

# Connectivity Analysis in Wireless-Powered Sensor Networks with Battery-less Devices

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**Abstract**—The emerging Internet of Things paradigm has triggered an explosion in ad-hoc applications that require connectivity among the nodes of wireless networks. However, the channel randomness and the random deployment of such networks could cause missed detections by isolated (i.e., unable to disseminate their messages) or inactive (i.e., without enough energy to transmit) nodes. Moreover, as the number of nodes increases, the use of “green” solutions such as wireless energy harvesting for powering battery-less devices could eliminate the maintenance costs and boost immensely the network lifetime. In this paper, we study the connectivity in a wireless-powered sensor network (WPSN) with battery-less devices under two common routing schemes, namely unicast and broadcast. We provide an analytical model for the ability of a WPSN to be reliable and evaluate the trade-offs among the different scenarios via simulation.

**Index Terms**—Wireless Sensor Networks, Connectivity, Wireless Energy Harvesting, Routing, Poisson Point Process

## I. INTRODUCTION

In virtue of the great advancements in wireless technology over the last years, an increasing number of Internet of Things applications consisting of numerous and, usually, randomly-deployed nodes assist us in our everyday life, e.g., transportation, intrusion detection or health care [1]. As each of these applications becomes crucial for our safety and security, the ability of all nodes to communicate with each other, either directly or via multiple hops, denoted as full connectivity, becomes imperative. To satisfy this requirement, two issues should be taken into account: i) the communication performance among the nodes should ensure that every node is connected to at least one neighbor, and ii) the energy supply of each wireless node should allow for uninterrupted and, thus, reliable operation.

Regarding the first issue, the communication among nodes should be carefully studied in order to consider both the random node deployment and the channel randomness, i.e., fading, in a link between a set of nodes. To elaborate, in the absence of fading, a deterministic range around a node can be calculated, in which successful communication with all the neighbors is ensured, while the nearest neighbor always provides the strongest wireless link [2]. On the other hand, in fading environments, the range is not deterministic and the strongest link may not correspond to the nearest neighbor [3]. This outcome demonstrates the significance of the

routing scheme employed in the presence of fading, where the differences in the performance of the unicast (i.e., point-to-point transmission) and broadcast (i.e., point-to-multiple points) routing schemes could be vast in terms of lifetime and quality of service [4]. Therefore, to design a reliable and fully connected network in fading environments, it is necessary to evaluate the connectivity probability for the different schemes.

Furthermore, as the density of wireless devices grows, the energy supply becomes a crucial issue. Battery-powered devices require high maintenance costs due to the inconvenience of the traditional methods to replenish their energy (i.e., battery replacement or cable-charging). On the other hand, energy harvesting can provide a “green” solution to avoid such costs and ensure a sustainable network operation. However, most of the natural sources are scarce in urban environments (e.g., workplaces or houses) and they can not provide a stable energy supply to the wireless devices. At the same time, Wireless Energy Harvesting (WEH) [5] can be an effective solution for urban environments where radio-frequency (RF) signals are usually in abundance. With WEH, it is possible to scavenge the energy of RF signals and convert them to direct current (DC) electricity. In this way, it is even possible to employ low-powered battery-less wireless devices, if the amount of received energy at a temporary storage unit, e.g., a capacitor, is at the same level as the consumed energy. Also, in such wireless-powered sensor networks (WPSNs), the devices are free to move or even be embedded in walls or human bodies without affecting extensively their ability to replenish their energy.

In our recent works that study the communication performance of WSNs [6], [7], it is demonstrated that the lifetime of wireless nodes can increase significantly as a result of WEH from ambient RF signals. However, it is shown that WEH is not able to provide enough power to counterbalance the consumed energy in realistic scenarios, mainly due to the path loss between the receiver and the transmitters and the losses from the RF-to-DC conversion. Nevertheless, with the use of dedicated power transmitters or power beacons (PB) [9], it is possible to solve the aforementioned problem and provide the battery-less wireless devices with sufficient energy. By employing this technique, the nodes harvest energy for a certain period of time and then consume it for communication.

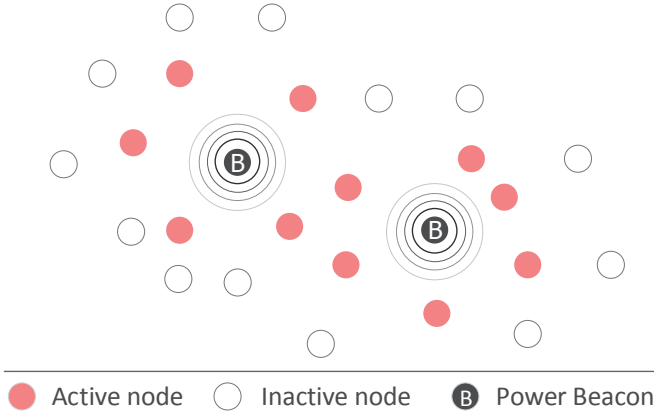


Fig. 1: A random distribution of nodes and PBs. Coloured nodes surpass the  $\theta$  threshold at the end of the HP.

In this way, the large-scale network can greatly increase its lifetime and reduce its maintenance costs.

Although many noteworthy works study the probability of full connectivity in ad-hoc networks [2], [3], as well as the connectivity in such networks under different routing schemes [4], they do not consider the energy supply, which is an important factor for the sustainability of a network. Furthermore, in works on ad-hoc networks with WEH as in [6], [8], the authors discuss various network metrics, e.g., spatial throughput, but not the probability of connectivity, which guarantees the reliability of safety-critical applications. Moreover, in [9], the authors present an algorithm that maximizes the network lifetime with solar harvesting nodes, while the connectivity is guaranteed. Nonetheless, the connectivity is not derived mathematically, but it is given as a constraint in the optimization problem, while the channel conditions are not taken into account.

To that end, in this paper, we first study the connectivity of a WPSN. We assume that a set of beacons is transmitting energy to a network of low-power wireless sensor nodes and derive the probability of connectivity by taking into account the channel randomness (i.e., Rayleigh fading) and routing schemes, i.e., unicast and broadcast. The nodes and the PBs are modeled through two different Poisson point processes (PPPs), which is considered a realistic approach for ad-hoc networks [10]. Our contribution can be summarized as follows: i) We derive the probability of active (i.e., with enough energy to transmit) node with and without fading, ii) we analytically derive the probability of connectivity for the two routing schemes while taking into account the harvested energy from PBs, and, finally, iii) we compare the two routing schemes and provide insights regarding the network design.

The remaining part of this paper is organized as follows. In Section II, we describe the system model. The mathematical derivations of the connectivity for the WPSN are presented in Section III. The results are provided and discussed in Section IV. Finally, Section V concludes the paper.

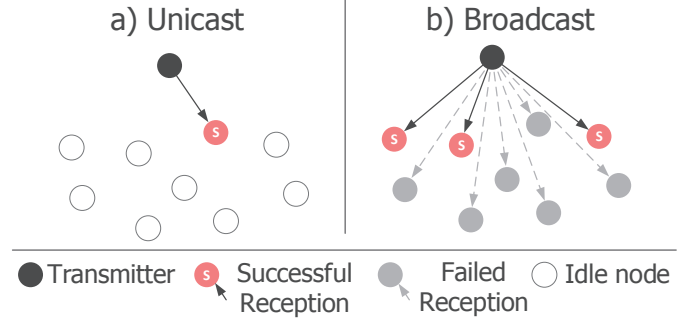


Fig. 2: Routing schemes: a) Unicast and b) Broadcast.

## II. SYSTEM MODEL

We consider a large-scale wireless network on the Euclidean plane and model the random locations of  $m$  nodes according to a homogeneous PPP  $\Phi_S = \{x_1, x_2, \dots, x_m\}$  with intensity  $\lambda_s$ , where  $x_i, \forall i \in \mathbb{N}$ , denotes the location (i.e., Cartesian coordinates) of the  $i^{th}$  node. On the same plane, we distribute  $q$  PBs according to a homogeneous PPP  $\Phi_B = \{y_1, y_2, \dots, y_q\}$  with intensity  $\lambda_B < \lambda_s$ , where  $y_j, \forall j \in \mathbb{N}$ , denotes the location of the  $j^{th}$  PB.

We assume that all PBs transmit with power  $P_b$  and are connected to the electricity grid, thus having a reliable power supply. Time is divided into two periods: i) The harvesting period (HP) that consists of  $S$  time slots, in which all nodes accumulatively harvest RF energy from the PBs with RF-to-DC conversion efficiency  $\epsilon$ , and ii) The communication period (CP) which has a duration of 1 slot. A node is considered active during the CP if, at the end of the HP, it has received and stored temporarily, e.g., at a capacitor, an amount of at least  $\theta$  Joules. In Fig. 1, we illustrate the network and the effect of PBs at the end of the HP. At the beginning of the CP, each active node transmits with power  $P_{tx}$  or receives a message from a neighboring node with power  $P_{rx} = P_{tx}$ . Therefore, at the end of the CP all active nodes have transmitted or received a message and, thus, their stored energy is depleted as  $\theta$  threshold guarantees enough energy for only one transmission or reception plus an energy margin  $\delta$  for other node operations, e.g., sensing and processing. Hence,  $\theta = P_{tx}t_s + \delta$ , where  $t_s$  is the duration of the node transmission in seconds. A node that has harvested less energy than the  $\theta$  threshold is assumed to deplete its stored energy before the next HP.

In our analysis, we examine the ability of a source to connect to a given node, based on the received power denoted as  $P_R = P_{tx}hr^{-\alpha}$ , where  $r$  is the distance between the receiver and its transmitter (i.e., without loss of generality, we assume that the respective receiving node is located at the origin according to Slyvnyak's theorem [10]),  $\alpha$  is the path loss exponent and  $h$  is the power fast fading coefficient, which is independent and identically distributed (i.i.d.). The Rayleigh fading environment is considered suitable for modeling fast fading in dense urban environments [11]. For this reason, the amplitude fading  $\sqrt{h}$  is Rayleigh distributed with a scale parameter  $\sigma = 1$ , thus  $h$  is exponentially distributed with mean

value  $\mu = 1$ . Therefore, a node is considered connected with its  $n^{th}$  nearest neighbor (i.e., is able to decode a received message), when the received signal to noise ratio (SNR) is higher than a threshold  $\gamma$ , as it is given in

$$\text{SNR}_n = \frac{P_{tx} \cdot h \cdot r_n^{-\alpha}}{W} \geq \gamma, \quad (1)$$

where  $r_n$  is the Euclidean distance between the two nodes and  $W$  denotes an additive white Gaussian noise power, modeled as a constant zero mean Gaussian random variable.

Regarding the communication, illustrated in Fig. 2, we study two routing mechanisms. In the first scenario, shown in Fig. 2(a), we demonstrate the unicast routing mechanism, in which a node is considered connected only if the nearest neighbor can decode successfully the transmitted message. In the second scenario, depicted in Fig. 2(b), a source node broadcasts its message to every node and it is considered connected if at least one of the receivers is able to decode the message, regardless of its proximity to the source node.

### III. WPSN CONNECTIVITY ANALYSIS

In this section, we present the analytical derivations of the probability of connectivity for a WPSN with battery-less nodes under different routing protocols, i.e., unicast and broadcast.

The probability of connectivity  $\mathcal{C}$  in a WPSN depends on two statistically independent events: i) Event  $A$  (with probability  $p_a$ ) that a node is active after harvesting RF energy from  $q$  PBs in  $S$  time slots, or

$$p_a = \mathbb{P}(\text{harvested energy after HP} \geq \theta), \quad (2)$$

and ii) Event  $B$  (with probability  $p_s$ ) that all active nodes are able to successfully deliver their measurements either directly or via multihop to a final destination.

To clarify,  $p_s$  provides the probability of connectivity for a network consisting only of the set of active nodes. Thus, to account for the whole network, the inactive nodes should be considered. Therefore, the probability of connectivity for the WPSN is the joint probability of the statistically independent events  $A$  and  $B$ , given by

$$\mathcal{C} = \mathbb{P}(A, B) = p_a \cdot p_s. \quad (3)$$

Regarding  $p_s$  and according to [12], if the number of nodes  $m$  is high enough, then

$$p_s = \mathbb{P}(d_{min} \geq 1), \quad (4)$$

where  $d_{min}$  denotes the minimum node degree which is the sum of connections of the node with the fewest connections.

In order to determine if the minimum node degree of the network is equal or higher than one (i.e., full connectivity), we need to calculate the probability that all nodes are connected with at least one of their neighbors. Assuming statistically independent wireless links, this probability is

$$\mathbb{P}(d_{min} \geq 1) = \mathbb{P}(\text{SNR}_n \geq \gamma)^m, \quad (5)$$

where  $m$  denotes the total number of nodes, and  $\text{SNR}_n$  is: i) for the unicast case, the signal to noise ratio at the nearest receiving node, i.e.,  $n = 1$ , and ii) for the broadcast case, the signal to noise ratio at the receiver with the strongest link.

#### A. In the absence of fading

Nonetheless, when fading is not taken into account, the nearest neighbor provides always the strongest link. Hence, in this case, it is sufficient to identify whether the source node is able to connect with its nearest neighbor for both routing schemes. To that end, the connectivity probability  $\mathcal{C}$  without fading is provided in the following proposition.

**Proposition 1.** *The probability of connectivity in the absence of fading for both unicast and broadcast, assuming  $\alpha = 4$  is given by*

$$\mathcal{C} = \text{erf}\left(\frac{\pi^{\frac{3}{2}} \lambda_B}{2} \sqrt{\frac{SP_b \epsilon}{\theta}}\right) \left[1 - e^{-\lambda_s \pi \sqrt{\frac{P_{tx}}{\gamma W}} \text{erf}\left(\frac{\pi^{\frac{3}{2}} \lambda_B}{2} \sqrt{\frac{SP_b \epsilon}{\theta}}\right)}\right]^m, \quad (6)$$

where  $\text{erf}(x) = 1 - \text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$ .

*Proof.* To derive the probability  $p_a$ , we have to consider the accumulated received power from the set of the PBs and calculate the probability that this amount is higher than the threshold  $\theta$ . Hence, we obtain

$$p_a = \mathbb{P}\left(S \cdot \sum_{j=1}^q \epsilon P_b |y_j|^{-\alpha} \geq \theta\right) = \quad (7)$$

$$= \mathbb{P}\left(\sum_{j=1}^q |y_j|^{-\alpha} \geq \frac{\theta}{S \epsilon P_b}\right), \quad (8)$$

where the sum in (7) is the total harvested power from PBs at a node located in the origin and  $|y_j|$  denotes the Euclidean distance between the  $j$ th PB and the origin.

To calculate (8), we have first to focus on the distribution of the sum  $Y = \sum |y_j|^{-\alpha}$  and derive its characteristic function  $F_I(\omega) = \mathbb{E}(e^{j\omega Y})$ . According to [10], by conditioning on having  $k$  nodes in a disk of radius  $\rho$  and then de-conditioning on the Poisson number of nodes, while letting  $\rho$  go to infinity, we obtain

$$F_I(\omega) = \exp(-\lambda_B \pi \Gamma(1 - 2/\alpha) \omega^{2/\alpha} e^{-j\pi/\alpha}), \quad (9)$$

where  $\Gamma(t) = \int_0^\infty x^{t-1} e^{-x} dx$  is the gamma function.

It can be noticed that (9) is a stable distribution with shift 0, skew 1, stability  $2/\alpha$  and scale  $(\lambda_B \pi \Gamma(1 - 2/\alpha) \cos(\pi/\alpha))^{\alpha/2}$ . Therefore, the complementary cumulative distribution function (CCDF) in (8) can be found as an infinite series [14]

$$p_a = \sum_{k=1}^{\infty} \frac{\Gamma(2k/\alpha)}{\pi k!} \left( \frac{\lambda_B \pi \Gamma(1 - 2/\alpha)}{(\frac{\theta}{S \epsilon P_b})^{2/\alpha}} \sin(k\pi(1 - 2/\alpha)) \right)^k. \quad (10)$$

For the special case of  $\alpha = 4$ , (9) reduces to a Lévy distribution with shift 0 and scale  $\pi^3 \lambda_B^2 / 2$ , yielding

$$p_a = \text{erf}\left(\frac{\pi^{\frac{3}{2}} \lambda_B}{2} \sqrt{\frac{SP_b \epsilon}{\theta}}\right). \quad (11)$$

Furthermore, to calculate the probability  $p_s$ , we have to consider only the set of active nodes. Hence, the actual node intensity that takes into account only the active nodes is given, according to the colouring theorem [13], by

$$\lambda_a = \lambda_s \cdot p_a. \quad (12)$$

Therefore, following a similar approach as in [2] and taking into account (12), it is easy to derive that the probability  $p_s$  in the absence of fading is given by

$$p_s = \left(1 - e^{-\lambda_a \pi \left(\frac{P_{tx}}{\gamma W}\right)^{2/\alpha}}\right)^m. \quad (13)$$

Substituting (11) and (13) in (3), concludes the proof.  $\square$

**Remark 1.** The connectivity for a network with Battery-powered devices can be obtained by applying  $\theta = 0$  in (6). Setting  $\theta = 0$  yields  $p_a = 1$  and, thus,  $C = p_s$ . This implies that the nodes do not require energy from the PBs to operate and that all nodes are considered active (i.e.,  $\lambda_a = \lambda_s$ ).

### B. In the presence of fading

In a more realistic scenario where fading is present, the results differ substantially. As we have already explained, in fading environments, the nearest node does not have necessarily the strongest link due to the randomness that is introduced at the received power from fading. Hence, in this case, it is important to define the routing mechanism that is used in the network, before proceeding to the derivations of connectivity. Therefore, in the following, we study the unicast and broadcast routing mechanisms, as discussed in Section II.

1) *Unicast:* In the unicast case, the connectivity  $C_u = p_a \cdot p_s$  is defined by the ability of the nodes to connect with their nearest neighbor and it is given by the following proposition.

**Proposition 2.** The probability of connectivity of a WPSN for the unicast case, denoted as  $C_u$ , is given by

$$C_u = \text{erf} \left( \frac{\lambda_B \Gamma(S + \frac{1}{2})}{2\Gamma(S) \pi^{-3/2}} \sqrt{\frac{P_b \epsilon}{\theta}} \right) \left[ \frac{\pi^{\frac{3}{2}} \lambda_a \text{erfc} \left( \frac{\pi \lambda_a \sqrt{P_{tx}}}{2\sqrt{\gamma W}} \right)}{2e^{-\frac{\pi^2 \lambda_a^2 P_{tx}}{4\gamma W}} \sqrt{\frac{\gamma W}{P_{tx}}}} \right]^m. \quad (14)$$

*Proof.* To calculate  $p_a$  in the presence of fading, we have to follow a similar approach as in (7)-(11). Following [8] and [10], we derive

$$p_a = \text{erf} \left( \frac{\lambda_B \Gamma(S + \frac{1}{2})}{2\Gamma(S)} \sqrt{\frac{\pi^3 P_b \epsilon}{\theta}} \right). \quad (15)$$

Moreover, similar to the analysis provided for the case where fading is considered absent,  $p_s$  is obtained by

$$p_s = \mathbb{P}(\text{SNR}_1 \geq \gamma)^m = \mathbb{P}\left(hr^{-\alpha} \geq \frac{W\gamma}{P_{tx}}\right)^m. \quad (16)$$

This is a joint probability distribution of the independent random variables  $h$  and  $r$ . Therefore, we have

$$p_s = \mathbb{P}\left(h \geq \frac{r^\alpha W\gamma}{P_{tx}}\right)^m = \quad (17)$$

$$= \left( \int_0^\infty \int_{\frac{y^\alpha W\gamma}{P_{tx}}}^\infty f_h(x) f_r(y) dx dy \right)^m = \quad (18)$$

$$= \left( \int_0^\infty \int_{\frac{y^\alpha W\gamma}{P_{tx}}}^\infty 2\pi \lambda_a y e^{-\pi \lambda_a y^2} e^{-x} dx dy \right)^m, \quad (19)$$

where (18) follows from the joint distribution of independent variables and (19) follows from the probability density function (PDF) of the distance  $r$  of a node to its nearest active neighbor  $f_R(r) = 2\lambda_a \pi r e^{-\lambda_a \pi r^2}$  [10] and the PDF of an exponential variable with mean value 1. The integral in (19) can be solved either by employing the modified Gauss-Hermite quadrature as in [4] or by assuming  $\alpha = 4$ , which yields

$$p_s = \left( \frac{\pi^{\frac{3}{2}} \lambda_a e^{\frac{\pi^2 \lambda_a^2 P_{tx}}{4\gamma W}} \text{erfc} \left( \frac{\pi \lambda_a \sqrt{P_{tx}}}{2\sqrt{\gamma W}} \right)}{2\sqrt{\frac{\gamma W}{P_{tx}}}} \right)^m. \quad (20)$$

Multiplying (20) with (15), concludes the proof.  $\square$

2) *Broadcast:* In the broadcast case, the connectivity  $C_b = p_a \cdot p_s$  is defined by the ability of a node to connect with any neighbor, regardless of the distance between them, and it is provided by the following proposition.

**Proposition 3.** The probability of connectivity for the broadcast routing scheme, denoted as  $C_b$ , is given by

$$C_b = \text{erf} \left( \frac{\lambda_B \Gamma(S + \frac{1}{2})}{2\Gamma(S) \pi^{-\frac{3}{2}}} \sqrt{\frac{P_b \epsilon}{\theta}} \right) \left[ 1 - e^{-\frac{\lambda_a \pi^{\frac{3}{2}}}{2} \sqrt{\frac{P_{tx}}{\gamma W}}} \right]^m. \quad (21)$$

*Proof.* Again, to calculate the connectivity probability, we have first to derive the probabilities  $p_s$  and  $p_a$ . However, in this case,  $p_a$  is given by (15), while to calculate  $p_s$  we have to follow a different approach. According to [3], the isolation probability for an active node, while considering the channel randomness is given by

$$\mathbb{P}_I = e^{-\lambda_a \pi \mathbb{E}[R^2]}. \quad (22)$$

Furthermore,

$$\mathbb{E}[R^2] = \int_0^\infty 2r \mathbb{P}\left(l(r) \geq \frac{W\gamma}{P_{tx}}\right) dr = \quad (23)$$

$$= \int_0^\infty 2r \int_{\frac{W\gamma}{P_{tx}}}^\infty r^\alpha e^{-r^\alpha h} dr dh = \quad (24)$$

$$= \int_0^\infty 2r e^{-\frac{r^\alpha W\gamma}{P_{tx}}} dr = \left(\frac{2}{\alpha}\right) \Gamma\left(\frac{2}{\alpha}\right) \left(\frac{\gamma W}{P_{tx}}\right)^{-\frac{2}{\alpha}}, \quad (25)$$

where  $R$  is the random variable of the communication range. (24) follows after considering that the path loss  $l(r)$  is an exponential random variable with mean value  $r^{-\alpha}$  [15]. By substituting (25) to (22), the probability  $p_s$  for the broadcast case is given by

$$p_s = \left(1 - e^{-\frac{2\lambda_a \pi}{\alpha} \Gamma\left(\frac{2}{\alpha}\right) \left(\frac{\gamma W}{P_{tx}}\right)^{-2/\alpha}}\right)^m. \quad (26)$$

To that end, by multiplying (26) for  $\alpha = 4$  with (15), we obtain the connectivity probability in the broadcast case.  $\square$



TABLE I:  
SIMULATION PARAMETERS

Simulation Parameter	Symbol	Value
Path loss exponent	$\alpha$	4 (urban env.)
Threshold ratio	$\gamma$	-10 dB
Node transmission power	$P_{tx}$	[-20, 30] dBm
Beacon Transmission power	$P_b$	[26, 36] dBm
Energy margin in $\theta$	$\delta$	$2 \cdot 10^{-3}$ Joule
RF-to-DC conversion efficiency	$\epsilon$	0.7
Noise power	$W$	-60 dBm
Node Intensity	$\lambda_s$	[0.1, 0.5] per m <sup>2</sup>
PB Intensity	$\lambda_B$	[0.01, 0.1] per m <sup>2</sup>
Area	$A$	$5 \cdot 10^3$ m <sup>2</sup>

#### IV. ANALYTICAL AND SIMULATION RESULTS

In this section, we present the simulation setup, we validate the analytical derivations obtained in Section III via Monte Carlo simulations and we discuss the results of our experiments. It should be noted that all simulations are conducted using the toroidal distance metric, as explained in [2].

##### A. Simulation Setup

We study the connectivity in a WPSN for two routing mechanisms (i.e., unicast and broadcast) with and without fading conditions. Furthermore, following Remark 1, we set  $\theta = 0$  to obtain the connectivity for battery-powered devices and compare it with the battery-less case where  $\theta = P_{tx}t_s + \delta$ . Moreover, the intensity of the nodes varies between  $\lambda_s = 0.1$  and  $\lambda_s = 0.5$  nodes per m<sup>2</sup> and the simulation area is set at  $A = 5 \cdot 10^3$  m<sup>2</sup>. Hence, the number of deployed nodes for the different simulations, varies between  $m = \lambda_s A = 500$  and  $m = 2500$ . Similarly, the PB intensity varies between 0.01 and 0.1 PBs per m<sup>2</sup> or between 50 and 500 PBs in the area  $A$ . The rest system parameters are summarized in Table I.

##### B. Results

In order to validate the analytical derivations of Section III, we present in Fig. 3 the effects of channel randomness and WEH from PBs on the connectivity probability versus the transmission power  $P_{tx}$  for all analytically derived scenarios (i.e., with/without fading, unicast/broadcast). To begin with, we observe that all results show a perfect match with the theory. In Fig. 3(a), we validate the probability  $p_s$  that all active nodes are able to successfully deliver their measurements. We observe that, in the broadcast scheme,  $p_s$  is much higher than in the unicast case due to the fading conditions, as less nodes are able to connect with their nearest neighbors, although they could connect with nodes that are farther away. To the contrary, the broadcast routing scheme is not affected drastically by the channel randomness. Moreover, in Fig. 3(b), we depict the probability of active node  $p_a$  with and without fading. In this case, we notice a significant drop as  $P_{tx}$  increases over 10 dBm, as the nodes require more energy to be active at the beginning of the CP (recall that  $\theta$  is an increasing function of  $P_{tx}$ ). Also,  $p_a$  is not strongly affected by fading as it drops merely by  $\sim 3\%$  when fading is present. Furthermore, in Fig. 3(c), we demonstrate the connectivity

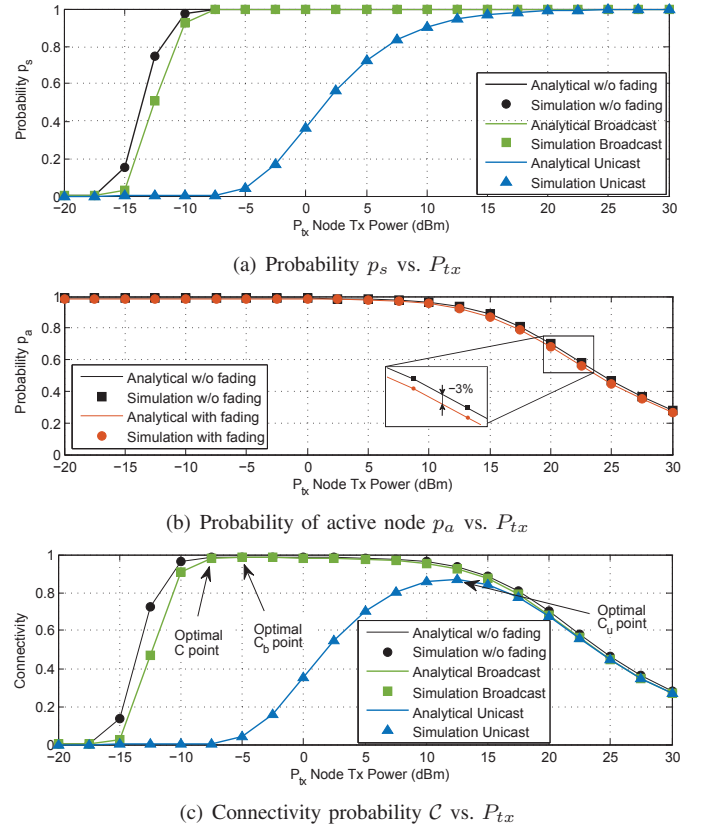


Fig. 3: Effects of channel randomness and WEH in the probability of connectivity. Parameters:  $\lambda_s = 0.1$ ,  $S = 3$ ,  $P_b = 30$  dBm and  $\lambda_B = 0.02$ .

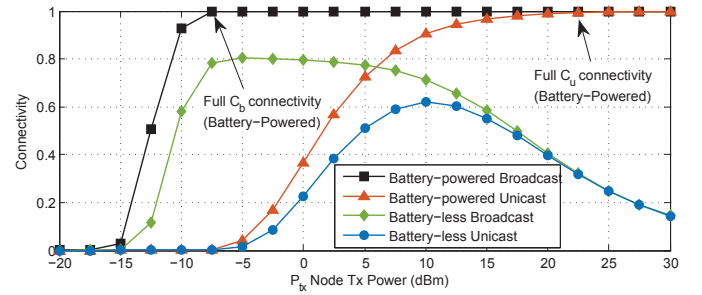


Fig. 4: Connectivity vs.  $P_{tx}$  for different scenarios. Parameters:  $\lambda_s = 0.1$ ,  $S = 1$ ,  $P_b = 30$  dBm and  $\lambda_B = 0.02$ .

probability  $C$  for the three scenarios. It is interesting to notice that the result in  $p_a$  affects significantly the connectivity as  $P_{tx}$  increases, creating an optimal case for each scenario, i.e.,  $\sim 12$  dBm for unicast and approximately  $-6$  dBm for the other two scenarios. Also, we observe that the unicast case never achieves full connectivity, due to the combination of low node intensity and low  $p_a$  probability.

Furthermore, in Fig. 4, we compare the connectivity probability versus the transmission power in four different scenarios, i.e., unicast/broadcast and battery-less/battery-powered. In this case, we have set  $S = 1$ , which will provide faster communication rate, but less active nodes for the battery-less

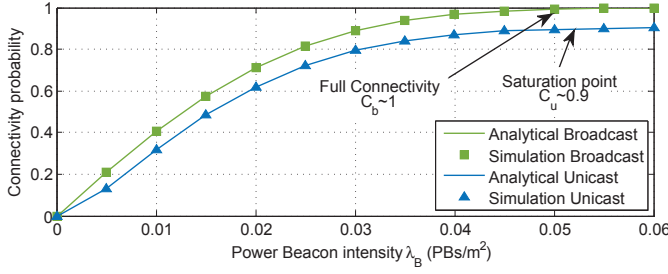


Fig. 5: Connectivity vs. PB intensity for the different schemes. Parameters:  $S = 1$ ,  $P_b = 30$  dBm,  $P_{tx} = 10$  dBm,  $\lambda_s = 0.1$ .

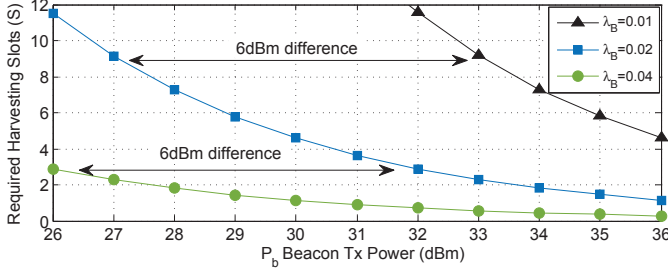


Fig. 6: Harvesting period duration in  $S$  required to achieve  $p_a = 0.99$  vs. the PB transmission power for different PB intensities in fading conditions.

case. We observe that the battery-powered scenarios are able to provide full connectivity to the network, while the battery-less cases achieve low connectivity with optimal points at 0.8 for the broadcast and 0.6 for the unicast case. Thus, there is a significant dependence of the communication rate with the ability of the nodes to be active. However, this can be adjusted by increasing the number of PBs or their transmission power.

In Fig. 5, we confirm that by increasing the number of PBs, while keeping  $S = 1$ , a network with battery-less devices can be fully connected for  $\lambda_B > 0.05$  PBs/m<sup>2</sup>. However, in the unicast case, the network connectivity saturates at  $\sim 90\%$ , although all nodes are active for high PB intensities. This occurs due to the low  $P_{tx}$  of the nodes (i.e., 10 dBm). From Fig. 4, we can confirm that even the battery-powered unicast case cannot achieve full connectivity for  $P_{tx} = 10$  dBm and it should be increased to more than 20 dBm to achieve a fully connected network.

Finally, in Fig. 6, we demonstrate the effects of the PB intensity and transmission power to the harvesting period duration in  $S$  that are required to achieve at least 99% of the nodes to surpass the power threshold  $\theta$ . In order to calculate the results for this figure, we have set  $p_a = 0.99$  and solved (15) for  $S$ . Obviously, for higher values of the PB transmission power or as the PB intensity increases, the required harvesting time slots to achieve high percentage of active nodes decreases. Moreover, an interesting observation is that, as the intensity doubles, the transmission power of the PBs is reduced by a factor of 4 (i.e., drops by 6 dBm) to achieve the same number of active nodes. To that end, Fig. 6 demonstrates an inversely proportional relation of  $\lambda_B$  with the square of  $P_b$  that provides

useful design guidelines for an energy efficient WPSN.

## V. CONCLUSION

In this paper, we studied the connectivity of a WPSN under different routing mechanisms (i.e., unicast, broadcast) and fading conditions. For each scenario, we analytically derived the probability of connectivity, while considering the probability that the nodes are active and validated them through extensive Monte Carlo simulations. Moreover, we compared the different routing mechanisms by assuming both battery-powered and battery-less nodes that harvest RF energy from PBs and showed the circumstances under which a WPSN is connected. In the future, we plan to extend this work in three ways: i) by employing variable RF-to-DC conversion efficiency in the model, which will provide more accurate and realistic results, ii) by deriving analytically the optimum solutions that provide the highest connectivity, and iii) by studying the energy consumption of the PBs and identify the optimal parameters for an energy efficient WPSN.

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