An Autonomous Wireless Sensor Network in a Substation Area Using Wireless Transfer of Energy

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ABSTRACT A smarter power grid can improve the maintenance system by providing a real-time measurement of equipment operating conditions. Such a monitoring system requires the deployment of an increased number of sensors. However, the wiring sensors in a high voltage environment such as power substation is a very expensive procedure. An autonomous wireless sensor network can reduce the installation cost and make sensors more viable throughout the network. In this paper, we study the possibility of deploying an autonomous wireless sensor network in a substation environment. To this end, we merge energy harvesting and wireless transfer of energy to propose a hierarchical energy harvesting model. In this paper, we show that despite of the wasteful nature of the wireless transfer of energy and with an efficiency not more than what existing technologies can provide, a self-sustainable wireless sensor network in a substation area can be accomplished.

INDEX TERMS Energy harvesting, wireless power transfer, smart grids.

I. INTRODUCTION

One of the important promises of a smarter power grid is the potential to evolve from the current notion of preventive maintenance to that of predictive maintenance [1]. Monitoring of grid and asset conditions requires the deployment of an increased number of sensors. It is however important to realize that the deployment of wiring in high voltage (HV) environments such as power substations is a very expensive procedure [1]. Using wireless sensor networks (WSNs) can reduce the installation costs. One of the important concerns related to the use of WSNs is that sensors will eventually run out of energy, as they are not directly wired to a source of energy. Changing sensor batteries in high voltage environments is a procedure that is expensive and that involves safety risks for the operators. As a result, for the purpose of condition monitoring in high voltage environments, autonomous WSNs appear to be the solution of choice. In such systems, wireless nodes harvest energy from their environment, resulting in a self-powered network, that does not require

any battery change. In this paper we will use the terms *autonomous* and *energy-harvesting* interchangeably.

An energy harvester may scavenge energy from different surrounding resources. In general the sources of energy can be characterized by their controllability, predictability and their magnitude [2], [3]. Within a power system and in a substation environment, the alternating electric and magnetic field around HV devices provides an excellent and controllable source for harvesting energy. Many studies have been done around energy harvesting from HV devices. Theoretical and experimental results suggest that different designs are able to harvest a significant enough amount of power in this environment [4]–[10]. In this work, our assumptions on the amount of the energy that can be harvested would not exceed the values that are verified in our references.

In practice, the performance of the energy harvester depends on a variety of factors such as the source of energy, the energy scavenging technology and dimensions of the energy harvester. One key parameter is the availability of the

sources of energy. In a substation area, the available energy is closely dependent on the location of the energy harvester. As we get closer to HV terminals, the electric field gets stronger and as a result more energy can be harvested. However, in practice, the location of sensors will be determined by the location of equipment to be monitored, more than by the proximity to a source of energy that can be harvested. Additionally, the dimensions of the energy harvester typically influence strongly the amount of energy that can be harvested; an example that is close to our application is an inductive energy harvester consisting of a coil around an iron core [9], which is designed to harvest energy form the electrical field around power lines. Not surprisingly, the amount of energy that this design can harvest is proportional to the number of turns of the coil and the length of the core. On the other hand, it is also usually desirable to have a small form factor for sensors in a WSN, so as to ease deployment and installation.

These practical constraints lead us to propose a hierarchical energy harvesting model. In this paper we study a system that combines energy harvesting from the surrounding electrical field and wireless transfer of energy from the harvester to sensors.

Wireless energy transfer (WET) was first conducted experimentally by Nikola Tesla in late 19th century. Nowadays, there are three main technologies for WET, namely, *Inductive coupling*, *Magnetic resonance coupling* and *Electro Magnetic* (EM) radiation. Inductive Coupling technology is used for short ranges of transmission (tens of centimetres) [11]; Magnetic Resonance Coupling technology is efficient for mid-range transmission (several meters) [12], [13]; finally, the EM technology can be used for long ranges of transmission (up to tens of kilometres) [12], [14]–[16]. In the latter method, power is converted to Radio Frequency (RF) signals using a microwave generator and then transmitted through free space by radiating electromagnetic beams to the target, where the received signal is converted back to power using a device called rectifying antenna or *rectenna* [17]–[20]. This device converts RF signals to a DC voltage using a diode-based circuit. Corresponding receivers can be very small and are able to maintain RF to DC conversion efficiency over a wide range of operating conditions [21]. Therefore, using EM technology is a good choice for charging nodes in a WSN [21], [22]. Despite of the wasteful nature of wireless transfer of energy using RF signals, new advances show that this technology is practical and mature enough to be marketed. Companies like *Powercast*, *Energous* and *Ossia* have already commercialized transmitter and receiver designs for WET using EM radiations [23]. Considering the deal between Energous and Apple chip supplier Dialog Semiconductor, there is a chance that long distance WET have a future in next generations of smart phones [24]. The new advances in WET using RF signals is making this topic to become increasingly popular. In [12] the idea of WET using RF signals is applied to hybrid cellular networks, consisting of power and information towers. Energy is transmitted by radiating RF signals to the mobile users at each cell and

the down_link and up_link communications with the users is managed through the information towers. A mobile ad hoc network (MANET) is considered in [25] where energy arrives randomly to transmitters. Upon receiving enough energy, a transmitter transmits with a fixed power to an intended receiver. In [15] a stochastic geometry approach is used to study Simultaneous Information and power Transfer (SWIPT) over a large scale wireless network.

In this work, a hierarchical energy harvesting model is proposed. The objective is to study the possibility of deploying an autonomous WSN in a substation area. In this model the required energy for the sensors is scavenged in two levels: (*i*) First, energy harvesters that are located close to HV terminals harvest energy from the ambient electrical field. We refer to these nodes as *power nodes*. Power nodes can be larger in size compared to a normal sensor. As result and because of being located at hot spots, power nodes are able to harvest more energy compared to what a sensor would potentially be able to harvest. (*ii*) In the second step, a portion of the energy scavenged by the power node will be distributed to nearby sensor nodes by radiating RF signals to them. Sensor nodes will be energized by receiving the RF signals.

Our proposed hierarchical energy harvesting model allows us to address the issue of non-uniform availability of the electric field in a substation area. This system model can potentially provide us with a self sustainable WSN in a substation area. Section II explores the single-sensor single-power node scenario. Namely, it assumes that we have only one energy harvester and only one sensor which is energized by the energy harvester. In Section III, we then extend the results to a scenario with multiple sensors, where a power node needs to energize more than one sensor. Section IV presents simulation results that illustrate the performance of the proposed system, and Section V concludes the paper.
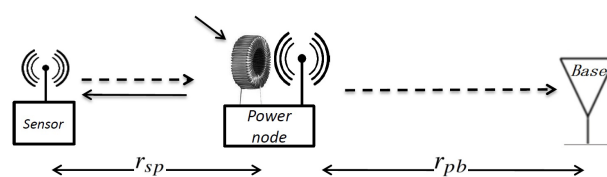

FIGURE 1. Single sensor-single power node scenario.

II. SINGLE SENSOR SCENARIO
A. SYSTEM MODEL
In the simplified scenario considered in this section, we have one power node, located close to a HV terminal or power line, and one sensor node in a location that is suitable for its sensing task, e.g. on the body of a transformer. Fig. 1 illustrates this single sensor-single power node scenario. The dashed arrows between the nodes represent data transfer and the solid arrows represent energy transfer, through harvesting or wireless transmission.

The power node uses the surrounding alternating electric field to harvest energy. A portion of the scavenged energy is

transmitted to the sensor by radiating RF signals. The other portion is used by the power node to relay the received data from the sensor back to the base node. Two transmission periods are assigned to the power node: one for transmitting energy to the sensor and the other one for transmitting data to the base node. Issues occur when the power node does not have enough energy to relay the data received from the sensor node to the base node. In this case, the system would be considered in outage.

The sensor harvests and stores energy from the received RF signals, radiated from the power node. After a defined period of time, if the sensor has enough energy, it transmits its data to the power node. If enough energy is not available, the system would again be considered to be in outage. It is necessary to mention that in our problem formulation, it is assumed that both power node and sensor have no limitations for storing energy.

The channel and the relative distances between the sensor and the power node, and the power node and the base node are random variables denoted by $\mathbf{h}_{sp}$ and r_{sp}, and $\mathbf{h}_{pb}$ and r_{pb} respectively. Using Friis equation, the Signal-to-Noise Ratio (SNR) at the power node then can be written as:

$$SNR_{sp} = \frac{P_s G_{sp} \mathbf{h}_{sp} \mathbf{O}_s r_{sp}^{-\alpha} (4\pi f)^{-\alpha}}{P_N}, \quad (1)$$

where P_s is the transmission power for the sensors and G_{sp} is the antenna gain for the sensor's transmitter. The propagation-loss exponent is denoted by α, f is the transmission frequency and P_N is the noise power. Random Variable $\mathbf{O}_s$ represents the event that the sensor node has enough energy to transmit, i.e., $\mathbf{O}_s = 1$ if the sensor has enough energy to initiate the transmission and $\mathbf{O}_s = 0$ otherwise.

Similarly, the SNR at the base node would be:

$$SNR_{pb} = \frac{P_{pb} G_{pb} \mathbf{h}_{pb} \mathbf{O}_{pb} r_{pb}^{-\alpha} (4\pi f)^{-\alpha}}{P_N}, \quad (2)$$

where P_{pb} is the transmission power for the power node to the base and G_{pb} is the antenna gain for the power node's transmitter. $\mathbf{O}_{pb} = 1$ if the power node has enough energy to initiate the transmission to the base node and $\mathbf{O}_{pb} = 0$ otherwise.

In this system, the outage probability can be defined as the probability that the received signal at the base or at the power node is less than a certain threshold. As a result, the outage probability can be written as:

$$\mathbb{P}_{out} = \mathbb{P}\left\{SNR_{sp} < \Omega_{sp} \cup SNR_{pb} < \Omega_{pb}\right\}, \quad (3)$$

where Ω_{sp} and Ω_{pb} represent the acceptable threshold for SNR_{sp} and SNR_{pb} respectively. Note that the definition of SNR in equations (1) and (2) above already includes a term that accounts for the cases in which no transmission at all would be possible because of a lack of energy.

The objective of this work is to derive an expression of the outage probability and to study the corresponding practical system parameters that will lead to acceptable values for the outage probability.

B. ANALYTICAL RESULTS

In order to determine the outage probability, we need to determine the probability that either of the power or sensor nodes do not have enough energy to transmit. To this end, and inspired by [25], we will study the evolution of accumulated energy in the sensor and power node.

We start by discretizing time into slots of length t_ϵ. All other time values used later in this paper will be assumed to be integer multiples of this basic timeslot length.

1) EVOLUTION OF ENERGY AT THE SENSOR NODE
The evolution of the energy level at the sensor node can be written as:

$$\begin{cases} E_n^s = E_{n-1}^s + Z_n^s - P_s t_t I(E_{n-1}^s \geq P_s t_t) & n = iT_s/t_\epsilon, \ i \in \mathbb{N} \\ E_n^s = E_{n-1}^s + Z_n^s & \text{otherwise,} \end{cases}$$
$$(4)$$

where

- E_n^s is the sensor's energy at time $t = nt_\epsilon$ with $n \in \mathbb{N}$;
- T_s is the interval of time between sensor transmissions to the power node;
- t_t is the duration for the signal to be transmitted from the sensor to the power node;
- Z_n^s is the energy received by the sensor between time $t = nt_\epsilon$ and time $t = nt_\epsilon - T_s$
- $I(\cdot)$ is an indicator function equal to 1 if its argument is true and to 0 otherwise;
- P_s is the transmission power at the sensor node;

By changing variables, equation (4) can be rewritten as:

$$E_{n'}^s = E_{n'-1}^s + \sum_{n=(n'-1)T_s/t_\epsilon}^{n=n'T_s/t_\epsilon} Z_n^s - P_s t_t I(E_{n'-1}^s \geq P_s t_t) \quad (5)$$

with $n' \in \mathbb{N}$. By taking the expected value of (5) we have:

$$\mathbb{E}\left\{E_{n'}^s\right\} = \mathbb{E}\left\{E_{n'-1}^s\right\} + \mathbb{E}\left\{\sum_{n=(n'-1)T_s/t_\epsilon}^{n=n'T_s/t_\epsilon} Z_n^s\right\} - P_s t_t \mathbb{E}\left\{I(E_{n'-1}^s \geq P_s t_t)\right\} \quad (6)$$

In steady state, $\mathbb{E}\left\{E_n^s\right\} = \mathbb{E}\left\{E_{n-1}^s\right\}$. As a result, they will be canceled out from the both sides of the equation. Let λ_s denote the average received power by the sensor. In other words, $\lambda_s = \mathbb{E}\left\{Z_n^s\right\}/t_\epsilon$. Therefore:

$$\mathbb{E}\left\{\sum_{n=(n'-1)T_s/t_\epsilon}^{n=n'T_s/t_\epsilon} Z_n^s\right\} = T_s \lambda_s. \quad (7)$$

by replacing (7) in (6), it can be concluded that:

$$\mathbb{P}\{\mathbf{O}_s = 1\} = \mathbb{E}\left\{I(E_n^s \geq P_s t_t)\right\} = \min(1, \frac{T_s \lambda_s}{P_s t_t}). \quad (8)$$

The minimum function needs to be added to keep the probability less than one. In other words, when the average received energy is larger than average energy used, $\mathbb{P}\{\mathbf{O}_s = 1\} = 1$.

2) EVOLUTION OF ENERGY AT THE POWER NODE

The harvested energy at the power node is divided in two parts. One part is stored and used for wirelessly energizing the sensor. The other part is stored and used for communication with the base node. If the energy harvested by the power nodes between between times $t = nt_\epsilon$ and $t = (n-1)t_\epsilon$ is denoted by Z_n^p, the evolution of the energy can be written in two parts as follows:

$$\begin{cases} E_n^{ps} = E_{n-1}^{ps} + rZ_n^p - P_{ps}t_t I(E_{n-1}^{ps} \geq P_{ps}t_t) & n = \dfrac{iT_{ps}}{t_\epsilon} \\ E_n^{ps} = E_{n-1}^{ps} + rZ_n^p & \text{otherwise,} \end{cases}$$
(9)

$$\begin{cases} E_n^{pb} = E_{n-1}^{pb} + (1-r)Z_n^p - P_{pb}t_t I(E_{n-1}^{pb} \geq P_{pb}t_t) \\ \qquad\qquad\qquad\qquad\qquad n = \dfrac{iT_{pb}}{t_\epsilon} \\ E_n^{pb} = E_{n-1}^{pb} + (1-r)Z_n^p \\ \qquad\qquad\qquad\qquad\qquad \text{otherwise,} \end{cases}$$
(10)

where

- $0 < r < 1$ is the ratio in which the energy harvested by the power node is divided between the tasks of transferring energy to the sensor and communicating with the base node. Namely, after each time slot, %100r of the harvested energy is used for radiating energy to the sensor and %100$(1-r)$ is stored to be used for transmitting with the base node;
- E_n^{ps} is the power node's energy at time $t = nt_\epsilon$ to be used to wirelessly energizing the sensor;
- E_n^{pb} is the power node's energy at time $t = nt_\epsilon$ which is only used for communicating with the base node;
- P_{ps} and P_{pb} represent the transmission powers from the power node to the sensor and base node respectively
- T_{ps} and T_{pb} represent the transmission periods at which, if enough energy is available, the power node transmits its energy signal to the sensor and its data signal to the base, respectively.

Similar to the sensor node, it can be shown that:

$$\mathbb{P}\{\mathbf{O_{ps}} = 1\} = \mathbb{E}\{I(E_n^{ps} \geq P_{ps}t_t)\} = \min(1, \frac{rT_{ps}\lambda_p}{P_{ps}t_t})$$
(11)

and

$$\mathbb{P}\{\mathbf{O_{pb}} = 1\} = \mathbb{E}\{I(E_n^{pb} \geq P_{pb}t_t)\} = \min(1, \frac{(1-r)T_{pb}\lambda_p}{P_{pb}t_t}),$$
(12)

where $\lambda_p = \frac{\mathbb{E}\{Z_n^p\}}{t_\epsilon}$ and $\mathbf{O_{ps}} = 1$ if the power node has enough energy to initiate the transmission to the sensor node and $\mathbf{O_{ps}} = 0$ otherwise.

3) SYSTEM OUTAGE PROBABILITY

Assuming that all the channels are Rayleigh distributed with unit expected value, the power of the channel fading is exponential with the unit variance. According to the Friis equation,

the average received power at the sensor is:

$$\lambda_s = \frac{\mathbb{E}\{Z_n^s\}}{t_\epsilon} = P_{ps}G_{ps}G_s r_{sp}^{-\alpha}(4\pi f)^{-\alpha} \min(1, \frac{rT_{ps}\lambda_p}{P_{ps}t_t}).\frac{t_t}{T_{ps}},$$
(13)

where G_{ps} is the power node's antenna gain for transmitting RF signals to the sensor and G_s is the antenna gain for the sensor's receiver.

Assume that the power node would relay the data, as soon as it receives a signal from the sensor. Therefore $T_{pb} = T_s$. However, to keep the consistency with the rest of the paper we keep the notations for T_{pb} and T_s unchanged. The outage probability from (3) can then be broken down as:

$$\mathbb{P}_{out} = \mathbb{P}\{SNR_{pb} < \Omega_{pb}|SNR_{sp} \geq \Omega_{sp}\}\mathbb{P}\{SNR_{sp} \geq \Omega_{sp}\} + \mathbb{P}\{SNR_{sp} < \Omega_{sp}\}. \quad (14)$$

The expressions for $\mathbb{P}\{SNR_{sp} < \Omega_{sp}\}$ and $\mathbb{P}\{SNR_{pb} < \Omega_{pb}|SNR_{sp} \geq \Omega_{sp}\}$ can also be broken down as follows:

$$\mathbb{P}\{SNR_{sp} < \Omega_{sp}\}$$
$$= \mathbb{P}\{SNR_{sp} < \Omega_{sp}|\mathbf{O_s} = 1\}\mathbb{P}\{\mathbf{O_s} = 1\} + \mathbb{P}\{\mathbf{O_s} = 0\}$$
$$= \mathbb{P}\left\{\frac{P_sG_{sp}\mathbf{h}_{sp}r_{sp}^{-\alpha}(4\pi f)^{-\alpha}}{P_N} < \Omega_{sp}\right\}\min(1, \frac{T_s\lambda_s}{P_st_t})$$
$$\quad + (1 - \min(1, \frac{T_s\lambda_s}{P_st_t}))$$
$$= \left(1 - \mathbb{P}\left\{\mathbf{h}_{sp} \geq \frac{P_N\Omega_{sp}r_{sp}^{\alpha}(4\pi f)^{\alpha}}{P_sG_{sp}}\right\}\right)\min(1, \frac{T_s\lambda_s}{P_st_t})$$
$$\quad + (1 - \min(1, \frac{T_s\lambda_s}{P_st_t}))$$
$$= \left(1 - \exp(-\frac{P_N\Omega_{sp}r_{sp}^{\alpha}(4\pi f)^{\alpha}}{P_sG_{sp}})\right)\min(1, \frac{T_s\lambda_s}{P_st_t})$$
$$\quad + (1 - \min(1, \frac{T_s\lambda_s}{P_st_t}))$$
$$= 1 - \min(1, \frac{T_s\lambda_s}{P_st_t})\exp(-\frac{P_N\Omega_{sp}r_{sp}^{\alpha}(4\pi f)^{\alpha}}{P_sG_{sp}}). \quad (15)$$

Similarly, we have:

$$\mathbb{P}\{SNR_{pb} < \Omega_{pb}|SNR_{sp} \geq \Omega_{sp}\}$$
$$= \mathbb{P}\{SNR_{pb} < \Omega_{pb}|SNR_{sp} \geq \Omega_{sp}, \mathbf{O_{pb}} = 1\}\mathbb{P}\{\mathbf{O_{pb}} = 1\}$$
$$\quad + \mathbb{P}\{\mathbf{O_{pb}} = 0\}$$
$$= \mathbb{P}\left\{\frac{P_{pb}G_{pb}\mathbf{h}_{pb}r_{pb}^{-\alpha}(4\pi f)^{-\alpha}}{P_N} < \Omega_{pb}\right\}$$
$$\quad \times \min(1, \frac{(1-r)T_{pb}\lambda_p}{P_{pb}t_t}) + (1 - \min(1, \frac{(1-r)T_{pb}\lambda_p}{P_{pb}t_t}))$$
$$= 1 - \min(1, \frac{(1-r)T_{pb}\lambda_p}{P_{pb}t_t})\exp(-\frac{P_N\Omega_{pb}r_{pb}^{\alpha}(4\pi f)^{\alpha}}{P_{pb}G_{pb}}). \quad (16)$$

By substituting (16) and (32) in (14), the outage probability is determined as follows:

$$
\begin{aligned}
\mathbb{P}_{out} \\
= 1 - \min(1, \frac{T_s \lambda_s}{P_s t_t}) \min(1, \frac{(1-r)T_{pb}\lambda_p}{P_{pb}t_t}) \\
\times \exp(-\frac{P_N \Omega_{sp} r_{sp}^\alpha (4\pi f)^\alpha}{P_s G_{sp}}) \exp(-\frac{P_N \Omega_{pb} r_{pb}^\alpha (4\pi f)^\alpha}{P_{pb} G_{pb}}).
\end{aligned}
\tag{17}
$$

where λ_s is also a function of r and is determined by (13).

4) MINIMIZATION OF OUTAGE PROBABILITY

In Appendix A it is shown that if the power values can be unlimitedly large, then to minimize the outage probability, we should have:

$$
\begin{cases}
\textbf{I}) \ P_{pb}t_t = (1-r)T_{pb}\lambda_p \\
\textbf{II}) \ P_{ps}t_t = rT_{ps}\lambda_p \\
\textbf{III}) \ P_s t_t = T_s \lambda_s
\end{cases}
\tag{18}
$$

Using (**III**) and (13) we have:

$$
P_s = K_1 P_{ps}
\tag{19}
$$

where $K_1 = T_s/T_{ps}G_{ps}G_s r_{sp}^{-\alpha}(4\pi f)^{-\alpha}$.

Let assume that the transmission power for the transmitters has to be limited to a maximum power of $P_{\max}$. By substituting (**I**), (**II**) and (19) in (17), the minimization problem for the outage probability can be stated as:

$$
\min_{P_{pb}, P_{ps}} \ P_{out} = 1 - \exp(\frac{-K_2}{P_{pb}}) \exp(\frac{-K_3}{K_1 P_{ps}})
$$
$$
\text{subject to } P_{ps}, \ P_{pb}, \ P_s \leq P_{\max}
\tag{20}
$$

where $K_2 = \frac{-P_N \Omega_{pb} r_{pb}^\alpha (4\pi f)^\alpha}{G_{pb}}$ and $K_3 = \frac{P_N \Omega_{sp} r_{sp}^\alpha (4\pi f)^\alpha}{G_{sp}}$.
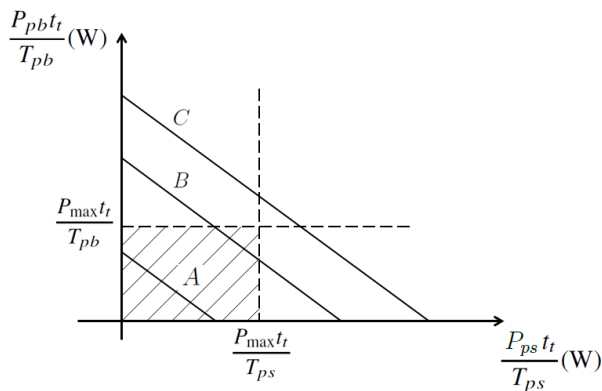

FIGURE 2. Allowable region for the optimum regions of P_{ps} and P_{ps}.

Fig. 2 shows three possible scenarios for the optimization problem, in the $P_{pb}t_t/T_{pb}$—$P_{ps}t_t/T_{ps}$ plane. Lines A to C represent three examples of the $P_{ps}t_t/T_{ps} + P_{pb}t_t/T_{pb} = \lambda_p$ constraint, which can be derived from conditions **I** and **II**, for different values of the parameters. The shaded area shows the acceptable region for the optimum power values.

When $\lambda_p < \min(P_{\max}t_t/T_{ps}, P_{\max}t_t/T_{pb})$ (case A), the optimum value will be on the constraint line. This line is entirely located within the acceptable region. To find the optimum value we have $P_{ps} = T_{ps}/t_t(\lambda_p - P_{pb}t_t/T_{pb})$. As a result P_{out} can be defined based on only one parameter. By taking the derivative and having $T_s = T_{pb}$, we have:

$$
\begin{cases}
r_{opt} = \dfrac{1}{1 + \sqrt{\dfrac{\Omega_{pb}}{\Omega_{sp}} \cdot \dfrac{G_{sp}G_{ps}G_s}{G_{pb}} \cdot (\dfrac{r_{pb}}{r_{sp}^2})^\alpha (4\pi f)^{-\alpha}}} \\
P_{pb}t_t = \lambda_p T_{pb}(1 - r_{opt}) \\
P_{ps}t_t = \lambda_p T_{ps} r_{opt} \\
P_s t_t = \dfrac{T_s}{T_{ps}} G_{ps}G_s r_{sp}^{-\alpha}(4\pi f)^{-\alpha} P_{ps}
\end{cases}
\tag{21}
$$

If $\min(P_{\max}t_t/T_{ps}, P_{\max}t_t/T_{pb}) \leq \lambda_p < P_{\max}t_t/T_{ps} + P_{\max}t_t/T_{pb}$ (case B), the optimum value is located on a constraint line that is partially in the allowed region. For this case we can first use (21) to get an initial optimum point. If $P_{pb}, P_{ps} < P_{\max}$, then the optimum values are in the acceptable region. If P_{pb} or P_{ps} are larger than $P_{\max}$, then the larger power will be set to be equal to $P_{\max}$ and the other power would be determined using $P_{ps}t_t/T_{ps} + P_{pb}t_t/T_{pb} = \lambda_p$. The logic behind this setting is that we know the optimum point has to be on the line $P_{ps}t_t/T_{ps} + P_{pb}t_t/T_{pb} = \lambda_p$. On the other hand from solving the optimization problem for case A we know we have a convex problem and there is only one optimum point on the line. As a result, when the optimum point is outside of the acceptable region, the closest point on the line within the acceptable region would be the next best choice.

The last possible scenario is when $\lambda_p \geq P_{\max}t_t/T_{ps} + P_{\max}t_t/T_{pb}$ (case C). For this case the constraint line does not have any intersection with the acceptable region. In this scenario, there is enough harvested energy available to have $P_{pb} = P_{ps} = P_{\max}$. To find the optimum region for r, from (18) it can be concluded that for all the values of r that keep both P_{pb} and P_{ps} greater than $P_{\max}$, the maximum allowed power can be assigned to the transmitters and the outage probability would be minimum and independent of the value of r. Therefore, from (**I**) and (**II**) in (18) we have $(1-r)T_{pb}\lambda_p \geq P_{\max}t_t$ and $rT_{ps}\lambda_p \geq P_{\max}t_t$. In other words, $\frac{P_{\max}}{T_{ps}\lambda_p} \leq r \leq 1 - \frac{P_{\max}}{T_{pb}\lambda_p}$.

III. MULTIPLE SENSORS SCENARIO

Multiple sensors scenario can be considered as a direct extension of the single sensor case, under the condition that nodes are not interfering with one another. To this end we assume that more than one sensor is assigned to one power node and sensors are located at different distances from the power node and work and transmit independently. It is also assumed that sensors are synchronized and use Time Devision Multiple Access (TDMA) protocol to access the channel. Therefore there is no interference. In this work we are not considering the energy consumption required to keep the sensors synchronized. Similar to the previous section, when a sensor has

a signal to transmit, the signal is transmitted using directed antennas to the power node. A power node would relay the data as soon as it receives a signal. Therefore, by considering that we have n sensors, a sensor's transmission period would be n times longer than a power node. The power node also uses directed antennas to energize the sensors. As far as the *SNR* for each sensor is concerned, this set up does not make any significant difference with the single sensor scenario. In other words, from the perspective of one sensor, we still have an interference free transmission link with the power node and the sensor is being energized periodically. However, because the power node is energizing more than one sensor, the period at which each sensor receives the energy signal would be longer and proportional to the number of sensors.

In Appendix B we show that the optimum value for r would approximately be:

$$r_{opt} \approx \cfrac{1}{1 + \sqrt{\cfrac{\Omega_{pb}}{\Omega_{sp}} \cdot \cfrac{G_{sp}G_{ps}G_s}{G_{pb}} \cdot (4\pi f)^{-\alpha} \cdot \cfrac{nr_{pb}^{\alpha}}{\sum_{i=1}^{n} r_{s_ip}^{2\alpha}/\sigma_i}}} \quad (22)$$

where n is the number of the sensors and r_{s_ip} is the distance between the sensor s_i and the power node. Finally, similar to the single sensor scenario, assuming that all the channels are Rayleigh distributed, the power of the channel fading is exponential and the variance is assumed to be σ_i^2.

By having the optimum value for r, other parameters can be computed similar to (18). Therefore we would have:

$$\begin{cases} P_{pb}t_t = \lambda_p T_{pb}(1 - r_{opt}) \\ P_{ps}t_t = \lambda_p T_{ps}r_{opt} \\ P_{s_i}t_t = T_s\lambda_{s_i} \end{cases} \quad (23)$$

where λ_{s_i} is:

$$\lambda_{s_i} = \cfrac{\mathbb{E}\left\{Z_n^{s_i}\right\}}{t_\epsilon}$$
$$= \sigma_i P_{ps}G_{ps}G_s r_{s_ip}^{-\alpha}(4\pi f)^{-\alpha} \min(1, \cfrac{rT_{ps}\lambda_p}{P_{ps}t_t}).\cfrac{t_t}{nT_{ps}} \quad (24)$$

Note that in this setting P_{ps} is not being adjusted for each sensor individually. The value of P_s however, is both a function of its distance from the power node and also the channel in between. Moreover, if the optimum powers are larger than the maximum allowed power, a similar process as the single sensor case will be carried out. With the only difference that λ_{s_i}, and therefore P_{s_i} would be adjusted for each sensor individually.

IV. SIMULATION RESULTS

In the proposed simulation setup for the single-sensor single-power node case, the distances between power node and sensor node and power node and base node are assumed to be 4m and 10m respectively. These distances are chosen based on the size of a regular transformer and the distance between the transformers and the base in a typical substation like the one that is studied in [26]. The thresholds of the acceptable SNR at the receivers are assumed to be $\Omega_{sp} = \Omega_{pb} = 1$.

The transmission periods from sensor to the power node and from the power node to the base are $T_s = T_{pb} = 10$ minute, while the transmission period at which the power node energizes the sensor is $T_{ps} = 1$s. To reduce the transmission loss, directed antennas are used. All the transmission gains are assumed to be $G_{ps} = G_{sp} = G_{pb} = 10$. The maximum transmission power is $P_{\max} = 0.3$W. As a result the transmission power multiplied by the antenna gain would not exceed $3\,W$. The receiver's gain is $G_s = 2$. The energy harvester is located on top of a transformer, close to high voltage terminal. From [27] the electric field around a high voltage terminal can be considered to be around 1.5×10^4 V/m. The amount of the harvested energy is computed based on the formulation from [27], with the following parameters: the volume of the energy harvester is assumed to be 0.4m^3, the number of switching cycles and the energy consumed by switches per cycle similar to [27] are $N = 100$ and $w_s = 100$nJ respectively. Therefore, the amount of the average harvested power would be around $\lambda_p = 0.04$W. Finally, the assigned transmission powers are adjusted according to the results of Section II. The above settings would be fall under case *B* and the optimum values are adjusted as $P_s = 30$mW, $P_{ps} = 40$mW and $P_{pb} = 0.3$W.

Fig. 3 represents the outage probability for two values of the propagation loss exponent, as a function of the noise power. As it can be observed for a long range of the noise power, the outage probability remains relatively small.
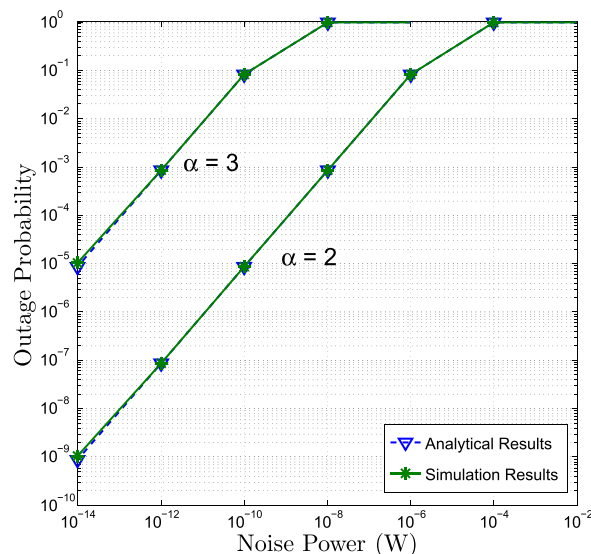
FIGURE 3. The outage probability for different values of the propagation loss exponent, with respect to the noise power (single sensor scenario).

Fig. 4 evaluate the performance of the system for different data transmission periods. As it is explained above, the power node relays the information to the base node as soon as it receives a signal from the sensor. Therefore $T_{pb} = T_s$. The frequency at which a sensor needs to transmit to the power node however, varies for different applications. We should note that there is a limit on the maximum power value which
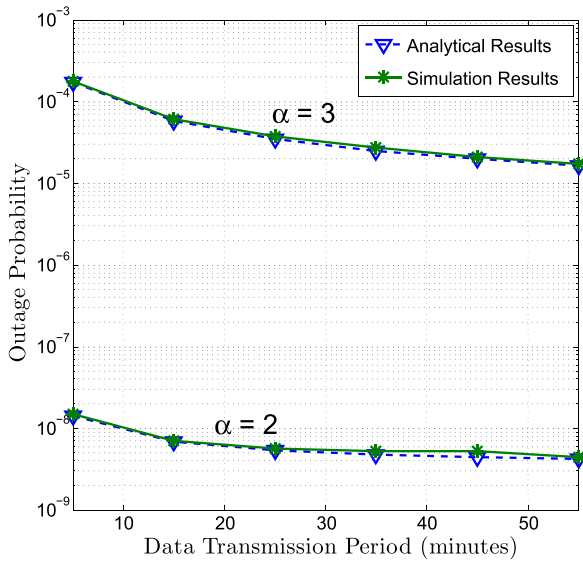
FIGURE 4. The outage probability for different data transmission periods (single sensor case).
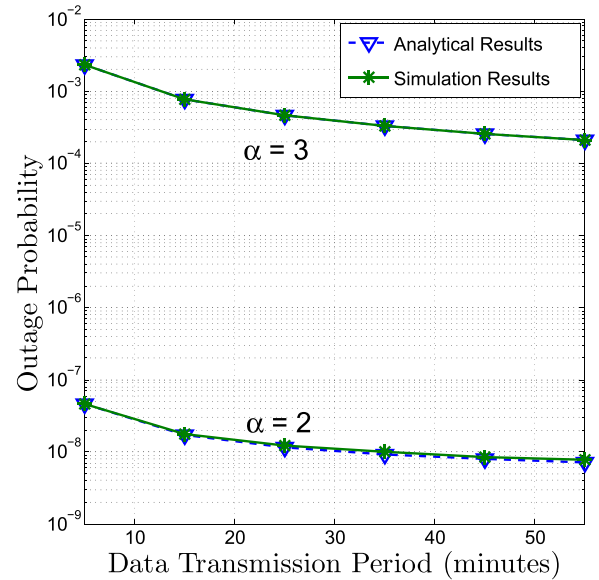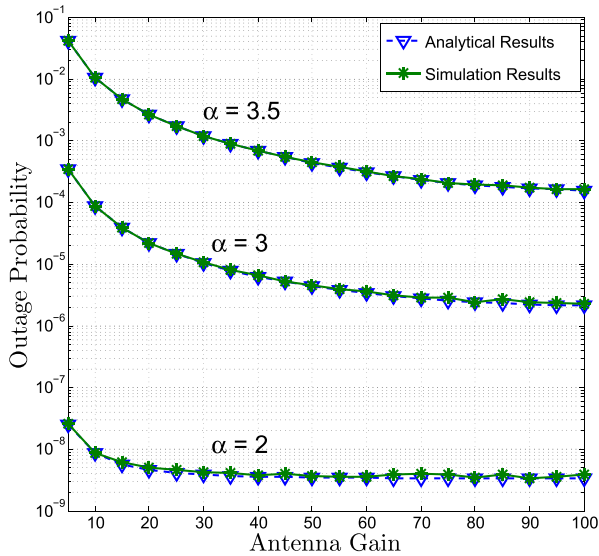

FIGURE 5. The outage probability for different values of antenna gains (single sensor case).

can be assigned to the nodes ($P_{max} = 0.3$W). Therefore, increasing the transmission period would not decrease the outage probability when all the nodes receive the maximum allowed values.

Fig. 5 shows the outage probability for different transmitters' antenna gains. Similar to the previous figures, it is assumed that $G_{pb} = G_{ps} = G_{sp} = G$. The noise power is $P_N = 10^{-13}$W. The maximum transmission power is assumed to be $P_{max} = \frac{3}{G}$Watts. Therefore $P_{max} \times G$ would not exceed 3W. Increasing the antenna gain makes nodes to be able to reach to the maximum transmission power for a fixed value of λ_p. However, similar to Fig. 4, when nodes reach to the maximum transmission power, increasing the antenna gain would not improve the outage probability anymore.

FIGURE 6. The outage probability for different data transmission periods (multiple sensors scenario).

Fig. 6 shows the outage probability for the multiple sensors scenario. It is assumed that 5 sensors are surrounding the power node. The distances between sensors and the power node is assumed to be [4, 8, 2, 5, 2]m. Following Section III, a power node would relay the information to the base node as soon as it receives a signal from a sensor. Therefore, $T_s = 5 T_{pb} = 5 T_{data}$. Note that although the number of the sensors are increased and as a result each sensors receives less power from the power node, but sensors are also transmitting to the power node 5 times slower. This setup allows us to have a fair comparison with the single sensor scenario. In other words, if all the sensors were located 4m away from the power node, the performance of the system would be exactly the same as Fig. 4.

V. CONCLUSION
In this work we studied the possibility of deploying a self sustainable WSN by harvesting the alternating electric field around HV devices. A hierarchical energy harvesting model was proposed. The proposed model allowed us to address the issue of non-uniform availability of the electric field in a substation area. The main focus of this paper was on single sensor scenario where only one sensor is being energized by the power node. Multiple sensors scenario was briefly discussed by considering a network where all the sensors are synchronized. A more elaborate study on multiple sensors scenario will be conducted in future works by considering other channel accessing protocols, the interference effect, data aggregation and clustering methods.

APPENDIX A
Consider the following function:

$$f(x) = \min(1, \frac{c_1}{x}) \exp(\frac{-c_2}{x}) = \begin{cases} e^{\frac{-c_2}{x}} & 0 < x \le c_1 \\ \frac{c_1}{x} e^{\frac{-c_2}{x}} & x > c_1. \end{cases}$$

Since $e^{\frac{-c_2}{x}}$ is an absolutely increasing function, for $0 < x \le c_1$, $x = c_1$ maximizes $f(x)$. on the other hand, $\frac{c_1}{x} e^{\frac{-c_2}{x}}$ has a maximum value at $x = c_2$ and then decreases monotonically. Therefore, if $c_2 \le c_1$, the maximum value for $f(x)$ still occurs at $x = c_1$.

The outage probability from (17) can be written as:

$$\mathbb{P}_{out} = 1 - \min(1, \frac{c_1}{P_s}) \exp(-\frac{c_2}{P_s}) \min(1, \frac{c_3}{P_{pb}}) \exp(-\frac{c_4}{P_{pb}}). \quad (25)$$

In practice, by considering the order of the numbers for variables, it is safe to assume that $c_2 < c_1$ and $c_4 < c_3$. To minimize the outage probability, we assume that the aforementioned inequalities are held. However, if for some initial settings these inequalities cannot be held, a very similar process can be carried out to find the new optimum values.

By comparing (25) and (17) we have:

$$P_s t_t = T_s \lambda_s \quad (26)$$

and

$$P_{pb} t_t = (1 - r) T_{pb} \lambda_p \quad (27)$$

$\frac{P_{pb} t_t}{T_{pb}}$ represents that at the time unit of t_t, how much power needs to be assigned for transmitting to the base node. By considering the fact that the harvested energy at the power node is divided by a ratio of r to energize the sensor or communicate with the base, it can be concluded that $\frac{P_{ps} t_t}{T_{ps}} = r\lambda_p$, or:

$$P_{ps} t_t = r T_{ps} \lambda_p \quad (28)$$

By substituting the above expressions for the powers in (17) and taking the derivative, the optimum value for r, for the case that the power values can be unlimitedly large is found as:

$$r_{opt} = \cfrac{1}{1 + \sqrt{\frac{\Omega_{pb}}{\Omega_{sp}} \cdot \frac{G_{sp} G_{ps} G_s}{G_{pb}} \cdot (\frac{r_{pb}}{r_{sp}^2})^\alpha (4\pi f)^{-\alpha}}} \quad (29)$$

where $T_s = T_{pb}$ cancel each other out.

APPENDIX B
Since $T_s = n.T_{pb}$ and all the transmission lines are independent, its possible to evaluate the overall performance of the system as n independent systems, corresponding to each sensor. We assume that all the channels are Rayleigh distributed. Therefore the power of the fading channel is exponential with some variance that we represent by σ_i. The harvested power by sensor s_i would be:

$$\lambda_{s_i} = \frac{\mathbb{E}\{Z_n^{s_i}\}}{t_\epsilon}$$
$$= \sigma_i P_{ps} G_{ps} G_s r_{sip}^{-\alpha} (4\pi f)^{-\alpha} \min(1, \frac{r T_{ps} \lambda_p}{P_{ps} t_t}) . \frac{t_t}{n T_{ps}} \quad (30)$$

The outage probability, just from the perspective of the sensor s_i is:

$$\mathbb{P}_{out}^{s_i} = \mathbb{P}\{SNR_{pb} < \Omega_{pb} | SNR_{sip} \ge \Omega_{sp}\} \mathbb{P}\{SNR_{sip} \ge \Omega_{sp}\}$$
$$+ \mathbb{P}\{SNR_{sip} < \Omega_{sp}\}. \quad (31)$$

Similar to the single sensor scenario, it can be shown $\mathbb{P}\{SNR_{sip} < \Omega_{sp}\}$ is:

$$\mathbb{P}\{SNR_{sip} < \Omega_{sp}\}$$
$$= 1 - \min(1, \frac{T_s \lambda_{s_i}}{P_{s_i} t_t}) \exp(-\frac{P_N \Omega_{sp} (4\pi f)^\alpha r_{sip}^\alpha}{P_{s_i} G_{sp} \sigma_i}). \quad (32)$$

The outage probability from power node to the base would be similar to (16). Therefore, the outage probability for the sensor s_i would be:

$$\mathbb{P}_{out}^{s_i} = 1 - \min(1, \frac{T_s \lambda_{s_i}}{P_{s_i} t_t}) \min(1, \frac{(1-r) T_{pb} \lambda_p}{P_{pb} t_t})$$
$$\times \exp(-\frac{P_N \Omega_{sp} (4\pi f)^\alpha r_{sip}^\alpha}{P_{s_i} G_{sp} \sigma_i}) \exp(-\frac{P_N \Omega_{pb} (4\pi f)^\alpha r_{pb}^\alpha}{P_{pb} G_{pb}}). \quad (33)$$

Similar axioms to (18) is used to minimize the above expression.

In order to find the optimum value for r, we have the overall outage probability as:

$$\mathbb{P}_{out} = \frac{1}{n} \sum_{i=1}^{n} \mathbb{P}_{out}^{s_i} \quad (34)$$

By having λ_{s_i} from (30) and $P_{ps} = r T_{ps} \lambda_p / t_t$, $\mathbb{P}_{out}$ can be expressed only as a function of r. Unlike single sensor case, taking the derivative of $\mathbb{P}_{out}$ respect to r cannot be solved in closed form. However, we know that for the optimum value of r which minimizes $\mathbb{P}_{out}$, $\exp(\cdot)$ would be very close to 1. Therefore, after taking derivative, by assuming $\exp(\cdot) \approx 1$ and by considering that $T_s = n T_{pb}$, the optimum value for r can be estimated as:

$$r_{opt} \approx \cfrac{1}{1 + \sqrt{\frac{\Omega_{pb}}{\Omega_{sp}} \cdot \frac{G_{sp} G_{ps} G_s}{G_{pb}} . (4\pi f)^{-\alpha} . \frac{n r_{pb}^\alpha}{\sum_{i=1}^{n} r_{sip}^{2\alpha}/\sigma_i}}} \quad (35)$$

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