# Assessing the cost of RF-power harvesting nodes in Wireless Sensor Networks

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## Abstract

Wireless sensor networks (WSNs) consist of nodes with limited power resources. A potential method to prolong the lifespan of a node is the use of an antenna which can harvest energy from radio frequency (RF) signals. In this paper, we model a network consisting of nodes with energy harvesting capabilities and a number of dedicated energy transmitters (ETs) which send data to the nodes. We identify those parameters which affect the consumption of the nodes and we design a method to achieve multi-hop energy transfer between the nodes. However, the ultimate purpose of this paper is to examine whether the cost of the investment of using energy harvesting nodes can be covered by achieving a lower operation cost; that is longer operation times and, thus, less frequent maintenance. We consider three scenarios with different node densities and transmitter populations. Simulation results show that the use of RF-energy harvesting nodes can save a significant amount of energy, while the cost of the investment can be covered in less than 8 years for dense networks.

## 1 Introduction

Wireless sensor networks are capable of periodically monitoring their vicinity and reporting important information about the integrity and security of their environment. The sensor nodes are powered by batteries and depending on how often they take measurements and communicate with other devices, their energy may be depleted fast. The replacement of the battery may be a hard task since the nodes are often positioned in inaccessible places or the cost of replacement may be high.

To tackle this problem, a new technology has been recently developed by harvesting energy from the transmitted RF signals. This technology uses a new type of antenna which can convert part of the received signal power to electricity. Depending on the transmitted power and the distance between the transmitting source and the receiver, a node can harvest from some uW to some mW of power [5]. However, this technology is still new and presents some major limitations mainly due to the low efficiency of the conversion unit [9]. First, the harvested power dramatically decreases when the receiver is moving more than few meters away from the source. Second, the conversion efficiency is substantial only for a small range of distance, and third, there is a minimum received signal power, below which no conversion is possible.

Taking into account these limitations, we model a network consisting of nodes which can acquire energy from a set of ETs. The ETs are placed at fixed positions and omnidirectionally transmit fake data to the network. We divide the time in rounds and every round includes two phases. The first phase allows the transmission of sensing data while the second phase is used for fake data transmission during which the nodes get recharged. The reason of having two separate phases is to avoid interference between sensing and fake data transmissions. We compute the theoretical maximum allowed number of fake transmissions during a round and we account the performance gains in terms of energy savings. Nodes that are close to the ET present the highest energy gains. These nodes usually harvest more energy than they consume, thus, we design a method to spend this extra energy by transmitting extra fake messages to the network. This action, known as multi-hop energy transfer, can extend the energy transfer range beyond the borders of the harvesting distance between the transmitters and their one-hop nodes. We show that due to the current hardware limitations the performance gain is very limited for average or high distances.

In this paper, we give another dimension to our problem by computing the capital and the operating expenditures of deploying and maintaining an RF-power harvesting network. Taking into consideration the extra cost of the harvesting units, the cost of ETs, the cost of electricity, as well as the labor cost of maintaining a WSN, we introduce the "Minimum Reimbursement Time" problem. In this problem, we assess the time needed to cover the investment cost by the reduced maintenance cost of a harvesting network. Since the maintenance cost is strongly connected with the network density, we examine three scenarios with different node populations. Extended simulation results are presented.

The contribution of this paper is threefold. First, we design a network consisting of RF-energy harvesting nodes and ETs. We present the theoretical background and the limitations of the approach. Second, we propose a method to use multi-hop energy transfer in the network, and third, we introduce the “Minimum Reimbursement Time” problem where we investigate whether the cost of the investment can be covered by the reduced operating costs.

# 2 Related work

In the last few years there is an increased research effort for energy harvesting technologies due to the increased demand of power resources. The work of Basagni et al. [1] surveys all these technologies presenting their advantages and disadvantages. In this paper we focus on RF-power harvesting which is frequently met in an indoor or outdoor environment since, nowadays, plenty of devices operate wirelessly, like television broadcasting, cell phones, Internet equipment etc..

RF-energy harvesting networks have been extensively studied from different research aspects. For a complete literature review the reader can refer to [9] and [2]. We cite, here, some categories of recent research activities closer to our work.

The first category includes works which deal with the circuit design and their main challenge is to improve the RF-to-DC efficiency of the harvesting devices. Current harvester implementations achieve a maximum efficiency of 80-85% but it falls bellow 5-10% as the receiver moves away from the source [14]. However, despite the current low conversion efficiency of RF-energy harvesting units, there is still much room for improvement using better materials and new MAC layer protocols [10].

Another group of works focuses on throughput fairness and scheduling problems. The scope of these articles is to provide solutions to efficiently schedule the access to the medium in order to meet specific QoS criteria, like throughput, delay and packet loss [4, 7, 8]. These works usually consider a number of dedicated transmitters which are actually playing the role of the access-point at the same time.

Finally, a promising method to extend the energy harvesting range is the use of multi-hop energy transfer [6, 11]. In [6], two-hop energy transfer has been experimentally tested. The findings show that the optimal position for maximizing the performance gain has been found to be when the intermediate node is closer to the source. In [11], sparse and dense network deployment cases are tested. The results show an average 2-hop performance gain of 6% to 12%. However, both experiments use devices very close to each other.

# 3 System architecture

## 3.1 Energy harvesting model

The network consists of $n$ wireless sensor nodes which can be equipped with an extra RF module capable of harvesting power from transmitted signals. A number of ETs with omni-directional antenna and fixed positions are used to send fake packets to the network and recharge the nodes.

The amount of power each node receives is affected by its distance to the transmission source and the environmental conditions. Eq. (1) describes the total energy harvested by a node $i$ surrounded by $T$ energy transmitters.

$$E_{h_i} = \int_0^\infty \sum_{j=1}^{T} P_{rx}^{d_{ij}} f^{d_{ij}} \frac{ps \cdot k'}{dr} dt, \tag{1}$$

where $P_{rx}^{d_{ij}}$ is the received power, $f^{d_{ij}}$ is the efficiency of the harvesting antenna at distance $d_{ij}$, $ps$ is the packet size, $k'$ is the number of fake packets transmitted per time unit and $dr$ is the transmission data rate.

The received power at distance $d$ is given by the following propagation model [15]:

$$P_{rx}^{d} = P_0 \frac{e^{2\sigma G}}{d^{2b}}, \tag{2}$$

where $e^{2\sigma G}$ has a log-normal distribution with a shadowing coefficient $\sigma$ ($G \sim N(0,1)$). The term $1/d^{2b}$ accounts for the far-field path loss with distance $d$, where the amplitude loss exponent $b$ is environment-dependent. $P_0$ is the received power at reference distance of 1 meter and is computed by Friis equation:

$$P_0 = P'_{tx} G_T G_R \left(\frac{\lambda}{4\pi 1}\right)^{2b}. \tag{3}$$

$P'_{tx}$ is the transmitted power of the ETs, $G_T$ and $G_R$ are the antenna gains, $\lambda$ is the wave length and $\rho$ is the reference distance.

From the equations we have so far we can observe that the harvested energy depends on the distance between the nodes and the transmission source as well as on the transmission time. However, another factor which strongly influences the harvested power is the efficiency of the harvesting module. For example, the best efficiency of Powercast's commercial RF-harvesting module is achieved when the input power is around 4mW (i.e., less than 1 meter distance). Consequently, positioning the nodes in that way so that the best efficiency is achieved, is an important task in RF-energy harvesting WSNs.

## 3.2 Communication model

The ETs send fake packets to the network to decrease their energy consumption. Apparently, the more the packets the higher the energy gain. However, a very high packet rate could cause network problems like interference, collisions and delays. For this reason, we split the transmission time in rounds where each round has two phases (see Figure 1). During the first phase, named "Sensing data phase", the nodes communicate with the sink and transmit their sensing data. We allow two or more nodes transmitting at the same time, unless they are in the communication range of each other. We, also, assume a fair resource allocation model where all the nodes have the same opportunity to access the network. In the second phase, named "Fake data phase", we allow the transmission of fake packets. All the stations can transmit packets at the same time during this phase. The higher the rate of fake packets the longer the "Fake data phase". If the two phases overlap each other, a number of nodes will interfere with the stations.

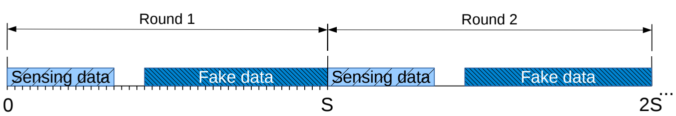


Figure 1: Transmission slots, phases and rounds.

The transmission time is divided in $S$ slots and we allow only one transmission per slot within the vicinity of a single node to avoid interference. We assume that the nodes are well synchronized using a precise time synchronization protocol [13]. Each time a node is ready to transmit a packet it switches to active mode while it remains in sleep mode if it is not transmitting. In sleep mode a node consumes much less energy but it can still harvest energy from the RF-harvesting antenna.

As a consequence, the number of data transmissions during the "Sensing data phase" determines the maximum number of fake packet transmissions. Assuming a time period equal to one round and $k$ packet transmissions per round, it holds that:

$$\frac{ps}{dr}(k(N_{max}+1)+k') \leq \tau, \tag{4}$$

where $N_{max}$ is the maximum number of neighbors among the nodes in the network and $\tau$ is the duration of the round. The higher the node density, the higher the number of neighbors and the lower the maximum possible transmissions of fake packets.

### 3.3 Multiple-hop energy transfer

Since some nodes which are very close to the stations may absorb more energy than they consume, we allow them to spend this extra amount of energy by transmitting some extra fake packets to their neighbors. In this way, we aim to extend the harvesting zone beyond the current harvesting range of the stations. In fact, a node plays the role of the energy relay between the ET and its neighbors. All these extra transmissions take part during the second phase of a round. A node $i$ can send fake packets within a round of $\tau$ time units if the following condition holds:

$$E_{extra_i} l(\delta t) \geq P'_{tx}\frac{ps}{dr}, \tag{5}$$

where,

$$E_{extra_i} = \int_0^\tau dt \left( \sum_{j=1}^{T} P_{rx}^{d_{ij}} f^{d_{ij}} \frac{ps \cdot k'}{dr} - P_{tx}\frac{ps \cdot k}{dr} \right) - E_{rest}. \tag{6}$$

$P_{tx}$ is the transmitted power of the nodes (for sensing data) and $E_{rest}$ is the energy cost for the rest of operations. $l(\delta t)$ is a function which describes the energy loss due to discharge properties of the capacitor [3]. $\delta t$ is the time between two recharges.

Condition (5) ensures that the extra energy is higher than the energy cost of sending at least one packet. The total number of fake packets that is sent (i.e., $K_i$) depends on how much energy a node harvests during the "Fake data phase" and it is given by Eq. (7). In order to technically achieve multi-hop recharges, we assume that the extra amount of energy is stored in a super-capacitor and it is used when the capacitor and the node battery energy levels are above a threshold.

$$K_i = \left\lfloor E_{extra_i} l(dt) \frac{dr}{ps\ P'_{tx}} \right\rfloor. \tag{7}$$

## 4 The minimum reimbursement time problem

In this section we formulate the minimum reimbursement time (MRT) problem as a function of the capital expenditures (CAPEX) and operating expenses (OPEX). MRT is a minimization problem of the time needed to cover the investment cost of deploying a WSN with harvesting capabilities.

Specifically, the CAPEX and the OPEX of deploying and maintaining a WSN with and without harvesting is compared. For each deployment, notated with $D$, we optimize MRT by minimizing the "Reimbursement Ratio (RR)" as follows:

$$RR(D) = \min\left(\frac{CAPEX_D^{wh} - CAPEX_D^{woh}}{OPEX_D^{woh} - OPEX_D^{wh}}\right),$$

$s.t.$

$$CAPEX_D^{woh} = n(C_{nd} + C_b), \tag{8}$$
$$CAPEX_D^{wh} = n(C_{nd} + C_{rb} + C_{hu}) + T \cdot C_{st}, \tag{9}$$
$$OPEX_D^{woh} = n(C_{mnt} + C_b), \tag{10}$$
$$OPEX_D^{wh} = p(C_{mnt} + C_{rb}) + C_{el},\ p \leq n, \tag{11}$$
$$C_{mnt} = t_{mnt} C_{mh}, \tag{12}$$
$$C_{el} = T(C_{el_b} t_{el_b} + C_{el_r} t_{el_r}) \frac{P'_{tx} ps\ k'}{dr}, \tag{13}$$
$$OPEX_D^{woh} > OPEX_D^{wh}, \tag{14}$$

where $wh$ and $woh$ stand for "with harvesting" and "without harvesting" respectively. All the individual costs and times are defined in Table 1. In fact, $RR(D)$ determines how much time is needed to cover the extra CAPEX with a reduced OPEX. The higher the difference between the two OPEX's the shorter the time of reimbursement.

Table 1: Costs and times that affect CAPEX and OPEX.

| Cost/Time | Definition |
|---|---|
| $C_{nd}$ | node cost |
| $C_b$ | battery cost |
| $C_{rb}$ | rechargeable battery cost |
| $C_{hu}$ | harvesting unit cost |
| $C_{st}$ | energy transmitter cost |
| $C_{mnt}$ | maintenance cost to replace a battery |
| $t_{mnt}$ | time to replace a battery |
| $C_{mh}$ | man-hour cost |
| $C_{el}$ | electricity cost of the stations |
| $C_{el_b}$ | electricity cost in peak hours |
| $C_{el_r}$ | electricity cost in off-peak hours |
| $t_{el_b}$ | number of peak hours |
| $t_{el_r}$ | number of off-peak hours |

The CAPEX includes the cost of the nodes (with or without a harvesting unit), the batteries (rechargeable or not) and the ETs. On the other hand, the OPEX consists of the spare battery cost, the maintenance cost by a technician and the electricity cost of the stations in case of harvesting. The electricity cost depends on the packet rate of the stations and it is divided in the cost during the peak hours of the day and the cost during the off-peak hours of the day (typically during the night). In this work, we assume that the packet rate remains the same during the peak and off-peak hours. The maintenance cost depends on how much time a technician spends to replace the battery and the man-hour cost.

OPEX with harvesting is affected by the number of nodes that need maintenance (i.e., $p$). The higher the harvested energy, the lower the $p$ and the operating costs. In other words, $p$ strongly depends on the maximum fake data packet rate described by Eq. (4). On the other hand, a higher fake data rate increases the electricity cost. Hence, the MRT problem is transformed to a problem of finding a trade-off between electricity and maintenance cost.

# 5 Evaluating RF-energy harvesting network scenarios

## 5.1 Evaluation methodology

In this section we evaluate the proposed model by presenting theoretical and simulation results. We assume three types of scenarios with 256, 100, and 36 nodes respectively. We call the three scenarios, "Dense", "Normal", and "Sparse" respectively. The nodes as well as the transmitters are placed on a square grid-based terrain of 50 meters side. We assume that the transmitters are located at a slightly different level to the rest of the nodes to avoid blocking and shadow loss effects [10]. We, also, vary the number of ETs from 2 to 8. Regarding the node and ET characteristics, we consider the following values: $P_{tx} = 65mW$, $ps = 127bytes$, $dr = 250Kbps$, $k = 1/30$, $P'_{tx}G_T = 3W$ (EIRP), $P_{rest} = 0.15mW$, $G_R = 6dBi$, $\lambda = 0.3279m$, $\sigma = 1$, and $b = 1$. $R_c = 30m$ and $R'_c = 100m$ are the transmission ranges of the nodes and stations, respectively. 5% energy loss between recharges is considered. Node parameters correspond to Mica2 sensor nodes [12] using a Zigbee communication module at 915MHz. Regarding the harvesting efficiency we used the values provided by Powercast for P2110B model (version 1.1) operating at the same frequency. The values used for the propagation/shadowing model correspond to indoor communication only.

Due to the presence of random values, we run each instance 100 times and the average results are presented. The 95% confidence intervals are, also, shown when it is necessary.

## 5.2 Theoretical & simulation results

In this section, we present the theoretical upper bounds of the fake packet rate and the maximum number of multihop transmissions as well as simulation results of the average energy consumption with and without harvesting.

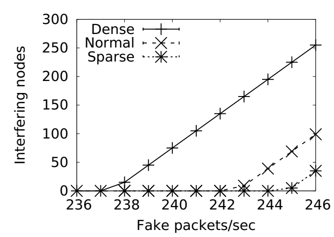


Figure 2: Interfering nodes in relation with the number of fake packets/sec.

As it is described in Eq. (4) the maximum possible number of fake packet transmissions depends on the density of the nodes. If we exceed this number, some nodes may interfere with the stations and consume more energy. Figure 2 shows the number of interfering nodes for the three scenarios (dense, normal, sparse) and 4 ETs. The upper limit of fake packets is 237, 242 and 244 packets per second for the dense, normal and sparse scenario respectively. We must, also, mention that the number of stations does not affect the number of interfering nodes since multiple stations can transmit at the same time.

Figure 3 presents the theoretical number of packets

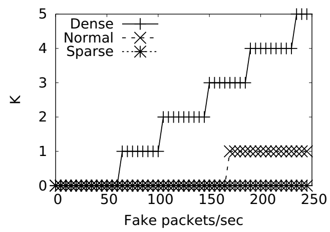


Figure 3: Number of multi-hop packets for different node distances.

transmitted by a node which is located at different positions. The results obtained using (7) with a single ET and show that the number of multi-hop packets is limited when the distance between the nodes is high and it could only slightly affect the overall performance. We must, also, mention that the gain is even less considering blocking-loss effects between the nodes.

Figure 4 shows the percentage of nodes having a consumption lower than $X\%$ of the energy cost without harvesting. $X$ varies, here, from 0 to 100% with an increment of 25%. 0% means that a node consumes no energy and 100% means that it cannot harvest any energy. We can observe that increasing the node density, (i.e., increasing the amount of nodes in transmitters range), we achieve lower energy consumption in the network and less nodes that need maintenance. More specifically, more than half of the nodes do not consume any energy for all the three scenarios. The other half has an energy consumption of about 25-75% of the maximum, while all the nodes have a lower consumption level than the maximum one.

Figure 5 depicts the position of the nodes (dots), the position of the stations (X's) as well as the nodes consumption during a single round (color). A scenario with 100 nodes is considered. Each plot corresponds to 2, 4 and 8 ETs respectively. The theoretical maximum number of fake packets is used. We can see that nodes close to the stations have a very low or even zero consumption. On the contrary, nodes close to the borders of the terrain or nodes far from the stations exhibit the highest consumption since they do not harvest almost any energy.

# 6 Assessing capital and operating costs

In order to evaluate OPEX and CAPEX, the following values are used for the parameters of Table 1. All the costs are in Euros. $C_{nd}$=50[1], $C_b$=1, $C_{rb}$=1.5, $C_{hu}$=30, $C_{st}$=100[2], $t_{mnt}$=10 min[3], $C_{mh}$=35[4], $C_{el_b}$=0.1636 per KWh, $C_{el_b}$=0.1150 per KWh, $t_{el_b}$=16h, and $t_{el_r}$=8h[5].

In this section, we assume that the battery capacity is enough to provide power to a node for one year without harvesting. We consider that a technician maintains the network every 6 months after the first year. When harvesting is used, some nodes may last for 1, 2 or more years, which means that different number of nodes is maintained every six months. For example, in the first year, all the batteries which cannot last more than 1.5 years are replaced. The second maintenance includes the replacement of the batteries which cannot last 6 months more and so on. However, batteries replaced after the first year, will still need to be replaced again during the next maintenances. We keep track of battery replacements within the first 4 years and we compute the expenses per maintenance visit as well as the average results within these 4 years.

Figure 6 presents the OPEX of the first maintenance when 4 ETs are used. For the dense scenario, we see that the best result is achieved when approximately 170 packets/sec are transmitted. At that point, the OPEX with harvesting is almost 3 times lower than the cost without harvesting. In the second scenario, the cost presents a zig-zag shape which is explained as follows. As the packet rate increases more and more nodes save more energy. It means that at certain levels of packet rate an amount of nodes lying on the same distance away from the stations will have enough energy to operate more than 1.5 years and, thus, the OPEX massively decreases. In the meantime between these specific levels of packet rate, the OPEX slightly increases due to the increased electricity cost. The combination of the reduction of the consumption and the increase of the electricity cost causes the zig-zag effect. Concerning the sparse scenario, the OPEX with harvesting hardly exceeds the OPEX without harvesting, which means that the CAPEX will take long time to be covered.

The average results of the three scenarios for all station populations are displayed on Figure 7. The best packet rate instance is used to compute the reimbursement ratio (RR) for different transmitter populations. The results show that for the dense scenario, the more the ETs the better the ratio. For the normal scenario, the best performance is achieved when four stations are deployed. Finally, for the sparse scenario, the RR is very high and more than 20 years are needed to get back the cost of the investment. The general rule derived from the examined scenarios is that the higher the density, the better the performance, thus, the shorter the reimbursement time.

[1] Approximate TelosB node price for a big bulk order.

[2] The prices provided by http://www.mouser.fr/

[3] Approximate average time to unscrew the node box, change the battery, screw the box back and move to the next node.

[4] Approximate man-hour labor cost in France as provided by Eurostat.

[5] The values are available on EDF website.

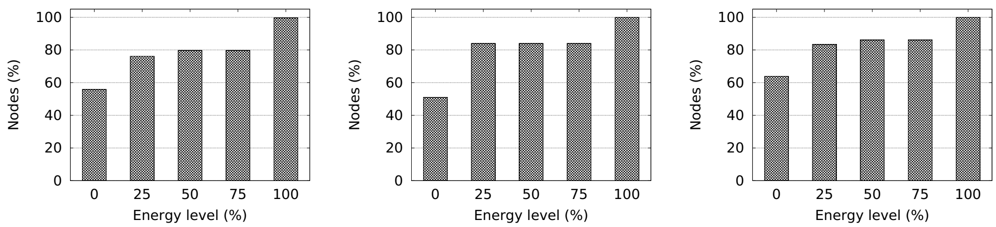


Figure 4: Percentage of nodes with X% of the maximum energy consumption for the dense, normal and sparse scenario respectively (4 ETs are used)

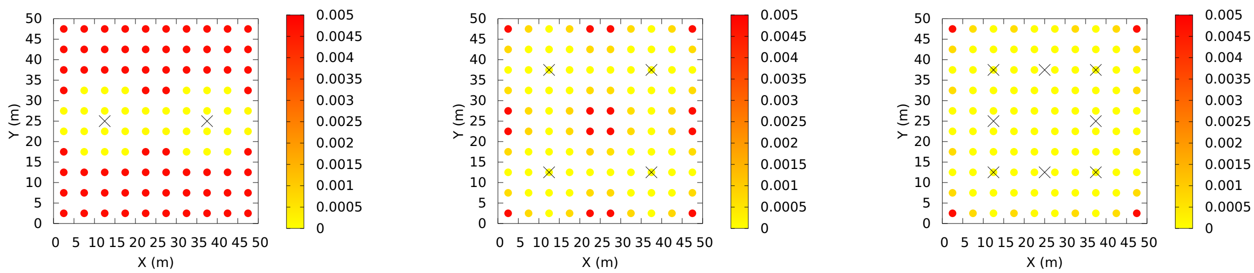


Figure 5: A grid with 100 nodes and 2, 4, or 8 ETs respectively.

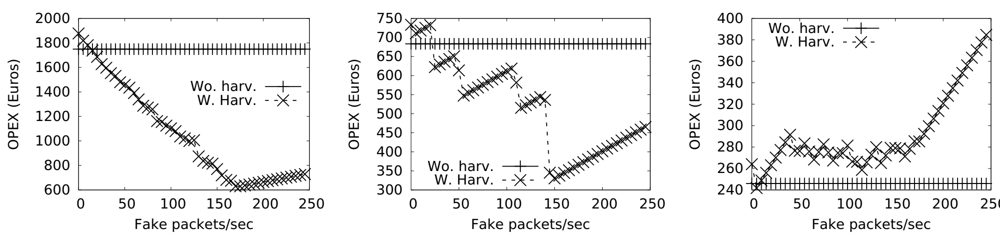


Figure 6: OPEX of the first year in relation with the number of fake packets/sec for the dense, normal and sparse scenario respectively (4 ETs are used).

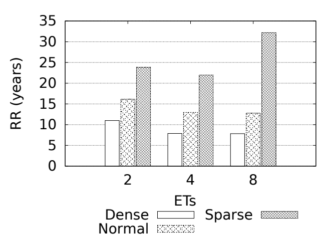


Figure 7: RR over the best packet rate instance (the lower the better).

# 7 Discussion

In this section we discuss the outcomes of this research and we suggest solutions to further decrease the deployment or operation costs and, thus, the reimbursement time.

The scenarios exploited during our simulations had a density ratio of 0.1024, 0.04 and 0.0144 nodes per $m^2$ for the "Dense", "Normal" and "Sparse" scenario respectively. However, there are applications presenting or requiring much higher network density (e.g. agricultural applications) or in case of a random placement the density can be locally high. Considering that the operating cost reduces with the increase of the density, the reimbursement time in those applications can be much lower. Figure 8 depicts the Reimbursement Ratio of a scenario with a density ratio of 1 and a minimum RR equal to 5.2 years.

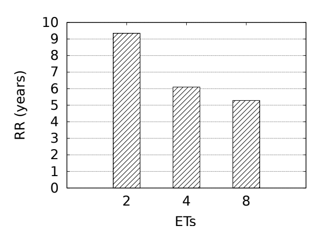


Figure 8: RR over the best packet rate instance for a very dense scenario.

Moreover, since the distance between the nodes and the transmitters plays an important role in network performance, optimizing the position of the transmitters can lead to better performance and lower operating cost. The optimization of the number of the transmitters should be considered as well.

As we can see from Figure 5, the nodes close to the borders of the terrain cannot harvest any energy or this energy is not enough to postpone their actual maintenance schedule. This implies that the extra cost of deploying a harvesting unit for those nodes can be saved improving the reimbursement ratio.

Finally, since the lifetime of the nodes varies depending on how much energy they absorb, the maintenances can be scheduled in that way, so that the minimum number of nodes is maintained each time. One way to achieve this is to increase the frequency of the maintenances or to increase the battery capacity of the nodes with higher energy consumption. Our simulation results showed a 15% cost savings when the nodes are maintained twice per year instead of once per year.

## 8 Conclusion & future work

A wireless sensor network consisting of nodes with RF-energy harvesting capabilities was considered in this paper. A number of ETs was used to periodically recharge the nodes. We modeled the energy consumption of the nodes and we showed that it mainly depends on the network density and the number of transmitted packets. We, also, proposed a method to spread the harvesting energy among multiple hops with better applicability on dense networks. We gave another dimension to our problem by introducing the problem of minimizing the reimbursement time of the investment. Theoretical and simulation results showed that a network with RF-energy harvesting nodes saves up to the two thirds of the consumed energy compared to the case where no harvesting is used. In terms of cost, the results obtained by the current technology encourage the use of RF harvesting for networks with higher node density. In the future, we plan to use a multi-hop communication model for data delivery as well as to consider the problem of finding the optimal positions of the ETs.

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