

Energy Efficiency Maximization for RIS-Aided Symbiotic Networks Under Channel Aging

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Abstract—We develop a symbiotic operation framework of primary downlink communication and secondary backscatter communication via multiple reconfigurable intelligent surfaces (RIS) with energy harvesting (EH) capabilities. The framework employs alternating optimization for energy efficiency (EE) maximization, considering mobility-induced channel aging effects.

Index Terms—energy efficiency, backscatter communication, reconfigurable intelligent surfaces.

I. INTRODUCTION

Spectrum congestion is driving the narrative for efficient spectrum and resource sharing between networks. One of the paradigms pushing this narrative is symbiotic radio (SR) where a secondary network (SN) relies on the ambient radio frequency (RF) signals of a primary network (PN), while the PN's spatial diversity is improved via the SN's transmission [1], [2].

In this paper, we adopt the concept of SR in a reconfigurable intelligent surface (RIS)-aided vehicle-to-everything (V2X) network in symbiosis with an Internet of Things (IoT) reader. Specifically, we consider the impact of channel aging resulting from the mobility of the users. To achieve effective MSR functioning, our framework employs an alternating optimization (AO) approach for resource allocation, aiming at energy efficiency (EE) maximization while accounting for channel estimation errors caused by user mobility.

II. SYSTEM AND CHANNEL MODEL

We consider an SR network where the PN consists of an M -antenna base station (BS) communicating with L mobile users (MUs) via non-orthogonal multiple access (NOMA)-based downlink transmission. The SN comprises K RIS devices (each equipped with N_k elements) with energy harvesting (EH) capabilities and an N_r -antenna reader. The symbiotic relationship materializes when the SN relies on the ambient BS

RF signals to embed and reflect IoT signals to the reader, while assisting the PN transmissions through multipaths established by RIS reflections.

Using the channel estimation process similar to [3], the channel of MU l at time index n is given as $\mathbf{H}_l[n] = \delta \hat{\mathbf{H}}_l[n-1] + \mathbf{Z}_l[n]$, where $\hat{\mathbf{H}}_l[n-1]$ represents the previously estimated channel and $\mathbf{Z}_l[n]$ encompasses the channel error and variations due to user mobility. $\delta = J_0(2\pi f_D T)$ is the temporal correlation coefficient, where T is the estimation interval, $J_0(\cdot)$ denotes the zeroth-order Bessel function of the first kind, and $f_D = v f_c / c$ is the Doppler frequency, with f_c , v , and c denoting the carrier frequency, user speed, and the speed of light, respectively [3].

The received signals at MU l or reader during downlink NOMA transmission are expressed as

$$\mathbf{y}_{z_1} = \sum_{l=1}^L \mathbf{H}_{z_1} \mathbf{W}_l \mathbf{x}_l + \sum_{k=1}^K \mathbf{G}_{k,z_1} \Theta_k^{1/2} \mathbf{F}_k x_{k,r} \sum_{l=1}^L \mathbf{W}_l \mathbf{x}_l + \mathbf{n}_{z_1}, \quad (1)$$

where $z_1 \in (l, r)$. $\mathbf{x}_l$ and $x_{k,r}$ are the signals intended for MU l and the reader. $\mathbf{W}_l \in \mathbb{C}^{M \times N_l}$ is the transmit beamforming matrix. $\mathbf{H}_l \in \mathbb{C}^{N_l \times M}$, $\mathbf{F}_k \in \mathbb{C}^{N_k \times M}$ and $\mathbf{H}_r \in \mathbb{C}^{N_r \times M}$ denote the channels from BS to MU l , RIS k and reader, respectively. The channels from RIS k to MU l and the reader are defined as $\mathbf{G}_{k,l} \in \mathbb{C}^{N_l \times N_k}$ and $\mathbf{G}_{k,r} \in \mathbb{C}^{N_r \times N_k}$, respectively. $\mathbf{n}_{z_1}$ represents noise at MU- l /reader, while $\Theta_k = \text{diag}(\{\eta_{k,c} e^{j\theta_{k,c}}\}_{c=1}^{N_k})$ denotes the reflection coefficient of RIS k , where $\theta_{k,c}$ and $\eta_{k,c}$ are the phase shifts and amplitudes, respectively.

The signal-to-interference-plus-noise ratio (SINR) at MU l and the reader are expressed in (2) and (3), respectively, as

$$\tilde{\gamma}_l = \mathbf{A}_l^H (\mathbf{B}_l + \mathbf{C}_l + \mathbf{D}_l + \mathbf{E}_l + \sigma_l^2 \mathbf{I}_{N_l})^{-1} \mathbf{A}_l, \quad (2)$$

$$\tilde{\gamma}_{k,r} = \mathbf{A}_{k,r}^H (\mathbf{B}_{k,r} + \mathbf{C}_{k,r} + \mathbf{D}_{k,r} + \sigma_r^2 \mathbf{I}_{N_r})^{-1} \mathbf{A}_{k,r}. \quad (3)$$

By letting $\mathbf{H}_{el} = \mathbf{G}_{k,l} \Theta_k^{1/2} \mathbf{F}_k$ and $\mathbf{H}_{ek} = \mathbf{G}_{k,r} \Theta_k^{1/2} \mathbf{F}_k$, and applying PN and SN filters ($\tilde{\mathbf{W}}_l \in \mathbb{C}^{N_l \times M}$, $\tilde{\mathbf{W}}_{k,r} \in \mathbb{C}^{N_r \times M}$), the terms in (2) and (3) are expressed as

$$\begin{aligned} \mathbf{A}_l &= \delta (\tilde{\mathbf{W}}_l^H \mathbf{H}_l \mathbf{W}_l + \sum_{k=1}^K \tilde{\mathbf{W}}_l^H \mathbf{H}_{el} \mathbf{W}_l), \\ \mathbf{A}_{k,r} &= \sum_{l=1}^L \tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_{ek} \mathbf{W}_l, \\ \mathbf{B}_l &= \sum_{j \neq l}^L \beta_j \delta^2 (\tilde{\mathbf{W}}_l^H \mathbf{H}_l \mathbf{W}_j)^H (\tilde{\mathbf{W}}_l^H \mathbf{H}_l \mathbf{W}_j), \end{aligned}$$

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$\mathbf{B}_{k,r} = \sum_{l=1}^L (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_r \mathbf{W}_l)^H (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_r \mathbf{W}_l),$
 $\mathbf{C}_l = \sum_{j \neq l}^L \sum_{k=1}^K \beta_j (\tilde{\mathbf{W}}_l^H \mathbf{H}_{el} \mathbf{W}_j)^H (\tilde{\mathbf{W}}_l^H \mathbf{H}_{el} \mathbf{W}_j),$
 $\mathbf{C}_{k,r} = \sum_{l=1}^L \sum_{j \neq k}^K \beta_{k,j} (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_{ej} \mathbf{W}_l)^H (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_{ej} \mathbf{W}_l),$
 $\mathbf{D}_l = \sum_{j=1}^L \sum_{k=1}^K \beta_j (\tilde{\mathbf{W}}_l^H \mathbf{H}_{el} \mathbf{W}_j)^H (\tilde{\mathbf{W}}_l^H \mathbf{H}_{el} \mathbf{W}_j),$
 $\mathbf{D}_{k,r} = \sum_{j=1}^L \sum_{k=1}^K \beta_{k,j} (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_{ek} \mathbf{W}_l)^H (\tilde{\mathbf{W}}_{k,r}^H \mathbf{H}_{ek} \mathbf{W}_l),$
 $\mathbf{E}_l = \sum_{l=1}^L (1 - \delta^2) (\tilde{\mathbf{W}}_l^H \mathbf{U}_l \mathbf{W}_l)^H (\tilde{\mathbf{W}}_l^H \mathbf{U}_l \mathbf{W}_l).$ Here, the terms $\mathbf{A}_l$, $\mathbf{B}_l$, and $\mathbf{C}_l$ represent the desired MU l signal, set of other MUs ($\{\text{MU}_j\}_{j \neq l}^L$) interferences, and set of all RIS ($\{\text{RIS}_k\}_{k=1}^K$) interferences, respectively. $\mathbf{E}_l$ denotes the channel aging component whose innovation component is $\mathbf{U}_l$. Likewise, the terms $\mathbf{A}_{k,r}$, $\mathbf{B}_{k,r}$ and $\mathbf{C}_{k,r}$ are respectively, the desired signal of RIS k at reader, set of all MUs ($\{\text{MU}_l\}_{l=1}^L$) interferences, and ($\{\text{RIS}_j\}_{j \neq k}^K$) interference signals present at the reader. $\mathbf{D}_l$ and $\mathbf{D}_{k,r}$ are inter-RIS interference signals encountered during RIS backscatter communication (BackCom). Based on the SINRs, the achievable rates are deduced as

$$\begin{aligned}
 R_l &= \log_2 \det(\mathbf{I}_{N_l} + \tilde{\gamma}_l), \text{ and} \\
 R_{k,r} &= \log_2 \det(\mathbf{I}_{N_r} + \tilde{\gamma}_{k,r}).
 \end{aligned} \quad (4)$$

The system EE is defined as

$$\text{EE} = \frac{\sum_{l=1}^L R_l + \sum_{k=1}^K R_{k,r}}{\sum_{l=1}^L \text{Tr}(\mathbf{W}_l \mathbf{W}_l^H) + P_{\text{lum}} + \sum_{k=1}^K \hat{P}_{c,k}}, \quad (5)$$

where $P_{c,k}$ is the power harvested by using the multi-stage rectifier model and $\hat{P}_{c,k}$ is the power consumed at RIS k for excitation and BackCom [4]. P_{lum} represents the sum of lumped hardware budgets at the MUs, BS and reader.

III. RESOURCE ALLOCATION SOLUTION

The EE maximization problem, optimizing $\{\mathbf{W}_l\}_{l=1}^L$ and $\{\boldsymbol{\theta}_k\}_{k=1}^K$ is formulated as

$$\begin{aligned}
 &\text{maximize} && \text{EE} \\
 &\{\mathbf{W}_l, \tilde{\mathbf{W}}_l\}_{l=1}^L, \{\boldsymbol{\theta}_k, \tilde{\mathbf{W}}_{k,r}\}_{k=1}^K
 \end{aligned} \quad (6a)$$

$$\text{subject to} \quad \sum_{l=1}^L \text{Tr}(\mathbf{W}_l \mathbf{W}_l^H) \leq P_T, \quad (6b)$$

$$P_{c,k} \geq \hat{P}_{c,k} \geq 0, \quad \forall k, \quad (6c)$$

$$\mathbf{0} < \boldsymbol{\theta}_k < \mathbf{i}, \quad \forall k, \quad (6d)$$

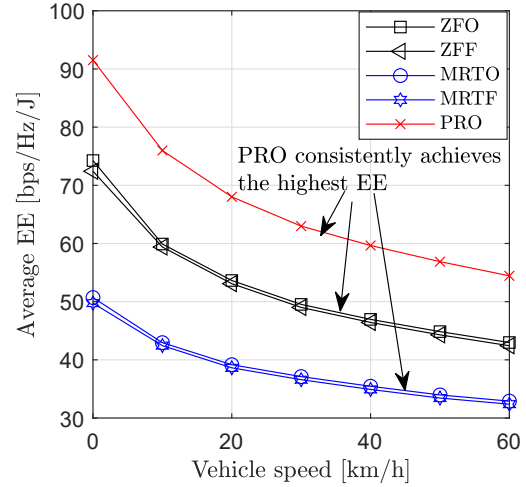
$$\text{Tr}(\tilde{\mathbf{W}}_l^H \tilde{\mathbf{W}}_l) \leq 1, \quad \forall l, \quad (6e)$$

$$\text{Tr}(\tilde{\mathbf{W}}_{k,r}^H \tilde{\mathbf{W}}_{k,r}) \leq 1, \quad \forall k. \quad (6f)$$

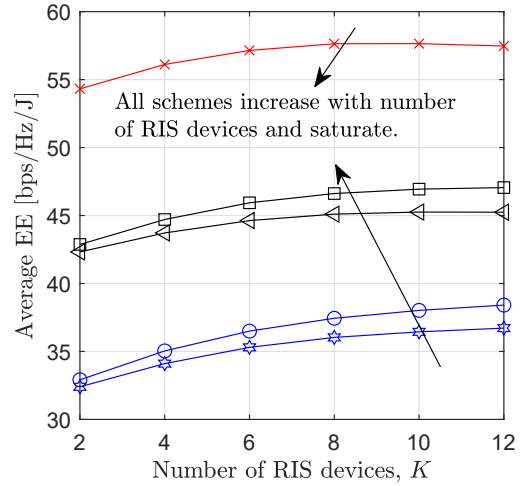
IRS Reflection Coefficient Optimization: Exploiting the Dinkelbach method coupled with the weighted minimum mean-square error (WMMSE) approach and fixing $\{\mathbf{W}_l\}_{l=1}^L$, we employ the root-finding algorithm [4], [5]. To find the reflection coefficients, problem (6) can be transformed into (7) as

$$\begin{aligned}
 &\text{minimize} && \hat{\Pi} + \hat{\gamma} \Omega \\
 &\{\boldsymbol{\theta}_k\}_{k=1}^K
 \end{aligned} \quad \text{subject to (6c) and (6d)}, \quad (7)$$

where $\hat{\Pi} = \sum_{l=1}^L \phi_l + \sum_{k=1}^K \phi_{k,r}$ and $\hat{\gamma} = \hat{\Pi}/\Omega$. ϕ_l and $\phi_{k,r}$ are the weighted MSEs, $\hat{\Pi}$ is the WMMSE sum rate equivalent, and Ω is the denominator of (5). Accordingly,



(a) EE vs. user speed



(b) EE vs. number of RIS devices

Fig. 1: $M = 4$, $N_l = 2$, $N_r = 2$, $N_k = 10$, $K = 2$, $L = 2$, $P_T = 30$ dBm, $P_{\text{lum}} = 10$ dBm, $\sigma_l^2 = \sigma_r^2 = -130$ dBm, $\beta_x = 10^{-5}$, $v = 60$ km/h, $c = 3 \times 10^8$ m/s, $f_c = 2.5$ GHz, $T = 0.1$ ms.

the reflection coefficient vector of RIS k is obtained as $\boldsymbol{\theta}_k^* = \mathbf{i} - \left(\mathcal{J}_k^{-1} \mathbf{x}_k^{\frac{1}{4}*} \right)^H \left(\mathcal{J}_k^{-1} \mathbf{x}_k^{\frac{1}{4}*} \right)$ [4].

Transmit Beamformer Optimization: For the formulation in (8), we set the gradient of the Lagrangian with respect to $\mathbf{W}_l$ to zero.

$$\begin{aligned}
 &\text{minimize} && \hat{\Pi} + \hat{\gamma} \Omega \\
 &\{\mathbf{W}_l\}_{l=1}^L
 \end{aligned} \quad \text{subject to (6b)}. \quad (8)$$

Similar to the closed-form solution in [4], the optimal beamformer is obtained as $\mathbf{W}_l^* = (\boldsymbol{\Xi}_l)^{-1} \boldsymbol{\Sigma}_l$.

IV. NUMERICAL RESULTS

For evaluation, we consider the urban macro path loss model outlined by 3GPP [6] and Rician fading for the small-scale fading component. We compare the proposed scheme, PRO

to the zero-forcing beamforming with optimized and fixed θ_k (ZFO and ZFF) and maximum ratio transmission beamforming with optimized and fixed θ_k (MRTO and MRTF), respectively.

Fig. 1 shows the average EE for varying v and K . The decreasing behavior as v varies can be attributed to the increasing f_D effect, which results in high channel aging components. The PRO scheme benefits from the joint optimization enabling it to outperform the other schemes. Additionally, we observe that increasing the number of RIS devices results in an increase in sum rate across all schemes. Due to increased interferences and harvested power, EE saturates as K increases.

REFERENCES

- [1] Q. Zhang, Y.-C. Liang, H.-C. Yang, and H. V. Poor, "Mutualistic mechanism in symbiotic radios: When can the primary and secondary transmissions be mutually beneficial?" *IEEE Trans. Wireless Commun.*, vol. 21, no. 10, pp. 8036–8050, Apr. 2022.
- [2] H. Guo, Y. Ye, H. Sun, L. Shi, and R. Q. Hu, "Resource allocation for mutualistic symbiotic radio with hybrid active-passive communications," *IEEE Trans. Cog. Commun. Network.*, 2025.
- [3] J. Zheng, J. Zhang, E. Björnson, and B. Ai, "Impact of channel aging on cell-free massive MIMO over spatially correlated channels," *IEEE Trans. Wireless Commun.*, vol. 20, no. 10, pp. 6451–6466, Apr. 2021.
- [4] S. K. Menanor, D. K. P. Asiedu, M. Benjillali, S. Saoudi, and K.-J. Lee, "Symbiotic radio massive MIMO IoT network with wireless powered RIS backscatter communications," *IEEE Trans. Cog. Commun. Network.*, vol. 10, pp. 2849–2864, May 2026.
- [5] S. S. Christensen, R. Agarwal, E. De Carvalho, and J. M. Cioffi, "Weighted sum-rate maximization using weighted MMSE for MIMO-BC beamforming design," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 4792–4799, Dec. 2008.
- [6] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," Mar. 2018.