ELEC9123: Design Task E
(Optimization for Green IoT)
Secrecy Rate Maximization in Beamforming-Assisted Backscatter Communication

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1 Background

In today's world of ubiquitous wireless connectivity, safeguarding the confidentiality of transmitted data has become a critical challenge, especially for the Internet of Things (IoT). This design task explores an advanced and timely solution: Physical Layer Security (PLS), a promising approach to protect backscatter communication (BackCom) from eavesdropping threats. You will investigate a monostatic BackCom system, where a reader exchanges information with a passive backscatter device while a malicious eavesdropper attempts to intercept the communication. Backscatter communication is chosen for its role as an enabling technology for green IoT, due to its ultra-low power consumption and energy efficiency. This task not only deepens your understanding of secure wireless systems but also connects directly to the future of sustainable and secure IoT networks. The objective is to model the system mathematically and formulate the secrecy rate maximization problem. Then, you need to develop a solution methodology to solve the problem using `MATLAB` and `CVX toolbox`.

1.1 Backscatter Communication

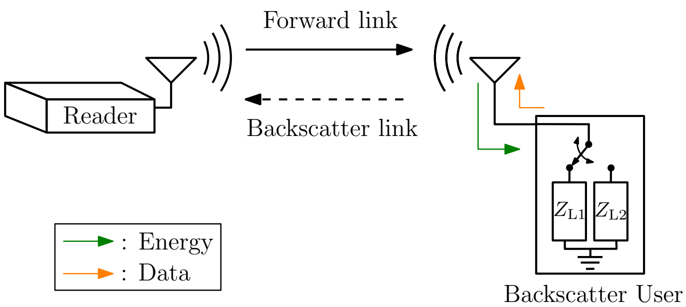

Figure 1: Monostatic backscatter communication system model.

A basic monostatic BackCom system consists of a reader and a passive backscatter user, as illustrated in Fig. 1. The reader functions both as the transmitter of the continuous Radio Frequency (RF) signal and as the receiver of the backscattered signal. In the forward link, the reader emits an unmodulated RF carrier toward the passive backscatter user. Since the backscatter user does not have an onboard power source, it harvests energy from the incident RF signal to operate. The passive backscatter tag also leverages the incident RF signal to transmit information with load modulation. Specifically, the backscatter tag changes the impedance load connected to the antenna's output terminal, which alters the amplitude or phase of the reflected signal. This modulated signal, called the backscattered signal, is then reflected back along the backscatter link and received by the same reader.

1.2 Wireless Channel Models

In the forward link of the monostatic BackCom system, the reader continuously transmits an unmodulated RF signal, denoted as x_{t}, with an average transmit power of $\mathbb{E}\left[|x_{\mathrm{t}}|^2\right] = P_{\mathrm{t}}$. The wireless channel between the reader and the backscatter user is represented by h_{RU}. Assuming free-space path loss, the corresponding channel power gain is given by $\mathbb{E}\left[|h_{\mathrm{RU}}|^2\right] = \left(\frac{\lambda}{4\pi d_{\mathrm{RU}}}\right)^2$, where λ is the wavelength of the RF signal and d_{RU} denotes the distance between the reader and the backscatter user.

The received signal at the backscatter user can be expressed as:

$$y_{\mathrm{bu}} = h_{\mathrm{RU}} x_{\mathrm{t}} + n_{\mathrm{bu}}, \tag{1}$$

where n_{bu} is the additive white Gaussian noise (AWGN) at the backscatter user.

In this task, we consider a binary digital modulation scheme, where the backscatter user transmits information bits '0' or '1'. Assuming that the structural mode scattering component can be effectively filtered out at the reader, the backscattered signal is given by:

$$x_{\mathrm{b}i} = \sqrt{\eta_{\mathrm{b}}} y_{\mathrm{bu}} \Gamma_{\mathrm{i}}, \quad i \in \{0, 1\}, \tag{2}$$

where η_{b} is the backscattering efficiency and Γ_i denotes the complex reflection coefficient. Specifically, Γ_i depends on the load impedance $Z_{\mathrm{L}i}$ connected to the antenna's output terminal. By switching between different impedances, the tag alters the amplitude and/or phase of the reflected signal. Without loss of generality, we assume that transmitting bit 'i' corresponds to connecting the antenna to $Z_{\mathrm{L}i}$, which results in the reflection coefficient Γ_i. It should be noted that $|\Gamma_i| \leq 1$ as the intrinsic property of passive backscattering.

The backscattered signal propagates back through the same wireless channel and is received at the reader. The received signal at the reader is expressed as:

$$y_{\mathrm{R}i} = h_{\mathrm{RU}} x_{\mathrm{b}i} + n_{\mathrm{R}}, \tag{3}$$

where $n_{\mathrm{R}} \sim \mathcal{CN}(0, \sigma_{\mathrm{R}}^2)$ is the AWGN at the reader. For simplicity, we assume the noise power in the BackCom system is -80 dBm, and hence $\sigma_{\mathrm{R}}^2 = -80$ dBm.

It is worth noting that although the backscatter user receives noise n_{bu} in the forward link, its contribution to the received backscattered signal at the reader is negligible due to the passive nature of the tag and the double path loss. Therefore, for analytical simplicity, the impact of n_{bu} on the backscattered signal is commonly omitted in the performance analysis.

1.3 Physical Layer Security

In traditional networked systems, security is often handled at the network layer or above, for example, through encryption, secure protocols (e.g. SSL / TLS) or cryptographic key exchanges. These methods are generally effective when the transmission medium is wired or physically secured, as shown in Fig. 2. However, in wireless communication systems, signals are broadcast over the air, making them inherently vulnerable to eavesdropping, jamming, and interception. Unlike wired channels, the wireless medium is open, and any nearby adversary can potentially capture or disrupt the transmission.

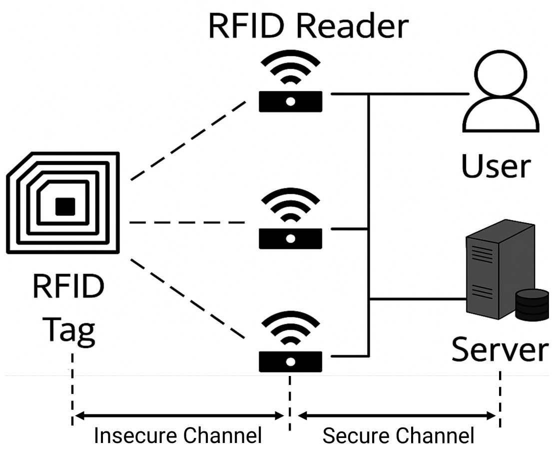

Figure 2: Physical Layer Security Attacks on RFID Tag.

Physical Layer Security (PLS) is a technique that aims to protect wireless communication to address this challenge by leveraging the characteristics of the wireless channel itself, rather than relying on cryptographic methods at higher layers. In a typical wireless setting, as shown in Fig. 3, a legitimate transmitter (Alice) communicates with a legitimate receiver (Bob), while an unauthorized user (Eve) attempts to intercept the transmission. PLS strategies focus on degrading the signal quality at Eve without significantly affecting Bob's reception.

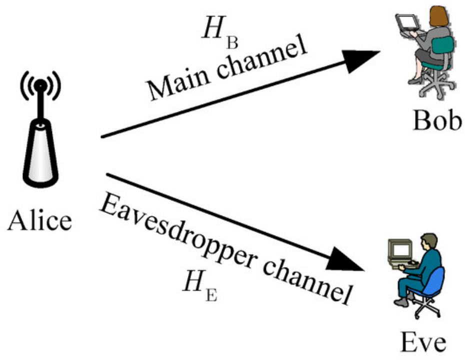

Figure 3: A wireless communication system with a legitimate transmitter (Alice), a legitimate receiver (Bob), and an eavesdropper (Eve).

2 Performance metrics

In this task, we consider the following two key performance metrics to evaluate the effectiveness of the BackCom system:

- Harvested power,
- Spectral efficiency

The details of each metric are discussed below.

2.1 Harvested Power

Since the backscatter user is a passive device without an onboard power source, it fully relies on wireless energy harvesting from the incident RF signal transmitted by the reader to power its internal circuitry. The proportion of the incident RF energy that is harvested versus reflected depends on the reflection coefficient selected at each modulation state. Under a linear energy harvesting model, the harvested power when transmitting bit 'i' is given by:

$$P_{\mathrm{L}i} = \eta_\mathrm{e}\mathbb{E}\left[|h_{\mathrm{RU}}x_\mathrm{t}|^2\right]\left(1-|\Gamma_i|^2\right), \quad i \in \{0,1\}, \tag{4}$$

where η_e is the energy harvesting efficiency. Clearly, a smaller $|\Gamma_i|$ results in more energy being absorbed and less being reflected, thus increasing the harvested power.

Assuming equiprobable signaling, the average harvested power is given by:

$$P_{\mathrm{L,avg}} = \frac{1}{2}P_{\mathrm{L0}} + \frac{1}{2}P_{\mathrm{L1}}. \tag{5}$$

In practice, it is essential that the average harvested power $P_{\mathrm{L,avg}}$ exceeds a minimum required threshold P_{th} to ensure that the backscatter user can maintain reliable operation.

2.2 Spectral Efficiency

Spectral efficiency (SE) reflects the data rate per unit bandwidth that can be achieved by the backscatter user and is a key indicator of communication performance. In general, SE is closely related to the signal-to-noise ratio (SNR), with higher SNR typically enabling higher data throughput. In this task, the SE at the reader is defined as:

$$\begin{aligned} R_\mathrm{R} &= \log_2(1+\mathrm{SNR}) \\ &= \log_2\left(1+\frac{\mathbb{E}\left[\left|\frac{1}{2}h_{\mathrm{RU}}\left(x_{\mathrm{b0}}-x_{\mathrm{b1}}\right)\right|^2\right]}{\sigma_\mathrm{R}^2}\right). \end{aligned} \tag{6}$$

It can be observed that R_R is dependent on the modulation index m, defined as:

$$m = \frac{|\Gamma_0 - \Gamma_1|}{2}. \tag{7}$$

A higher modulation index improves the signal separation at the receiver, thereby enhancing detection accuracy. To ensure a satisfactory bit error rate (BER) in the BackCom system, the modulation index should exceed a predefined threshold m_{th}.

3 Objective

This task aims to enhance the secrecy rate (SR) of the backscatter user in the presence of a potential eavesdropper in a BackCom system. In this setting, the eavesdropper attempts to intercept the information reflected by the backscatter user. To quantify secure communication, we define the SE at the eavesdropper as R_{E}, and the secrecy rate is then given by:

$$\mathrm{SR} = R_{\mathrm{R}} - R_{\mathrm{E}}. \tag{8}$$

A positive and sufficiently large secrecy rate implies that the backscatter user's information is securely transmitted, as the eavesdropper is unable to reliably decode the signal.

The system model and performance metrics discussed above are derived with single-antenna configurations at both the reader and the backscatter user. This task introduces a more advanced scenario, in which the reader is equipped with multiple antennas, whereas the backscatter user and eavesdropper each have a single antenna. The use of multiple antennas at the reader enables advanced spatial signal processing, such as beamforming, to enhance the desired signal reception.

As a result, this task involves the design of the reader's precoding and combining vectors to improve the reception of the backscattered signal. Within this framework, you are required to formulate and solve an optimization problem that maximizes the secrecy rate of the backscatter user. The optimization variables include:

- The reflection coefficients at the backscatter user,
- The precoding vector for the forward link transmission,
- The combining vector for the backscatter link reception at the reader.

Additionally, the optimization must comply with the practical operational constraints of the BackCom system as discussed earlier. In this task, the backscatter user employs the amplitude-shift keying (ASK) modulation scheme, and the reflection coefficients will be real values.

The specific design requirements and implementation details are provided in the following sections.

4 Design Task Requirements

Unless otherwise stated, considering the default system parameters as below:

Table 1: Default Simulation Parameters

Parameters	**Notations**	**Value**	**Unit**
RF signal's Frequency	f	915	MHz
Speed of Light	c	$3 \cdot 10^8$	ms^{-1}
Transmission power	P_{t}	0.5	W
Noise Power at Reader	σ_{R}^2	-80	dBm
Noise Power at Eavesdropper	σ_{E}^2	-80	dBm
Backcattering Efficiency of the Tag	η_{b}	0.8	-
Energy Harvesting Efficiency of the Tag	η_{e}	0.8	-
Distance between Reader and Backscatter User	d_{RU}	10	m
Harvested Power Threshold	P_{th}	10^{-6}	W
Backscatter Reflection Coefficient Threshold	m_{th}	0.2	-

1. The signal model and performance metrics presented above are based on a single-antenna reader. In this task, you are required to extend the analysis to a more general setting, where the reader is equipped with N antennas, while both the passive backscatter user and the eavesdropper each have a single antenna. Under this system configuration, you need to derive the following components for the simulation environment:
   - Rayleigh channel models for all communication links:
     - Reader to Backscatter User
     - Reader to Eavesdropper
     - Backscatter User to Eavesdropper

- Received signal expressions with precoder and combiner:
  - RF signal received at the Backscatter User from the Reader
  - Backscattered signal received at the Eavesdropper
  - Backscattered signal received at the Reader from the Backscatter User
- Performance metrics for the BackCom system
  - Spectral efficiency at the Reader
  - Spectral efficiency at the Eavesdropper
  - Average harvested power at the tag
- Express the secrecy rate of the BackCom system

2. Optimization problem formulation:
   - Define the objective function
   - Identify and justify all relevant constraints for the optimization problem
   - Provide a proof for the convexity of the objective function and constraints

3. Solution Methodology:
   - Apply and justify the practical assumptions to simplify the optimization problem
   - Develop an efficient method to solve the problem and obtain the solution

   Note: To achieve a **pass grade**, you **MUST** at minimum implement a **brute force** method to demonstrate that a solution exists. Higher grades require more efficient methods such as convex optimization (e.g., using **CVX**) or iterative/heuristic algorithms.

4. `MATLAB` Implementation:
   To ensure your MATLAB simulation and optimization implementation meets the expectations of this design task, please adhere to the following requirements. These aspects will be directly assessed in your design task evaluation:
   - Be implemented in `MATLAB`. All primary functions and scripts must be clearly structured and stored as `.m` files
   - For optimization tasks, you **MUST** use the **CVX Framework**.
   - Each `.m` file should include a brief header comment describing its purpose
   - Your code should be clean, modular, and readable
   - Include meaningful inline comments that explain the purpose of key operations
   - Use consistent indentation and variable naming for clarity
   - You should verify that the code is functional and produces valid outputs

5. Simulation Results and Analysis:
   To demonstrate the correctness and insights of your simulation and optimization results, you are required to generate the following plots and provide a brief but insightful analysis for each:
   - SR vs. Transmission Distance: Plot the secrecy rate as a function of the transmission distance between the Backscatter User and the Eavesdropper d_{UE} for $N = 3, 4, 5, 6$ (all curves in a single plot). Additionally, include the benchmark result obtained using the brute force method for comparison.
   - Reflection Coefficient (Γ_i) vs. Transmission Distance (d_{UE}): Plot the optimized backscattering reflection coefficient as a function of the transmission distance between the backscatter user and the eavesdropper for $N = 3, 4, 5, 6$.
   - SE at Reader (R_{R}) vs. Transmission Distance (d_{UE}): This plot should illustrate R_{R} as a function of the transmission distance between the Backscatter User and the Eavesdropper. Curves for different numbers of reader antennas ($N = 3, 4, 5, 6$) should be included in a single plot for comparison.
   - Convergence plot: If your solution method involves an iterative approach to approximate the optimal solution, you are required to include a convergence plot. This plot should illustrate how the objective value approaches the optimized value over iterations, demonstrating the efficiency of your proposed method.

6. To maintain academic integrity and transparency in your design task, you are required to:

- Properly cite all external sources you have consulted or directly used in your work.
- If you have used any AI-based tools (e.g., ChatGPT, Copilot, Gemini, deepseek), you **MUST** clearly disclose this in your report.

5 Useful Facts

- Drawing a complete system diagram can help you visualize the BackCom architecture, clarify signal flow, and support your analytical formulation.
- Use the 'randn' command in `MATLAB` with a fixed random seed to generate reproducible random channel coefficients from a standard normal distribution.
- Normalize the precoding and combining vectors to ensure consistent power levels across simulations.
- During the simulation, you may consider the transmission distance between the Backscatter User and the Eavesdropper within the range $d_{\mathrm{UE}} \in [5, 50]$ meters.
- `CVX` is a MATLAB-based modeling framework for solving convex optimization problems. It provides a user-friendly interface for specifying optimization objectives and constraints using standard MATLAB syntax. You can download `CVX` from the official website at: http://cvxr.com/cvx/download. The homepage also includes example code demonstrating how to define and solve a convex optimization problem using `CVX`, which can serve as a helpful reference for this task.

6 Reference Materials

The following reference materials may be helpful in guiding the development of your solution methodology:

[R1] Boyd, Stephen P., and Lieven Vandenberghe. Convex optimization. Cambridge university press, 2004.

[R2] Karthaus, Udo, and Martin Fischer. "Fully integrated passive UHF RFID transponder IC with 16.7-μW minimum RF input power." IEEE Journal of solid-state circuits 38.10 (2003): 1602-1608.

[R3] Shen, Kaiming, and Wei Yu. "Fractional programming for communication systems—Part I: Power control and beamforming." IEEE Transactions on Signal Processing 66.10 (2018): 2616-2630.

[R4] A. C. Y. Goay, D. Mishra, M. Matthaiou and A. Seneviratne, "Range Maximization by Optimizing Tag-to-Tag Cooperative Backscatter Communication," in IEEE Transactions on Green Communications and Networking (2025).

7 Attendance Requirements

- Student attendance in each laboratory session (Wednesday and Friday) will be **recorded**.
- In order to receive a grade for this design task, it is **mandatory** to attend all required lectures/labs, including the lab assessments.
- To ensure consistency and fairness among different simulation and hardware-focused students, all the lab-based questions will be answered or addressed only during the two three-hour weekly lab sessions.

8 Design Journal Submission

- It is mandatory to maintain a journal or report describing your design process, implementation code, and results, which must be documented via an MS Word or .pdf file.
- The design journal should include a functioning and well-commented `MATLAB` file containing your design that meets the requirements of the design task and must be submitted to the **Moodle Design Task X submission link**, where X is 1, 2, or 3 depending on whether you chose this task as your first, second, or third design task.
- Please ensure that the `MATLAB` simulation file is formatted according to the requirements listed in Section 4.
- During the assessment, you will also need to demonstrate the functionality of the `MATLAB` code, explain your design journal and your design to the lab demonstrator and answer any questions they may have about your design.
- Assessment for this task will take place during the designated evaluation period, which will be announced during the lab sessions. The marking will be based on both the demonstration of your implemented solution and the quality of your lab notebook, report, or project journal.

- **Submission File Format:**
  - The simulation file must be saved as a '.m' file (`MATLAB` file). The name of this file must be: **zID_LastName_DTE_2025.m.** Here if any student has written their code in multiple MALTAB files, then they can compress all the .m together in a single zip folder while exactly mentioning which file to run and what does each .m file is doing by adding a README text file explaining the role of each .m file. The name of this zip folder, in this case, must be: **zID_LastName_DTE_2025.zip**
  - Your simulation file should already have all the subparts required to showcase the necessary functionality along with detailed comments explaining all the steps. You may be penalized if significant additions or changes are required to show functionality as per the mentioned requirements.
  - The brief portable document format (.pdf) report summarising the outcomes of this Design task and your steps in obtaining them must be saved as a '.pdf' file (readable text file). The name of this file must be: **zID_LastName_DTE_2025.pdf**

9 Design Task Schedule and Assessment Timeline

- Each design task must be completed over a span of six lab sessions. Term 2 is structured to accommodate three design tasks to be selected by each student out of the 7 available options, with the following schedule:
  - Task 1: Week 1 Wednesday lab session to Week 3 Friday lab session,
  - Task 2: Week 4 Friday lab session to Week 7 Wednesday lab session,
  - Task 3: Week 8 Wednesday lab session to Week 10 Friday lab session.
- Each task has a specific assessment session and submission deadline:
  - If this task is completed as Task 1:
    * Assessment: Wednesday lab session of Week 4,
    * Deadline: 11:59 PM, Tuesday, June 24, 2025.
  - If this task is completed as Task 2:
    * Assessment: Friday lab session of Week 7,
    * Deadline: 11:59 PM, Thursday, July 17, 2025.
  - If this task is completed as Task 3:
    * Assessment: Wednesday lab session of Week 11,
    * Deadline: 11:59 PM, Tuesday, August 12, 2025.

10 Assessment Criteria and Marking Rubric

- The assessment breakdown for each design task, showing different components involved, is shown in Table 2.

Table 2: The assessment breakdown for Design Task E

Deliverable	Percentage of Assignment Grade
Demonstration of Correct Working Design	20%
Explanation of the Implementation and Results	40%
Ability to Answer Questions	20%
Design Journal or Notebook	20%

- The Correct Working Design component, worth 20%, requires that **all objectives are accurately met** according to the details given in Section 4.
- The Explanation of Implementation and Results is evaluated based on the following four aspects:
  - **Clarity and explanation of plots** - how well the plots are presented and interpreted.
  - **Code efficiency and commenting** - the quality, readability, and documentation of the code.
  - **Working code and its explanation** - whether the code runs correctly and is clearly explained.
  - **Explanation of Results** - how well the outcomes are analysed and related to the design objectives.

- The "Ability to Answer Questions" component is based on the quality of responses to the **two to four questions** based on the design task.
- The Design Journal component is evaluated based on four equally weighted areas. First, students must provide a brief **problem description** that clearly outlines the design task. Second, they should present their **understanding and logic**, explaining their approach and reasoning in a structured and coherent manner. Third, the journal should include a **demonstration of results**, showcasing the outcomes of their design work with appropriate interpretation. Finally, students must include **project management** details, such as weekly progress updates, a declaration of any AI tools used, and proper referencing of all sources.
- Overall, during the assessment, students will need to demonstrate the functionality of the `MATLAB` code, explain their design journal and design to the lab demonstrator, and answer any questions they may have about their design.
- All design tasks in this course **MUST** be completed individually. Copying from others is not permitted and may result in a **failing (UF) grade** [1], reinforcing the importance of academic integrity.
- Please note that design tasks must be submitted by the set deadline, and extensions will not be granted, except in cases of approved special consideration, which may allow students to redo the task during Weeks 11 and 12.
- **Passing Requirement and Hurdle**: To pass this course, you must:
  - Achieve an overall course mark of 50% or higher, where this overall mark is calculated as follows:
    * 30% from each of the three design tasks (totaling 90%),
    * 10% from the lab exam, which will be conducted during the Friday lab session of Week 11, and
  - Pass at least two out of your three design tasks. This means you can fail only one design task.
- **Redo Opportunity**: If you fail a design task, you will have a chance to redo it during Weeks 11 and 12.
  - Lab sessions for redoing tasks will run from 9:00 AM to 3:00 PM on:
    * 6-hour lab session on Wednesday of Week 11
    * 6-hour lab sessions on Wednesday and Friday of Week 12
  - If your resubmitted task meets the requirements for a satisfactory grade, you will receive a mark of 50% for that task.
  - The grading and assessment will be conducted on the Friday lab session of Week 12 after the student submits their task during the same session.
  - Please be aware that you are allowed to **redo ONLY one design task**.
- **Supplementary Lab Sessions**: The above-mentioned three 6-hour lab sessions in Weeks 11 and 12 can also be used as make-up sessions for students who missed earlier labs due to approved special consideration. In such cases, students will be assessed normally and will receive their actual earned mark, rather than the fixed 50% awarded for task redos. Please be aware that students are strictly permitted to complete only one design task during the supplementary lab sessions in Weeks 11 and 12. No exceptions will be made beyond this single opportunity.
- If needed, students may be given access to open lab sessions to work outside regular lab hours. However, lecturer and demonstrator support will only be available during the two scheduled weekly lab sessions.
- **Formal feedback** will be provided well within two weeks of the relevant submission date through Moodle, followed by a brief discussion during the lab session.
- **Note**: Use of AI tools (such as ChatGPT or Copilot) for your learning in this course is allowed, but you are responsible for everything you produce - designs, reports, graphs, etc. (keeping in mind that the output from AI tools can be incorrect). Any use of AI tools must be declared.

[1] https://www.student.unsw.edu.au/grade