Thesis Title: Smart Reflection and Passive Communication: Synergizing Backscatter Communication and 6G Technologies for Future Wireless Networks

Submitted by: Sahar Idrees

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Log of Changes in the Revised Thesis

Summary of Major Changes in the Revised Thesis

I am thankful to all the reviewers for their careful reading of the manuscript and thoughtful suggestions for improvement. I have addressed all the comments. As needed, I have written point-by-point response to the comments and mentioned the corresponding action on the thesis. Throughout this document, I use the following conventions:

- ◇ *Blue text in Italics* = The reviewers' comments.
- ◇ Red and underlined text = Changes in the thesis.
- ◇ Black text = The author's responses.

Reviewer 1: Log of Changes

General Comments:

In this thesis, the candidate investigates the potential of Backscatter Communication (BackComm) in the context of Internet of Things (IoT) systems. In particular, it tackles some inherent drawbacks of BackComm, such as improving its bit error rate (BER) performance, and extending its communication range, by integrating it with emerging technologies such as intelligent reflecting surfaces (IRS), wireless power transfer and deep learning techniques.

The main contributions of the thesis are divided into 3 chapters, Chapters 2-4.

In Chapter 2, design of ambient backscatter training for wireless power transfer (WPT) is considered where an energy transmitter equipped with a large phased antenna array performs retrodirective WPT towards an energy receiver (ER), which backscatters a received ambient signal. The problem of recovering the weak backscattered signal in the presence of strong direct ambient signal interference is tackled by designing a pseudo-noise like training signal. The average harvested energy at the ER and the optimal pattern of the training sequence and its properties under perfect and imperfect synchronization are investigated. It is shown that under small synchronization offset, the proposed design is robust in terms of the amount of average harvested energy at the ER. The work from this chapter is published in the IEEE Transactions on Wireless Communication and IEEE ICC conference 2020.

In Chapter 3, the BER minimization problem is studied for an IRS assisted ambient backscatter system. To distinguish the maximize the difference between the backscattered signal energy between bit "1" and bit "0", an optimization problem is formulated as a joint optimization over the IRS phase shifts and the receive beamforming. This joint optimization problem is nonconvex, and is solved suboptimally by a minorization-maximization algorithm, by alternately optimizing iteratively and separately over the IRS phase shifts and the receive beamforming vectors. Even though this scheme is suboptimal, it effectively improves the BER for realistic channel parameters. The results of this chapter are published in an IEEE Access paper.

In Chapter 4, the focus is on extending the range of monostatic BackCom. This is achieved by using an IRS as well as a multi-antenna reader. The joint design of the phase shifts at the IRS and the beamforming pattern at the reader becomes a non-convex problem due to the coupling between these two variables. For benchmarking purposes, the signal-to-noise ratio maximization problem is studied with a conventional semi-definite programming approach, which still turns out to be computationally expensive. Therefore a deep residual convolutional neural network based approach is proposed to solve this problem, which is computationally less complex and outperforms the traditional approach even for moderately sized IRS.

Overall, the quality of thesis is good in terms of the considered problems, and the techniques used to solve them, although the proposed problems and their solutions follow predictable paths. Nevertheless, the solutions provided in this thesis will be useful for future design strategies for Backscatter communication systems.

Response: Thank you to the examiner for summarising the thesis. These comments do not require any changes in the thesis itself.

Comment 1: *In Chapter 2, in addition to studying the average harvested energy, one could look at studying the variance (ideally the distribution of the harvested energy, which may be hard), even if numerically.*

- ◇ **Response:** I have chosen the average harvested power at the energy receiver as the metric to evaluate the designed system. Average/mean values provide a straightforward measure of central tendency that is easy to understand and interpret. Furthermore, computing and analyzing the mean value of a random variable often requires less computational effort and statistical analysis compared to considering its entire distribution, especially in complex systems like ours where we have already considered non-linear energy harvester and Nakagami fading channels, leading to an inability to obtain a closed form expression for the average harvested power itself. Moreover, in particular for energy harvesting applications, studying the average harvested power is the accepted standard in literature for making decisions or drawing conclusions.
  Despite the above mentioned factors, I am aware of the fact that focusing solely on the mean value may overlook important aspects of the distribution, such as variability or tails of the distribution. However, these are relevant for particular use cases where variability is crucial or where extreme values have significant consequences (e.g., an energy receiver in outage for a critical application). I value the reviewer's suggestion and will consider it in future work for such particular use cases.
- ◇ **Action on Thesis:** I have added the followings sentence on page 54, at the end of Section 2.7:
  "Another interesting direction for future work is to study the distribution of the harvested energy, which may be relevant for particular use cases."

Comment 2: *In Chapter 3, the constraints (3.16b) seem redundant in their current form, since any complex number on the unit circle has unity magnitude. I presume that, as presented in [92], the phase shifts should be between 0 and 2π.*

- ◇ **Response/Action on Thesis:** I accept the reviewer's suggestion and have modified constraint (3.16b) as follows:
  $\theta_n \in [0, 2\pi] \ \forall n \in \{1, 2, ..., N\}$

Comment 3: *In Chapter 4 (page 79), while claiming the non-convexity of problem P1, the statement "...as the objective function and the constraints are highly non-convex" seems to be incorrect. While the objective function is non-convex, the constraint 4.6c is certainly convex. Such technical imprecision needs to be checked and corrected throughout the thesis.*

- ◇ **Response/Action on Thesis:** I accept the reviewer's suggestion and have made corrections as advised, i.e., on page 79, I have corrected the mentioned sentence to:
  "The objective function is highly non-convex."

Comment 4: *In several places, channel reciprocity is used as an assumption. Although it has been used in the literature before, it would be good to add a comment regarding what alternatives can be used if channel reciprocity does not hold.*

- ◇ **Response/Action on Thesis:** I accept the reviewer's suggestion and have added the following footnote on page 29 in the thesis:

  "An alternative to the channel reciprocity assumption is to utilize some sort of feedback mechanism from the energy receiver, once it receives training sequences from the energy transmitter [42, 43] ".

Comment 5: *There are some typos etc., for example (i) page 32: in the last line, the formula for $r_b(t)$ is missing the variable "g", (ii) page 55, third line in the first paragraph: "..when it arrives at the ,..", the sentence is incomplete, (iii) on some occasions, a chapter is referred to as a "paper". In revising the thesis, a thorough proofreading is recommended.*

- ◇ **Response/Action on Thesis:** I have duly corrected all the typos.

Reviewer 2: Log of Changes

General Comments:

Backscatter Communication (BackCom) has been envisioned as a key enabler for ubiquitous connectivity in the Internet of Things (IoT), by passively modulating and reusing existing radio-frequency signals. To become a pivotal technology within the IoT framework, BackCom faces various challenges including limited coverage, inflexibility in deployment, low data rates etc.

The primary focus of this thesis is on BackCom, studying its key challenges, and enhancing its capabilities. It addresses these issues by exploring system configurations to extend range and enhance BER. Additionally, it explores synergies with emerging technologies like intelligent reflecting surfaces, wireless power transfer, and machine learning to future proof BackCom.

To this end, the candidate made several contributions as specified in later chapter such as Chapters 2-4 while providing a theoretical background and relevant literature in Chapter 1.

More specifically,

- ◇ The thesis investigates wireless power transfer (WPT) from an energy transmitter (ET) with a large phased antenna array to an energy receiver (ER) capable of ambient backscatter. Retrodirective WPT eliminates the need for explicit channel estimation at the ET, while ambient backscattering obviates the necessity for active transmission at the ER. The candidate proposes a training sequence design to mitigate direct-link interference from ambient sources by varying the reflection coefficient at the ER. As demonstrated in this thesis, with known ambient symbol duration, the proposed design achieves full cancellation of ambient interference. Analytical modeling, considering Nakagami-M fading channels and non-linear energy harvesting, is conducted to evaluate the average harvested power at the ER. The findings indicate robustness to small timing offset mismatches at the correlator. Additionally, when interference from neighboring sources is minimal, the ER can harvest tens to hundreds of micro-watts of power, offering significant benefits for low-power IoT devices. This solid contribution is shown in Chapter 2.

- ◇ The candidate addresses a critical challenge in ambient BackCom concerning the susceptibility of backscatter signals to strong direct-link interference, which constrains the bit error rate (BER) and subsequently the transmission rate and range of ambient BackCom systems. Meanwhile, intelligent reflecting surfaces (IRS) introduce new capabilities to enhance various systems by manipulating their propagation environments and signals. A a novel approach is introduced to enhance the detection performance of an ambient BackCom system using an IRS positioned nearby. The IRS optimizes the quality of the backscatter signal received by adjusting its phase shifts to balance signal strengths, thereby enhancing energy detection performance at the receiver. The key findings demonstrate that a reasonably sized IRS can significantly enhance the BER performance of ambient backscatter, representing a crucial advancement for low-power IoT systems. These important contributions are reported in Chapter 3.

- ◇ The candidate also tackles the issue of limited range in monostatic BackCom systems by considering such a system assisted by an IRS and controlled seamlessly by data driven deep learning (DL) based approach. A deep residual convolutional neural network (DRCNN) named BackIRSNet is proposed that exploits the unique coupling between the IRS phase shifts and the beamforming at the reader, to jointly optimize these quantities in order to maximize the effective signal to noise ratio (SNR) of the backscatter signal received at the reader. The performance of a trained BackIRSNet is shown to be close to the conventional optimization based approach while requiring much less computational complexity and time, which indicates the utility of this scheme for real-time deployment. The results show that an IRS of moderate size can significantly improve backscatter SNR, resulting in range extension by a factor of 4 for monostatic BackCom, which is an important improvement in the context of BackCom based IoT systems. These contributions are reported in Chapter 4.

Response: Thank you to the examiner for summarising the thesis. These comments do not require any changes in the thesis itself.

Comment 1: *Page 34, explain "i" in equation (2.1).*

- ◇ **Response/Action on Thesis:** I have added the phrase "where i is the index of the ambient symbol" following equation 2.1 on page 34 in the thesis for clarification.

Comment 2: *Page 35, what does "g" stand for in equation (2.6)?*

- ◇ **Response:** In equation (2.6), "g" represents the AS to ER fading channel coefficient, as described in Section 2.1.1 "Channel Assumptions". It appears first in equation (2.3), before finally showing up in (2.6) when the expression for $r_b(t)$ is substituted from (2.3) to into (2.6).
- ◇ **Action on Thesis:** Nevertheless, I have added the following phrase in the explanation on page 35, following equation (2.3): " and g is the AS to ER fading channel coefficient."

Comment 3: *Page 39, what are the meaning and value range of "k" in the "Design Criterion" subsection?*

- ◇ **Response:** As noted in the definition of the *Design Criterion*, k is a positive integer, i.e., $k \in \{1, 2, \cdots\}$.
- ◇ **Action on Thesis:** For better clarification, I have added "$k \in \{1, 2, \cdots\}$" to the already present descriptive statement on page 40 in the thesis.

Comment 4: *Page 44, what is the definition of Ts' in section 2.5.2, and what is the relationship between Ts' and Ts?*

- ◇ **Response/Action on Thesis:** I have removed Section 2.5.2 on page 44 and concisely incorporated it with Section 2.6.3.2. Therein, I have defined T_s' and its significance in the discussion of the simulations. In particular, on page 51, in subsection 2.6.3.2, I have modified the explanation as follows:
  "In this subsection, we consider the scenario in which the system is designed for an ambient symbol duration T_s. However, when the system is actually deployed, the available ambient symbol has a different duration, i.e., T_s'."

Comment 5: *Page 45, explain "v" in equation (2.29)? And what is the unit of it?*

- ◇ **Response:** The symbol "ν" in equation (2.29) is defined in (A.6) in the appendix and it reproduced below. It is used to represent the correlation of the training sequence with the ambient symbol expressed as a sum.

$$\nu = \left| \sum_{i=1}^{N_s} \sum_{n=\frac{N_c}{N_s}(i-1)}^{\frac{N_c}{N_s}i-1} c_n s_i^* \right|^2 = \left| \sum_{i=1}^{N_s} \sum_{n=\frac{N_c}{N_s}(i-1)}^{\frac{N_c}{N_s}i-1} c_n s_i \right|^2 . \tag{1}$$

- ◇ **Action on Thesis:** I have added the following sentence in the thesis on page 45 below (2.29):
  "where ν is defined in (A.6) in the appendix. Substituting..."

Comment 6: *Page 52, all lines in Fig. 2.10 reach the same point at $Ns' = 10$, any explanation on this symptom?*

- ◇ **Response/Action on Thesis:** I have have added the following explanation to Section 2.6.3.2 on page 53 in the thesis:
  "It can be further noted from the figure that the point where all the three curves meet, i.e., $N_s' = 10$ corresponds to the ideal scenario when the number of ambient symbols fitting within the backscatter phase is precisely 10, i.e., the value for which the system is designed. Therefore, regardless of the ratio of N_c/N_s, as long as the number of ambient symbols in the backscatter phase is equal to the value for which the system is designed, we receive the best performance, i.e., maximum value of average harvested energy."

Comment 7: *Page 58, $\mathbf{f_B}$ is expressed by multiplication of $\mathbf{h_{A-B}}$, $\mathbf{h_{B-I}}$, $\mathbf{h_{B-R}}$, and $\mathbf{h_{I-R}}$. h_{A-B} is expressed as scalar, but the other three are matrix. A detailed explanation of this is necessary for a clear understanding of $\mathbf{f_B}$.*

- **Response/Action on Thesis:** $\mathbf{f_B}$ is the effective composite channel from the ambient source to backscatter device to the reader. It is defined by

$$\mathbf{f}_B(\boldsymbol{\Theta}) = \left(\sqrt{\beta_{A-B}}h_{A-B} + \sqrt{\beta_{A-I-B}}\mathbf{h}_{B-I}^H\boldsymbol{\Theta}\mathbf{h}_{A-I}\right)\times\left(\sqrt{\beta_{B-R}}\mathbf{h}_{B-R} + \sqrt{\beta_{B-I-R}}\mathbf{H}_{I-R}\boldsymbol{\Theta}\mathbf{h}_{B-I}\right). \quad (2)$$

  For better clarification, I have added the following explanation to the thesis on page 58, following equation (3.5):

  "Note that there are N elements of IRS and M antennas at the reader. The channels from the ambient source, backscatter device and the reader to the IRS are $\mathbf{h}_{A-I} \in C^{N\times 1}$, $\mathbf{h}_{B-I} \in C^{N\times 1}$ and $\mathbf{H}_{R-I} \in C^{N\times M}$ respectively. Similarly, the channels from the ambient source to the backscatter device and the reader are represented by $h_{A-B} \in C^{1\times 1}$ and $\mathbf{h}_{A-R} \in C^{M\times 1}$ respectively, while the channel from the BD to the RX is represented by $\mathbf{h}_{B-R} \in C^{M\times 1}$. h_{A-B} is a scalar as there is a single channel coefficient between the ambient source and the backscatter device, whereas the other channels are multi-dimensional and hence expressed as vectors/matrices."

Comment 8: *Page 67, Fig. 3.2 demonstrates the BER of "Exhaustive Search" for $N = 4, 8$. However, the BER of other methods covers the range of $N = 4, 16$. It would be helpful to cover more result points of "Exhaustive Search" for performance comparison.*

- **Response:** The plot for exhaustive search results has only three data points highlighted by Δ for $N \in \{4, 6, 8\}$. Further data points could not be obtained because the exhaustive search method demands excessive computational resources.
- **Action on Thesis:** I have added the following sentences on page 68 in Section 3.5.2:

  "The main motivation for providing exhaustive search results was to establish the viability of the proposed scheme, i.e., despite being suboptimal, it provides results close to those obtained by exhaustive search. Fewer data points were plotted for in this benchmark because the exhaustive search method demands excessive computational resources and it is difficult to implement for larger values of N. "

Comment 9: *Page 69, the result of "EBF with optimized IRS" is the best among all other methods. Any discussion on complexity of these methods?*

- **Response:** The proposed scheme EBF with optimized IRS is a two step approach. In step 1, (P2) is solved, i.e., the IRS is optimized to maximize the strength of the backscatter signal received at the reader. This scheme has a computational complexity of $O(IN)$, as discussed in Section 3.4.1. The next step is to solve (P3), which is the generalized eigenvector problem having a computational complexity of $O(M^3)$. Therefore, the overall complexity of this scheme is $O(IN) + O(M^3)$.

- **Action on Thesis:** As per the reviewer's suggestion, I have added a footnote on page 69 in the thesis:

  The overall computational complexity of the EBF with optimized IRS is $O(IN) + O(M^3)$.

Comment 10: *Page 77, what is the definition of $\mathbf{w_s}$ in equation (4.1)?*

- **Response:** In equation (4.1), $\mathbf{w}$ stands for the transmit beamforming vector of the reader, whereas s is the signal sent out by the reader.
- **Action on Thesis:** A description of these two symbols is presented in Section 4.1, prior to the occurrence of equation (4.1). I have also added the following sentences on page 77 preceeding equation (4.1):

  "Thus, if the signal sent out by the reader is denoted by s and $\mathbf{w}$ stands for the transmit beamforming vector of the reader, the signal arriving..."

Comment 11: *Pages 84-86, the deep residual convolutional neural network-based beamforming is proposed, as demonstrated in Fig. 4.2. Any explanation on the selection of this architecture would be useful for better understanding the proposed design.*

- ◇ **Response:** The considered system model comprised of an IRS as well as a multi-antenna reader. Due to the higher dimension of the input features, a convolutional neural network is required. Although in general, a deeper neural network (with more layers) is more efficient in parameterizing functions, it requires more computational complexity in term of running time and CPU/GPU memory and sometimes suffers from gradient vanishing and exploding issues. To solve these issues, we added ResNet feature to the convolutional neural network, leading to the design of a Deep Residual Convolutional Neural Network (DRCNN). ResNet is a widely used structure in deep learning aided wireless systems design. Therefore, instead of discussing its architecture in detail, I just cited it and succinctly expressed the motivation for employing this structure.
- ◇ **Response/Action on Thesis:** I have added the following sentences to page 85 of the thesis, prior to equation (4.21):

  To solve these issues, we added ResNet feature to the convolutional neural network, leading to the design of a Deep Residual Convolutional Neural Network (DRCNN). ResNet is a widely used structure in deep learning aided wireless systems design [133]."

Comment 12: *Pages 87-88, as stated in the thesis, an offline training is processed firstly to train the proposed architecture ready, however, the offline training can ensure the effectiveness of the proposed architecture under certain specific conditions only. Beyond those conditions, the architecture will require re-training process. So how often is the re-training process required? In other words, is generalization an issue considered in this thesis?*

- ◇ **Response/Action on Thesis:** I have added the following explanation to the thesis on page 92, at the end of Section 4.5.1:

  "The network requires offline training prior to deployment for a certain system configuration/location of system components. However, to demonstrate the generalization of the network to different datasets corresponding to different channel conditions, we have performed simulations using four test datasets with channels corresponding to Rician fading with a K- factor of : 3, 6, 9 , 10. These are processed using the neural network trained on dataset corresponding to K = 9. The average SNR achieved for each of these test datasets is:
  For dataset corresponding to K = 9: SNR = 42.7dB
  For dataset corresponding to K = 10: SNR = 41.618dB
  For dataset corresponding to K = 6: SNR = 40.805dB
  For dataset corresponding to K = 3: SNR = 39.066dB
  It is notable that as the channel conditions change, there is some degradation but the performance is still acceptable. However, if channel conditions are drastically different, then for best performance, it is expected that *BackIRS-Net* be retrained on a larger dataset covering the highly varied channel conditions. "

Comment 13: *Table 4.3, what is the number of iterations in the training process?*

- ◇ **Response/Action on Thesis:** I have added the following explanation to page 90, Section 4.5:

  "The number of iterations of the training process depends upon the DRCNN size, which in turn depends upon the size of IRS, e.g., for the IRS of size $N = 16$, the network took about 50 iterations to train whereas for the IRS of size $N = 25$ the network took close to 80 iterations to train."

Reviewer 3: Log of Changes

General Comments:
Backscatter Communication (BackCom) has been considered as a promising technology for further wireless networks. It can passively modulate and re-use existing radio-frequency signals, thus has the potential to enable the energy-efficient connectivity for future massive IoT. However, its main challenge is the relatively weaker backscatter signal compared to interference, leading to limited coverage, low data rate, and high bit error rate.

In this thesis, the candidate presents comprehensive research addressing challenges in BackCom. Several scenarios are carefully investigated, including ambient-BackCom in energy harvesting, integration of ambient-BackCom with Intelligent Reflecting Surface (IRS), and beamforming design for Monostatic-BackCom with IRS. All chapters are underpinned by theoretical analyses and performance evaluations through simulations. The Introduction and technical sections are well supported by clear and adequate references when needed. The literature review is thorough and extensive.

In general, this thesis is well-written and organized. It provides a fluent reading experience and clear information to potential readers. Its contributions have resulted in several papers in top IEEE journals and conferences, showcasing the candidate's extensive knowledge of BackCom. The technical details of the thesis appear sound, and their publication endorsement supports this. Additionally, the research methodology displays the candidate's strong skills in mathematics, optimization, and machine learning.

Response: Thank you to the examiner for summarising the thesis. These comments do not require any changes in the thesis itself.

Comment 1-14: Typos and minor edits

- ◇ **Response/Action on Thesis:** I have duly corrected all the typos and minor edits in text that the reviewer has kindly suggested.

Comment 15: *On page 44, I suggest removing Section 2.5.2, as it is too short and can be concisely incorporated in Section 2.6.3.2.*

- ◇ **Response/Action on Thesis:** As per the reviewer's suggestion, I have removed Section 2.5.2 and incorporated the discussion within Section 2.6.3.2. For completeness, I have added the following sentences at the end of the first paragraph of Section 2.5.
  "In this regard, we analytically examine the impact of imperfect synchronization at the correlator in the following subsection. Another important scenario is when the duration of the ambient symbol is unknown and therefore an even number of chips or backscatter coefficient changes do not fit in each ambient symbol. In this situation, it is difficult to present any analytical results. Hence, we will investigate its impact using simulations in Section 2.6.3.2. Lastly, we discuss the effect of other interference from neighbouring ambient sources in this section."

Comment 16: *In section 2.6, it will be helpful if the proposed training sequence schemes can be compared with methods without training sequence.*

- ◇ **Response:** In Section 2.6.1 we have already presented results with using a Pseudo-Noise (PN) sequence instead of our proposed training sequence. We have plotted average harvested energy versus the duration of the backscatter phase. These results can be compared to the results corresponding to our proposed scheme and clearly delineate the advantage of the training sequence.
- ◇ **Action on Thesis:** I have added the following explanation to Section 2.6.2 on page 48 of the thesis:
  "Secondly, comparing the $T_s = 5\mu s$ plot with Fig. 2.4, it can be observed that the energy harvested at the ER increases significantly as compared to the case when a pseudo-random sequence is employed at the ER during the backscatter phase. This is due to the fact that the proposed scheme completely eliminates the ambient component. As a result, during retrodirective WPT the ET forms a focused beam directed back at the ER

alone, with no energy leaking to the AS. This clearly delineates the advantage of using the designed training sequence."

Comment 17-22: Typos and minor edits

- ◇ **Response/Action on Thesis:** I have duly corrected all the typos and minor edits in text that the reviewer has kindly suggested.