A Cooperative Beam Selection Scheme for Wireless Sensor with RF Energy Harvesting

by

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B.Sc., University of BUPT, 2012

A Report Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF ENGINEERING

in the Department of Electrical and Computer Engineering

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ABSTRACT

RF energy harvesting is a promising potential solution to provide convenient and perpetual energy supplies to low-power wireless sensor networks. In this paper, we investigate the energy harvesting performance of a wireless sensor node powered by harvesting RF energy from an existing MISO system. Specifically, we propose a random unitary beamforming (RUB) based cooperative beam selection scheme to enhance the energy harvesting performance at the sensor. Under a constant total transmission power constraint, the MISO system tries to select a best active beams for data transmission, while satisfying the energy harvesting requirement at the sensor. We derive the exact closed-form expression for the distribution function of harvested energy in a coherence time over Rayleigh fading channels. We further investigate the performance tradeoff of the average harvested energy at the sensor versus the throughput of the MISO system.

Contents

List of Figures

Chapter 1

Introduction

Wireless sensors are used in a wide range of applications, such as environment monitoring, surveillance, health care, intelligent buildings and battle field control [1]. The sensor nodes are usually powered by batteries with finite life time, which manifests as an important limiting factor to the functionality of wireless sensor network (WSN). Replacing or charging the batteries may either incur high costs for human labor or be impractical for certain application scenarios (e.g. applications that require sensors to be embedded into structures). Powering sensor nodes through ambient energy harvesting has therefore received a lot of attentions in both academia and industrial communities [2, 3]. Various techniques have been developed to harvest energy from conventional ambient energy sources, including solar power, wind power, thermoelectricity, and vibrational excitations [4, 5, 6, 7].

RF energy is another candidate ambient energy source for powering sensor nodes. Recently, there has been a growing interest in RF energy harvesting due to the intensive deployment of cellular/WiFi wireless systems in addition to traditional radio/TV broadcasting systems [8]. It has been experimentally proved that RF energy harvesting is feasible from the hardware implementation viewpoint. In [9], the authors developed prototypes for devices that communicate with each other using ambient RF signals from TV/cellular systems as the only power source. In [10], the authors present the experimental performance (e.g., charging time of the sensor and received signal power at the sink) of RF energy harvesting using PowerCast energy harvesters [11]. Although these previous works have proved a visible future for the wireless applications based on RF energy harvesting, most performance results are obtained through laboratory experiments. There is still a lack of effective theoretical models that can analytically predict the performance of WSNs powered by RF energy harvesting.

1.1 Previous works

Previous literature on RF energy harvesting can be summarized as following. The fundamental performance limits of simultaneous wireless information and energy transfer systems over point-to-point link were studied in [23, 24]. In [25], the authors consider a three-node multiple-input multiple-output (MIMO) wireless system, where one receiver harvests energy and another receiver decodes information from the signal transmitted by a common transmitter. A cognitive network that can harvest RF energy from the primary system is considered in [26]. The authors propose an optimal mode selection policy for sensor nodes to decide whether to transmit information or to harvest RF energy based on Markov modelling. In [27], the authors investigate mode switching between information decoding and energy harvesting, based on the instantaneous signal channel and interference condition over a point-to-point link.

On another front, considerable research effort has been carried out on the packet transmission performance analysis and optimization for WSN powered by harvesting energy from conventional energy sources [12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. The optimal packet scheduling policies in an energy harvesting communication systems were investigated over AWGN channels under the assumption of predictable energy arrival in [12] and [13]. Specifically, [12] targets at minimizing the packet delivery delay under data and energy arrival causality constraints and [13] also takes into account the finite energy storage capacity. In [14, 15, 16, 17, 18, 19], throughput maximization and packet delay minimization problems with energy harvesting constraints are studied for different channel environments. In [20], energy management policies that stabilize the data buffer have been proposed for single-user communication scenario by applying linear energy-rate approximations. In [21], medium access control (MAC) protocols for single-hop wireless sensor networks are designed and analyzed. A save-then-transmit protocol is proposed in [22] to minimize the outage probability of energy harvesting transmitters by finding the optimal time fraction for energy harvesting in a time slot, during which the wireless channel is assumed to be constant. It is worth noting that these works can not directly apply to RF energy harvesting. First of all, most of these work focus on the design of off-line packet scheduling strategies with predictable channel or energy state information, which is not available for RF energy harvesting over time-varying wireless channels. Furthermore, the amount of energy that can be harvested from RF energy sources over a short period of time (e.g. a channel coherence time) is typically much less than that from conventional energy sources. As such, WSN powered with RF energy harvesting can only support low data rate applications with simply transmission strategies.

1.2 Contributions

In [30], the authors propose a cooperative beam selection scheme, where an existing multiuser MIMO system helps improve the harvested energy of a RF-energy-powered sensor node by properly allocating transmission power to a maximal number of active beams. Inspired by [30], we consider a practical cooperative charging scenario in this paper, where an existing single-user MISO system helps the energy harvesting of a RF-energy-powered sensor node, while simultaneously serving its own user. We adopt random unitary beamforming (RUB) as the transmission scheme for the MISO system, which requires very low feedback load, and has been incorporated in several wireless standards [31, 32].

We propose a RUB-based cooperative beam selection scheme, where the base station (BS) of the MISO system selects the best beam for transmission, while trying to satisfy energy harvesting requirement of the sensor, i.e. the harvested energy over each coherence time is above a predefined energy threshold. Meanwhile, the number of usable beams that the BS can select from to serve its user is reduced. Different from [30], the BS first selects a maximal number of usable beams, which can satisfy the energy requirement at the sensor, and then serves its user with the best beam from all usable beams to achieve the largest throughput. To evaluate the performance tradeoff between the average harvested energy at the sensor and the throughput of the existing MISO system, we derive the closed-form statistical distribution of the amount of energy that can be harvested with the proposed cooperative RF energy harvesting scheme. These analytical results will help determine the optimal energy threshold value that can satisfy requirements of certain sensing applications, while considering the negative effect on the MISO system.

In Chapter 2, we introduce the system and channel model of the RUB-based MISO system, and propose the cooperative beam selection scheme. In Chapter 3, we derive the closed form expression of the distribution of the number of usable beams for the MISO system. Throughput analysis is given in Chapter 4. In Chapter 5, the distribution of harvested energy over one coherence time and the average harvested energy are obtained. Numerical examples are given in Chapter 6, and conclusions are presented in Chapter 7.

Chapter 2

System and channel model

2.1 System Model

We consider a single-antenna wireless sensor node deployed in the coverage area of an existing RUB-based MISO system, which could be cellular or WiFi systems. The sensor [1] can harvest RF energy from the transmitted signal of the MISO system, and use it as its sole energy source, as illustrated in Fig. 2.1. The MISO system consists of single BS with M antennas and one single-antenna user. The generalization to multiuser system with user selecting can be carried out, but omitted here for clarity. The BS can serve its user using random orthonormal beams generated from an isotropic distribution. Let $\mathcal{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_M]^T$ denote the set of beam vectors, assumed to be known to both the BS and its user. The transmitted signal vector from M antennas over one symbol period can be written as $\mathbf{x} = \sqrt{P_T}\mathbf{w}_j s$, where s denotes the information symbol for the user. Here, we assume that the transmission power P_T is constant.

2.2 Channel Model

We adopt a log-distance path loss plus Rayleigh block slow fading channel model for the operating environment while ignoring the shadowing effect [29]. In particular, the channel gain between the BS and the sensor remains constant over one channel coherence time, denoted by T_c, and changes to an independent value afterward. Let $\mathbf{h}_e = [h_{e_1}, h_{e_2}, \dots, h_{e_M}]^T$ denote the fading channel gain vector from the BS to the

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[1] The sensor can also be a special user of single user MISO system.

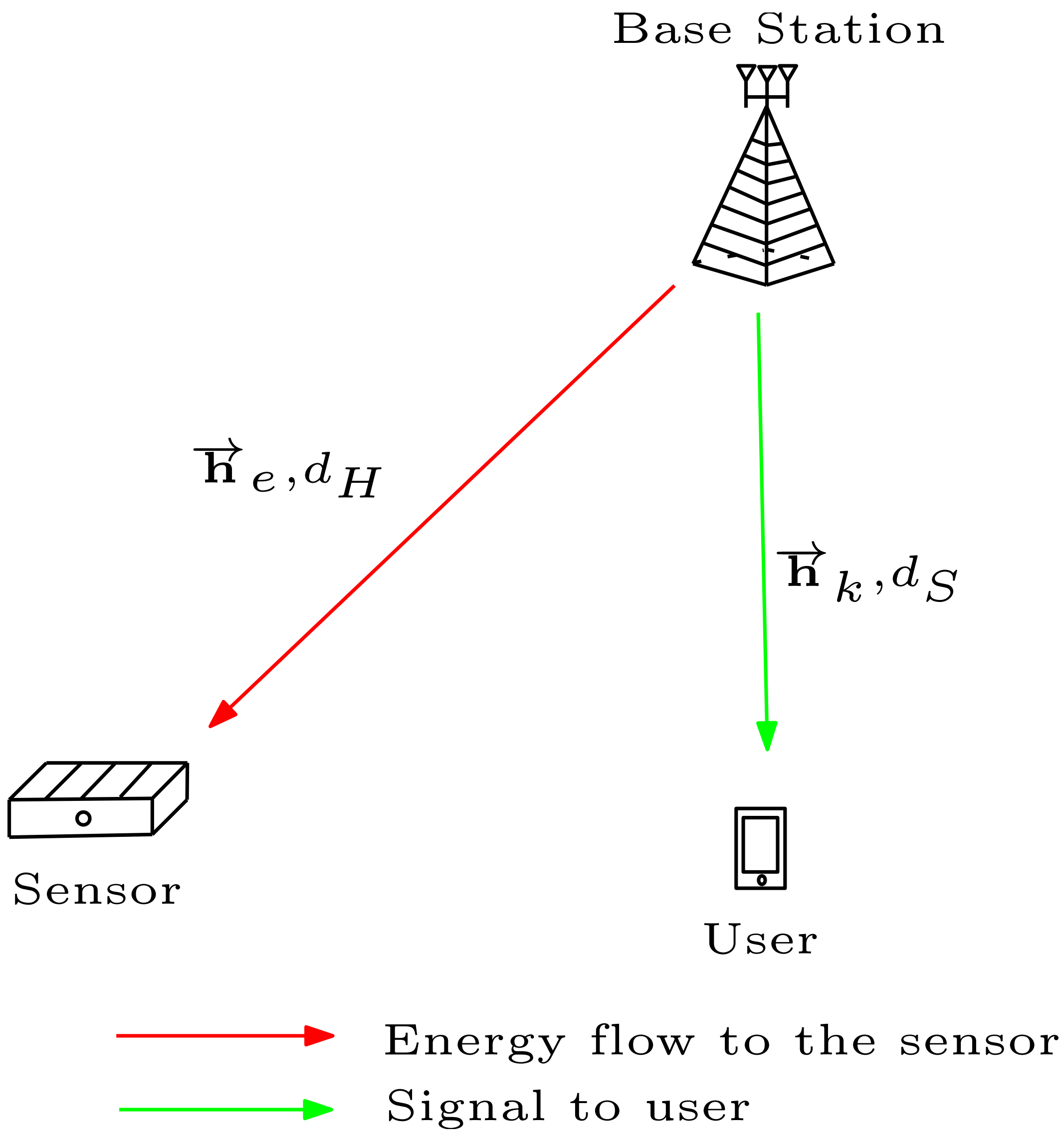

Figure 2.1: System model for RUB-based cooperative RF energy harvesting.

sensor, where $h_{e_m} \in \mathcal{CN}(0,1)$. Then the harvested energy at the sensor, when ith beam is used for transmission, can be given by

$$E_i = \left(\frac{\eta P_T T_c}{\Gamma d_H^{\lambda}}\right) |\mathbf{h}_e^T \mathbf{w}_i|^2, \quad i = 1, 2, \ldots, M, \tag{2.1}$$

where d_H is the distance from BS to the sensor, η is the energy harvesting efficiency, λ is the path loss exponent, ranging from 2 to 5, and Γ is a constant parameter of the log-distance model. Specifically, $\Gamma = \frac{PL(d_0)}{d_0^{\lambda}}$, where d_0 is a reference distance in the antenna far field, and $PL(d_0)$ is linear path loss at distance d_0, depending on the propagation environment. For notational conciseness, we use α_m to denote the amplitude square of the projection of $\mathbf{h}_e$ onto $\mathbf{w}_m$, i.e. $\alpha_m = |\mathbf{h}_e^T \mathbf{w}_m|^2$, whose probability density function (PDF) for Rayleigh fading channel under consideration is given by

$$f_{\alpha_m}(x) = e^{-x}. \tag{2.2}$$

2.3 RUB-based Cooperative Energy Harvesting

With the proposed cooperative energy harvesting scheme, the BS will select the best beam to serve the user, while ensuring that the harvested energy at the sensor node during each coherence time is above a predefined energy threshold E_{th}.

At the beginning of each channel coherence time, the BS first estimates the channel vector from the BS to the sensor. The BS then calculates and ranks the projection amplitude square α_m for each beam, the order version of which is denoted by $\alpha_{m:M}$, where $\alpha_{1:M} \geq \alpha_{2:M} \geq \cdots \geq \alpha_{M:M}$. After that, the BS calculates the amount of RF energy that the sensor can harvest when the BS uses each beam, corresponding to $\alpha_{1:M}$ to $\alpha_{M:M}$. Specifically, the harvested energy denoted by $E_{i:M}$, when the ith best beam are used for transmission, is given by

$$E_{i:M} = \left(\frac{\eta P_T T_c}{\Gamma d_H^{\lambda}}\right) \alpha_{i:M}, \quad i = 1, 2, \ldots, M. \tag{2.3}$$

If the harvested energy from the ith best beam is larger than the predefined energy threshold E_{th}, whereas the harvested energy from the $(i+1)$th best beam is less than E_{th}, i.e. $E_{i:M} \geq E_{th}$, and $E_{i+1:M} < E_{th}$, then the BS selects one beam from best i beams, corresponding to $\alpha_{1:M}$ to $\alpha_{i:M}$, to serve its user. It is worth noting that the amount of harvested energy at the sensor may be smaller than E_{th} even when the BS allocates all transmission power P_T to beam j^* corresponding to $\alpha_{1:M}$, i.e. $j^* = \arg\max_j(|\mathbf{h}_e^T \mathbf{w}_j|^2)$. In this case, the BS will still use beam j^* with transmission power P_T to charge the sensor as well as serve ith user.

Chapter 3

Distribution of the Number of Usable Beams

In the following, we derive the probability mass function of the number of usable beams M_a $(1 \leq M_a \leq M)$ that the BS can use, which will be applied to the throughput analysis for the MISO system.

According to our proposed cooperative beam selection scheme, the number of usable beams M_a is equal to m $(1 < m < M)$ if and only if $E_{m:M} \geq E_{th}$, and $E_{m+1:M} < E_{th}$. Furthermore, the number of usable beams M_a is equal to 1 if the energy threshold can not be satisfied with all transmission power P_T allocated to the best beam, i.e., $E_{1:M} < E_{th}$, or if only the best beam can lead to harvest energy larger than E_{th}, i.e., $E_{1:M} \geq E_{th}$, and $E_{2:M} < E_{th}$. The number of usable beams M_a is equal to M if the harvested energy is larger than E_{th} with P_T allocated to the worst beam, i.e., $E_{M:M} \geq E_{th}$. Therefore, the probability that M_a beams are usable can be given by

$$\Pr[M_a = i] = \begin{cases} \Pr[E_{1:M} < E_{th}] + \Pr[E_{1:M} \geq E_{th}, E_{2:M} < E_{th}], & i = 1, \\ \Pr[E_{i:M} \geq E_{th}, E_{i+1:M} < E_{th}], & 1 < i < M, \\ \Pr[E_{M:M} \geq E_{th}], & i = M. \end{cases} \tag{3.1}$$

After substituting (2.3) into (3.1) and some manipulations, (3.1) can be rewritten as

$$\Pr[M_a = i] = \begin{cases} \int_0^{\frac{E_{th}}{\Lambda}} f_{\alpha_{1:M}}(x)dx + \int_0^{\frac{E_{th}}{\Lambda}} \int_{\frac{E_{th}}{\Lambda}}^{\infty} f_{\alpha_{1:M},\alpha_{2:M}}(x,y)dxdy, & i = 1, \\ \int_0^{\frac{E_{th}}{\Lambda}} \int_{\frac{E_{th}}{\Lambda}}^{\infty} f_{\alpha_{i:M},\alpha_{i+1:M}}(x,y)dxdy, & 1 < i < M, \\ \int_{\frac{E_{th}}{\Lambda}}^{\infty} f_{\alpha_{M:M}}(x)dx, & i = M, \end{cases} \tag{3.2}$$

where Λ is a constant parameter equal to $\frac{\eta P_T T_c}{\Gamma d_H^{\lambda}}$, the PDF of $\alpha_{1:M}$, and $\alpha_{M:M}$, and the joint PDF of $\alpha_{i:M}$ and $\alpha_{i+1:M}$, can be given by [28]

$$f_{\alpha_{1:M}}(x) = M(1 - e^{-x})^{M-1}e^{-x}, \tag{3.3}$$

$$f_{\alpha_{i:M},\alpha_{i+1:M}}(x,y) = \frac{M!e^{-ix-y}(1 - e^{-y})^{M-i-1}}{(i-1)!(M-i-1)!},\ x > y, \tag{3.4}$$

and

$$f_{\alpha_{M:M}}(x) = Me^{-Mx}, \tag{3.5}$$

respectively. By substituting (3.3), (3.4), and (3.5) into (3.2) and carrying out integration, the close form expression of $\Pr[M_a = i]$ is calculated as

$$\Pr[M_a = i] = \begin{cases} M \sum_{j=0}^{M-1} \binom{M-1}{j} \frac{(-1)^j (1-e^{-(j+1)\frac{E_{th}}{\Lambda}})}{j+1} + \frac{M!e^{-\frac{E_{th}}{\Lambda}}}{(M-2)!} \sum_{j=0}^{M-2} & \\ \binom{M-2}{j} \frac{(-1)^j (1-e^{-(j+1)\frac{E_{th}}{\Lambda}})}{j+1}, & i = 1, \\ \frac{M!e^{-i\frac{E_{th}}{\Lambda}}}{i!(M-i-1)!} \sum_{j=0}^{M-i-1} (-1)^j \binom{M-i-1}{j} \frac{1}{j+1} (1 - e^{-(j+1)\frac{E_{th}}{\Lambda}}), & 1 < i < M, \\ e^{-M\frac{E_{th}}{\Lambda}} & i = M, \end{cases} \tag{3.6}$$

Chapter 4

Throughput Performance Analysis for the MISO System

We are interested in the average throughput of the MISO system, which can be calculated as

$$R = \sum_{i=1}^{M} \Pr[M_a = i] R_i, \tag{4.1}$$

where $\Pr[M_a = i]$ denotes the probability that i beams are usable, given in (3.6), R_i is the average throughput when i beams are usable, which can be calculated using the distribution of the largest SNR among all usable beams, as

$$R_i = \int_0^\infty \log_2(1+x) f_{\gamma_{1:M_a}}(x) dx, \quad i = 1, 2, \ldots, M, \tag{4.2}$$

where $f_{\gamma_{1:M_a}}(x)$ is the PDF of the largest received SNR $\gamma_{1:M_a}$ at the user, given by [28]

$$f_{\gamma_{1:M_a}}(x) \quad = \quad \frac{M_a}{\overline{\gamma}} e^{-\frac{x}{\overline{\gamma}}} (1 - e^{-\frac{x}{\overline{\gamma}}})^{M_a - 1}, \tag{4.3}$$

where $\overline{\gamma}$ denotes the common average received SNR for each beam. By sustituting (4.3) into (4.1) and some manipulation, the close form expression of the throughput of the MISO system can be calculated as

$$R \quad = \quad \sum_{i=1}^{M} \Pr[M_a = i] \Bigg\{ \frac{M_a}{\ln 2} \sum_{n=0}^{M_a - 1} (-1)^{n+1} C_{M_a - 1}^{n} \frac{e^{\frac{n+1}{\overline{\gamma}_S}}}{n+1} \mathrm{Ei}\bigg(- \frac{n+1}{\overline{\gamma}} \bigg) \Bigg\}, \tag{4.4}$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral function.

Chapter 5

Energy Harvesting Performance Analysis

To evaluate the energy harvesting performance, we derive the exact statistical distribution of the harvested energy over one coherence time T_c at the sensor, which can be used for calculating average harvested energy, as well as packet transmission performance of the sensor [30]. Conditioning on the number of usable beams for transmission, the cumulative distribution function (CDF) of E_H can be represented as

$$F_{E_H}(x) = \sum_{m=1}^{M} \Pr[E_H < x, M_a = m]. \tag{5.1}$$

According to our proposed cooperative beam selection scheme, the BS selects the best beam from all M_a usable beams to achieve the largest throughput, whereas the probability that each of M_a usable beams is selected to charge the sensor is equal to $\frac{1}{M_a}$. Therefore, we can rewrite (5.1) as

$$\begin{aligned} F_{E_H}(x) = &\sum_{m=1}^{M-1} \frac{1}{m} \sum_{i=1}^{m} \Pr\left[E_{i:M} < x, E_{m:M} \geq E_{th}, E_{m+1:M} < E_{th}\right] \\ &+ \Pr[E_{1:M} < x, E_{1:M} < E_{th}] + \frac{1}{M} \sum_{i=1}^{M} \Pr\left[E_{i:M} < x, E_{M:M} \geq E_{th}\right]. \end{aligned} \tag{5.2}$$

For the case of $x \leq E_{th}$, (5.2) can be simply calculated as

$$F_{E_H}(x) = \Pr[E_{1:M} < x] = \int_0^{\frac{x}{\Lambda}} f_{\alpha_{1:M}}(y)dy, \quad x \leq E_{th}, \tag{5.3}$$

By substituting (3.3) into (5.3), $F_{E_H}(x)$ can be calculated as

$$F_{E_H}(x) = M \sum_{j=0}^{M-1} \binom{M-1}{j} \frac{(-1)^j}{j+1} (1 - e^{-(j+1)\frac{x}{\Lambda}}), \; x \leq E_{th}. \tag{5.4}$$

For the case of $x > E_{th}$, (5.2) can be rewritten as

$$\begin{aligned} F_{E_H}(x) = & \sum_{m=1}^{M-1} \frac{1}{m} \Bigg\{ \int_{\frac{E_{th}}{\Lambda}}^{\frac{x}{\Lambda}} \int_0^{\frac{E_{th}}{\Lambda}} f_{\alpha_{m:M},\alpha_{m+1:M}}(y,z)dydz \\ & + \sum_{i=1}^{m-1} \int_{\frac{E_{th}}{\Lambda}}^{\frac{x}{\Lambda}} \int_{\frac{E_{th}}{\Lambda}}^{w} \int_0^{\frac{E_{th}}{\Lambda}} f_{\alpha_{i:M},\alpha_{m:M},\alpha_{m+1:M},}(w,y,z)dwdydz \Bigg\} \\ & + \frac{1}{M} \Bigg\{ \int_{\frac{E_{th}}{\Lambda}}^{\frac{x}{\Lambda}} f_{\alpha_{M:M}}(y)dy + \sum_{i=1}^{M-1} \int_{\frac{E_{th}}{\Lambda}}^{\frac{x}{\Lambda}} \int_{\frac{E_{th}}{\Lambda}}^{y} f_{\alpha_{i:M},\alpha_{M:M},}(y,z)dydz \Bigg\} \\ & + \int_0^{\frac{E_{th}}{\Lambda}} f_{\alpha_{1:M}}(y)dy, \quad x > E_{th}, \end{aligned} \tag{5.5}$$

where the joint PDF of $\alpha_{i:M}$, $\alpha_{m:M}$ and $\alpha_{m+1:M}$, and the joint PDF of $\alpha_{i:M}$ and $\alpha_{M:M}$ can be given by

$$f_{\alpha_{i:M},\alpha_{m:M},\alpha_{m+1:M}}(x,y,z) = \frac{M! e^{-ix-y-z}(e^{-y} - e^{-x})^{m-i-1}(1 - e^{-z})^{M-m-1}}{(i-1)!(m-i-1)!(M-m-1)!}, \quad x > y > \tag{5.6}$$

and

$$f_{\alpha_{i:M},\alpha_{M:M}}(y,z) = \frac{M!}{(i-1)!(M-i-1)!} e^{-iy-z}(e^{-z} - e^{-y})^{M-i-1}, \quad y > z, \tag{5.7}$$

respectively[28]. By substituting (3.3), (3.4), (5.6) and (5.7) into (5.5) and carrying out integrations, we can obtain the closed form expression of $F_{E_H}(x)$ for $x > E_{th}$ as

$$\begin{aligned}
F_{E_H}(x) = {} & \sum_{m=1}^{M-1} \frac{1}{m} \Bigg\{ \sum_{j=0}^{M-m-1} \binom{M-m-1}{j} \frac{(-1)^j}{j+1} (1 - e^{-(j+1)\frac{E_{th}}{\Lambda}}) \Bigg\} \times \\
& \Bigg\{ \frac{M!(e^{-m\frac{E_{th}}{\Lambda}} - e^{-m\frac{x}{\Lambda}})}{m!(M-m-1)!} + \sum_{i=1}^{m-1} \frac{M!}{(i-1)!(m-i-1)!(M-m-1)!} \sum_{k=0}^{m-i-1} \binom{m-i-1}{k} \\
& \frac{(-1)^{m-i-k-1}}{k+1} \times \left[e^{-(k+1)\frac{E_{th}}{\Lambda}} \frac{e^{-(m-k-1)\frac{E_{th}}{\Lambda}} - e^{-(m-k-1)\frac{x}{\Lambda}}}{m-k-1} - \frac{e^{-m\frac{E_{th}}{\Lambda}} - e^{-m\frac{x}{\Lambda}}}{m} \right] \Bigg\} \\
& + \frac{1}{M} \Bigg\{ e^{-M\frac{E_{th}}{\Lambda}} - e^{-M\frac{x}{\Lambda}} + \sum_{i=1}^{M-1} \frac{M!}{(i-1)!(M-i-1)!} \sum_{j=0}^{M-i-1} \binom{M-i-1}{j} \frac{(-1)^{M-i-j-1}}{j+1} \\
& \left[\frac{e^{-(j+1)\frac{E_{th}}{\Lambda}}}{M-j-1} (e^{-(M-j-1)\frac{E_{th}}{\Lambda}} - e^{-(M-j-1)\frac{x}{\Lambda}}) - \frac{1}{M} (e^{-M\frac{E_{th}}{\Lambda}} - e^{-M\frac{x}{\Lambda}}) \right] \Bigg\} \\
& + M \sum_{j=0}^{M-1} \binom{M-1}{j} \frac{(-1)^j}{j+1} (1 - e^{-(j+1)\frac{E_{th}}{\Lambda}}), \qquad x \geq E_{th}.
\end{aligned} \tag{5.8}$$

After taking derivative of (5.4) and (5.8), the closed-form expression of the PDF of the harvested energy over one coherence time can be calculated as

$$f_{E_H}(x) = \begin{cases}
\frac{M}{\Lambda} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} e^{-(j+1)\frac{x}{\Lambda}}, & x < E_{th}, \\
\sum_{m=1}^{M-1} \frac{e^{-m\frac{x}{\Lambda}}}{m\Lambda} \Bigg\{ \sum_{j=0}^{M-m-1} \binom{M-m-1}{j} \frac{(-1)^j}{j+1} (1 - e^{-(j+1)\frac{E_{th}}{\Lambda}}) \Bigg\} & \\
\times \Bigg\{ \frac{M!}{(m-1)!(M-m-1)!} + \sum_{i=1}^{m-1} \frac{M!}{(i-1)!(m-i-1)!(M-m-1)!} \sum_{k=0}^{m-i-1} \binom{m-i-1}{k} & \\
\frac{(-1)^{m-i-k-1}}{k+1} \left[e^{-\frac{(k+1)(E_{th}-x)}{\Lambda}} - 1 \right] \Bigg\} + \frac{e^{-M\frac{x}{\Lambda}}}{M\Lambda} \Bigg\{ M + \sum_{i=1}^{M-1} \frac{M!}{(i-1)!(M-i-1)!} & \\
\sum_{k=0}^{M-i-1} \binom{M-i-1}{k} \frac{(-1)^{M-i-k-1}}{k+1} \left[e^{-\frac{(k+1)(E_{th}-x)}{\Lambda}} - 1 \right] \Bigg\}, & x \geq E_{th},
\end{cases} \tag{5.9}$$

which can be used to calculate the average harvested energy $\overline{E}_H$ as

$$\begin{aligned}
\overline{E}_H &= \int_0^\infty x f_{E_H}(x)dx \\
&= M\sum_{j=0}^{M-1}(-1)^j\binom{M-1}{j}\left[\frac{-E_{th}}{j+1}e^{-(j+1)\frac{E_{th}}{\Lambda}}+\frac{\Lambda}{(j+1)^2}(1-e^{-(j+1)\frac{E_{th}}{\Lambda}})\right] \\
&\quad +\sum_{m=1}^{M-1}\frac{e^{-m\frac{E_{th}}{\Lambda}}}{m}\left\{\sum_{j=0}^{M-m-1}\binom{M-m-1}{j}\frac{(-1)^j}{j+1}(1-e^{-(j+1)\frac{E_{th}}{\Lambda}})\right\} \\
&\quad \times\left\{\frac{M!(E_{th}+\frac{\Lambda}{m})}{m!(M-m-1)!}+\sum_{i=1}^{m-1}\frac{M!}{(i-1)!(m-i-1)!(M-m-1)!}\right. \\
&\quad \left.\sum_{k=0}^{m-i-1}\binom{m-i-1}{k}\frac{(-1)^{m-i-k-1}}{k+1}\left[\frac{E_{th}}{m-k-1}+\frac{\Lambda}{(m-k-1)^2}-\frac{E_{th}}{m}-\frac{\Lambda}{m^2}\right]\right\} \\
&\quad +\frac{e^{-M\frac{E_{th}}{\Lambda}}}{M}\left\{E_{th}+\frac{\Lambda}{M}+\sum_{i=1}^{M-1}\frac{M!}{(i-1)!(M-i-1)!}\sum_{k=0}^{M-i-1}\binom{M-i-1}{k}\frac{(-1)^{M-i-k-1}}{k+1}\right. \\
&\quad \left.\left[\frac{E_{th}}{M-k-1}+\frac{\Lambda}{(M-k-1)^2}-\frac{E_{th}}{M}-\frac{\Lambda}{M^2}\right]\right\}, \qquad (5.10)
\end{aligned}$$

In Fig. 5.1, we plot the PDF of the harvested energy with $E_{th} = 0.0006J$ and $M = 4$ antennas in comparison with the simulation results. As we can see, the analytical result matches the simulation result perfectly, where the harvested energy concentrates around the energy threshold E_{th}, as expected.

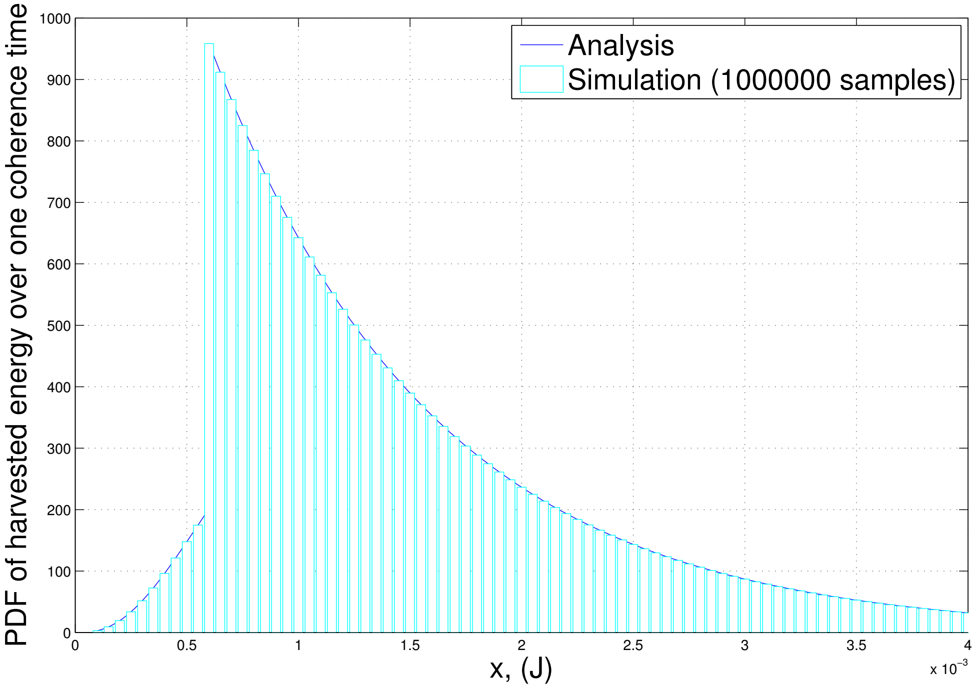

Figure 5.1: Distribution of harvested energy at the sensor.

Chapter 6

Numerical Examples

In Fig. 6.1, we plot the average harvested energy $\overline{E}_H$ as a function of the energy threshold E_{th} for different antenna number M. We can observe that more antennas leads to larger average harvested energy, as expected. We can also see that the average harvested energy at the sensor quickly increases as E_{th} increased, and gradually converges to a constant value when E_{th} is large. This is because when E_{th} is large enough, the BS will only use the best beam to charge the sensor.

In Fig. 6.2, we plot the average throughput of the MISO system as a function of the energy threshold E_{th} for different antenna number M. We can observe that larger antenna number leads to larger throughput, due to the beam selection benefit. We also observe that the throughput reduces gradually to a constant value with the increase of E_{th}. This is because when E_{th} is large, the BS will only use the best beam, from the energy harvesting perspective, to serve its selected user. Combined with Fig. 6.1, we can see there exists a tradeoff of average harvested energy at the sensor versus throughput of the MISO system. In particular, larger E_{th} leads to larger average harvested energy, but smaller throughput. We can achieve desired energy harvesting performance by properly adjusting E_{th} at the expense of certain throughput degradation in the MISO system.

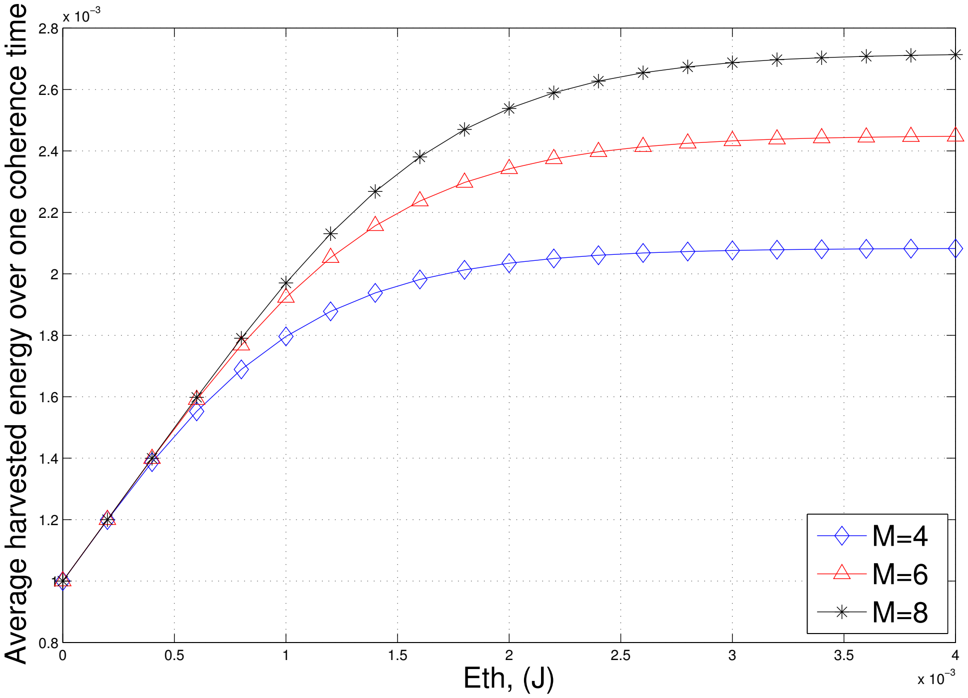

Figure 6.1: Average harvested energy at the sensor.

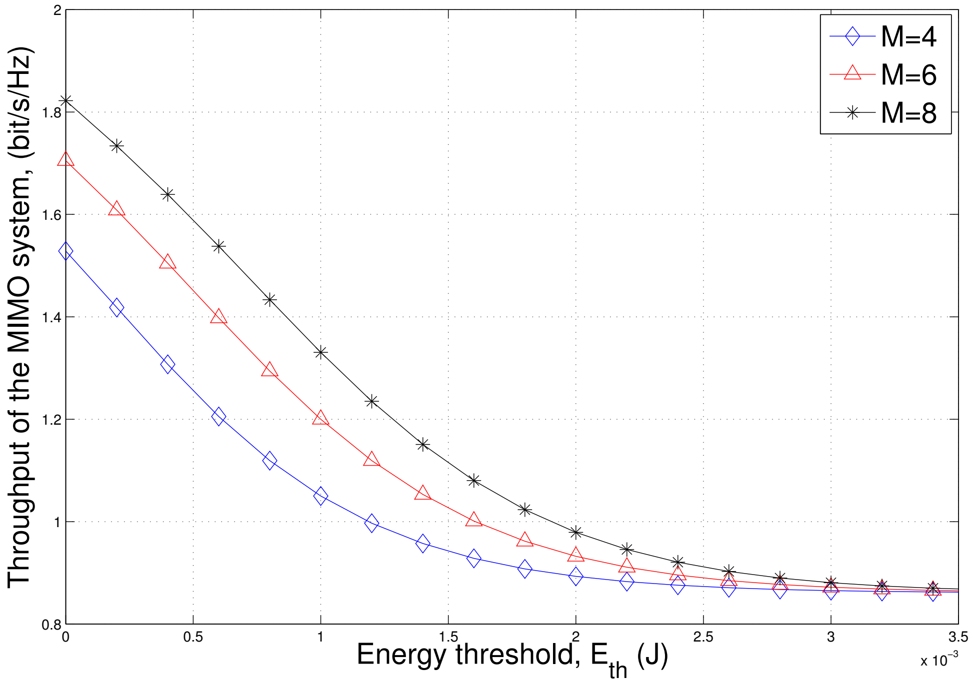

Figure 6.2: Throughput of the MISO system.

Chapter 7

Conclusion

We proposed a RUB-based cooperative beam selection scheme, using which the existing MISO system can help increase the amount of harvested energy of a wireless sensor node. We obtained the closed-form expression of the distribution of harvested energy and the average harvested energy of the sensor node, based on which, we investigated the tradeoff of the average harvested energy versus the throughput of the MISO system.

In the future, we will extend our work to another cooperative beam selection scheme, where the BS selects the best beam to serve its user without considering the sensor if the harvested energy requirement can not be satisfied.

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