Transmit Probability Designs for Wireless Peer Discovery With Energy Harvesting

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***Abstract*— This letter studies wireless peer discovery (WPD), which identifies the existence of neighbor nodes to establish link in systems where some nodes can harvest energy. In conventional WPD, each node operates in three different modes, namely, packet transmitting (Tx), data receiving, and sleeping modes. However, since the sleeping nodes neither transmit nor receive data, to make more efficient use of the resources, we consider a scenario where the sleeping nodes harvest energy from the signals radiated by the Tx nodes. First, we analyze the average number of discovered peers (ADP) and the amount of energy harvested per unit area as a function of the node densities. Then, we examine the ADP performance by addressing an ADP maximizing problem under the energy harvesting constraints, which is difficult to solve due to non-convexity. To tackle the problem, we focus on the asymptotic performance in the interference-limited scenario and provide an insightful closed-form solution. Numerical simulations confirm that our solution achieves near-optimal performance over all levels of interference with reduced complexity.**

***Index Terms*— Energy harvesting, peer discovery, stochastic geometry.**

I. Introduction

PEER-TO-PEER communications play an important role in various proximity services and public safety networks [1]. To enable communications among peers, each peer should be aware of the existence of other peers in advance, and this can be done by wireless peer discovery (WPD) operations [2]. In conventional WPD, each node operates in three different modes, i.e., data transmitting (Tx), data receiving (Rx), and sleeping nodes [3].

The Rx nodes attempt to detect neighboring peers by decoding the discovery signals broadcasted by the Tx nodes. In contrast, the nodes in the sleeping mode neither transmit nor receive signals to avoid high congestion and save power [3]–[5]. Baccelli *et al.* [4] and Kwon and Choi [5] analyzed the average number of discovered peers (ADP) in a sense that the Tx nodes can be successfully discovered if the received signal-to-interference-plus-noise ratio (SINR) at the Rx node is above a certain threshold. In [6], a transmission probability, which stands for the probability that a node is in the Tx mode, was optimized to maximize the ADP. However, in the conventional WPD [3]–[6], there exists a waste of resources since the sleeping nodes neither transmit nor receive the signals.

In the meantime, since the radio-frequency (RF) signal in the conventional wireless communication network can simultaneously carry both information and energy, the energy harvesting (EH) method using the RF energy has been regarded to be useful in many situations [7]-[11]. Particularly, Huang and Lau [12] and Psomas and Krikidis [13] evaluated the performance of EH networks using a stochastic geometry approach which is a powerful mathematical tool for modeling and designing a system. If the sleeping nodes can harvest the RF signals, we expect WPD systems with prolonged lifetimes. However, a stochastic geometric modeling and performance evaluation of the WPD with EH nodes has not been covered in the literature.

In this letter, we introduce a new EH technique where each node in the sleeping mode can harvest energy from RF signals of other Tx nodes. In this scenario, we first introduce a new system model for a random access based WPD with EH (WPD-EH) consisting of three types of nodes, namely, Tx, Rx, and EH nodes. Then, we give an analytical expression for the ADP by means of Poisson point processes (PPP), which is a key metric for the performance evaluation of the WPD-EH. Also, to measure the amount of harvested energy in the networks, we examine a performance metric called *area harvested energy* (AHE) which represents the amount of successfully harvested energy per unit area.

Based on our analytical results, we formulate an ADP maximization problem subject to the minimum required AHE constraint. Since the problem is generally non-convex and complicated, it is intractable to find a simple analytical solution. To overcome this difficulty, we focus on the interference-limited scenario with a high node density as adopted in many related works [4]–[6], [12]. Then, we provide an insightful closed-form solution that can be attained by a simple one dimensional bisection process. Although the proposed scheme is sub-optimal when the interference power is small, simulation results demonstrate that our solution exhibits good performance for all levels of interference.

II. System Model and Problem Formulation

In this section, we introduce a system model for the WPD-EH and present two performance metrics that will be used throughout the letter. We consider a system where all nodes are equipped with a single antenna and their locations are distributed according to the homogeneous PPP of density λ, denoted by $\Phi(\lambda)$. In each time slot, each node may operate

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in either of Tx, EH, and Rx modes with probabilities ρ_1, ρ_2 and $1-\rho_1-\rho_2$, respectively. Then, the distributions of Tx and EH nodes follow PPPs $\Phi(\rho_1\lambda)$ and $\Phi(\rho_2\lambda)$, respectively, according to the thinning property of PPPs [14]. In the Tx mode, the nodes broadcast the discovery signals with constant power P to inform the nearby nodes on their presence. In contrast, the EH and Rx nodes try to harvest energy and decode information from the RF signals transmitted by the Tx nodes, respectively.

Thanks to the Slivnyak's theorem [14], we can locate a typical (reference) Rx or EH node at the origin without loss of generality. Let σ^2 be the noise power at the Rx nodes. Denoting the position of the i-th Tx node by X_i, the received SINR at the typical Rx node for the signals from the i-th Tx node is given by

$$\gamma_{i,D} = \frac{|X_i|^{-\alpha}h_i}{\sum_{k\in\Phi(\rho_1\lambda)\setminus X_i}|X_k|^{-\alpha}h_k \;+\; \frac{1}{\nu^2}},$$

where α, h_i, and $\nu^2 \triangleq \frac{GP}{\sigma^2}$ represent the path loss exponent, the channel gain from the i-th Tx node to the typical Rx (or EH) node, and the average received signal to noise ratio (SNR) at unit distance, respectively. Here, G denotes the path-loss gain at reference distance.

The i-th Tx node is successfully discovered if $\gamma_{i,D}$ is larger than the minimum required SINR $\gamma_{th,D}$. Thus, the average number of discovered peers D can be written as

$$D = (1-\rho_1-\rho_2)\mathbb{E}\Bigg[\sum_{i\in\Phi(\rho_1\lambda)}\Pr(\gamma_{i,D} > \gamma_{th,D})\Bigg], \quad (1)$$

where the term $1-\rho_1-\rho_2$ comes from the fact that the typical node should be in the Rx mode. We assume that all channel gains $\{h_i\}$ follow an exponential distribution with unit mean.

Meanwhile, the amount of harvested energy at the typical EH node is obtained by

$$E_H = \sum_{k\in\Phi(\rho_1\lambda)}\xi GP|X_k|^{-\alpha}h_k,$$

where ξ indicates the conversion efficiency from the RF signal to DC voltage, which is set to be 1 unless stated otherwise. In fact it has been shown in [8] and [12] that to harvest a meaningful amount of energy at EH nodes, the harvested energy at the typical EH node E_H should be above a certain receiver activation threshold $\gamma_{th,E}$.

Thus, we can consider the energy outage probability (EOP) as follows

$$P_{out} = \Pr(E_H \le \gamma_{th,E}). \quad (2)$$

Then, the AHE can be formulated in terms of the EH node density $\rho_2\lambda$ as

$$E_{area} = \rho_2\lambda(1-\epsilon_E)\gamma_{th,E},$$

where ϵ_E implies the target outage probability, which determines the total amount of harvested energy. The AHE is interpreted as the amount of energy successfully harvested by EH nodes per unit area. Thus, it serves as a useful measure of the energy available in the WPD-EH network.[1]

[1]It is important to remark that the AHE is similar to the transmission capacity in [15] which represents the spectral efficiency of successful transmission per unit area.

For given ADP and EOP expressions, we can formulate a joint ADP maximization problem with respect to ρ_1, ρ_2 and ϵ_E as

$$\text{(P-a)} \quad \max_{\rho_1,\rho_2,\epsilon_E} \; D \quad (3)$$
$$\text{s.t. } P_{out} \le \epsilon_E, \quad (4)$$
$$E_{area} \ge E_{th}, \quad (5)$$
$$0\le\rho_1\le 1, \quad 0\le\rho_2\le 1, \; 0\le\rho_1+\rho_2\le 1,$$

where $\gamma_{th,E}$ and E_{th} are fixed constants. Without EH constraints (4) and (5), the problem with $\rho_2 = 0$ becomes equivalent to the conventional WPD problem in [6]. Thus, problem (P-a) provides a generalized solution which includes the WPD as a special case. One may solve problem (P-a) exploiting an exhaustive search algorithm which examines all possible values of ρ_1, ρ_2 and ϵ_E. However, such a full search method suffers from high computational complexity and furthermore hardly provides meaningful insights. The goal of our paper is to offer an insightful closed-form solution that can be obtained with low complexity.

III. Probability Designs of Transmit and EH Modes

In this section, we present useful analytical results of problem (P-a) by focusing on the case of the interference limited environment ($\sigma^2 \to 0$) with $\alpha = 4$.[2] First, we develop analytic expressions for both the ADP and the EOP. Then, we identify a simple closed-form solution and offer insightful observations. Let us first introduce the following lemma which provides the analytic expressions of the ADP and the EOP for the general cases.

Lemma 1: The ADP D in (1) and the EOP P_{out} in (2) are respectively expressed by

$$D = \lambda\pi\rho_1(1-\rho_1-\rho_2) \times \int_0^\infty \exp\Bigg(-\frac{2\lambda\pi^2\gamma_{th,D}^{\frac{2}{\alpha}}}{\alpha\sin\left(\frac{2\pi}{\alpha}\right)}\rho_1 t - \frac{\gamma_{th,D}}{\nu^2}\sqrt{t^\alpha}\Bigg)dt, \quad (6)$$

$$P_{out} = 1-\frac{1}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^{k+1}\sin(\frac{2\pi k}{\alpha})\Gamma(\frac{2k}{\alpha})}{k!}\Bigg(\frac{2\lambda\sqrt{GP}\pi^2\rho_1}{\alpha\sin(\frac{2\pi}{\alpha})\gamma_{th,E}^{2/\alpha}}\Bigg)^k, \quad (7)$$

where $\Gamma(m) = \int_0^\infty x^{m-1}\exp(-x)\,dx$ stands for the Gamma function.

Proof: Defining $I = \sum_{k\in\Phi(\rho_1\lambda)\setminus X_i}|X_k|^{-\alpha}h_k$ and $\delta = r^\alpha\gamma_{th,D}$, the ADP in (1) can be rephrased as

$$D = (1-\rho_1-\rho_2)\mathbb{E}\Bigg[\sum_{k\in\Phi(\rho_1\lambda)}\Pr(\gamma_{k,D} > \gamma_{th,D})\Bigg]$$
$$= 2\lambda\pi\rho_1(1-\rho_1-\rho_2)\int_0^\infty r\Pr\Big(h > \delta(I+\frac{1}{\nu^2})\Big)dr, \quad (8)$$

where (8) follows from the Campbell's theorem [14] with a change of variable $r = |X|$. Then, by employing the probability generating functional of the PPP [14] and

[2]Although here we resort to some specific scenarios, these assumptions are not only practical, but also significantly simplify a solution as discussed in the majority of related papers [4], [5], [12]. The analysis for more general cases, i.e., $\sigma^2 > 0$ or $\alpha \ne 4$ could be discussed in future works.

setting $|X_n| = z$, we have

$$\Pr\Big(h > \delta(I + \frac{1}{\nu^2})\Big)$$
$$= \mathbb{E}_{\Phi(\rho_1\lambda)}\Big[\Pi_{n\in\Phi(\rho_1\lambda)\setminus X_i}\mathbb{E}_{\{h_n\}}\big[\exp(-\delta|X_n|^{-\alpha}h_n)\big]\Big]\exp(-\frac{\delta}{\nu^2})$$
$$= \exp\Big(2\pi\rho_1\lambda\psi\Big)\exp(-\frac{\delta}{\nu^2}), \tag{9}$$

where $\psi \triangleq \int_0^\infty \big(1 - \mathbb{E}_h[\exp(-\delta z^{-\alpha}h)]\big)zdz = \frac{\pi}{\alpha\sin(2\pi/\alpha)}\delta^{\frac{2}{\alpha}}$ which is derived from the facts that $\int_0^\infty \big(1 - \exp(-\delta z^{-\alpha}h)\big)zdz = -\frac{1}{\alpha}\Gamma(\frac{-2}{\alpha})(\delta h)^{\frac{2}{\alpha}}$ and $\Gamma(1-\frac{2}{\alpha})\Gamma(1+\frac{2}{\alpha}) = \frac{2\pi}{\alpha\sin(2\pi/\alpha)}$. Therefore, by plugging (9) into (8) and replacing r^2 to t, we can obtain (6).

In the meantime, the EOP in (2) is given by $P_{out} = F_{E_H}(\gamma_{th,E})$, where $F_X(\cdot)$ denotes the cumulative distribution function (CDF) of a random variable X. Then, one can prove that the probability density function (PDF) of E_H, denoted by $f_{E_H}(\cdot)$, is Levy-stable [14] with a dispersion factor $\frac{2\lambda\pi^2\rho_1\cos(\pi/\alpha)(GP)^{\frac{2}{\alpha}}}{\alpha\sin(2\pi/\alpha)}$. Therefore, we can derive the EH outage probability in (7) by computing $\int_0^{\gamma_{th,E}} f_{E_H}(x)dx$. Details are omitted for brevity. ∎

Now, by setting $\alpha = 4$, the results in Lemma 1 can be simplified as the following corollary.[3]

Corollary 1: When $\alpha = 4$, the ADP and the EOP in (6) and (7) are respectively given by

$$D = \sqrt{\frac{8}{\pi\gamma_{th,D}}}\eta\rho_1(1-\rho_1-\rho_2)Q\big(\eta\rho_1\big)\exp\Big(\frac{\eta^2}{2}\rho_1^2\Big), \tag{10}$$

$$P_{out} = 2Q\Bigg(\frac{\lambda\pi^2\sqrt{GP}\rho_1}{\sqrt{8\gamma_{th,E}}}\Bigg), \tag{11}$$

where $\eta \triangleq \frac{\lambda\pi^2\nu}{2\sqrt{2}}$, and $Q(x) \triangleq \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-u^2/2)du$ denotes the Gaussian Q-function.

Proof: Setting $\alpha = 4$ in (6), D becomes

$$D = \lambda\pi\rho_1(1-\rho_1-\rho_2)\int_0^\infty \times \exp\Big(-\frac{\lambda\pi^2\sqrt{\gamma_{th,D}}}{2}\rho_1 t - \frac{\gamma_{th,D}}{\nu^2}t^2\Big)dt.$$

Thus, (10) is immediate from $\int_0^\infty \exp(-\alpha x - \beta x^2)dx = \sqrt{\frac{\pi}{\beta}}Q\big(\frac{\alpha}{\sqrt{2\beta}}\big)\exp\big(\frac{\alpha^2}{4\beta}\big)$ for $\alpha \ge 0$ and $\beta \ge 0$. It is also easy to show that E_H has a Levy distribution [14] with a dispersion factor $\kappa = \frac{\lambda\pi^2\sqrt{GP}}{2\sqrt{2}}\rho_1$ when $\alpha = 4$, which leads to the result in (11). ∎

We now have closed-form expressions for D and P_{out} in (10) and (11) for $\alpha = 4$. However, unfortunately, problem (3) is still non-convex, and the complicated form of D in (10) prevents us from having an explicit solution of problem (3). To circumvent the problem, we assume that the aggregated interference power at the typical Rx node is much larger than the noise power such that $\frac{1}{\nu^2} \to 0$ in (1). Then, it follows

$$D \approx \lambda\pi\rho_1(1-\rho_1-\rho_2)\int_0^\infty \exp\Big(-\frac{\lambda\pi^2\sqrt{\gamma_{th,D}}}{2}\rho_1 t\Big)dt$$
$$= \frac{2}{\pi\sqrt{\gamma_{th,D}}}(1-\rho_1-\rho_2). \tag{12}$$

[3]Closed-form expressions for the EOP are available only for $\alpha = 4$.

This result shows that in the interference limited scenario, the ADP maximization problem under the AHE constraint can simply be regarded as the maximizing the number of Rx nodes.

Finally, plugging (12) into problem (P-a), we attain a simplified ADP problem as

$$\text{(P-b)}\quad \max_{\rho_1,\rho_2,\epsilon_E} \frac{2}{\pi\sqrt{\gamma_{th,D}}}(1-\rho_1-\rho_2)$$
$$\text{s.t. } 2Q\Bigg(\frac{\lambda\pi^2\sqrt{GP}\rho_1}{\sqrt{8\gamma_{th,E}}}\Bigg) \le \epsilon_E, \tag{13}$$
$$\rho_2\lambda(1-\epsilon_E)\gamma_{th,E} \ge E_{th}, \tag{14}$$
$$0 \le \rho_1 \le 1,\quad 0 \le \rho_2 \le 1,\ 0 \le \rho_1+\rho_2 \le 1.$$

The objective function in (P-b) is monotonically decreasing with ρ_1 and ρ_2. Also, the Q-function in (13) is monotonically decreasing with ρ_1. Thus, the outage constraint in (13) is always tight with the optimal ϵ_E given by

$$\epsilon_E^* = 2Q\Bigg(\frac{\lambda\pi^2\sqrt{GP}}{\sqrt{8\gamma_{th,E}}}\rho_1\Bigg). \tag{15}$$

Similarly, one can show that the AHE constraint in (14) also holds with equality as $\rho_2\lambda(1-\epsilon_E)\gamma_{th,E} = E_{th}$ at the optimal point. Thus, substituting (15) into (14) yields

$$\rho_2^* = \frac{E_{th}}{\lambda\gamma_{th,E}\Big(1-2Q\Big(\frac{\lambda\pi^2\sqrt{GP}}{\sqrt{8\gamma_{th,E}}}\rho_1\Big)\Big)}. \tag{16}$$

We notice from (15) and (16) that as the number of Tx nodes increases, the energy outage probability ϵ_E at the typical EH node decreases. Thus, it is seen from (14) that for a large ρ_1 (or small ϵ_E), we need a smaller number of EH nodes to meet the AHE constraint E_{th}. Unlike the previous designs in [6], however, the number of Rx nodes is neither increasing nor decreasing with respect to ρ_1. Thus, to maximize the ADP, we need to solve the following problem which is recast from (P-b) using (15) and (16) as

$$\text{(P-c)}\quad \min_{\rho_1} h(\rho_1)$$
$$\text{s.t. } 0 \le \rho_1 \le 1,\quad \frac{b}{1-2Q(a\rho_1)} \le 1,\ h(\rho_1) \le 1,$$

where $h(\rho_1) \triangleq \frac{b}{1-2Q(a\rho_1)} + \rho_1$ with $a \triangleq \frac{\lambda\pi^2\sqrt{GP}}{\sqrt{8\gamma_{th,E}}} > 0$ and $b \triangleq \frac{E_{th}}{\lambda\gamma_{th,E}} > 0$.

It is easy to show that problem (P-c) is convex by examining the second order derivative of $h(\rho_1)$ as $\frac{\partial^2 h(\rho_1)}{\partial\rho_1^2} = \frac{4a^2 b\exp(-2a^2\rho_1^2)\big(2+a\sqrt{\pi}\rho_1\exp(a^2\rho_1^2)(1-2Q(a\rho_1))\big)}{\pi\big(1-2Q(a\rho_1)\big)^3} \ge 0$. Thus, we can always find a unique optimal value ρ_1^* satisfying the zero-gradient condition $\frac{\partial h(\rho_1)}{\partial\rho_1}|_{\rho_1=\rho_1^*} = 0$ by utilizing the simple bisection method [16] such that

$$\frac{\exp(-(a\rho_1^*)^2)}{\big(1-2Q(a\rho_1^*)\big)^2} = \frac{\sqrt{\pi}\lambda\gamma_{th,E}}{2aE_{th}}. \tag{17}$$

Plugging the resulting ρ_1^* into (15) and (16), we also determine ϵ_E^* and ρ_2^*.

A careful examination of (17) reveals that ρ_1^* is increasing with E_{th}. Thus, as the AHE requirement E_{th} goes high,

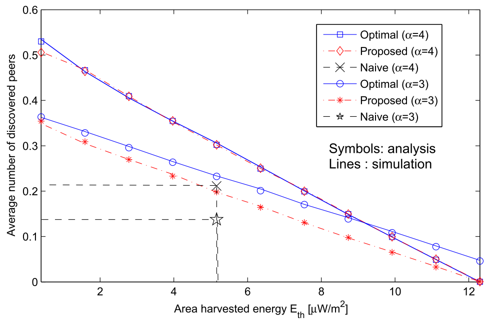

Fig. 1. ADP performance comparison with respect to E_{th} with SNR $= 17$ dB and $\lambda = 2$.

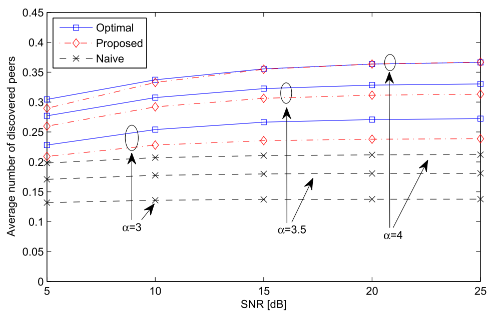

Fig. 2. ADP performance comparison with respect to SNR with $\lambda = 1.7$ and $E_{th} = 3\mu$W/m^2.

the ADP performance becomes lower, since the number of Tx nodes and EH nodes increase simultaneously. We also recognize from the result that a large E_{th} leads to the interference limited scenarios due to the increased interference power at the typical Rx node. Therefore, we can infer that the proposed method approaches the optimum as the AHE requirement becomes larger.[4]

IV. Simulation Results

In this section, we present numerical results and investigate performance of the proposed scheme. Although our analytic scheme is based on the noiseless assumption, the numerical performance is evaluated in the presence of the noise, i.e., $\sigma^2 > 0$. Throughout the simulations, we set $P = 350$ mW, $\gamma_{th,D} = 0$ dB, $\gamma_{th,E} = 8$ μW, $\xi = 0.5$, and a path loss at 1 m of $G = -40$ dB.

In Fig. 1, we illustrate the tradeoff region between the ADP D and the AHE E_{th} with $\lambda = 2$ when $\alpha = 3$ and 4. The "Naive" scheme represents a simple method with $\rho_1 = \rho_2 = \frac{1}{3}$. It is worth noting that the proposed algorithm achieves near-optimal performance when $\alpha = 4$ with reduced complexity. In contrast, the ADP performance of the naive scheme is irrelevant to E_{th}, and cannot fulfil high AHE requirements due to the fixed values of $\rho_1 = \rho_2$. When $\alpha = 4$, except for a very low E_{th} region, the proposed scheme performs almost the same as the optimal one. As E_{th} decreases, the system becomes noise-limited due to the reduced transmit probability ρ_1^* as shown in (17). Although, the proposed algorithm experience a little performance loss compared to the optimal when $\alpha = 3$, our method still exhibits a larger ADP-AHE region than the naive scheme.

Fig. 2 presents the ADP performance as a function of SNR with various path loss exponents. When $\alpha = 4$, it is obvious that as the SNR goes over 15 dB, the proposed scheme quickly approaches the optimum. The gap between the optimal solution and the proposed method decreases as α increases. It is worthwhile to note that unlike our proposed scheme, the naive method may not achieve the minimum energy requirement when E_{th} increases as shown in Fig. 1 due to the fixed transmit probability. From the simulation results, we confirm that our closed-form solution exhibits good performance over all cases with reduced complexity when $\alpha = 4$. Even though the gap between optimal and proposed method exists when $\alpha \neq 4$, our scheme provides substantially better performance than the conventional scheme.

[4]In the line-of-sight (LOS) environment with Rician fading, it is not easy to derive analytic solutions due to the absence of the closed-form expression. However, from simulation, we confirmed that the Rician factor may not affect much the performance of the ADP, and the proposed scheme is robust with respect to the Rician factor. Due to the page limitation, we have not included the simulation results in the letter.

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