Guest Editors
IEEE Journal on Selected Areas in Communications

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Re: Major revision of manuscript JSAC-SI-ESIT-1570874111

Dear Editors and Reviewers,

Thank you for giving us the opportunity to submit a revised version of "RIScatter: Unifying Backscatter Communication and Reconfigurable Intelligent Surface". We would like to express our sincere gratitude to you for the valuable comments and suggestions, which helped us improve the quality of the manuscript significantly. Below, we prepare a point-to-point response and describe all the changes made to the manuscript. We hope that the revisions and clarifications make the manuscript meet the standards of JSAC publications.

Yours sincerely,

Yang Zhao and Bruno Clerckx

Reviewer 1

This paper introduces the concept of RIScatter, a unified architecture that combines Backscatter Communication (BackCom) and Reconfigurable Intelligent Surface (RIS) technologies, where the scatter nodes can modulate their own information and in the same time manipulate the wireless channel based on the information source, channel state information (CSI), and quality of service (QoS). The achievable primary-total-backscatter rate region in a single-user multi-node RIScatter system is investigated by designing the input distribution at scatter nodes, the active beamforming at the Access Point (AP), and the energy decision regions at the user. Numerical results show that RIScatter nodes can effectively utilize the scattered paths, enabling seamless transitions between backscatter modulation and passive beamforming techniques.

Although the paper presents a novel idea and tackles an interesting problem, it requires great effort to improve the presentation, the language, and the mathematical derivations. Detailed comments are given as follows:

1.1. The abstract and the number of keywords exceed the specified authorized limit. Please check IEEE JSAC guidelines.

> We apologize for the mistake. The abstract and the number of keywords have been revised to meet the specifications.

1.2. The manuscript contains multiple grammatical errors and unclear sentences that require correction. Please revise the manuscript for improved clarity. For instance, in the first paragraph of Section II, Subsection B, the sentence ”It is assumed that the signal reflected by two or more times is negligible” is not clear.

> We have thoroughly revised the manuscript to address the grammatical errors and improve sentence clarity. The example sentence has been revised to “It is assumed that the signal going through two or more RIScatter nodes is too weak to be received by the user.”

1.3. Please consider defining all acronyms (e.g., MRC) and all the notations in Section I (e.g., the mutual information, probabilities, etc.,).

> Thank you for the suggestion and we understand it can be very difficult for readers to keep track of all acronyms and notations throughout the paper. Due to the space limitation, we have made the decision not to include the list, but have taken the necessary steps to ensure that all acronyms and notations are clearly defined before their first usage. We appreciate your understanding in this matter.

1.4. Please ensure that all variables and symbols are properly defined and explained before their usage (e.g., P, σ_1^2,...,σ_L^2, etc.). Also, $\mathbf{h}_E^H$ in eq. (46) is used without prior definition.

> The issue has been addressed in the revised manuscript.

1.5. Please ensure consistency with the notation introduced in Section I throughout the manuscript. For instance, in Section II, Subsection B, after eq. (4b), the dimensions for $\mathbb{I}$ are not defined.

We have revised the manuscript to ensure consistency with the notation introduced in Section I. In the provided example, $\alpha_k \in \mathbb{I}$ refers to $\alpha_k \in \mathbb{I}^1$ and the 1 was omitted for brevity.

1.6. To ensure consistency and clarity, please maintain uniformity in the usage of mathematical symbols and technical terms throughout the paper. For example, in eq. (3), the amplitude scattering ratio of the node is defined as β_m, while in eq. (4a), it is referred to as α_k. Additionally, there is a discrepancy in the usage of the term 'node' throughout the manuscript and 'tag' in the appendix. Please use a consistent term to refer to the same entity throughout the entire paper to avoid confusion and improve clarity.

Thank you for bringing this to our attention. We were trying to be rigorous and consistent with the notation used in the literature, but didn't realize the confusion it may cause to the readers. In BackCom literatures, α_k is a constant that measures the *average* reflection efficiency (irrelevant to the state) for node k. In RIS literatures, β_m measures the scattering ratio of one element at state m. We have unified the notation and terminology in the revised manuscript.

1.7. The expression in eq. (1) represents the conjugate of the reflection coefficient, not the reflection coefficient itself.

After a careful investigation, we found there are different definitions for the reflection coefficient in the literature:

1. $\mathit{\Gamma}_m = \frac{Z_m - Z^*}{Z_m + Z}$ in overview papers [1, 2];
2. $\mathit{\Gamma}_m = \frac{Z_m - Z^*}{Z_m + Z^*}$ in BackCom paper [3];
3. $\mathit{\Gamma}_m^* = \frac{Z^* - Z_m}{Z + Z_m}$ in RF paper [4],

where Z_m is the load impedance at state m and Z is the antenna impedance. It is guessed that they choose different reference (antenna and space). However, we are not microwave engineering experts and would be grateful to hear your valuable opinion on this issue. The current version sticks to the seeming most popular definition 1.

1.8. It is unclear what is meant by relative QoS. Additionally, there is a lack of clarity regarding the derivation of eqs. (17-19) and how the relative QoS of the primary link is incorporated in those equations. The defined expressions should be clearly explained and justified. Please provide additional details and reasoning.

We apologize for the confusion caused by poor wording. QoS refers to the relative priority of the primary link, and it should be either "QoS" or "relative priority". We have added a footnote on this. Besides, the information theory part (including the derivation of eqs. (17-19)) has been incorporated into Section II.B with proper explanation. We also modified Remark 1 and added Remark 2 to clarify the derivation of achievable rates.

1.9. The link between eq. (9) and eq. (25) lacks clarity and misses intermediate steps. Also, the expression of the function Q provided in eq. (25) appears to be independent of the active beamforming $\boldsymbol{w}$. It is unclear how the derivation of Q with respect to $\boldsymbol{w}$ is performed in this case. Please clarify the relationship between Q and $\boldsymbol{w}$ and provide a clear derivation for better understanding. The same remark about clarity applies to eq. (28) and eq. (33).

$Q\left(N, \frac{t_{l-1}}{\sigma_{m_{\mathcal{K}}}^2}, \frac{t_l}{\sigma_{m_{\mathcal{K}}}^2}\right)$ is the regularized incomplete Gamma function that depends on the variance of accumulated receive energy $\sigma^2_{m_\mathcal{K}}$, which is a function of $\boldsymbol{w}$. We have added a reminder on this, and have added the intermediate steps from (9) to (25) with proper details. The corresponding part has been completely rewritten to improve logic and clarity.

1.10. Is the BCD algorithm convergent for the optimization problem (20)?

The BCD algorithm is convergent for the optimization problem (20), since the input distribution and active beamforming subproblems converge and the thresholding subproblem attains global optimality. This argument has been added prior to the convergence results in Fig. 7.

1.11. Please write the mathematical expression of eq. (40) properly. Moreover, there appears to be a mistake in the sign of the Lagrangian function of the optimization problem stated in Equation (21). If the optimization problem is intended to be a minimization problem, it should be explicitly mentioned to avoid any ambiguity or confusion.

In the revised manuscript, we have simplified many notations and rewritten (40) properly. Problem (21) is a maximization problem and the sign of the Lagrangian function has been corrected.

1.12. The expression of the primary achievable rate in eq. (37) seems to be wrong since the primary message is also included in the cascaded channel and cannot be ignored.

We appreciate your careful reading. The primary message is indeed included in the scattered component. However, since the user decodes both links independently, the backscatter uncertainty cannot be eliminated when decoding the primary link. That is to say, the scattered component should be treated as interference with average power $\mathbb{E}\{\sum_k \alpha_k \boldsymbol{h}^{\mathsf{H}}_{\mathrm{C},k} x_k \boldsymbol{w} s[n]\} = \sum_k |\alpha_k \boldsymbol{h}^{\mathsf{H}}_{\mathrm{C},k} \boldsymbol{w}|^2$. The same reasoning was considered in [5]. We have revised the corresponding footnote to justify this.

1.13. In Figure 7, it is unclear why the KKT, PGD, and BCD algorithms are plotted separately since the BCD algorithm encompasses both the KKT and PGD algorithms. If there is a specific reason for displaying them separately, please provide a justification to enhance the understanding of the reader. Additionally, please provide the unit for the weighted sum rate axis.

In company with BCD, we also plotted the convergence results of KKT and PGD algorithms to show how much performance gain is provided by solving each subproblem (over the initialization method specified in the previous paragraph). The unit of the y axis is bit/s/Hz and we have added this in the revised manuscript.

1.14. Is the decoding of the backscatter information based on an energy detector reliable in this case, especially with high-order modulation or large number of scatter nodes? In other words, can the user in practice decode the backscatter information especially in the presence of the noise and signal variations due to the fading or the interference, etc.?

The energy detector is a simple and practical method for backscatter information decoding, and its reliability is improved by the adaptive input distribution and thresholding design. With high-order modulation or large number of scatter nodes, its performance can be further enhanced by increasing the spreading factor N or using stronger error correction codes with lower code-rate. In practice, the user can decode backscatter nodes ranging from few to hundreds of meters in the presence of noise and interference, and the backscatter throughput can reach few Kbps to tens of Mbps. We have added a footnote on this, and the reviewer is referred to Table 2 in [6] for more details.

1.15. In Section III, the aim is to characterize the primary-total-backscatter rate region where the user retrieves both the backscatter information and the primary message. Why is the weighted sum mutual information maximized with respect to only the input distribution of the backscatter information and not jointly with respect to the input distribution of the primary message 's' as well? In other words, is the choice of $s \sim \mathcal{CN}(0,1)$ optimal?

This is indeed a very good question. The choice of $s \sim \mathcal{CN}(0,1)$ is generally not optimal for weighted sum mutual information. To the best of our knowledge, the optimal primary distribution in this case remains an open issue, but some insights were given in those papers:

- If there is no direct link and the node is with *average* power constraint, then the optimal distribution for *weighted sum mutual information* requires a time-sharing between those modes [7]:
  - s follows zero-mean Gaussian distribution and x is a constant;
  - x follows zero-mean Gaussian distribution and s is a constant;
  - s and x equal 0.
- If there is no direct link and the node is with *peak* power constraint, then the optimal distribution for *sum mutual information* is not unique, for example [8] (came out after our submission):
  - s follows zero-mean Gaussian distribution and x is a constant;
  - s follows Rayleigh distribution and x follows uniform distribution on $[0,2\pi]$;

Despite not optimal, the assumption of Gaussian primary source and finite-support backscatter source are relatively practical and widely adopted in relevant literatures. We have added Remark 3 on this, but intentionally avoided the discussion of optimal distribution, since it is beyond the scope of this paper and may confuse the readers. We appreciate your understanding in this matter.

1.16. In Section IV, Subsection B, it is stated that the RIS always ensures constructive superposition of direct and scattered components which is not true. The RIS can also add those components destructively which could be used for example to enhance the physical layer security of a system in the presence of an eavesdropper.

We apologize for the oversight. It has been modified to "Here, RIS ensures constructive superposition of direct and scattered components."

Reviewer 2

The paper studies the achievable rates for both primary transmission and backscatter information, assuming a Gaussian distribution for primary transmission and K tags (with M loads each) and a single source-destination primary link; the authors assume full CSI knowledge and formulate a mutual information maximization problem, with probability distribution of loads per tag as a function to be optimized (in conjunction with beamforming weights for the multi-antenna transmitter and energy thresholds for the energy-based detector for the backscatter information). The problem is non-convex and challenging, and the authors revert to a series of approximations to relax it and offer a solution. The methodology is interesting in two ways: a) the authors do not employ SIC, but instead focus first on the tags' (weak) information signal, since its knowledge renders the detection of the primary information as a simple coherent detection problem, and b) borrow techniques from the discrete memoryless MAC/discrete memoryless thresholding channel literature, in order to calculate the average rate of the backscattered information.

The authors balance rate of primary transmission with rate of backscattered tags in a unified, user-controlled way and offer comparison results with prior art in the field (e.g., bistatic backscatter, where no primary link information is present, ambient backscatter, symbiotic (cooperative) ambient backscatter and RIS). Of particular importance is the fact that the authors have modeled both small-scale (through Rice) and large-scale (through distance) fading link parameters, typically omitted in many comm theory papers, even though backscattered links are operating in the presence of the much stronger primary link.

Overall, the methodology and overall presentation is rigorous and deserves further attention. Having said that, the following remarks are offered:

2.1. CSI estimation impact: the notion of full and perfect CSI knowledge is a very strong assumption; the authors do point at footnote 4, page 8 (single column version) to CSI estimation literature. However, CSI estimation for ambient backscatter employs several assumptions and simplifications and it is not perfect or ideal. The authors should perhaps study in terms of simulations the impact of imperfect CSI and necessary degrees of freedom (for channel estimation) on the achieved rates, carefully taking into account the tag(s) small SNR as well as the primary link much stronger SNR.

2.2. Modeling assumptions: the overall model is based on Gaussian codebooks for the primary link and lack of structural mode for backscattering; the latter is assumed absorbed by the channel parameters (Section II.A), while the tags are assumed with a demodulator/receiver of the primary information; it is also assumed that both full CSI and reflection efficiency parameters $\{\alpha_k\}, k \in \{1,2,...,K\}$ are known for all tags, while each tag is equipped with a receiver/demodulator (for the primary information). The reviewer believes that the structural mode cannot be absorbed by the channel parameters, since it offers a DC term, while there is no practical way to estimate separately the cascaded channel from the reflection efficiency; moreover, receivers in tags either increase the complexity or reduce the tag's sensitivity, especially when envelope detectors are used (as in Fig. 3). Moreover, the assumption for perfect symbol-level synchronization between tags and source, or the integer ratio between tags and source symbol duration is also very strong. Some discussion on the above is necessary, while some thoughts on non-Gaussian codebooks and how the methodology could be extended is perhaps important.

2.3. Independent distributions across tags: (10) assumes independence among distributions of tag loads across tags; IV.D.1 talks about joint nodes encoding; pls clarify. In addition, some more discussion is needed at IV.C and Fig. 9; for $\rho = 1$, i.e., primary transmission maximum prioritization, Fig. 9 shows that only one load (out of 4) should be used. The reviewer was puzzled by this. Perhaps, values of the loads used in the simulations and respective reflection coefficients should be explicitly offered, in conjunction with more discussion regarding the wireless channel impact. When the channel changes, one would expect the distribution of the tags' loads to be sensitive on channel statistics.

2.4. All simulation results and respective optimization solutions are offered with relatively small number of K and M; some discussion on ways to extend the methodology for larger networks and loads should be helpful.

2.5. Finally, the list of references is perhaps incomplete; many references do not include publication venues, while prior art backscatter radio, including coherent as well as non-coherent detection, structural mode, receiverless tags etc., both in terms of theory as well as experimentation, are not given. For example see work that bridges backscatter radio and RIS, including theory and experimental results for any number of tags and loads in the following: ”Intelligently Wireless Batteryless RF-Powered Reconfigurable Surface: Theory, Implementation & Limitations”, IEEE Transactions on Wireless Communications (TWC), available as early access in ieeexplore, Nov. 2022, conference version available at IEEE Globecom 2021.

Reviewer 3

This paper introduces the concept of RIScatter, a unified architecture that combines Backscatter Communication (BackCom) and Reconfigurable Intelligent Surface (RIS) technologies, where the scatter nodes can modulate their own information and in the same time manipulate the wireless channel based on the information source, channel state information (CSI), and quality of service (QoS). The achievable primary-total-backscatter rate region in a single-user multi-node RIScatter system is investigated by designing the input distribution at scatter nodes, the active beamforming at the Access Point (AP), and the energy decision regions at the user. Numerical results show that RIScatter nodes can effectively utilize the scattered paths, enabling seamless transitions between backscatter modulation and passive beamforming techniques.

The manuscript presents a novel concept, i.e., RIScatter, and studies an interesting problem. However, there are several problems with the manuscript, namely:

3.1. Literature review: the literature review on rate characterization for backscatter communications is deficient. Some recent and closely related works are missing:

- J. Qian, Y. Zhu, C. He, F. Gao and S. Jin, ”Achievable Rate and Capacity Analysis for Ambient Backscatter Communications,” in IEEE Transactions on Communications, vol. 67, no. 9, pp. 6299-6310, Sept. 2019.
- Z. Dai, R. Li, J. Xu, Y. Zeng and S. Jin, ”Rate-Region Characterization and Channel Estimation for Cell-Free Symbiotic Radio Communications,” in IEEE Transactions on Communications, vol. 71, no. 2, pp. 674-687, Feb. 2023.
- H. E. Hassani, A. Savard, E. V. Belmega and R. C. de Lamare, ”Multi-user downlink NOMA systems aided by ambient backscattering: achievable rate regions and energy-efficiency maximization,” in IEEE Transactions on Green Communications and Networking, 2023.

3.2. Technical aspects: RIScatter is able to balance rate of primary transmission with rate of backscattered tags in a unified, user-controlled way, which brings technical advantages over existing approaches. This reviewer wonders why the authors only considered perfect CSI and did not assessed the impact of imperfect CSI on information rates (not the region!) given the limitations of tags and devices. Moreover, this reviewer is also sceptical about the assumption of perfect synchronization between the tags and the source. Can you explain why this is reasonable?

3.3. Simulation results: the authors opted for showing the results in terms of rate regions for several existing schemes and the proposed RISscatter. This is not properly motivated. Could explain why not include results such as information rates versus SNR or BER versus SNR?

3.4. Overall, the technical approach of the paper is credible, there is a clear technical contribution although there are aspects related to the use of English and presentation that must be revised.

References

[1] N. V. Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 20, pp. 2889–2922, 2018.

[2] Y. C. Liang, Q. Zhang, J. Wang, R. Long, H. Zhou, and G. Yang, "Backscatter communication assisted by reconfigurable intelligent surfaces," *Proceedings of the IEEE*, 2022.

[3] C. Boyer and S. Roy, "Backscatter communication and RFID: Coding, energy, and MIMO analysis," *IEEE Transactions on Communications*, vol. 62, pp. 770–785, Mar 2014.

[4] R. Hansen, "Relationships between antennas as scatterers and as radiators," *Proceedings of the IEEE*, vol. 77, pp. 659–662, May 1989.

[5] R. Long, Y.-C. Liang, H. Guo, G. Yang, and R. Zhang, "Symbiotic radio: A new communication paradigm for passive internet of things," *IEEE Internet of Things Journal*, vol. 7, pp. 1350–1363, Feb 2020.

[6] W. Wu, X. Wang, A. Hawbani, L. Yuan, and W. Gong, "A survey on ambient backscatter communications: Principles, systems, applications, and challenges," 10 2022.

[7] S. R. B. Pillai, "On the capacity of multiplicative multiple access channels with awgn." IEEE, 10 2011, pp. 452–456.

[8] Q. Zhang, H. Zhou, Y.-C. Liang, S. Sun, W. Zhang, and H. V. Poor, "On the capacity region of reconfigurable intelligent surface assisted symbiotic radios," *arXiv:2304.09400*, 4 2023.