

Outage Performance Analysis of HARQ Assisted STAR-RIS-NOMA/RSMA for V2V Communications

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Abstract

As a key enabling technology for sixth-generation (6G) wireless communication systems, the simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) can dynamically reconfigure its electromagnetic elements to effectively extend wireless network coverage. The deployment of STAR-RIS in vehicle-to-vehicle (V2V) communications effectively mitigates vehicle non-line-of-sight transmission issues and improves the reliability of vehicular communication. This paper investigates two typical multiple access schemes, namely non-orthogonal multiple access (NOMA) and rate splitting multiple access (RSMA). Considering both perfect and imperfect successive interference cancellation (SIC) conditions, we adopt hybrid automatic repeat request (HARQ) technology to further enhance communication reliability. We analyze the outage performance of receiving vehicles in HARQ-aided STAR-RIS-NOMA/RSMA systems and derive the closed-form expressions for outage probability. Numerical simulations validate the correctness of the theoretical derivations and reveal the following results. First, for both multiple access schemes, RSMA delivers better system performance than NOMA, and the systems under perfect SIC outperform those under imperfect SIC. Second, the introduction of HARQ can significantly boost the performance of STAR-RIS-NOMA/RSMA V2V communication systems.

Keywords

STAR-RIS, HARQ, NOMA, RSMA, V2V communications

1 Introduction

Driven by the rapid development of intelligent transportation systems (ITS) in the 6G era, vehicle-to-vehicle (V2V) communication has become a core technology supporting autonomous driving and vehicle-infrastructure cooperation [1, 2]. However, in complex urban road environments, wireless link blockages caused by buildings, vehicles and other obstacles severely limit the reliability of conventional V2V communication systems. Simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) is capable of realizing concurrent signal transmission and reflection. It can reconstruct 360° full-dimensional electromagnetic environments by independently adjusting transmission and reflection coefficients [3]. Deployed on roadside traffic facilities, building facades, and in-vehicle devices, STAR-RIS effectively extends the coverage of vehicle-to-everything (V2X) communications, making it a pivotal technology for anti-blockage transmission and channel quality optimization in V2X networks.

The integration of non-orthogonal multiple access (NOMA) and STAR-RIS can significantly alleviate interference and resource scarcity in high-density V2X networks. Existing studies have constructed cognitive CR-NOMA networks with eavesdropping nodes to investigate the outage and intercept probabilities of RIS/STAR-RIS-assisted V2X systems under imperfect channel state information [4]. Some other works have introduced unmanned aerial vehicle (UAV) communications and derived closed-form outage probability solutions for multiple vehicular users [5]. Ghadi et al. [6] compared single and dual RIS/STAR-RIS deployment architectures and verified that cooperative dual intelligent surface deployment can substantially improve the system's ergodic capacity and energy efficiency. Several studies have further integrated RIS with HARQ-CC and HARQ-IR mechanisms to derive the outage probability of SISO/MIMO IoT systems, where phase shift and transmit power optimization are adopted to reduce the age of information [7, 8].

Wu et al. [9] also analyzed the physical layer security of RIS-assisted communication under the HARQ framework and obtained closed-form expressions for connection outage probability and secrecy outage probability. Sheng et al. [10] constructed a STAR-RIS, CR-NOMA, and HARQ integrated V2X system, derived the transmission outage probability, secrecy outage probability, and average transmission attempts under random retransmission protocols, and designed a cognitive power allocation strategy for delay-sensitive V2X services.

As an emerging multiple access scheme for advanced interference management, rate-splitting multiple access (RSMA) addresses the inherent limitations of NOMA and space division multiple access (SDMA) in handling severe interference, serving as a superior alternative to conventional NOMA [11–13]. For V2X scenarios, Fan et al. [14] proposed a multi-layer RSMA scheme. In low signal-to-noise ratio and dense vehicular scenarios, this scheme achieves a higher aggregate transmission rate than traditional NOMA, with significantly better outage performance than NOMA and conventional cooperative communication frameworks. Karim et al. [15] focused on STAR-RIS-assisted downlink RSMA communication, defined two STAR-RIS operating protocols (energy splitting and mode switching), and derived closed-form user outage probability expressions. The HARQ retransmission mechanism has been introduced into RSMA systems to compensate for insufficient transmission reliability. At present, a few studies have preliminarily explored HARQ protocols in RIS-assisted RSMA networks and compared the outage performance of different retransmission strategies [16, 17]. Nevertheless, existing research still has prominent limitations. First, most existing works focus on conventional passive RIS and fail to exploit the full-dimensional coverage advantage of the STAR-RIS transmission-reflection cooperative architecture. Second, few studies have established STAR-RIS-RSMA/NOMA-HARQ vehicular networking models for dynamic mobile V2V scenarios.

Accordingly, this paper develops a HARQ-assisted STAR-RIS-RSMA/NOMA V2V communication model. We comprehensively analyze the outage performance of receiving vehicles for both NOMA and RSMA schemes, considering both perfect and imperfect successive interference cancellation (SIC) conditions. The closed-form outage probability expressions are derived, and systematic comparisons are conducted to quantify the impacts of inter-vehicle distance variation, maximum retransmission times, and STAR-RIS element quantity on the outage performance of NOMA and RSMA systems.

The remainder of this paper is organized as follows. Section 2 presents the system model of the HARQ-enabled STAR-RIS-assisted V2V communication system. Section 3 derives the outage probabilities of NOMA and RSMA under perfect and imperfect SIC conditions. Section 4 provides numerical simulation results and detailed discussions. Finally, Section 5 concludes this paper.

2 System model

This paper investigates a STAR-RIS-assisted V2V communication system under the specific scenario depicted in Fig. 1. As illustrated, the direct communication links between vehicles at road intersections are usually blocked by surrounding buildings. To tackle this non-line-of-sight transmission issue, a STAR-RIS is deployed on roadside buildings and infrastructures. By virtue of its simultaneous transmission and reflection characteristics, the STAR-RIS can construct alternative communication links to relay signals toward target vehicles, thereby improving the robustness of inter-vehicle transmission. Furthermore, hybrid automatic repeat request (HARQ) is integrated into the transmission framework to further enhance the reliability of vehicular communication.

Fig. 2 presents a simplified abstraction of the practical scenario shown in Fig. 1, which consists of a building-mounted STAR-RIS, three vehicles, and the corresponding communication links. In this system, vehicle S acts as the transmitting node and delivers signals to vehicles P and Q. Since the direct transmission paths are blocked by buildings, vehicle S communicates with vehicles P and Q by relying on the transmission and reflection capabilities of the STAR-RIS.

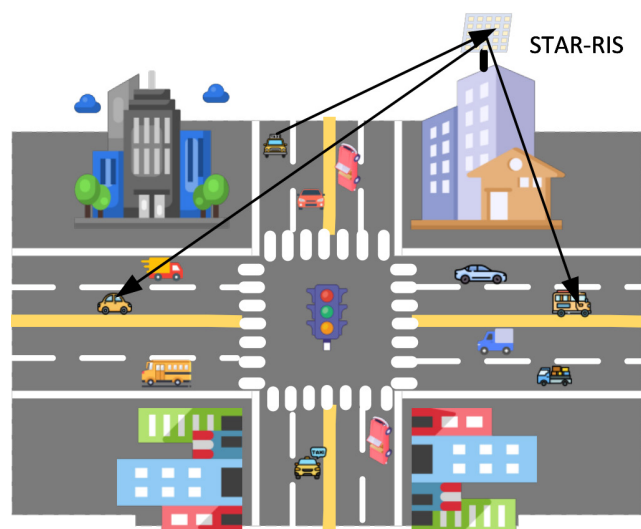


Fig. 1 Scenario diagram of STAR-RIS-assisted vehicle communication at an intersection

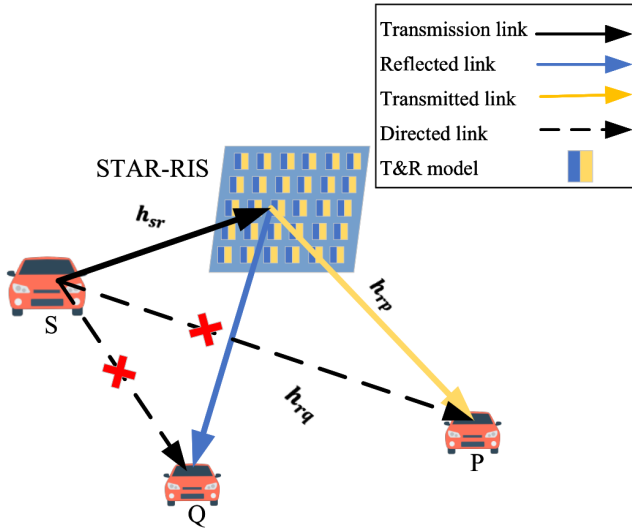


Fig. 2 System model for STAR-RIS-assisted vehicle communication at an intersection

Assume that the STAR-RIS consists of M elements. Let $T_m = \sqrt{\beta_m^T} e^{j\theta_m^T}$ and $R_m = \sqrt{\beta_m^R} e^{j\theta_m^R}$ denote the transmission and reflection coefficients of the m^{th} ($m = 1, 2, \dots, M$) element, respectively [18]. According to the energy splitting protocol of the STAR-RIS [19], all M elements operate simultaneously in both transmission and reflection modes. Thus, we have $|T_m|^2 + |R_m|^2 \leq 1$, which can also be expressed as $\beta_m^T + \beta_m^R \leq 1$, $\beta_m^T, \beta_m^R \in [0, 1]$, where $\theta_m^T, \theta_m^R \in [0, 2\pi]$ denote the phase shift of the transmitting and reflecting signals from the m^{th} element, respectively. These phase shifts can be independently configured to regulate the electromagnetic propagation environment.

In this system, two distinct STAR-RIS-assisted V2V communication links are considered:

1. S-STAR-RIS-P: vehicle S transmits signals to vehicle P *via* the transmitting elements of the STAR-RIS;
2. S-STAR-RIS-Q: vehicle S reflects signals to vehicle Q *via* the reflecting elements of the STAR-RIS.

Let $h_{sm,l}$ represent the channel coefficients between vehicle S and the m^{th} transmitted/reflected element of the STAR-RIS in the l^{th} round. Let $h_{mp,l}$ denote the channel coefficient between the m^{th} transmission element and the vehicle P in the l^{th} round, and $h_{mq,l}$ denote the channel coefficient between the m^{th} reflection element and the vehicle Q in the l^{th} round, respectively. Let $\sqrt{d_{sr}^{-\alpha}}$, $\sqrt{d_{rp}^{-\alpha}}$ and $\sqrt{d_{rq}^{-\alpha}}$ denote the path loss function, with α representing the path loss exponent, d_{sr} , d_{rp} , d_{rq} stand for the distances from vehicles S, P, Q to the STAR-RIS board, respectively. The corresponding channel vectors for the S-STAR-RIS, STAR-RIS-P, and STAR-RIS-Q links are denoted as:

$$\mathbf{h}_{sr,l} = \sqrt{d_{sr}^{-\alpha}} [h_{s1,l}, h_{s2,l}, \dots, h_{sM,l}]^H,$$

$$\mathbf{h}_{rp,l} = \sqrt{d_{rp}^{-\alpha}} [h_{1p,l}, h_{2p,l}, \dots, h_{Mp,l}]^H,$$

$$\mathbf{h}_{rq,l} = \sqrt{d_{rq}^{-\alpha}} [h_{1q,l}, h_{2q,l}, \dots, h_{Mq,l}]^H, \text{ respectively,}$$

where $\mathbf{h}_{sr,l}, \mathbf{h}_{rp,l}, \mathbf{h}_{rq,l} \in \mathbb{C}^{M \times 1}$.

Let $\mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l}$ and $\mathbf{h}_{sr,l}^H \Theta_R \mathbf{h}_{rq,l}$ denote the equivalent channel power gains of the S-STAR-RIS-P and S-STAR-RIS-Q links in the l^{th} round, respectively, where:

$$\Theta_T = \text{diag}(\sqrt{\beta_1^T} e^{j\theta_1^T}, \sqrt{\beta_2^T} e^{j\theta_2^T}, \dots, \sqrt{\beta_M^T} e^{j\theta_M^T}),$$

$$\Theta_R = \text{diag}(\sqrt{\beta_1^R} e^{j\theta_1^R}, \sqrt{\beta_2^R} e^{j\theta_2^R}, \dots, \sqrt{\beta_M^R} e^{j\theta_M^R}).$$

Let $L(1 < l < L)$ be the maximum number of HARQ transmission rounds per message. The signals received by vehicle P and vehicle Q in the l^{th} round are given as follows, respectively:

$$y_{p,l} = \mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l} x + n_p, \quad (1)$$

$$y_{q,l} = \mathbf{h}_{sr,l}^H \Theta_R \mathbf{h}_{rq,l} x + n_q, \quad (2)$$

where $x = \sqrt{\alpha_p P_s} x_p + \sqrt{\alpha_q P_s} x_q$ denotes the signal transmitted by vehicle S in the l^{th} round, $E\{|x_p|^2\} = 1$, $E\{|x_q|^2\} = 1$, and $E\{\cdot\}$ denoting the expectation operator, α_p and α_q denote the power allocation factors associated with vehicle P and vehicle Q, respectively, $\alpha_p + \alpha_q = 1$. P_s represents the transmit power of vehicle S, and $n_p, n_q \sim \mathcal{CN}(0, \delta^2)$ denotes the additive Gaussian white noise (AWGN) term.

2.1 Small-scale fading model

This paper assumes that each STAR-RIS element experiences independent and identically distributed (i.i.d.) Nakagami- m fading, and the superposition of signals from multiple RIS elements yields a composite cascaded channel. When the number of RIS elements M is sufficiently large, the distribution of the composite channel power gains can be approximated by a Gamma distribution $\Gamma(k, \theta)$ [20], whose shape and scale parameters are given by:

$$\begin{cases} k = \frac{\Gamma\left(m + \frac{1}{2}\right)^2}{4\left(m\Gamma(m)^2 - \Gamma\left(m + \frac{1}{2}\right)^2\right)} M \\ \theta = 4\Omega M - \frac{4\Omega}{m} \left(\frac{\Gamma\left(m + \frac{1}{2}\right)}{\Gamma(m)}\right)^2 M \end{cases}, \quad (3)$$

where m and Ω are the shape and spread parameters of the underlying Nakagami- m fading distribution.

3 OP analysis

To achieve error-free signal recovery, this paper adopts the selection combining (SC) scheme [21] combined with Type I HARQ. The principle of SC is to select the received signal from all transmission and retransmission rounds that yields the maximum channel gain.

3.1 NOMA

Without loss of generality, since the STAR-RIS can adjust energy allocation coefficients β_m^T and β_m^R via the energy splitting protocol, a higher energy allocation can be assigned to the reflected link.

Following the NOMA principle, we assume that a larger power share is allocated to vehicle P, i.e., $\alpha_p > \alpha_q$. Accordingly, a SIC receiver is employed at vehicle Q, vehicle P decodes its own signal x_p , the signal of x_q is regarded as additional noise. Vehicle Q first detects and subtracts the signal x_p , and then decodes its own signal x_q without any interference. The instantaneous signal-to-interference-plus-noise-ratio (SINR) of the l^{th} round of decoding is given by:

$$\gamma_{\text{sic},l} = \frac{\alpha_p \rho |h_{sr,l}^H \Theta_R h_{rq,l}|^2}{\alpha_q \rho |h_{sr,l}^H \Theta_R h_{rq,l}|^2 + 1} = \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{R,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + 1}, \quad (4)$$

where:

$$\rho = \frac{P_s}{\delta^2},$$

$$|h_{R,l}| = \left[[h_{s1,l}, h_{s2,l}, \dots, h_{sM,l}]^H \Theta_R [h_{1q,l}, h_{2q,l}, \dots, h_{Mq,l}] \right].$$

The SINR for the l^{th} round of decoding x_q at Q is given by:

$$\gamma_{q,l} = \frac{\alpha_q \rho |h_{sr,l}^H \Theta_R h_{rq,l}|^2}{\omega \rho |h_{sq,l}|^2 + 1} = \frac{\alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\omega \rho |h_{sq,l}|^2 + 1}, \quad (5)$$

where $h_{sp,l} \sim \mathcal{CN}(0, \delta_{sq}^2)$ stands for the residual interference caused by imperfect SIC (ipSIC). In particular, $\omega = 0$ corresponds to perfect SIC (pSIC) and $\omega = 1$ denotes ipSIC.

For vehicle P, which only needs to decode its own signal while treating the signal for Q as interference, the SINR for the l^{th} round of decoding its own signal at P is given by:

$$\gamma_{p,l} = \frac{\alpha_p \rho |h_{sr,l}^H \Theta_T h_{rp,l}|^2}{\alpha_q \rho |h_{sr,l}^H \Theta_T h_{rp,l}|^2 + 1} = \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1}, \quad (6)$$

where:

$$|h_{T,l}| = \left[[h_{s1,l}, h_{s2,l}, \dots, h_{sM,l}]^H \Theta_T [h_{1p,l}, h_{2p,l}, \dots, h_{Mp,l}] \right].$$

The OP for vehicle P is analyzed below.

Conditioned on the SINR of vehicle P, the achievable data rate is:

$$I_{p,l} = \log(1 + \gamma_{p,l}) = \log \left(1 + \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1} \right). \quad (7)$$

If vehicle P fails to decode its own signal correctly after L rounds of retransmission, an outage occurs. This happens when the achievable data rate at vehicle P is less than or equal to the target rate R_p , the OP for vehicle P is expressed as:

$$\begin{aligned} P_{\text{out},l}^p &= \Pr \{ I_{p,l} \leq R_p \} \\ &= \Pr \left\{ \log \left(1 + \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1} \right) \leq R_p \right\} \\ &= \Pr \left\{ \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1} \leq 2^{R_p} - 1 \right\} \\ &= \Pr \left\{ |h_{T,l}|^2 \leq \frac{2^{R_p} - 1}{\rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]} \right\} \\ &= F \left(\frac{2^{R_p} - 1}{\rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]} \right) \\ &= \frac{1}{\Gamma(k)} \gamma \left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]} \right). \end{aligned} \quad (8)$$

The final analytical expression for the OP at vehicle P is given by:

$$P_{\text{out}}^p = \left[\frac{1}{\Gamma(k)} \gamma \left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]} \right) \right]^L. \quad (9)$$

The OP for vehicle Q is analyzed as follows:

The achievable data rate for vehicle Q to decode the signal at vehicle P is:

$$I_{\text{sic},l} = \log(1 + \gamma_{\text{sic},l}) = \log \left(1 + \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + 1} \right). \quad (10)$$

The achievable data rate for vehicle Q to decode its own signal is:

$$I_{q,l} = \log(1 + \gamma_{q,l}) = \log \left(1 + \frac{\alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\omega \rho |h_{sq,l}|^2 + 1} \right). \quad (11)$$

The OP of vehicle Q consists of two parts. First, vehicle Q fails to decode the signal from vehicle P, which occurs

when $I_{sic,l}$ is less than or equal to R_p . Second, vehicle Q fails to decode its own signal, meaning $I_{q,l}$ at most R_q , resulting in an outage at vehicle Q. The OP at vehicle Q after L retransmission rounds is given in Eq. (12):

$$\begin{aligned}
 P_{out,l}^p &= Pr\{I_{sic,l} \leq R_p, I_{q,l} \leq R_q\} \\
 &= Pr\left\{ \begin{aligned} &\log\left(1 + \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + 1}\right) \leq R_p, \\ &\log\left(1 + \frac{\alpha_p \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\omega \rho |h_{sq,l}|^2 + 1}\right) \leq R_q \end{aligned} \right\} \\
 &= \begin{cases} \frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]}\right) \\ \times \gamma\left(k, \left(\frac{(2^{R_p} - 1)(\rho \delta_{sq}^2 + 1)}{\theta \alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha}}\right)\right), \omega = 1, \text{ipSIC} \\ \frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]}\right) \\ \times \gamma\left(k, \left(\frac{2^{R_p} - 1}{\theta \alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha}}\right)\right), \omega = 0, \text{pSIC} \end{cases} \quad (12)
 \end{aligned}$$

By exploiting the properties of the SC scheme, the final expression for the OP of vehicle Q is obtained as follows:

$$\begin{aligned}
 P_{out}^q &= \left[\begin{aligned} &\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]}\right) \\ &\times \gamma\left(k, \left(\frac{(2^{R_p} - 1)(\rho \delta_{sq}^2 + 1)}{\theta \alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha}}\right)\right) \end{aligned} \right]^L, \omega = 1, \text{ipSIC} \\
 &= \left[\begin{aligned} &\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{2^{R_p} - 1}{\theta \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_p - \alpha_q (2^{R_p} - 1)]}\right) \\ &\times \gamma\left(k, \left(\frac{2^{R_p} - 1}{\theta \alpha_q \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha}}\right)\right) \end{aligned} \right]^L, \omega = 0, \text{pSIC} \quad (13)
 \end{aligned}$$

3.2 RSMA

In the RSMA case, suppose the vehicle S has two messages, M_1 and M_2 , which are sent to vehicles P and Q respectively. M_1 and M_2 are each split into two parts: M_1^p and M_1^c for vehicle P, M_2^q and M_2^c for vehicle Q. M_1^c and M_2^c are

encoded into a common message x_c , while M_1^p and M_2^q are encoded into two private messages x_{p1} and x_{q2} for vehicles P and Q respectively. The transmission powers of x_c , x_{p1} and x_{q2} are P_c , P_p and P_q , where $P_c = \alpha_0 P_s$, $P_p = \alpha_1 P_s$ and $P_q = \alpha_2 P_s$. Here, P_s is the total transmit power of the vehicle S, so $\alpha_0 + \alpha_1 + \alpha_2 = 1$, and $0 \leq \alpha_0, \alpha_1, \alpha_2 \leq 1$ represent the power allocation coefficients.

The signals received by vehicle P and vehicle Q in the l^{th} round are given as follows, respectively:

$$\gamma_{p,l} = \mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l} x_R + n_p, \quad (14)$$

$$\gamma_{q,l} = \mathbf{h}_{sr,l}^H \Theta_R \mathbf{h}_{rq,l} x_R + n_q, \quad (15)$$

where $x_R = \sqrt{\alpha_0 P_s} x_c + \sqrt{\alpha_1 P_s} x_{p1} + \sqrt{\alpha_2 P_s} x_{q2}$ denotes the signal transmitted by vehicle S in the l^{th} round.

According to the RSMA principle, each user needs to first decode the common message and then treat the private messages of other users as interference, using SIC to decode the private message they need. Therefore, the SINR for vehicle P to receive and decode the common information stream is:

$$\begin{aligned}
 \gamma_p^c &= \frac{\alpha_0 \rho |\mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l}|^2}{(\alpha_1 + \alpha_2) \rho |\mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l}|^2 + 1} \\
 &= \frac{\alpha_0 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{(\alpha_1 + \alpha_2) \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1}. \quad (16)
 \end{aligned}$$

After decoding the common message, vehicle P further decodes its own private message stream from the remaining signal, the SINR for this step is:

$$\begin{aligned}
 \gamma_p^s &= \frac{\alpha_1 \rho |\mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l}|^2}{\alpha_2 \rho |\mathbf{h}_{sr,l}^H \Theta_T \mathbf{h}_{rp,l}|^2 + 1} \\
 &= \frac{\alpha_1 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_2 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + \omega \rho |h_{sp,l}|^2 + 1}, \quad (17)
 \end{aligned}$$

where $h_{sp,l} \sim CN(0, \delta_{sp}^2)$ stands for the residual interference caused by ipSIC at vehicle P. In particular, $\omega = 0$ corresponds to pSIC, and $\omega = 1$ denotes ipSIC.

Similarly, the SINR for vehicle Q to decode the common information stream and private message stream is:

$$\begin{aligned}
 \gamma_q^c &= \frac{\alpha_0 \rho |\mathbf{h}_{sr,l}^H \Theta_R \mathbf{h}_{rq,l}|^2}{(\alpha_1 + \alpha_2) \rho |\mathbf{h}_{sr,l}^H \Theta_R \mathbf{h}_{rq,l}|^2 + 1} \\
 &= \frac{\alpha_0 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{(\alpha_1 + \alpha_2) \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + 1}, \quad (18)
 \end{aligned}$$

$$\begin{aligned}\gamma_q^s &= \frac{\alpha_2 \rho |h_{sr,l}^H \Theta_R h_{rq,l}|^2}{\alpha_1 \rho |h_{sr,l}^H \Theta_R h_{rq,l}|^2 + 1} \\ &= \frac{\alpha_2 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\alpha_1 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + \omega \rho |h_{sq,l}|^2 + 1},\end{aligned}\quad (19)$$

where $h_{sq,l} \sim CN(0, \delta_{sq}^2)$ stands for the residual interference caused by ipSIC at vehicle Q. In particular, $\omega = 0$ corresponds to pSIC, and $\omega = 1$ denotes ipSIC.

The OP for vehicle P is analyzed below.

The OP at vehicle P consists of two parts. First, vehicle P unsuccessfully decodes the common information stream, meaning $\gamma_p^c < \gamma_{p,c}^{th}$, where $\gamma_{p,c}^{th} = 2^{R_{p,c}} - 1$, and $R_{p,c}$ is the target rate threshold for the common information stream of vehicle P. Second, vehicle P unsuccessfully decodes its own private information stream, meaning $\gamma_p^s < \gamma_{p,s}^{th}$, where $\gamma_{p,s}^{th} = 2^{R_{p,s}} - 1$, and $R_{p,s}$ is the target rate threshold for the private information stream of vehicle P. If either happens, an outage occurs at vehicle P. After L rounds of retransmission, the OP at vehicle P is expressed as follows:

$$\begin{aligned}P_{out}^P &= \left[Pr\{\gamma_p^c < \gamma_{p,c}^{th}, \gamma_p^s < \gamma_{p,s}^{th}\} \right]^L \\ &= \left[1 - Pr\left\{ \begin{aligned} &\frac{\alpha_0 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{(\alpha_1 + \alpha_2) \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + 1} \geq \gamma_{p,c}^{th}, \\ &\frac{\alpha_1 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2}{\alpha_2 \rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} |h_{T,l}|^2 + (\omega \rho \delta_{sp}^2 + 1) + 1} \geq \gamma_{p,s}^{th} \end{aligned} \right\} \right]^L \\ &= \left[\begin{aligned} &\left[\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{\zeta_{p1}}{\theta}\right) \right]^L, \zeta_{p1} > \zeta_{p2} \\ &\left[\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{\zeta_{p2}}{\theta}\right) \right]^L, \zeta_{p1} < \zeta_{p2} \end{aligned} \right],\end{aligned}\quad (20)$$

where:

$$\begin{aligned}\gamma_p^{th} &= \max\{\zeta_{p1}, \zeta_{p2}\}, \\ \zeta_{p1} &= \frac{\gamma_{p,c}^{th}}{\rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_0 - (\alpha_1 + \alpha_2) \gamma_{p,c}^{th}]}, \\ \zeta_{p2} &= \frac{\gamma_{p,s}^{th} (\omega \rho \delta_{sp}^2 + 1)}{\rho d_{sr}^{-\alpha} d_{rp}^{-\alpha} [\alpha_1 - \alpha_2 \gamma_{p,s}^{th}]}.\end{aligned}$$

The OP for vehicle Q is analyzed as follows:

Similarly, the OP at vehicle Q also consists of two parts. First, vehicle Q unsuccessfully decodes the common information stream, i.e., $\gamma_q^c < \gamma_{q,c}^{th}$, where $\gamma_{q,c}^{th} = 2^{R_{q,c}} - 1$,

and $R_{q,c}$ is the target rate threshold for the common part of vehicle Q's information stream. Second, vehicle Q unsuccessfully decodes its own private information stream, meaning $\gamma_q^s < \gamma_{q,s}^{th}$, where $\gamma_{q,s}^{th} = 2^{R_{q,s}} - 1$, and $R_{q,s}$ is the target rate threshold for the private part of vehicle Q's information stream. If either occurs, an outage happens at vehicle Q. After L retransmission rounds, the OP at vehicle Q is expressed as follows:

$$\begin{aligned}P_{out}^Q &= \left[Pr\{\gamma_q^c < \gamma_{q,c}^{th}, \gamma_q^s < \gamma_{q,s}^{th}\} \right]^L \\ &= \left[1 - Pr\left\{ \begin{aligned} &\frac{\alpha_0 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{(\alpha_1 + \alpha_2) \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + 1} \geq \gamma_{q,c}^{th}, \\ &\frac{\alpha_2 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2}{\alpha_1 \rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} |h_{R,l}|^2 + \omega \rho |h_{sq,l}|^2 + 1} \geq \gamma_{q,s}^{th} \end{aligned} \right\} \right]^L \\ &= \left[\begin{aligned} &\left[\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{\zeta_{q1}}{\theta}\right) \right]^L, \zeta_{q1} > \zeta_{q2} \\ &\left[\frac{1}{\Gamma(k)^2} \gamma\left(k, \frac{\zeta_{q2}}{\theta}\right) \right]^L, \zeta_{q1} < \zeta_{q2} \end{aligned} \right],\end{aligned}\quad (21)$$

where:

$$\begin{aligned}\gamma_q^{th} &= \max\{\zeta_{q1}, \zeta_{q2}\}, \\ \zeta_{q1} &= \frac{\gamma_{q,c}^{th}}{\rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_0 - (\alpha_1 + \alpha_2) \gamma_{q,c}^{th}]}, \\ \zeta_{q2} &= \frac{\gamma_{q,s}^{th} (\omega \rho \delta_{sq}^2 + 1)}{\rho d_{sr}^{-\alpha} d_{rq}^{-\alpha} [\alpha_2 - \alpha_1 \gamma_{q,s}^{th}]}.\end{aligned}$$

4 Numerical results and discussion

Section 4 presents numerical results obtained through MATLAB simulations [22] to validate the theoretical analysis. The system parameters are configured as follows unless specified otherwise: $\alpha = 2$, $R_p = 2$ bps/Hz, $R_q = 1$ bps/Hz, $R_{p,s} = 0.2$ bps/Hz, $R_{p,c} = 0.8$ bps/Hz, $R_{q,s} = 0.2$ bps/Hz, $R_{q,c} = 0.8$ bps/Hz, $\alpha_p = 0.8$, $\alpha_q = 0.2$, $\alpha_0 = 0.6$, $\alpha_1 = 0.3$, $\alpha_2 = 0.1$, $m = 2$, $\Omega = 1$.

Fig. 3 illustrates the variation of OP with respect to transmit power, demonstrating that OP decreases as transmit power increases with $L = 2$. It can be observed from the figure that the OP achieved with perfect SIC is lower than that achieved with ipSIC. This is because ipSIC introduces residual interference, which negatively impacts signal decoding at the receiver. Under NOMA, the OP of the receiving vehicle is higher than that under RSMA.

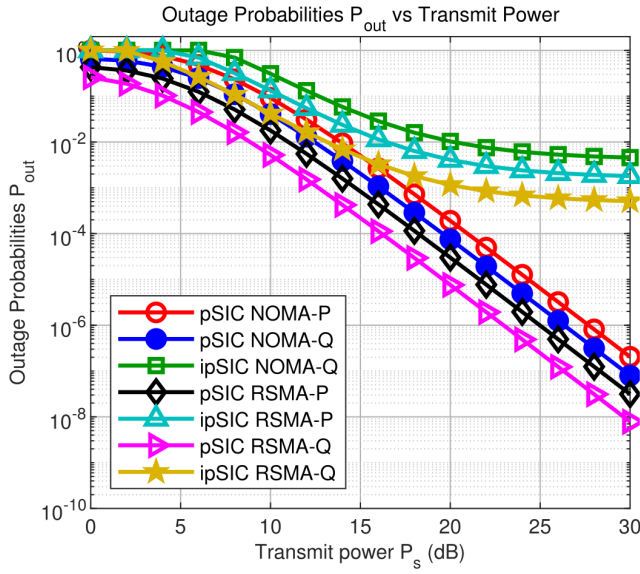


Fig. 3 Curve of transmission power P_s versus OP

Although RSMA outperforms NOMA in overall performance, and the transmit power allocated to vehicle P is higher than that allocated to vehicle Q, the OP at vehicle P remains higher than that at vehicle Q. This is because the SIC process at vehicle Q improves its effective channel conditions. In the RSMA scheme, the power allocated to vehicle P is greater than that allocated to vehicle Q, and the experimental results also confirm that the OP at vehicle P is higher than that at vehicle Q.

Fig. 4 illustrates the relationship between the number M of STAR-RIS elements and OP, with other parameters as specified. The simulation results show that the OP gradually decreases with the increase of M . The range of M set in this simulation is 0–100, which is consistent with the channel assumptions adopted in the theoretical analysis

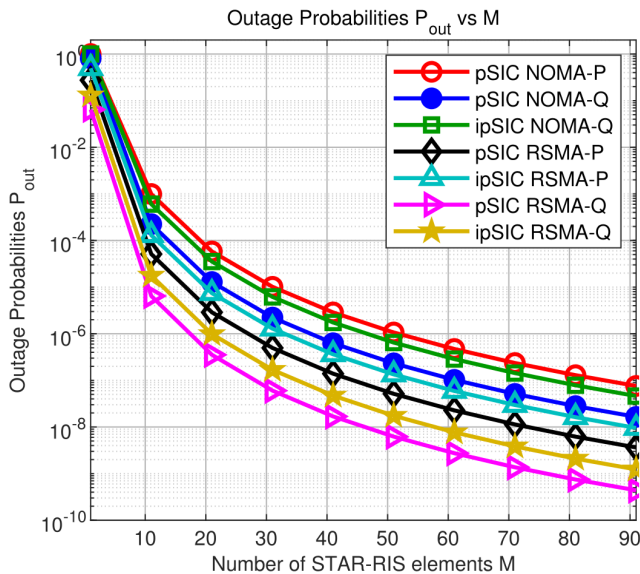


Fig. 4 Curve of the number of STAR-RIS elements M versus OP

of this paper. It is further verified that the proposed theoretical derivation remains valid even when the number of STAR-RIS elements is small. The experimental results also indicate that the OP obtained under the pSIC assumption is lower than that under the ipSIC assumption, and the OP of the receiving vehicle adopting the NOMA scheme is higher than that of the vehicle adopting the RSMA scheme.

Fig. 5 presents the variation of OP with respect to the maximum HARQ retransmission number L . The numerical results show that OP decreases with the increase of L , and the performance improvement brought by the growth of L is significant. It can be observed from the figure that the overall OP of receiving vehicles under NOMA is higher than that under RSMA, which is attributed to the superior performance of RSMA over NOMA. The results verify that HARQ can effectively reduce OP and improve the reliability of communication systems.

Fig. 6 depicts the variation of OP with respect to the travel distance of vehicle S to the STAR-RIS. The experimental results show that the OP increases synchronously as the distance increases, and ultimately approaches 1. The mobility of the vehicle leads to the fluctuation of OP: when the distance increases, the transmission and reception of the vehicle's signal become unstable, and the OP rise accordingly, which is consistent with theoretical expectations. It can also be observed from this figure that the OP under the pSIC assumption is lower than that under the ipSIC assumption, and the OP of the receiving vehicle under the NOMA scheme is higher than that under the RSMA scheme.

Fig. 7 demonstrates the relationship between residual interference and OP in the ipSIC scenario. The obtained results show that in the ipSIC scenario, the OP of the

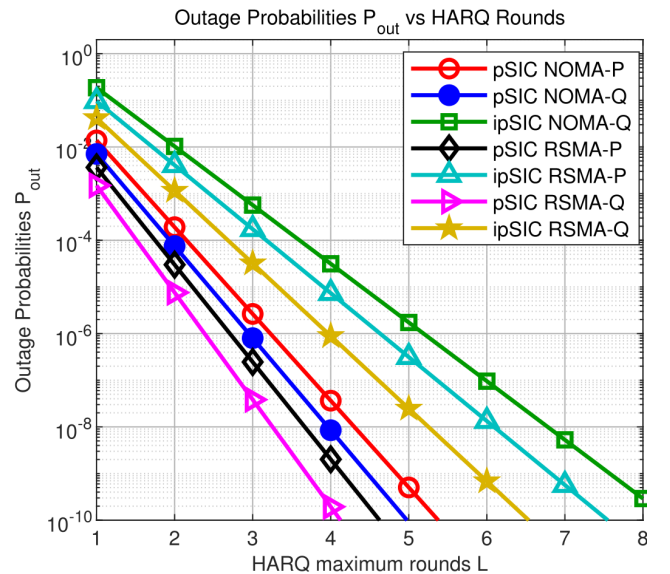


Fig. 5 Curve of HARQ maximum transmission rounds L versus OP

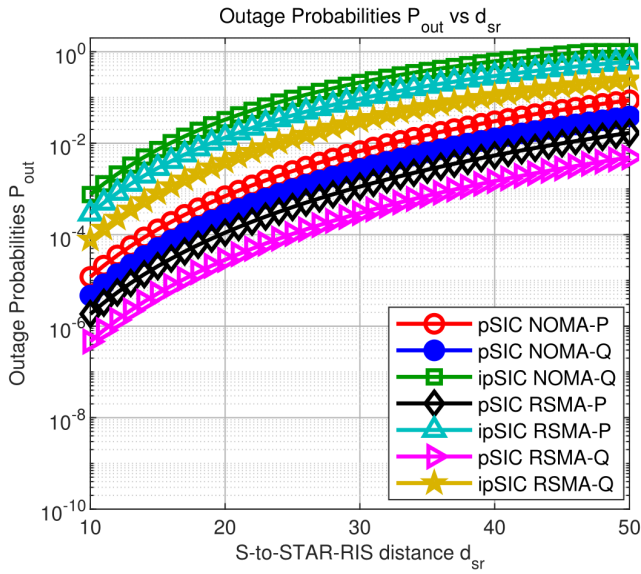


Fig. 6 S to STAR-RIS distance d_{sr} versus OP

receiving vehicle increases synchronously as the channel gain increases, and eventually approaches 1; while in the pSIC scenario, the OP remains unchanged. It can also be observed from Fig. 7 that in the ipSIC scenario, the OP of NOMA is higher than that of RSMA. The above experimental results are consistent with the corresponding theoretical derivation.

5 Conclusion

In this work, we take the OP as the core performance indicator to evaluate the communication performance of STAR-RIS-assisted V2V networks. This paper analyzes the OP of the receiving vehicle under two scenarios, namely pSIC and ipSIC, for the two multiple access schemes where NOMA/

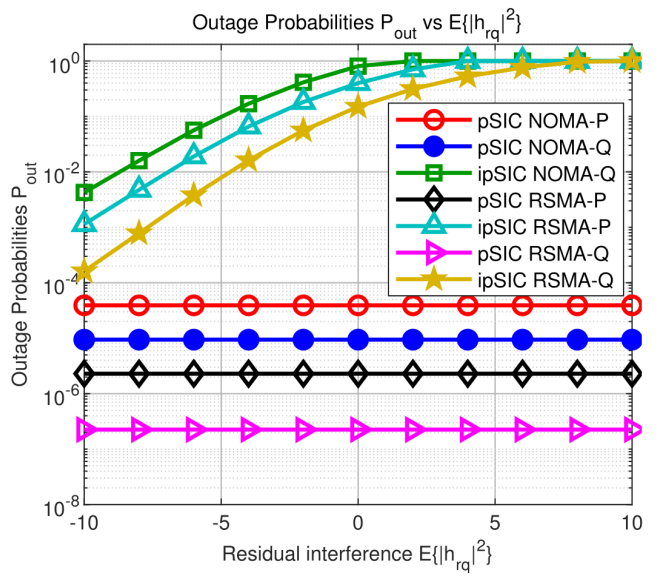


Fig. 7 $E\{|h_{rq}|^2\}$ versus OP

RSMA are combined with HARQ, respectively. The derived theoretical results are verified by extensive simulations, and the relationships between multiple key system parameters (including transmit power, the number of STAR-RIS elements, and the maximum HARQ retransmission number) and the OP are clarified. Furthermore, this paper reveals the influence mechanism of these parameters on the overall system communication performance. Numerical results show that, between the two compared multiple access schemes, RSMA outperforms NOMA in terms of overall system performance, and the system performance of each scheme in the pSIC scenario is superior to that in the ipSIC scenario. The HARQ assisted STAR-RIS-NOMA/RSMA system achieves a remarkable performance improvement.

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