Resource Allocation for IRS-Assisted Symbiotic Vehicular RSMA and Backscatter Communication

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***Abstract*—We develop a symbiotic operation framework of primary downlink vehicular communication using rate-splitting multiple access (RSMA) and secondary backscatter communication of an intelligent reflecting surface (IRS). The framework employs alternating optimization for resource allocation, considering channel estimation errors caused by vehicular mobility.**

***Index Terms*—rate splitting multiple access (RSMA), backscatter communication, intelligent reflecting surface (IRS).**

I. Introduction

Vehicular communication is expected to become prevalent in the near future, offering reliable data services to moving vehicles and their passengers. Intelligent reflecting surfaces (IRS) and rate-splitting multiple access (RSMA), both considered promising technologies for 6G communication, may also enhance vehicular communication by increasing spectral efficiency under unfavorable propagation conditions.

In this paper, we develop a vehicular communication framework that enables the symbiotic operation of IRS-aided primary downlink communication for multiple vehicles using RSMA and secondary backscatter communication of the IRS. This approach extends beyond the limitations of existing research, which primarily focuses on nonorthogonal and time-division multiple access schemes with primary communication only [1], [2]. To achieve effective symbiotic radio functioning, our framework employs an alternating optimization approach for resource allocation, aiming at sum-rate maximization while accounting for channel estimation errors caused by vehicular mobility.

II. System and Channel Model

We consider the system architecture illustrated in Fig. 1, where the primary network (PN) consists of an N_S-antenna base station (primary transmitter (PT)) labeled S, communicating with V single-antenna vehicles (primary receivers (PRs), $v = 1, \ldots, V$), supported by an IRS device (secondary transmitter (ST)) denoted by I, with M reflective elements. The secondary network (SN) consists of the IRS device, which uses backscatter communication to transmit its data to a single-antenna secondary backscatter reader (SR) labeled R. The PN

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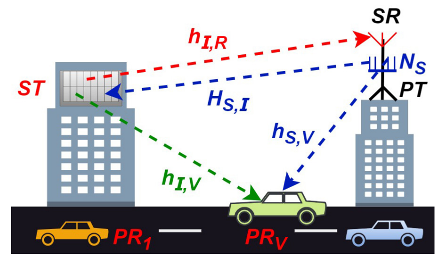


Fig. 1: IRS-assisted symbiotic vehicular radio system model.

utilizes RSMA to transmit data from the PT to PRs, while the IRS device backscatters the PT's signals to both assist in PT's transmission and transmit its data. The received signals at node $z \in \{v, R\}$ (either PR$_v$ or SR) is given by

$$\hat{y} = \underbrace{\sum_{v=1}^{V} \mathbf{h}_{S,z}^H \mathbf{p}_{S,v} x_{P,v} + \mathbf{h}_{S,z}^H \mathbf{p}_{S,C} x_C + n_z}_{\text{Direct-link (private+common) signal + noise}} \\ + \underbrace{\mathbf{H}_{S,I}^H \Big(\sum_{v=1}^{V} \mathbf{p}_{S,v} x_{P,v} + \mathbf{p}_{S,C} x_C \Big) x_I \boldsymbol{\Theta}_I \mathbf{h}_{I,z}}_{\text{IRS backscattered signals (IRS data+private+common)}}, \quad (1)$$

where $\mathbf{h}_{S,z} \in \mathbb{C}^{N_S \times 1}$ is the PT-to-z channel, $\mathbf{p}_{S,C} \in \mathbb{C}^{N_S \times 1}$ and $\mathbf{p}_{S,v} \in \mathbb{C}^{N_S \times 1}$ are the beamforming vectors between PT and PR$_v$ for the common and private channels, respectively. $\mathbf{H}_{S,I} \in \mathbb{C}^{N_S \times M}$, $\mathbf{h}_{I,v} \in \mathbb{C}^{M \times 1}$, and $\mathbf{h}_{I,R}$ are the PT-to-IRS channel, the IRS-to-PR$_v$ channel, and the IRS-to-SR channel, respectively. $\boldsymbol{\Theta}_I = \mathrm{diag}(\theta_{I,1}, \cdots, \theta_{I,M}) \in \mathbb{C}^{M \times M}$ is the IRS's reflection coefficient matrix with $\theta_{I,m} = e^{j\phi_{I,m}}$ and $\phi_{I,m} \in [0, 2\pi)$. $x_{P,v}$ and x_C are the private message of PR$_v$ and the common message of the PRs, respectively, while x_I is the IRS data. According to [3], the fading channel under mobility is modeled as $h[t] = \sqrt{\epsilon^2} h[t-1] + \sqrt{1-\epsilon^2} e[t]$, where the current time t channel $\triangleq h[t] \sim \mathcal{CN}(0,1)$, and the channel for the previous time $(t-1) \triangleq h[t-1] \sim \mathcal{CN}(0, 1-\sigma_e^2)$. $e[t] \sim \mathcal{CN}(0, \sigma_e^2)$ is the channel estimation error, and ϵ denotes the time correlation coefficient, given by $\epsilon = J_0(2\pi f_d T)$. The maximum Doppler frequency f_d is defined as $f_d = \nu f_c / C$, where f_c is the carrier frequency, ν is the vehicle speed, and C is the speed of light. T is the channel instantiation interval.

The signal-to-interference-plus-noise ratio (SINR) for the common and private data of the PR$_v$ is defined in (2), and the

IRS backscattered received SINR at R is deduced in (3):

$$\hat{\gamma}^{C}_{S,v} = \frac{\hat{y}^{C(des)}_{S,v}}{\hat{y}^{C(intf)}_{S,v} + \sigma_v^2} \qquad \hat{\gamma}^{P}_{S,v} = \frac{\hat{y}^{P(des)}_{S,v}}{\hat{y}^{P(intf)}_{S,v} + \sigma_v^2}, \tag{2}$$

$$\hat{\gamma}_{I,R} = \frac{\sum_{v=1}^{V} |\mathbf{H}^H_{S,I}\mathbf{p}_{S,v}\mathbf{\Theta}_I\mathbf{h}_{I,R}|^2 + |\mathbf{H}^H_{S,I}\mathbf{p}_{S,C}\mathbf{\Theta}_I\mathbf{h}_{I,R}|^2}{B_{S,R} + D_{I,v} + \sigma_R^2}, \tag{3}$$

$$\begin{aligned}
&\hat{y}^{C(des)}_{S,v} = |\mathbf{h}^H_{S,v}\mathbf{p}_{S,C}|^2 + |\mathbf{H}^H_{S,I}\mathbf{p}_{S,C}\mathbf{\Theta}_I\mathbf{h}_{I,v}|^2,\\
&\hat{y}^{C(intf)}_{S,v} = \textstyle\sum_{j=1}^{V}(|\mathbf{h}^H_{S,v}\mathbf{p}_{S,j}|^2 + 2|\mathbf{H}^H_{S,I}\mathbf{p}_{S,j}\mathbf{\Theta}_I\mathbf{h}_{I,v}|^2),\\
&\hat{y}^{P(des)}_{S,v} = |\mathbf{h}^H_{S,v}\mathbf{p}_{S,v}|^2 + |\mathbf{H}^H_{S,I}\mathbf{p}_{S,v}\mathbf{\Theta}_I\mathbf{h}_{I,v}|^2,\\
&\hat{y}^{P(intf)}_{S,v} = \textstyle\sum_{j\neq v}^{V} |\mathbf{h}^H_{S,v}\mathbf{p}_{S,j}|^2 + \sum_{j\neq v}^{V} |\mathbf{H}^H_{S,I}\mathbf{p}_{S,j}\mathbf{\Theta}_I\mathbf{h}_{I,v}|^2\\
&\qquad + \textstyle\sum_{j=1}^{V} |\mathbf{H}^H_{S,I}\mathbf{p}_{S,j}\mathbf{\Theta}_I\mathbf{h}_{I,v}|^2,\\
&B_{S,R} = |\mathbf{H}^H_{S,R}\mathbf{p}_{S,C}|^2 + \textstyle\sum_{v=1}^{V} |\mathbf{H}^H_{S,R}\mathbf{p}_{S,v}|^2,\\
&D_{I,v} = (\textstyle\sum_{v=1}^{V} |\mathbf{H}^H_{S,I}\mathbf{p}_{S,v}\mathbf{\Theta}_I\mathbf{h}_{I,R}|^2 + |\mathbf{H}^H_{S,I}\mathbf{p}_{S,C}\mathbf{\Theta}_I\mathbf{h}_{I,R}|^2).
\end{aligned}$$

III. Resource Allocation Solution

The target sum-rate maximization problem, optimizing $\{\mathbf{p}_{S,v}\}_{v=1}^{V}, \mathbf{p}_{S,C}$, and $\mathbf{\Theta}_I$ is formulated as

$$\underset{\{\mathbf{p}_{S,v}\}_{v=1}^{V}, \mathbf{p}_{S,C}, \mathbf{\Theta}_I}{\text{maximize}} \sum_{v=1}^{V} R_v + R_{I,R} \tag{4a}$$

$$\text{s.t. } |\theta_{I,m}| = 1, \forall m, \tag{4b}$$

$$\sum_{j\neq v}^{V} C_{S,j} \leq \log_2(1 + \hat{\gamma}^{C}_{S,v}), \forall v \tag{4c}$$

$$\sum_{v=1}^{V} \|\mathbf{p}_{S,v}\|^2 + \|\mathbf{p}_{S,C}\|^2 \leq P_T, \tag{4d}$$

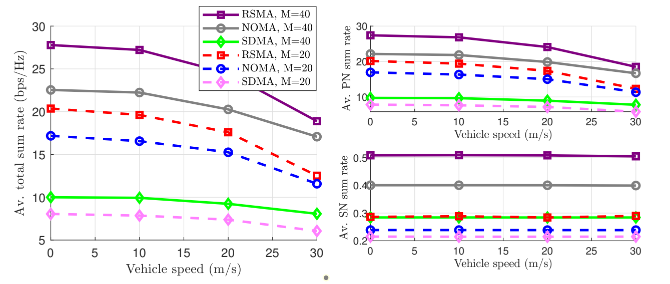
where $C_{s,j}$ is the common channel rate of PR_j, $R_v = \log_2(1 + \hat{\gamma}^{P}_{S,v}) + C_{S,v}$, $R_{I,R} = \log_2(1 + \hat{\gamma}_{I,R})$, and P_T is the maximum transmit power of the PT. The following two optimization processes are alternated until both converge.

Transmit Beamformer Optimization: Exploiting the weighted minimum mean-square error (WMMSE) approach [4] to find the optimal beamformers, Problem (4) can be transformed into

$$\underset{\{\mathbf{p}_{S,v}\}_{v=1}^{V}, \mathbf{p}_{S,C}}{\text{minimize}} \quad \sum_{v=1}^{V} (\xi_{C,v} + \xi_{P,v}) + \xi_{I,R}, \ \forall v \in V, \ \text{s.t. (4c)} \tag{5}$$

; $\min_{\omega_{C,v}, m_{C,v}} \xi_{C,v} = 1 - (\log_2(1/\varepsilon^{MMSE}_{C,v}))$, $\min_{\omega_{P,v}, m_{P,v}} \xi_{P,v} = 1 - (\log_2(1/\varepsilon^{MMSE}_{P,v}))$, $\min_{\omega_{I,R}, m_{I,R}} \xi_{I,R} = 1 - (\log_2(1/\varepsilon^{MMSE}_{I,R}))$, where $\omega^*_{C,v}, \omega^*_{P,v}, \omega^*_{I,R}, m^*_{C,v}, m^*_{P,v}$ and $m^*_{I,R}$ denote the optimal weights and optimal receive filters for the common, private, and backscatter data respectively. $\varepsilon^{MMSE}_{C,v}$, $\varepsilon^{MMSE}_{P,v}$ and $\varepsilon^{MMSE}_{I,R}$ denote the MMSE function of the common, private, and backscatter messages respectively. Problem (5) is convex and can be solved efficiently using existing solvers.[1]

[1] We used the Matlab CVX toolbox to obtain the numerical results.



(a) Total sum-rate (b) PN and SN rates

Fig. 2: Total, PN, and SN sum-rates for varying vehicle speeds

IRS Reflection Coefficient Optimization: We employ the Riemannian conjugate gradient algorithm [5] to iteratively update each $\theta_{I,m}$, where the nth update is given as

$$\theta_{I,m}[n+1] = \frac{(\theta_{I,m}[n] + \tau\kappa)}{|(\theta_{I,m}[n] + \tau\kappa)|}. \tag{6}$$

Here, τ denotes the step size, and κ is the search direction, which is obtained as the tangent vector conjugate to the Riemannian gradient of the objective function (4a).

IV. Numerical Results

For evaluation, we extend the urban grid scenario outlined by 3GPP [6]. The carrier frequency is set to 2.4 GHz. We configure the transmit power P_T to 25 dBm and T to 1 ms.

Fig. 2 shows the sum-rate results of the proposed framework for varying vehicular speeds. Due to the symbiotic operation of the PN and SN, the SN rate is also achieved, albeit much lower than the PN rate. We observe that RSMA outperforms both NOMA and SDMA. While all methods exhibit decreasing PN rates with increasing vehicle speeds due to rising channel estimation errors, the SN rates remain negligibly affected. Additionally, we observe that increasing the number of IRS elements from 20 to 40 results in an increase in both the PN and SN rates across all schemes. The increase in SN rates is more significant compared to the increase in PN rates with the increase in IRS elements.

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