_{\Delta_e} = 0.01$ and LBI $\sigma^2_{\Delta_{r,\ell}} = 0.1$, we compare the outage performance of FD, HD and HR AF modes for different data rates. For both high data rate and low data rate modes, the HR scheme always achieves best performance. There are floors for both FD and HD modes, FD mode suffers more serious floor problem since the additional high LBI. As the transmit power increases above a certain limit, the HD mode outperforms the FD mode. The high LBI dominates the SINR of the relay when transmit power is rather high. HR mode by switching between FD and HD modes gives significant performance improvement. adhering to either conventional mode. When the SNR is low, static FD relaying mode achieves the same performance with hybrid FD/HD mode switching. This is because then the lower transmit power significantly reduce the LBI which makes FD the chosen mode. As the switching threshold is to compare the γ_r^{LI} and $\epsilon_{ar}(\Upsilon + 1)$, lower data rate will lead to a more earlier switching between FD and HD modes. The DF protocol benefits more from HR switching than the AF protocol.

Fig. 8 compares the outage performance of VRV scenario and RVV scenario, where $\sigma_h^2 = 1$, $\sigma^2_{\Delta_e} = 0.01$ and $\sigma^2_{\Delta_{r,\ell}} = \sigma^2_{\Delta_{b,\ell}} = \sigma^2_{\Delta_\ell}$. For both scenarios, there will be a floor of FD transmission caused by high residual LBI when p/N_0 is in high-SNR area. For the same duplex modes, the VRV scenario is always superior to RVV scenario in terms of outage probability. This is because that vehicle-to-vehicle link follows the double Rayleigh fading channel. All the transmission modes in Rayleigh fading channels enjoys a better performance than double Rayleigh channels. If the relay exploits perfect LBI cancellation, FD mode achieves better performance than HD mode for all practical SNR values.

VI. CONCLUSION

In this paper, we investigate the outage performance of full-duplex relaying for vehicular communications. Two vehicular communication scenarios are considered, including RVV and VRV scenarios. For RVV scenario, the vehicle-to-vehicle link is modeled as double Rayleigh fading channel. The upper bounds of outage probability for FD and HD on AF relaying protocols were analyzed. We also derived the approximate expressions of outage probability for FD and HD on DF relaying protocols, respectively. For VRV scenario, the closed form expressions of outage probability of FD and HD on AF and DF relaying protocols are derived. Furthermore, we studied the outage performance of the optimal HR scheme based on FD/HD switching in terms of instantaneous end-to-end capacity. The HR transmission achieves best performance for all practical SNR. Both channel estimation errors and residual LBI will deteriorate the outage performance and can lead to a floor. For the same duplex mode, DF relaying is always superior to the AF relaying. The performance gap of relaying protocols is gradually reduced as the SNR increases. For high residual LBI, lower data rate will lead to a more earlier duplex mode switching. Finally, it is shown that the VRV scenario has a better performance than RVV scenario. The slope of outage probability with the Rayleigh fading channel curves are steeper than the corresponding one with double Rayleigh channel curves at the same SNRs.

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