Place-&-Play Industrial Router addressing Potential Explosive Atmospheres

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Abstract — In general, deployments of Wireless Sensors Networks in industrial rigs face several constrains, especially those concerning power supply of scattered devices: cabling is expensive and takes a long time, and, on the hand, batteries are sensitive to both current peaks and high temperatures, thus requiring periodic replacement. This work presents a low power router which, by gathering energy from a tiny solar panel and storing it in a supercapacitor, addresses the stringent regulations that have to be met to work in potentially explosive atmospheres and, still, keep working continuously so as to serve communication requirements of wireless networks in such harsh environments: evaluation of the energy balance under different harvesting and consumption conditions was carried out, whose results ensure the feasibility of this technology.

Keywords — wireless sensor networks; energy storage; energy harvesting; potential explosive atmospheres.

I. INTRODUCTION

Wireless Sensors Networks (WSN) suit low-range clusters of smart sensors for industrial applications and may also address control devices, since the network is able to guarantee both real-time performances and high robustness. In industrial WSN, routers play a key role in the integration of wireless devices that may be deployed in large numbers across large-scale plants in the process industries sector, thus ensuring connectivity amongst field devices and remote application interfaces. Thus, though implementing mesh topology, and mechanisms of channel hopping and synchronism, very often network robustness ultimately relies on the capabilities of routers. Beyond being continuously ‘alive’, so ensuring real-time response, industrial routers have to be prepared to handle data from different clusters and participate on network security [1] [2] [3]. Thus, beyond network resilience, power supply options are critical in the decision process of replacing wired, reliable solutions by new low-cost and easy to deploy wireless technology. In fact, it is clear for industry how expensive is installing cables upon addition of a few more instruments; in refineries, for instance, cables on trays must be covered with flame-retardant coatings, according to the Bill of Specifications (BoS) of each process, and according to both regulations and good practices. Also, most of industrial rigs are shut-down for maintenance every 4 years’ time, so that replacing hundreds of batteries in shorter periods becomes inadmissible. Moreover, energy storage elements, especially in outdoor areas, are subjected to wide temperature variations, and have to endure current peaks whenever supplying radio units; batteries’ lifetimes have a huge dependency on these operating conditions and, therefore, do not represent the best option in these application scenarios. Furthermore, rechargeable batteries face yet another limitation: the charging process, whose heating makes it virtually unfeasible in devices directly exposed to the sun. On the other hand, supercapacitors can handle both current peaks and wider temperatures ranges more easily, even while being charged [4]. Besides, this energy storage technology permits an almost complete energy draining, and a number of charging cycles – usually 10k cycles –, much higher than secondary batteries. That means that a router based on this technology would be ‘alive’ for 30 years, provided it might be fully charged every day. This is of paramount importance in the most dangerous ATEX areas, for energy storage devices are hard to be replaced in there, even because they must be buried in epoxide-type materials, so as to meet IEC 60079 standard regulations.

Energy harvesting from light sources is a natural path on a significant number of WSN deployments. In particular, due to the energy density that is commonly available, and, mainly, to the wireless power needs, solar harvesting technology has been deeply studied [5], in cases addressing not only outdoors automation but also indoor environments [6]. Reduced size solar panels are nowadays available, which makes them suitable for application in sensors [7] and routers [8], especially in cases where low-power (sleeping) modes can be considered. Otherwise, full performance routers exist, but are powered up by large batteries and huge solar panels, at costs out of the typical WSN scope [9] [10]. Therefore, for the moment solar cells are the only harvesting technology capable of powering wireless routers, given the demanding profiles in both performance and energy consumption; vibration, thermoelectric and loud acoustic sources are easy to find in industrial rigs, but with much lower power density [11]. Dimensioning supercapacitors to handle communications for several days, and solar panels for fully charge the storage capacity in a few hours at sunny days, may be the key for the wireless dissemination on harsh scenarios, permitting to overcome both cabling costs and the limitations of batteries.

This paper presents an industrial low power router that, by resorting to solar energy harvesting, is capable of ensuring full performance any daytime, and was designed so as to minimize
installation and maintenance costs in potentially explosive gas atmospheres. Section II presents the application requirements, in a specific scope of a Real-time Location System (RTLS), and the main issues concerning the potential explosive regulations to be met. Section III presents an overview of the network protocol, and some advantages of using a dual channel router. Autonomy is then evaluated in section IV, for two different duty cycles, and charging tests in different weather conditions are also analysed. Conclusions are presented in section V.

II. THE LOCATION READER

A. Functional Description

The device was conceived for a RTLS purpose and consists on a router encompassing two parallel radiofrequency interfaces: (i) one addressing the communication with tags – RSSI readings and tags reconfigurations –, and (ii) another one for transporting data over the WSN routers to a Location Engine (LE). As wireless transceivers cannot receive and transmit at the same time [1], a stand-alone router programmed as reader is prone to miss readings from tags whenever handling previous readings to the LE. The aim of a double radio interface (illustrated in figure 1) is to overcome such a possibility.

B. Hardware Structure

A prototype was constructed by resorting to a proprietary technology based on an ISM (Industrial, Scientific, and Medical) sub-GHz radiofrequency (RF) band (433 MHz), given its superior EMC and radio-range in environments hostile to RF signal-propagation. Other RF technologies and network protocols can be considered, depending on previously existing infrastructures.

A block diagram of this device is shown in figure 2, thus representing the major functional blocks and their respective interconnections, as follows:

- A tiny solar panel used to gather energy from the sunlight, and respective adaptation circuitry addressing ATEX requirements, namely “Ex ia” [12], for both current and voltage limitations and connected through a ground ‘make-first’, ‘break-last’ (MFLB) socket;
- Two supercapacitor cells in series, charged with automatic cell balancing in order to prevent overvoltage damage to either of them, while maximizing charging rate with maximum power point tracking implementation (MPPT) – this circuit is protected from overvoltage and overcurrent addressing “Ex nA” [13]; a step-down regulator (TI TPS78233) is then used to bring the 5.2 V obtained from the supercapacitor cells to a constant output voltage of 3.3V;
- A temperature sensor for monitoring the router condition, mainly to evaluate the condition of supercapacitors, which is based on a 13-bit resolution digital sensor (Analog Devices ADT7301), a tiny device that dissipates a very low power (1.6 mA @3.3V when active, and a mere 200 nA in shutdown mode), and relates to the microcontroller via SPI;
- Vibration measuring was added also to monitor the condition of the router, but now concerning its integrity; by sending alarms of violation whenever detecting major impacts – this need is a lesson learned from location solutions, due to the fact that readers are violated occasionally; a very low-power MEMS device (ST Microelectronics LIS3DH) is used, which is programmed to generate an interrupt signal above a predetermined acceleration threshold;
- A control unit addressing local monitoring, such as its own status condition, and the detection of tags and the evaluation of the respective signal strength, which is carried out by an ultra-low-power SoC (TI CC430F5137), that integrates a 16-bit RISC microcontroller and the selected RF solution, by combining the performance of the CC1101 sub-GHz RF transceiver with the MSP430 CPU;
- A second control unit based on the same technology, which is dedicated to route information to the central database or end-user applications;
- A network protocol called SimpliciTi [14] designed by Texas Instruments was used – this is an API for easy implementation on several Texas MCU-radio and SoC solutions; in order to avoid transmission faults due to noise and multipath interferences, the protocol supports frequency agility and a maximum bandwidth of 250kbps.

This router is organized in two different parts (figure 2), due to the fact that supercapacitors and solar panels do not fit the same ATEX norm (moreover, a solar panel solidary with antennas might constrain the performance of each sub-system). The total capacitance of the supercapacitors involved in the router supersedes completely the maximum allowed for it to be intrinsically safe [12]. On the other hand, conformity assessment according to “type N” [13] encompasses an IK (impact) test, to be met by the entire device embodiment. In order to prevent the solar panel damage and guarantee the certification – given that the limiting electronics for this “power supply unit” complies with [12] –, the separation in two embodiments was found to be, by far, the best constructive approach whenever powering autonomous devices – irrespective of form factor – from small solar panels.

![Figure 1: Traffic management scheme.](image)
C. Installation impacts

Costs for a real scenario were projected to a 3D RTLS project in a refinery hydrocracker, in Portugal, with the following dimensions (in meters): 300 in length, 125 in width, and 12-40 in height, depending on platforms and processing towers. A solar harvesting router may cost about the double of an equivalent cable powered up one, but the installation cost of the latter may count 10 times as much as that of the former – in the scenario referred to above, the overall cost of the wired solution approximately doubles that of the wireless one. This evaluation was obtained considering 20 routers in each case, with the respective attachment accessories and installation manpower; for a wired solution, cables, junction boxes, cable coatings and additional manpower were accounted for.

In order to understand the impact in the present application, an evaluation was made based on the analysis at the level of the Data Link/PHY layer: as mechanism of access control, SimpliciTi uses a non-persistent CSMA [15], which waits a random time when the channel is found busy, before trying to transmit again. Due to its ‘pessimistic’ nature, the non-persistent CSMA performs better under heavy traffic loads, rather than situations of sparse communication [16]. Tests made with SimpliciTi communication frames, with fixed 9-byte payloads, without security, led to results as presented next.

Thus, results shown in figure 3 report to situations where a tag broadcasts a frame to all routers in range, and each of these will forward that message frame: a higher throughput in the forwarding process is required, comparing to the receiving process. If using a router communicating over a single channel, the respective data rate becomes conditioned by the forwarding process only: setting higher data rates in the receiving process will lower the range for receiving messages from tags [17]. But, with two different channels permanently ascribed to either functions of receiving and transmitting, a router may perform differently, i.e., at different data rates for receiving from tags and for transmitting information to the upper level: in this manner, the communication range between n tags and k routers is increased, with no penalty to the high data rates required to dispatch n.k messages. Furthermore, dual channel operation also contributes to minimize the collision probability in the RSSI reading process, thus improving the estimation precision.

Figure 2: Diagram block of the Router circuitry.

III. NETWORK ANALYSIS

SimpliciTi addresses cheap battery-powered devices with low energy consumption, thus allowing for both solutions of MCU plus radio unit, and SOC solutions which embed radio and MCU in a single chip. The protocol defines three types of devices: access point, range extender and end-devices and, therefore, the system is structured so that the router is an access point device, while the localization tags are end-devices.

SimpliciTi protocol encompasses three layers: Application, Network and Data Link/PHY. The Application layer includes native applications (such as “ping”) that enable network management. The Network layer (NWK), constitutes an abstraction for the Application layer and provides access to some networks parameters, such as data rate, modulation, frame size, etc. Finally, in the Data Link/PHY layer there are two modules known as Minimal RF Interface (MRFI) and Board Support Package (BSP), which are responsible for the communication between different radios.

Figure 3 - Number of frames with 9-byte payloads.

IV. ENERGY BALANCE

A. Overall energy storage

Under continuous operation, with the profile presented in TABLE I, this device will take about 119mW of power. This is the profile of one SoC receiving messages from tags, and another SoC transmitting one message per second, and listening to other routers while not transmitting. An ideal autonomy would guarantee full performance operation for 3 to 4 days under cloudy weather conditions.
For this evaluation, two 3000 F supercapacitors (2.7 Vdc) were installed in series, thus allowing a full charge voltage of 5.4 Vdc to be reached, for a nominal capacitance of 1500 F. Considering an operation in between 5.2 Vdc (optimal charging point) and 2.1 Vdc (minimum voltage for processors to work), the energy provisioned is 17 kJ; in this scenario, about 40 hours of continuous work, with no light, can be expected.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Power consumption</th>
<th>SoC 1 profile</th>
<th>SoC 2 profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitting</td>
<td>75.9 mW</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>Receiving</td>
<td>59.4 mW</td>
<td>100%</td>
<td>99%</td>
</tr>
</tbody>
</table>

### B. Solar energy harvesting

The correlation between the intensity of charging currents and the weather conditions was evaluated, with the router operating in circumstances according to profiles described in TABLE I. A monocristalline solar panel of 17x17cm in size was used for a number of experiments (and in the final prototype), providing a maximum power of 3.6 W at a nominal voltage of 6 Vdc.

Extensive tests were held at eneida® wireless & sensors [18], in March 2014, always in the morning until 13:00 hours, having the solar panel facing West, in the shadow of a building, as shown in figure 4. As predictable, the highest charging current occurred in conditions of a clear sky, with supercapacitors at 2.5 Vdc, and, irrespective of weather conditions, full charge was obtained in less than a day’s time, irrespective of weather conditions. But, obviously, the intensity of charging currents and, therefore, the time to reach full charge greatly depends on the existing daylight which, in turn, varies with the weather conditions and the time of day. Hence, in order to have a picture of the efficiency of the solar panel as a transducer, current measurements were taken at different daylight conditions and the respective times to reach full charge were determined based on charging increments measured every 30 seconds, for a time period – TABLE II. summarizes the relevant results. In short, as a measure of feasibility, a device of this may be expected to get fully charged (from 2.75 Vdc) and, therefore, provide continuous operation, even on a cloudy day, considering 12 hours of daylight (what is real for March, in Portugal).

### C. Autonomy evaluation

Live tests were performed, starting at 5.2 Vdc (full charge condition), the solar panel having been removed. In this kind of test, one SoC was configured for receiving messages from a personal tag, and the other one to retransmit all received messages (as got from the first SoC, via SPI) to a gateway connected to a server. Two systems were tested simultaneously, using 3 RF channels, one for each tag, and the other for the gateway. Tags emitting a blast were configured with different duty cycles: 1s, and 1 minute. In these WSN, transmitted messages occupy the carrier for 10 ms, the results of the respective discharging regimes being shown in figure 5.

### D. Discussion

Practical results are consistent with the estimated ones. The system that had been configured for a duty cycle of 1s lasted for 44 hours and stopped transmitting at 2.0 Vdc. The other system reached 2.3 Vdc after 53 hours working. In figure 5, a mean voltage drop of 1 Vdc per night can be noticed.

![Figure 4: Router elements on charging tests.](image1)

![Figure 5: Supercapacitor discharging at different operation duty cycles.](image2)
Considering a minimum light level to maintain the voltage on the storage devices during daylight, these results are consistent with an expectation of full, continuous operation of this router for a period of 3 days. Data referring to 11h30, in TABLE II, corresponds to a condition of no direct exposure to the sun, once a building still projects its shadow over the panel; still, charging power already doubles power consumption. Based on these results, it is sensible to forecast that these solar powered WSN routers are appropriate to work, with no compromise, in all parts of the world where daylight lasts for a minimum of 6 hours’ time. In places with no such conditions, amorphous solar panels should be selected [6] to harvest energy from artificial light.

V. CONCLUSION

A solar powered WSN router addressing harsh and potential explosive environments was designed and evaluated, so as to meet the everlasting economic objectives throughout industrial sectors, and, especially, the stringent constraints that have to be met to work in potentially explosive atmospheres, according to IEC 60079 regulations.

In order to support safety applications involving high data volumes, such as RSSI-based location system, this router was designed for permanent operation over two RF channels, so as to take advantage on both sides: (i) increasing the communication range with tags, at a low data rate yet appropriate to sparse messages, and (ii) using high data rates to upload all incoming messages from a number of tags.

Also, given the typical high temperatures and electric current peaks that such devices must endure, energy is stored in supercapacitors rather than in batteries – a supercapacitor is the best choice to store energy obtained from energy harvesting technologies. In this specific design, resorting to tiny solar panels proved to be more than adequate to support full, continuous operation of a critical routing device.

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