Evaluating a Transmission Power Self-Optimization Technique for WSN in EMI Environments

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Abstract — **Wireless Sensor Networks (WSNs) can be used to monitor hazardous and inaccessible areas. The WSN is composed of several nodes each provided with its separated power supply, e.g. battery. Working in hardly accessible places it is preferable to assure the adoption of the minimum transmission power in order to prolong as much as possible the WSN's lifetime. Though, we have to keep in mind that the reliability of the data transmitted represents a crucial requirement. Therefore, power optimization and reliability have become the most important concerns when dealing with modern systems based on WSN. In this context, we propose to evaluate the effectiveness of a Transmission Power Self-Optimization (TPSO) technique for WSNs in an Electromagnetic Interference (EMI) Environment. The TPSO technique consists of an algorithm able to guarantee an equally high Quality of Service (QoS), concentrating on the WSN's Efficiency (*Ef*), while optimizing the transmission power necessary for data communication. Thus, the main idea behind our approach is to reach a trade-off between *Ef* and energy consumption in an environment with inherent noise.**

Keywords-WSN; QoS; energy optimization; EMI.

I. INTRODUCTION

Recent advancements in wireless communication and electronic technology have made possible the development of small, low-cost, low-power and multifunctional sensor nodes [5][6]. Wireless Sensor Networks (WSNs) are composed of small communication nodes, which contain sensing, data processing and communication components as well as power supply, typically a battery. In more detail, these nodes are able to collect different types of data and to communicate with each other. Nowadays, WSNs have been increasingly deployed for both civil and military applications which typically work in harsh environments. Considering sensor nodes, resources like processor, memory and battery are generally restricted, since their replacement is considered prohibitive due to hazardous and inaccessible places where they are supposed to operate [1]. Considering network's WSNs, where nodes are likely to operate on limited battery life, power conservation can be considered one of the most important issues [10]. Transmitting at unnecessarily high power not only reduces the lifetime of the nodes and the WSN, but also introduces excessive interference. Thus, to transmit at the lowest possible power while preserving the network connectivity as well as the fault tolerance or the WSN's *Ef* has become very important issues for WSNs [7][10]. In this paper, *Ef* is defined as mumber of received messages by the Master Node (MN) in relation to the estimated number of sent messages by the Slave Nodes (SNs). Indeed the reliability and robustness of communications in WSN are affected by the possible radio interference generated by WLAN, Bluetooth, IEEE 802.15.4, microwave ovens, and all other electronic devices that share the 2.4 Ghz band [11]. This evokes some concerns about the robustness of sensor network communications and limits the wide adoption of WSN by the industry.

Usually, WSNs are required to perform timely detection, processing and delivery of information interacting with their environment. Due to the real-time constraints, the high degree of faults, the noise and non-determinism caused by the uncontrolled aspects of the environment, it does not surprise that WSNs frequently show faulty behavior or in other words demonstrate poor Quality of Service (QoS) [3].

One strategy to cope with the QoS requirements is to adopt data fusion techniques. In dense networks, they are used in order to increase the sensor's reading dependability, to achieve a more accurate estimation of monitored environment and finally to assure a longer network lifetime [1]. In these approaches, sensed scalars are sent to Master Nodes (MNs) that fuse the data with the objective to extract useful information from a set of readings.

Moreover, the increasing number of nodes that compose WSNs leads to a high complexity of the system and the impossibility of human administration. Facing this problem, the development of computing systems that do not need human intervention to operate correctly has emerged. Thus, systems with so called self-management characteristics, computer

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systems that are able to manage themselves based on high-level objectives given by the administrators, have been developed to cope with the increasing complexity [4].

In this paper, we present a complete evaluation of the effectiveness of the Transmission Power Self-Optimization (TPSO) technique in an Electromagnetic Interference (EMI) environment. In other words, the paper aims to determine the impact of Electromagnetic (EM) noise on the communications performance of the WSNs. The TPSO technique has been initially presented in [9] and is able to adjust the transmission power guaranteeing the achievement of a target WSN's *Ef*. Thus, the main idea behind the self-optimization algorithm is to assure the trade-off between QoS and energy consumption and consequently achieve a prolonged sensor node lifetime. The effectiveness of the proposed technique has been evaluated using a case study composed of nine sensor nodes exposed to an EMI environment. The main goals of this paper are:

1. To provide experimental results showing the impact of EMI in WSN's communication. In more detail, to demonstrate that EMI decreases the WSN's *Ef* and consequently increasing the necessity to communicate using higher transmission power level to maintain the targeted WSN's *Ef*.
2. To demonstrate the effectiveness of the TPSO technique showing that it can guarantee the targeted WSN's *Ef* while reducing the energy consumption with regards to the data transmission increasing the battery lifetime.

The obtained results during the experiments quantified the impact of the EMI in WSN's as well as demonstrated the effectiveness of the proposed solution. In more details, the experimental results show that the TPSO technique significantly reduces the energy consumption with respect to the data transmission while maintaining the target WSN's *Ef*.

This paper has been organized as follows: in Section II we present the TPSO technique detailing the communication model as well as the self-optimization algorithm. Section III presents the case study adopted during the experiments, details the EMI environment adopted and summarizes the obtained results. Finally, in Section IV we draw the conclusions.

II. The Proposed Technique

The Transmission Power Self-Optimization Technique has been initially proposed in [9] and deals with the trade-off between WSN's *Ef* and energy consumption. In the next paragraphs we will describe the communication model adopted and the TPSO technique.

A. Communication Model

The adopted model considers one MN, also called base station, and *n* SNs according to Fig. 1. In more detail, the data collected by the SNs is sent to the MN that performs data fusion. All the SNs reach the master using just one hop.

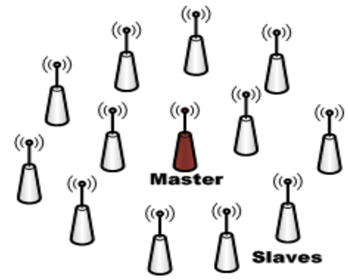

Figure 1. WSN model

In this work, the concept of session monitoring is adopted. A session *S* is composed of *t* session time (ST) rounds with the length *R*. Therefore, *S* is composed of ST_0, ST_1, ST_2, …, $ST_{(t-1)}$. The round concept is used to synchronize nodes, and it also represents the periodicity of the data fusion task [1].

Regarding the MN, it performs the data fusion considering only the messages that arrived on time. In this particular work, the MN only fuses data that arrived within the same session. Thus, the number of required messages, the round time (RT) and the session time (ST) parameters are sent by the MN at the beginning of each session, forming the so called checkpoint [1]. Moreover, the MN computes the performance metrics during the checkpoint round in order to adjust the WSN.

In the communication model adopted in this work, we considered the Efficiency (*Ef*) metric. In more detail, *Ef* is measured considering the number of received messages by the MN before finishing the session in execution in relation to the estimated number of sent messages by the SNs. Thus, *Ef* is calculated according to the following equation:

$$Ef = \frac{\sum_{i=1}^{N} Mr}{E_{Ms}} \tag{1}$$

Where N is the number of rounds, Mr is the number of received messages and E_{Ms} is the estimative of the sent messages by the SNs. In more detail, E_{Ms} is given by the equation (2) where K represents the number of required messages by the MN and De is the SN's density in the considered WSN. Thus, this metric indicates how many messages are used during data fusion task:

$$E_{Ms} = K \times De \times N \tag{2}$$

Finally, Quality of Fusion (*QoF)* is the average number of received messages by the MN during the ST [1]. Although we adopt a case study composed of more than one SN, it is important to point out that the *QoF* metric will be taken into account in future works only.

B. The Transmission Power Self-Optimization Technique

The TPSO technique has been initially presented in [9] and is based on a simple and decentralized algorithm that runs on the application layer of the WSN. The main idea behind the TPSO technique is to adjust the transmission power taking into consideration the entire network's *Ef*. It is important to highlight that the TPSO technique uses the *Ef* associated to each SN to compute the WSN's *Ef*. In more detail, the MN is responsible to compute the WSN's *Ef* as well as the *Ef* associated to each SN. Indeed, the MN sends the specific *Ef* to each SN. Finally, the SNs are in charge of adjusting their own transmission power levels based on their *Ef* by performing the TPSO algorithm. In Fig. 2 it is possible to see the block diagram of the self-optimization algorithm.

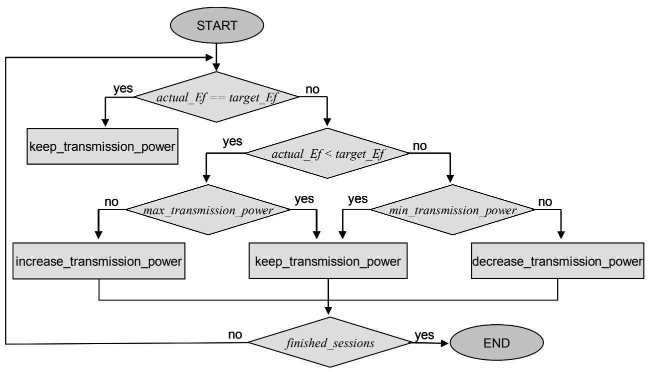

Figure 2. TPSO algorithm

Observing the block diagram depicted in Fig. 2, it is possible to note that the transmission power is adjusted based on the result obtained from the comparison between the *actual_Ef*, computed at the end of each session, and the *target_Ef*, set at the beginning of the communication. In more detail, the *actual_Ef* is computed using the data collected during the ST, that is, while the set of messages that compose the considered session are sent. It is important to highlight that the sensor nodes have a pre-defined minimum and maximum transmission power, which can not be exchanged or overwritten by the algorithm. Indeed, the transmission power is increased or decreased step-by-step passing through all the transmission power levels available for each node. Finally, the TPSO algorithm is performed by the SNs that compose the WSN and it can be adopted in WSNs that do not provide any type of transmission power optimization.

Fig. 3 shows the conceptual idea of the TPSO technique related to the temporal execution of the self-optimization algorithm. Observing Fig. 3, it is possible to see that between two consecutive sessions the adjustment of the transmission power is performed during the so called *optimization time*. In detail, the MN computes the *Ef* associated to each SN during the *optimization time* and sends these values to them. The algorithm running on the SN then adjusts the transmission power level according to the *actual_Ef* when it is necessary.

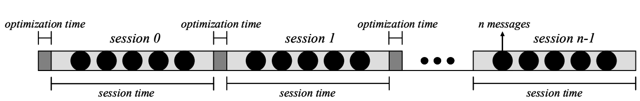

Figure 3. Conceptual idea of the proposed technique

III. EXPERIMENTAL RESULTS

In this section we present the case study adopted during the experiments performed in an EMI environment. The main goals of these experiments have been twofold: (1) to demonstrate the impact of the EM noise on the WSN's *Ef* and (2) to demonstrate the effectiveness of the TPSO technique with respect to energy consumption optimization.

A. Case Study

In order to demonstrate the effectiveness of the TPSO technique in an EMI environment, we developed a case study composed of nine sensor nodes according to Fig. 4.

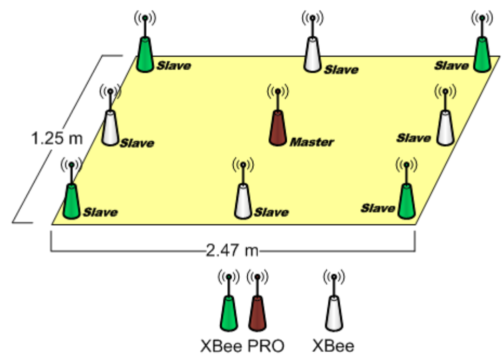

Figure 4. Case study adopted

Observing Fig. 4 we can see that the case study adopted is composed of one MN and eight SNs. The Master and four Salve Nodes are XBee PRO modules, while the remaining four SNs adopt an XBee hardware module. They perform the following tasks:

Master Node (MN): it starts the communication, performs the data fusion and it is responsible for sending the parameters necessary for the transmission power optimization by the SNs.

Slave Node (SN): it executes the TPSO algorithm in order to optimize the transmission power based on the parameters sent by the MN and sends the messages containing the data to MN.

In more detail, the *XBee* and *XBee PRO* modules adopt the IEEE 802.15.4 networking protocol for fast point-to-multipoint or peer-to-peer networking [8]. The IEEE 802.15.4 is a standard that specifies the lower two layers of the wireless communication protocol: (1) the physical layer (PHY) and (2) the media access control (MAC). Indeed, the IEEE 802.15.4 supports the unique needs of low cost, low power and low rate WSN. The PHY layer can operate with 250 Kbps of maximum transmission rate. Regarding the MAC, it supports two types of operational modes: (1) beaconless mode, a non-slotted Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) and (2) beacon mode, where beacons are sent periodically by a PAN coordinator [2]. In the latter case, nodes are synchronized by a super frame structure.

Regarding the transmission power, the *XBee* and *XBee PRO* modules can be configured to operate using five different transmission power levels that range from 0 to 4. Table I summarizes the transmission power levels of the two different types of sensor nodes adopted in these experiments.

TABLE I. TRANSMISSION POWER LEVELS

Level	XBee [dBm]	XBee PRO [dBm]
0	-10	10
1	-6	12
2	-4	14
3	-2	16
4	0	18

During the experiments in an EMI environment, we defined each experiment as a set of 50 sessions, each one composed of the same 10 messages. In other words, these 10 messages are sent during each session by the SN nodes. The ST has been configured to be of 10s and the *optimization time* to be of 0.5s. The experiments have been performed using an anechoic chamber and an antenna, which irradiates noise over the WSN. Fig. 5 depicts the EMI environment adopted where it is possible to see the antenna and the WSN placed on the table according diagram presented in Fig. 4.

In more detail, the WSN has been exposed to EMI according to the following noise characteristics:

Carrier frequency of 2.4093 GHz (channel 11 of 802.15.4)

AM/FM simultaneous modulation

Signal bandwidth: 40kHz

AM modulated signal frequency: 20 kHz

Power generator from -20 dBm to -10 dBm

B. *Results' Discussion*

The next paragraphs present the experimental results divided in two different phases. The main goal of the experiments' first phase has been to define the impact of the EM noise on the WSN's *Ef*. In more detail, two different scenarios have been considered during this first phase:

Scenario 1: it consists of 5 experiments where each one adopts one of the different transmission power levels from 0 to 4 according to Table I. These experiments have been performed without EMI.

Scenario 2: it is similar to Scenario 1, but during these experiments the WSN has been exposed to EMI.

Fig. 6 summarizes the results obtained during the first phase of the experiments. In more detail, each point present in the graph is associated to a specific transmission power level from 0 to 4 represented by its total value of WSN's energy consumption (axis x) during the 50 sessions with respect to the WSN's *Ef* (axis y).

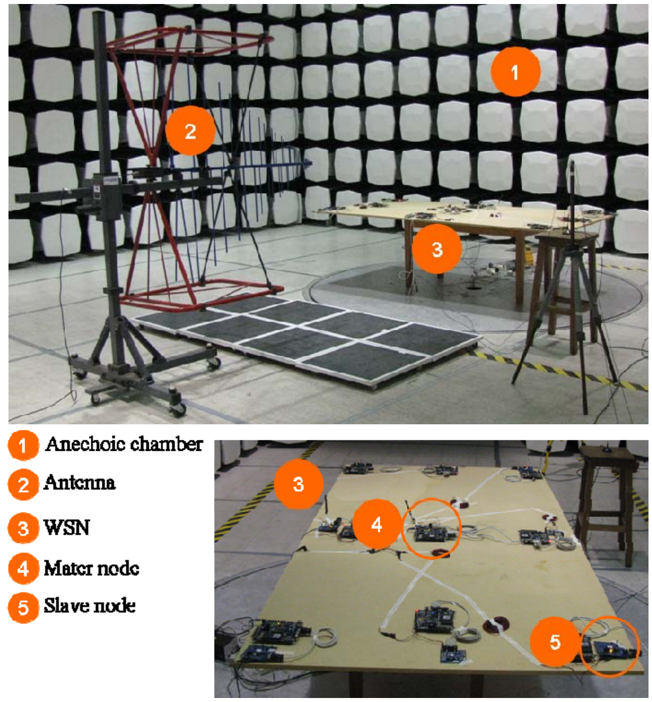

Figure 5. EMI environment adopted

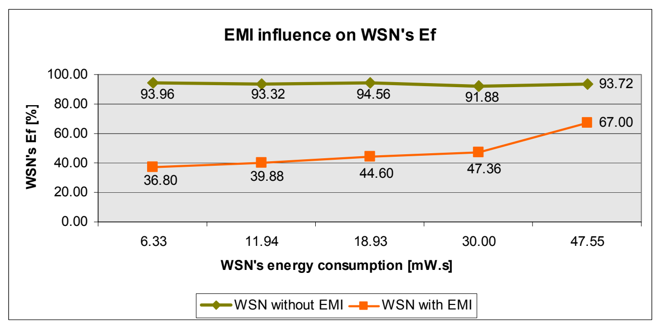

Figure 6. EMI influence on WSN's *Ef* applying AM/FM noise of -10 dBm

Considering the WSN's *Ef*, the average value mentioned has been computed using the 50 WSN's *Ef* with respect to each session. Regarding the WSN's energy consumption, it has been obtained throughout the sum of the energy consumed during the 50 sessions. Thus, considering the transmission power level of 0, it is possible to see that the noise drastically affects the WSN's *Ef*, since the average has been reduced from about 93.96% to 36.8% when exposed to EMI. Indeed, we can observe that the reduction of the WSN's *Ef* is smaller when the WSN has been configured to transmit at the transmission power level of 4, which represents the maximum transmission power that the WSN can adopt. In this case, the reduction of the WSN's *Ef* has been from 93.72% to 67.00%.

Fig. 7 depicts the comparison between the WSN's *Ef* with and without EMI considering the experiment where the WSN has been configured to communicate using the maximum transmission power level. The AM/FM noise applied has been of -10 dBm.

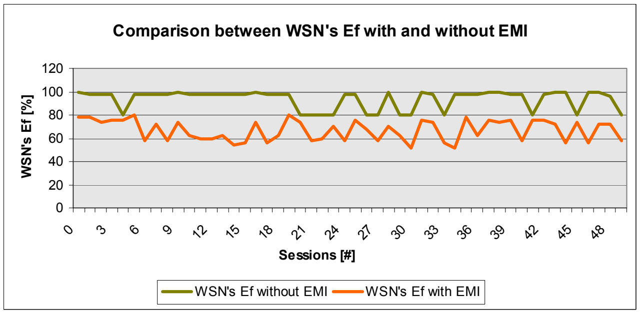

Figure 7. Comparison between WSN's *Ef* with and without EMI

Observing Fig. 7 we can see that during the 50 sessions, the WSN's *Ef* always oscillates in a range of 20%. Comparing the two graphs we can conclude that the EMI causes a drop of the WSN's *Ef* of up to 45% and an average reduction of 27%. Therefore, we can assume the relevance of this paper.

During the second phase of the experiments, the main goal was to evaluate the effectiveness concerning the TPSO technique when the WSN is exposed to EMI. Thus, the idea is to maintain a targeted WSN's *Ef* while reducing the power consumption during the data transmission. It is important to highlight that during this entire set of experiments the noise has been only applied during one half of the 50 sessions that compose an experiment. In more detail, during the sessions numbered 0 to 24 the noise generator was switched off and during the sessions numbered 25 to 49 the noise generator was switched on and applies an AM/FM noise of -20 dBm.

Fig. 8 shows the comparison between the WSN adopting the five pre-defined transmission power levels and the WSN adopting the TPSO technique with respect to the WSN's *Ef* and of WSN's energy consumption. In more detail, each green point in the graph is associated to an average of the WSN's *Ef* and the WSN's consumption with respect to a specific transmission power level, when considering the first set of points. Finally, the orange points represent the average of the WSN's *Ef* and the WSN's total energy consumption when the WSN adopts the self-optimization algorithm set to target the following WSN's *Ef* values: 60%, 70%, 75%, 80% and 90%. In other words, each point represents the average of the WSN's *Ef* as well as of the WSN's total energy consumption with respect to the five levels of transmission power and to the five different WSN's *Ef* targeted. Considering Fig. 8, we can observe that the WSN adopting the TPSO technique reaches a higher WSN's *Ef* than the WSN using fixed transmission power levels while consuming much less energy during the data transmission.

In order to better illustrate the effectiveness of the TPSO technique, Fig. 9 and Fig. 10 depict the WSN's *Ef* and the WSN's total energy consumption associated to two different experiments considering the following situations: (1) the WSN transmitting with the transmission power level fixed in 4 and (2) the WSN adopting the TPSO algorithm set to target 90% of WSN's *Ef*.

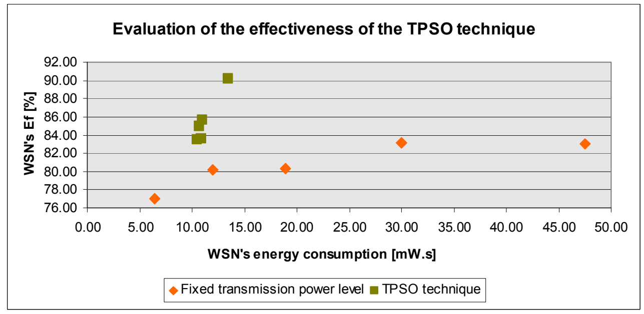

Figure 8. Evaluation of the TPSO technique with respect to WSN's Ef and WSN's energy consumption applying AM/FM noise of -20 dBm

Observing Fig. 9 and Fig. 10 it is clearly possible to see the influence of the EMI, which was applied only from the session 25 until the session 49. In more detail, the WSN's *Ef* changes proportionally to the applied EMI. Regarding Fig. 10 it is important to highlight that when the WSN has been exposed to EM noise, the transmission power does not significantly increase, since the WSN's *Ef* does not decrease and oscillates all the time around the WSN's *Ef* targeted. In other words, the targeted WSN's *Ef* has not been significantly affected by the noise of -20 dBm, which means that the transmission power level adopted was enough to guarantee the targeted WSN's *Ef*.

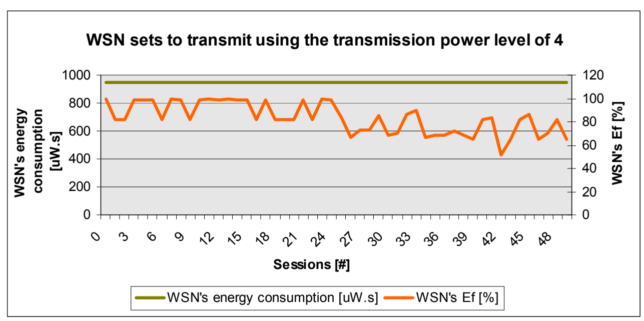

Figure 9. WSN using transmission power level of 4 applying AM/FM noise of -20 dBm

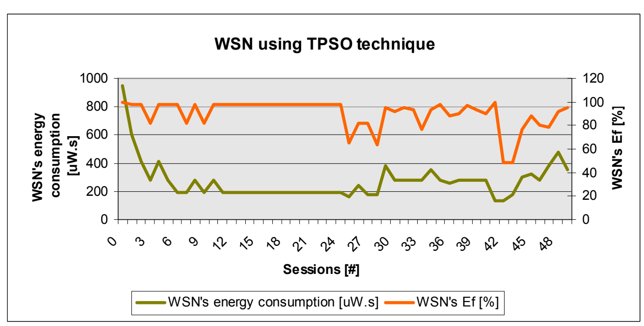

Figure 10. WSN using the TPSO technique applying AM/FM noise of -20 dBM

The next graphs show the results obtained applying an AM/FM noise of -14 dBm to the sessions 25 to 49 only. Fig. 11 shows the WSN's *Ef* and the WSN's energy consumption with respect to the WSN using the five pre-defined transmission power levels and to the WSN adopting the TPSO technique. In Fig. 11 we can observe the effectiveness of the TPSO technique with respect to the use of pre-fixed transmission power levels in WSN. In detail, we can see that the WSN using the transmission power level of 4 reaches about 80% of WSN's *Ef,* but consumes about 50 mW.s, while the WSN adopting the TPSO algorithm reaches the same WSN's *Ef* consuming only about 25 mW.s.

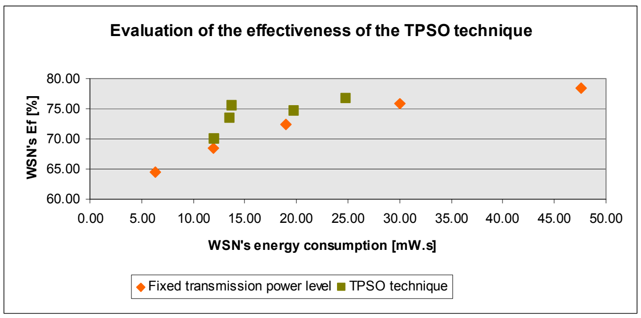

Figure 11. Evaluation of the TPSO technique with respect to WSN's Ef and WSN's energy consumption applying AM/FM noise of -14 dBm

Fig. 12 shows the reduction of the WSN's *Ef* when the WSN is exposed to EMI. This behavior is evident when we observe the WSN's *Ef* associated to the session 25 to 49 that corresponds to the period where the noise has been applied.

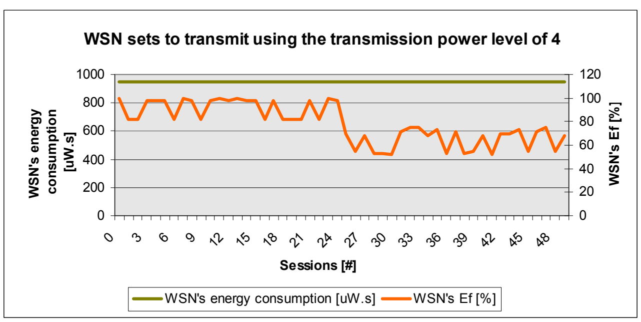

Figure 12. WSN using transmission power level of 4 applying AM/FM noise of -14 dBm

Finally, in Fig. 13 we can clearly see that the self-optimization algorithm increases the transmission power level in order to maintain the WSN's *Ef* set to 90% thereby demonstrating the effectiveness of the technique.

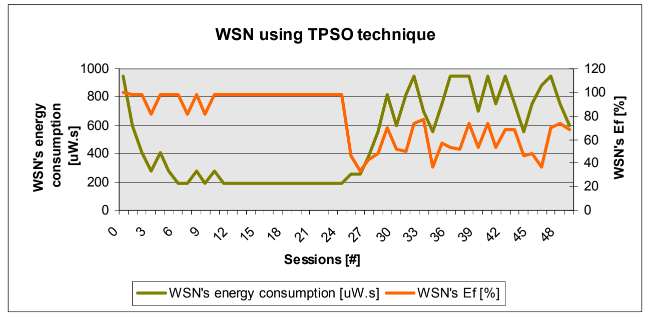

Figure 13. WSN using the TPSO technique applying AM/FM noise of -14 dBM

In more detail, the TPSO algorithm significantly increased the transmission power level in order to compensate the decrease of the SN's *Ef*, which is associated to the extremely high AM/FM noise applied as well as to maintain the QoS.

IV. Final Considerations

In this paper we evaluate the influence of EMI in a WSN as well as the effectiveness of the TPSO technique presented initially in [9]. Based on the information computed by the MN, the TPSO algorithm makes possible to adjust the transmission power level that is associated to each SN. Consequently the self-optimization algorithm assures the compromise between WSN's *Ef* and energy consumption. Therefore, the adoption of the TPSO technique increases the lifetime of the WSNs in noisy environments without affecting their QoS.

The results obtained during the EMI experiments demonstrated the convenience of using the self-optimization algorithm. When a WSN without the TPSO technique is considered, the transmission power is set at the beginning of the communication and remains the same during its entire lifetime. This characteristic can be negative considering a WSN in a real environment where the inherent noise is not necessarily constant. To give an example, considering a WSN set to communicate using the maximum transmission power in an environment of inherent noise variation and supposing that it reaches an *Ef* of 90% during periods of time where the noise variation is high. In this situation, we can assume that the WSN considered can reach an equivalent *Ef* using a lower transmission power in periods of time when the environment presents less noise and consequently saves energy throughout the WSN's lifetime.

Finally, in all cases, the TPSO technique is able to guarantee the target WSN's *Ef* and maintain a more balanced trade-off between *Ef* and energy consumption.

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