Self-Powered Wireless Sensor Nodes for Monitoring Radioactivity in Contaminated Areas using Unmanned Aerial Vehicles

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***Abstract*— A self-sustainable wireless sensor node for the monitoring radiation in contaminated and poorly accessible areas is presented. The node is designed to work in collaboration with an unmanned aerial vehicle used for two essential mission steps: air-deploying the wireless sensor nodes at suitable locations and acquiring data logs via ultra-low power, short-range radio communication in fly-by mode, after a wake-up routine. The system allows for the use of off-the-shelf components for defining mission, drop-zone and trajectory, for compressing data, and for communication management. The node is equipped with a low-power nuclear radiation sensor and it was designed and implemented with self-sustainability in mind as it will be deployed in hazardous, inaccessible areas. To this end, the proposed node uses a combination of complementary techniques: a low-power microcontroller with non-volatile memory, energy harvesting, adaptive power management and duty cycling, and a nano-watt wake-up radio. Experimental results show the power consumption efficiency of the solution, which achieves 70uW in sleep mode and 500uW in active mode. Finally, simulations based on actual field measurements confirm the solution's self-sustainability and illustrate the impact of different sampling rates and that of the wake-up radio.**

Keywords*— *Energy harvesting, energy management, energy neutral WSN, WSN, radiation monitoring.

I. INTRODUCTION

The continuous monitoring of ambient radioactivity over wide contaminated areas has become a hot topic, as dramatically illustrated in the aftermath of the Fukushima Daiichi nuclear power plant incident in March 2011 [1]. However, conventional radioactivity monitoring systems face severe drawbacks when having to continuously monitor an extensive, inaccessible, and hazardous area. In fact, they generally cannot be deployed safely, quickly, flexibly and effectively in potentially contaminated areas, as there may be physical obstacles, a lack of communication infrastructure, and an unknown level of exposure. Their deployment is not automated further increasing potential human exposure or is restricted to ground robots with limitations in terms of speed and coverage area. As a general result, most systems are uneconomic in terms of installation, operation, maintenance and mission fulfillment.

More recently, wireless sensor networks (WSN) have become a mature technology for a wide range of applications, among them environmental monitoring, healthcare, security, and industrial surveillance, mainly thanks to the flexible distribution of WSN nodes [3]-[4]. WSN offer a new approach to the above mentioned challenge of ambient radioactivity monitoring, as they eliminate the dependence on in-place infrastructure and on-site manpower [5]. On the other hand, the operational lifetime of the WSN's individual sensor nodes is limited by energy constraints as wireless sensor nodes are commonly powered by batteries. Power consumption for long term monitoring is an even more critical constraint when applications require long-range communication technologies (e.g., GSM, WLAN) and/or power-hungry devices such as Geiger-Müller counters, traditionally used as radioactivity sensors [6]. To overcome the obstacle of power consumption in long-range communication, novel approaches which combine WSN with Unmanned Aerial Vehicles (UAV) or Micro Aerial Vehicles (MAV) are gaining increased attention, due to their potential for reducing the power consumption of long-range communication and for accessing hazardous areas. In these new systems, there is a clear separation between the short-distance communication of the WSN and the long-range communication performed by the UAV vehicles, once they have collected data from the WSN [11]-[13]. New technologies can further reduce power consumption by limiting the radio activities to their strict minimum, as is the case with a wake-up radio (WUR) [20], or dynamically reducing the sensor's sample rate when the battery level becomes critically low to guarantee the self-sustainability of the nodes in applications where their inaccessibility prohibits a change of batteries. Finally, energy harvesting (EH) is becoming an established method for enabling long term monitoring by WSN and has been employed in several applications involving self-powered systems [8][22].

New criteria are needed in the hardware and software design of both the nodes and their communication. Combining low-power design, power management techniques and EH increases network lifetime by several orders of magnitude compared with conventional WSN, due to increased energy availability and reduced power consumption [15][16]. Node networks with a very long or even unlimited operating life become feasible. There is, of course, a trade-off between effective energy management and monitoring quality [16].

In this paper, we describe the design and the implementation of a self-powered wireless sensor node suitable for deployment by UAV for radioactivity monitoring in contaminated areas. Its main features are a high sustainability and long life-time. We achieve this by using solar energy harvesting, adaptive power management for unpredictable EH conditions, high endurance non-volatile memory for reliable data acquisition (DAQ), and an optimized wake-up procedure to minimize energy waste during idle-listening, providing a purely asynchronous mechanism.

The remainder of the paper is organized as follows. Related work is presented in section II. The proposed sensor node's architecture is discussed in detail in section III. The proposed algorithms for our node's self-sustainability are shown in section IV. Section V presents the experimental results and simulation for evaluating the proposed solution. Finally, we conclude our work in section VI.

II. RELATED WORK

Research on WSN has been very prolific in recent years with a variety of solutions in a wide range of application scenarios. Between them, there are many examples of implemented and deployed WSN that attempt to exploit intelligent sensing, wireless communication and computing abilities to monitor environmental phenomena [1]. In this area, WSN have recently been regarded as a promising candidate for contaminated or dangerous areas, especially after the Fukushima disaster to monitor nuclear radiation [5]-[12]. Nuclear radiation has typically been detected via hand-held Geiger-Müller counters which are particularly suited for detecting radioactivity via the strongly ionizing effect of alpha particles [6]. Geiger-Müller Counters (GMC) can also be used for radioactivity detection in autonomous WSN sensor nodes [9]. In [7], the authors propose a radiation sensing node with a GMC to be used in nuclear facilities. However, the limitations of using GMC's in terms of size (mainly dictated by the tube length), weight, cost and power consumption make them a poor choice for miniaturized, low-energy, low-cost sensor nodes. In our design, a novel nuclear radiation sensor based on an array of customized PIN diodes is used. The sensor is capable of detecting beta radiation, gamma radiation and X-rays with very low power requirements.

A major challenge in WSN is the limited energy storage capacity in the node, usually in the form of batteries or supercapacitors. The use of energy harvesters in combination with energy storage elements attempts to overcome this issue, and in some applications even achieves self- sustainability [16]. Researchers have been very active in this field, and many promising approaches are presented in literature [8][16][19]. In applications where wireless sensor nodes monitoring contaminated areas are expected to operate long-term without human maintenance, EH is essential. As they usually imply an outdoor setting, the most commonly available ambient energy sources are photovoltaic, wind turbine or mechanical energy (harvesting from vibrations or strain) [8]. A photovoltaic energy harvester has been demonstrated as a mature technology to achieve self-sustainability in outdoor scenarios when the system is well designed and dimensioned. In this paper, we target self-sustainability using a photovoltaic cell and a commercial integrated circuit for power management with a small form factor which guarantee state-of-the-art performance in terms of efficiency and power management.

Another important issue for WSN in wide and poorly accessible areas is the nodes' deployment and the collection of data from the base station [18]. Some approaches use GSM band [1], but these approaches are expensive in terms of cost and power and it is not always possible to guarantee network coverage. One recent and promising technique for sensor network deployment is to have a specialized device fly across the monitoring area to collect the data [19]. In this approach, UAV and MAV are enabling the cooperation with ground wireless sensor nodes for cooperative surveillance and tracking operations. In [16][11], the authors developed a system for the cooperation of UAV, static nodes, and mobile nodes, where GPS was used for position estimation. The authors described communication issues between nodes after deployment due to their positioning. In addition to the use of UAV, sensor network deployment using unmanned ground vehicles has received considerable attention from the research community. In [2][12][13], data collection from unmanned explorations or monitoring is proposed. The approach is similar to the one proposed in this paper, however, the authors do not use any power management and EH, and the ground network does not achieve self-sustainability. Moreover, the radio activities are very expensive in terms of power (using Bluetooth or similar power hungry communication) and no low-power mechanisms are used, rendering it unsuitable for long-term self-sustainable monitoring.

In this paper, we present a self-sustainable sensor node able to monitor radiation levels. Surprisingly, there are no research-oriented or market products that offer similar functionalities proposed by our system. The main contribution of this work is the design, implementation and in-field testing of wireless sensor node for hazardous areas which combines energy harvesting, adaptive duty cycling, low power wake up radio and advanced power management to achieve self-sustainability. This approach is demonstrated with simulation based on short-term in-field measurements of power harvested, power consumption and node performance.

III. SYSTEM ARCHITECTURE

The proposed system can be conceptually divided in two parts. The first part is hardware comprising a microcontroller, a radio chip and a WUR, harvester circuits and a radiation sensor. On the software side, we use an adaptive data acquisition algorithm to calculate the radiation levels from the sensor input, and power management techniques to reduce the total energy consumption and extend the node's lifetime.

Figure 1 shows the block diagram of the developed wireless sensor node with its four main units: the *sensor subsystem* with the Teviso RD2014 sensor, the *power management unit*, in charge of harvesting energy, recharging the supercapacitor and powering the node, the ultra-low power *microcontroller unit* with non-volatile memory, and finally the *communication unit* which uses an ultra-low power WUR in sleep mode to detect the UAV's presence and the CC1100L as the main transceiver.

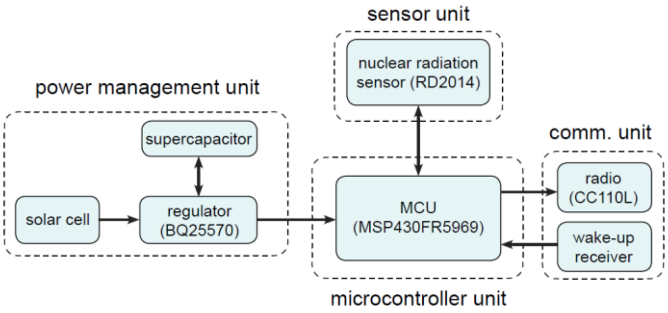


Fig. 1. Sensor node architecture.

Microcontroller unit: The MSP430FR5969 from Texas Instruments was selected as the processing core of the designed node. This microcontroller ensures ultra-low power consumption with enough computational resources and 64KB FRAM, a novel fast on-chip non-volatile memory. The non-volatile RAM is critical for systems with harvesters as it enables data storage even under adverse EH conditions. The microcontroller acquires processes, stores and sends the data via the radio when the UAV is ready to collect them.

Radioactive Sensor: Measuring radioactive levels typically requires the use of an accurate Geiger counter. However, these devices operate at a high voltage range (400-2,000V) [26] and require a Geiger-Müller tube containing an inert gas at low pressure. The Teviso RD2014 solid state nuclear radiation sensor, used in our design, is based on customized PIN diodes which generate temperature compensated TTL pulses. It was chosen because of its low power consumption of only 400µA at 3V, small size and weight. It should be noted that while the number of pulses per unit of time (given in counts per minute, or cpm) depends on the radiation level, the width of these pulses is variable. The width depends on how much of a ray's energy is absorbed by the diode's electron-hole pair. Fig. 2 shows the sensor's response, on a logarithmic scale, with respect to the measured radioactivity. In normal ambient conditions, radiation levels are in the order of magnitude of 50-100 nSv/h. During radioactive emergencies, such as Fukushima Daiichi nuclear power plant incident, the radiation levels reached 2 mSv/h [1].

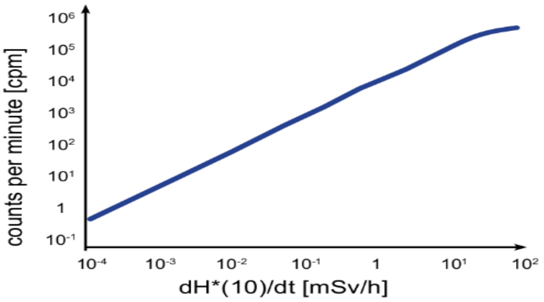


Fig. 2. Sensor response as a function of the radioactivity level.

In order to measure the radiation level, the number of pulses generated by the sensor needs to be counted, and the time taken to reach a statistically significant number of pulses needs to be measured. According to the manufacturer, 1K samples was their threshold for statistical significance. With these two values, the node is able to calculate the equivalent counter per minute [cpm], which can then be translated to a radiation level in [mSv/h] units. The radiation level can be calculated either continuously (with a moving average), or it can be duty-cycled. For a low-power, self-sustainable application, continuous sensing is too expensive, so one must periodically activate the sensor for a limited amount of time. Note that with the radiation levels achieved in Fukushima, the sensor would generate $\sim 10^4$ cpm, meaning that in less than 200 ms, one could obtain a measurement of statistical significance. On the other hand, at normal levels, it would take approximately 1000 minutes. For our application scenario, we have selected a time window of 60 seconds since it can provide an accurate reading in high radiation environments, and it still detects ambient radiation though with less accuracy. The node will make one of these measurements every hour and store the results in non-volatile memory until the UAV passes over to collect the data.

Energy Harvesting: To achieve self-sustainability, a system needs to have EH capabilities. For our application scenario, Sanyo's AM-1417 solar panel fulfills our small form restrictions, and is able to provide enough energy for continued operation despite its small form factor. The power that can be extracted from the solar panel depends not only on its size, which is already fixed at 11.7mm x 35.0mm, but also on the amount of light (luminosity) available, which will be variable. The P-V characterization of the selected solar panel can be seen in Fig. 3. It can be seen that under good lighting conditions, i.e., a luminosity of 10,000 lux, the panel can generate a maximum power of ~0.85 mW. To have the maximum power transfer at different operating conditions and load impedances, the BQ25570 energy harvester circuit was used. This IC implements a maximum power point tracking (MPTT) network that dynamically adjusts its impedance, ensuring maximum power transfer from the solar panel to the energy storage device.

Wake-Up Radio: The radio typically consumes a large amount of the energy in a wireless sensor node. As a result, any optimization that can be made in the communication system has a big impact on the node's self-sustainability requirements. The WUR works as an ultra-low power, always-on receiver detecting specific messages from a remote host. A broad variety of solutions have been proposed addressing the main trade-off between power, range, and addressing capabilities [24]. With a WUR, the node is able to avoid power-hungry idling of the main radio, thereby allowing the radio to enter a low-power sleep state. The main radio will be activated only when the WUR detects a wake-up message. Fig. 4 shows the architecture of the WUR used in this work. Besides the antenna, one of the biggest factors in the receiver's performance and range is the impedance matching network. The impedance matching was optimized for the 915 MHz transmission frequency. Afterwards, a passive rectifier, composed of two high sensitivity demodulation diodes, rectifies the received signal. The signal then goes through a passive filter, which only detects a specific preamble, ensuring the comparator generated the interrupt signal only when the appropriate wake-up message has been received. The receiver was configured to detect a 50 µs on-off keying sequence.

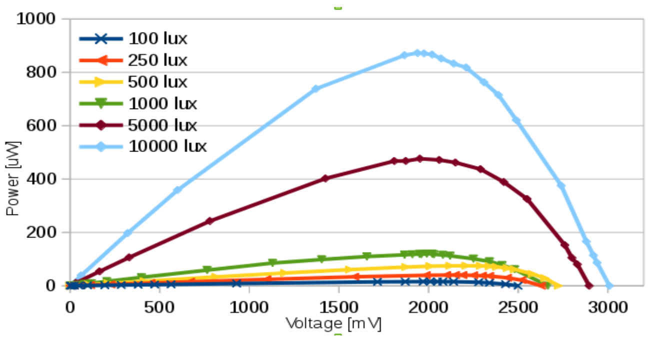


Fig. 3. Solar panel characterization.

Our application scenario does not require any addressing capabilities as the UAV needs to wake up all the nodes in its range. As a result, the receiver's proposed architecture minimizes the total power consumption, which is dominated by the always-on comparator. The AS1976 comparator from Austrian Microelectronics was chosen for its ultra-low power consumption. The implemented receiver's power consumption was measured to be 600nW at 3V. Moreover, in-field experimental results demonstrate the range of 25meter with a 3dBi omnidirectional antenna.

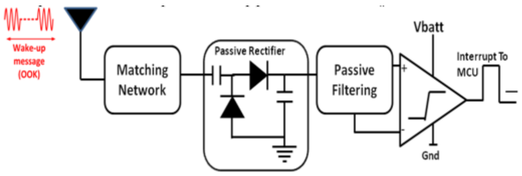
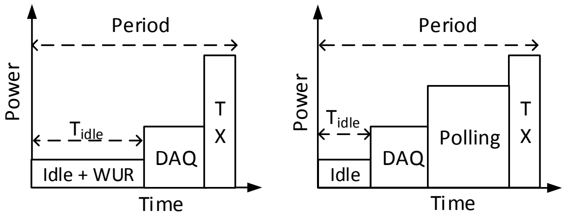


Fig. 4. Nano-watt wake-up reciever architecture.

IV. SELF-SUSTAINABILITY ALGORITHM AND MODELS

The self-sustainability model of our application scenario will now be introduced under two different methodologies, as shown in Fig. 5. The first requires the use of a WUR, which detects the request for data retrieval from the UAV and triggers the data transmission. The second methodology does not use a WUR, but instead duty-cycles a polling mechanism to detect a transmission request. The sensor nodes will periodically register the radiation levels until a transmission request from a UAV is detected.



a). With WUR. b) With Polling.

Fig. 5. Periodic sampling requires several phases: data acquisition (DAQ), transmission (TX), and polling. **Note**: Figures not to scale.

During the data acquisition (DAQ) phase, the radiation sensor is kept active for 60 seconds to obtain one measurement, in which the MSP430 counts the pulses generated by the radiation sensor. During the transmission (TX) phase, the CC110L radio is activated to transmit the data stored in the node. If polling is used to detect the TX request, there is an additional phase (polling), during which the CC110L is activated for 10 seconds every minute, waiting for the UAV's request. If instead a WUR is being used, there is no need for additional polling, since the WUR is designed to be always listening for the wake-up request. This comes at the cost of a slight increase in the idle power, in the order of hundreds of nanowatts. Thus, the energy consumption for both methodologies can be summarized in the following equations:

$$E_{Consumed,WUR} = E_{DAQ} + E_{TX} + E_{Idle\_wur} \quad (2)$$

$$E_{Consumed,\ POLL} = E_{DAQ} + E_{TX} + E_{Polling} + E_{Idle} \quad (3)$$

Where E_{DAQ}, E_{Tx}, $E_{Polling}$ and E_{Idle} are the node's periodic energy consumption from the data acquisition, data transmission, polling and idle phases, respectively.

The nano-watt WUR is an import component in reducing the node's power consumption, since it allows the other components to be in sleep mode and generates an interrupt only when needed. However, minimizing a node's power consumption alone is not enough to reach self-sustainability. Energy harvesting is necessary to replenish the available energy for uninterrupted operation. In our application scenario, the solar panel will harvest energy from the available sunlight, which varies with time. Within a period, the difference in energy can be expressed as follows:

$$\Delta E_{Period} = E_{Harvested} - E_{Consumed} \quad (4)$$

In systems with energy storage, ΔE can either be positive or negative. If it is positive, it means more energy was harvested that consumed; as a result, the amount of stored energy will increase. On the other hand, if the ΔE is negative, it means more energy was consumed than harvested, and the amount of stored energy will decrease.

$$E_{Storage}(t+Period) = E_{Storage}(t) + \Delta E_{Period}(t) \quad (5)$$

Where $E_{Storage}(t)$ and $E_{Storage}(t+Period)$ are the energy storage levels at the time t and t + Period. Since the storage element has a limited capacity, E_{Max}, the storage level cannot surpass it. On the other hand, $E_{Storage}$ has to guarantee that there will always be enough energy to acquire and transmit data when necessary, otherwise data can be lost, and the node will no longer be self-sustainable. This minimal value, E_{Min}, is simply $E_{Consumed}$. Therefore, at any time t, the following equation has to be satisfied:

$$E_{max} \geq E_{store}(t) \geq E_{min} \quad (6)$$

V. EXPERIMENTAL RESULTS

The node presented in Section III has been developed and deployed to carry out experiment results. This section presents the experimental evaluation of our proposed solution. As was shown in Section III, our energy budget is given by EH and energy storage. In order for the proposed solution to be self-reliable, this budget must be large enough for our application requirements. To this end, we present our power measurements for the sensor node during its different states. These

TABLE I. NODE'S POWER AND TIMING CHARACTERISTICS.

Node Phase	**Description**	**Avg. Power (mW)**	**Time (s)**
Data acquistion (DAQ)	MSP430 active, CC110L in LPM3	0.5	60
Data transmission (TX)	MSP430 active, CC110L TX	7	0.100
Polling	MSP430 active, CC110L RX	5	10
Idle	MSP430 + CC110L in LPM3	0.070	3539.9
Idle_wur	MSP430 + CC110L in LPM3 + WUR	0.070	3509.9

measurements demonstrate the viability and self-reliability of our proposed solution.

A. Power consumption measurements

TABLE I. shows the sensor node's power consumption with a 3.3V power supply and with the microcontroller running at 8MHz. The measurements were made for both methodologies proposed in Section IV: 1) WUR and 2) Polling. In both, there will be a DAQ phase and a TX phase with the same power consumption. During the DAQ phase, the MSP430 is in low-power mode LPM3, and counters are used to measure time and register the pulses from the radiation sensor. The pulse from the sensor is useevidenzd as a waking interrupt to update the node's bookkeeping. As a result, the node only consumes, on average, 0.5mW mostly due to the sensor. During the TX phase, the main radio is turned on and used to transmit data back to the UAV. Data transmission is the most power hungry phase, needing 7mw, and lasting approximately 100ms.

When using the WUR, the node enters the ultra-low power *idle_wur* phase, in which the WUR awaits a transmission request. In this state, the node consumes 70uW + 600nW from the WUR. On the other hand, when using polling, the main radio must remain active while listening for a transmission request. This polling is duty-cycled to 10 seconds every minute. This window is large enough to react to a request from a UAV passing over the node to collect the stored data. It should be noted that once data has been transmitted, there is no more need for polling until at least one new measurement has been performed. For our simulations, we modeled the UAV arrival as once per hour, with an average offset of 30 minutes from the node's measurement. This means that for each hour, it will do polling for the first 30 minutes, while for the last 30 minutes, it will remain in the ultra-low power idle mode. In this mode the power consumption will be 70uW, virtually the same as the idle mode with WUR.

B. Simulation and self-sustainability

Fig. 6 shows the experimental measurement from our selected solar panel in an outdoor environment. They show how the amount of sunlight can vary the available power considerably during the day, due to unpredictable weather conditions. In order to demonstrate the self-sustainability of our proposed solution, these measurements are used as input to our Matlab simulation. Based on the model presented in Section IV, it calculates the energy storage level for both the case of polling and a WUR. Fig. 7 shows the results of how the sensor node would operate under the conditions presented in Fig. 6. There are three lines, the dark and light blue represent the polling solution, while the red uses a WUR. The difference between the light and dark blue is that the dark blue is configured to have a high reactivity. The dark blue line keeps the main radio listening for 10 seconds every minute. While this reactivity is desirable, it can be seen that it comes at a considerable energy cost. Indeed, the node is without any energy for almost half of the time. The light blue line, on the other hand, has a much more relaxed reaction time. Here, the main radio is kept on for 10 seconds every 18 minutes. It can be seen that it is able to achieve self-sustainability, since there is always enough energy for data acquisition and transmission. However, the self-sustainability comes at the cost of reactivity. With such high latencies, the UAV passing by might have to wait intolerably long times before being able to extract the data.

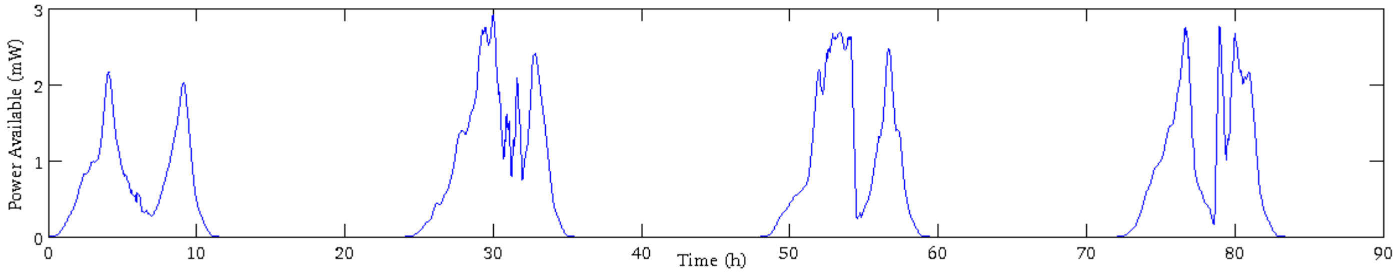


Fig. 6. Measured available power during 4 days in an outdoor environment using solar panels.

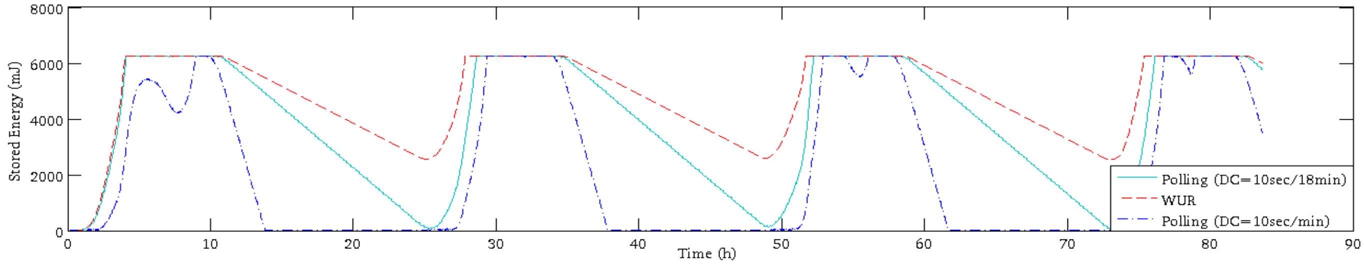


Fig. 7. Simulated energy storage level in supercapacitor during 4 day experirment based in field power measurement of the node and energy harvested.

Lastly, the red line shows the proposed solution with a WUR. It can be seen that the energy storage level never goes below half. Furthermore, it has an ultra-fast reaction time in the microsecond range. This extra energy can even be used either to increase the accuracy of the measurements (by increasing the sensor's duty cycling), or kept as conservative buffer for possibly unfavorable sunlight conditions. Overall, it can be seen that while self-sustainability can be achieved through polling, it comes at a considerable performance cost. The use of a WUR, while requiring one additional subsystem, can greatly reduce the energy requirements for self-sustainability and yields no performance losses.

VI. CONCLUSIONS

This work has presented a self-sustainable radioactive sensor node for environmental monitoring in hazardous environments. The node has been designed to have a small form factor, enabling it to be distributed by UAV's across an area too dangerous or inaccessible to human operators. The node contains solar panels and a supercapacitor, which enables it to gather enough energy for continuous periodic sensing. Furthermore, with the combination of an ultra-low power WUR and radio transceiver, the node is able to transmit its sensed data back to the UAV with very high energy efficiency. As a result, the proposed solution is able to produce and continuously update an accurate map of radioactivity levels in industrial accident sites. The power measurements demonstrate the viability of a self-sustainable node with periodic sampling. The results show that with a WUR, one can reach the self-sustainability level with a low latency, providing measurements with fine time resolution. One the other hand, typical solutions with polling would require aggressive duty-cycling, and a coarser time resolution, to achieve the same self-sustainability.

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