Power Beacons Deployment in Wireless Powered Communication with Truncated Poisson Cluster Process

Siyuan Zhou(✉), Jinhang Zhao, Guoping Tan, Xujie Li, and Qin Yan

College of Computer and Information, Hohai University, Nanjing, China
{siyuan.zhou,gptan,lixujie}@hhu.edu.cn,
yuyun555@126.com, yanqin@ieee.org

Abstract. Wireless powered communication (WPC) is able to provide the wireless devices (WDs) practically infinite energy for information transmission, by deploying multiple power beacons (PBs) as dedicated energy source. The performance of wireless energy transfer and wireless information transmission may significantly vary depending on the locations of the wireless nodes and the channels used for signal transmission. To enable efficient transmission and overcome the doubly-near-far problem in WPC, this paper proposes a PB deployment strategy where the distribution of PBs is subject to a truncated Poisson cluster process (PCP), and analytically investigates the performance of WPC in terms of the SNR outage probability. Specifically, we consider a harvest-then-transmit communication network, where WDs use RF harvested energy for the information transmission in each time block. The wireless energy transfer between WDs and PBs is achieved by either directed mode (WD is served by the closed PB) or isotropic mode (WD is served by multiple PBs). We first investigate the distribution of the distance between WD and an arbitrary PB in the associated cluster. Then, we derive a numerically computable form of the SNR outage probability for directed mode and a tight upper bound of the SNR outage probability for isotropic mode. Finally, numerical results verify the accuracy of the analytical results, present performance comparisons with varied network parameters, and reveal the advantages of the truncated PCP based PB deployment over the random PB deployment and the symmetric PB deployment.

Keywords: Wireless powered communication (WPC) · Power beacons (PBs) · Doubly-near-far problem · Poisson cluster process (PCP) · SNR outage probability

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1 Introduction

Radio frequency (RF) energy harvesting is a potential and efficient approach to provide electricity for energy-constrained wireless devices (WDs) in the forthcoming 5G networks. By leveraging such solution, WDs are able to harvest energy from RF signals and convert it into electricity, without replacing or recharging batteries manually. Basically there are two main architectures to apply RF energy harvesting in wireless communication networks: simultaneous wireless information and power transfer (SWIPT), and wireless powered communication (WPC). In SWIPT scheme, WDs within long information transmission distance might not be able to collect energy from RF signals, due to the huge gap on the operational threshold level of the received signal strength between RF energy harvesting and wireless information transmission. WPC architecture is thus established by transferring energy signal to WDs from the dedicated power beacons (PBs) in the network [1,2]. In WPC network, a WD first harvests energy from PBs and then communicates with the access point (AP) using the stored energy. As such, the performance of WPC depends on the interactions between PBs, WDs, and AP.

1.1 Literature Study

The performance analysis of WPC starts from a landmark contribution [1], where WDs served by single PB is called *directed mode* and WDs served by multiple PBs simultaneously is called *isotropic mode*. Thus, a paradigm shift is initiated where the required energy can be transferred to WDs from PBs on request resulting in uninterrupted power supply. In WPC architecture, each time block is partitioned into two phases for energy harvesting between PBs and WD and information transmission between WD and AP. Without considering the transmit power constraint on the WD, the power of the received information signal at AP can be characterized by exploiting the product distribution of channel gains belonging to energy harvesting and information transmission channels, if the geometric location of all nodes are fixed and known. Within this derived closed-form distributions, the network performance is analyzed in [3,4].

In a large-scale WPC networks, the path-loss effect of the signal transmission becomes more crucial for both wireless energy transfer and wireless information transmission. Plenty of literature on performance of WPC has been carried out by assuming the locations of PBs, WDs, and AP to be deterministic. In practice, however, due to the distributed nature of the network and the mobility of terminals, their locations are usually dynamic. The ever-growing randomness and irregularity in the locations of nodes in WPC has led to a growing interest in the application of stochastic geometry for modeling a tractable network [2,5]. Considering the scenario where PBs are uniformly distributed, performance of energy harvesting and information transmission is evaluated by using a homogeneous Poisson Point Process (PPP) model [2]. In [6], a Poisson Cluster Process (PCP) is adopted to model the hotspot deployment of PBs when PBs are densely distributed and the performance of wireless powered backscatter communication is analyzed. By assuming the PB is located in the cluster center, the distribution of users around the PB is characterized by a truncated PCP model that creates a guard zone for preventing the singularity of the path-loss effect [7].

1.2 Motivations and Contributions

The doubly-near-far problem in WPC results from the fact that if both energy source and information receiver are collocated, a far-away WD is highly vulnerable to the SNR outage compared to a nearby WD. When multiple low-cost PBs can be distributed to overcome such problem, the performance of energy harvesting and information transmission highly depends on the deployment strategy of PBs [8]. An optimization approach of node deployment in WPC is exploited in [9] by jointly optimize the locations of PBs and APs. If AP is located in the center and the WDs are uniformly distributed, the analytical performance of WPC when PBs are uniformly scattered in each cluster (also known as Matern PCP) can be considered as a performance benchmark. A symmetric PB deployment is proposed to achieve the performance improvement in terms of the SNR outage zone in [10]. Since the far-away WDs exhibit both larger PDF of the distance to AP [11] and higher probability to suffer the SNR outage, it is apparently inefficient to place dense PBs closed to AP and more reasonable to correlate the distribution of PBs with that of WDs.

To this end, this paper develops a mathematical architecture of WPC based on a two-tier heterogeneous network (HetNet) model, characterizes the distribution of the transmission distance between WDs and PBs, presents the expressions of the SNR outage probability, and compares the performance of WPC under various PB deployment strategies. The key contributions of this work can be summarized as follows.

– The two-tier WPC HetNet with correlated WD and PB locations is developed. In particular, The WDs are distributed as a Matern PCP where the parent point process of the PCP stands for the distribution of APs. Using the same parent point process, PBs are located based on a truncated PCP model. The common parent point process of two different PCPs captures the coupling effect between the locations of WDs and PBs.
– The analytical performance of the proposed WPC network for both directed energy transfer mode and isotropic energy transfer mode is investigated. The distance distributions between a WD and an arbitrary PB is characterized in a piecewise fashion. Consequently, the SNR outage probability of a randomly distributed WD in directed energy transfer mode is given in a semi-closed form. The upper bound of the SNR outage probability in isotropic energy transfer mode is provided. The simplified expressions of the SNR outage probability in special cases are also presented.
– The improvement of the proposed truncated PCP based PB deployment is analyzed. The minimum SNR outage probability can be achieved by optimizing the radius of the hole in the truncated PCP. Numerical results validate the

analytical expressions, compare the proposed PB deployment with the random PB deployment and the symmetric PB deployment, and provide insights into the system design of the PB assisted WPC networks.

2 System Model

We consider a WPC network as depicted in Fig. 1, where WDs powered by surrounding PBs communicate with the associated APs. In this harvest-then-transmit WPC model, each time block is partitioned into two phases for wireless energy transfer (WET) and wireless information transmission (WIT). We assume the WDs are supercapacitor equipped and all energy harvested in one time block is used for the information uplink. WET can be achieved in two modes: *directed mode* where one PB is paired with the closed PB (as shown in cell 1 of Fig. 1), and *isotropic mode* where one PB receive energy signals from all intra-cluster PBs (as shown in cell 2 of Fig. 1).

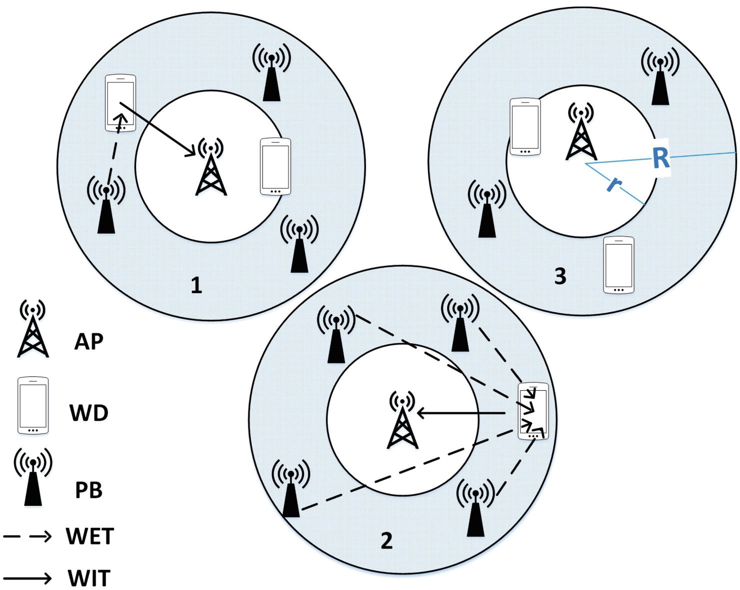

Fig. 1. A network model of PB assisted WPC communications.

2.1 Spatial Model

The clustering nature of the WDs is captured by assuming the WDs are randomly distributed as a Matern PCP. The PBs also exhibit clustering pattern and can be modeled by a truncated PCP. The correlation between PBs and WDs is captured by placing APs as the parent point process of two PCPs, modeling the geographical centers of hotspots. A similar HetNet model with two correlated PCPs is also presented in [12].

Specifically, we model the locations of APs as a homogeneous PPP $\mathbf{x} \in \Psi_a$. Since we aim to investigate the information uplink from WD to AP, the AP in the representative cluster is assumed to be located at the origin. Denoting Ψ_a as the common parent point process, the locations of WDs are characterized by a Matern PCP Ψ_s, and the layout of PBs are modeled by a truncated MCP Ψ_p. As shown in the Fig. 1, the PBs are randomly distributed in the shaded area. The radius of the hole in the truncated PCP (the lower bound of the offspring point distribution) is denoted by r and the cluster radius (the upper bound of the offspring point distribution) of two PCPs is represented by R, as illustrated in cell 3 of Fig. 1. The offspring point process of WDs with respect to the AP $\mathbf{x}$ is denoted by $\{\mathbf{y}_s\} \equiv B_s(\mathbf{x}, R)$, and similarly, the offspring point process of PBs with respect to the AP $\mathbf{x}$ is denoted by $\{\mathbf{y}_p\} \equiv B_p(\mathbf{x}, r, R)$. The number of WDs and PBs in each cluster is Poisson distributed with mean $\bar{m}_l, l \in \{s, p\}$.

As such, in each cluster, the PBs are uniformly distributed around the corresponding AP in the annulus area, with density

$$f_{\mathbf{Y}_p}(\mathbf{y}_p) = \frac{1}{\pi(R^2 - r^2)},\ r \leq \| \mathbf{y}_p \| \leq R \tag{1}$$

where $||\mathbf{y}_p|| = v$ is the distance of an arbitrary PB to the cluster center, and the PDF of v is expressed as

$$f_v(x) = \frac{2x}{(R^2 - r^2)},\ r \leq x \leq R \tag{2}$$

Meanwhile, the WDs are uniformly distributed around the AP in the circular area with density $f_{\mathbf{Y}_s}(\mathbf{y}_s) = \frac{1}{\pi R^2},\ 0 \leq \| \mathbf{y}_s \| \leq R$, and the PDF of the distance between an arbitrary WD to the cluster center is $\tilde{f}_v(x) = \frac{2x}{R^2},\ 0 \leq x \leq R$.

2.2 Propagation Model

Assuming one transmission period is L seconds, in the first phase with length $\tau L, 0 < \tau < 1$, the WD harvests energy from PBs. Then, by using all stored energy, the WD sends the information to the AP in the rest of the time with length $(1-\tau)L$. We assume WIT is influenced by Rayleigh fading and the path-loss effect, while WET is impaired by the path-loss effect without fading due to the relatively short distance of efficient WET [6]. The characterization of WET can be divided into two categories: directed mode and isotropic mode.

Directed Mode: In directed mode, the WD is paired with the nearest PB in the cluster. The associated PB is able to deliver energy signal to the WD by beamforming, while other non-associated PBs keep silent. By neglecting the effects of the noise, the received energy at the WD in each WET phase is written as

$$E_s = \tau L \mu P_p w d_c^{-\alpha} \tag{3}$$

where μ represents the energy conversion efficiency, P_p is the transmit power of PB, w stands for the antenna array gain, and d_c represents the distance between WD and the closed PB.

Isotropic Mode: In isotropic mode, all PBs in the cluster transmit energy signals in an omni-directional manner to all WDs in the WET phase. Thus the WD can receive energy signal from all PBs in the corresponding cluster. The received energy at the WD in each WET phase is expressed as

$$E_s = \tau L \mu \sum_{i \in B_p(\mathbf{x}, r, R)} P_p d_i^{-\alpha} \tag{4}$$

where d_i represents the distance between the WD and the i-th PB.

Depending on the amount of the harvested energy, the WDs transmit information signal to AP in the second phase with power P_s. Since the WD is equipped with super-capacitor, it is able to quickly store and release energy from dedicated energy sources. Without considering the transmit power limits, the energy for information transmission in one time period is less than or equal to the harvested energy in the first phase. The relationship between E_s and P_s is characterized as

$$P_s = \frac{E_s}{(1-\tau)L} \tag{5}$$

Assuming the distance between the reference WD and the associated AP is v and the Rayleigh fading of the WIT channel is denoted by h_s, the SNR outage probability of WIT is expressed as the probability that the received SNR γ at AP is less than the SNR outage threshold γ_{th},

$$\mathcal{O} = \mathbb{P}(\gamma < \gamma_{th}) = \mathbb{P}\Big(\frac{P_s h_s v^{-\alpha}}{N_0} < \gamma_{th}\Big) \tag{6}$$

where N_0 represents the power of the thermal noise. Note that there is no intra-cluster interference since each WD transmits during its allocated time slot [10]. The influence of the inter-cell interference is also neglected and could be the extension of this work.

3 Distance Distribution

In order to analyze the performance of the proposed WPC model, it is crucial to characterize of the distance distribution between WDs and PBs. We consider a randomly selected WD is located in the origin and the distance between AP (cluster center) and the WD is v. The statistics of the distance d_R between the WD and an arbitrary PB in the cluster depends on the relationship between d_R, v, r and R, due to the fact that the distribution of PBs and WDs are two correlated PCPs. The conditional PDF of d_R can be derived in the following proposition.

Table 1. Conditional PDF of d_R with different parameters configuration.

	$v \in [0, r)$	$v \in [r, \frac{R-r}{2})$
$f_{d_R}(u \mid v)$ *when* $r < \frac{R}{3}$	E1, $u \in (0, r-v]$	E2, $u \in (0, v-r]$
	E3, $u \in (r-v, r+v]$	E3, $u \in (v-r, v+r]$
	E2, $u \in (r+v, R-v]$	E2, $u \in (r+v, R-v]$
	E4, $u \in (R-v, R+v]$	E4, $u \in (R-v, R+v]$
	$v \in [\frac{R-r}{2}, \frac{R+r}{2})$	$v \in [\frac{R+r}{2}, R)$
	E2, $u \in (0, v-r]$	E2, $u \in (0, R-v]$
	E3, $u \in (v-r, R-v]$	E4, $u \in (R-v, v-r]$
	E5, $u \in (R-v, r+v]$	E5, $u \in (v-r, v+r]$
	E4, $u \in (r+v, R+v]$	E4, $u \in (v+r, R+v]$
	$v \in [0, \frac{R-r}{2})$	$v \in [\frac{R-r}{2}, r)$
$f_{d_R}(u \mid v)$ *when* $r \geq \frac{R}{3}$	E1, $u \in (0, r-v]$	E1, $u \in (0, r-v]$
	E3, $u \in (r-v, r+v]$	E3, $u \in (r-v, R-v]$
	E2, $u \in (r+v, R-v]$	E5, $u \in (R-v, r+v]$
	E4, $u \in (R-v, R+v]$	E4, $u \in (r+v, R+v]$
	$v \in [r, \frac{R+r}{2})$	$v \in [\frac{R+r}{2}, R)$
	E2, $u \in (0, v-r]$	E2, $u \in (0, R-v]$
	E3, $u \in (v-r, R-v]$	E4, $u \in (R-v, v-r]$
	E5, $u \in (R-v, r+v]$	E5, $u \in (v-r, v+r]$
	E4, $u \in (r+v, R+v]$	E4, $u \in (v+r, R+v]$

Proposition 1. *In the proposed WPC model, the conditional PDF $f_{d_R}(u|v)$ of the distance between a WD and an arbitrary PB given the distance between the WD and AP is presented in a piecewise fashion for each specific configuration between u, v, r, and R, as shown in Table 1 at the top of the next page. The expressions of E1–E5 in Table 1 are written in (7)–(11).*

$$\mathrm{E1} = 0 \tag{7}$$

$$\mathrm{E2} = \frac{2u}{R^2 - r^2} \tag{8}$$

$$\mathrm{E3} = \frac{2u}{R^2 - r^2}\Big(1 - \frac{1}{\pi}\arccos\big(\frac{v^2 + u^2 - r^2}{2uv}\big)\Big) \tag{9}$$

$$\mathrm{E4} = \frac{2u}{\pi(R^2 - r^2)}\arccos(\frac{u^2 + v^2 - R^2}{2vu}) \tag{10}$$

$$\begin{aligned}\mathrm{E5} = &\frac{2u}{\pi(R^2 - r^2)}\Big(\arccos\big(\frac{u^2 + v^2 - R^2}{2vu}\big)\\ &- \arccos\big(\frac{v^2 + u^2 - r^2}{2uv}\big)\Big)\end{aligned} \tag{11}$$

Proof. The proof is given in Appendix.

Then, for each parameters configuration, the conditional CDF of d_R can be obtained by integrating $f_{d_R}(u|v)$, written as $F_{d_R}(u|v) = \int_0^u f_{d_R}(x|v)\,\mathrm{d}x$. Hence, the conditional CDF of the distance between a WD and the closed PB is expressed as $F_{d_C}(u|v) = 1 - \exp(-\bar{m}_p F_{d_R}(u|v))$. The conditional PDF of d_C can be derived as,

$$f_{d_C}(u|v) = \bar{m}_p \exp(-\bar{m}_p F_{d_R}(u|v)) f_{d_R}(u|v) \tag{12}$$

4 Performance Analysis

We first derive the generalized form of the SNR outage probability for each energy transfer mode. Then, the simplified expressions in certain special cases are presented.

4.1 Directed Mode

In the directed mode, the statistics of the harvested energy depends on the distribution of the distance d_C. Assuming the channel gain and the locations of nodes keep unchanged during the transmission period L, the SNR outage probability at AP is written as

$$\begin{aligned}\mathcal{O}_d &= \mathbb{P}(\tau\mu P_p d_C^{-\alpha} < \gamma_0 N_0 v^{\alpha} g^{-1}(1-\tau)) \\ &= \mathbb{P}(g < \frac{\gamma_0 N_0 d_C^{\alpha}(1-\tau)}{\mu P_p v^{-\alpha}\tau}) \\ &= \mathbb{E}_{d_c,v}[1 - \exp(-C d_C^{\alpha} v^{\alpha})]\end{aligned} \tag{13}$$

where $C = \frac{\gamma_0 N_0(1-\tau)}{\mu P_p \tau}$ and the last step follows from the exponential distribution of g. Since the PDF of d_C is a piecewise function depending on v, $\mathcal{O}_d$ can be computed by integrating over each interval, shown in the following proposition.

Proposition 2. *When WET is achieved in directed mode, the SNR outage probability can be expressed in a semi-analytical form as,*

$$\mathcal{O}_d = \int_0^R \mathbb{E}_{d_C}[1 - \exp(-C d_C^{\alpha} v^{\alpha})] \frac{2v}{R^2}\,\mathrm{d}v \tag{14}$$

where the conditional PDF of d_C is expressed in (12).

The computation of (12) can be adopted by resorting to Gauss-legendre quadrature. Due to the conditional PDF of d_C is a piecewise function, it is complicated to analytically express the SNR outage probability in the generalized case. However, when the location of WD is known and the distribution of PB is subject to a truncation-free PCP model, the SNR outage probability can be further simplified.

4.2 Isotropic Mode

In the isotropic mode, the WD is able to receive the energy signal from all PBs in the cluster. As such, different to the directed mode, the statistics of the harvested energy depends on the distribution of the distance d_R and the number of PBs. Assuming the channel gain and the locations of nodes keep unchanged during the transmission period L, the SNR outage probability at AP is written as

$$\begin{aligned}\mathcal{O}_i =&\ \mathbb{P}(\tau\mu P_p \sum_i d_i^{-\alpha} < \gamma_0 N_0 v^\alpha g^{-1}(1-\tau)) \\ \overset{(a)}{=}&\ 1 - \mathbb{E}\big[\exp\big(-\frac{Cv^\alpha}{\sum_i d_i^{-\alpha}}\big)\big] \\ =&\ 1 - \mathbb{E}_v\big[\exp\big(-Cv^\alpha \int_0^\infty \exp(-t\sum_i d_i^{-\alpha})\,\mathrm{d}t\big)\big] \\ \overset{(b)}{\leq}&\ 1 - \mathbb{E}_v\big[\exp\big(-Cv^\alpha \int_0^\infty \mathbb{E}_{B_p(\mathbf{x},r,R)}\big[\mathrm{e}^{-t\sum_i d_i^{-\alpha}}\big]\,\mathrm{d}t\big)\big]\end{aligned}$$

where (a) is obtained by incorporating the exponential distribution of g and (b) follows from the Jensen inequality. The expectation with respect to all PBs belonging to $B_p(\mathbf{x}, r, R)$ in last equation can be derived due to the fact that the number of PBs per cluster is Poisson distributed [13],

$$\begin{aligned}&\mathbb{E}_i\big[\exp(-t\sum_i d_i^{-\alpha})\big] \\ &= \exp\big(-\bar{m}_p \int_0^{R+v} (1-\mathrm{e}^{-tu^{-\alpha}}) f_{d_R}(u|v)\,\mathrm{d}u\big)\end{aligned} \tag{15}$$

As such, an upper bound of the SNR outage probability is expressed in next proposition.

Proposition 3. *When WET is achieved in isotropic mode, the upper bound of the SNR outage probability can be expressed in a semi-analytical form written as,*

$$\begin{aligned}\mathcal{O}_i^u = 1 - \int_0^R &\exp\big(-Cv^\alpha \int_0^\infty \exp\big(-\bar{m}_p \\ &\cdot(1 - \int_0^{R+v} \mathrm{e}^{-tu^{-\alpha}} f_{d_R}(u|v)\,\mathrm{d}u)\big)\,\mathrm{d}t\big)\frac{2v}{R^2}\,\mathrm{d}v\end{aligned} \tag{16}$$

Note that the integrals in the above expression can be accurately computed by resorting to Gauss quadrature.

4.3 Special Case: Fixed WD Location and Truncation-Free Distribution of PB

In the truncation-free PCP model with $r = 0$, the conditional PDF of d_R is simplified to the following expression,

$$\tilde{f}_{d_R}(u|v) = \begin{cases} \frac{2u}{R^2}, & 0 \leq u \leq R-v \\ \frac{2u}{\pi R^2}\arccos(\frac{u^2+v^2-R^2}{2vu}), & R-v \leq u \leq R+v \end{cases}$$

Note that the same expression of the conditional PDF in a different network layout is presented in [14]. The simplified expressions of the SNR outage probability in two energy transfer modes are provided in the following.

Directed Mode: In this case, the SNR outage probability with a fixed WD location v can be derived as

$$\begin{aligned}
\tilde{\mathcal{O}}_d &= \mathbb{E}_{d_c}[1-\exp(-Cd_C^{\alpha}v^{\alpha})] \\
&= 1-\int_0^{R-v}\exp(-Cv^{\alpha}u^{\alpha})f_{d_C}(u|v)\,\mathrm{d}u \\
&\quad -\int_{R-v}^{R+v}\exp(-Cv^{\alpha}u^{\alpha})f_{d_C}(u|v)\,\mathrm{d}u \\
&= 1-\int_0^{(R-v)^2}\exp(-Cv^{\alpha}x^{\frac{\alpha}{2}}-\frac{\bar{m}_p}{R^2}x)\frac{\bar{m}_p}{R^2}\,\mathrm{d}x \\
&\quad -\int_{R-v}^{R+v}\exp(-Cv^{\alpha}u^{\alpha})\bar{m}_p\frac{2u}{\pi R^2}\arccos(\frac{u^2+v^2-R^2}{2vu}) \\
&\quad \cdot\exp\big[-\bar{m}_p\big(\frac{(R-v)^2}{R^2}+C_1(u)\big)\big]\,\mathrm{d}u
\end{aligned} \tag{17}$$

where $C_1(u)=\int_{R-v}^{u}\frac{2x}{\pi R^2}\arccos(\frac{x^2+v^2-R^2}{2vx})\,\mathrm{d}x$.

Isotropic Mode: When the path-loss factor $\alpha=2$, the upper bound of SNR outage probability with a known WD location v can be simplified into

$$\begin{aligned}
\tilde{\mathcal{O}}_i^u &= 1-\exp\big(-Cv^2\int_0^{\infty}\exp\big(-\bar{m}_p(1-\frac{1}{R^2} \\
&\quad \cdot(t\mathrm{Ei}(\frac{-t}{(R-v)^2})+\mathrm{e}^{\frac{-t}{(R-v)^2}}(R-v)^2)-C_2(t))\big)\,\mathrm{d}t\big)
\end{aligned} \tag{18}$$

where $C_2(t)=\int_{R-v}^{R+v}\mathrm{e}^{-tx^{-2}}\frac{2x}{\pi R^2}\arccos(\frac{x^2+v^2-R^2}{2vx})\,\mathrm{d}x$, and $\mathrm{Ei}(\cdot)$ denotes the exponential integral.

5 Numerical Results

In this section, we numerically investigate the performance of the proposed WPC network for different PB deployment strategies. The accuracy of the derived distribution of the distance between a WD and an arbitrary PB and the expressions of the SNR outage probability are verified by comparing them in the results with the Monte-Carlo simulations. In addition to our analytical results, the performance of the WPC network when PBs are randomly distributed or symmetrically located are also shown. A comparative performance analysis of the three considered deployments is conducted.

The cluster radius is taken as $R=90\,\mathrm{m}$ and the path-loss factor is assumed as $\alpha=3$. In the WET process, the average number of PBs in each cluster is set as $\bar{m}_p = 50$, which represent a scenario where PBs are densely distributed. The transmit power of PBs are identical as $P_p = 10\,\mathrm{W}$, the energy conversion efficiency is set as $\mu = 0.8$, the proportion of time slot allocated for WET is $\tau = 0.6$, and the antenna array gain for directed mode is $w = 20$. In the WIT process, the thermal noise power is $N_0 = 10^{-9}\,\mathrm{W}$, and the threshold of SNR outage is $\gamma_{th} = 5\,\mathrm{dB}$.

The SNR outage probability of directed mode and isotropic mode is presented in Figs. 2 and 3, respectively. In both figures, the Monte Carlo results and the analytical results for the truncated PCP based PB deployment are shown in circle symbols and solid line, respectively. The results for the symmetric PB deployment are shown in dashed line, and the results for the random PB deployment are displayed in dotted line. It can be observed that with the increasing of the radius r of the hole in truncated PCP, the Monte Carlo results match the analytical expressions of the SNR outage probability well in directed WET mode, and the simulation results are tightly bounded by the proposed upper bound of the SNR outage probability in isotropic WET mode.

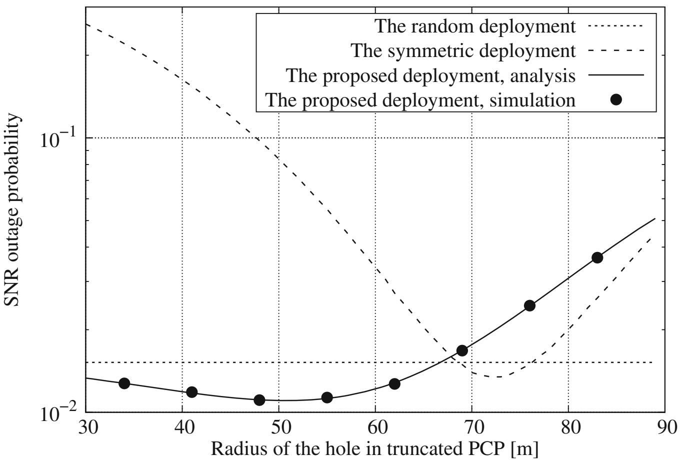

Fig. 2. The SNR outage probability versus r with different PB deployments in directed WET mode.

It is also observed that with the optimized value of r, the minimum of the SNR outage probability can be obtained for the truncated PCP based PB deployment in both energy transfer modes. Besides, in this scenario with dense PBs, the optimal placement of the PBs in a truncated PCP model outperforms both the random PB deployment and the symmetric PB deployment. The reason is that when WDs are randomly distributed in the cluster, the WDs located far away from the AP suffers severer outage probability than the nearby WDs due to the doubly-near-far problem. Thus it is necessary to deploy the PBs more densely in the area far away from the cluster center. Moreover, When PBs are

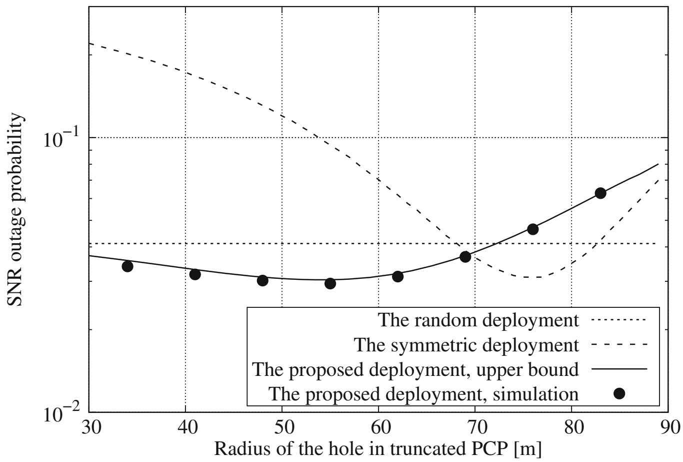

Fig. 3. The SNR outage probability versus r with different PB deployments in isotropic WET mode.

densely distributed, the symmetric PB deployment is not only inefficient but also impractical.

6 Conclusion

In order to improve the performance of PB-assisted WPC, a truncated PCP based PB deployment strategy is proposed in this paper. Based on the constructed harvest-then-transmit model, the PCP distributed WD is wireless powered by either one closed PB or multiple PBs in the cluster. The performance of such WPC network is analytically investigated in terms of the SNR outage probability. Specifically, the distance distribution between a WD and an arbitrary PB is first derived, followed by the distance distribution between a WD and the closed PB. Consequently, a semi-analytical expression for the SNR outage probability in directed WET mode is presented, and a tight upper bound of the SNR outage probability in isotropic WET mode is given. The simplified versions of the SNR outage probability in two WET modes are provided for special cases. Our analysis is validated by showing the excellent match between the results obtained through our exact expressions and those obtained via Monte Carlo simulations. The advantage of the proposed PB deployment is pointed out through comparison with the random PB deployment and the symmetric deployment. The derived results could provide valuable insights for designing the practical WPC systems.

Appendix

Let us denote the reference WD chosen uniformly at random in the representative cluster is located at origin. Without loss of generality, we assume the location of the AP in the cluster is denoted by $\mathbf{x}_o = (v, 0)$, and the region where PB can be distributed is represented by $A_p = B_p(\mathbf{x}_o, r, R)$ (the shaded regions in Fig. 4). The expression of the CDF of the distance d_R is

$$\begin{aligned} F_{d_R}(u|v) &= \int_{B(o,u)\cap A_p} f_{\mathbf{Y}_p}(\mathbf{y}_p)\,\mathrm{d}\mathbf{y}_p \\ &= |B(o,u)\cap A_p| \frac{1}{\pi(R^2 - r^2)} \end{aligned} \tag{19}$$

where $B(o, u)$ denotes the circle centered at origin with radius u (red circles in Fig. 4) and $|\Xi|$ represents the area covered by any generic region $\Xi \in \mathbb{R}^2$. The area of the joint region between A_p and $B(o, u)$ can be computed for different configurations between r, R, u, and v. As shown in Fig. 4, when $r \geq \frac{R}{3}$, with the increasing of v, four different configurations have to be considered and thus four varied piecewise function of $F_{d_R}(u|v)$ can be derived. The similar characterization can be carried out for $r < \frac{R}{3}$. Finally, the expressions of PDF of d_R is obtained by differentiating $F_{d_R}(u|v)$ with respect to u.

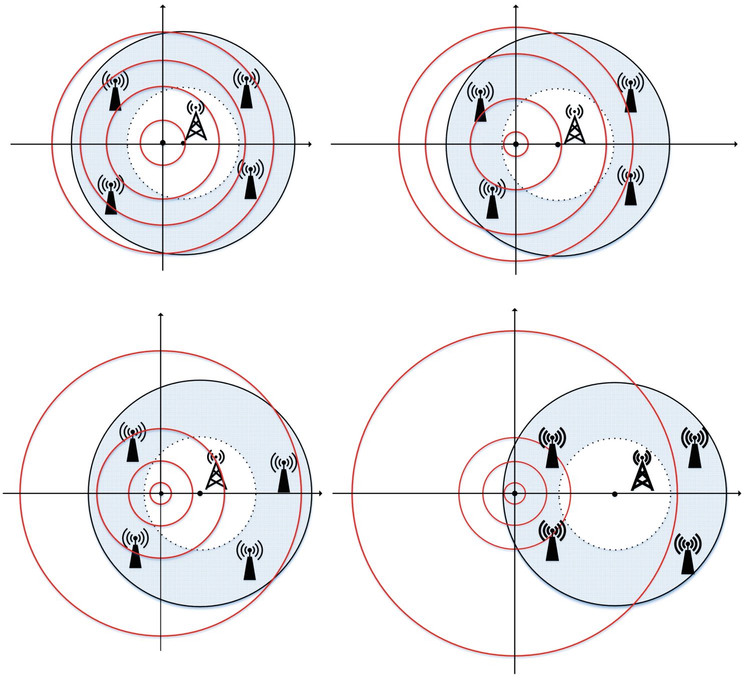

Fig. 4. Graphical illustration of the different parameters configuration in computation of the area of the joint region ($r \geq \frac{R}{3}$). (Color figure online)

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