Determination of a Power-Saving Method for Real-Time Wireless Sensor Networks

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Abstract—**In wireless sensor networks, battery life is a key resource that must be conserved as much as possible. Nowadays, the main way of achieve power saving in this type of circuits is to implement low-power RF (Radio Frequency) circuitry and network protocols that try to minimize the number of transmissions by the air. We think that adaptation to RF environment can minimize the power consumption and supply an extra saving of energy in this type of systems. This paper presents a power-saving method for wireless sensor networks with real-time constrains. Description of an example of this type of systems will be done in order to supply background where needs and challenges will be presented. Then, method will be presented with some results in order to obtain conclusions and an estimation of future works and applications.**

Keywords: RSSI, Wireless sensor networks, 802.15.4, Real-Time communicatons, estimation, power-saving.

I. INTRODUCTION

It is well known that energy saving is one of the main issues of any Wireless Sensor Network (WSN). It is also known that data communication is the major source of energy expenditure, much higher than sensing or data processing [1]. Even idle listening (i.e., listening to receive possible traffic that is not sent) is a concern: WSNs are characterized by low data rates, so nodes can be in idle mode for most of the time and therefore idle listening becomes one of the major sources of energy waste in WSNs. A relatively simple way to save energy is to keep awake nodes the minimum time required to exchange data, switching off the radio during the inactive period. This method is also called Passive Power Control (PPC) [2], as opposed to Active Power Control (APC). APC does not switch off the radio but achieves energy saving through energy-efficient network protocols [2]. Some of the most interesting APC techniques are based on adjusting the transmission power according to the network operating conditions [3]. On the other hand, APC may also be used not to save energy, but to improve the reliability of a link by increasing the transmission power if a low quality link is detected [4].

Similar techniques have been used in other types of wireless devices, such as GSM [5,6] mobile telephones. In this case, the station senses the link quality of terminals and sends indications about the desirable transmission power to each terminal. This centralized approach is desirable for star topology networks (like GSM) but it is not always desirable in wireless sensor networks where mesh topologies are used when a high quantity of nodes must cover an area. Moreover, placing the sensing equipment in the station saved hardware costs in terminals (telephones) given that, in mid 1990s, the cost of including this circuitry in the telephone was too high. The situation is very different nowadays, and link quality sensing hardware can be found in a large range of products without cost increase. This fact allows exploring de-centralized solutions where more than one device can sense the link quality and react individually.

Going back to WSNs, many commercially available devices do include mechanisms to allow link quality sensing at no additional cost. For instance, Received Signal Strength Indicator (RSSI) is a standard feature found in many wireless devices requiring no additional hardware and keeping power consumption, sensor size and cost approximately at the same level. Since distances between neighboring sensors can be estimated from the received signal strength measurements, one of the most common uses of RSSI is the localization of nodes with respect to reference nodes or *anchors* [7]. However, there are other potential uses of this indicator, especially those oriented towards increasing energy efficiency in data transmission. Most of them are based on an estimation of the link quality using the received signal strength as the input of the prediction scheme. This estimation allows reducing power consumption by choosing a proper transmission power for each packet transmission [3,4,8,9], as well as minimizing interferences with other ISM devices [10], adapting data rate [11], dynamically selecting routes [12], etc. A very recent and extremely detailed experimental evaluation of many of these issues can be found in [13].

This paper is devoted to show the application of APC methods in a Real-Time WSN, the SemiWheelNav Sensor Subsystem (SWN-SS) [14], although some of our results allow applying it generally to other WSNs. SWN-SS is based on a polling mechanism on top of the 802.15.4 standard. This polling allows us to meet the real-time requirements of our system. The main aim of this work is to show that it also allows us to reduce the power consumption of the battery operated nodes. This reduction will be estimated both analytically and experimentally.

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The paper is organized as follows: in section 2 a brief description of basic concepts of the 802.15.4 standard will be made. Then, in section 3 the SWN-SS will be briefly presented, allowing us to show some characteristics that affect the design of our power-saving method. In section 4 the method is presented, and section 5 and 6 are devoted to results. Conclusions and future work will be presented in section 7.

II. 802.15.4 OVERVIEW

802.15.4 is a *de facto* standard for wireless sensor networks that tries to solve the problem of communicating low-cost devices with minimum hardware and software complexity, as well as increasing the battery-life of these devices to months or years (with very fine-tuning of network protocol parameters, in some cases). 802.15.4 achieves its objectives by implementing a communication network designed for low power consumption and, at the same time, with very scarce machine-resources, that allow its implementation in very cheap circuits.

In the 802.15.4 standard there are several available configurations [15]. Two different topologies can be used: Star and Mesh (Peer-to-Peer). In the star topology, communication is controlled by a PAN Coordinator, also called *Zigbee Coordinator-ZC*. All devices (up to 255) communicate only with the ZC. In the Peer-to-Peer topology direct communication between devices is possible. Also, two different synchronization modes are possible: beaconless and beacon-enabled. On one hand, the beaconless mode is essentially an unslotted CSMA/CA mode, where nodes can send data to the coordinator at will. In case the coordinator wants to send data to the node, then it must be invited by the node to communicate. No time synchronization occurs in this mode. On the other hand, in the beacon-enabled mode the ZC periodically transmits beacon frames that establish a superframe structure. In this superframe, devices may transmit using a slotted CSMA/CA medium access, with an optional Contention-Free Period-CFP (see Figure 1). Even if these CFPs are not used, the periodic transmission of beacons provides a way to synchronize all nodes. Also, it is possible to change the duty cycle to achieve low power consumptions: the device, upon receiving the first beacon, gets current superframe structure and thus knows when to active its receiver for the next beacon (just a bit earlier to save power). The device periodically enables its radio to receive the beacon frame, performs the required transmissions and then changes to a lower consumption mode during the inactive period.

Therefore, generally speaking, when there are energy and/or timing requirements, the right choice is the beacon-enabled mode. Furthermore, when any node is mobile (i.e. not fixed) the beaconless mode is not suitable because there is no periodical beacons transmission, so the mobile node may assume its association although it may have lost the link with the coordinator [16]. In the beacon-enabled mode, if a node does not receive a predetermined number of beacon frames then it considers itself as an "orphan" node, beginning a realignment procedure to get associated again with a coordinator.

The beacon-enabled mode is currently limited to Star Topologies, with a network coverage limited to the transmission range of the Zigbee Coordinator, although several attempts try to extend this mode to general Cluster-Tree topologies [17]. However, we think that we can use twin devices (composed by two 802.15.4 devices, one acting as ZC and one as leave node) to implement a tree-structure of ZCs in beacon enable mode, where camera nodes are connected to leaf nodes of the ZC tree. This possibility will be not considered now because it is out of the scope of this paper. So, in SWN-SS, we limit ourselves to a star topology, beacon-enabled configuration.

The standard 802.15.4 allows adjusting a lot of parameters, including how much time the device must be waiting for new packets (active part of superframe) and how much time the device can be asleep (or simply, waiting). This way the designer can adjust the system to his/her power requirements. Another thing that can be done is to fix the device's transmission power. This parameter are kept at the beginning of the device's operation. After that, transmission power and network parameters keep fixed. The basic idea is to reduce the RF active power consumption up to the minimum required to send a message to destination, ensuring its correct reception.

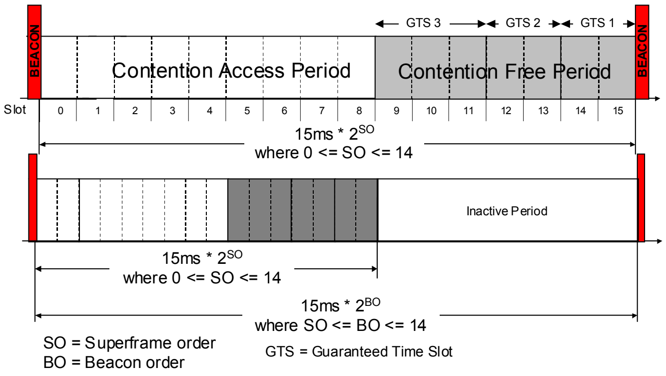

Figure 1. 802.15.4 Basic superframe format (upper) and superframe with inactive period (lower). This figure shows the relation between parameters SO and BO, and the time between beacons.

III. THE SEMIWHEELNAV SENSOR SUBSYSTEM

In this section, we briefly describe the communication subsystem of a prototype for a smart wheelchair guidance system [14]. This system includes a Wireless Sensor Network (WSN) that is the base to support indoor navigation of a wheelchair. 802.15.4 is the wireless technology chosen to support our system, so it can benefit from advantages like low power consumption (mainly important for the mobile devices-wheelchair, hand-held devices, etc.), large number of devices, low installation cost, easiness to move and reconfigure public buildings with relatively frequent repartitioning of space (commercial buildings, hospitals, residences), etc.

The aim of SemiWheelNav is to use sensors that are external to the wheelchair, that is, they are part of the environment. These sensors, including CMOS cameras, perform detection and tracking of a mobile object (wheelchair), taking into account possible obstacles. Therefore, in the simplest case, the system is composed by a WSN that has a specific number of cameras, a network coordinator (ZC), and one wheelchair. In this way, camera nodes placed on the ceiling broadcast their obstacle information (a grid indicating the position of obstacles) when ordered by the ZC. The ZC gathers all the grids from the camera nodes and obtains both wheelchair positions and obstacle information in order to make a local/global navigation that allows avoiding obstacles. Then, this information is processed and sent to the wheelchairs.

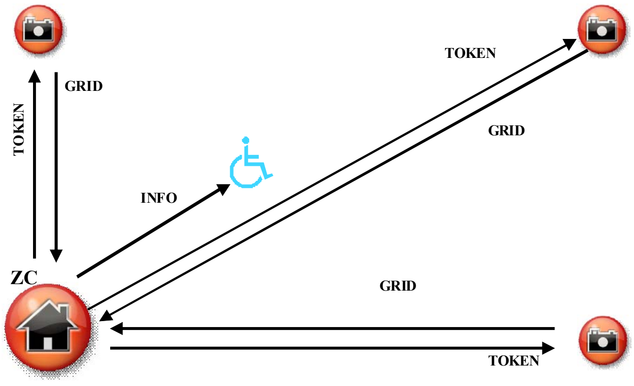

Figure 2. Deployment of SWN-SS.

The system obviously has temporal requirements since our objective is the real-time navigation assistance of a wheelchair. For instance, on detection of environmental changes it is required that a timely reaction takes place. A Time-Triggered (TT) architecture is an interesting alternative: it is based on a synchronous design, with each task and message planned a priori in a static schedule. This approach has several advantages: it provides temporal predictability, allows an easy verification of the timing constraints, facilitates fault-tolerance, etc. Furthermore, it makes it easier to implement the periodic measurements required by the multi-sensor fusion approach. And more important, as we will show in this paper, the power consumption may be reduced.

A distributed TT architecture needs a common time base shared by all the nodes. In our simple prototype (only one or two cameras, static and relatively large obstacles, etc.) the beacon-enabled Zigbee mode may provide this synchronization as well as enough bandwidth to support our system, as we will see in the following paragraphs.

In the nodes used in our prototype [18],Contention-Free Periods (CFP) are not available. Nevertheless, given that a star topology, beacon enabled configuration is used, it is possible to implement an application that takes into account the timing requirements of our system. Briefly, since all communications must go through the Zigbee Coordinator, we let this ZC to manage the order of transmissions. However, several nodes may try to transmit at the same time when a beacon is sent by the ZC, thus causing collisions. The standard tries to avoid these collisions using a slotted CSMA/CA mechanism, waiting a random number of backoff periods previously to any transmission attempt.

But this mechanism cannot guarantee successful transmissions with upper-bounded delays. Since the active period of a superframe (so called Superframe Duration-SD) is limited to 16 slots, it may occur that this period be insufficient to accommodate all the necessary transmissions (for instance if several nodes want to transmit). In this case, these pending transmissions must wait for the next superframe, being resumed after the next beacon frame. Depending on the duty cycle, the inactive time may cause some timing constraints to be violated. Furthermore, all collisions waste power and bandwidth with useless transmissions.

In order to avoid this situation, we implemented a polling scheme as an alternative approach to share the available bandwidth. Of course, the ZC is the best candidate to perform this polling. The usual way to send data from a coordinator to a given node requires that first the node transmits a data request message. The coordinator then sends an ACK and finally the node is able to send its data. However, this mechanism does not avoid more than one data requests from several nodes, probably causing collisions. A simple solution is to let the ZC transmit a kind of *token* to the selected node, whose address must be listed in the beacon frame. This approach works in such a way that only one node (the one that has previously received this token) is allowed to transmit.

Briefly, the system works as follows (see Figures 2 and 3). We have one Coordinator (ZC), a number of cameras on the ceiling (C_1 to C_N, in this example N=2) and a wheelchair. We assume that all these devices are situated within the transmission range of the ZC, which periodically transmits beacon frames defining the superframe structure. The ZC includes in every beacon payload the address of the following polled device. This polled device automatically sends its data by means of broadcast packet(s) to the ZC. Nodes that don't see their address listed in the beacon frame may still be interested in transmitting their data, but they must wait for the token to be received before they are allowed to transmit.

First, camera C_1 is polled, so it is allowed to transmit the grid map to the ZC with the free areas and the obstacles detected by camera C_1. The grid map may occupy several 802.15.4 frames. For instance, 3 messages are needed in our case.

These frames are transmitted with no competition from other nodes since only the node that received the token is allowed to transmit. This polling policy can be described as an Exhaustive Limited Service Round Robin policy: every node sends all its pending data, with the limit of the superframe duration (more than enough for typical grid sizes).

In the following superframe, the ZC polls camera 2 by sending its address in the next beacon and then camera 2 is allowed to transmit its information to all nodes of the WSN (including the wheelchair/s). At last, obstacle information is sent to the wheelchair, so ZC sends a beacon with the wheelchair's address and sends data.

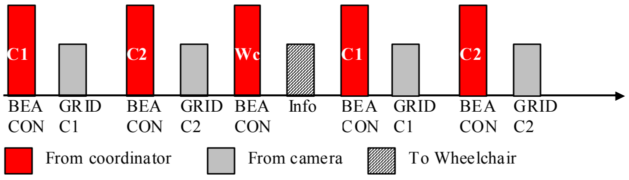

Figure 3. Polling mechanism for two cameras and one wheelchair.

IV. TRANSMISSION POWER CALCULATION

Since power-saving is one of the most important issues in any WSN, it would be interesting that all sending devices powered by batteries adjust their transmission power in order to save energy. This is the case of the cameras and the wheelchairs. The main idea of the method described in this section is that, based on an estimation of the link quality, these devices can make decisions about how much transmission power must be used. This decision-making must be done as quickly and as efficiently as possible. So, given the scarce resources (battery, memory, and computing power) available in these devices, a balance between resource consumption, computing time and suitability to our application must be achieved. These issues influence the way we estimate link quality and transmission power.

RSSI is a good estimator for link quality and it is implemented in the devices that we use in our system [19]. In TI-CC2430, RSSI can be obtained for every received packet, as the mean of 8 RSSI samples measured at packet reception. If the minimum number of samples is not achieved, RSSI is indicated as failed and not used in our calculations.

Once we have a valid RSSI from ZC, the calculation is done taking in mind that the objective is to send the next message with enough power to be received correctly. We name this parameter *desired* RSSI ($RSSI_d$). $RSSI_d$ is calculated taking into account the physical characteristics of the received signal in order to estimate the signal attenuation. Therefore, a propagation model has to be considered. There are a lot of choices for the propagation model [20] (Rayleigh, Ray models, Rician, AWGN). In our system we need a model which includes important effects like attenuation, but simple enough to meet our real-time and power consumption restrictions.

Therefore, as a first approximation, we have chosen a simple log-normal shadowing model [21]:

$$RSSI = P_T - P_L(d_0) - 10n\log_{10}(d/d_0) + X_\sigma \tag{1}$$

Where, RSSI is the RSSI received from the current packet, P_T is the transmission power employed to transmit the current packet, $P_L(d_0)$ is the path loss at distance d_0, n is the path loss exponent and X_σ is a Gaussian random variable with zero mean and σ^2 variance to model the Additive White Gaussian Noise (AWGN). The value of d_0, n and $P_L(d_0)$ must be estimated empirically, depending on the environment (obstacles, free space, walls, etc.). A general form of eq. (1) is:

$$RSSI = P_T - S_L + X_\sigma \tag{2}$$

where S_L is the signal loss. Note that (2) ignores the nature of physical effects suffered by the signal and the value of variables commented before. It only tries to estimate how much power is lost in the reception. So, if P_T is known (because we know the default transmission power applied) and RSSI can be measured directly from the device as we commented above, S_L can be easily obtained. Therefore, the new value for the transmission power P_T', the power needed to successfully reach the destination, can be expressed as a function of the *desired* RSSI at the other part of the communication:

$$P_T' = P_T - RSSI + RSSI_d + X_\sigma' \tag{3}$$

As can be seen, X_σ' explains the variance of RSSI due to AWGN. In order to give a stable estimation of next transmission power P_T', a correction must be made in eq. (3).

$$P_T' = P_T - RSSI_{AV} + RSSI_d + X_\sigma' \tag{4}$$

Where $RSSI_{AV}$ is the average RSSI of the past *n* packets. In figure 4 an example of RSSI measurement of a moving device is shown.

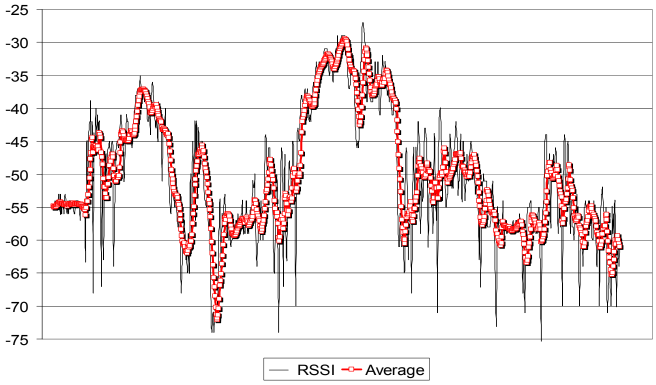

Figure 4. RSSI measurements (in dbm) and their average over 10 samples vs time for a moving device during a time period of 2 minutes.

Fig. 4 shows the RSSI measurements of each received packet in black (narrow line) and the average of the past 10 packets is shown in red line with shapes. As can be seen, RSSI measurements tend to suffer sudden variations that cannot be predicted. However, the average of the measures shows a more stable behavior that can be more easily predicted. It is for this reason that we use the average RSSI to compute the transmission power. Of course, the more samples used to get the average, the less abrupt variations in RSSI. In Fig 5, 50 measurements are used to make the average.

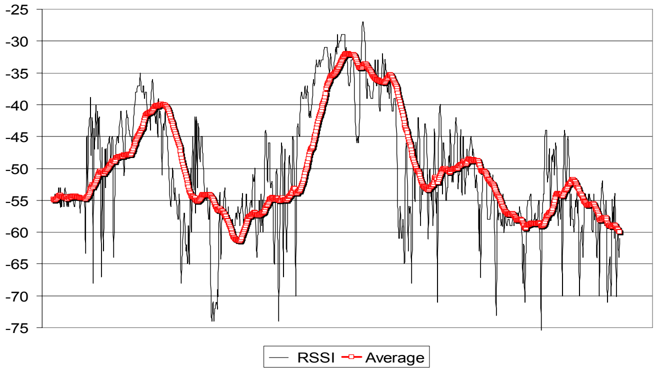

Figure 5. RSSI measurements averaged over 50 samples (in dbm) vs time for a moving device during a time period of 2 minutes.

So, from the point of view of a camera node, RSSI must be computed averaging over the past *n* values and then, the estimation of next transmission power is done taking in mind the desired reception power level at the coordinator. The value of n can be fixed and determined experimentally, or can be changed dynamically, in function of the desired smoothness of RSSI curve.

Of course, other methods could be used to estimate and/or predict the RSSI [22], like linear regressions, quadratic regressions, adaptive filters, ARIMA models, LMMSE models, etc, but we have to take in mind that more complex algorithms for RSSI calculation would require more resources and would take more time (with the risk of breaking the real-time constrains of our system). Also, we have to take in mind the unpredictable nature of AWGN, and the fact that the most relevant parameter is the trend of RSSI and not its instant values. For this reason we have chosen the average as an efficient estimation of RSSI to be used in the calculation of the power for the next transmission.

From the point of view of a Wheelchair, processed information is received from the ZC and no transmissions are needed so, this method is not applicable to this case.

V. EXPERIMENTAL RESULTS

In this section, a small experiment of application of the power saving method is shown. By means of it, we will have a way to compute the amount of the power saved and to compare the energy wasted with and without the implementation of the method described above.

The experiment implements a SWN-SS with one coordinator and a number of camera nodes disposed spatially in a radial configuration at a constant radius *r* from the ZC. As said before, wheelchair nodes are not included in our experiment because they do not use the power-saving method.

Measurements are taken from ZC and one camera (the reference camera node), because the rest of cameras have a similar behavior given that they are at the same distance from the ZC as the reference camera. On the other hand, we collect in ZC the RSSI received from reference camera packets. In the camera, we collect the following data:

- RSSI received from ZC beacons
- Average received RSSI
- Calculated transmission power.

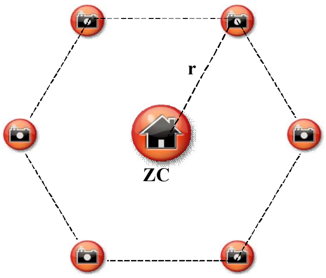

Figure 6. Experiment's Spatial configuration with 6 cameras.

First, we must study the nature of the energy saving in our system. The power consumption in camera nodes can be broken into two parts. The first one is constant, the power consumption produced by the parts of the circuitry that are always active. The second one is variable and is the power consumption due to elements that can enter in low power mode. In our case, these elements correspond to the RF circuitry. Also, we have to take in mind that the RF circuitry waste power in both reception and transmission and that we only obtain benefit by controlling the transmission power. Let's see a power consumption waveform from one camera, operating with SO=0 and BO=3, with a power transmission of -19dbm.

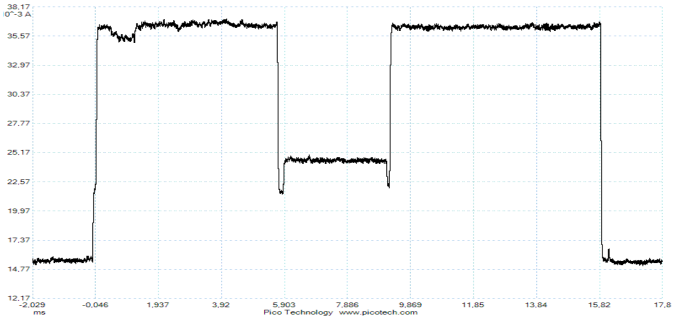

Figure 7. Power consumption waveform at camera when RF is active, with reduction of transmission power.

In figure 7 we can see the constant part of the current consumption that is the baseline of the waveform. Only when RF circuitry becomes active the current consumption grows up to 30.5mA that is the power needed to receive (the small hole found before the transmission corresponds to beacon reception). Only when the camera transmits a packet, consumption can be lowered, as shown by the short period with a lower value between the two "mountains". The rest of time that RF is active is due to the device waiting for a packet. In this state the RF circuitry must be switched on in order to be ready for receiving a packet. So, initially, the origin of our power saving is that short period of time when the camera transmits. This is only 3.6ms out of 15.6ms of the total RF active time. The rest of time, RF circuitry keeps inactive until the time the next superframe is received.

The total amount of current saved in an experiment with duration T can be calculated once the transmission power of each packet sent during the experiment is known. In Fig 8, the relation between TX power and intensity consumption is shown. The CC2430 is capable of delivering transmission power between -25dbm and 0dbm, but this delivering is not linear because of the logarithmic nature of power unit.

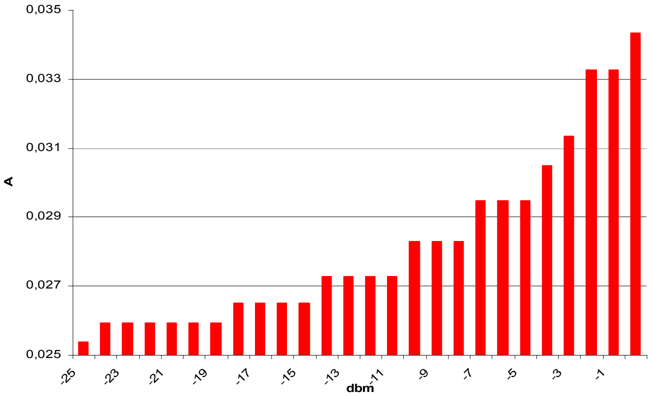

Figure 8. Transmission Power vs wasted Intensity for TI-CC2430DB.

The electric consumption per packet sent by the camera is:

$$EC= (2^{BO}-2^{SO})0.015I_{BASE}+(2^{SO}\cdot 0.015- TX_T)I_{RX}+TX_T\, I_{TX} \quad (5)$$

Where SO is the superframe order, BO is the beacon order, I_{BASE} is the intensity wasted when RF is inactive, TX_T is the time of a packet transmission, I_{RX} is the intensity wasted on packet reception, and I_{TX} is the intensity wasted on packet transmission, which is controlled by the power-saving method and depends on the values of fig. 8. Note that we use the default value for *aBaseSuperframeDuration*=15.36ms≈0.015s. This way, the total electric consumption of the experiment is the sum of all ECs computed by eq. (4). If no power-saving method is applied, the EC and the energy saved in one packet are given by the following equations, respectively:

$$EC' = (2^{BO}-1)0.015I_{BASE}+(2^{SO}\cdot 0.015)I_{RX} \quad (6)$$

$$EC_{SAVED} = TX_T\,(I_{RX} - I_{TX}) \quad (7)$$

Note that in our devices the intensity wasted on packet transmission is by default the same as the intensity wasted on packet reception.

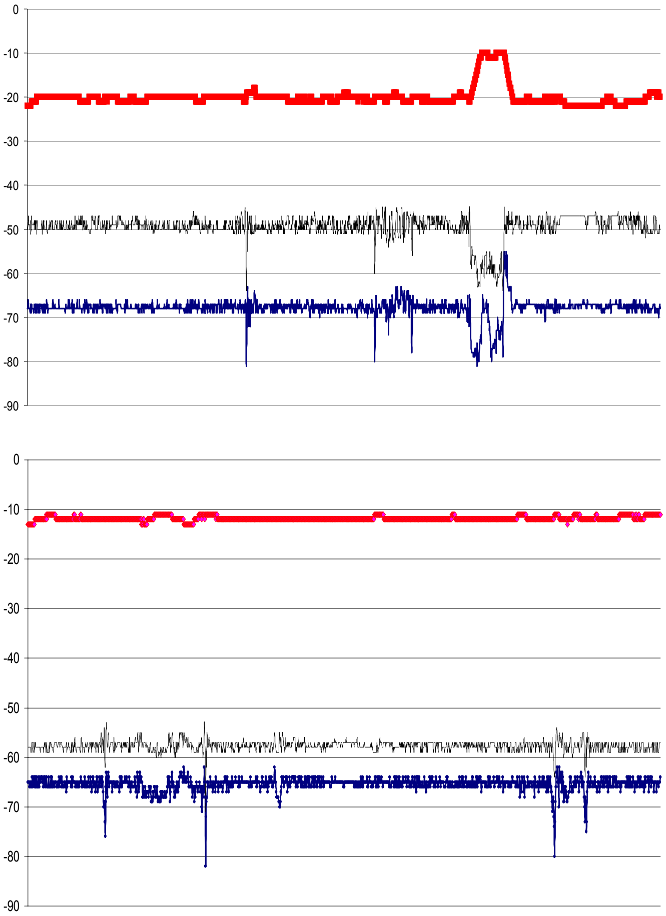

Figure 9. Waveforms at 2m (upper part) and 4m (lower part) of distance respectively between ZC and camera. Upper line: Camera TX power. Middle: Camera RSSI. Lower: ZC RSSI. Desired RSSI = -65dbm. The power consumption of devices without power control is constant (-4dbm).

As an example, we show in fig. 9 the power control method applied to a camera node that has a desired RSSI of -65dbm. Two experiments were made placing at open air both devices at 2 meters and 4 meters of distance between them. In each experiment, 3 people crossed the line of sight (LOS) between devices in order to produce some signal variations. The duration of each experiment was approximately 2 minutes. The duration of packet transmission was 3.6ms. Experiments were made using two Texas Instruments CC2430DB development boards. Desired RSSI (-65dbm) was chosen to be comfortably over minimum threshold needed for correct reception: -80dbm in this case. The default transmission power is -4dbm in these devices (without transmission power control).

Transmission power always remains below of the default transmission power (-4dbm), achieving a power saving in all cases. Note that when an obstacle crosses the LOS (right side of Fig. 9), the power control system increases the transmission power in order to compensate the loss in the received signal. In general, wide variations of RSSI due to obstacles in LOS are compensated by TX power control. However, small variations due to AWGN are ignored by the RSSI estimation but this is not a drawback because it allows the RSSI received by the ZC to be fixed within acceptable limits. Finally, the smaller the distance between the devices, the greater the energy savings achieved. Ignoring these transient obstacles, we can take an average transmission power, and then the saved electrical consumption can be estimated as a ratio of the whole energy consumption:

$$EC_{SAVE\text{-}RATIO} = 1- (EC / EC') \quad (8)$$

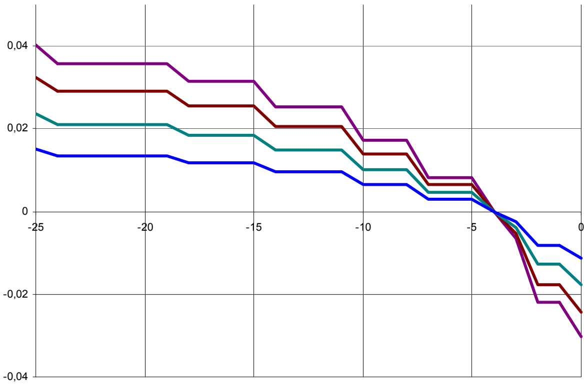

Figure 10. Saved energy ratio vs transmission power for SO=0 and BO=0 (upper line at left side) BO=1, BO=2 and BO=3 (placed below, respectively).

Fig. 10 shows the energy saving ratios calculated for several values of BO. The lowest power consumption in the default 802.15.4 is obtained by fixing SO to 0. Therefore, we compare our approach with the default 802.15.4 in this case (SO=0), reducing to the minimum the time that RF circuitry is active. So, increasing BO we increase the time that the RF is inactive because no more transmissions are expected. In fact, the power-saving ratio is low even in the best cases, and it puts on evidence the small fraction of power saved in relation with the whole power wasted having RF circuitry active.

VI. IMPROVING THE POWER-SAVE RATIO

An improvement proposed to solve this issue is to reduce the time that RF is active after the transmission of the packet.

In SWN-SS, due to the MAC polling scheme described in section III, a camera will not receive any additional packet in the same superframe after its packet transmission. Because ZC makes a round robin polling over the cameras, once a camera have sent its packet it is for sure that no more packets are expected until the ZC carry out the new poll by means of the next beacon packet. Furthermore, if the superframe's beacon doesn't contain the camera's address, then there will be no interesting information to receive, so the camera can turn off its RF circuitry immediately after beacon reception.

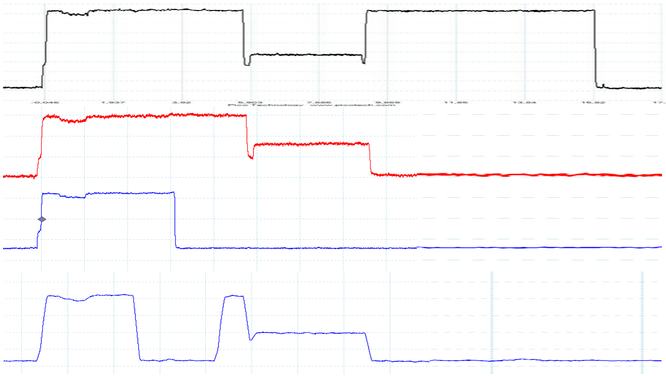

Figure 11. Composition of waveforms (for comparative purposes) of power consumption of one camera with improved power savings. From top to bottom: A= TX power reduction only. B= RF activity after TX reduced. C= reduction of RF activity after a non-interesting beacon. D= reduction of case B, and reduction of RF activity between beacon RX and TX.

Therefore, the second submit in fig. 7 can be lowered to the baseline simply turning off the RF after the transmission. Furthermore, some time between beacon reception and packet transmission can be saved also. In the case of a non-interesting beacon reception, camera can turn off its RF immediately after the beacon reception. In fig. 11, all cased exposed above are compared graphically. The first waveform shows a camera implementing only TX power reduction. Second one implements reduction after TX, additionally. Third corresponds to the reception of a non-interesting beacon, reducing its power after beacon reception and decoding, and Fourth shows a more optimized camera that receive an interesting beacon reducing power after beacon reception, packet transmission, and after packet transmission. Note that in this latter case, not all the power between beacon reception and packet transmission can be saved due to the response times of circuitry. So, for the last two cases, the eq. 5 becomes (assuming that both summits of first case are identical in the average):

$$EC= [(2^{BO}-2^{SO})0.015I_{BASE} + ((2^{SO}\cdot 0.015-TX_T)/2-BETX_T)I_{RX}+ ((2^{SO}\cdot 0.015-TX_T)/2+BETX_T)I_{BASE} + TX_T\, I_{TX} + N((2^{BO}-2^{SO})0.015I_{BASE} + (2^{SO}\cdot 0.015- B_T)(I_{BASE}) + B_T\cdot I_{RX})]/N \quad (9)$$

Where B_T is the time elapsed from the beginning of RX activity to the end of beacon reception, $BETX_T$ is the period of time between the end of beacon reception and the beginning of packet transmission that can be reduced to base intensity, and N is the total number of devices (cameras and wheelchairs) in the network. The new curves of saved-energy ratio are shown in figure 12. This time, at the same SO and BO, the more devices in the network, the more power is saved. The energy saved on transmissions has no relevance because it becomes smaller as increase the number of devices. Therefore, the only relevant parameters are the number of devices and the ratio between RF active and inactive time existing between two beacons (determined by BO). Anyway, the increasing of number of devices produce minor variations in the energy save ratio, because the most of the wasted energy is produced in the RF inactive time, as BO increases. Fig. 12 shows the small variation between networks of two, six and 255 devices (maximum allowed in 802.15.4). With this solution, we can obtain up to a 57.5% of saved energy, applying the enhanced method, in the best of cases. It seems that it is not necessary to apply the transmission power control to obtain a good power save ratio. However, the reduction of transmission power implies other benefits to our system, like a better coexistence with other networks that uses the same frequency spectrum as told in [4].

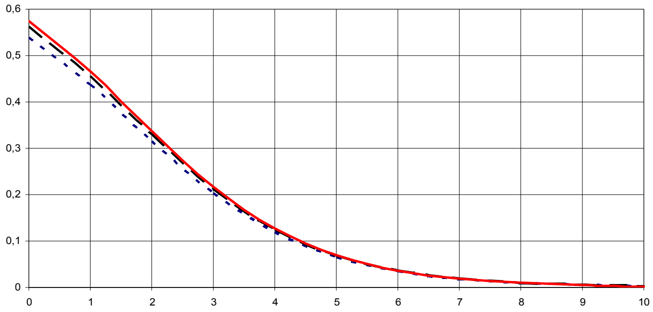

Figure 12. BO vs improved saved energy ratio for SO=0 at maximum transmission power for networks with N=2 (lower, dotted) N=6 (middle), and N=255 (solid).

VII. CONCLUSIONS AND FUTURE WORK

This paper we propose a power saving method implemented in an Ambient Intelligent Wireless Sensor Network that uses a modification of the standard 802.15.4 MAC protocol to obtain predictability on maximum packet delay time. Although the experimental results probe that the method reduces efficiently power transmitted and ensures a minimum signal level, the power reduction on transmission is not enough due to the small fraction of power that can be reduced. Therefore, this method is useful only when transmission time is the main part of RF active time. The TT-architecture used in our system allows to greatly reducing of the RF active time and it reveals major improvements in our power-saving ratios. So, combining both methods, battery-life and network coexistence can be improved, maintaining the real-time constrains of our system at the same time. The study presented above shows that the major source of power waste in this kind of devices is the inactivity RF time. In 802.15.4 devices, several inactivity modes can be used in order to reduce this waste but (in fact, we use one of them) only the hibernation mode has a power leak low enough to bring better power-saved ratios. However, the drawback of hibernation mode is the loss of network synchronization, the necessity of external stimulus to exit from this mode and the time expended to awake the entire system.

All these reasons lead us to believe that a Time Triggered architecture implemented by means of 802.15.4 beacon-enabled mode has demonstrated to be useful to achieve reduction of energy consumption at the same time that real-time predictability. 802.15.4 beaconless mode can be used to save energy employing hibernation modes but it's very difficult to achieve real-time predictability for these kind of networks.

Future works in energy saving must be addressed to implement best hibernation modes with lower power leaks, without the drawback of current hibernation modes. Also, long-term signal prediction can be useful, in order to decide when it's worth to active the RF circuitry (or to exit from the sleep mode). A lot of techniques exists to predict the future signal conditions, but we have to take in mind the real-time constrains of these kind of systems at time to implement one of them. On the other hand, signal prediction can be used for another network layers in order to take decisions about routing, or can be used as a parameter to organize a time scheduling for sending data in the best possible conditions.

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