BER-Aware Backscattering Design for Energy Maximization at RFID Passive Tag

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***Abstract*—The radio frequency identification (RFID) passive tag is a wireless communication device with high energy sustainability, such that it uses the incident radio frequency (RF) signal to backscatter its information. This paper investigates the output load power maximization with optimal load impedances selection in the backscatter communication (BackCom) network. The considered BackCom system comprises a reader broadcasting an unmodulated carrier to the passive tag in the downlink. The tag backscatters its information signal to the reader with binary amplitude-shift keying (BASK) modulation in the uplink. We formulated an average output load power maximization problem by jointly optimizing the reflection coefficients while satisfying the minimum bit error rate (BER) requirement and tag sensitivity constraint. To simplify the problem, we transform the BER constraint to the modulation index constraint and reduce the 4 variables problem to 2 variables convex optimization problem. Using the Karush-Kuhn-Tucker (KKT) conditions, we design an algorithm to obtain the closed-form expression for the global optimal reflection coefficients that maximize the output load power. The simulation results provide insight into the impact of the information bit probability, tag sensitivity constraint, and BER on the achievable average load power. An overall gain of around 16% signifies the utility of our proposed design.**

***Index Terms*—Backscattering, RFID, Passive Tag, ASK, Energy Maximization, BER, Optimization.**

I. INTRODUCTION

RAdio Frequency Identification (RFID) device is a wireless communication tag that transmits information when activated by an interrogation pulse from a dedicated RFID interrogator. The first RFID passive tag was invented in the 1970s by Mario Cardullo but did not gain attention from the world. With the advent of the Internet of Things (IoT), RFID technology gained lots of interest and significant development. RFID and wireless sensor networks (WSNs) are the two main technologies being used and are becoming the two pillars of IoT [1]. RFID technology has played an important role in complementing the limitations of WSNs in IoT, specifically in manufacturing cost and energy source supplement of sensor nodes. The wireless sensor nodes will no longer require any active radio frequency (RF) component and have low power consumption, which all benefit from integrating the backscattering technique of RFID. However, the low energy efficiency in RFID far-field applications is still a major bottleneck to overcome [2]–[4].

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A. State-of-the-Art

In a backscatter communication (BackCom) system, a transmitter broadcasts a RF signal to power the passive RFID tag. The tag is a data carrier device designed to backscatter its information to the reader when interrogated, known as the wireless information transfer (WIT) [5]. In general, the passive tag generates information by load modulation, which switches the output loads to modulate and 'reflect' the incoming signal into a backscattered signal [6]. The 2 prominent load modulation schemes are amplitude-shift keying (ASK) and phase-shift keying (PSK) [7].

The RFID tag performance can be characterized by the data transmission rate, tag-to-reader transmission range, output load power, and bit error rate (BER) [8], [9]. The output load power depends on the connected output load in the load modulation scheme. The tag transfers the maximum load power with a perfectly matched output load, whereas the load power decreases with the mismatching degree. Since the tag performance is highly load-dependent [10], [11], existing research has revealed that load selection plays a huge role in the BackCom system. In [9], Muralter et al. have shown that the maximum transmission range varies significantly with the different output loads. Another work demonstrated simple rules for load selection to achieve a long transmission range, with one load in perfectly matched condition and another load greatly mismatched [12], [13]. Besides, in [11], Bletsas et al. illustrated the load selection policy for minimizing BER for ASK and PSK modulations without considering tag power sensitivity.

On the other hand, De Vita et al. proposed an output load selection with an equal mismatch in both states [7], which is different from [11]–[13]. In [14], Karthaus et al. investigated the load impedance selections exploited in [7], [11], [12], and showed the power efficiency varies with modulation depth.

Here it maybe also noted that recently there has been increasing focus on using multiple antennas at the reader and emitter [15]–[17] to exploit beamforming gains for overcoming the shortcomings of BackCom. However, this paper aims at enhancing the performance of single antenna reader aided RFID-based BackCom systems by optimally designing the underlying reflection coefficients at the tag.

B. Motivation and Contributions

The BackCom system has poor efficiency in far-field applications because the harvested output energy decreases dramatically over longer distances [18]. Therefore, the utility of the tag can be significantly improved by maximizing the

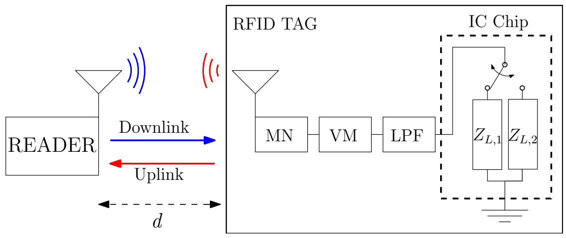

Fig. 1: BackCom system and its transmission protocol.

of the tag can be significantly improved by maximizing the output load power. Thus, allowing the tag to perform more on-board tasks and suit more applications. Unlike existing works considering equal probability for bits '0' and '1' during transmission, we determine the maximum average load power with unequal information bits probability for binary ASK (BASK) modulation scheme.

Besides, authors in [7], [11]–[14] have stated different load selections without finding the optimal value for enhancing the tag performance. *To the best of our knowledge, the average load power maximization with optimal load impedance selection under the BER and energy constraints has not been investigated yet.* This work will act as a benchmark whose results can be extended for other modulation schemes like M-ary ASK and PSK in the future.

The key contribution of this work is three-fold. 1) We formulated an RFID tag output load power maximization problem by jointly optimizing the reflection coefficients while considering the BER and tag sensitivity constraints. 2) We transformed the original 4-variable problem into a reduced optimization 2-variable convex problem. Then, we proposed an algorithm to determine the closed-form expression for the global optimal solution with the Karush-Kuhn-Tucker (KKT) conditions. 3)Simulation results are presented to quantify the maximum average load power for different applications under the varying value of the key system parameters. Here, we provided the design insight on the optimal value of the load impedances and verified the utility of the proposed optimal design by determining the achievable gain over the benchmark gain.

II. SYSTEM DESCRIPTION

A. System Model and Transmission Protocol

Fig.1 shows a monostatic BackCom system with one reader and one passive RFID tag separated by distance d in a free-space transmission medium. As a dedicated power source, the reader stably broadcasts an unmodulated RF carrier with constant power P_t to the passive tag in the downlink. Then, the tag transmits the backscattered signal to the reader in the uplink. The passive tag comprises a receiver antenna, matching network (MN), voltage multiplier (VM), low-pass filter (LPF), and an integrated circuit (IC) chip[1] [18]. When a sinusoidal electromagnetic (EM) wave is presented, the tags will transfer the power of the EM wave into DC power and deliver it to power the IC chip. Once the IC chip is activated, it generates the information signals by switching between 2 output loads $(Z_{L,1}, Z_{L,2})$. These loads are selected depending on the modulation scheme, in which we consider the BASK in this paper. Therefore, we set the information bits '0' and '1' are generated when the output load impedances are $Z_{L,1}$ and $Z_{L,2}$, respectively. Also, we consider that the passive tag operates with the minimum scattering antenna.

[1]In the latest research, the traditional RFID tag integrated with sensing electronics, transforming it into a sensing and computational platform, has been studied for IoT applications. The tag with sensing capability is called computational RFID (CRFID), which has higher power consumption during operation [1].

B. RFID Tag Load Power Analysis

As we aim to maximize the average load power transfer to the tag, we first study the key parameters. According to Kurokawa [19], the power wave reflection coefficient is defined as the ratio of the reflected power wave to the total incident power wave. This paper denotes Γ_i as the power wave reflection coefficient, for $i \in \{1,2\}$ represent when the tag connects to $Z_{L,1}$ and $Z_{L,2}$, respectively. The Γ_i is given by [19]:

$$\Gamma_i \triangleq \frac{Z_{L,i} - \bar{Z}_A}{Z_{L,i} + Z_A}, \quad \forall i = \{1,2\}, \tag{1}$$

where $Z_A = R_A + jX_A$ is the antenna impedance, $\bar{Z}_A$ is the conjugate of Z_A, and $Z_{L,i} = R_{L,i} + jX_{L,i}$ [19]. The $R_{L,i}$ and R_A are the output load resistance and antenna resistance, respectively, whereas $X_{L,i}$ and X_A are the output load reactance and antenna reactance. To simplify the design optimization without the loss of generality, we consider the normalized load impedance $Z_{n,i} \triangleq R_{n,i} + jX_{n,i}$, and given that [12]:

$$R_{n,i} + jX_{n,i} \triangleq \frac{R_{L,i}}{R_A} + j\frac{X_{L,i} + X_A}{R_A}, \quad \forall i = \{1,2\}, \tag{2}$$

where $R_{n,i}$ is the normalized load resistance and $X_{n,i}$ is the normalized load reactance. Therefore, Γ_i can be expressed in $Z_{n,i}$ as below:

$$\begin{aligned}\Gamma_i &\triangleq \frac{Z_{n,i} - 1}{Z_{n,i} + 1}\\ &= \frac{R_{n,i}^2 + X_{n,i}^2 - 1 + j2X_{n,i}}{(R_{n,i}+1)^2 + X_{n,i}^2}\\ &= \Gamma_{a,i} + j\Gamma_{b,i}, \quad \forall i = \{1,2\},\end{aligned} \tag{3}$$

where $\Gamma_{a,i} \triangleq \frac{R_{n,i}^2 + X_{n,i}^2 - 1}{(R_{n,i}+1)^2 + X_{n,i}^2}$ and $\Gamma_{b,i} \triangleq \frac{2X_{n,i}}{(R_{n,i}+1)^2 + X_{n,i}^2}$.

The output load power $P_{L,i}$ delivered to the IC chip is given by [20]:

$$\begin{aligned}P_{L,i} &\triangleq P_a\left(1 - |\Gamma_i|^2\right)\\ &= P_a\left(1 - \Gamma_{a,i}^2 - \Gamma_{b,i}^2\right), \quad \forall i = \{1,2\},\end{aligned} \tag{4}$$

where $P_a \triangleq P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$ is the maximum available power of $P_{L,i}$ [10]. The parameter P_t is the transmit power of the reader, G_t and G_r are the antenna gain of tag and reader, respectively, and λ is the wavelength of the RF carrier.

III. PERFORMANCE METRICS FOR BACKSCATTERING

In [8], [9], the authors elaborated the main factors that decide the maximum transmission range are load power, backscattered power, and BER. This paper considers the tag power sensitivity and the BER minimum requirement as the operation constraints to determine the optimal load impedances and the maximum average load power.

A. Tag Power Sensitivity

In the BackCom system, the tag remains in sleep mode and is only activated when enough power and a minimum threshold voltage are provided. Therefore, $P_{L,i}$ must be greater than the minimum load power threshold $P_{L,min}$, which is the sustainability requirement of the BackCom system. When $P_{L,i} < P_{L,min}$, the tag is not activated, and no information will be generated.

B. Bit Error Rate

The second factor that limits the tag performance is the BER, which is defined as the number of bits misidentified by the reader over the total number of transmitted bits at a given time interval [21]. The probability P_e is the ratio of bits in error to the total number of bits, which can be determined by the following equation [22]:

$$P_e = \frac{1}{2}\text{erfc}\left(\frac{|V_1 - V_2|}{4\sqrt{2}\cdot\sigma}\right) = \frac{1}{2}\text{erfc}\left(\frac{|V_0|\cdot m}{2\sqrt{2}\cdot\sigma}\right), \quad (5)$$

where V_i is the voltage applied to the reader's output load when the tag is connected to $Z_{L,i}$, and $V_i = V_0$ is when the tag is operated in perfectly matched condition $\left(Z_{L,i} = \bar{Z}_A\right)$. The inevitable additive white Gaussian noise n_r is assumed to have zero mean with $\mathbb{E}\{|n_r|^2\} \triangleq \sigma^2$.The modulation index m $(0 \le m \le 1)$ is the characteristic difference between the backscattered signal bits '0' and '1', and is defined as below [22]:

$$m \triangleq \frac{|\Gamma_1 - \Gamma_2|}{2} = \frac{\sqrt{(\Gamma_{a,1} - \Gamma_{a,2})^2 + (\Gamma_{b,1} - \Gamma_{b,2})^2}}{2}, \quad (6)$$

We set $\nu \triangleq \frac{|V_0|\cdot m}{2\sqrt{2}\cdot\sigma}$, and the complementary error function erfc $(\nu) = 1 -$ erf (ν). Given that erf (ν) is the error function, this implies the higher the m, the lower the BER.

IV. PROBLEM DEFINITION

A. Optimization Formulation

When the tag is activated, it generates signal information with bits '0' and '1'. We denote p_1 and p_2 $(0 \le p_1, p_2 \le 1)$ as the occurrence probability of bits '0' and '1', respectively, with $p_1 + p_2 = 1$. In general, it is not necessary that the bits '0' and '1' have the same occurrence probability. Therefore, we consider p_1 and p_2 as application dependent constants, and the average load power $P_{L,avg}$ is given by:

$$P_{L,avg} \triangleq p_1 P_{L,1} + (1 - p_1) P_{L,2}, \quad (7)$$

Given the average load power $P_{L,avg}$ as a function of Γ_i, we are interested in determining the optimal reflection coefficient to maximize $P_{L,avg}$, subjecting to the following constraints. Constraint $C1$ defines the domain of the power reflection coefficient $|\Gamma_i| \le 1$, whereas $C2$ and $C3$ include the boundary conditions for $\Gamma_{a,i}$ and $\Gamma_{b,i}$, respectively. To meet the minimum BER requirement, the passive tag must operate with a threshold m_{th} for the modulation index m as in constraint $C4$. Furthermore, constraint $C5$ refers to the minimum load power threshold $P_{L,min}$ that must be achieved at each state. Incorporating these constraints, we maximize the average load power $P_{L,avg}$, and the corresponding optimization problem $(P1)$ can be defined as:

$$
\begin{aligned}
(P1) : &\max_{\mathbf{\Gamma}} \quad P_{L,avg} \\
\text{subject to } C1 :&\Gamma_{a,i}^2 + \Gamma_{b,i}^2 \le 1, \quad \forall i = \{1, 2\}, \\
C2 :&\Gamma_{a,i} \in [-1, 1], \quad \forall i = \{1, 2\}, \\
C3 :&\Gamma_{b,i} \in [-1, 1], \quad \forall i = \{1, 2\}, \\
C4 :&\frac{\sqrt{(\Gamma_{a,1} - \Gamma_{a,2})^2 + (\Gamma_{b,1} - \Gamma_{b,2})^2}}{2} \ge m_{th}, \\
C5 :&P_a\left(1 - \Gamma_{a,i}^2 - \Gamma_{b,i}^2\right) \ge P_{L,min}, \ \forall i = \{1, 2\}.
\end{aligned}
$$

where $\mathbf{\Gamma} \triangleq [\Gamma_{a,1}, \Gamma_{a,2}, \Gamma_{b,1}, \Gamma_{b,2}]$.

Remark 1 *The IC chip will consume the power $P_{L,min}$ to generate the information signal, whereas the remaining power is delivered to a storage system. The total stored energy $E_{st} = (P_{L,avg} - P_{L,min})T$ over the operation period T is then used for the on-board task during the non-interrogating period. Therefore, the allowable on-board tasks depend on $P_{L,avg}$.*

The problem $(P1)$ is a 4-variable optimization problem, which is then reduced to a 2-variable problem with the following Lemmas.

Lemma 1 *The average load power is maximized when either $\Gamma_{a,i} = 0$ or $\Gamma_{b,i} = 0$.*

Proof *First, we set $\Gamma_{b,i}$ as a constant and we found that $\frac{\partial^2 P_{L,i}}{\partial\Gamma_{a,i}^2} = -2P_a$, which implies $P_{L,i}$ is a concave function in $\Gamma_{a,i}$. Therefore, for a given $\Gamma_{b,i}$, the maximum load power as obtained by solving $\frac{\partial P_{L,i}}{\partial\Gamma_{a,i}} = 0$ is $\Gamma_{a,i} = 0$. Likewise, we set $\Gamma_{a,i}$ as a constant and we found that $\frac{\partial^2 P_{L,i}}{\partial\Gamma_{b,i}^2} = -2P_a$, which implies $P_{L,i}$ is also a concave function in $\Gamma_{b,i}$. Similarly, for a given $\Gamma_{a,i}$, the maximum load power as obtained by solving $\frac{\partial P_{L,i}}{\partial\Gamma_{b,i}} = 0$ is $\Gamma_{b,i} = 0$. Hence, we proved Lemma 1.*

Lemma 2 *To ensure better receiver sensitivity at the reader while maximizing the average load power, we have to set $\Gamma_{b,i} = 0$ as compared to $\Gamma_{a,i} = 0$.*

Proof *Refer to Appendix A for the proof of Lemma 2.*

The following remark explains the practical use of Lemma 2 in the tag design.

Remark 2 *Since our BackCom system considers ASK modulation, the backscattered signal of the passive tag is designed to satisfy the phase-equality condition. Accordance to Lemma 2, we set $X_{n,i} = 0$, and $R_{n,i} = \frac{1+\Gamma_{a,i}}{1-\Gamma_{a,i}}$. The normalized load impedance plays a key parameter in the backscatter tag design [20].*

Using Lemma 2, and assuming $\Gamma_{a,1} \geq \Gamma_{a,2}$ without any loss of generality, we can reformulate the optimization problem $(P1)$ into $(P2)$ as defined below:

$$
\begin{aligned}
&(P2): \max_{\Gamma_{a,1},\Gamma_{a,2}} \quad P_{L,avg}\\
&\text{subject to} \quad C2,\\
&\qquad C6: \frac{\Gamma_{a,1}-\Gamma_{a,2}}{2} \geq m_{th},\\
&\qquad C7: P_a\left(1-\Gamma_{a,i}^2\right) \geq P_{L,min}, \quad \forall i=1,2.
\end{aligned}
$$

V. Proposed Solution Methodology

A. Problem Feasibility and Convexity

Before solving problem $(P2)$, we discuss its feasibility condition with Lemma 3.

Lemma 3 *If problem $(P2)$ is feasible, $m_{th} \leq \sqrt{1-\frac{P_{L,min}}{P_a}}$ is always true.*

Proof *Refer to Appendix B for the proof of Lemma 3.*

Next, we discuss the convexity of problem $(P2)$ with Lemma 4.

Lemma 4 *The problem $(P2)$ is a convex problem.*

Proof *Refer to Appendix C for the proof of Lemma 4.*

B. Implementation Detail

We denote the maximum average load power for problem $(P2)$ as $P^*_{L,avg}$, and the underlying optimal solution as $\mathbf{\Gamma}^* = \left[\Gamma^*_{a,1}, \Gamma^*_{a,2}, \Gamma^*_{b,1}=0, \Gamma^*_{b,2}=0\right]$. Since $(P2)$ is a convex problem, we can claim that the Karush-Kuhn-Tucker (KKT) point gives the global optimal solution. The Lagrangian of $(P2)$ is:

$$
\begin{aligned}
\mathcal{L} = &-p_1 P_a\left(1-\Gamma_{a,1}^2\right) - (1-p_1)P_a\left(1-\Gamma_{a,2}^2\right)\\
&+\lambda_1\left(m_{th}-\frac{\Gamma_{a,1}-\Gamma_{a,2}}{2}\right) + \lambda_2\left(\Gamma_{a,1}^2-1+\frac{P_{L,min}}{P_a}\right)\\
&+\lambda_3\left(\Gamma_{a,2}^2-1+\frac{P_{L,min}}{P_a}\right),
\end{aligned} \tag{8}
$$

where λ_1 represents the Lagrange multipliers associated with $C6$, and λ_2, λ_3 correspond to $C7$ for $i \in \{1,2\}$, respectively. The KKT point can be found by solving the following equations.

$$\frac{\partial \mathcal{L}}{\partial \Gamma_{a,1}} = 2p_1 P_a \Gamma_{a,1} - \frac{1}{2}\lambda_1 + 2\lambda_2\Gamma_{a,1} = 0, \tag{9}$$

$$\frac{\partial \mathcal{L}}{\partial \Gamma_{a,2}} = 2(1-p_1)P_a\Gamma_{a,2} + \frac{1}{2}\lambda_1 + 2\lambda_3\Gamma_{a,2} = 0, \tag{10}$$

$$\lambda_1\left(m_{th}-\frac{\Gamma_{a,1}-\Gamma_{a,2}}{2}\right) = 0, \tag{11}$$

$$\lambda_2\left(\Gamma_{a,1}^2-1+\frac{P_{L,min}}{P_a}\right) = 0, \tag{12}$$

$$\lambda_3\left(\Gamma_{a,2}^2-1+\frac{P_{L,min}}{P_a}\right) = 0. \tag{13}$$

where (9) and (10) are the sub-gradient conditions, and (11),(12),(13) are the complementary slackness conditions. While solving (9) – (13), we obtain $\mathbf{\Gamma}^*$ in terms of the constant parameters, and thereby determine $P^*_{L,avg}$. Subsequently, we discuss the method to determine the KKT point in Lemma 5.

Lemma 5 *We can obtain the global optimal solution $\mathbf{\Gamma}^*$ by considering 3 cases, which are case $(a): \lambda_1 \neq 0, \lambda_2 = \lambda_3 = 0$, case $(b): \lambda_1, \lambda_2 \neq 0, \lambda_3 = 0$, and case $(c): \lambda_1, \lambda_3 \neq 0, \lambda_2 = 0$.*

Proof *Since the objective function is decreasing with $\Gamma_{a,1}$ and $\Gamma_{a,2}$, the optimal solution without the constraints will have $\Gamma_{a,1} = \Gamma_{a,2} = 0$. However, constraint $C6$ requires a minimum separation between $\Gamma_{a,1}$ and $\Gamma_{a,2}$. Therefore constraint $C6$ is satisfied at equality, which implies λ_1 is always positive. It is noticed that λ_2 and λ_3 simultaneously greater than zero only when $m_{th} = \sqrt{1-\frac{P_{L,min}}{P_a}}$, which will obtain the same $\mathbf{\Gamma}^*$ at $\lambda_2 \neq 0$. Therefore, the optimal solution is given by either or both λ_2 and λ_3 are zero, while $\lambda_1 > 0$.*

Using Lemma 5, we proposed an algorithm to solve problem $(P2)$ and determine $\mathbf{\Gamma}^*$ and $P^*_{L,avg}$. We first consider case (a) and obtain the optimal solution by assuming it satisfied the boundary condition, denoted as $\Gamma^{(a)}_{a,i}$. Since λ_2 is associated with constraint $C7$, and $\Gamma_{a,1} \geq \Gamma_{a,2}$, the upper boundary condition will always satisfied when we set $\lambda_2 > 0$. Similarly, the lower boundary condition will always be satisfied when we set $\lambda_3 > 0$. Therefore, the global optimal solution is obtained from case (b) when $\Gamma^{(a)}_{a,1}$ is greater than the upper bound, and case (c) when $\Gamma^{(a)}_{a,2}$ is smaller than the lower bound. We summarize the problem $(P2)$ solving steps in Algorithm 1.

Algorithm 1 Optimal reflection coefficient design to maximize $P_{L,avg}$.

Input: p_1, m_{th}, $P_{L,min}$ and P_a

Output: $\Gamma^*_{a,1}$, $\Gamma^*_{a,2}$, $P^*_{L,avg}$

Set $\lambda_1 \neq 0, \lambda_2 = \lambda_3 = 0$,

$\Gamma^{(a)}_{a,1} = 2(1-p_1)m_{th}$, $\Gamma^{(a)}_{a,2} = -2p_1 m_{th}$

if $\Gamma^{(a)}_{a,1} > \sqrt{1-\frac{P_{L,min}}{P_a}}$ **then**

  Set $\lambda_1, \lambda_2 \neq 0, \lambda_3 = 0$,

  $\Gamma^*_{a,1} = \sqrt{1-\frac{P_{L,min}}{P_a}}$, $\Gamma^*_{a,2} = \sqrt{1-\frac{P_{L,min}}{P_a}} - 2m_{th}$

else if $\Gamma^{(a)}_{a,2} < -\sqrt{1-\frac{P_{L,min}}{P_a}}$ **then**

  Set $\lambda_1, \lambda_3 \neq 0, \lambda_2 = 0$,

  $\Gamma^*_{a,1} = -\sqrt{1-\frac{P_{L,min}}{P_a}} + 2m_{th}$, $\Gamma^*_{a,2} = -\sqrt{1-\frac{P_{L,min}}{P_a}}$

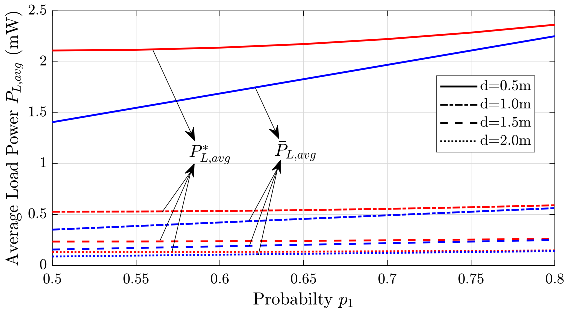

Fig. 2: Maximum average load power $P^*_{L,avg}$ for different probability p_1 with $m_{th} = 0.5$.

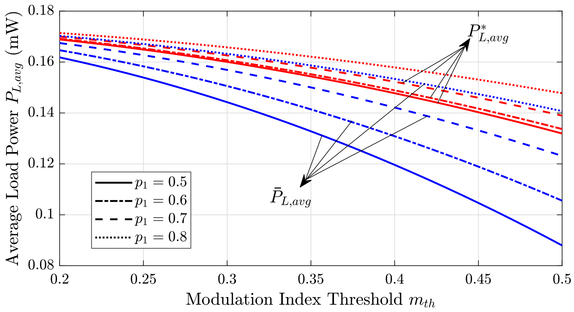

Fig. 4: Maximum average load power $P^*_{L,avg}$ for different m_{th}.

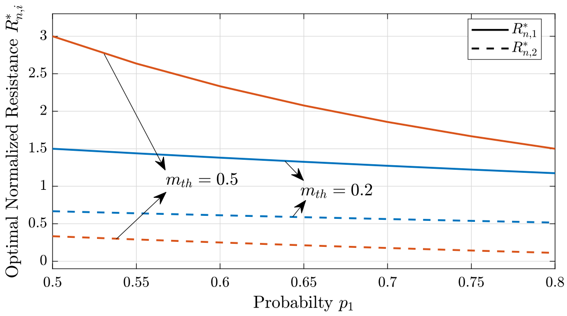

Fig. 3: Optimal normalized load resistance $R^*_{n,i}$ versus probability p_1 for $m_{th} = 0.2, 0.5$.

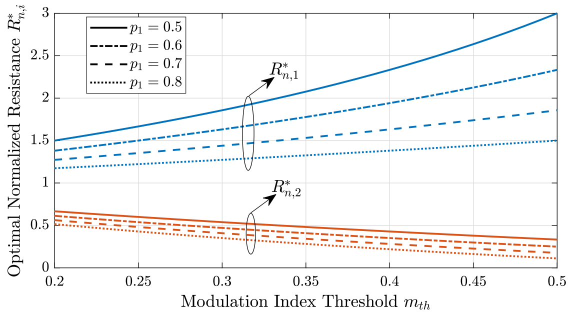

Fig. 5: Optimal normalized load resistance $R^*_{n,i}$ versus m_{th}.

else

$\quad \Gamma^*_{a,1} = \Gamma^{(a)}_{a,1}, \Gamma^*_{a,2} = \Gamma^{(a)}_{a,2}$

end

$P^*_{L,avg} = p_1 P_a \left(1 - \left(\Gamma^*_{a,1}\right)^2\right) + (1-p_1) P_a \left(1 - \left(\Gamma^*_{a,2}\right)^2\right)$

Algorithm 1 requires the system parameters p_1, m_{th}, $P_{L,min}$ and P_a as the input. After that, it generates decision making process subjected to the conditions derived from Lemma 5. Consequently, we obtain $\mathbf{\Gamma}^*$ along with the $P^*_{L,avg}$.

VI. RESULTS AND DISCUSSION

We numerically demonstrate the performance of the optimal results obtained from problem $(P2)$. Unless otherwise stated, we set $P_t = 1$W with RF $f = 900$MHz, $\lambda = \frac{1}{3}$m, $G_t = G_r = 1$, $P_{L,min} = 10^{-4.9}$W, and $m_{th} = 0.5$. We consider the tag design in [11]–[13] as the benchmark to highlight the merits of our optimal design. Hence, we denote $\bar{P}_{L,avg}$ as the average load power of the benchmark result, with the underlying load impedances $\bar{Z}_{n,1} = 1$ and $\bar{Z}_{n,2} = \frac{1+2m_{th}}{1-2m_{th}}$ correspond to bits '0' and '1'.

A. Impact of Probability p_1 on the Optimal Average Load Power $P^*_{L,avg}$

Here, we investigate the relationship between probability p_1 and $P^*_{L,avg}$ with $m_{th} = 0.5$. Specifically, we plot the maximum average load power $P^*_{L,avg}$ for different values of p_1 and transmission distance d.

In Fig. 2, we notice that the $P^*_{L,avg}$ is greater than $\bar{P}_{L,avg}$ for $d = 0.5, 1.0, 1.5, 2.0$ m. The proposed optimal maximum load power achieves an average gain of 22.6% over the benchmark. However, the gain decreases with p_1 because the benchmark result has the highest allowable average load power when $p_1 = 1$, and the increases in p_1 will approach this outcome. Hence, as p_1 increases, the optimal load impedances $Z^*_{n,1}$ and $Z^*_{n,2}$ will approach the benchmark load selection (see Fig. 3), resulting in $P^*_{L,avg}$ approaching $\bar{P}_{L,avg}$. Besides, we observe that $P^*_{L,avg}$ is increased with p_1. This is because $P^*_{L,1}$ increases, whereas $P^*_{L,2}$ decreases with p_1, resulting in greater $P^*_{L,avg}$. It is also noticed that $P^*_{L,avg}$ increases at a shorter transmission distance d because the output load power is inversely proportional to d.

Fig.3 gives insight into the optimal load impedance $Z^*_{n,i} = R^*_{n,i} + jX^*_{n,i}$ for different p_1. As the output power is maximum when $R_{n,i} = 1$, we observed that $R^*_{n,1}$ approaches 1 as p_1 increases, whereas $R^*_{n,2}$ approaches 0 to meet the BER requirement. Furthermore, as proved in Lemma 2, $X^*_{n,1} = X^*_{n,2} = 0$. We also noticed that $Z^*_{n,i}$ does not vary with d because the transmission range is not the optimal reflection coefficient variable.

B. Impact of m_{th} on Optimal Average Load Power $P^*_{L,avg}$

The value of m_{th} varies in different applications, which depends on the BER requirement. Therefore, we study the maximum average load power $P^*_{L,avg}$ for different modulation index thresholds m_{th} at $d = 2$m. Fig.4 shows $P^*_{L,avg}$ versus m_{th} for $p_1 = 0.5, 0.6, 0.7$ and 0.8, where the optimal normalized load impedance $Z^*_{n,i}$ is depicted in Fig.5. Likewise, we observed that $P^*_{L,avg} > \bar{P}_{L,avg}$. The average gain achieved by the proposed optimal result over the benchmark is 9.9%. It is also noticed that $P^*_{L,avg}$ decreases with m_{th} due to a greater mismatch degree between the backscattered signals, as shown in Fig.5.

VII. CONCLUSION

This paper aimed to maximize the average load power of the RFID passive tag with the optimal reflection coefficients while meeting the tag sensitivity and BER constraints. We transformed the original 4 variables problem into 2 variables convex optimization problem, and obtained the closed-form expression for the global optimal reflection coefficients. The simulation results have shown that the information bits probability and modulation index can significantly impact the maximum average load power. Besides, we found that the average load power with the optimal load impedances provided an average gain of 16.3% over the benchmark.

APPENDIX A
PROOF OF LEMMA 2

In the BackCom system, there is a minimum power requirement for the backscattered signal to ensure the reader can successfully identify the signal. The backscattered power $P_{s,i}$ when the tag connected to $Z_{L,i}$ is given by [23]:

$$\begin{aligned} P_{s,i} &\triangleq P_a G_r |1-\Gamma_i|^2 \\ &= P_a G_r \left[(1-\Gamma_{a,i})^2 + \Gamma_{b,i}^2\right], \quad \forall i = \{1,2\}, \end{aligned} \tag{14}$$

Now, we compare the 2 considered cases, where the first case assumed the reflection coefficient $\Gamma_{a,i}^{(1)} \neq 0, \Gamma_{b,i}^{(1)} = 0$, with the load power and backscattered power denoted as $P_{L,i}^{(1)}$ and $P_{s,i}^{(1)}$, respectively. The second case assumed the reflection coefficient $\Gamma_{a,i}^{(2)} = 0, \Gamma_{b,i}^{(2)} \neq 0$, with the load power and backscattered power denoted as $P_{L,i}^{(2)}$ and $P_{s,i}^{(2)}$, respectively. Then, we express the backscattered power in terms of load power as below:

$$P_{s,i}^{(1)} = P_a G_r \left(2 - \frac{P_{L,i}^{(1)}}{P_a} + 2\sqrt{1 - \frac{P_{L,i}^{(1)}}{P_a}}\right), \forall i = \{1,2\}, \tag{15}$$

$$P_{s,i}^{(2)} = P_a G_r \left(2 - \frac{P_{L,i}^{(2)}}{P_a}\right), \quad \forall i = \{1,2\}. \tag{16}$$

If we select the load impedance that gives $P_{L,i}^{(1)} = P_{L,i}^{(2)}$, we can clearly observed that $P_{s,i}^{(1)}$ is always greater than $P_{s,i}^{(2)}$. Hence, we proved Lemma 2.

APPENDIX B
PROOF OF LEMMA 3

Since $P_{L,min} \leq P_a$, constraint $C2$ will always satisfy when constraint $C7$ is satisfied in problem $(P2)$. Hence, from $C7$, we obtain the boundary condition for $\Gamma_{a,i}$ as below:

$$-\sqrt{1 - \frac{P_{L,min}}{P_a}} \leq \Gamma_{a,i} \leq \sqrt{1 - \frac{P_{L,min}}{P_a}} \tag{17}$$

As we consider $\Gamma_{a,1} \geq \Gamma_{a,2}$, the range of $(\Gamma_{a,1} - \Gamma_{a,2})$ from (17) is given by:

$$0 \leq (\Gamma_{a,1} - \Gamma_{a,2}) \leq 2\sqrt{1 - \frac{P_{L,min}}{P_a}} \tag{18}$$

Then, we rearrange constraint $C6$ of problem $(P2)$, and obtain the boundary condition for $(\Gamma_{a,1} - \Gamma_{a,2})$ as below:

$$\Gamma_{a,1} - \Gamma_{a,2} \geq 2m_{th} \tag{19}$$

While combining (18) and (19), we obtain:

$$m_{th} \leq \frac{\Gamma_{a,1} - \Gamma_{a,2}}{2} \leq \sqrt{1 - \frac{P_{L,min}}{P_a}} \tag{20}$$

Subsequently, we observe $m_{th} \leq \sqrt{1 - \frac{P_{L,min}}{P_a}}$ as the feasible condition to obtain a possible optimal solution when solving problem $(P2)$. Hence, we proved Lemma 3.

APPENDIX C
PROOF OF LEMMA 4

We determine the Hessian matrix of problem $(P2)$ objective function, which is given as [24]:

$$\begin{aligned} \mathbb{H} &= \begin{bmatrix} \frac{\partial^2 P_{L,avg}}{\partial \Gamma_{a,1}^2} & \frac{\partial^2 P_{L,avg}}{\partial \Gamma_{a,1} \partial \Gamma_{a,2}} \\ \frac{\partial^2 P_{L,avg}}{\partial \Gamma_{a,2} \partial \Gamma_{a,1}} & \frac{\partial^2 P_{L,avg}}{\partial \Gamma_{a,2}^2} \end{bmatrix} \\ &= \begin{bmatrix} -2p_1 P_a & 0 \\ 0 & -2(1-p_1) P_a \end{bmatrix} \end{aligned}$$

We observed that the diagonal entries of $\mathbb{H}$ are ≤ 0, and the determinant of $\mathbb{H}$ being non-negative, $|\mathbb{H}| \geq 0$. Hence, we proved that the objective function of the problem $(P2)$ is a concave function. Besides, it is clearly noticed that constraints $C2$ and $C6$ are linear, which are also convex.

Next, we set $f_i \triangleq P_{L,min} - P_a\left(1 - \Gamma_{a,i}^2\right)$ corresponds to constraint $C7$. The second derivative of f_i with respect to $\Gamma_{a,i}$ is $\frac{\partial^2 f_i}{\partial \Gamma_{a,i}^2} = 2P_a \geq 0$, which implies constraint $C7$ is convex. Since the objective function is a concave function, and the constraints $C2$, $C6$ and $C7$ are all convex, problem $(P2)$ is a convex optimization problem. Hence, we proved Lemma 4.

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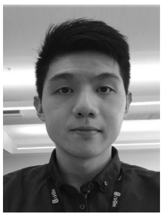

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