Long range wireless sensing powered by plant-microbial fuel cell

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***Abstract*—Going low power and having a low or neutral impact on the environment is key for embedded systems, as pervasive and wearable consumer electronics is growing. In this paper, we present a self-sustaining, ultra-low power device, supplied by a Plant-Microbial Fuel Cell (PMFC) and capable of smart sensing and long-range communication. The use of a PMFC as a power source is challenging but has many advantages like the only requirement of watering the plant. The system uses aggressive power management thanks to FRAM technology exploited to retain microcontroller status and to shutdown electronics without losing context information. Experimental results show that the proposed system paves the way to energy neutral sensors powered by biosystems available almost anywhere on Earth.**

I. Introduction

An important and open question that developers have to tackle when implementing IoT devices is the design of the power sources. This is particularly of interest since new embedded systems with ultra low-power specifications hit the market every day, while the solutions to power efficiently these devices are more rare.

Energy harvesting (EH) is proven to be a valid substitute for batteries in many applications [1], [2], providing also the fundamental advantage of decreasing the maintenance costs related to batteries [3], [4]. Moreover, with the advent of low-power long-range radio communication technology, the paradigm of Internet of Things is becoming real and affordable also for harsh applications that require to exchange information over large areas as it happens for example in agriculture or forest monitoring.

By merging these two technologies, low-power embedded systems can achieve self sustainability thanks to the energy available in the very same environment. In this work we focus on a rather exotic energy source that exploits bacteria normally present in any environment on Earth, namely Microbial Fuel Cells (MFCs). The main advantage is that they provide a low (hundreds of μW) but almost constant power that slowly varies, because it mostly depends on environmental temperature and water concentration of the culture where they live. A rather interesting idea is to put a plant in the MFC, taking advantage of the organic matter released through its roots in the soil. The insertion of the plant in a MFC leads to higher power produced by bacteria and to extend the lifetime of the bacteria because of the more nutrients in the soil. The monitoring system presented in this paper embeds the whole set of technologies just introduced and is intended for bringing IoT advantages in any environment where a plant can live, whether is the backyard or an agricultural field.

The paper is organized as follows. Related works are discussed in Sec. II, while Sec. III presents the design of the system and of each single module. Experimental results are described in Sec. IV and concluding remarks are discussed in Sec. V.

II. Related works

Recently, the potential of the MFCs has been explored more in depth and some interesting applications includes the realization of electrochemical sensing devices [5] that are fully integrated with the MFC that realizes an unobtrusive energy supply system. An interesting feature is the capability of colony of bacteria to survive in harsh environments even if the capability of power generation depends mainly on environmental conditions [6]. Different cathodes and catalyst elements have be exploited, as well as different plant species in [7] and different soils [8], since any soil can host electrogenic bacteria. There already exists some example of usage of MFC to power electronics, for instance simulation are performed in [9] and actual deployments can be found as well, as in [10] where an aquatic sediment-MFC is used to power a single WSN node. Different authors design a specific management system to exploit MFC and sense temperature and humidity with an average frequency of one measure per hour [11] or 15 minutes [12]. The addition of flora inside the MFC ecosystem is proven to boost the performance of the cell [13]. Some commercial examples of both simple MFC and plant-MFC approached the market in the last years. Plant-e [14] and Planta lampara [15] are two prototypes of energy neutral lamps, which are pushing the performances of these systems to new levels.

III. System architecture

The complete IoT neutral monitoring system is presented as a prototype in Fig. 1, while the block-scheme of Fig. 2 illustrates the various modules used and their connection. The main core of the system is based on the MSP430FR5969 chip, one of the lowest power microcontroller (MCU) available on the market nowadays, capable of less than 360 nA current

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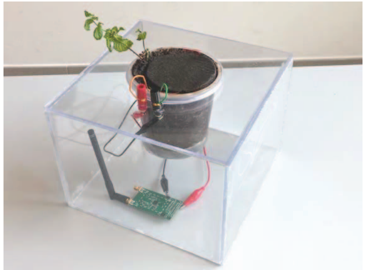

Fig. 1. Prototype of the developed system.

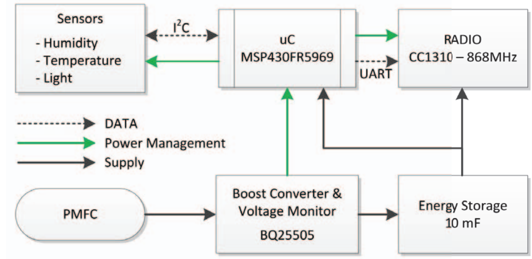

Fig. 2. Block scheme of the system.

consumption when in ultra-low Power Mode. The energy supply of the embedded monitoring system is a terrestrial PMFC and a boost converter is used to shape and store the extracted energy into a supercapacitor.

A properly dimensioned 10 mF supercapacitor is the output storage of the boost converter and data are gathered and transmitted only if there is enough energy available.

A. Power Source and Conditioning

Microbial Fuel Cells (MFCs) are bio-electrochemical systems that provide electric current by exploiting the capability of particular species of microorganisms to produce electrons as a result of cellular respiration processes during the metabolism of organic nutrients. The charges are pushed from one electrode to the other, and in general a liquid electrolyte is placed in between to facilitate the flow.

Plant-Microbial Fuel Cells can be seen as an evolution of soil-based MFCs and make use of naturally occurring processes around the roots of plants to provide additional nutrients to the bacteria. A schematic view of the PMFC is shown in Fig. 3-left with the flow of nutrients and reagents involved. Thanks to photosynthesis, the plant produces both carbon dioxide and organic matter and up to 70% of this matter ends up in the soil as dead root material that then feeds the bacteria. Our prototype of PMFC consists of a cylindrical plastic vessel enclosing the cathode exposed to air and an anode deep in soil; Mentha was chosen for its endurance in water-rich soil. We employed a high-surface-area graphite fiber felt electrodes. The PMFC provides an average output voltage of 0.5 V, thus requiring a boost converter. The Texas Instruments BQ25505 energy harvesting IC was chosen. It embeds a programmable maximum power point tracking (MPPT) that allows to increase the efficiency of the system. By experimental evaluation, we measured that the optimal MPPT configuration is at the 80% of the VoC (open-circuit voltage), as for the photovoltaic harvesters [16].

B. Non-Volatile RAM

Ferroelectric Random-Access Memory (FRAM) is a recent technology for Non-Volatile Memories (NVMs) based on the physical property of ferroelectric materials to store a charge when an electric field is applied and to keep it when the field is removed. As a main advantage over conventional ferromagnetic-based storage units, FRAM can go as low as 150 ns for a write operation, still slower than (but comparable to) DRAM, but way faster than a flash memory that has an average period in the order of a millisecond. Secondly, FRAM requires smaller voltages than flash and EEPROM memories (1.5 V against 10-14 V); finally FRAM does not require a refresh operation as in DRAM, resulting in hundreds of trillion read/write cycles of lifetime. Hibernus library [17], [18] is a software library that permits to fully exploit the advantage of FRAM in power-constrained applications. It provides a set of functions to take a snapshot of the application state including external peripherals and pending tasks. This allows to save MCU context (registers and RAM) in the NVM when a critical supply level is approaching, and restoring the application state without reboot initialization when the normal supply voltage is reestablished.

C. Sensors and Applications

To build the sensor node we exploit two sensors, namely a VELM7700 light sensor and a HDC1080 temperature and humidity sensor. Both have been chosen for the low-power consumption, that permits to be supplied drectly from a digital port of the MCU, only when needed. The main application is built exploiting a state machine that discriminates the type of boot, meaning that the system is aware of the previous conditions that caused the shut-down or hibernate events. In this way, we tune the power consumption to fit the health state of the PMFC, that is intrinsically not constant. The program flow is depicted in Fig. 3. At the boot (INIT label), if the FRAM is filled with the configuration from the previous state a restore operation is performed, otherwise the system boots normally (initializing the FRAM if needed). At this point the peripherals have to be configured: everytime the

TABLE I
PARAMETERS FOR BREAK-EVEN TIME EVALUATION

Parameters	
P_FRAM P_LPM3 P_LPM3.5	4.8 [mW] 0.0015 [mW] 0.00075 [mW]
T_FRAM [R+W]	0.01 [s]
E_FRAM = P_FRAM * T_FRAM	0.48 [mJ]
E_sleep_3.5 = P_LPM3.5 * T_sleep + E_FRAM	
E_sleep_3 = P_LPM3 * T_sleep	

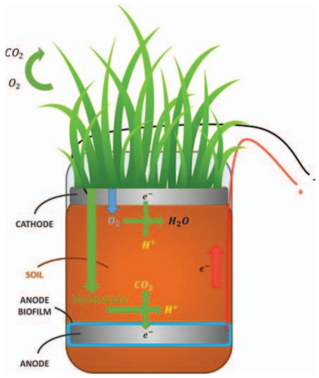

Fig. 3. PMFC features representation (left) and flowchart of the application exploiting NVM features (right).

node faces a power loss the communication peripherals are reinitialized. Finally the *data sense* and *transmit* tasks are executed. When completed, the RTC is enabled to fix the next wake-up operation to a specific time interval and the system enters the low power mode 3.5 (LPM3.5). An extra control on the voltage level is provided by the BQ25505 energy harvesting IC, that is set to provide a signal when the supply voltage crosses 3 V. These warning interrupts can occur in two different ways: a Falling Edge event (V_BAT_INT FE label) triggers a *snapshot* (i.e. save the state of the system in FRAM memory) and to enter the deep sleep without RTC (LPM 4.5), while a Rising Edge event (V_BAT_INT RE label) will turn on the microcontroller from a deep sleep state.

In normal condition, the system waits for the trigger from the real-time Clock (RTC_INT) until the sleeptime count is reached, i.e. 30 minutes. According to the transient computing paradigm [19], all these operations are performed using Hibernus mechanism to address the power loss and to fully exploit the NVM and LPM x.5 states [17]. A portion of FRAM memory holds the state of the execution and enables to restore the application when a power loss event is fixed. The state of the sensors and the radio configuration are not stored and therefore not restored, because has been proved not to be energy efficient. In our modified Hibernus we execute a conventional snapshot operation in case of power loss.

To evalute and demonstrate the advantage of NVM and LPM x.5 we computed the break-even point in time of the application, such as the instant in which the amount of power drained and time consumed to use the FRAM (read+write) and the advantage of the LPM3.5 is exactly equal to not to use the FRAM and keep the RAM active with the LPM3 state of the MCU, since the active time of the application is the same. Parameters and equations are summarized in Tab. I. As a result, our design can fully exploit NVM if a sleep interval is larger than one minute (T_sleep $\geq$ 64 s).

D. Long Range Radio

We used Texas Instruments CC1310 sub-GHz radio for the wireless conectivity, because of the lowest power consumption when in sleep mode. We configured a transmission in the 868 MHz band @ 0 dBm with a baud rate of 625 bps. We selected a fixed 20-byte payload to transmit 18 byte of data (plus 2 required by the network stack) correspondig to 3 measures of 2 bytes for each sensor. We performed some experiments in a dense urban environment to evaluate its performance, summarized in Tab. II. The goodness of the wireless link is quite clear, allowing us to use the prototype for a range of applications such as agriculture and urban monitoring.

IV. Results

The most important feature of PMFCs is their endurance over long period of time, we verified through several experiments that a well started colony of bacteria (after at least one week from the setup) in a PMFC system requires just the effort of 10 ml of water every two days to live and provide energy virtually forever. On the contrary two main limitations must be taken into account, the energy generated is extremely low (we experienced a maximum of 400 μW) and it can not be drained continuously, since bacteria needs time to duplicate and metabolize nutrients. So the application is constrained to be duty-cycled. The plots of Fig. 4 present the results obtained during one of the experiments conducted to evaluate performance of the proposed system. In this particular case we used 1 minute sleep interval with RTC clock enabled to speed-up the tests, while standard configuration for such task is 30 min. In particular, during LPM4.5 (from seconds 122 to 246 and 437 to 716) the MSP430 consumes in average $\approx$ 1 μW and $\approx$ 2 μW while in LPM3.5 (for example between 300 to 360 seconds). The application takes $\approx$ 950 ms to execute with an average current consumption of $\approx$ 3.4 mA @ $\approx$ 3 V,

TABLE II
Link quality in urban environment w.r.t distance and gain

Dist. [m]	GAIN 0 dB		GAIN 14 dB	
	Packet loss [%]	RSSI [abs]	Packet loss [%]	RSSI [abs]
95	0	-105	0	-86
110	2.5	-101	1	-76
157	0.5	-99	0	-80
235	76.5	-122	2.5	-106
301	100	n.d.	0	-110
398	100	n.d.	32.5	-121

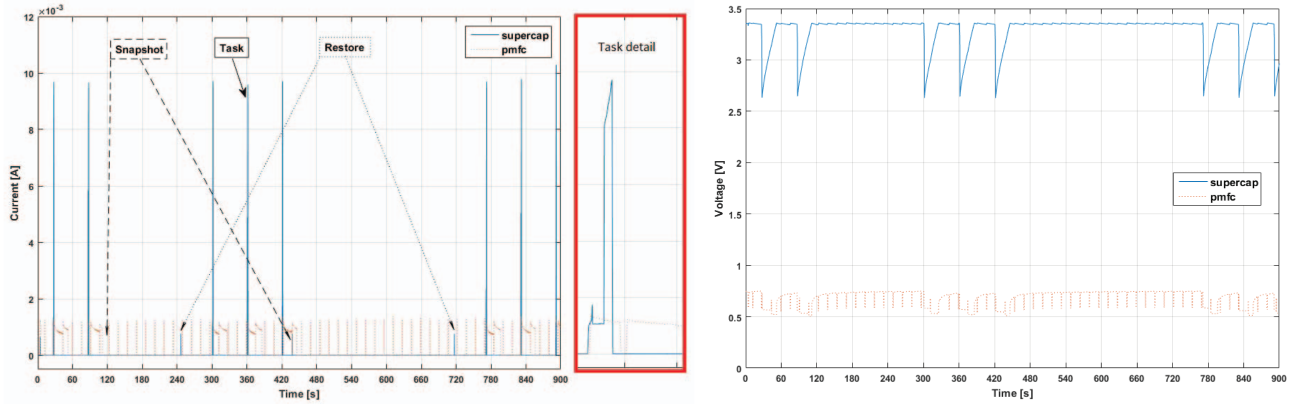

Fig. 4. Performance evaluation test, current profile of PMFC and drained by the prototype (left) and corresponding voltage (right)

corresponding to $\approx$ 10 mJ of energy.

The detail of the application consumption profile is shown on the plot in the center of Fig. 4. Considering the PMFC, from the graph one can notice that the power is extracted in very short bursts of current thanks to the MPPT feature of the boost converter, while $\approx$ 35 s are required to recharge the supercap when the application task is performed. In this case, the average power extracted from the cell is $\approx$ 640 μA @ $\approx$ 590 mV for an average power of $\approx$ 390 μW. As previously introduced, this impulsive drain of current favors the normal activity of bacteria of the PMFC. In field operations, by setting the sleep time to a value at least of 30 minutes, corresponding to a duty-cycle of 0.05%, this characteristic is further emphasized leading to an optimal working condition for the PMFC.

These results demonstrate that the advantage provided by FRAM memory and the ultra low-power sleep states of the MSP430 can be fully exploited by a smart software architecture that mixes state retention and Hibernus library to adapt a microwatt power source with a milliwatt power consuming monitoring task. In the end, we demonstrated that a small PMFC can sustain such infrastructure virtually forever requiring the user just the effort of watering the plant.

V. Conclusion

We presented the design of a complete smart wireless sensor node that runs on a hybrid Plant-Microbial Fuel Cell. The results obtained and described in the paper are easily portable to different application field. Moreover, we demonstrated that a PMFC in combination with energy-aware design choices, can be used to realize self-sustainable IoT enabled remote sensors.

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