Prof. Liang Xiao
Editor
IEEE Transactions on Communications

Re: Decision on TCOM-TPS-20-1501 (Intelligent Reflecting Surface-Aided SWIPT: Joint Waveform, Active and Passive Beamforming Design)

Dear Prof. Liang Xiao and Reviewers,

We would like to express our appreciation for the time and effort dedicated to the reviewing of our paper. The manuscript has been revised carefully based on your valuable comments and suggestions. In particular, we attempted to clarify the motivations and contributions of this work. To answer the questions and concerns, we include a point-to-point response below, which also describes all modifications made to the manuscript. We hope that the revisions and explanations are to the editor's and reviewers' satisfaction.

Best Regards,

Yang Zhao, Bruno Clerckx and
Zhenyuan Feng

Reviewer 1

Comment 1.1 — *This paper assumed that the perfect channel state information (CSI) of the whole system is available at the base station. However, since the IRS is in general not equipped with a radio frequency chain, the accurate CSI of the reflecting links established by the IRS is very challenging to obtain. The reviewer wonders if the proposed algorithm can also be applied to a case where the imperfect CSI of the network is available at the base station.*

Response: Thank you for pointing out the issue of CSI acquisition in presence of IRS. Practical protocols based on element-wise on/off switching [24], joint training sequence and reflection pattern design [R1] and compressed sensing [R2] have been developed to estimate the cascaded AP-IRS-user link for specific applications, yet channel estimation and codebook design for multi-carrier SWIPT remain unresolved and are beyond our current scope. The proposed algorithm is based on the assumption of cascaded CSIT (not individual AP-IRS and IRS-user ones) and can be readily extended to the imperfect CSIT case, where the joint waveform and beamforming design is based on a quantized CSI feedback.

Comment 1.2 — *This paper considered a relatively simple system model where there is only one user in the system. However, in practice, there can be many users co-existing in the SWIPT systems and there may also be two different and independent quality of service requirements: energy harvesting requirement and information decoding requirement. It could be better if the authors can clarify if the proposed algorithm can be employed in a more general case where the base station and the IRS cooperate to serve multiple users in the same time slot.*

Response: We appreciate your suggestion on IRS-aided multi-user SWIPT and believe it would be very promising. To extend the current work, we would first need to tackle the waveform and active beamforming design for a multi-user SWIPT system. For a multi-carrier network, each subcarrier only serves one information user but may serve all power user simultaneously (as whole received signal can be used for energy harvesting), and it involves an additional resource allocation problem that cannot be solved by the proposed GP algorithm.

To see the reason, recall that in the single-user scenario, the optimal information beamformer and power beamformer coincide at MRT [see TODO] with corresponding waveform as given by (25), which decouples the design in the spatial domain (beamformer) and frequency domain (power allocation $s^2_{\mathrm{I/P},n}$) thus satisfy $\boldsymbol{h}_n^H \boldsymbol{w}_{\mathrm{I/P},n} = \|\boldsymbol{h}_n\| s_{\mathrm{I/P},n}$. Apparently, picking $s_{\mathrm{I/P},n}$ as nonnegative value would maximize (27) and make (28) a real-value optimization problem, thus enable GP tools.

However, this is not generally the case in a multi-user scenario. For any optimal information and power waveform $\boldsymbol{w}^\star_{\mathrm{I},n}, \boldsymbol{w}^\star_{\mathrm{P},n}$ on subband n, they generally cannot be decoupled as (25) because users have different channel response, and the optimization should be performed over complex field. Some attempts were made for WPT in [32], but the extension to SWIPT is not straightforward as the power splitting ratio at all users require a joint update as well.

Extending our problem to the multi-user case would require first to solve relevant problems in the non-IRS case above. It is not the intention of this paper and may be considered in our further research.

Comment 1.3 — *It is well known that after employing semidefinite programming for handling the phase shift matrix at the IRS, it is very unlikely to obtain a rank-one phase shift matrix without any further modification. The reviewer notices that the authors proposed the Gaussian randomization method to ensure a rank-one solution. Also, the convergence of the proposed overall algorithm also relies on the unit-rank solution. Therefore, to make this paper more comprehensive and convincing, it is suggested to provide more results (such as figures, tables, and data analysis) in the simulation part to show that the rank-one solution can always be obtained even without applying the Gaussian randomization. As this is a very important and* *interesting conclusion to the colleagues working in the same area, it could be better if the authors can further discuss, interpret, and clarify this in a remark.*

Response: The rank-1 property of $\mathbf{\Phi}$ to the relaxed problem (24) is suggested by simulation under different configurations. As indicated by the comment, the strict convergence of the AO algorithm relies on this conclusion (as $\boldsymbol{\phi}$ can be retrieved without performance loss), but it is hard to prove in theory due to the nonlinear objection function (24a) and the sum rate constraint (24b). Instead, we considered 300 individual channel realizations for different M, N and L. The extensive numerical results show that the proposed SCA Algorithm 1 returned unit-rank solution $\mathbf{\Phi}$ for all channel realizations, at all rate constraints, and during all iterations. Therefore, the convergence and performance are guaranteed for all tested scenario, and we believe that Algorithm 1 is feasible to address the passive beamforming issue in IRS-aided SWIPT systems.

Comment 1.4 — *The figures in the current version are relatively small, it is suggested to provide larger figures to help the readers better understand the results.*

Response: We apologize for the inconvenience. The figures would be amplified in future versions.

Comment 1.5 — *In the current version, the authors claimed that by applying semidefinite relaxation and omitting the rank-one constraint, the performance loss is negligible. The reviewer wonders if this is because of the relatively simple system model, as there is only one single user who has both power and information requirements. It could be better if the authors can further discuss this issue for a more general multiple user scenario.*

Response: We agree with the reviewer that the performance loss by relaxing the rank-one constraint deserves more attention. In [R3], we investigated the joint waveform and beamforming design for multi-user WPT (with no information waveform and rate requirements) and formulated the WSE problem as complex constant-modulus QP to enable SDR with at least $\gamma = \pi/4$ approximation to the original objective function. However, due to the reason mentioned in Response 1.2, we did not extend the work to multi-user SWIPT in this paper.

In contrast, the performance guarantee of rank relaxation in our single-user problem is only demonstrated by simulation. Due to the coupling of the information and power waveform, the objective function (23) involves

$$(t_{\mathrm{I},0}^{(i)} - t_{\mathrm{P},0}^{(i)})^2 = \left(\mathrm{Tr}(\boldsymbol{C}_{\mathrm{I},0}\mathbf{\Phi}^{(i)}) - \mathrm{Tr}(\boldsymbol{C}_{\mathrm{P},0}\mathbf{\Phi}^{(i)})\right)^2 = \mathrm{Tr}\left((\boldsymbol{C}_{\mathrm{I},0} - \boldsymbol{C}_{\mathrm{P},0})\mathbf{\Phi}^{(i)}\right)^2 \tag{1}$$

which is not a semidefinite objective (due to the square). Also, the sum-rate constraint (24b) is not a semidefinite constraint. Therefore, existing SDR bounds cannot be applied directly to problem (24).

Reviewer 2

Comment 2.1 — *New RIS models are now being adopted as in [23] where it has been shown that the reflected signals depend on the direction of the arriving signal and this needs to be included in the analysis for realistic quantification.*

Response: Thank you for sharing this acknowledged paper, which investigated the impact of non-zero effective resistance on the reflection pattern and pointed out that the amplitude of the reflection coefficient depends on the phase shift forced on the incoming signal when power dissipation is considered at the IRS. It also proposed an analytical IRS model together with an AO algorithm to maximize the achievable rate by passive beamforming. Simulation results emphasized the importance of modeling such a relationship in practical IRS design. We actually thought about integrating these new models in our system design, but finally decided to use the most common and simplest IRS model in the current stage to reduce the design complexity and provide a primary benchmark for IRS-aided SWIPT.

Comment 2.2 — *Why is MRT considered as precoder by (25) rather than optimizing it? Is it globally optimal too?*

Response: The waveform design involves the optimization in the spatial domain (beamformer) and frequency domain (power allocation $s^2_{\mathrm{I/P},n}$). For the single-user scenario, MRT is global optimal for both information and power transmission. This is because the sum rate (7) and DC components (10) – (13) only involve waveform in terms of $\boldsymbol{h}_n^H \boldsymbol{w}_{\mathrm{I/P},n}$ thus can be simultaneously maximized by MRT precoder. However, this is not the case for multi-user SWIPT (since users have different channels) where the beamformer and power allocation require a joint optimization.

Comment 2.3 — *Some strong assumptions like perfect CSI availability limit the practical utility of the proposed analytical results.*

Response: The reviewer is referred to Response 1.1. Indeed, the assumption of perfect CSIT is very ideal and the existing protocols may not provide a good enough estimation in practice. We follow the convention of most existing papers on this topic and expect some breakthroughs in future research.

Comment 2.4 — *All the assumptions and relaxations adopted used in the derivation of results as in (23) need to be explicitly mentioned along with appropriate justification for the same.*

Response: We appreciate your suggestion. The original objective function (19) is differentiable and non-concave in $\mathbb{C}^{4N-2}$, and we approximate (linearize) the second-order terms by their first-order local Taylor expansions (20) – (22) to formulate a series of convex problems. These problems are SCA to the original passive beamforming problem (maximize (19) s.t. (24b) – (24e)), and the objective function (23) is obtained by plugging (20) – (22) into (19), which is an affine and satisfies $\tilde{z}(\boldsymbol{\Phi}^{(i)}, \boldsymbol{\Phi}^{(i)}) = z(\boldsymbol{\Phi}^{(i)}) \geq \tilde{z}(\boldsymbol{\Phi}^{(i)}, \boldsymbol{\Phi}^{(i-1)})$. We start from any feasible point and approach the original solution by SCA.

Comment 2.5 — *Some transformations have been made while solving the original problem, but it has not been explicitly mentioned whether it is equivalent to transformation or not.*

Response: Thank you for pointing this out. All transformations are equivalent to their original form and we would make this clear in the revised manuscript.

Comment 2.6 — *Are the proposed solutions locally optimal or globally optimal? It is not clear whether the convergence of proposed solution methodologies is local or global? Also, how fast is it?*

Response: Algorithm 1 – 3 only provide local optimal solutions with local convergence proof, and the performance indeed depends on the initialization. For different sum rate constraints, we use water-filling with MRT to initialize the modulated waveform while use scaled matched filter to initialize the unmodulated waveform (corresponding to a transmit power of $2P$, regulated afterwards). We also initialize the IRS phase shift by uniform distribution over $[0, 2\pi)$. Nevertheless, as the solutions are locally optimal, some result points on the R-E boundary may be strictly worse (with lower rate and energy) than another, especially for a large M and L. To address this, we draw the R-E boundary from high-rate low-energy (lower right) points to low-rate high-energy (upper left) points. If the issue above happens, we discard the dominated result and reinitialize the waveform and IRS phase shift by the solution at the previous point.

For a tolerance of $\epsilon = 10^{-8}$, the SDR-based Algorithm 1 usually converge within 3 iterations while the GP-based Algorithm 2 tends to converge within 8 iterations. The AO-based Algorithm 3 typically converge within 3 iterations.

Comment 2.7 — *The time complexity of the proposed algorithms, especially involving branch and bound methods, seems to be high especially applications assuming perfectly CSI availability as the coherence times are practically pretty low. So, the authors would like to justify it so that the proposed solution can be obtained over relatively short coherence intervals.*

Response: We agree with the reviewer that the proposed algorithm (especially Algorithm 2) could be too time-consuming for practical applications with relatively short coherence time. The proposed algorithms ensure best performance by iteratively solving intricate optimization problems and may not be implemented in practice, while suboptimal design (e.g. scaled matched filter) is expected to achieve a good performance.

Comment 2.8 — *How practical is it to consider lossless reflection from the RIS? Specifically, by considering the magnitude to be 1, the reflection losses at the RIS have been ignored.*

Response: Green's decomposition indicates that the backscattered/reflected signal of an antenna can be decomposed into the *structural mode* component and the *antenna mode* component. The former is fixed for a given antenna and can be regarded as part of the environment multipath, while the latter is adjustable and depends on the mismatch of the antenna and load impedances. The reflection coefficient of the l-th IRS element is thus defined as

$$\phi_l = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{2}$$

where Z_0 is the characteristic impedance and $Z_l = R_l + jX_l$ is the impedance of the l-th IRS element. It implies that $|\phi_l| \leq 1$ for $R_l \geq 0$, and we assume Z_l is pure reactive such that

$$\phi_l = \frac{jX_l - Z_0}{jX_l + Z_0} = e^{j\theta_l} \tag{3}$$

which corresponds to the lossless reflection model adopted in the paper. Nevertheless, due to the non-zero power consumption at the IRS in practice, R_l would be positive and $|\phi_l|$ indeed depends on the the reflection coefficient not only has a magnitude smaller than 1 but also depends on the phase shift. [23] found that $|\phi_l|$ experiences a trough as low as 0.2 for $R_l = 2.5\,\Omega$ at zero phase shift, which suggests that the position and direction of the IRS should be carefully designed.

Comment 2.9 — *Minor comment: The size of all the numerical results figures is too small.*

Response: We apologize for the inconvenience. The figures would be amplified in future versions.

Reviewer 3

Comment 3.1 — *First of all, motivations of studying the IRS on SWIPT is very unclear to me. Please clarify.*

Response: We appreciate your suggestion and have modified the manuscript to emphasize this point. A major challenge for SWIPT is that the information decoder and energy harvester have different sensitivity – although conventional radios as Wi-Fi and Bluetooth can support a signal strength of -90 to -100 dBm, most existing harvesters only capture signals at -20 to -30 dBm. Since the transmit power is strictly subject to regulations, it is crucial to increase the energy efficiency to boost the signal strength and extend the system coverage. Therefore, we believe the effective channel enhancement and the low power consumption of IRS is a perfect match for SWIPT.

Comment 3.2 — *Also, the contributions of this work are rather unclear, and thus, those should be better mentioned.*

Response: Thank you for the opinion and the manuscript has been revised accordingly. This paper proposed an IRS-aided SWIPT network and considered a joint waveform and beamforming design over spatial and frequency domains under energy harvester nonlinearity. To the best of our knowledge, relevant existing papers assumed linear harvester model where the RF-to-DC conversion efficiency is a constant regardless of its input. However, the harvester consists of an antenna to intercept RF signal and a diode rectifier (nonlinear device) to produce DC power, and the RF-to-DC efficiency indeed depends on the power and shape of the input waveform. By exploiting the joint impact of passive beamforming and harvester nonlinearity, we found that:

- the IRS should be developed next to the transmitter or the receiver due to double fading;
- the optimal transceiving mode depends on the SNR and the number of subbands;
- the power scaling laws of active and passive beamforming are in the order of M^2 and L^4, respectively;
- the IRS reflection coefficient cannot be designed per subband and there exists a tradeoff in subchannel enhancement;
- the optimal passive beamforming can be approximated in closed form for narrowband transmission but varies at different R-E points for broadband transmission.

Comment 3.3 — *Please explain the derived results more intuitively for better understanding.*

Response: TODO

Comment 3.4 — *Authors assumed the unrealistic situation: the channels are assumed to be perfectly known. However, in practice, the channel should be estimated, e.g., as studied in [R1], [R4]. It would be much better to discuss the channel estimation issue by citing the above references.*

Response: The reviewer is referred to Response 1.1. We have incorporated the channel estimation issue into the revised manuscript by citing those references.

Comment 3.5 — *More simulation results should be added to better and aggregately validate the effectiveness of the proposed method.*

Response: TODO

Comment 3.6 — *The sizes of figures are too small.*

Response: We apologize for the inconvenience. The figures would be amplified in future versions.

References

[R1] J.-M. Kang, "Intelligent Reflecting Surface: Joint Optimal Training Sequence and Refection Pattern," *IEEE Communications Letters*, vol. 24, no. 8, pp. 1784–1788, aug 2020.

[R2] P. Wang, J. Fang, H. Duan, and H. Li, "Compressed Channel Estimation for Intelligent Reflecting Surface-Assisted Millimeter Wave Systems," *IEEE Signal Processing Letters*, vol. 27, pp. 905–909, 2020.

[R3] Z. Feng, B. Clerckx, and Y. Zhao, "Waveform and Beamforming Design for Intelligent Reflecting Surface Aided Wireless Power Transfer: Single-User and Multi-User Solutions," *arXiv preprint arXiv:2101.02674*, 2021.

[R4] C. You, B. Zheng, and R. Zhang, "Intelligent Reflecting Surface with Discrete Phase Shifts: Channel Estimation and Passive Beamforming," in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*. IEEE, jun 2020, pp. 1–6.