Outage Probability of Ad Hoc Networks With Wireless Information and Power Transfer

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***Abstract*—This letter considers simultaneous wireless information and power transfer in ad hoc networks, where each transmitter (TX) is wirelessly powered by power beacons (PBs) and uses the aggregate received power from PBs to transmit to its desired receiver (RX). Using stochastic geometry, we formulate the total outage probability at a typical RX in terms of the power and channel outage probability. The former incorporates a power receiver activation threshold at TX while the latter incorporates maximum transmit power at TX and interference at RX. For the special case of path-loss exponent of 4, we derive accurate expressions for the power, channel and total outage probability and study the effect of the system parameters on the outage performance.**

***Index Terms*—Outage probability, ad hoc networks, wireless power transfer, power beacon, Poisson point process.**

I. Introduction

Radio frequency (RF) enabled simultaneous information and power transfer (SWIPT) has emerged as an attractive solution to power future wireless networks [1], [2]. There are currently three architectures for SWIPT [1], [2]: (i) *integrated SWIPT* enables information and power to be extracted from the same signal transmitted by a base station (BS), (ii) *closed-loop SWIPT* utilizes downlink from BS to users for power transfer (PT) and uplink for information transmission (IT), and (iii) *decoupled SWIPT* overlays traditional cellular networks with special power beacons (PBs), which do not require a backhaul link, to provide dedicated PT. Both integrated SWIPT and closed-loop SWIPT do not require additional infrastructure. However, they suffer from correlation among IT and PT and hence it is not easy to support longer range transmissions [1]. This makes decoupled SWIPT, although it requires additional infrastructure in the form of PBs, suitable for small scale deployments envisioned in 5G [3].

Recently, many papers have considered integrated SWIPT for cellular, ad hoc, relay, cooperative and other communication scenarios [4]–[7]. Some papers have considered closed-loop SWIPT, e.g., see [8], [9] and references therein. Only a few papers have investigated decoupled SWIPT [10], [11]. Using stochastic geometry, the feasibility of deployment of PBs for powering a cellular network, subject to certain outage constraint on the uplink data transmission, was analyzed in [10]. Considering pico-cell BSs overlaid with PBs, algorithms to maximize the power received by users were proposed in [11]. To the best of our knowledge, the outage probability of ad hoc networks with decoupled SWIPT has not yet been derived in the literature. In addition, a common assumption in [4]–[11] is that they did not take into account the minimum RF energy required to activate the energy harvesting circuit, which is not realistic especially when the received power has a large dynamic range.

Letter Contributions: In this letter, we consider a wireless ad hoc network overlaid with PBs. The transmitter (TX) nodes are wirelessly powered by PBs and adopt the harvest-then-transmit protocol [1] with variable transmit power according to the amount of harvested power, i.e., they use the aggregate received power from PBs to transmit their data to their desired receiver (RX) node. The novel contributions of this work are: (i) we adopt a realistic model of wirelessly powered TX nodes incorporating a power receiver activation threshold (to account for the minimum RF energy required to activate the energy harvesting circuit) and a maximum transmit power (to account for the power amplifier rating), (ii) with the facilitation of Poisson point process (PPP) model and stochastic geometry tools from [12], [13], we formulate the total outage probability at a typical RX node in terms of the power outage probability and the channel outage probability. In the proposed formulation, the newly defined power outage probability measures the probability that the received power at a typical TX is less than a power receiver activation threshold, causing it to be inactive[1] and the desired RX to be in outage. The channel outage probability is defined as the probability that the signal-to-interference-plus-noise ratio (SINR) at a typical RX is below a certain threshold,[2] (iii) assuming path-loss exponent $\alpha = 4$, we derive expressions for the power, channel and total outage probability. Simulation results confirm the accuracy of the derived expression. The results show that decreasing the power receiver activation threshold for low TX density, increasing the power beacon density and the power beacon transmit power improves the total outage probability.

II. System Model

We consider a two-dimensional wireless ad-hoc network with TX and RX pairs. The location of TXs is assumed to follow a homogeneous PPP, denoted as Φ_{TX}, with node density λ_{TX}. Each TX has a desired RX located at a distance d_0 from the corresponding TX in a random direction. Note that we do not consider the relative motion between TX and RX. The PBs are randomly deployed and are modeled as a homogeneous PPP,

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[1]Our definition of power outage probability is fundamentally different from [10]. The power outage probability defined in [10] measures the chance of the harvested power at the mobile user being insufficient to support its transmission and is treated as a controlled parameter set to zero or a sufficiently small value to ensure uninterrupted transmission (and hence interference) from mobile users.

[2]In prior work, the outage probability in ad hoc networks without SWIPT has been formulated using channel outage probability only, e.g., see [14].

denoted as $\Phi_{\rm PB}$, with node density $\lambda_{\rm PB}$. We assume $\Phi_{\rm TX}$ and $\Phi_{\rm PB}$ are independent. The PB's transmit power is $P_{\rm PB}$. Let X_i denote both the random location as well as the i-th TX itself, Y_i denote both the location and the corresponding i-th RX and Z_i denote both the location and the i-th PB itself.

The TXs are wirelessly powered by the PBs. We make the following assumptions regarding the PT and IT:

- The PT from PBs and IT from TXs are sufficiently separated in frequency. Further, the PT and IT are isotropic such that each TX/RX can receive the PB/TX signals, respectively, from all directions.
- Time is divided into slots and TXs employ time-switching receiver architecture for IT and PT [15]. Thus, in each time slot (T), PT occurs in the first ρT seconds and IT in the remaining $(1-\rho)T$ seconds.
- In order to activate the energy harvesting circuit at any RX, the aggregate received power from all the PBs must be greater than a power receiver activation threshold $\beta_{\rm PT}$.[3]
- Each TX has a maximum transmit power $P_{\max}$ due to the power amplifier rating.
- $P_{\max}$ is sufficiently large such that the probability that the aggregate received power from all the PBs exceeds $P_{\max}$ is negligible. Hence, all the amount of received power during PT is used for IT, i.e., no energy storage involved.

We assume that all the channel links are modeled as identical and independent distributed (i.i.d.) Rayleigh block-fading channels.[4] Thus, in general the received power at any TX (from a PB) or RX (from a TX) can be expressed as $P_t h d^{-\alpha}$, where d is the propagation distance, α is the path-loss exponent, h denotes the power gain due to fading which follows the exponential distribution with unit mean [12] and P_t denotes the transmit power. Note that for PB, $P_t = P_{\rm PB}$ and for TX, P_t will be be defined later in (5). In this letter, we are interested in the outage probability at a typical RX. This is formulated in the next section.

III. Outage Probability Formulation and Analysis

In the considered setup, an outage can occur at a typical RX due to either of the following two conditions: (i) due to the random network topology and the fading channels, the received power at a TX is a random variable. If the aggregate received power from all the PBs is below $\beta_{\rm PT}$, the TX is inactive. Thus no IT can occur and the RX is in *power outage*, and (ii) if a TX is active (i.e., not in power outage), the RX may still be in *channel outage* if the RX's SINR is below a certain threshold. This can occur because both the TX transmit power, which depends on the random received power from PBs, and the interference received by RX are random variables. Thus, the total outage can be formulated as

$$\mathcal{P}_{\rm out} = \mathcal{P}_{\rm out}^{\rm P} + \left(1-\mathcal{P}_{\rm out}^{\rm P}\right)\mathcal{P}_{\rm out}^{\rm C}, \tag{1}$$

where $\mathcal{P}_{\rm out}^{\rm P}$ denotes the power outage probability and $\mathcal{P}_{\rm out}^{\rm C}$ denotes the channel outage probability. Note that both $\mathcal{P}_{\rm out}^{\rm P}$ and $\mathcal{P}_{\rm out}^{\rm C}$ need to be averaged with respect to the spatial node distributions and the fading distribution. In order to determine the outage probabilities, we add a reference receiver Y_0 at the origin and its associated transmitter X_0 at a distance d in a random direction. By Slivnyak's theorem, adding a point in a PPP does not change the distribution of the rest of the process [12]. In the following subsections, we derive expressions for these outage probabilities.

Power Outage Probability: The instantaneous aggregate received power from PBs at a typical TX, X_0, is given by

$$P_{{\rm PT}_i} = \sum_{Z\in\Phi_{\rm PB}} P_{\rm PB} h_Z d_Z^{-\alpha}, \tag{2}$$

where h_Z is the fading power gain on the PT link and $d_Z = |Z_i - X_0|$ denotes the distance between a PB and X_0. Due to the stationary property of PPP [12], the distribution of the received power is identical for all TXs. Thus, we drop the index i in (2).

The power outage probability is the probability that the aggregate received power $P_{\rm PT}$ at a typical TX is lower than the power receiver activation threshold, $\beta_{\rm PT}$. It is given by

$$\mathcal{P}_{\rm out}^{\rm P} = \mathbb{P}(P_{\rm PT} < \beta_{\rm PT}) = F_{P_{\rm PT}}(\beta_{\rm PT}), \tag{3}$$

where $\mathbb{P}(\cdot)$ denotes the probability and $F_{P_{\rm PT}}(\cdot)$ denotes the cumulative distribution function (CDF) of the received power.

Given the form of (2), which is similar to well known existing models of traditional ad hoc networks [12], a closed-form expression for $F_{P_{\rm PT}}(\cdot)$ exists for path-loss exponent $\alpha = 4$ only. In the following, we consider the special case of $\alpha = 4$ to determine the power, channel and total outage probability. However, this does not diminish the contribution of this letter since the proposed formulation in (10) is valid for any path-loss exponent.[5]

Proposition 1: The CDF of the aggregate received power $P_{\rm PT}$ for $\alpha = 4$ is given by

$$F_{P_{\rm PT}}(p_{\rm PT}) = 1 - \operatorname{erf}\left(\pi^2\lambda_{\rm PB}\frac{\sqrt{P_{\rm pb}}}{4\sqrt{p_{\rm PT}}}\right). \tag{4}$$

Proof: When $\alpha = 4$, using the existing results for ad hoc networks [12], we can show that $P_{\rm PT}$ follows the Levy distribution with dispersion coefficient $\zeta = \frac{\pi}{2}(\lambda_{\rm PB} P_{\rm PB}^{0.5}\mathbb{E}[h_Z^{0.5}]\pi)^2$, where $\mathbb{E}[\cdot]$ is the expectation operator, $\mathbb{E}[h_Z^{0.5}] = \Gamma[1.5]$ for exponential distribution. ■

Substituting (4) into (3), $\mathcal{P}_{\rm out}^{\rm P}$ can be obtained.

Channel Outage Probability: Based on our system model, the instantaneous transmit power for each *active* TX can be written as

$$P_{\rm TX} = \begin{cases} \gamma P_{\rm PT}, & P_{\rm PT} > \beta_{\rm PT}; \\ P_{\max}, & P_{\rm PT} > \gamma^{-1} P_{\max}; \end{cases} \tag{5}$$

where $\gamma = \eta\frac{\rho}{1-\rho}$ and η is a factor representing the power conversion efficiency. Note that the first condition in (5) is due to the fact that the received power at an active TX must be greater than $\beta_{\rm PT}$. The second condition in (5) is due to the maximum transmit power of active TXs. Next we determine the probability density function of $P_{\rm TX}$.

[3] $\beta_{\rm PT}$ is typically in the range -30 dBm to -10 dBm [1].

[4] We do not consider shadowing but it can be included using the composite fading model in [16].

[5] Our framework can also be easily modified to the scenario where each TX harvests energy from its nearest PB only, in which case $F_{P_{\rm PT}}(\cdot)$ can be obtained using stochastic geometry for any α. However, this is outside scope of this paper.

Proposition 2: The PDF of the transmit power $P_{\rm TX}$ for an active TX for $\alpha = 4$ is given by

$$f_{P_{\rm TX}}(p_{\rm TX}) = \begin{cases} \frac{\pi^{1.5}\lambda_{\rm PB}\sqrt{P_{\rm PB}\gamma}}{4p_{\rm TX}^{1.5}(1-\mathcal{P}_{\rm out}^{\rm P})}\exp\left(-\frac{\pi^4\lambda_{\rm PB}^2 P_{\rm PB}\gamma}{16p_{\rm TX}}\right), p_{\rm TX} > \gamma\beta_{\rm PT}; \\ \frac{1-F_{P_{\rm PT}}\left(\frac{P_{\max}}{\gamma}\right)}{1-p_{\rm out}^{P}}\textbf{Dirac}(p_{\rm TX}-P_{\max}), p_{\rm TX}>P_{\max}; \end{cases} \tag{6}$$

where $\textbf{Dirac}(\cdot)$ is the Dirac function [12].

Proof: Taking the derivative of (4), we obtain the PDF of $P_{\rm PT}$. Combining it with (5) and using variable transformation, we can derive (6). ∎

Using (6), we can also obtain the expectation term $\mathbb{E}\{\sqrt{P_{\rm TX}}\}$ for $\alpha = 4$ as

$$\mathbb{E}\{\sqrt{P_{\rm TX}}\} = \frac{\pi^{1.5}\lambda_{\rm PB}\sqrt{P_{\rm PB}\gamma}}{4\left(1-\mathcal{P}_{\rm out}^{\rm P}\right)}\Gamma\left[0, \frac{\pi^4\lambda_{\rm PB}^2 P_{\rm PB}\gamma}{16P_{\max}}, \frac{\pi^4\lambda_{\rm PB}^2 P_{\rm PB}}{16\beta_{\rm PT}}\right] + \frac{1-F_{P_{\rm PT}}(\gamma^{-1}P_{\max})}{1-\mathcal{P}_{\rm out}^{\rm P}}\sqrt{P_{\max}}. \tag{7}$$

In the proposed system model, the location of the active TXs as well as their transmit powers rely strongly on the PB locations. Indeed active TXs are likely to be located closer to PBs, which means that their transmit powers and locations are correlated. In this letter, we assume that each active TX's transmit power and location is independent. Thus, we approximate the active TXs as a homogeneous PPP with node density $\lambda'_{\rm TX} = (1-\mathcal{P}_{\rm out}^{\rm P})\lambda_{\rm TX}$, denoted as $\Phi'_{\rm TX}$. The instantaneous SINR at reference RX, Y_0, is then given as

$$SINR = \frac{P_{{\rm TX}_0} g_0 d_0^{-\alpha}}{\sum_{X\in\Phi'_{\rm TX}} P_{{\rm TX}_X} g_X X^{-\alpha} + N}, \tag{8}$$

where N is the additive white Gaussian noise (AWGN) power and g_0 and g_X denote the fading power gains on the reference link and interference link, respectively. Note that $P_{{\rm TX}_0}$ and $P_{{\rm TX}_X}$ are the transmit power for the reference TX and other active TXs, respectively, which have the same distribution as given in (6). The channel outage probability for the reference link is then given by

$$\begin{aligned} \mathcal{P}_{\rm out}^{C} &= \mathbb{P}(SINR < \beta_c) \\ &= \mathbb{E}_{P_{{\rm TX}_0}}\left\{\mathbb{P}\left(g_0 < \frac{\sum_{X\in\Phi'_{\rm TX}} P_{{\rm TX}_X} g_X X^{-\alpha} + N}{P_{{\rm TX}_0} d_0^{-\alpha}\beta_c^{-1}}\right)\right\} \\ &= \mathbb{E}_{P_{{\rm TX}_0}}\left\{\mathbb{E}_{G,X,P_{\rm TX}}\left\{F_{G_0}\left(\frac{\sum_{X\in\Phi'_{\rm TX}} P_{{\rm TX}_X} g_X X^{-\alpha} + N}{P_{{\rm TX}_0} d_0^{-\alpha}\beta_c^{-1}}\right)\right\}\right\} \\ &= \mathbb{E}_{P_{{\rm TX}_0}}\left\{1 - \exp\left(-\frac{N d_0^{\alpha}}{P_{{\rm TX}_0}}\beta_c\right)\right. \\ &\quad \left.\times\mathbb{E}_{G,X,P_{\rm TX}}\left\{\exp\left(\frac{\sum_{X\in\Phi'_{\rm TX}} P_{{\rm TX}_X} g_X X^{-\alpha}}{P_{{\rm TX}_0} d_0^{-\alpha}\beta_c^{-1}}\right)\right\}\right\} \\ &= \mathbb{E}_{P_{{\rm TX}_0}}\left\{\underbrace{1 - \exp\left(-\frac{N d_0^{\alpha}}{P_{{\rm TX}_0}}\beta_c\right)\exp\left(-\frac{\lambda'_{\rm TX}\pi^2 d_0^2\sqrt{\beta_c}}{2\sqrt{P_{{\rm TX}_0}}}\mathbb{E}\{\sqrt{P_{\rm TX}}\}\right)}_{\mathcal{P}_{\rm out}^{\rm C}|_{P_{{\rm TX}_0}}(P_{{\rm TX}_0})}\right\}, \end{aligned} \tag{9}$$

where β_c is the SINR threshold, the term $\mathcal{P}_{\rm out}^{\rm C}|_{P_{{\rm TX}_0}}(P_{{\rm TX}_0})$ can be regarded as the outage probability which is conditioned on the transmit power of the reference TX, $F_{G_0}(\cdot)$ is the CDF of the fading power gain on the reference link which follows the exponential distribution and $\mathbb{E}\{\sqrt{P_{\rm TX}}\}$ is given in (7).

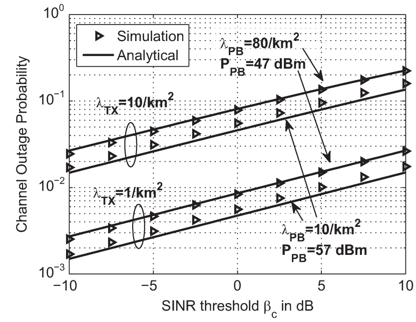


Fig. 1. The channel outage probability versus the SINR threshold β_c.

Total Outage Probability: Finally, combining the power outage probability in (3) and the channel outage probability in (9), the total outage probability at a typical RX, Y_0, is

$$\begin{aligned} \mathcal{P}_{\rm out} &= \mathcal{P}_{\rm out}^{\rm P} + \left(1 - F_{P_{\rm PT}}(\gamma^{-1}P_{\max})\right)\left(\mathcal{P}_{\rm out}^{\rm C}|_{P_{{\rm TX}_0}}(P_{\max})\right) \\ &+ \left(1 - \mathcal{P}_{\rm out}^{\rm C}\right)\int_{\gamma\beta_{\rm PT}}^{P_{\max}} |_{P_{{\rm TX}_0}}(p_{{\rm TX}_0}) f_{P_{{\rm TX}_0}}(p_{{\rm TX}_0})\, dp_{{\rm TX}_0}. \end{aligned} \tag{10}$$

Note that (10) cannot be expressed in closed-form due to the complexity of the term $\mathcal{P}_{\rm out}^{\rm C}|_{P_{{\rm TX}_0}}(P_{{\rm TX}_0})$ which is inside the integration. However, (10) can be easily evaluated numerically.

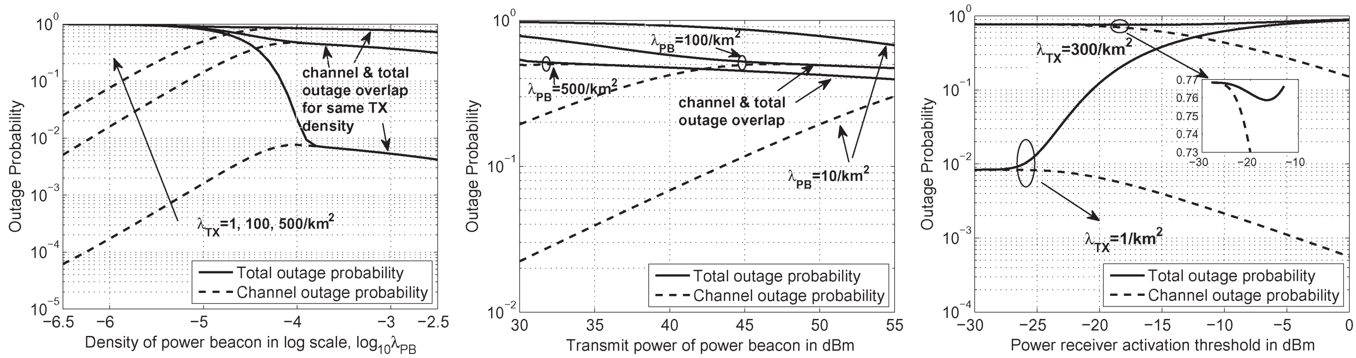
IV. Results

In this section, we first establish the accuracy of the analytical results in (9) by comparing with simulations. Unless specified otherwise, the main system parameters are set as follows: $\alpha = 4$, $d_0 = 20$ m, $\beta_{\rm PT} = -30$ dBm [1], $\beta_c = 0$ dB [12], $N = -130$ dBm, $\rho = 0.5$, $\eta = 0.5$ and $P_{\max} = 30$ dBm. All power values are expressed in dBm.

Accuracy of Derived Analytical Results: Fig. 1 plots $\mathcal{P}_{\rm out}^{\rm C}$ versus SINR threshold β_c with $\lambda_{\rm PB} = 10, 80/\text{km}^2$, $\mathcal{P}_{\rm PB} = 47, 57$ dBm and $\lambda_{\rm TX} = 1, 10/\text{km}^2$. The simulation results are averaged over 1 million realizations. The figure shows that there is a small gap between the analytical and simulation results. This is due to the independence assumption of the active TX's location and transmit powers, which has been used in the derivation. However, the trend of the analytical results is the same as the simulation results. This confirms the accuracy of the derived analytical expressions. In addition, we can see that increasing β_c degrades $\mathcal{P}_{\rm out}^{\rm C}$ because the SINR is less likely to achieve the higher SINR threshold β_c value.

Next, we will use the analytical results to show the impact of the important system parameters (i.e., $\lambda_{\rm PB}$, $\mathcal{P}_{\rm PB}$ and $\beta_{\rm PT}$) on the outage probability.

Effect of $\lambda_{\rm PB}$: Fig. 2(a) plots $\mathcal{P}_{\rm out}^{\rm C}$ and $\mathcal{P}_{\rm out}$ versus the PB density $\lambda_{\rm PB}$, with $P_{\rm PB} = 47$ dBm and $\lambda_{\rm TX} = 1, 100, 500/\text{km}^2$. First we examine the effect on $\mathcal{P}_{\rm out}^{\rm C}$. Fig. 2(a) shows that as $\lambda_{\rm PB}$ increases, $\mathcal{P}_{\rm out}^{\rm C}$ first increases and then decreases. This can be explained as the result of interplay between two factors: the probability of being active for TXs $(1 - P_{\rm out}^{\rm P})$ and the PDF of the transmit power $f_{\mathcal{P}_{\rm TX}}(\mathcal{P}_{\rm TX})$. When $\lambda_{\rm PB}$ increases, the probability of being active increases and also the peak of $f_{\mathcal{P}_{\rm TX}}(\mathcal{P}_{\rm TX})$ is shifted to the right, which means that $P_{\rm TX}$ is more likely to be greater. Initially, the probability of being active plays the dominant role in Fig. 2(a). Consequently, as the probability of being active increases, the number of interferer TXs increases, which generates more interference and degrades $\mathcal{P}_{\rm out}^{\rm C}$. However, when $\lambda_{\rm PB}$ increases beyond a certain



(a) (b) (c)

Fig. 2. Effect of PB density (λ_{PB}), PB transmit power (P_{PB}), power receiver activation threshold (β_{PT}) on the channel and total outage probabilities. (a) Effect of λ_{PB}, (b) Effect of P_{PT}, (c) Effect of β_{PT}.

value, $f_{P_{\mathrm{TX}}}(p_{\mathrm{TX}})$ begins to plays the dominant role. Thus, even though the number of interferer TXs is large, the reference TX is likely to support its RX with a higher transmit power which slightly improves $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$. Next, we examine the effect on $\mathcal{P}_{\mathrm{out}}$. Initially, $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ plays the dominant role in determining $\mathcal{P}_{\mathrm{out}}$. This is because when λ_{PB} is small, $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ is several orders of magnitude greater than $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$. $\mathcal{P}_{\mathrm{out}}^{\mathcal{P}}$ decreases as λ_{PB} increases and so does P_{out}. Eventually, $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ plays the dominant role and $\mathcal{P}_{\mathrm{out}}$ and $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ overlap when λ_{PB} is large.

Effect of P_{PB}: Fig. 2(b) plots $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ and $\mathcal{P}_{\mathrm{out}}$ versus the PBs' transmit power P_{PB}, with $\lambda_{\mathrm{PB}} = 10, 100, 500/\mathrm{km}^2$ and $\lambda_{\mathrm{TX}} = 100/\mathrm{km}^2$. The figure shows that the effect of P_{PB} depends on the value of λ_{PB}. When $\lambda_{\mathrm{PB}} = 10/\mathrm{km}^2$ (i.e., small), $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ is an increasing function of P_{PB} in the considered range of P_{PB}. However, in this case the majority of TXs are in power outage. Hence, $\mathcal{P}_{\mathrm{out}}$ is largely determined by $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$. When $\lambda_{\mathrm{PB}} = 100/\mathrm{km}^2$, increasing P_{PB} improves $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ and hence $\mathcal{P}_{\mathrm{out}}$, until $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ becomes dominant when the $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ and $\mathcal{P}_{\mathrm{out}}$ curves merge. Finally, when $\lambda_{\mathrm{PB}} = 500/\mathrm{km}^2$ (i.e., large), nearly all TXs are always active. Hence, $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ and $\mathcal{P}_{\mathrm{out}}$ overlap and slightly decrease as P_{PB} increases. These trends, which we have observed to be valid as long as λ_{TX} is not too large, can be easily explained using similar arguments as before.

Effect of β_{PT}: Fig. 2(c) plots $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ and $\mathcal{P}_{\mathrm{out}}$ versus the power receiver activation threshold β_{PT}, with $\lambda_{\mathrm{TX}} = 1, 300/\mathrm{km}^2$, $\lambda_{\mathrm{PT}} = 200/\mathrm{km}^2$ and $P_{\mathrm{PT}} = 47$ dBm. From the figure, we can see that $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ decreases as β_{PT} increases. This is because a larger value of β_{PT} prohibits more TXs from being active and the interference at the reference RX is consequently reduced. As for the total outage, when λ_{TX} is small, $\mathcal{P}_{\mathrm{out}}$ increases as β_{PT} increases. This is because $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ (which is $\gg \mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$) increases as β_{PT} increases and plays the dominant role in determining $\mathcal{P}_{\mathrm{out}}$. When λ_{TX} is large, $\mathcal{P}_{\mathrm{out}}$ first decreases and then increases with increasing β_{PT}. This is due to the interaction of $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ and $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$, since $\mathcal{P}_{\mathrm{out}}^{\mathrm{P}}$ increases as β_{PT} increase, while $\mathcal{P}_{\mathrm{out}}^{\mathrm{C}}$ decreases.

V. Conclusion

In this letter, we have formulated the outage probability of a wireless ad hoc network with decoupled SWIPT, assuming a realistic model for wirelessly powered TX nodes. For $\alpha = 4$, we have derived analytical results for the power outage probability and channel outage probability, which determine the total outage probability. The results have shown that the total outage probability improves by decreasing the power receiver activation threshold for low TX density, increasing the power beacon density and the power beacon transmit power.

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