Harvested Energy Maximization in Wireless Peer Discovery Systems

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***Abstract*— This letter studies energy harvesting systems, which perform peer discovery. Wireless peer discovery is a network operation performed to identify the existence of peers in the network. In this operation, some fractions of the peers broadcast the discovery message to nearby peers. In such a system, a receiver decodes the message while harvesting energy from the received signal through the power splitting circuit. An optimization problem is examined for maximizing the harvested energy in the peer discovery network with an arbitrary value of the path loss exponent. A low-complexity algorithm is proposed, which utilizes bisection search. The numerical results demonstrate that the proposed algorithm achieves almost the same performance as the optimal exhaustive search algorithm with much reduced complexity.**

***Index Terms*— Peer discovery, Poisson point process (PPP), radio frequency energy harvesting.**

I. Introduction

PEER discovery is a network operation that is periodically carried out in modern networks for various purposes [1]. Primary reasons for performing the peer discovery may include proximal social and commercial networking. Generally, in the peer discovery operation, some fractions of the peers broadcast the discovery message which may reach remaining peers. A peer is considered to be discovered if its transmitted discovery message is successfully decoded.

In recent literature on the peer discovery, in order to analyze a large network, it is assumed that peers are spatially distributed according to a homogenous Poisson point process (PPP) [2]. In this context, the average number of discovered peers is a useful performance indicator, and was analyzed in [3], [4] by checking if the received signal-to-interference-plus-noise ratio (SINR) is greater than a specific threshold.

Different research works have optimized various design parameters to maximize certain performance metrics in the peer discovery. In [2], the transmit probability of a network with half duplex peers was examined which maximizes the average number of discovered peers. The transmit probability design was devised for a heterogeneous wireless network [1] with the aim to achieve fairness among the half/full-duplex discovered peers. The authors in [5] have investigated the design principles for maximizing the average number of discovered peers in heterogeneous networks. Since the transmit power is an important communication resource, the transmit probability and the transmit power were optimized in [6] to minimize the area transmit power when the path loss exponent is 4.

In the meantime, due to advancement in the radio frequency (RF) energy harvesting technology [7], it has become possible to harvest energy from the RF signals present in the ambient environment. Recently, energy harvesting methods were incorporated in the peer discovery process in [8]. In their work, the transmit and receive probabilities were studied to maximize an upper bound on the average number of discovered peers while satisfying a constraint on the average harvested energy with the path loss exponent equal to 4 for the ease of analysis. To our best knowledge, none of the existing works on wireless peer discovery considered the RF energy harvesting in wireless peer discovery with general values of the path loss exponent.

In this letter, we devise a new optimization problem which maximizes the average harvested energy at the receiving peers with an arbitrary value of the path loss exponent. The problem is non-convex, and hence a low complexity algorithm is proposed to find a near-optimal solution. It is observed that the proposed algorithm achieves almost the same performance as the exhaustive search with much reduced computational complexity.

II. System Model and Problem Formulation

We consider a system where peers are spatially distributed according to PPP $\Phi(\lambda)$ with uniform density λ. During any given time slot, the density of the transmitting peers is ν while that of the receiving peers is $1-\nu$. Hence, there are no sleeping peers in our system model. A peer is assumed to be discovered if the received SINR is higher than a specific threshold γ_{th}. The receiving peers not only try to decode the transmitted message but also harvest energy from the received signal.

For harvesting energy from the received signal, the receiving peers employ a power splitting protocol, where a typical receiver splits the received signal into two parts. One part ρ is fed to the energy harvesting circuitry while the remaining part is passed to the information decoding circuitry [9]. Assuming that the transmit power of a typical transmitter is P_t, we can write the received SINR at a typical receiver as [9]

$$\gamma_i = \frac{(1-\rho)P_t|X_i|^{-\alpha}h_i}{\sum_{k\in\Phi(\nu\lambda)\setminus X_i}(1-\rho)P_t|X_k|^{-\alpha}h_k+\sigma^2},$$

where $|X_i|$ is the distance between the i-th transmitter and the typical receiver, α indicates the path loss exponent, h_i represents the Rayleigh fading channel gain [8] between the transmitter and the receiver, $\Phi(\nu\lambda)$ stands for PPP of the transmitting peers, and σ^2 equals the noise variance.

According to the SINR expression, the average number of discovered peers at a typical peer can be obtained as

$$\omega(\rho,\nu) = (1-\nu)E\Bigg(\sum_{i\in\Phi(\nu\lambda)}\mathbf{1}_{(\gamma_i>\gamma_{th})}\Bigg),$$

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where $\mathbf{1}_{(.)}$ is the indicator function and $E[X]$ denotes the expectation of a random variable X. After some mathematical simplifications, we have [2]

$$\omega(\rho,\nu)=\pi\lambda\nu(1-\nu)\int_0^\infty \exp\left(-\frac{\gamma_{th}\sigma^2\ x^{\frac{\alpha}{2}}}{(1-\rho)P_t}-\pi\lambda\nu\gamma_{th}^{\frac{\alpha}{2}}x\Gamma\left(1-\frac{2}{\alpha}\right)\Gamma\left(1+\frac{2}{\alpha}\right)\right)dx, \quad (1)$$

where $\Gamma(x)=\int_0^\infty z^{x-1}\exp(-z)dz$ [10]. Eq. (1) is a generalized expression for the average number of discovered peers, as the result in [2] can be obtained with $\rho=0$. It can be seen that $\omega(\rho,\nu)$ is a decreasing function of ρ for a given ν. The maximum possible value of $\omega(0,\nu)$ is computed as [6]

$$\theta \triangleq \lim_{\nu\to 0}\lim_{P_t\to\infty}\omega(0,\nu)=\frac{1}{\Gamma\left(1-\frac{2}{\alpha}\right)\Gamma\left(1+\frac{2}{\alpha}\right)\gamma_{th}^{\frac{2}{\alpha}}}.$$

The signal part at the energy harvesting circuitry is expressed as

$$y_h=\sum_{k\in\Phi(\nu\lambda)}\sqrt{\rho P_t|X_k|^{-\alpha}h_k}x_k,$$

where x_k is the signal transmitted from the k-th transmitter. The harvested power P_h at the energy harvesting circuitry is

$$P_h=\rho P_t\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}h_k.$$

In this work, we employ a lower bound on the harvested power as

$$E[P_h]=\rho P_t E\left[\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}h_k\right] \quad (2)$$

where expectation is taken with respect to the point process $\Phi(\nu\lambda)$ and the fading channels h_k. Due to the independence between the point process and the fading gains, we have

$$E[P_h]=\rho P_t E_{\Phi(\nu\lambda)}\left[\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}E_h[h_k]\right], \quad (3)$$

where $E_{\Phi(\nu\lambda)}[.]$ denotes the expection with respect to the point process and $E_h[.]$ represents the expection with respect to the channel gain. Since $E[h_k]=1$ in our work, it follows

$$E[P_h]=\rho P_t E_{\Phi(\nu\lambda)}\left[\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}\right]. \quad (4)$$

A lower bound on $E_{\Phi(\nu\lambda)}\left[\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}\right]$ is [11]

$$E_{\Phi(\nu\lambda)}\left[\sum_{k\in\Phi(\nu\lambda)}|X_k|^{-\alpha}\right]=\sum_{k=1}^{\infty}E[X_k^{-\alpha}]>\sum_{k=1}^{\infty}E[X_k^{\alpha}]^{-1} \quad (5)$$

where $E[X_k^{\alpha}]$ is given as [11]

$$E[X_k^{\alpha}]=\left(\frac{1}{\nu\lambda\pi}\right)^{\frac{\alpha}{m}}(n)_{\frac{\alpha}{2}} \quad (6)$$

where $(n)_{\frac{\alpha}{m}}=\frac{\Gamma(n+\frac{\alpha}{m})}{\Gamma(n)}$ indicates the Pochhammer symbol notation. Putting (6) into (5), we get

$$E[P_h]>\frac{P_t\rho(\lambda\nu)^{\frac{\alpha}{2}}}{(\frac{\alpha}{2}-1)\Gamma(\frac{\alpha}{2})}=P_h^L(\rho,\nu), \quad (7)$$

where we have used the fact that $\sum_{n=1}^{\infty}\frac{1}{(n)_{\frac{\alpha}{2}}}=\frac{1}{(\frac{\alpha}{2}-1)\Gamma(\frac{\alpha}{2})}$. The average harvested power per unit area is calculated by multiplying $P_h^L(\rho,\nu)$ with the density of receiving peers. Therefore, the average harvested power per unit area $\zeta(\rho,\nu)$ is obtained as[1]

$$\zeta(\rho,\nu)=\frac{P_t\rho\lambda^{\frac{\alpha}{2}+1}\nu^{\frac{\alpha}{2}}(1-\nu)}{(\frac{\alpha}{2}-1)\Gamma(\frac{\alpha}{2})}. \quad (8)$$

In this situation, we are interested in how to find the appropriate values of ρ and ν in the energy harvesting peer discovery system model. In the following, we propose an optimization problem which addresses this issue. For the given analytical expressions for $\omega(\rho,\nu)$ and $\zeta(\rho,\nu)$, we can devise the optimization problem with respect to ν and ρ as

$$\max_{0<\nu,\rho<1}\ \zeta(\rho,\nu) \quad \text{s.t. } \omega(\rho,\nu)\geq\eta\theta, \quad (9)$$

where η ($0<\eta<1$) is a constant. The constraint of (9) indicates that the average number of discovered peers should be greater than a certain fraction of the maximum discoverable peers. The problem (9) is non-convex, and it can be solved using exhaustive search, which examines all possible values of ρ and ν. To reduce the computational complexity of the exhaustive search, we devise an efficient low complexity optimization algorithm for maximizing harvested energy while satisfying a constraint on the minimum number of discovered peers.

III. Maximization of Harvested Energy With a Constraint on Discovered Peers

It is not possible to derive a closed form expression for (1), which makes it difficult to design ρ and ν. To obtain $\omega_L(\rho,\nu)$ from (1), we replace $\exp\left(-\frac{\gamma_{th}\sigma^2\ x^{\frac{\alpha}{2}}}{(1-\rho)P_t}\right)$ by its lower bound $1-\frac{\gamma_{th}\sigma^2\ x^{\frac{\alpha}{2}}}{(1-\rho)P_t}$ [1], [2], [8] to get

$$\omega_L(\rho,\nu)=\pi\lambda\nu(1-\nu)\int_0^\infty\left(1-\frac{\gamma_{th}\sigma^2\ x^{\frac{\alpha}{2}}}{(1-\rho)P_t}\right)\times\exp\left(-\pi\lambda\nu\gamma_{th}^{\frac{\alpha}{2}}x\Gamma\left(1-\frac{2}{\alpha}\right)\Gamma\left(1+\frac{2}{\alpha}\right)\right)dx. \quad (10)$$

Using the fact that $\Gamma(x)=\int_0^\infty z^{x-1}\exp(-z)dz$, we obtain

$$\omega_L(\rho,\nu)=\theta(1-\nu)(1-\frac{a\nu^{-\frac{\alpha}{2}}}{1-\rho}), \quad (11)$$

where $a=\sigma^2\Gamma\left(1+\frac{\alpha}{2}\right)/\left(P_t\left(\pi\lambda\Gamma\left(1+\frac{2}{\alpha}\right)\Gamma\left(1-\frac{2}{\alpha}\right)\right)^{\frac{\alpha}{2}}\right)$.

By removing the constant term in the objective function of (9) and replacing $\omega(\rho,\nu)$ with $\omega_L(\rho,\nu)$, the problem (9) can be simplified as

$$\max_{0<\nu,\rho<1}\ \nu^{\frac{\alpha}{2}}\rho(1-\nu) \quad \text{s.t.} (1-\nu)\left(1-\frac{a\nu^{-\frac{\alpha}{2}}}{1-\rho}\right)\geq\eta. \quad (12)$$

It can be observed that the objective of the optimization problem increases with ρ. However, the left hand side (LHS) of the constraint decreases with increasing ρ.

[1] A similar dependence of the harvested energy on ρ and ν is shown in [12], [13].

Therefore, in order to maximize the objective function, we can choose the maximum value of ρ that satisfies the constraint with equality. Hence, the optimization problem can be written as

$$\max_{0<\nu<1-\eta} \nu^{\frac{\alpha}{2}}(1-\nu)\left(1-a\frac{1-\nu}{(1-\nu-\eta)\nu^{\frac{\alpha}{2}}}\right) \quad (13)$$

where ρ in the objective function of (12) is replaced by $\rho = 1-a\frac{1-\nu}{(1-\nu-\eta)\nu^{\frac{\alpha}{2}}}$. The constraint on ν is also changed from $0<\nu<1$ to $0<\nu<1-\eta$. This is because if $\nu \geq 1-\eta$, then ρ will be greater than 1, which violates the constraint on ρ.

The objective function of the optimization problem (13) is not concave. For ease of notation, we define the following functions

$$t(\nu) \triangleq \nu^{\frac{\alpha}{2}}(1-\nu), \qquad g(\nu) \triangleq 1-a\frac{1-\nu}{(1-\nu-\eta)\nu^{\frac{\alpha}{2}}}.$$

We have the following proposition for $g(\nu)$.

Proposition 1: For any α, $g(\nu)$ is a strictly quasi-concave function for $0<\nu<1-\eta$, and its maximum value is achieved at

$$\nu_2 = \frac{2\alpha+\eta(2-\alpha)-\sqrt{\eta^2(\alpha^2+4)+4\eta\alpha(2-\eta)}}{2\alpha}.$$

Proof: The first derivative of $g(\nu)$ can be written as

$$g'(\nu) = -\frac{\nu^{-\frac{\alpha}{2}-1}(2\eta\nu-\alpha(\nu-1)(\eta+\nu-1))}{2(1-\nu-\eta)^2}.$$

It can be seen that $\lim_{\nu\to 0} g'(\nu)\to\infty$ and $\lim_{\nu\to 1-\eta} g'(\nu)\to -\infty$. Therefore, there is at least one point in $0<\nu<1-\eta$ where $g'(\nu)$ becomes zero. This point can be obtained by solving the second order equation

$$2\eta\nu-\alpha(\nu-1)(\eta+\nu-1)=0.$$

Two possible solutions of the above equation are given as

$$\nu_1,\nu_2 = \frac{2\alpha+\eta(2-\alpha)\pm\sqrt{\eta^2(\alpha^2+4)+4\eta\alpha(2-\eta)}}{2\alpha},$$

It can be checked that ν_1 cannot lie in $(0,1)$ because $\eta(2-\alpha)+\sqrt{\eta^2(\alpha^2+4)+4\eta\alpha(2-\eta)}>0$. Therefore, we conclude that $g(\nu)$ strictly increases for $0<\nu<\nu_2$ and strictly decreases for $\nu_2<\nu<1-\eta$. Hence, $g(\nu)$ is maximized at $\nu=\nu_2$. □

We denote the point at which $g(\nu)$ becomes 0 in $0<\nu<\nu_2$ as ν_L. Let us define the objective function of (13) as $f(\nu)$. Then, using the quasi-concavity of $g(\nu)$ in proposition 1, we have the following propositions for $f(\nu)$.

Proposition 2: If $\nu_2>\frac{\alpha}{\alpha+2}$, the objective function $f(\nu)$ is quasi-concave over the interval $\frac{\alpha}{\alpha+2}<\nu<\nu_2$. Otherwise, the objective function is quasi-concave over the interval $\nu_2<\nu<\max(\frac{\alpha}{\alpha+2},1-\eta)$, where $\frac{\alpha}{\alpha+2}$ is the unique maximizer of $t(\nu)$. In other words, $t(\nu)$ strictly increases for $0<\nu<\frac{\alpha}{\alpha+2}$, while $t(\nu)$ strictly decreases for $\frac{\alpha}{\alpha+2}<\nu<1$.

Proof: First, we show that $t(\nu)$ strictly increases for $0<\nu<\frac{\alpha}{\alpha+2}$ and it strictly decreases for $\frac{\alpha}{\alpha+2}<\nu<1$. The derivative of $t(\nu)$ is given as

$$t'(\nu) = \nu^{\frac{\alpha}{2}-1}\left(\frac{\alpha}{2}-\left(\frac{\alpha}{2}+1\right)\nu\right).$$

It can be easily verified that $t'(\nu)$ is positive for $0<\nu<\frac{\alpha}{\alpha+2}$ and is negative for $\frac{\alpha}{\alpha+2}<\nu<1$. Further, $t'(\nu)$ is zero at $\nu=\frac{\alpha}{\alpha+2}$, and thus $t(\nu)$ is maximized at $\nu=\frac{\alpha}{\alpha+2}$.

If $\nu_2>\frac{\alpha}{\alpha+2}$, there can be two possibilities: $\nu_L>\frac{\alpha}{\alpha+2}$ or $\nu_L<\frac{\alpha}{\alpha+2}$. If $\nu_L<\frac{\alpha}{\alpha+2}$, $f(\nu)$ is a quasi-concave function for $\frac{\alpha}{\alpha+2}<\nu<\nu_2$, because it is a product of the positive increasing function $g(\nu)$ and the positive decreasing function $t(\nu)$ [14]. Similarly, if $\nu_L>\frac{\alpha}{\alpha+2}$, $f(\nu)$ is quasi-concave for $\nu_L<\nu<\nu_2$. Further, it can be shown that the derivative of $f(\nu)$ cannot be negative for $\frac{\alpha}{\alpha+2}<\nu<\nu_L$. Therefore, the upper level set of $f(\nu)$ for $\frac{\alpha}{\alpha+2}<\nu<\nu_L$ is also a convex set. Hence, it follows that the function $f(\nu)$ is quasi-concave over $\frac{\alpha}{\alpha+2}<\nu<\nu_2$ if $\nu_2>\frac{\alpha}{\alpha+2}$.

Similarly, we can prove that if $\nu_2<\frac{\alpha}{\alpha+2}$, the function $f(\nu)$ is quasi-concave for $\nu_2<\nu<\nu_U$, where ν_U is the unique solution for $g(\nu)=0$ in the interval $\nu_2<\nu<1-\eta$. Also, the derivative of $f(\nu)$ cannot be positive for $\nu_U<\nu<\max(\frac{\alpha}{\alpha+2},1-\eta)$, because $f(\nu)$ is a product of the negative decreasing function $g(\nu)$ and the positive increasing function $t(\nu)$ for $\nu_U<\nu<\frac{\alpha}{\alpha+2}$. Therefore, the upper level set is a convex set. Hence, $f(\nu)$ is quasi-concave over $\nu_2<\nu<\max\left(\frac{\alpha}{\alpha+2},1-\eta\right)$ if $\nu_2<\frac{\alpha}{\alpha+2}$. □

Proposition 3: If $\nu_2>\frac{\alpha}{\alpha+2}$, the maximum value of $f(\nu)$ lies in $\frac{\alpha}{\alpha+2}<\nu<\nu_2$. Otherwise, the maximum value of $f(\nu)$ exists in $\nu_2<\nu<\max(\frac{\alpha}{\alpha+2},1-\eta)$.

Proof: First, we prove for the case $\nu_2>\frac{\alpha}{\alpha+2}$. Since the other case follows a similar approach and thus will be omitted. Since both $g(\nu)$ and $t(\nu)$ are decreasing for $\nu_2<\nu<1-\eta$, any point in $\nu_2<\nu<1-\eta$ achieves a smaller objective value compared to $\nu=\nu_2$. Further, if $\nu_L>\frac{\alpha}{\alpha+2}$, the objective function is negative for $0<\nu<\frac{\alpha}{\alpha+2}$, and thus no point in this interval can be optimal. On the other hand, if $\nu_L<\frac{\alpha}{\alpha+2}$, then $t(\nu)$ and $g(\nu)$ are strictly increasing in $\nu_L<\nu<\frac{\alpha}{\alpha+2}$, and thus no point in this interval can have a higher value of the objective function than that achieved at $\nu=\frac{\alpha}{\alpha+2}$. Therefore, we conclude that if $\nu_2>\frac{\alpha}{\alpha+2}$, then the optimal ν can only lie in the interval $\frac{\alpha}{\alpha+2}<\nu<\nu_2$. □

Therefore, a bisection search can be performed over the interval $[\frac{\alpha}{\alpha+2},\nu_2]$ if $\nu_2>\frac{\alpha}{\alpha+2}$ or $[\nu_2,\max(\frac{\alpha}{\alpha+2},1-\eta)]$ if $\nu_2<\frac{\alpha}{\alpha+2}$ to find the optimal ν that maximizes $f(\nu)$. It should be noted that the optimal power splitting ratio ρ^* obtained from the optimal transmit probability ν^* satisfies the constraint of (12) with equality. However, since the LHS of the constraint of (12) is a lower bound of $\omega(\rho,\nu)$, we can increase ρ from ρ^* to $\rho^\dagger$ so that $\omega(\rho^\dagger,\nu^*)=\eta\theta$ to further increase the objective function. This is because, for a fixed ν, $\omega(\rho,\nu)$ in (1) is a monotonically decreasing function of ρ. Utilizing the aforementioned properties of the objective function, we propose an efficient optimization algorithm to solve the optimization problem (9) as below.

Algorithm 1 Optimization Algorithm

if $\nu_2>\frac{\alpha}{\alpha+2}$ **then**
  Find ν^* which maximizes $f(\nu)$ using the bisection search over $\frac{\alpha}{\alpha+2}<\nu<\nu_2$.
else
  Find ν^* which maximizes $f(\nu)$ using the bisection search over $\nu_2<\nu<\max(\frac{\alpha}{\alpha+2},1-\eta)$.
end if
Fix $\nu=\nu^*$, and find $\rho^\dagger$ using bisection search over $\rho^*<\rho<1$ such that $\omega(\rho^\dagger,\nu^*)-\eta\theta=0$.

The proposed algorithm can be implemented with two bisection searches, and hence its computational complexity

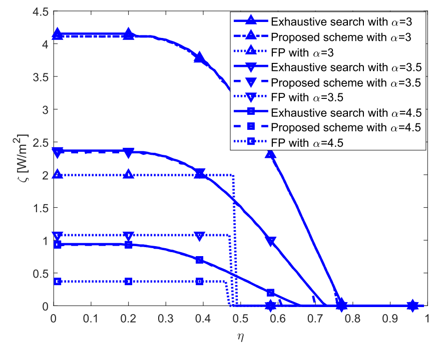

Fig. 1. Harvested energy with respect to η.

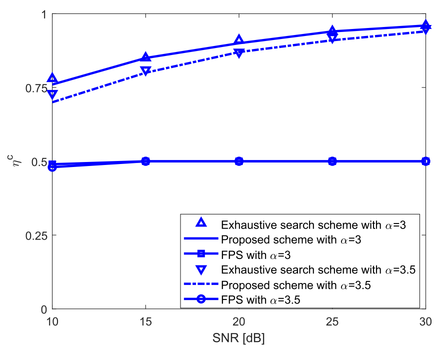

Fig. 2. η^c with respect to SNR.

is substantially reduced compared to the exhaustive search scheme. Specifically, denoting μ as the step size in the bisection search, the computational complexity of the proposed algorithm is smaller than $\lceil -\log_2(\mu^2) \rceil$, where $\lceil x \rceil$ means the smallest integer greater than x. On the other hand, the computational complexity of the exhaustive search scheme is μ^{-2}. For example, for a step size of 10^{-3}, the complexity of the proposed algorithm is only 0.002% of that for the exhaustive search.

IV. Numerical Results

In this section, we present the numerical results for the proposed scheme with $\lambda = 1/m^2$ and SNR$= P_t/\sigma^2$ [2], [8]. We compare the performance of the proposed method with the fixed parameter (FP) scheme, where ν and ρ are fixed to $1/2$. The exhaustive search scheme solves (9) by examining all possible values of ρ and ν.

In Fig. 1, we compare the maximized value of the objective function for various algorithms with respect to η. It can be observed that the proposed scheme outperforms the FP scheme, and provides the result almost identical to the exhaustive search scheme. The performance decreases as η grows. This is due to the fact that as η increases, more power is required at the information decoding circuitry to meet the constraint of (9). This results in smaller power available for energy harvesting and a subsequent reduction in the objective function of (9).

Furthermore, it can be seen in Fig. 1 that the objective function for all the schemes becomes zero after a specific η, which we denote as η^c. Fig. 2 shows the dependence of η^c on the SNR. We can see that the gap between η^c for the proposed scheme and the exhaustive search scheme reduces as SNR grows. This reduction in the performance gap demonstrates

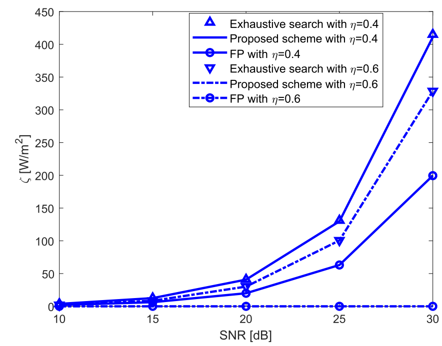

Fig. 3. Harvested energy with respect to SNR.

that a lower bound on the number of average discovered peers in (11) is accurate at high SNR.

Fig. 3 compares the performance of the proposed scheme with other schemes for different SNRs with $\eta \in \{0.4, 0.6\}$. The performance improves as SNR increases for the proposed scheme and the exhaustive search scheme. This is because the power splitting factor is adjusted in such a way that only necessary power required to meet the constraint on the average number of discovered peers is fed to the information decoding circuitry, while the surplus power is passed to the energy harvesting circuitry.

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