A low-cost wireless sensor network

Abstract - **This paper presents a wireless sensor network (WSN), which were designed for application in industrial measurements wit the use of low-cost commercial components. The concept of the WSN is presented, as well as *hot*-topics concerning its implementation, in order to make the communication between the nodes and the base-station as reliable as possible. The architecture, protocols and the reasons that governed the choice of the components are also discussed.**

Keywords - **WSN, protocols, microcontrollers, PIC16F628.**

I. INTRODUCTION

Wireless communication microsystems with high density of nodes and simple protocol are emerging for low-data-rate distributed sensor network applications such as those in home automation and industrial control [1]. It is available a huge range of solutions, concerning the implementation of wireless sensors networks (WSN). A few companies [2-4] are offering products such as radios (motes) and sensor interfaces. The motes are battery-powered devices that run specific software. In addition to running the software networking stack, each mote can be easily customized and programmed, since it runs open-source operating systems which provides low-level event and task management. Mote Processor/ Radio module families working at 2.4 GHz ISM band and supporting IEEE802.15.4 and ZigBee are available. However, the implementation of a wireless bus in certain applications requires compact and miniaturized solutions. Moreover, a chip-size antenna included in the RF microsystem will be crucial, as is the case presented in [5] for application in wearables. However, this type of solutions are to much expensive for use in industrial networks. Moreover, low-cost and ready-to-deploy solutions are more attractive for the Portuguese's small-and-medium industries (PMEs), as is the case of restaurants and snack-bars, where it is mandatory to make the temperature record and logging of the frizzing cameras on periods not more than an hour. If this is not respected, the ASAE (*Autoridade de Segurança Alimentar e Económica)* organism acts in conformity, and penalties going from monetary dues to the close of the facilities are some of the consequences to work out of the law. This requires the use of an automated and efficient process to make the record and logging. One of the possible solutions relies in a wired infrastructure. However, this can be a problem, specially in older facilities, where holes must be made in the wall to pass the cables. Another way is the installation of a wireless infrastructure, in which a multi-hop networks can be installed without making severe changes in the facilities with the advantage to be easy to increase the number of network nodes. Moreover, other nodes with other type of functions can be installed. To finish this paper presents a wireless sensor network, which were developed for industrial applications with a low-cost in a ready to use fashion. The next section presents some WSN aspects that were behind this network.

II. IMPLICATIONS OF THE RADIO SYSTEM

In the majority of the applications, the contributions of the electronics in a node has a low contribution in the total power consumption of this node. In fact, the fact of the available technologies be more and more low-power, this don't relief the fact the transceiver be the bloc with the bigger power consumption [6]. The co-investigation of new architectures and algorithms of control, is a topic of increased interest, e.g., it is even more important to know the detailed implication of radio-frequency (RF) system in the power consumption [7].

The first step to save power, is to guaranty that the network work the lowest usage periods, e.g., the working time of the network is T_u [s], for a total living time, T_f [s], is the smallest. The next step, is the use of the more suitable clock frequency, e.g., if the transceiver is not transmitting neither receiving, the use of a small frequency clock to make local signal processing, will help to save power. Moreover, to save more power, after finish the processing, the node can enter in the sleep mode [8]. The next two key-factors to reduce the power consumption, are the start-up and the transmission times. The first one is the time that lasts between an enable order and the instant the electronics starts to work. The second, is the time to send a complete packet of data. The optimisation of these times gives a big contribution in the power consumption reduction of the transmitter. Normally, the nodes for low-power applications has low usage periods (duty-cicles), as well as short packet lengths, thus, the start-up time can have a significative impact in the whole power supply. In the context formerly presented, the transmitter must send the data in the lowest period of time (high baud-rates), while simultaneously must present the lowest start-up time [9]. Another way to save power is to process data before to be transmitted. Low volumes of data, requires less time in the transmission, e.g., it implies low power consumptions [10]. Furthermore, the loss of data or receptions with errors must be avoided, in order to don't have unecessary wastes of power [11]. Moreover, the nodes must be able to select the lowest but suitable power transmission, in order to save power to. A receiver strength indicator (RSSI) is of major interest to achieve this goal. Basically, a RSSI is an envelope detector followed by a logarithmic amplifier [12]. Known the transmitted power and once the received power is obtained, the next step is to select the power of transmission. Unfortunately and contrary to the transmitter, the number of available options to the receiver are very limited, because this one can't know exactly when a data transmission is targeted to it, thus, the receiver must always be activated and receiving data [11]. The only solution, is to use the RSSI circuit detect the presence of a carrier with a significant power and use this event to wake-up the network node. Even the used modulation can be a limiting factor, due to the power consumption. A remind must be made in order to say that compared with a simple narrow amplitude modulation (AM), the use of a direct sequence spread spectrum (DSSS) technique available in the IEEE 802.15.4 has the advantage to make the data transmission more reliable, with the cost of an increasing in the power consumption [13,14]. To finish, in wireless communications, the antenna is one of the most critical subsystem, thus, in order to not compromise the desired miniaturization, the antenna must be small enough to comply with size constraints of the microsystems. The investigation of new frequency bands [15] and new geometries [16] will make possible to have smaller antennas to integrate in wireless microsystems [5,17]. This makes the chose of the most suitable frequency, one of the more decisive aspects in the design of RF transceivers. Normally, the desired range, baud-rate and power consumptions are key-aspects in the design to take in account, when the frequency of operation is to be selected. At a start-up point, the range limits the maximum usable frequency, because the loss suffered by the radiowaves in the free-space increases with the distance. However, to keep or even increase the useful life of the batteries, such a variation in the transmitted power is not possible to do. Moreover, in the case of applications requiring higher baud-rates, the transmitted bandwidth must also be higher, in order to support these applications. However, the frequency can't be arbitrarily increased, because this have implications in the power consumptions, e.g., at high frequencies, the transistors must switch faster, thus the energy dissipation will be bigger.

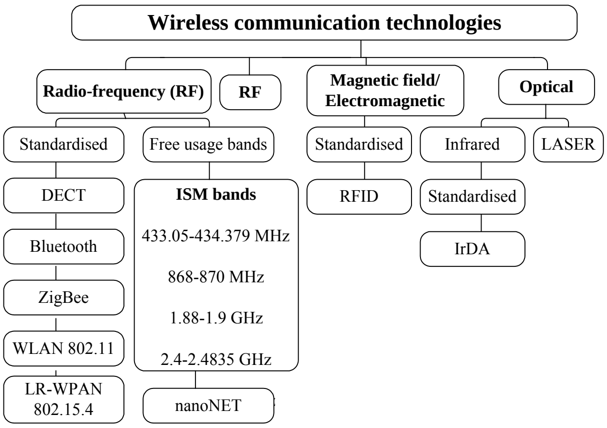

Figure 1: Available frequency bands and respective applications.

Figure 1 shows the available frequency bands for the different technologies used in wireless communications. The most suitable frequencies are those belonged to the so called ISM band (Industrial, Scientific and Medical), which are not subjected to standardization and can be freely used, since the emitted power are maintained below the maximum levels imposed by the legislation. Such a flexibility leaded to the rising and spreading of interesting applications.

III. IMPLEMENTATION OF THE WIRELESS SENSORS NETWORK

A. *System architecture*

The fabricated network nodes has sensors readout, which are constituted by analog-to-digital converters (ADCs) of eight bits, digital circuits to control the read-outs, by the Microchip's PIC16F628 microcontroller, which provides basic services for communication purposes. The core services also makes possible the extension of additional services. The Figure 2 shows the block diagram of network nodes, which contains the supracited sensors read-out, the RF interface and a optional RS-232 interface to transfer data towards an external laptop computer, a PDA or a mobile phone.

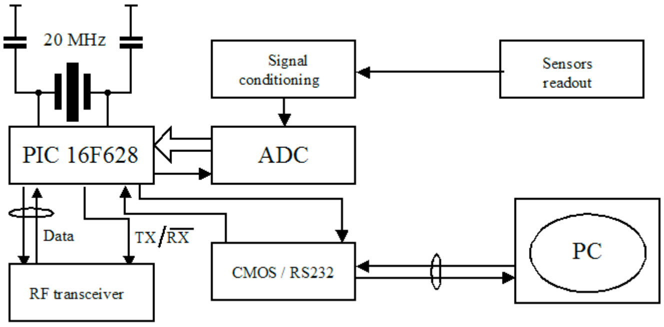

Figure 2: The block diagram of the wireless sensors network nodes prototype.

The prototype uses a commercial RF transceiver, which operates at 433 MHz. The microcontroller PIC16F628 was select, due to its frequency clock of 20 Mhz, which corresponds instructions with an execution speed of 0.2 µs. Using this clock, and the maximum baud-rate of 40 kbps imposed by the RF transceiver, a total of 500 instructions are executed for each transmitted bit. However, and as will be discussed further, the implemented line code reduces the effective baud-rate to half, e.g., doubling the processing time for each transmitted bit.

B. *Frame formatting*

As shown in Figure 1, two types of frames were defined: the general use and the command frames.

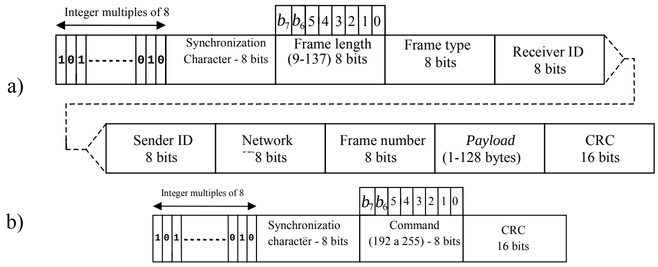

Figure 3: Existing fields in a) the general use and in b) the control frames.

The general frames has two purposes, one is to carry information in the payload field between the nodes and the base-station, in a coordinator fashion. The second function is to send commands from the base-station to the network nodes. The command frames are used by the base-station to send commands toward the network nodes that were already identified by the base-station, where the need to identify it, is not needed. These frames sends commands that are quickly identified, such as confirmations of good (ACK-

Acknowledgements) or bad reception (NACK - Nacknowledgements) of previously received data. In the first frames, the payload length is variable. In the case of this frame be used to send commands, the field Frame type is 01h (00 00 00 01b), its length is minimum and is of only nine bytes. The default case is when the frame carries data, e.g., the value in the Type field is 00h (00 00 00 00b). In the future, additional types can be defined, for values in the Type field of 02h (00 00 00 10b) of higher. These frames, allows to identify the destiny (the receiver), to numbering the network and to check with the help of the CRC field, the existence of transmission errors. This is also allowed in command frames.

C. *Line coding*

This is perhaps the most important issue in the WSN. Very long sequences of ones or zeros can result in a data imbalance, which can cause the lost of carrier and bad symbol synchronisation. To have a good data balance, e.g., one level transition for a set of two consecutive data bits, a sequence of two symbol bits are transmitted at twice the effective baud-rate (the data-rate). The symbol bits sequences '10' and '01' are transmitted, when the information bit '1' or '0' is to be send. Moreover, this scheme also helps to synchronise the clock of the receiver with the clock of the transmitter [18].

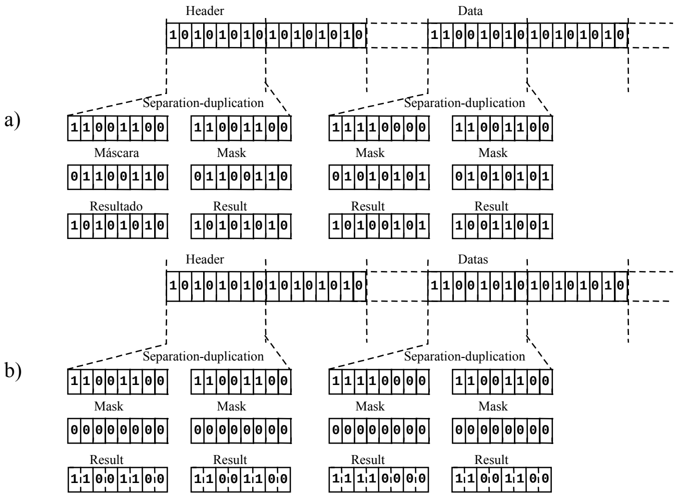

Figure 4: Used masks when the Manchester code a) is applied to the frames, and b) for uncoded frames.

As shown in Figure 4, before a node send the byte $b_7b_6b_5b_4b_3b_2b_1b_0$, a program call must be made, to divide that byte in two parts, and to create two new (separated) bytes $b_7b_7b_6b_6b_5b_5b_4b_4$ and $b_3b_3b_2b_2b_1b_1b_0b_0$. If the older byte belong to the header, then the exclusive or (XOR) is executed in the two new bytes, using the mask "01 10 01 10b". However, if the older byte don't belong to the header, then the XOR is made with the mask "01 01 01 01b". Independently the result of the XORs, the two resulted bytes are transmitted at the twice the data-rate of the information contained in the frame. If the user choices to not code the frames, then the same program is also called, but the mask is always "00 00 00 00b". In this case, a data balancing will not ensured. Compared with the coded case, and in order to have a real double data-rate, the software must double the processing rate.

D. *Synchronisation of frames*

To a correct reception of frames, the receiver must evaluate with accuracy the start of the frames. As depicted in Figure 5, this is done using a window, which is no more than a FIFO with a capacity of 16 bits, which is filled with the symbol bits as they arriving. This window starts to fell the presence of the header, and as soon as the synchronisation character (FAW) is fully received and fully fills the FIFO, then the reception of the frame and the data in the payload fields will start to happen. Figures 5 and 6, illustrates this process taking the synchronisation character 1Bh (00 01 10 11b) as an example.

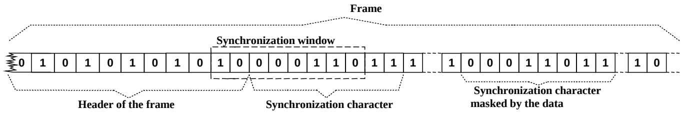

Figure 5: Window to detect the synchronisation character 1Bh (00 01 10 11b).

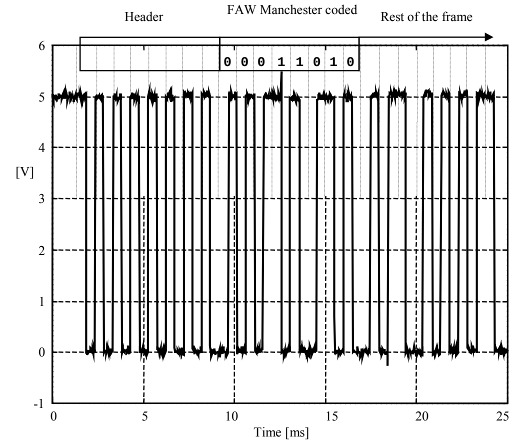

Figure 6: Acquired received base-band signal, where it is possible to observe the header and the synchronisation character 1Bh (00 01 11 10b) , which is Manchester coded, "01 01 01 10 - 10 01 10 10b".

E. *Error controlling*

The data transmission is not immune to errors in the channel. Thus, it was defined a error control field with a length of sixteen bits, in the footer of both types of frames, e.g. the CRC (cyclic redundancy check) field. The CRC is correlated with the transmitted data. After receiving the entire frame, the receiver make the calculation of CRC of that frame and then compares this value with the CRC contained in the footer of the frame. If both CRCs are equal, the receiver assumes that the data were received without errors. In the opposite case (inequality of the CRCs) the data has errors.

The CRC is generated according the polynomial [19] $p(x)=a_{16}x^{16}+a_{15}x^{15}+a_{14}x^{14}+\ldots+a_2x^2+a_1x+a_0$. The values a_k are zeros or ones, and imposes the existence of each of the feedback connections illustrated in Figure 7.

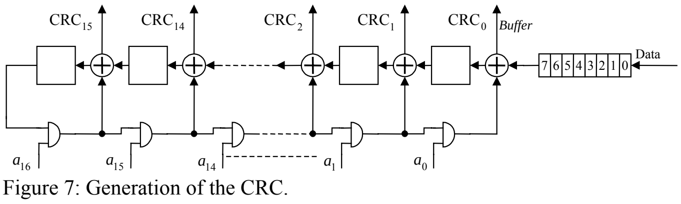

Figure 7: Generation of the CRC.

The CRC generation is very simple, and it is based on a calculator (CALCproc) procedure, which is called the number of the bytes to be used. The content of the shift-register (SR) of Figure 7 is cleaned and after an execution of the CALCproc, its value remains in the SR, in order to be available to the next byte to be processed. The CALCproc has an eight bits buffer to store and to make eight shifts duribg each call. The values CRC_{15} to CRC_0 give the temporary CRC number to be transmitted. This number also remains in the SR, until the last byte be fully processed, which is the CRC number to be encapsulated in the frame. After a complete frame construction, the SR is cleaned again and will be ready to the next CRC generation.

F. Hardware specificities of hardware implementation

In order to avoid deadlocks, it were implemented timeout mechanisms. The timeout makes a node to avoid the situation to be eternally waiting to receive a frame, which will never arrive. Moreover, the synchronisation of the receiver's clock with the transmitter was implemented, in order to avoid the lost of frames, due to bad timing references.

The timeout detection was make with the use of the PIC16F628's Timer 0 [20], which is set to a given value before a receiving operation to take place. A periodically decrement is made to this timer, while the start of a receiving frame is not detected. If the content of the Timer 0 reaches the null value, then a timeout event is declared by the node, and the receiving operation is aborted. A clock with a frequency of 20 MHz, allows to have fine variations of 13.1072 ms, and coarse variations for multiples of this value.

To make the synchronisation with the transmitter, it was used the PIC16F628's Timer 2 [20]. This timer is always initiated with the same value (PV), and it is putted to run continuously without stops. Then, every time a overflow is experimented, it will auto-initiate with the previously value, PV. The electrical state of the transmitting line is updated (e.g., a new bit is transmitted), whenever an overflow occurs. In this situation the flags are cleaned and it will start all again for the next bit. The new bit is putted in the line only with a new overflow. In the receiver's case, the process is identical. The crystals used in to provide the clock to the microcontrollers presents deviations from the nominal frequency of oscillation. This is not a problem for short frames, where the error integration can be neglected. In order to avoid the lost of data, for a clock with a tolerance of $\pm p$ [ppm], the number of bits, N_b, in the frame must be less than $(1\pm p)/p$.

G. Acquisition versus transmitting times

The known of the acquisition time and its comparation with the processing time is of extreme importance, because it allows to account the samples lost. In other words, it can happen the microntroller be executing other functions, which don't include the pure physical acquisition. In this case, some samples of real data can be lost. Thus, it must be known exactly what is the function of the network nodes, in order to don't happen this lost of data. Assuming a scenario with a number of network nodes, N_{nodes}, which are located at the distance d_k [m] from the base-station, and ready to transmit frames with a length of $N_{oct,k}$ bytes after a successful acquisition. Assuming also that the summing of the processing times in the transmitter, t_{proc_TX} [s], is constant and equal for all the nodes, as happens with the processing time in the receiver, t_{proc_RX} [s]. Moreover, the base-station has enough memory storage capacity, to transmit and to receive data. In this scenario, in order to avoid the lost of data, the (Manchester code or other) uncoded baud-rate, r_b [bps], must be at least:

$$r_b > f_s(N_{nodes} \times [9 + \underset{k}{max}(N_{oct,k}) + \underset{k}{max}(N_{control,k}) + 2N_{header}]) \times$$
$$\times 1/[1 - f_s \times N_{nodes} \times \left(\frac{2\underset{k}{max}(d_k)}{c} - t_{proc\_TX} - t_{proc\_TX} \right)] \qquad (1)$$

where N_{header} is the number of bits in the header. This equation is valid for both the general type and command frames, where for k^{th} node, $N_{control,k}$ is nine (#9) one (#1), respectively.

IV. CONCLUSIONS

This paper presented a industrial ready-to-install WSN, which were developed with the use of low-cost commercial components. It was also presented hot-features concerning its implementation.

REFERENCES

[1] P. Choi, *et al*, "An experimental coin-sized radio for extremely low-power WPAN (IEEE 802.15.4) application at 2.4 GHz", IEEE Journal of Solid-State Circuits, December 2003.
[2] Crossbow Inc., **www.xbow.com**.
[3] Dust Networks Inc., **www.dust-inc.com**.
[4] Sensicast Systems, **www.sensicast.com**.
[5] J. P. Carmo, *et al*, "5.7 GHz On-Chip antenna/RF CMOS transceiver for wireless sensor networks", Journal Sensors and Actuators A - Physical sensors, Vol. 132, pp. 47-51, Elsevier Science 2006.
[6] C. Enz, *et al*, "Ultra low-power radio design for wireless sensor networks", in Proc. IEEE International Workshop on Radio-Frequency Integration Technology, Singapore, November 2005..
[7] S. Bicelli, *et al.*, "Implementation of an energy efficient wireless smart sensor", in Proc. XIX Eurosensors, Barcelona, Spain, September 2005.
[8] C. Enz, *et al.*, "WiseNET: an ultra low-power wireless sensor network solution", IEEE Computer, Vol. 37, Nr. 8, pp. 62-67, August 2004.
[9] S. Cho, *et al*, "A 6.5-GHz energy-efficient BFSK modulator for wireless sensor applications", IEEE Journal of Solid-State Circuits. May 2004.
[10] I. F. Akyildiz, *et al.*, "Wireless sensor networks: a survey", Computer Networks, Elsevier Science, Vol. 38, pp. 393-422, 2002.
[11] E. Mackensen, *et al*, "Enhancing the lifetime of autonomous microsystems in wireless sensor actuator networks (WSANs)", in Proc. XIX Eurosensors, Barcelona, Spain, September 2005.
[12] AD8309: 5-500 MHz, 100 dB demodulating logarithmic amplifier with limiter output datasheet, Analog Devices.
[13] E. Callaway, *et al.*, " Home networking with IEEE 802.15.4: A developing standard for low-rate wireless personal area networks", IEEE Communications Magazine, pp. 2-9, August 2002.
[14] J. Gutierrez, *et al.*, "IEEE 802.15.4: Develping standards for low-power low-cost wireless personal area networks", IEEE Network, Sept. 2001.
[15] N. Celik, *et al*, "Implementation and experimental validation of a smart antenna system operating at 60 GHz band", IEEE Transactions on Antennas and Propagation, Vol. 56, No. 9, pp. 2790-2800, Sept. 2008.
[16] P. M. Mendes, *et al*, " Integrated chip-size antennas for wireless microsystems: Fabrication and design considerations", Journal Sensors and Actuators A, Vol. 125, pp. 217-222, January 2006.
[17] F. Touati, M. Pons, " On-chip integration of dipole antenna and VCO using standard BiCMOS technology for 10 GHz applications", in Proc. 29th ESSCIRC, pp. 493-496, Estoril, Portugal, September 2003.
[18] B. Carlson, Communication systems - 2nd edition, McGraw-Hill, 1986.
[19] Microchip, CRC generation and checking. Application note 730, 2000.
[20] Microchip, PIC16F628 data sheet, 16-pin Flash 8-bit microcontroller.