A Thresholding-Based Antenna Switching in SWIPT-Enabled MIMO Cognitive Radio Networks with Co-Channel Interference

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Abstract

In this paper, we consider the simultaneous wireless power and information transfer (SWIPT) for spectrum sharing (SS) in cognitive radio (CR) networks with a multiple antenna SWIPT-Enabled secondary receiver (SR). The SR harvests the energy from the signals sent from the secondary transmitter (ST) and the interfering signals sent from the primary transmitter (PT). Moreover, the ST uses the antenna switching (AS) technique which selects a subset of the antennas to decode the information and the rest to harvest the energy. The antenna selection is performed via a thresholding strategy inspired from the maximum ratio combining (MRC) technique with an output threshold (OT-MRC). The thresholding-based antenna selection strategy is proposed in two ways: one is prioritizing the information data and the other is prioritizing the harvested energy. For the two proposed selection schemes, we study the probability mass function of the selected antennas, the average harvested energy, and the data transmission outage probability. Through the analytic expressions and the simulation results, we show that there is a tradeoff between the outage probability and the harvested energy for both schemes. We see also that the preference of one scheme on the other is also affected by this energy-data trade off.

Index Terms

Energy harvesting, Simultaneous Wireless Information and Power Transfer (SWIPT), cognitive radio (CR), spectrum sharing (SS), antenna switching (AS), maximum ratio combining (MRC), outage probability, average harvested energy.

I. Introduction

Energy consumption and spectrum scarcity are two major issues in wireless communication systems. For the next generation of wireless communication systems, it is challenging to assure the energy efficiency as well the spectrum efficiency. On the one hand, cognitive radio (CR) networks are a promising solution to solve the spectrum scarcity. CR networks allow the unlicensed users to use the spectrum whenever the licensed users are idle [1]. For the spectrum sharing (SS) in CR networks, the unlicensed users and licensed users are allowed to share the spectrum as long as the interference induced by the unlicensed users do not harm the licensed users [2]. Various works have studied the spectrum sharing in CR networks with single/multiple antennas at the primary and secondary networks [3]–[5].

On the other hand, energy harvesting is a promising solution to make the wireless communication systems more energy efficient and self-sustainable. Among the various energy sources, the radio frequency (RF) signals are found to be a good source for energy harvesting. The process of the simultaneous use of RF signals for energy transfer and information transfer is known in the literature as the simultaneous wireless power and information transfer (SWIPT). The SWIPT technique was studied in single-input single-output (SISO) communication systems in [6], [7], in multiple-input multiple-output (MIMO) communication systems in [8], and in MIMO relay systems [9], [10]. Among the EH practical schemes studied in the literature, we state the power splitting (PS), the time switching (TS), and the antenna switching (AS) that separate the information decoding (ID) and energy harvesting (EH) transfer over the power, the time, and the space, respectively.

Subsequently, it is interesting to investigate the SWIPT technique in cognitive radio networks. Recently, various researchers have shown their interest to study the SWIPT technique in CR networks [11]–[15]. In [11], an opportunistic spectrum access scheme was considered in CR networks where secondary transmitters (STs) either harvest energy from ambient transmissions or transmit signals when primary transmitters (PTs) are far away. In [12], [13], [16], CR relay networks were considered where the ST or the secondary relay assists the primary transmission while harvesting the energy using the PS or TS scheme. In [16],the joint optimization of the power splitter factor and the energy allocation over N time slots which maximizes the throughput was considered and a suboptimal management algorithm was proposed in an amplify-and-forward (AF) relay cognitive network with one primary receiver, one cognitive transmitter-receiver, and one EH relay. The EH relay harvests the energy from the received signals using the PS scheme. In [12], the primary and secondary outage probability and the rate-energy tradeoff between the maximum ergodic capacity and the maximum harvested energy in the secondary network were analyzed in amplify-and-forward (AF) cognitive relay network where the ST and the SR have energy harvesting capabilities using the PS scheme. Moreover, ST acts as a relay for the primary transmission, harvests the energy from the primary signal, and forwards the primary signal and transmits to its receiver simultaneously. In [13], the optimal cooperation strategy, the time allocation and the power allocation were investigated in non-cooperation and cooperation modes to maximize the secondary user's achievable throughout in a CR network system where the ST acts as a decode-and-forward (DF) based-relay for the primary transmission. The ST is self-powered and harvests the energy from the ambient transmitters using the save-then-transmit protocol. In [14], [15], an underlay CR network is studied where the ST is self-powered and harvests the energy from the primary transmission. In [14], the online optimal time allocation between the EH phase and ID phase is proposed which maximizes the average achievable rate of the cognitive radio system, subject to the ϵ-percentile protection criteria for the primary system where the ST harvests the energy from the primary transmission. In [15], a channel quality based threshold and opportunistic scheduling were exploited in CR networks with one ST and multiple EH SRs under the peak interference power constraint of the PR and the ST maximum transmit power limit. Each SR is scheduled to harvest energy if the channel condition is above the threshold or to decode information if the channel condition is below the threshold. In this context, the analytical expressions of the secondary ergodic capacity, symbol error rate (SER), throughput, and energy harvesting were investigated.

In line with the research scope, we propose to investigate the SWIPT for spectrum sharing in MIMO CR networks where the SR harvests the energy from the primary and secondary transmission using the antenna switching technique. The antenna selection is based on a thresholding technique based on the maximum ratio combining (MRC) with an output threshold (OT-MRC). The OT-MRC combining technique was studied before in [17] where the co-channel interference (CCI) was not considered. In this paper, we propose two antenna selection schemes employing a thresholding technique based on OT-MRC with CCI: one scheme is prioritizing the information data and the second is prioritizing the harvested energy. For the two selection schemes, we derive the analytical expressions of the probability mass function (PMF) of the selected number of antennas connected to the ID circuits at SR, the average of the harvested energy, and the data transmission outage probability and we show that there is an energy-data tradeoff for the two schemes.

II. System Model

We consider a cognitive network consisting of a primary transmitter PT, a primary receiver PR, a secondary transmitter ST and a secondary receiver SR. While the PT, PR and ST are battery powered, the

SR is self-powered by its harvested energy from the RF signals sent from ST and PT. All the nodes are equipped with single antennas, except the SR which is equipped with multiple antennas N_2. The channel between the PT and the PR, the channel between the PT and the j'th antenna of SR, the channel between the ST and the j'th antenna of SR, and the channel between the ST and the PR are denoted by h_{pp}, h_{pj}, h_{sj}, and h_{sp}, $\forall j = 1, \ldots, N_2$.

A. SWIPT-Enabled Secondary Receiver

The SR harvests energy using the antenna switching (AS) technique. In fact, the AS technique assigns a subset of the multiple antennas to harvest energy and the remaining to decode the received data information. Let K_2 be the number of antennas connected to the ID circuits and $N_2 - K_2$ be the number of antennas connected to the EH circuits, with $K_2 \leq N_2$. How to choose K_2 will be discussed later.

For a given K_2, the combined signal-to-interference ratio (SIR) at the SR is given by

$$\gamma_{ID}\left(K_2\right) = \frac{P_s}{P_p} \frac{\sum_{j=1}^{K_2} |h_{sj}|^2}{\sum_{j=1}^{K_2} |h_{pj}|^2} = \frac{\Gamma_s(K_2)}{\Gamma_p(K_2)}, \tag{1}$$

where P_s is the transmit power at ST, P_p is the transmit power at PT, σ_s^2 is the variance of the additive white Gaussian noise (AWGN) at the PR, $\Gamma_s(K_2) = P_s \sum_{j=1}^{K_2} |h_{sj}|^2$ and $\Gamma_p(K_2) = P_p \sum_{j=1}^{K_2} |h_{pj}|^2$.

The harvested energy at SR is given by

$$Q\left(K_2\right) = \begin{cases} \zeta\left(\overline{\Gamma}_s\left(K_2\right) + \overline{\Gamma}_p\left(K_2\right)\right), & \text{if } 0 \leq K_2 < N_2, \\ 0, & \text{if } K_2 = N_2, \end{cases} \tag{2}$$

$$= \begin{cases} \zeta \sum_{j=K_2+1}^{N_2} \left(P_s|h_{sj}|^2 + P_p|h_{pj}|^2\right), & \text{if } 0 \leq K_2 < N_2 \\ 0, & \text{if } K_2 = N_2, \end{cases} \tag{3}$$

where $\overline{\Gamma}_s\left(K_2\right) = P_s \sum_{K_2+1}^{N_2} |h_{sj}|^2$ and $\overline{\Gamma}_p\left(K_2\right) = P_p \sum_{K_2+1}^{N_2} |h_{pj}|^2$ are the harvested energy from ST and PT, respectively, and ζ is the conversion efficiency.

Now, the question to ask is how to choose K_2. For that, we present two selection schemes based on a thresholding technique inspired from the OT-MRC technique studied in [17].

B. Thresholding-Based Antenna Selection Technique

In order to select the number of antennas K_2, we use a thresholding technique inspired from the OT-MRC technique in the presence of the co-channel interference (CCI) from PT. Note that the OT-MRC technique was previously considered only in the no CCI case [17]. In order to derive the OT-MRC technique with CCI, we will follow the same steps in [17].

Let $\Gamma(K_2)$ be the combined utility function to be specified depending the selection scheme considered. With OT-MRC, the number of antennas K_2 is selected so that the chosen combined utility function $\Gamma(K_2)$ above a certain predefined threshold. Starting from the single-antenna case, the OT-MRC combiner gradually raises the number of antennas in a way to raise $\Gamma(K_2)$ above the threshold γ_{th}. For more details about OT-MRC, please refer to [17].

In what follows, we consider two selection schemes based on different combined utility functions.

- Prioritizing Data Selection Scheme (SC_1):
  - $\Gamma(K_2)$ stands for the received power at ID circuits at SR from the desired transmitter ST, i.e. $\Gamma(K_2) = \Gamma_s(K_2)$.
  - K_2 corresponds to the case where $\Gamma_s(K_2)$ is greater than the threshold γ_{th}.
- Prioritizing Energy Selection Scheme (SC_2):
  - $\Gamma(K_2)$ stands for the received power at EH circuits at SR (proportional to the harvested energy) from the desired transmitter ST, i.e. $\Gamma(K_2) = \overline{\Gamma}_s(K_2)$.
  - K_2 corresponds to the case where $\overline{\Gamma}_s(K_2)$ is greater than the threshold γ_{th}.

C. Performance Metrics

In order to evaluate the performance of the considered selection schemes, we propose to study the performance metrics such as the PMF $P_{K_2}(k_2)$ of K_2, the expected value of the harvested energy, and the data transmission outage probability. The expected value of the harvested energy is defined as

$$\overline{Q} = \mathbb{E}[Q] = \sum_{k_2=1}^{N_2-1} \mathbb{E}[Q(k_2) \mid K_2 = k_2] P_{K_2}(k_2) \tag{4}$$

$$= \zeta \sum_{k_2=1}^{N_2-1} \mathbb{E}\left[\overline{\Gamma}_s(k_2) + \overline{\Gamma}_p(k_2) \mid K_2 = k_2\right] P_{K_2}(k_2). \tag{5}$$

In addition, the data transmission outage probability at SR is defined as

$$P_{D,out}(x) = P(\gamma_{ID} < x) = \sum_{k_2=1}^{N_2-1} P(\gamma_{ID}(k_2) < x \,\&\, K_2 = k_2) \tag{6}$$

$$= \sum_{k_2=1}^{N_2-1} P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \,\&\, K_2 = k_2\right), \tag{7}$$

where $X = 2^R - 1$ and R is the transmission rate at ST. If the selection of K_2 is independent of $\Gamma_s(K_2)$ and $\Gamma_p(K_2)$, then

$$P_{D,out}(x) = \sum_{k_2=1}^{N_2-1} P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \mid K_2 = k_2\right) P_{K_2}(k_2). \tag{8}$$

III. Prioritizing Data Selection Scheme (SC_1)

A. Mode of Operation

The prioritizing data selection scheme SC_1 selects the antennas K_2 in a way to assure that the received power from the desired transmitter ST at the information decoding receivers at SR is above a certain predefined threshold. Here, the utility combined function stands for the received power at ID circuits at SR from the desired transmitter ST, i.e. $\Gamma(K_2) = \Gamma_s(K_2)$. The selected number of antennas K_2 corresponds to the case where $\Gamma_s(K_2)$ is greater than the threshold γ_{th}. For SC_1, the thresholding procedure is as follows:

- Start with $j = 1$ and $\Gamma_s(1) = \gamma_{s,1}$.
- If $\Gamma_s(j) < \gamma_{th}$, update $\Gamma_s(j+1) = \Gamma_s(j) + \gamma_{s,j+1}$ and $j = j + 1$.
- Repeat until $\Gamma_s(j) \geq \gamma_{th}$ or $j \geq N_2 - 1$.

At the end, K_2 will be equal to j.

Remark 1: Note that the selected number of antennas K_2 cannot be equal to zero or to N_2 in a way to avoid the two worse cases when all the receiving antennas are used for harvesting energy and no antennas are used for decoding information ($K_2 = 0$, i.e. no data) and when all the receiving antennas are used for decoding information and no antennas are used for harvesting energy ($K_2 = N_2$, i.e. no energy). Same remark hold for the selection scheme SC_2.

B. PMF of K_2

Based on the selection scheme SC_1, the PMF of K_2 is given by:

$$P^{(1)}_{K_2}(k_2) = \begin{cases} P\left(\Gamma_s(1) \geq \gamma_{th}\right), & \text{if } k_2 = 1, \\ P\left(\Gamma_s(k_2 - 1) < \gamma_{th} \leq \Gamma_s(k_2)\right), & \text{if } k_2 = 2, \dots, N_2 - 2, \\ P\left(\Gamma_s(N_2 - 2) < \gamma_{th}\right), & \text{if } k_2 = N_2 - 1. \end{cases} \tag{9}$$

$$= \begin{cases} 1 - F^{(1)}_{\gamma_s}\left(\gamma_{th}\right), & \text{if } k_2 = 1, \\ F^{(k_2-1)}_{\gamma_s}\left(\gamma_{th}\right) & \\ - \int_0^{\gamma_{th}} f^{(1)}_{\gamma_s}(z) F^{(k_2-1)}_{\gamma_s}\left(\gamma_{th} - z\right) \mathrm{d}z, & \text{if } k_2 = 2, \dots, N_2 - 2, \\ F^{(N_2-2)}_{\gamma_s}\left(\gamma_{th}\right), & \text{if } k_2 = N_2 - 1. \end{cases} \tag{10}$$

where $f^{(k_2)}_{\gamma_s}(\cdot)$ and $F^{(k_2)}_{\gamma_s}(\cdot)$ are the PDF and CDF of $\Gamma_s(k_2)$, respectively, for $k_2 = 1, \dots, N_2 - 1$.

C. Average of Harvested Energy

The average harvested energy at SR is given by

$$\overline{Q}^{(1)} = \zeta \sum_{k_2=1}^{N_2-1} (N_2 - k_2) \left(P_s \mathbb{E}\left[|h_{sj}|^2\right] + P_p \mathbb{E}\left[|h_{pj}|^2\right] \right) P_{K_2}^{(1)}(k_2). \tag{11}$$

D. Data Transmission Outage Probability

The outage probability at SR is given by

$$\begin{aligned} P_{D,out}^{(1)}(x) &= P\left(\frac{\Gamma_s(1)}{\Gamma_p(1)} < x \;\&\; \Gamma_s(1) \geq \gamma_{th} \right) \\ &\quad + \sum_{k_2=2}^{N_2-2} P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \;\&\; \Gamma_s(k_2-1) < \gamma_{th} \leq \Gamma_s(k_2) \right) \\ &\quad + P\left(\frac{\Gamma_s(N_2-1)}{\Gamma_p(N_2-1)} < x \;\&\; \Gamma_s(N_2-2) < \gamma_{th} \right) \qquad (12) \\ &= \mathcal{I}_1(x,\gamma_{th}) + \sum_{k_2=2}^{N_2-2} \mathcal{I}_{k_2}(x,\gamma_{th}) + \mathcal{I}_{N_2-1}(x,\gamma_{th}), \qquad (13) \end{aligned}$$

where

$$\mathcal{I}_1(x,\gamma_{th}) = P\left(\frac{\Gamma_s(1)}{\Gamma_p(1)} < x \;\&\; \Gamma_s(1) \geq \gamma_{th} \right), \tag{14}$$

$$\mathcal{I}_{k_2}(x,\gamma_{th}) = P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \;\&\; \Gamma_s(k_2-1) < \gamma_{th} \leq \Gamma_s(k_2) \right), \tag{15}$$

$$\mathcal{I}_{N_2-1}(x,\gamma_{th}) = P\left(\frac{\Gamma_s(N_2-1)}{\Gamma_p(N_2-1)} < x \;\&\; \Gamma_s(N_2-2) < \gamma_{th} \right), \tag{16}$$

which were shown in Appendix B to be given by

$$\mathcal{I}_1(x,\gamma_{th}) = \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy)\, f_{\gamma_p}^{(1)}(y)\, \mathrm{d}y - F_{\gamma_s}^{(1)}(\gamma_{th}) \left[1 - F_{\gamma_p}^{(1)}\left(\frac{\gamma_{th}}{x} \right) \right], \tag{17}$$

$$\begin{aligned} \mathcal{I}_{k_2}(x,\gamma_{th}) &= \int_{\frac{\gamma_{th}}{x}}^{\infty} \left[\int_{xy-\gamma_{th}}^{xy} F_{\gamma_s}^{(k_2-1)}(-z+xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z \right] f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y \\ &\quad - \left[1 - F_{\gamma_p}^{(k_2)}\left(\frac{\gamma_{th}}{x} \right) \right] \int_0^{\gamma_{th}} F_{\gamma_s}^{(k_2-1)}(\gamma_{th} - z)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z \\ &\quad + F_{\gamma_s}^{(k_2-1)}(\gamma_{th}) \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy - \gamma_{th})\, f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y, \end{aligned} \tag{18}$$

and

$$\begin{aligned} \mathcal{I}_{N_2-1}(x,\gamma_{th}) &= \int_{\frac{\gamma_{th}}{x}}^{\infty} \left[\int_{xy-\gamma_{th}}^{xy} F_{\gamma_s}^{(N_2-2)}(-z+xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z \right] f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y \\ &\quad + \int_0^{\frac{\gamma_{th}}{x}} \left[\int_0^{xy} F_{\gamma_s}^{(N_2-2)}(-z+xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z \right] f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y \\ &\quad + F_{\gamma_s}^{(N_2-2)}(\gamma_{th}) \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy - \gamma_{th})\, f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y. \end{aligned} \tag{19}$$

Consequently, the outage probability is given by (20), where $f_{\gamma_p}^{(k_2)}(\cdot)$ and $F_{\gamma_p}^{(k_2)}(\cdot)$ are the PDF and CDF of $\Gamma_p(k_2)$, respectively, for $k_2 = 1, \ldots, N_2 - 1$.

$$P_{D,out}^{(1)}(x) = \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy)\, f_{\gamma_p}^{(1)}(y)\, \mathrm{d}y - F_{\gamma_s}^{(1)}(\gamma_{th})\left[1 - F_{\gamma_p}^{(1)}\left(\frac{\gamma_{th}}{x}\right)\right] + \sum_{k_2=2}^{N_2-1} \int_{\frac{\gamma_{th}}{x}}^{\infty}\left[\int_{xy-\gamma_{th}}^{xy} F_{\gamma_s}^{(k_2-1)}(-z+xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y$$
$$+ \int_0^{\frac{\gamma_{th}}{x}}\left[\int_0^{xy} F_{\gamma_s}^{(N_2-2)}(-z+xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y - \sum_{k_2=2}^{N_2-2} \int_{\frac{\gamma_{th}}{x}}^{\infty}\left[\int_0^{\gamma_{th}} F_{\gamma_s}^{(k_2-1)}(\gamma_{th}-z)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y$$
$$+ \sum_{k_2=2}^{N_2-1} F_{\gamma_s}^{(k_2-1)}(\gamma_{th}) \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy-\gamma_{th})\, f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y. \tag{20}$$

E. Example: Rayleigh Fading Special Case

Let us assume that all the channels h_{pp}, h_{pj}, h_{kj}, and h_{kp} are modeled as flat fading with Rayleigh distribution with variances λ_{pp}, λ_{ps}, λ_{ss} and λ_{sp}, respectively.

1) PMF of K_2:

The PMF of K_2 can be written as

$$P_{K_2}^{(1)}(k_2) = \begin{cases} e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}, & \text{if } k_2 = 1, \\ \frac{\gamma\left(k_2-1, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)}{\Gamma(k_2-1)} \\ -\frac{e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}}{\Gamma(k_2-1)} \int_0^{\frac{\gamma_{th}}{P_s\lambda_{ss}}} e^u \gamma(k_2-1, u)\, \mathrm{d}u, & \text{if } k_2 = 2, \ldots, N_2-2, \\ \frac{1}{\Gamma(N_2-2)}\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right), & \text{if } k_2 = N_2-1, \end{cases} \tag{21}$$

where $\Gamma(\cdot)$ and $\gamma(\cdot,\cdot)$ are the Gamma function and the lower incomplete Gamma function [18], respectively. Using $\int_0^a \gamma(k-1,t)\, e^t\, \mathrm{d}t = \frac{e^a}{k-1}\gamma(k,a)$ which was proven in Appendix A-A, it can be shown that:

$$\int_0^{\frac{\gamma_{th}}{P_s\lambda_{ss}}} e^u \gamma(k_2-1, u)\, \mathrm{d}u = e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}\gamma\left(k_2-1, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) - \frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1}}{k_2-1}. \tag{22}$$

Subsequently, we deduce that

$$P_{K_2}^{(1)}(k_2) = \begin{cases} \frac{1}{\Gamma(k_2)}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1} e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}, & \text{if } k_2 = 1, \ldots, N_2-2, \\ \frac{1}{\Gamma(N_2-2)}\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right), & \text{if } k_2 = N_2-1, \end{cases} \tag{23}$$

where $\Gamma(\cdot)$ and $\gamma(\cdot,\cdot)$ are the Gamma function and the lower incomplete Gamma function [18], respectively.

2) Average of Harvested Energy:

For the Rayleigh fading channels, the average harvested energy at SR can be written as (25), where $\Gamma(\cdot,\cdot)$ is the upper incomplete gamma function [18]. Note that (25) was obtained using $\sum_{m=0}^{s-1} \frac{x^k}{\Gamma(k+1)} = \frac{e^x\Gamma(s,x)}{\Gamma(s)}$ in [18, (8.352.4)] and the corresponding derivative $\sum_{m=0}^{s-1} \frac{kx^{k-1}}{\Gamma(k+1)} = \frac{e^x\Gamma(s,x)}{\Gamma(s)} - \frac{x^{s-1}}{\Gamma(s)}$.

3) Data Transmission Outage Probability:

For the Rayleigh fading channels, we have shown in Appendix B that $\mathcal{I}_1(x,\gamma_{th})$, $\mathcal{I}_{k_2}(x,\gamma_{th})$ and $\mathcal{I}_{N_2-1}(x,\gamma_{th})$

$$\overline{Q}^{(1)} = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right)\left[e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\sum_{k_2=1}^{N_2-2}(N_2-k_2)\frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1}}{\Gamma(k_2)} + \frac{1}{\Gamma(N_2-2)}\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\right] \tag{24}$$

$$= \frac{\zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right)}{\Gamma\left(N_2-2\right)}\left[\left(N_2 - 1 - \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) + e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2} + \gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\right], \tag{25}$$

$$P_{D,out}^{(1)}(x) = \frac{xP_p\lambda_{ps}e^{-\gamma_{th}\left(\frac{1}{P_s\lambda_{ss}}+\frac{1}{xP_p\lambda_{ps}}\right)}}{xP_p\lambda_{ps} + P_s\lambda_{ss}} - \sum_{k_2=2}^{N_2-2}\frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1}e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}}{\Gamma(k_2)^2}\left[\frac{e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}\Gamma\left(k_2, \gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)\right)}{\left(x\frac{P_p\lambda_{ps}}{P_s\lambda_{ss}} + 1\right)^{k_2}} - \Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)\right]$$
$$- \frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2}\Gamma\left(N_2-1, \gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)\right)}{\Gamma(N_2-1)^2\left(x\frac{P_p\lambda_{ps}}{P_s\lambda_{ss}} + 1\right)^{N_2-1}} + \frac{(N_2-2)\,\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-1, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(N_2-1)^2}$$
$$+ \int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}\frac{\gamma\left(N_2-1, u\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)u^{N_2-2}e^{-u}}{\Gamma(N_2-1)^2}\,\mathrm{d}u. \tag{29}$$

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are given by

$$\mathcal{I}_1\left(x, \gamma_{th}\right) = \frac{xP_p\lambda_{ps}}{xP_p\lambda_{ps} + P_s\lambda_{ss}}e^{-\gamma_{th}\left(\frac{1}{P_s\lambda_{ss}}+\frac{1}{xP_p\lambda_{ps}}\right)}, \tag{26}$$

$$\mathcal{I}_{k_2}\left(x, \gamma_{th}\right) = \frac{e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1}}{\Gamma(k_2)^2}\left[\Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)\right.$$
$$\left. - \frac{e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}\Gamma\left(k_2, \gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)\right)}{\left(P_p\lambda_{ps}\right)^{k_2}\left(\frac{x}{P_s\lambda_{ss}} + \frac{1}{P_p\lambda_{ps}}\right)^{k_2}}\right], \tag{27}$$

and

$$\mathcal{I}_{N_2-1}\left(x, \gamma_{th}\right) = \frac{\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-1, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma\left(N_2-2\right)\Gamma\left(N_2-1\right)}$$
$$- \frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2}\Gamma\left(N_2-1, \gamma_{th}\left(\frac{1}{xP_p\lambda_{ps}} + \frac{1}{P_s\lambda_{ss}}\right)\right)}{\Gamma\left(N_2-1\right)^2\left(P_p\lambda_{ps}\right)^{N_2-1}\left(\frac{1}{P_p\lambda_{ps}} + \frac{x}{P_s\lambda_{ss}}\right)^{N_2-1}}$$
$$+ \frac{1}{\Gamma(N_2-1)^2}\int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}\gamma\left(N_2-1, u\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)u^{N_2-2}e^{-u}\,\mathrm{d}u. \tag{28}$$

Consequently, the outage probability is given by (29).

4) Remarks and Asymptotic Results:

- When $\frac{\gamma_{th}}{P_s\lambda_{ss}} \to 0$, we can see that $K_2 \approx 1$, $\overline{Q}^{(1)} \approx (N_2-1)q_1$, and

$$P_{D,out}^{(1)}(x) \approx \frac{xP_p\lambda_{ps}}{xP_p\lambda_{ps} + P_s\lambda_{ss}}e^{-\gamma_{th}\left(\frac{1}{P_s\lambda_{ss}}+\frac{1}{xP_p\lambda_{ps}}\right)}, \tag{30}$$

where $q_1 = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right) P_{K_2}^{(1)}(1) = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right) e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}$.

- When $\frac{\gamma_{th}}{P_s\lambda_{ss}} \to \infty$, we can see that $K_2 \approx N_2 - 1$, $\overline{Q}^{(1)} \approx q_2$, and

$$P_{D,out}^{(1)}(x) \approx \frac{\gamma\left(N_2 - 2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2 - 1, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(N_2 - 2)\,\Gamma(N_2 - 1)} \approx \frac{\Gamma\left(N_2 - 1, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(N_2 - 1)}, \tag{31}$$

where $q_2 = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right) P_{K_2}^{(1)}(N_2 - 1) = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right) \frac{1}{\Gamma(N_2-2)}\gamma\left(N_2 - 2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)$.

IV. Prioritizing Energy Selection Scheme (SC_2)

A. Mode of Operation

By contrast to the prioritizing data selection scheme SC_1, the prioritizing energy selection scheme SC_2 selects the antennas K_2 in a way to assure that the received power from the desired transmitter ST at the EH receivers at SR is above a certain predefined threshold. Hence, the utility combined function stands for the received power at EH circuits at SR (proportional to the harvested energy) from the desired transmitter ST, i.e. $\Gamma(K_2) = \overline{\Gamma}_s(K_2)$. The selected number of antennas K_2 corresponds to the case where $\overline{\Gamma}_s(K_2)$ is greater than the threshold γ_{th}. For SC_2, the thresholding procedure is as follows:

- Start with $j = N_2 - 1$ and $\overline{\Gamma}_s(N_2 - 1) = \gamma_{N_2}$.
- If $\overline{\Gamma}_s(j) < \gamma_{th}$, update$j = j - 1$ and $\overline{\Gamma}_s(j) = \overline{\Gamma}_s(j + 1) + \gamma_{s,j+1}$.
- Repeat until $\overline{\Gamma}_s(j) \geq \gamma_{th}$ or $j \leq 1$.

At the end, K_2 will be equal to j.

B. PMF of K_2

The PMF of K_2 is given by:

$$P_{K_2}^{(2)}(k_2) = \begin{cases} P\left(\overline{\Gamma}_s(2) < \gamma_{th}\right), & \text{if } k_2 = 1, \\ P\left(\overline{\Gamma}_s(k_2 + 1) < \gamma_{th} \leq \overline{\Gamma}_s(k_2)\right), & \text{if } k_2 = 2, \ldots, N_2 - 2, \\ P\left(\overline{\Gamma}_s(N_2 - 1) \geq \gamma_{th}\right), & \text{if } k_2 = N_2 - 1. \end{cases} \tag{32}$$

$$= \begin{cases} F_{\gamma_s}^{(N_2-2)}(\gamma_{th}), & \text{if } k_2 = 1, \\ F_{\gamma_s}^{(N_2-k_2-1)}(\gamma_{th}) - \int_0^{\gamma_{th}} f_{\gamma_s}^{(1)}(z) F_{\gamma_s}^{(N_2-k_2-1)}(\gamma_{th} - z)\, \mathrm{d}z, & \text{if } k_2 = 2, \ldots, N_2 - 2, \\ 1 - F_{\gamma_s}^{(1)}(\gamma_{th}), & \text{if } k_2 = N_2 - 1, \end{cases} \tag{33}$$

where $f_{\gamma_s}^{(N_2-k_2)}(\cdot)$ and $F_{\gamma_s}^{(N_2-k_2)}(\cdot)$ are the PDF and CDF of $\overline{\Gamma}_s(k_2)$, respectively, for $k_2 = 1, \ldots, N_2 - 1$.

$$P_{D,out}^{(2)}(x) = \sum_{k_2=1}^{N_2-1} P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \mid K_2 = k_2\right) P_{K_2}(k_2) = \sum_{k_2=1}^{N_2-1} \left[\int_0^\infty f_{\gamma_p}^{(k_2)}(y) F_{\gamma_s}^{(k_2)}(xy)\, \mathrm{d}y\right] P_{K_2}(k_2) \tag{35}$$

$$= \left[\int_0^\infty f_{\gamma_p}^{(1)}(y) F_{\gamma_s}^{(1)}(xy)\, \mathrm{d}y\right] F_{\gamma_s}^{(N_2-2)}(\gamma_{th}) + \sum_{k_2=2}^{N_2-2} \left[\int_0^\infty f_{\gamma_p}^{(k_2)}(y) F_{\gamma_s}^{(k_2)}(xy)\, \mathrm{d}y\right]$$
$$\times \left(F_{\gamma_s}^{(N_2-k_2-1)}(\gamma_{th}) - \int_0^{\gamma_{th}} f_{\gamma_s}^{(1)}(z) F_{\gamma_s}^{(N_2-k_2-1)}(\gamma_{th} - z)\, \mathrm{d}z\right) + \left[\int_0^\infty f_{\gamma_p}^{(N_2-1)}(y) F_{\gamma_s}^{(N_2-1)}(xy)\, \mathrm{d}y\right]\left(1 - F_{\gamma_s}^{(1)}(\gamma_{th})\right). \tag{36}$$

$$\overline{Q}^{(2)} = \zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right)\left[\frac{(N_2-1)}{\Gamma(N_2-2)}\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) + e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}} \sum_{k_2=2}^{N_2-1} (N_2-k_2)\frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-k_2-1}}{\Gamma(N_2-k_2)}\right] \tag{38}$$

$$= \frac{\zeta\left(P_s\lambda_{ss} + P_p\lambda_{ps}\right)}{\Gamma(N_2-2)}\left[(N_2-1)\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) + \left(1 + \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) - e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2}\right], \tag{39}$$

C. Average of Harvested Energy

The average harvested energy at SR is given by

$$\overline{Q}^{(2)} = \zeta \sum_{k_2=1}^{N_2-1} (N_2-k_2)\left(P_s\mathbb{E}\left[|h_{sj}|^2\right] + P_p\mathbb{E}\left[|h_{pj}|^2\right]\right) P_{K_2}^{(2)}(k_2). \tag{34}$$

D. Data Transmission Outage Probability

The outage probability at SR is given by (36).

E. Example: Rayleigh Fading Special Case

1) PMF of K_2:

Similarly to $P_{K_2}^{(1)}(k_2)$, we can show that

$$P_{K_2}^{(2)}(k_2) = \begin{cases} \frac{1}{\Gamma(N_2-2)}\gamma\left(N_2-2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right), & \text{if } k_2 = 1, \\ \frac{1}{\Gamma(N_2-k_2)}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-k_2-1} e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}, & \text{if } k_2 = 2, \ldots, N_2-1. \end{cases} \tag{37}$$

2) Average of Harvested Energy:

For the Rayleigh fading channels, the average harvested energy at SR can be written as (39), which was obtained in a similar way as (25).

$$P_{D,out}^{(2)}(x) = \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}} \frac{\gamma\left(N_2 - 2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)}{\Gamma(N_2 - 2)} + e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}} \sum_{k_2=2}^{N_2-1} \frac{\Gamma(2k_2)\left(xP_p\lambda_{ps}P_s\lambda_{ss}\right)^{k_2}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-k_2-1}}{\Gamma(k_2)^2 k_2 \Gamma(N_2 - k_2)\left(P_s\lambda_{ss} + xP_p\lambda_{ps}\right)^{2k_2}}$$

$$\times {}_2F_1\left(1, 2k_2; k_2 + 1; \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}}\right). \tag{43}$$

---

3) Data Transmission Outage Probability:

For the Rayleigh fading channels, we can write

$$\int_0^\infty f_{\gamma_p}^{(k_2)}(y) F_{\gamma_s}^{(k_2)}(xy)\,\mathrm{d}y = \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}}, \tag{40}$$

$$\int_0^\infty f_{\gamma_p}^{(k_2)}(y) F_{\gamma_s}^{(k_2)}(xy)\,\mathrm{d}y = \frac{1}{\Gamma(k_2)^2 \left(P_p\lambda_{ps}\right)^{k_2}} \int_0^\infty y^{k_2-1} e^{-\frac{y}{P_p\lambda_{ps}}} \gamma\left(k_2, \frac{xy}{P_s\lambda_{ss}}\right) \mathrm{d}y \tag{41}$$

$$= \frac{\Gamma(2k_2)}{\Gamma(k_2)^2 k_2} \frac{\left(xP_p\lambda_{ps}P_s\lambda_{ss}\right)^{k_2}}{\left(P_s\lambda_{ss} + xP_p\lambda_{ps}\right)^{2k_2}} {}_2F_1\left(1, 2k_2; k_2 + 1; \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}}\right), \tag{42}$$

where (42) was obtained using [18, (6.455.2)] and ${}_2F_1(a, b; c; z)$ is the Gaussian hypergeometric function. Hence, we deduce that the outage probability can be written as in (43).

4) Remarks and Asymptotic Results:

- First, we can see that $P_{K_2}^{(2)}(k_2) = P_{K_2}^{(1)}(N_2 - k_2)$ if SC_1 and SC_2 use the same predefined threshold γ_{th}.

- When $\frac{\gamma_{th}}{P_s\lambda_{ss}} \to 0$, we can see that $K_2 \approx N_2 - 1$, $\overline{Q}^{(2)} \approx q_1$, and

$$P_{D,out}^{(2)}(x) \approx e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}} \frac{\Gamma(2(N_2-1))}{\Gamma(N_2-1)^2(N_2-1)} \frac{\left(xP_p\lambda_{ps}P_s\lambda_{ss}\right)^{N_2-1}}{\left(P_s\lambda_{ss} + xP_p\lambda_{ps}\right)^{2(N_2-1)}} {}_2F_1\left(1, 2(N_2-1); N_2; \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}}\right). \tag{44}$$

- When $\frac{\gamma_{th}}{P_s\lambda_{ss}} \to \infty$, we can see that $K_2 \approx 1$, $\overline{Q}^{(2)} \approx (N_2 - 1)q_2$, and

$$P_{D,out}^{(2)}(x) \approx \frac{xP_p\lambda_{ps}\gamma\left(N_2 - 2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)}{\left(P_s\lambda_{ss} + xP_p\lambda_{ps}\right)\Gamma(N_2 - 2)} \approx \frac{xP_p\lambda_{ps}}{P_s\lambda_{ss} + xP_p\lambda_{ps}}. \tag{45}$$

V. Simulation Results

In this section, we present some selected simulations to show the accuracy of the obtained analytical expressions and to compare the two selection schemes SC_1 and SC_2. In all the figures, the channels follow the Rayleigh distribution. The number of simulations is $N_{sim} = 10^4$. The transmit power at PT is equal to $P_p = 10$ dBm. The variances of the channels are chosen equal to $\lambda_{pp} = \lambda_{sp} = 30$ dBm. The noise variances at PR and SR are both equal to $\sigma_p^2 = \sigma_s^2 = -110$ dBm. The conversion efficiency of the EH circuits at PR is $\zeta = 60\%$. The transmission rate at ST is chosen equal to 2 bps/Hz.

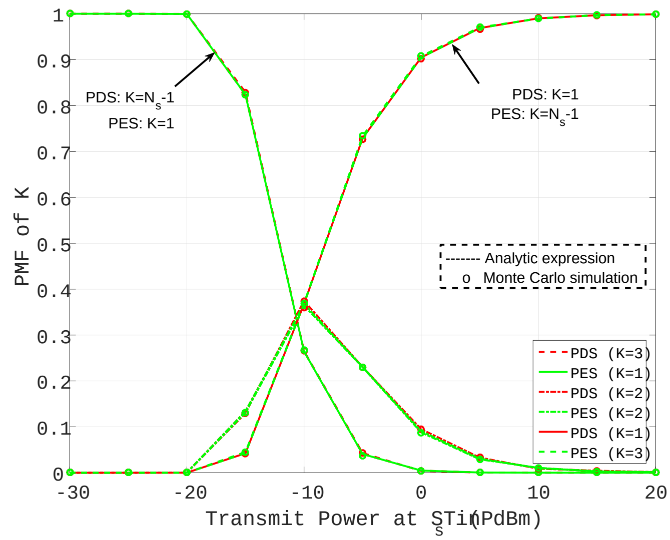
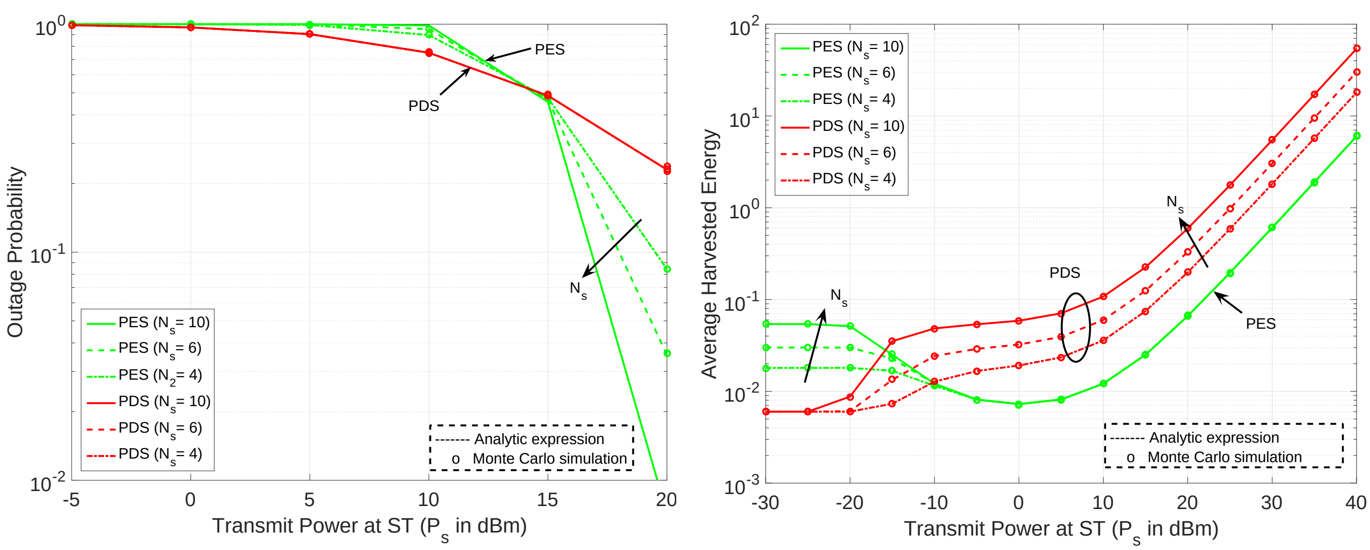


Figure 1: The probability mass function of K_2 versus the transmit power at SR P_s in dBm, with $N_2 = 4$, $\lambda_{ss} = \lambda_{ps} = 30$ dBm, and $\gamma_{th} = -10$ dBm for the two selection schemes SC_1 and SC_2.

In Fig. 1, we plotted the PMF of K_2 versus the transmit power P_s at ST in dBm, respectively, for $N_2 = 4$, $\lambda_{ss} = \lambda_{ps} = 30$ dBm, and $\gamma_{th} = -10$ dBm for the two selection schemes SC_1 and SC_2. We can see that for the low power regime, K_2 goes to $N_2 - 1$ for SC_1 and goes to 1 for SC_2. However, for the high power regime, K_2 goes to 1 for SC_1 and goes to $N_2 - 1$ for SC_2.

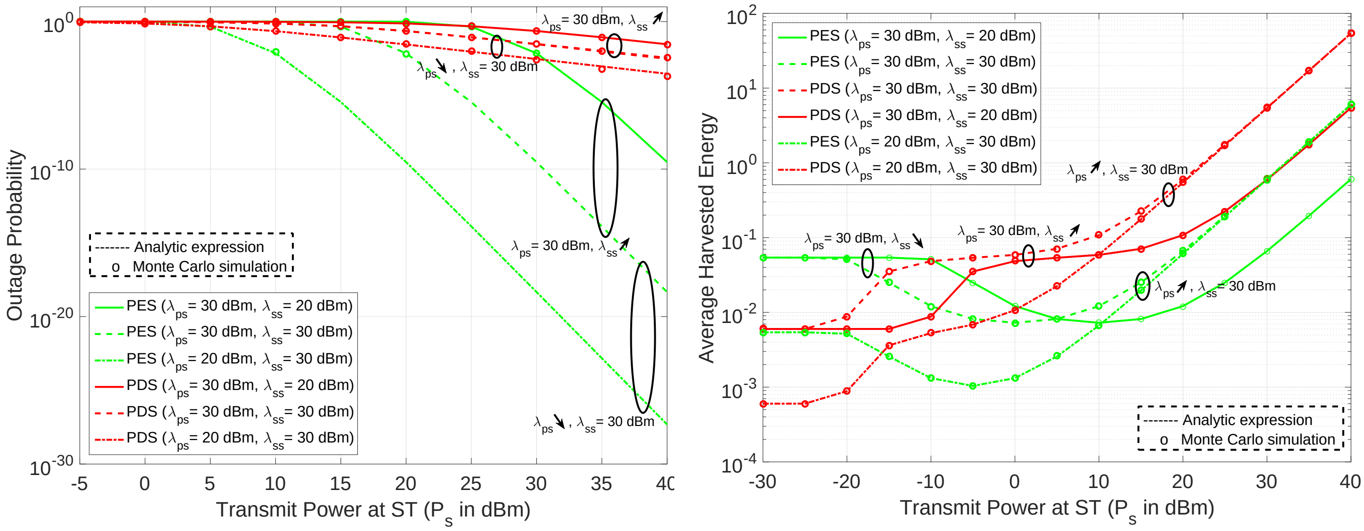


(a) (b)

Figure 2: (a) The outage probability $P_{D,out}$ and (b) the average harvested energy $\overline{Q}$ versus the transmit power at SR P_s in dBm, with $\lambda_{ss} = \lambda_{ps} = 30$ dBm, $\gamma_{th} = -10$ dBm and different values of N_2 for the two selection schemes SC_1 and SC_2.

In Figs. 2a and 2b, we plotted the outage probability and the average harvested energy versus the transmit power P_s at ST in dBm, respectively, for $\lambda_{ss} = \lambda_{ps} = 30$ dBm, $\gamma_{th} = -10$ dBm and different values of N_2 for the two selection schemes SC_1 and SC_2. On the one hand, from an outage probability stand point, we can see that SC_1 outperforms SC_2 for a transmit power constraint $P_s \leq 15$ dBm, while for $P_s \geq 15dB$, SC_2 outperforms SC_1. On the other hand, in terms of the average harvested energy, SC_2 outperforms SC_1 for $P_s \leq -20$dBm, while SC_1 outperforms SC_2 for $P_s \geq -10$dBm. This observation can be explained by the fact that, when the ratio $\frac{\gamma_{th}}{P_s\lambda_{ss}}$ becomes very large (low SNR regime), the number of selected antennas K_2 of SC_1 converges to N_2-1, while it goes to 1 for SC_2. Hence, for SC_1, more antennas are used to decode information and less are used to harvest energy. However, for SC_2, less antennas are used to decode information and more are used to harvest energy. Subsequently, the outage probability of SC_1 is better than the one of SC_2, while the average harvested energy of SC_2 is better than the one SC_1. However, when the ratio $\frac{\gamma_{th}}{P_s\lambda_{ss}}$ becomes small (high SNR regime), the number of selected antennas K_2 for SC_1 converges to 1, while it goes to $N_2 - 1$ for SC_2. For SC_1, only one antenna is used to decode the information and all the others are used to harvest energy. However, for SC_2, only one antenna is used to harvest energy and all the others are used to decode the information. Subsequently, the outage probability of SC_2 is better than the one of SC_1, while the average harvested energy of SC_1 is better than the one SC_2. At this point, we can see that there is a trade off between the outage probability and the average harvested energy when we use SC_1 or SC_2.

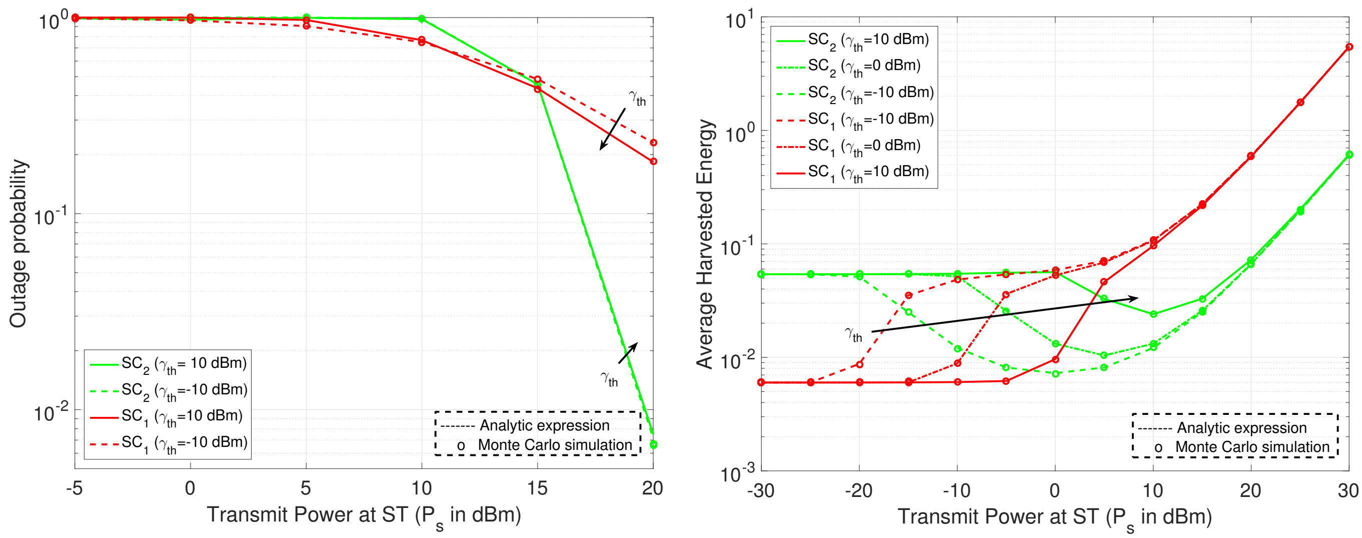
In addition, we can see that the outage probability of SC_1 is almost the same, as we increase the number of receiving antennas at ST. For the high SNR regime, this behavior is expected from (30). For the low SNR regime, this behavior is due to the fact that the ratio $\frac{\gamma_{th}}{xP_p\lambda_{ps}}$ is of the order of -50 dBm, so (31) converges to 1. However, the outage probability of SC_2 increases for $P_s \leq 15$ dBm, while it decreases for $P_s > 15$ dBm, as N_2 increases. On the other hand, as N_2 increases, the average harvested energy of SC_1 increases for $P_s \geq -25$ dBm and is almost constant otherwise, while the average harvested energy of SC_2 increases for $P_s \leq -10$ dBm and is almost constant otherwise. This constant behavior of the average harvested energy with respect to N_2 is due to the fact that K_2 is equal to 1 when SC_1 is in the high SNR regime and when SC_2 is in the low SNR regime.



(a) (b)

Figure 3: (a) The outage probability $P_{D,out}$ and (b) the average harvested energy $\overline{Q}$ versus the transmit power at SR P_s in dBm, with $N_2 = 10$, $\gamma_{th} = -10$ dBm and different values of λ_{ss} and λ_{ps} for the two selection schemes SC_1 and SC_2.

In Figs. 3a and 3b, we plotted the outage probability and the average harvested energy versus the transmit power P_s at ST in dBm, respectively, for $N_2 = 10$, $\gamma_{th} = -10$ dBm and different values of λ_{ss} and λ_{ps} for the two selection schemes SC_1 and SC_2. We can see that the outage probability of SC_1 and SC_2 improves with λ_{ss} while it worsens with λ_{ps}, which is an expected result since we know that the interference harm the data transmission. On the other hand, the average harvested energy of SC_1 and SC_2 improves with λ_{ps}, if we compare the cases when $\lambda_{ps} = 20$ dBm and $\lambda_{ps} = 30$ dBm, while $\lambda_{ss} = 30$ dBm. But, when λ_{ss} increases, the average harvested energy of SC_1 improves. However, for SC_2, the average harvested energy improves for $P_s > 5$ dBm. Moreover, we can see that the average harvested energy is highly affected by λ_{ps} at low SNR regime while it is highly affected by λ_{ss} at high SNR regime.



(a) (b)

Figure 4: (a) The outage probability $P_{D,out}$ and (b) the average harvested energy $\overline{Q}$ versus the transmit power at SR P_s in dBm, with $N_2 = 10$, $\lambda_{ss} = \lambda_{ps} = 30$ dBm and different values of γ_{th} for the two selection schemes SC_1 and SC_2.

In Figs. 4a and 4b, we plotted the outage probability and the average harvested energy versus the transmit power P_s at ST in dBm, respectively, for $N_2 = 10$, $\lambda_{ss} = \lambda_{ps} = 30$ dBm and different values of γ_{th} for the two selection schemes SC_1 and SC_2. We can see that as γ_{th} increases, the outage probability of SC_1 improves, while it slighly increases for SC_2 for high P_s. On the other hand, the average harvested energy decreases for SC_1 and increases for SC_2. This observation can be explained by the fact that as the threshold γ_{th} increases, more antennas are allocated to decode information for SC_1 while less antennas are allocated to harvest energy. However, for SC_2, as γ_{th} increases, more antennas are used to harvest energy and less antennas are used to decode information.

VI. Conclusion

In this paper, we investigate the SWIPT for spectrum sharing in MIMO CR networks where the SR harvests the energy from the primary and secondary transmission using the antenna switching technique. We propose a thresholding-based antenna selection strategy inspired from OT-MRC technique. We study two selection schemes: the first is the prioritizing data selection scheme (SC_1) and the second is the prioritizing energy selection scheme (SC_2). For both schemes, we derive the PMF of K_2, the average harvested energy, and the data transmission outage probability and we show the energy-data trade off for both schemes.

Appendix A

A. Proof of $\int_0^a \gamma(k-1,t)\, e^t \,\mathrm{d}t = \frac{e^a}{k-1}\gamma(k,a)$

$$\int_0^a \gamma(k-1,t)\, e^t \,\mathrm{d}t = \int_0^a \left[\int_0^t y^{k-2} e^{-y} \,\mathrm{d}y\right] e^t \,\mathrm{d}t \tag{46}$$
$$= \int_0^a y^{k-2} e^{-y} \left[\int_y^a e^t \,\mathrm{d}t\right] \mathrm{d}y \tag{47}$$
$$= e^a \int_0^a y^{k-2} e^{-y} \,\mathrm{d}y - \int_0^a y^{k-2} \,\mathrm{d}y \tag{48}$$
$$= e^a \gamma(k-1,a) - \frac{a^{k-1}}{k-1} \tag{49}$$
$$= \frac{e^a}{k-1}\gamma(k,a). \tag{50}$$

B. Proof of $\int_0^a t\gamma(k-1,t)\, e^t \,\mathrm{d}t = \frac{(a-1)e^a}{k-1}\gamma(k,a) + \frac{a^k}{k(k-1)}$

$$\int_0^a t\gamma(k-1,t)\, e^t \,\mathrm{d}t = \int_0^a \left[\int_0^t y^{k-2} e^{-y} \,\mathrm{d}y\right] t e^t \,\mathrm{d}t \tag{51}$$
$$= \int_0^a y^{k-2} e^{-y} \left[\int_y^a t e^t \,\mathrm{d}t\right] \mathrm{d}y \tag{52}$$
$$= (a-1)e^a \int_0^a y^{k-2} e^{-y} \,\mathrm{d}y - \int_0^a (y-1) y^{k-2} \,\mathrm{d}y \tag{53}$$
$$= (a-1)e^a \gamma(k-1,a) - \frac{a^k}{k} + \frac{a^{k-1}}{k-1} \tag{54}$$
$$= \frac{(a-1)e^a}{k-1}\gamma(k,a) + \frac{a^k}{k(k-1)}. \tag{55}$$

Appendix B

Expressions for $\mathcal{I}_1(x,\gamma_{th})$, $\mathcal{I}_{k_2}(x,\gamma_{th})$ and $\mathcal{I}_{N_2-1}(x,\gamma_{th})$

A. *Expression for $\mathcal{I}_1(x,\gamma_{th})$*

First, let us start with $\mathcal{I}_1(x,\gamma_{th})$:

$$\mathcal{I}_1(x,\gamma_{th}) = P\left(\frac{\Gamma_s(1)}{\Gamma_p(1)} < x \ \&\ \Gamma_s(1) \geq \gamma_{th}\right) \tag{56}$$

$$= P\left(\Gamma_s(1) < x\Gamma_p(1) \ \&\ \Gamma_s(1) \geq \gamma_{th}\right) \tag{57}$$

$$= P\left(\gamma_{th} \leq \Gamma_s(1) < x\Gamma_p(1) \ \&\ \Gamma_p(1) \geq \frac{\gamma_{th}}{x}\right) \tag{58}$$

$$= \int_{\frac{\gamma_{th}}{x}}^{\infty} P\left(\gamma_{th} \leq \Gamma_s(1) < xy\right) f_{\gamma_p}^{(1)}(y)\, \mathrm{d}y \tag{59}$$

$$= \int_{\frac{\gamma_{th}}{x}}^{\infty} \left[F_{\gamma_s}^{(1)}(xy) - F_{\gamma_s}^{(1)}(\gamma_{th})\right] f_{\gamma_p}^{(1)}(y)\, \mathrm{d}y \tag{60}$$

$$= \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy) f_{\gamma_p}^{(1)}(y)\, \mathrm{d}y - F_{\gamma_s}^{(1)}(\gamma_{th})\left[1 - F_{\gamma_p}^{(1)}\left(\frac{\gamma_{th}}{x}\right)\right], \tag{61}$$

For the Rayleigh fading channels, $\mathcal{I}_1(x,\gamma_{th})$ is equal to

$$\mathcal{I}_1(x,\gamma_{th}) = \frac{1}{P_p\lambda_{ps}} \int_{\frac{\gamma_{th}}{x}}^{\infty} \left(1 - e^{-\frac{xy}{P_s\lambda_{ss}}}\right) e^{-\frac{y}{P_p\lambda_{ps}}}\, \mathrm{d}y - \left(1 - e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\right) e^{-\frac{\gamma_{th}}{xP_p\lambda_{ps}}} \tag{62}$$

$$= \frac{xP_p\lambda_{ps}}{xP_p\lambda_{ps} + P_s\lambda_{ss}} e^{-\gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)}. \tag{63}$$

B. *Expression for $\mathcal{I}_{k_2}(x,\gamma_{th})$*

Then, let us compute $\mathcal{I}_{k_2}(x,\gamma_{th})$:

$$\mathcal{I}_{k_2}(x,\gamma_{th}) = P\left(\frac{\Gamma_s(k_2)}{\Gamma_p(k_2)} < x \ \&\ \Gamma_s(k_2-1) < \gamma_{th} \leq \Gamma_s(k_2)\right) \tag{64}$$

$$= P\left(\Gamma_s(k_2-1) + \gamma_{s,k_2} < x\Gamma_p(k_2) \ \&\ \Gamma_s(k_2-1) < \gamma_{th} \leq \Gamma_s(k_2-1) + \gamma_{s,k_2}\right) \tag{65}$$

$$\begin{aligned} &= \int_{\frac{\gamma_{th}}{x}}^{\infty} \left[\int_{xy-\gamma_{th}}^{xy} F_{\gamma_s}^{(k_2-1)}(-z + xy) f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y \\ &- \left[1 - F_{\gamma_p}^{(k_2)}\left(\frac{\gamma_{th}}{x}\right)\right] \int_0^{\gamma_{th}} F_{\gamma_s}^{(k_2-1)}(\gamma_{th} - z) f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z \\ &+ F_{\gamma_s}^{(k_2-1)}(\gamma_{th}) \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy - \gamma_{th}) f_{\gamma_p}^{(k_2)}(y)\, \mathrm{d}y. \end{aligned} \tag{66}$$

For the Rayleigh fading channels, $\mathcal{I}_{k_2}(x, \gamma_{th})$ can be shown equal to

$$\mathcal{I}_{k_2}(x, \gamma_{th}) = \frac{1}{\Gamma(k_2)\left(P_p\lambda_{ps}\right)^{k_2}} \int_{\frac{\gamma_{th}}{x}}^{\infty} \frac{1}{\Gamma(k_2 - 1)P_s\lambda_{ss}}$$

$$\times \left[\int_{xy-\gamma_{th}}^{xy} \gamma\left(k_2 - 1, \frac{-z + xy}{P_s\lambda_{ss}}\right) e^{-\frac{z}{P_s\lambda_{ss}}}\, \mathrm{d}z\right] y^{k_2-1} e^{-\frac{y}{P_p\lambda_{ps}}}\, \mathrm{d}y$$

$$- \frac{\Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(k_2)\Gamma(k_2 - 1)P_s\lambda_{ss}} \int_0^{\gamma_{th}} \gamma\left(k_2 - 1, \frac{\gamma_{th} - z}{P_s\lambda_{ss}}\right) e^{-\frac{z}{P_s\lambda_{ss}}}\, \mathrm{d}z$$

$$+ \frac{\gamma\left(k_2 - 1, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)}{\Gamma(k_2)\Gamma(k_2 - 1)\left(P_p\lambda_{ps}\right)^{k_2}} \int_{\frac{\gamma_{th}}{x}}^{\infty} \left(1 - e^{-\frac{xy-\gamma_{th}}{P_s\lambda_{ss}}}\right) y^{k_2-1} e^{-\frac{y}{P_p\lambda_{ps}}}\, \mathrm{d}y \tag{67}$$

$$= \frac{e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}}{\Gamma(k_2)^2\left(P_p\lambda_{ps}\right)^{k_2}} \gamma\left(k_2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right) \int_{\frac{\gamma_{th}}{x}}^{\infty} y^{k_2-1} e^{-y\left(\frac{x}{P_s\lambda_{ss}} + \frac{1}{P_p\lambda_{ps}}\right)}\, \mathrm{d}y$$

$$- \frac{\gamma\left(k_2, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(k_2)^2} + \frac{\gamma\left(k_2 - 1, \frac{\gamma_{th}}{P_s\lambda_{ss}}\right)}{\Gamma(k_2)\Gamma(k_2 - 1)}\left[\Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)\right.$$

$$\left. - \frac{e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}}{\left(P_p\lambda_{ps}\right)^{k_2}\left(\frac{x}{P_s\lambda_{ss}} + \frac{1}{P_p\lambda_{ps}}\right)^{k_2}} \Gamma\left(k_2, \gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)\right)\right] \tag{68}$$

$$= \frac{e^{-\frac{\gamma_{th}}{P_s\lambda_{ss}}}\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{k_2-1}}{\Gamma(k_2)^2}\left[\Gamma\left(k_2, \frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)\right.$$

$$\left. - \frac{e^{\frac{\gamma_{th}}{P_s\lambda_{ss}}}}{\left(P_p\lambda_{ps}\right)^{k_2}\left(\frac{x}{P_s\lambda_{ss}} + \frac{1}{P_p\lambda_{ps}}\right)^{k_2}} \Gamma\left(k_2, \gamma_{th}\left(\frac{1}{P_s\lambda_{ss}} + \frac{1}{xP_p\lambda_{ps}}\right)\right)\right]. \tag{69}$$

C. Expression for $\mathcal{I}_{N_2-1}(x, \gamma_{th})$

Finally, let us compute $\mathcal{I}_{N_2-1}(x, \gamma_{th})$:

$$\mathcal{I}_{N_2-1}(x, \gamma_{th}) = P\left(\frac{\Gamma_s(N_2 - 1)}{\Gamma_p(N_2 - 1)} < x \,\&\, \Gamma_s(N_2 - 2) < \gamma_{th}\right) \tag{70}$$

$$= P\left(\Gamma_s(N_2 - 2) + \gamma_{s,N_2-1} < x\Gamma_p(N_2 - 1) \,\&\, \Gamma_s(N_2 - 2) < \gamma_{th}\right) \tag{71}$$

$$= \int_{\frac{\gamma_{th}}{x}}^{\infty} \left[\int_{xy-\gamma_{th}}^{xy} F_{\gamma_s}^{(N_2-2)}(-z + xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y$$

$$+ \int_0^{\frac{\gamma_{th}}{x}} \left[\int_0^{xy} F_{\gamma_s}^{(N_2-2)}(-z + xy)\, f_{\gamma_s}^{(1)}(z)\, \mathrm{d}z\right] f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y$$

$$+ F_{\gamma_s}^{(N_2-2)}(\gamma_{th}) \int_{\frac{\gamma_{th}}{x}}^{\infty} F_{\gamma_s}^{(1)}(xy - \gamma_{th})\, f_{\gamma_p}^{(N_2-1)}(y)\, \mathrm{d}y. \tag{72}$$

For the Rayleigh fading channels, $\mathcal{I}_{N_2-1}(x,\gamma_{th})$ can be shown equal to

$$\begin{aligned}
\mathcal{I}_{N_2-1}(x,\gamma_{th}) &= \frac{1}{\Gamma(N_2-1)\left(P_p\lambda_{ps}\right)^{N_2-1}}\int_{\frac{\gamma_{th}}{x}}^{\infty}\frac{1}{\Gamma(N_2-2)P_s\lambda_{ss}} \\
&\times\left[\int_{xy-\gamma_{th}}^{xy}\gamma\left(N_2-2,\frac{-z+xy}{P_s\lambda_{ss}}\right)e^{-\frac{z}{P_s\lambda_{ss}}}\,\mathrm{d}z\right]y^{N_2-2}e^{-\frac{y}{P_p\lambda_{ps}}}\,\mathrm{d}y \\
&+\frac{1}{\Gamma(N_2-1)\left(P_p\lambda_{ps}\right)^{N_2-1}}\int_0^{\frac{\gamma_{th}}{x}}\frac{1}{\Gamma(N_2-2)P_s\lambda_{ss}} \\
&\times\left[\int_0^{xy}\gamma\left(N_2-2,\frac{-z+xy}{P_s\lambda_{ss}}\right)e^{-\frac{z}{P_s\lambda_{ss}}}\,\mathrm{d}z\right]y^{N_2-2}e^{-\frac{y}{P_p\lambda_{ps}}}\,\mathrm{d}y \\
&+\frac{1}{\Gamma(N_2-1)\left(P_p\lambda_{ps}\right)^{N_2-1}}F_{\gamma_s}^{(N_2-2)}(\gamma_{th}) \\
&\times\int_{\frac{\gamma_{th}}{x}}^{\infty}\left(1-e^{-\frac{xy-\gamma_{th}}{P_s\lambda_{ss}}}\right)y^{N_2-2}e^{-\frac{y}{P_p\lambda_{ps}}}\,\mathrm{d}y \qquad (73)\\
&=\frac{\gamma\left(N_2-2,\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-1,\frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(N_2-2)\,\Gamma(N_2-1)} \\
&-\frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2}\Gamma\left(N_2-1,\gamma_{th}\left(\frac{1}{xP_p\lambda_{ps}}+\frac{1}{P_s\lambda_{ss}}\right)\right)}{\Gamma(N_2-1)^2\left(P_p\lambda_{ps}\right)^{N_2-1}\left(\frac{1}{P_p\lambda_{ps}}+\frac{x}{P_s\lambda_{ss}}\right)^{N_2-1}} \\
&+\frac{1}{\Gamma(N_2-1)^2}\int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}\gamma\left(N_2-1,u\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)u^{N_2-2}e^{-u}\,\mathrm{d}u. \qquad (74)
\end{aligned}$$

where (74) was obtained using $\int_0^a t\gamma(k-1,t)\,e^t\,\mathrm{d}t=\frac{(a-1)e^a}{k-1}\gamma(k,a)+\frac{a^k}{k(k-1)}$ which was proven in Appendix A-B. Or, we can write:

$$\begin{aligned}
&\frac{1}{\Gamma(N_2-1)^2}\int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}\gamma\left(N_2-1,u\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)u^{N_2-2}e^{-u}\,\mathrm{d}u \\
&=\frac{1}{\Gamma(N_2-1)}\int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}u^{N_2-2}e^{-u}\,\mathrm{d}u \\
&-\frac{1}{\Gamma(N_2-1)}\sum_{m=0}^{N_2-2}\frac{\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)^m}{\Gamma(m+1)}\int_0^{\frac{\gamma_{th}}{xP_p\lambda_{ps}}}e^{-u\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}+1\right)}u^{N_2+m-2}\,\mathrm{d}u \qquad (75)\\
&=\frac{1}{\Gamma(N_2-1)}\gamma\left(N_2-1,\frac{\gamma_{th}}{xP_p\lambda_{ps}}\right) \\
&-\frac{1}{\Gamma(N_2-1)}\sum_{m=0}^{N_2-2}\frac{\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)^m\gamma\left(N_2+m-1,\frac{\gamma_{th}}{xP_p\lambda_{ps}}\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}+1\right)\right)}{\Gamma(m+1)\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}+1\right)^{N_2+m-1}}. \qquad (76)
\end{aligned}$$

Consequently, we obtain:

$$\mathcal{I}_{N_2-1}(x,\gamma_{th}) = 1 - \frac{\Gamma\left(N_2-2,\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)\Gamma\left(N_2-1,\frac{\gamma_{th}}{xP_p\lambda_{ps}}\right)}{\Gamma(N_2-2)\,\Gamma(N_2-1)} - \frac{\left(\frac{\gamma_{th}}{P_s\lambda_{ss}}\right)^{N_2-2}\Gamma\left(N_2-1,\gamma_{th}\left(\frac{1}{xP_p\lambda_{ps}}+\frac{1}{P_s\lambda_{ss}}\right)\right)}{\Gamma(N_2-1)^2\left(P_p\lambda_{ps}\right)^{N_2-1}\left(\frac{1}{P_p\lambda_{ps}}+\frac{x}{P_s\lambda_{ss}}\right)^{N_2-1}} - \frac{1}{\Gamma(N_2-1)}\sum_{m=0}^{N_2-2}\frac{\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}\right)^m\gamma\left(N_2+m-1,\frac{\gamma_{th}}{xP_p\lambda_{ps}}\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}+1\right)\right)}{\Gamma(m+1)\left(\frac{xP_p\lambda_{ps}}{P_s\lambda_{ss}}+1\right)^{N_2+m-1}}. \tag{77}$$

Appendix C

PDF and CDF of $Q^{(1)}(k_2)$ for $k_2 = 1,\dots,N_2-1$

Recall, for $k_2 = 1,\dots,N_2-1$, the harvested energy at SR is given by

$$Q^{(1)}(k_2) = \zeta\left(\overline{\Gamma}_s(k_2)+\overline{\Gamma}_p(k_2)\right), \tag{78}$$

where $\overline{\Gamma}_s(k_2) = P_s\sum_{k_2+1}^{N_2}|h_{sj}|^2$, $\overline{\Gamma}_p(k_2) = P_p\sum_{k_2+1}^{N_2}|h_{pj}|^2$ are the harvested energy from ST and PT, respectively.

The PDF and CDF of $\overline{\Gamma}_s(k_2)$ are denoted as $f_{\gamma_s}^{(N_2-k_2)}(\cdot)$, $F_{\gamma_s}^{(N_2-k_2)}(\cdot)$, respectively. In addition, the PDF and CDF of $\overline{\Gamma}_p(k_2)$ are denoted as $f_{\gamma_p}^{(N_2-k_2)}(\cdot)$, $F_{\gamma_p}^{(N_2-k_2)}(\cdot)$, respectively.

We can write the PDF and CDF of $Q^{(1)}(k_2)$ as

$$f_{Q^{(1)}(k_2)}(q) = f_{\zeta\left(\overline{\Gamma}_s(k_2)+\overline{\Gamma}_p(k_2)\right)}(q) \tag{79}$$

$$= \frac{1}{\zeta}f_{\overline{\Gamma}_s(k_2)+\overline{\Gamma}_p(k_2)}\left(\frac{q}{\zeta}\right) \tag{80}$$

$$= \frac{1}{\zeta}\int_0^{\frac{q}{\zeta}} f_{\overline{\Gamma}_s(k_2)}(x)\, f_{\overline{\Gamma}_p(k_2)}\left(\frac{q}{\zeta}-x\right)\mathrm{d}x \tag{81}$$

$$= \frac{1}{\zeta}\int_0^{\frac{q}{\zeta}} f_{\gamma_s}^{(N_2-k_2)}(x)\, f_{\gamma_p}^{(N_2-k_2)}\left(\frac{q}{\zeta}-x\right)\mathrm{d}x, \tag{82}$$

and

$$F_{Q^{(1)}(k_2)}\left(\gamma_q\right) = \frac{1}{\zeta}\int_0^{\gamma_q}\left[\int_0^{\frac{q}{\zeta}} f_{\gamma_s}^{(N_2-k_2)}(x)\, f_{\gamma_p}^{(N_2-k_2)}\left(\frac{q}{\zeta}-x\right)\mathrm{d}x\right]\mathrm{d}q \tag{83}$$

$$= \frac{1}{\zeta}\int_0^{\frac{\gamma_q}{\zeta}} f_{\gamma_s}^{(N_2-k_2)}(x)\left[\int_{\zeta x}^{\gamma_q} f_{\gamma_p}^{(N_2-k_2)}\left(\frac{q}{\zeta}-x\right)\mathrm{d}q\right]\mathrm{d}x \tag{84}$$

$$= \int_0^{\frac{\gamma_q}{\zeta}} f_{\gamma_s}^{(N_2-k_2)}(x)\, F_{\gamma_p}^{(N_2-k_2)}\left(\frac{\gamma_q}{\zeta}-x\right)\mathrm{d}x, \tag{85}$$

respectively.

For the Rayleigh fading channels, we have

$$f_{\gamma_s}^{(N_2-k_2)}(x) = \frac{1}{\Gamma(N_2-k_2)} \frac{x^{N_2-k_2-1}}{(P_s\lambda_{ss})^{N_2-k_2}} e^{-\frac{x}{P_s\lambda_{ss}}} \tag{86}$$

$$F_{\gamma_s}^{(N_2-k_2)}(x) = \frac{1}{\Gamma(N_2-k_2)} \gamma\left(N_2-k_2, \frac{x}{P_s\lambda_{ss}}\right) \tag{87}$$

$$f_{\gamma_p}^{(N_2-k_2)}(y) = \frac{1}{\Gamma(N_2-k_2)} \frac{y^{N_2-k_2-1}}{\left(P_p\lambda_{ps}\right)^{N_2-k_2}} e^{-\frac{y}{P_p\lambda_{ps}}} \tag{88}$$

$$F_{\gamma_p}^{(N_2-k_2)}(y) = \frac{1}{\Gamma(N_2-k_2)} \gamma\left(N_2-k_2, \frac{y}{P_p\lambda_{ps}}\right) \tag{89}$$

for $x \geq 0$, and $y \geq 0$. Then, the PDF of $Q^{(1)}(k_2)$ is written as

$$f_{Q^{(1)}(k_2)}(q) = \frac{e^{-\frac{q}{\zeta P_p\lambda_{ps}}}}{\zeta\Gamma(N_2-k_2)^2 (P_s\lambda_{ss})^{N_2-k_2} \left(P_p\lambda_{ps}\right)^{N_2-k_2}} \int_0^{\frac{q}{\zeta}} x^{N_2-k_2-1} \left(\frac{q}{\zeta}-x\right)^{N_2-k_2-1} e^{-x\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)} \mathrm{d}x \tag{90}$$

- For $P_s\lambda_{ss} \neq P_p\lambda_{ps}$

$$\begin{aligned} f_{Q^{(1)}(k_2)}(q) &= \frac{e^{-\frac{q}{\zeta P_p\lambda_{ps}}}}{\zeta\Gamma(N_2-k_2)^2 (P_s\lambda_{ss})^{N_2-k_2} \left(P_p\lambda_{ps}\right)^{N_2-k_2}} \Bigg[\sqrt{\pi} \left(\frac{q}{\zeta\left(-\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)} \right)^{N_2-k_2-1/2} \\ &\times e^{\frac{q}{2\zeta}\left(-\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)} \Gamma(N_2-k_2)\, I_{N_2-k_2-1/2}\left(\frac{q}{2\zeta}\left(-\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)\right)\Bigg] \end{aligned} \tag{91}$$

$$= \frac{\sqrt{\pi} e^{-\frac{q}{2\zeta}\left(\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)}}{\Gamma(N_2-k_2)\,\zeta^{N_2-k_2+1/2}\sqrt{P_s\lambda_{ss}P_p\lambda_{ps}}} \left(\frac{q}{P_s\lambda_{ss}-P_p\lambda_{ps}}\right)^{N_2-k_2-1/2} I_{N_2-k_2-1/2}\left(\frac{q}{2\zeta}\left(-\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)\right), \tag{92}$$

  where $I_n(\cdot)$ is the modified Bessel function of the first kind. (94) was obtained using [18, (3.383.2.11)].

- For $P_s\lambda_{ss} = P_p\lambda_{ps}$

$$f_{Q^{(1)}(k_2)}(q) = \frac{e^{-\frac{q}{\zeta P_s\lambda_{ss}}}}{\zeta\Gamma(N_2-k_2)^2 (P_s\lambda_{ss})^{2(N_2-k_2)}} \int_0^{\frac{q}{\zeta}} x^{N_2-k_2-1}\left(\frac{q}{\zeta}-x\right)^{N_2-k_2-1} \mathrm{d}x \tag{93}$$

$$= \frac{e^{-\frac{q}{\zeta P_s\lambda_{ss}}}}{\zeta\Gamma(N_2-k_2)^2 (P_s\lambda_{ss})^{2(N_2-k_2)}} \left(\frac{q}{\zeta}\right)^{2(N_2-k_2)-1} B(N_2-k_2, N_2-k_2) \tag{94}$$

$$= \frac{q^{2(N_2-k_2)-1} e^{-\frac{q}{\zeta P_s\lambda_{ss}}}}{\Gamma(2(N_2-k_2))(\zeta P_s\lambda_{ss})^{2(N_2-k_2)}}, \tag{95}$$

  where $B(\cdot,\cdot)$ is the Beta function. (94) was obtained using [18, (3.191.1)].

At the end, we have

$$f_{Q^{(1)}(k_2)}(q) = \begin{cases} \frac{\sqrt{\pi} e^{-\frac{q}{2\zeta}\left(\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)}}{\Gamma(N_2-k_2)\zeta^{N_2-k_2+1/2}\sqrt{P_s\lambda_{ss}P_p\lambda_{ps}}} \left(\frac{q}{P_s\lambda_{ss}-P_p\lambda_{ps}}\right)^{N_2-k_2-1/2} I_{N_2-k_2-1/2}\left(\frac{q}{2\zeta}\left(-\frac{1}{P_s\lambda_{ss}}+\frac{1}{P_p\lambda_{ps}}\right)\right), & \text{if } P_s\lambda_{ss} \neq P_p\lambda_{ps} \\ \frac{q^{2(N_2-k_2)-1} e^{-\frac{q}{\zeta P_s\lambda_{ss}}}}{\Gamma(2(N_2-k_2))(\zeta P_s\lambda_{ss})^{2(N_2-k_2)}}, & \text{if } P_s\lambda_{ss} = P_p\lambda_{ps} \end{cases} \tag{96}$$

Correspondingly, the CDF of $Q^{(1)}(k_2)$ is given by

$$F_{Q^{(1)}(k_2)}\left(\gamma_q\right) = \frac{1}{\Gamma(N_2-k_2)^2}\int_0^{\frac{\gamma_q}{\zeta}} \frac{x^{N_2-k_2-1}}{(P_s\lambda_{ss})^{N_2-k_2}} e^{-\frac{x}{P_s\lambda_{ss}}}\gamma\left(N_2-k_2, \frac{\frac{\gamma_q}{\zeta}-x}{P_p\lambda_{ps}}\right) \mathrm{d}x \tag{97}$$

$$= \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)^2\,(P_s\lambda_{ss})^{N_2-k_2}}\int_0^{\frac{\gamma_q}{\zeta}}\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{\frac{u}{P_s\lambda_{ss}}}\gamma\left(N_2-k_2, \frac{u}{P_p\lambda_{ps}}\right)\mathrm{d}u \tag{98}$$

$$= \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)\,(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[\int_0^{\frac{\gamma_q}{\zeta}}\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{\frac{u}{P_s\lambda_{ss}}}\,\mathrm{d}u$$
$$-\sum_{m=0}^{N_2-k_2-1}\frac{1}{\Gamma(m+1)P_p^m\lambda_{ps}^m}\int_0^{\frac{\gamma_q}{\zeta}} u^m\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{u\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)}\mathrm{d}u\Bigg] \tag{99}$$

$$= \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)\,(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}\int_0^{\frac{\gamma_q}{\zeta}} t^{N_2-k_2-1}e^{-\frac{t}{P_s\lambda_{ss}}}\,\mathrm{d}t$$
$$-\sum_{m=0}^{N_2-k_2-1}\frac{1}{\Gamma(m+1)P_p^m\lambda_{ps}^m}\int_0^{\frac{\gamma_q}{\zeta}} u^m\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{u\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)}\mathrm{d}u\Bigg] \tag{100}$$

$$= \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)\,(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}(P_s\lambda_{ss})^{N_2-k_2}\gamma\left(N_2-k_2, \frac{\gamma_q}{\zeta P_s\lambda_{ss}}\right)$$
$$-\sum_{m=0}^{N_2-k_2-1}\frac{1}{\Gamma(m+1)P_p^m\lambda_{ps}^m}\int_0^{\frac{\gamma_q}{\zeta}} u^m\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{u\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)}\mathrm{d}u\Bigg] \tag{101}$$

$$= \begin{cases} \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}(P_s\lambda_{ss})^{N_2-k_2}\gamma\left(N_2-k_2, \frac{\gamma_q}{\zeta P_s\lambda_{ss}}\right) \\ -\sum_{m=0}^{N_2-k_2-1}\frac{1}{\Gamma(m+1)P_p^m\lambda_{ps}^m}\int_0^{\frac{\gamma_q}{\zeta}} u^m\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1}\mathrm{d}u\Bigg], & \text{if } P_s\lambda_{ss}=P_p\lambda_{ps}, \\ \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}(P_s\lambda_{ss})^{N_2-k_2}\gamma\left(N_2-k_2, \frac{\gamma_q}{\zeta P_s\lambda_{ss}}\right) \\ -\sum_{m=0}^{N_2-k_2-1}\frac{1}{\Gamma(m+1)P_p^m\lambda_{ps}^m}\int_0^{\frac{\gamma_q}{\zeta}} u^m\left(\frac{\gamma_q}{\zeta}-u\right)^{N_2-k_2-1} e^{u\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)}\mathrm{d}u\Bigg], & \text{if } P_s\lambda_{ss}\neq P_p\lambda_{ps}, \end{cases} \tag{102}$$

$$= \begin{cases} \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}(P_s\lambda_{ss})^{N_2-k_2}\gamma\left(N_2-k_2, \frac{\gamma_q}{\zeta P_s\lambda_{ss}}\right) \\ -\sum_{m=0}^{N_2-k_2-1}\frac{\Gamma(N_2-k_2)}{\Gamma(N_2-k_2+m+1)P_p^m\lambda_{ps}^m}\left(\frac{\gamma_q}{\zeta}\right)^{N_2-k_2+m}\Bigg], & \text{if } P_s\lambda_{ss}=P_p\lambda_{ps}, \\ \frac{e^{-\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}}{\Gamma(N_2-k_2)(P_s\lambda_{ss})^{N_2-k_2}}\Bigg[e^{\frac{\gamma_q}{\zeta P_s\lambda_{ss}}}(P_s\lambda_{ss})^{N_2-k_2}\gamma\left(N_2-k_2, \frac{\gamma_q}{\zeta P_s\lambda_{ss}}\right) \\ -\sum_{m=0}^{N_2-k_2-1}\frac{\Gamma(N_2-k_2)}{\Gamma(N_2-k_2+m+1)P_p^m\lambda_{ps}^m}\left(\frac{\gamma_q}{\zeta}\right)^{N_2-k_2+m}{}_1F_1\left(m+1; N_2-k_2+m+1; \frac{\gamma_q}{\zeta}\left(\frac{1}{P_s\lambda_{ss}}-\frac{1}{P_p\lambda_{ps}}\right)\right), & \text{if } P_s\lambda_{ss}\neq P_p\lambda_{ps}, \end{cases} \tag{103}$$

where ${}_1F_1(a;b;z)$ is the Kummer confluent hypergeometric function. (103) was obtained using [18, (3.191.1)] and [18, (3.383.1)].

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