An IoT-Aware Architecture for Smart Healthcare Systems

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Abstract—Over the last few years, the convincing forward steps in the development of Internet of Things (IoT)-enabling solutions are spurring the advent of novel and fascinating applications. Among others, mainly radio frequency identification (RFID), wireless sensor network (WSN), and smart mobile technologies are leading this evolutionary trend. In the wake of this tendency, this paper proposes a novel, IoT-aware, smart architecture for automatic monitoring and tracking of patients, personnel, and biomedical devices within hospitals and nursing institutes. Staying true to the IoT vision, we propose a smart hospital system (SHS), which relies on different, yet complementary, technologies, specifically RFID, WSN, and smart mobile, interoperating with each other through a Constrained Application Protocol (CoAP)/IPv6 over low-power wireless personal area network (6LoWPAN)/representational state transfer (REST) network infrastructure. The SHS is able to collect, in real time, both environmental conditions and patients' physiological parameters via an ultra-low-power hybrid sensing network (HSN) composed of 6LoWPAN nodes integrating UHF RFID functionalities. Sensed data are delivered to a control center where an advanced monitoring application (MA) makes them easily accessible by both local and remote users via a REST web service. The simple proof of concept implemented to validate the proposed SHS has highlighted a number of key capabilities and aspects of novelty, which represent a significant step forward compared to the actual state of the art.

Index Terms—Constrained Application Protocol (CoAP), healthcare, hybrid networks, radio frequency identification (RFID), representational state transfer (REST), 6LoWPAN, smart environment, wireless sensor network (WSN).

I. INTRODUCTION

IMPROVING the efficiency of healthcare infrastructures and biomedical systems is one of the most challenging goals of modern-day society. In fact, the need of delivering quality care to patients while reducing the healthcare costs and, at the same time, tackling the nursing staff shortage problem is a primary issue. As highlighted in [1], in fact, current procedures for patient monitoring, care, management, and supervision are often manually executed by nursing staff. This represents, *de facto*, an efficiency bottleneck, which could be a cause of even tragic errors in practices.

Recent advances in the design of Internet-of-Things (IoT) technologies are spurring the development of smart systems to support and improve healthcare- and biomedical-related

processes [2]. Automatic identification and tracking of people and biomedical devices in hospitals, correct drug–patient associations, real-time monitoring of patients' physiological parameters for early detection of clinical deterioration are only a few of the possible examples.

Among others, ultra-high-frequency (UHF) radio frequency identification (RFID), wireless sensor network (WSN), and smart mobile represent three of the most promising technologies enabling the implementation of smart healthcare systems. RFID is a low-cost, low-power technology consisting of passive and/or battery-assisted passive (BAP) devices, named tags, which are able to transmit data when powered by the electromagnetic field generated by an interrogator, named reader. Since passive RFID tags do not need a source of energy to operate, their lifetime can be measured in decades, thus making the RFID technology well suited in a variety of application scenarios, including the healthcare one [3]–[5]. The recent availability of UHF RFID tags with increased capabilities, e.g., sensing and computation [6]–[8], represents a further added value. In fact, RFID-based sensing in healthcare enables zero-power, low-cost, and easy-to-implement monitoring and transmission of patients' physiological parameters. Nevertheless, the main drawback of RFID tags stems from the fact that they can operate solely under the reader coverage region, i.e., up to 15 and 25 m when, respectively, fully passive and BAP tags are used. Clearly, such an aspect limits the use of UHF RFID technology to object/patient identification and monitoring within quite small areas.

On the contrary, WSNs are basically self-organizing *ad hoc* networks of small, cost-effective devices (motes) that communicate/cooperate in a multihop fashion to provide monitor and control functionalities in critical applications including industrial, military, home, automotive, and healthcare scenarios. Currently, most WSN motes are battery-powered computing platforms integrating analog/digital sensors and an IEEE 802.15.4 radio enabling up to 100-m outdoor communication range (single hop).

Compared to UHF RFID tags integrating sensing and computing capabilities, WSN motes consume significantly more power, thus making the overall network lifetime the major limitations of such technology [9]–[11]. In such a context, RFID and WSN represent two complementary technologies whose physical integration might provide augmented functionalities and extend the range of applications [12], e.g., in the healthcare domain. To the best of authors' knowledge, only few attempts have been done to leverage the combined use of UHF RFID and WSN technologies in healthcare application

scenarios. Furthermore, none of the available solutions realizes a seamless integration of different technologies, according to the so-called IoT vision [13]. Based on this concept, IoT devices will be remotely accessible though the Internet, thus allowing the development of innovative applications able to exploit pervasive collected data and leverage on the new control possibility offered by the IoT-enabling solutions.

In this work, a novel IoT-aware smart hospital system (SHS) is presented and discussed. It is able to guarantee innovative services for the automatic monitoring and tracking of patients, personnel, and biomedical devices within hospitals and nursing institutes, by exploiting the potentialities offered by the joint use of different, yet complementary, technologies and standards, such as RFID, WSN, smart mobile, 6LoWPAN, and Constrained Application Protocol (CoAP). Specifically, the designed SHS is able to collect, in real time, both environmental conditions and patients' physiological parameters via an ultra-low-power hybrid sensing network (HSN) composed of 6LoWPAN nodes integrating UHF RFID Class-1 Generation-2 (Gen2 hereafter) functionalities. In particular, two new kinds of WSN nodes are proposed. The former integrates an RFID Gen2 reader, whereas the latter integrates an augmented RFID Gen2 tag in order to store sensor data and patient information. In this way, physiological parameters of patients can be easily retrieved by RFID Gen2 readers scattered in the hospital and delivered to a control center where an advanced monitoring application (MA) makes them easily accessible by both local and remote users via a representational state transfer (REST) web service. During normal operations, therefore, no WSN-based transmission is performed, thus reducing the node power consumption and limiting the impact on the network capacity. The designed system is also able to timely and reliably manage emergency situations. In fact, in this case, the WSN-based transmission is activated so as to promptly inform the nursing staff via push notifications (PN) on a customized mobile application. Doctors can also connect their smart phone to a portable UHF RFID reader and use the same mobile application to interact with patients' nodes during daily medical inspections.

This paper is organized as follows. In Section II, the related work is analyzed, while the architecture of the proposed SHS along with involved hardware and software components are outlined in Section III. Section IV discusses the adopted RFID–WSN integration strategy and provides some experimental results on RFID communication range and power consumption. Details on the implemented architecture are given in Section V, while a prototype implementation of the proposed SHS is described and validated in Section VI. Concluding remarks are drawn in Section VII.

II. RELATED WORK

Recent advances in microelectromechanical systems (MEMS) have opened up great opportunities for the implementation of smart environments. Especially in the medical field, several sensors to evaluate different types of vital signs (i.e., heartbeat, body pressure and temperature, ECG, and motion) have been developed, thus enabling the design of innovative

services able to substantially improve citizens' healthcare. In this field, among the several research activities already presented in the literature, those related on the use of the UHF RFID technology are mainly focused on tracking patients in hospitals and nursing institutes. In [3], authors combine together wearable tags and ambient tags to develop a fully passive RFID system, named NIGHT-Care, for monitoring the state of disabled and elderly people during the night. Specifically, NIGHT-Care relies on an ambient intelligence platform which is capable to estimate sleep parameters, classify the human activity, and identify abnormal events that require immediate assistance. In [4], RFIDLocator, a web-based application developed at the University of Fribourg (CH) in collaboration with Sun Microsystems, has been proposed to improve the quality of hospital services. Passive RFID technology has been successfully used also in [5] for equipment localization in hospitals. As evident from the cited literature, since RFID tags can operate solely under the reader coverage region, the use of UHF RFID technology is limited to patient/devices monitoring and tracking in quite small environments.

Another set of related work proposes the use of WSN technology to implement solutions able to meet the specific requirements of pervasive healthcare applications. In [1], a WSN providing patient localization, tracking, and monitoring services within nursing institutes is presented. The localization and tracking engine rely on the received signal strength indicator (RSSI) and particle filters while biaxial accelerometers are used to classify the movements of patients. In [14], a wireless localization network able to track the location of patients in indoor environments and also to monitor their physical status is presented. A location-aware WSN to track patients using a ranging algorithm based on environment and mobility adaptive filter (REMA) is proposed in [15]. A quite complete project providing patients' monitoring and tracking is WSN4QoL [16]. Specifically, WSN4QoL relies on a three-tier system architecture, where, at the lowest tier, a Bluetooth-enabled wireless body area network (WBAN) connects sensor nodes to a local collector which, in turn, sends measurements reports toward a gateway through an IEEE 802.15.4-based ZigBee network. Finally, the gateway performs local computation and forwards data to the public IP network toward the professional caregivers for real-time analysis. In [17], the 6LoWPAN standard and smart mobile communication techniques are combined to monitor the health condition of patients and provide several effective healthcare services. More in detail, the proposed solution makes use of WSN devices to measure photoplethysmogram (PPG) signals and deliver them to a server through the Internet. An Android device is used to provide a mobile healthcare service by means of a customized application. Unlike the UHF RFID technology, the use of WSN allows the patients to be monitored in a more efficient manner at the cost of complex algorithms required for their precise tracking. The combined use of the UHF RFID and WSN technologies, on the contrary, could bring considerable benefits, thus paving the way for the development of innovative, smart services.

A first example combining UHF RFID and WSN technologies is presented in [18] where a wireless localization system

for monitoring child position in theme park is implemented by equipping WSN nodes with UHF-RFID reader capabilities. The localization problem is also addressed in [19], where a grid of UHF RFID tags is used to enhance the localization accuracy of standard RSSI-based WSN algorithms. In [20], authors propose the integration of WSN nodes and UHF RFID readers for the development of a smart warehouse management system.

To the best of authors' knowledge, only few attempts have been done to leverage the combined use of UHF RFID and WSN technologies in healthcare scenarios. In [21], RFID, WSN, and GSM are exploited together to track patients in hospitals and monitor their physiological parameters. A smart system using active UHF RFID, WSN, and GSM for real-time supervision of patients is presented and discussed in [22]. An interesting attempt that aims to combine and integrate, at physical layer, heterogeneous technologies, adopts the RESTful paradigm and PN, and manages alert events in a smart hospital is reported in our prior work [23]. More in depth, it describes a smart system based on UHF RFID and ZigBee-based WSN solutions for the automatic monitoring and tracking of patients within hospitals. It is able to collect, in real time, both patients' physiological parameters and environmental conditions, and, in case of emergency, to promptly inform the nursing staff via a software application specifically designed for smart phones and tablets. In order to address the shared goal to design a seamless framework easily deployable in a variety of scenarios, the use of a WSN based on the Constrained Application Protocol (CoAP) for connecting and monitoring medical sensors is advocated [24]. The CoAP adoption in healthcare scenarios represents an important aspect since some CoAP built-in features, such as resource observation (particular useful for real-time monitoring of patients' vital signs) and discovery, enable a dynamic environment where the available resources are automatically discovered and configured.

III. System Architecture Overview

This work aims at designing and implementing an IoT-aware SHS having, as main peculiarity, the capability to readily combine different, yet complementary, technologies enabling novel functionalities. Basically, the system we envision should be able to collect, in real time, both environmental conditions and patients' physiological parameters and deliver them to a control center. At this point, an advanced MA should analyze the received data and send alert messages in case of emergency. The conceived SHS has been put into effect according to the architecture illustrated in Fig. 1. As shown, it is composed of three main parts: 1) the RFID-enhanced WSN, called HSN hereafter; 2) the IoT smart gateway; and 3) the user interfaces for data visualization and management.

The HSN consists of an integrated RFID-WSN 6LoWPAN network composed of four typologies: 1) 6LowPAN border routers (6LBR); 2) 6LowPAN routers (6LR); 3) 6LowPAN router readers (6LRR); and 4) 6LowPAN host tag (HT). According to the 6LoWPAN standard, the 6LBR is in charge of connecting the network to the Internet by translating 6LowPAN packets into IPv6 packets and vice versa, whereas the 6LR
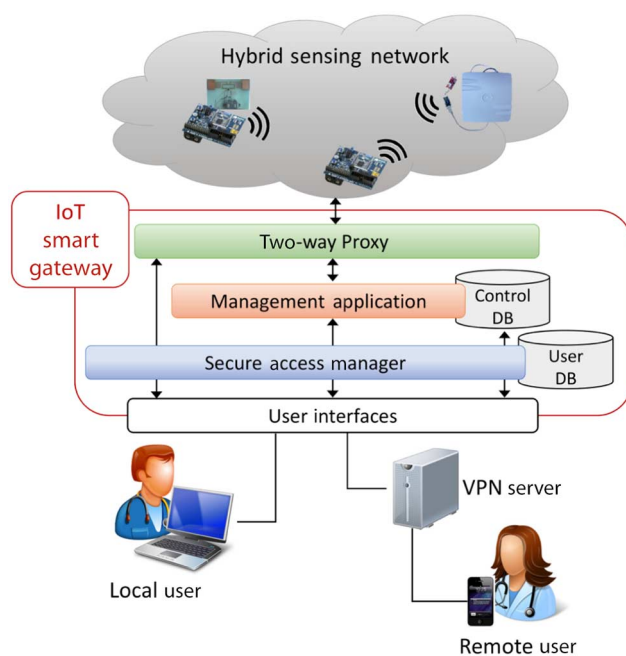

Fig. 1. Overview of the SHS architecture.

provides forwarding and routing capabilities. Referring to the proposed RFID-WSN integrated system, the 6LRR is defined as a 6LR node interfaced with an RFID Gen2 reader while HT identifies a typical 6LowPAN Host (i.e., a node without routing and forwarding capabilities) interfaced with an RFID Gen2 tag. More details about HSN nodes with RFID Gen2 capabilities are provided in Section IV.

At a finer level of detail, the proposed SHS assumes that several 6LR are deployed in the hospital to collect data from the environment, such as temperature, pressure, and ambient light conditions. In addition to the sensing capabilities, the main function of 6LRR nodes, instead, is to track patients, nursing staff, and biomedical devices labeled with RFID Gen2 tags. In particular, we envision patients wearing an HT node, which is capable to detect important physiological parameters, such as heartbeat and movement/motion. Sensed data are periodically logged on the user memory of the RFID Gen2 tag, thus allowing 6LRR nodes deployed in the environment to retrieve and deliver them to the IoT Smart Gateway. This last one is connected, on one hand, directly with the HSN and, on the other hand, with the Internet through a local area network (LAN). Therefore, in the proposed architecture, the gateway plays the role of 6LBR, enabling the communication between WSN nodes and remote users. An MA running on the gateway analyzes the received data and stores them into the database (control DB in Fig. 1). To make the collected data easily accessible by both local and remote users, the REST Web-based paradigm has been adopted. Specifically, a Web-based graphical interface allows network operators to manage environmental parameters of sensor and actuator nodes. The same interface allows doctors with specific privileges to access both real time and historical patient data. Such information can also be managed remotely by the medical staff through a customized mobile software application. Furthermore, doctors can be equipped with a smart phone

connected to a portable RFID Gen2 reader and running a customized application, named Medical App. Through this app, during the daily medical inspections in hospital, doctors can interact directly with the HT node worn by the patient and check his/her physiological parameters by reading the most recent information stored into the user memory of the RFID Gen2 tag or historical information stored into the control DB. The Medical App allows doctors also to update the memory content with important information to remind (e.g., the last visit, changes of patient therapy, and health examinations). As clarified in the next section, the RFID Gen2 technology not only provides standardized EPCglobal identification and tracking of both patients and nursing staff wearing the HT node, but also enables quasi-zero-power read/write memory operations.

By exploiting the RFID-WSN integration, the developed SHS architecture is also able to timely manage emergency situations. Indeed, only in case of critical events, such as patient falls or heartbeat irregularities, the HT node resorts to its long-range, high-power, reliable IEEE 802.15.4 radio transceiver to send a notification to the MA. This strategy allows the HT nodes to always use the RFID Gen2 radio interface for routine operations, e.g., medical inspections, data logging, identification/tracking, while keeping the IEEE 802.15.4 radio OFF for most of the time, thus maximizing battery lifetime.

At the IoT smart gateway, the MA exploits PN to inform the nursing staff about patient location (i.e., the last position where the RFID Gen2 tag has been read) and health status. The doctor can then check patient vital signs through the Web application or directly on his/her smart phone.

Since the system collects sensitive and confidential data, the platform must ensure an adequate level of security to data access and management. For this reason, users need to be authenticated before they can access the platform. Moreover, also local and remote communications must be adequately protected. In the former case, the mobile application could exploit a local access point (AP) for connecting to the LAN and interacting with the SHS. Obviously, the mobile app should be properly configured to guarantee the desired level of security. In the latter case, it is necessary to provide a stronger communication channel, since the interaction between the remote application and the SHS is performed through the public Internet. To do so, the proposed solution exploits a virtual private network (VPN) channel that links the mobile device with the IoT smart gateway. Once this access is granted, whether local or remote, the user can act on the system.

IV. Adding UHF RFID Capabilities to 6LowPAN Nodes

As discussed above, the envisioned reference scenario relies on two distinct levels of integration between IEEE 802.15.4-based WSN and RFID devices, namely reader-level and tag-level. In the former, a 6LR node and a standard RFID Gen2 reader, physically interconnected as sketched in Fig. 2, make up a 6LRR. In the latter, a dual-interface RFID Gen2 tag, a 6LowPAN node, and a customized multisensor board, physically interfaced as in Fig. 3, make up an HT.
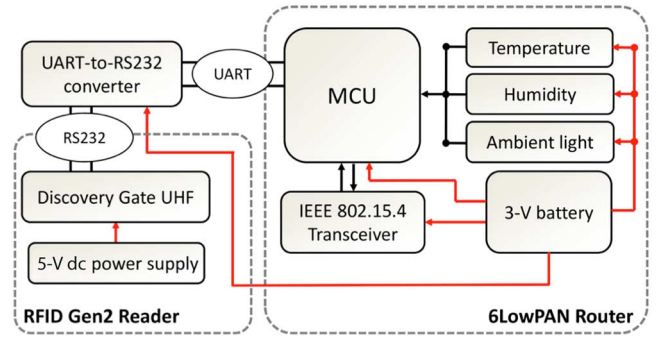

Fig. 2. 6LRR (6LowPAN Router Reader) architecture. Red connections show how the on-board power is routed to the functional blocks.
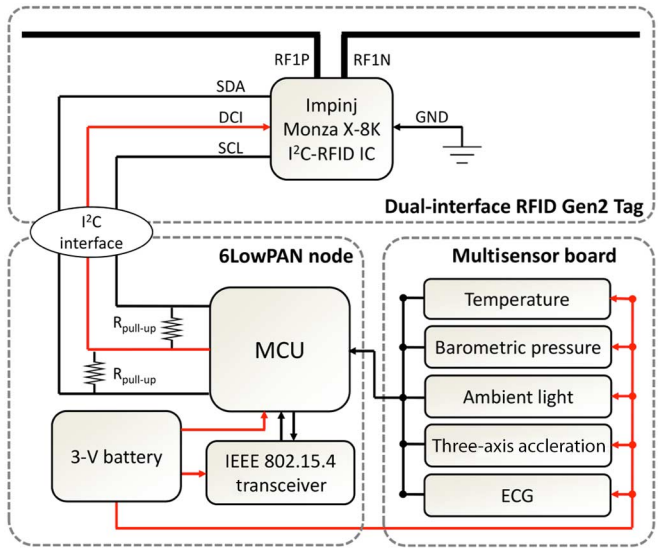

Fig. 3. HT node architecture. Red connections show how the on-board power is routed to the functional blocks.

It is worth emphasizing that the proposed integration strategy makes the information exchanged between the tag and the reader via the Gen2 air interface directly accessible by 6LowPAN devices, thus allowing standardized EPCglobal data to be relayed, in a multihop fashion, over the IEEE 802.15.4-based 6LowPAN network. Details about the hardware and software components making up the outlined RFID-WSN integration approach, along with experimental results, are provided in Sections IV-A–IV-C.

A. 6LRR Device: Hardware and Software Integration

As shown in Fig. 4 and accordingly to the architecture in Fig. 2, a 6LRR consists of a commercial off-the-shelf (COTS) RFID Gen2 reader interfaced with the XM1000 mote from Advanticsys via the universal asynchronous receiver/transmitter (UART) communication bus. The XM1000 in based on "TelosB" technical specifications, with upgraded 116-kb EEPROM, 8-kb RAM, and integrated temperature, humidity, and light sensors. It is equipped with a 16-bit ultra-low-power TI MSP430F2618 microcontroller unit (MCU). Wireless communication capabilities are provided by the IEEE 802.15.4-compliant TI CC2420 transceiver with
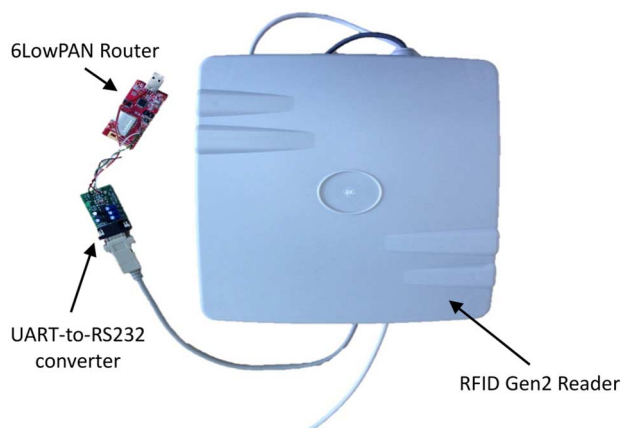
Fig. 4. Interconnected boards and devices realizing the 6LRR architecture envisioned in Fig. 2.

Fig. 5. Interconnected prototype boards realizing the HT architecture envisioned in Fig. 3.

transmission frequency of 2.4 GHz. The selected RFID Gen2 reader is the Sensor ID Discovery Gate UHF, which can be easily configured and controlled by the XM1000 board via the UART interface. The reader supports standard *read* (*write*) commands for reading (writing) data from (to) the RFID tag user memory via the Gen2 air interface. The reader operates in the standard European UHF RFID band (866–868 MHz) with a maximum equivalent isotropic radiated power (EIRP) of 2 W (33 dBm), adjustable via software.

The software aspects concerning the interfacing between XM1000 mote and Discovery Gate UHF RFID Reader have been implemented in Contiki OS, a popular open-source operating system targeted to small MCU-based architectures and developed by the Swedish Institute of Computer Science. Contiki OS communication stack is organized in several layers in which both protocol solutions and radio transceiver features can be thoroughly configured. Contiki OS provides a full IP network stack, with standard IP protocols such as UDP, TCP, and HTTP, in addition to new low-power standards. Specifically, Contiki OS supports also the recently standardized IETF protocols for low-power IPv6 networking, including the 6LowPAN adaptation layer, the RPL IPv6 multihop routing protocol, and the CoAP RESTful application-layer protocol. Furthermore, Contiki OS is highly memory efficient and provides a set of useful mechanisms for memory allocation. These features make Contiki OS the ideal choice for the development of new innovative smart applications, capable to exploit the new possibilities offered by the integration of RFID and WSN technologies.

Specifically, in the 6LRR node implementation, several functions allowing the XM1000 WSN mote to fully control hardware and software parameters of the Discovery Gate UHF RFID Reader, handle Gen2 inventory and Read/Write commands, manage the tag population, and retrieve data from Tags' user memory via the UART communication interface have been implemented in Contiki OS as system driver.

B. HT Device: Hardware and Software Integration

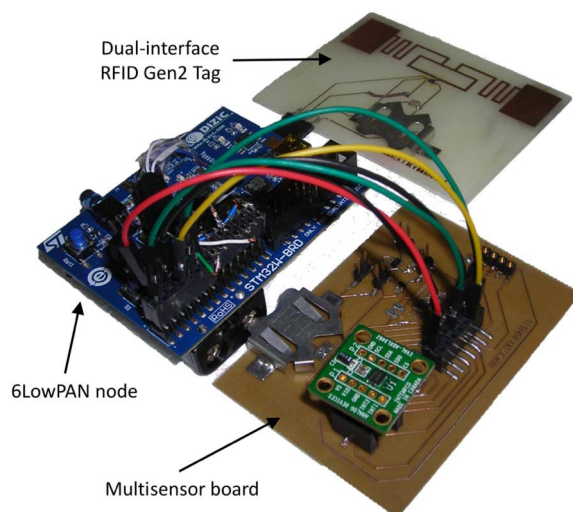As shown in Fig. 5 and accordingly to the overall architecture envisioned in Fig. 3, an HT node comprises three different parts interconnected with each other: a dual-interface RFID Gen2 tag, a 6LowPAN node, and a multisensor board. The dual-interface RFID Gen2 tag has been fabricated in our labs using a photolithography process on FR4 substrate and hand soldering off-the-shelf discrete components. The developed printed circuit board (PCB) is equipped with a battery holder (not exploited in the proposed RFID-6LoWPAN integration since the required power is fed directly from the 3-V battery of the 6LoWPAN node) enabling an auxiliary BAP mode of operation in addition to the standard fully-passive one.

A dipole-like UHF RFID antenna has been designed and patterned directly on the PCB. The antenna impedance has been tuned to achieve a complex conjugate matching with an Impinj Monza X-8K RFID chip exhibiting input impedance $Z_{\text{chip}} = R_{\text{chip}} + \text{j}X_{\text{chip}} = 20.83 - \text{j}181.39 \ \Omega$ at 866.5 MHz, i.e., the center frequency of the European UHF RFID band. Monza X-8K is a new-generation UHF RFID Gen2 integrated circuit (IC) with 8192 bits of nonvolatile memory (NVM) and an I^2C interface. As an I^2C device, Monza X-8K operates as a standard EEPROM whose contents can also be accessed via the Gen2 air interface. In the fabricated prototype, the small female header, which exposes the I^2C bus, is used to interface the RFID chip with the 6LoWPAN node as sketched in Fig. 3.

The 6LowPAN node comprises a ST Microelectronics MB851 board equipped with a 32-bit ARM Cortex-M3 MCU operating up to 24 MHz and embedding 16-KB RAM and 256-KB Flash ROM. It integrates also a 2.4-GHz wireless transceiver fully compliant with the IEEE 802.15.4 standard. The board is also equipped with an external antenna connector and 24 highly configurable GPIOs with Schmitt trigger inputs. Among the exposed GPIOs, the SDA and SCL lines, an analog-to-digital converter (ADC) input port, the ground pin (GND), and several output ports have been used respectively to implement I^2C communications, sample analog sensors, and power connected devices and sensors.

Like the RFID board, the multisensor prototype board has been fabricated in our labs using a photolithography process on FR4 substrate and hand soldering four COTS sensors.

TABLE I
HT Node Current Consumption (at 3-V Supply Voltage) Under Different Operating Conditions

Subsystem	Module	Operating condition	Supply current
6LoWPAN node	MCU	Deep sleep w/ clock	1.5 μA
		Active mode at 12 MHz	3 mA
	IEEE 802.15.4 transceiver	Transmit	30 mA
		Receive	25 mA
Dual-interface RFID Gen2 Tag	Gen2 wireless interface	Fully passive mode	0 μA
		BAP mode	25 μA
	I^2C wired interface	Read	25 μA
		Write	140 μA
Multisensor board	ADXL345 three-axis accelerometer	Measurement mode (1-Hz output data rate)	30 μA
	MAX44009 ambient light sensor		1.6 μA
	BMP180 pressure and temperature sensors		3 μA
	PS25251 ECG sensor		2 mA

Specifically, acceleration data are provided by the analog devices ADXL345 I^2C sensor, which is an ultra-low-power three-axis accelerometer with high-resolution measurements (13 bits/axis) up to ± 16 g. The MAX44009 sensor from Maxim Integrated is used to collect 16-bit ambient light measurements via the I^2C. Temperature and barometric pressure data are provided by the Bosch Sensortec BMP180 16-bit I^2C sensor while the PS25251 from Plessey Semiconductors is used as a dry-contact analog ECG sensor.

Similar to the 6LRR node implementation, Contiki OS has been chosen to develop the MCU firmware of the 6LoWPAN node. Specifically, the software components required for MB851 MCU to communicate with both sensors and RFID chip have been implemented in Contiki as system drivers. As for the sensor interface, I^2C read/write and ADC sampling routines have been developed to retrieve measurement data, respectively, from the digital and analog sensors equipping the multisensor prototype board. As for the RFID chip interface, instead, several functions to set hardware parameters, configure the RFID communication interface, and manage Monza X-8K memory spaces have been implemented in the form of I^2C communication routines.

C. Experimentation

In order to experimentally evaluate the performance of the proposed hybrid devices integrating both RFID Gen2 and 6LoWPAN technologies, a series of experiments was carried out. The achieved results are presented and discussed below.

One of the fundamental aspects to investigate is definitely the power consumption of HT nodes, being the available energy provided by the on-board battery a critical constraint when designing real-world WSN applications. As for the 6LRR, power consumption is not an issue, since such nodes make up a fixed network architecture and, therefore, they can be connected to the standard ac power grid. In order to provide excellent performance in terms of node (and therefore network) lifetime,

all the components and ICs making up the HT nodes have been accurately selected among the lowest-power ones available on the market. Table I summarizes the current consumption of different modules and peripherals of the HT node at 3-V supply voltage. Data have been retrieved from datasheets but the reported typical values have been confirmed by accurate measurements. Specifically, we used an Agilent DSO-X-2012A digital oscilloscope to track the voltage drop across a 1-kΩ precision shunt resistor connected in series with the HT node; then we calculated the absorbed dc current under different operating conditions by the Ohm's law. In addition to the power consumption, the achievable RFID Gen2 communication range is another fundamental aspect to evaluate for the HT node. In fact, in the envisioned application scenario, the HT node uses its Gen2 interface to deliver patient physiological parameters and environmental conditions to both 6LRRs and doctors' smart phones connected to portable Gen2 readers. At the same time, both 6LRR and portable Gen2 readers can write data into the HT user memory, still via the Gen2 air interface. Furthermore, the RFID Gen2 air interface can be exploited as a wake-up radio for the 6LoWPAN subsystem of the HT node. Such a possibility to selectively wake up HT nodes using the RFID Gen2 radio is enabled by the write wake up (WWU) functionality provided by the Monza X-8K chip. This feature is tied to memory write operations performed over the RFID Gen2 interface. More specifically, when the WWU mode is enabled and a Gen2 reader performs a write operation, the Monza X-8K asserts the SCL IO by pulling the I^2C SCL line low for the duration of the write operation (approximately 4 ms). This transition can then be detected by the sleeping MCU and used to wake up the 6LoWPAN subsystem.

Maximum wake-up and communication ranges were measured experimentally using a 6LRR set with 33-dBm transmit power and configured to perform read/write operation from/to the user memory of the Monza X-8K chip at different distances. The experiments were conducted in a large lecture room with 6LRR and HT nodes placed in the line of sight (LOS) 1.5 m
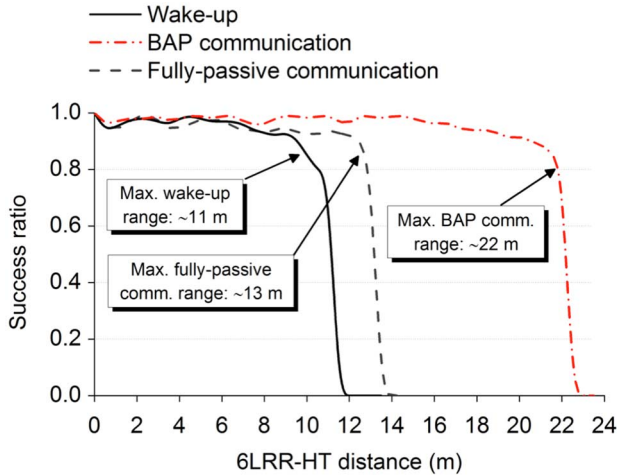
Fig. 6. Measured fraction of successful attempts (performed by a 6LRR) to wake up the 6LoWPAN subsystem of the HT node and to access to the Monza X-8K chip via the Gen2 air interface.

TABLE II
TYPOLOGIES OF RESOURCES AND RELATED COAP PATHS
IN THE SHS SYSTEM

Node	Resource	Examples of resource path
6LR	Ambient Sens.	`coap://[aaaa::1]/ambient/light` `coap://[aaaa::1]/ambient/temperature`
6LRR	Ambient Sens. RFID Reader	`coap://[aaaa::2]/ambient/temperature` `coap://[aaaa::2]/RFID/reader`

HT	Ambient Sens.
	Health Sens.
	RFID Tag
		`coap://[aaaa::3]/ambient/pressure`
		`coap://[aaaa::3]/health/motion`
		`coap://[aaaa::3]/RFID/tag`

above the floor, both oriented in the maximum-gain direction. The 6LRR-HT distance was increased in step of 0.5 m and, for each measurement point, the 6LRR was instructed to perform 100 attempts to access the Monza X-8K user memory. The fraction of successful wake-ups of the 6LoWPAN subsystem is plotted in Fig. 6 (black solid line). As shown, the success ratio remains above 80% up to 11 m before falling sharply to zero. As anticipated, in addition to the fully passive operation, the Monza X-8K RFID chip provides a BAP mode. In other words, read and write sensitivities of the chip are significantly boosted when a voltage is applied to the DCI pin. Using the same experimental setup of the previous experiment, we measured the fraction of successful read/write operations (i.e., communication attempts) performed by the 6LRR when the Monza X-8K is configured in both fully-passive and BAP mode. As shown in Fig. 6, the success ratio remains above 80% up to 13 m (dashed gray line) and 22 m (dotted–dashed red line) for the fully passive and BAP mode respectively. Interestingly, the BAP communication range is quite comparable to that exhibited by conventional IEEE 802.15.4 radios in WSN nodes when configured with transmit power levels suitable for indoor applications. Moreover, as reported in Table I, the current absorbed by the Monza X-8K in BAP mode is just 25 µA, which is roughly three orders of magnitude less than that absorbed by IEEE 802.15.4 transceivers.

V. ARCHITECTURAL DETAILS

The integration of RFID Gen2 functionalities into 6LoWPAN WSN nodes represents the basis in which the SHS architecture was designed. Implementation details and an accurate description of SHS components are provided in Sections V-A–V-C.

A. Hybrid Sensing Network

As previously outlined, the HSN consists of an integrated RFID-WSN 6LoWPAN network. In order to achieve a seamless

interoperability with the Internet, the REST Request/Response paradigm piggybacked on CoAP messages has been exploited in the HSN design. CoAP is one of the most used communication protocols in the IoT and its primary objective is to provide a lightweight access to physical resources in order to meet the limited capabilities of embedded devices. CoAP design is similar to that of HTTP since it provides a request/response model interaction between two end-points and includes key concepts of the Web, such as URI and media types. In addition, CoAP provides a resource observation mechanism, which allows a client to receive notifications upon every change in the state of resources it has previously subscribed to. Since in many cases, an observer is only interested in state changes that satisfy a specific condition (i.e., the state of a resource exceeds a specific value) an extension to the CoAP protocol based on the concept of conditional observations has been proposed [25].

Referring to the proposed HSN architecture, three different kinds of resources can be identified: 1) ambient sensor; 2) health sensor; and 3) RFID-related resources. More in detail, as summarized in Table II, 6LR nodes scattered in the hospital can monitor only environmental parameters and, therefore, expose just CoAP ambient sensor resources (e.g., coap : //[aaaa :: 1]/ambient/light and coap : //[aaaa :: 1]/ambient/temperature). In addition to such kind of resources, 6LRR nodes can expose an RFID resource (coap : //[aaaa :: 3]/RFID/reader) which represents an aggregated information of tags read within the 6LRR RFID range. Finally, HT nodes also expose an RFID resource (coap : //[aaaa :: 3]/RFID/tag, which identifies the user memory content of the integrated Monza X-8K Gen2 tag) in addition to both ambient and health (e.g., coap : //[aaaa :: 3]/health/motion, which provides sensor readings from the integrated three-axis accelerometer) sensor resources. Each resource can be individually accessed from anywhere in the Internet by using CoAP methods.

For the sake of simplifying the development of a new class of services capable to exploit the new possibilities offered by the RFID-WSN integration, we drawn on the implementation presented in [26] where Erbium (Er), a low-power REST engine for Contiki, is extended to support conditional observations through a Conditional Observation Module. Such implementation has been adapted to our hardware. Specifically, in order to get sensor readings, each sensor has been registered as a resource and a proper handler for each sensor has been defined. Upon receipt of a GET request coming from client applications, the handler polls the sensor and builds the response message

using the sensor state as payload. If the request is an observation request, the client is registered as an observer in the Conditional Observation Module for future notifications. The registration of a single observer will trigger the activation of a function that periodically checks for resource state changes and informs all registered observers.

As stated previously, in the proposed SHS, the HT node embeds sensors able to monitor not only environmental conditions, but also vital signs, e.g., heartbeat and motion, which should maintain predefined values in patients with good health conditions. However, if their values fit outside a specified range, it might indicate the patient needs attention. The use of conditional observation methods allows client applications to be notified not only when and how sensor values changes considerably but also when critical thresholds are violated.

B. IoT Smart Gateway

The IoT smart gateway represents the core of the proposed SHS. It is in charge of data collection and processing, system management, and service execution. Hence, it controls the overall SHS behavior. The different components of the IoT Smart Gateway are highlighted in Fig. 1 and described below.

1) Two-Way Proxy: The two-way Proxy enables transparent communication with CoAP devices. It has the burden of translating HTTP requests coming from user interfaces (i.e., web or mobile applications) and the MA into CoAP messages and vice versa. Specifically, the two-way Proxy is able to receive, process, and reply to requests, in JSON format, coming from the MA and the user interfaces. It has been developed using the Spring Framework and deployed on the Jetty application server installed on the IoT Smart Gateway. The Proxy logic has been extended by implementing a caching service, thus supporting multiple requests to the same resource and limiting the amount of traffic injected into the IoT peripheral network. This feature is particularly important for constrained nodes, which are not able to simultaneously manage requests from multiple clients. Furthermore, to simplify the automatic management of the network, the two-way Proxy also embeds a resource directory (RD), which maintains a list of resources, their corresponding server contact information, their type, and other system information. RD allows new devices to publish the description of the available resources and CoAP clients (i.e., the MA) to locate resources that satisfy certain criteria, such as specific resource types.

2) Management Application and Control DB: The MA is a standalone Java application, easily configurable and accessible via the user interfaces. It performs two different tasks: 1) it allows network operators to control hospital environmental conditions and 2) it is responsible for monitoring the patients' health status and alerting doctors in case of critical situations. For these purposes, the MA stores the information retrieved from the HSN nodes on a MySQL database, called control DB. The presence of this database decouples data collection from data processing and visualization, so that doctors and operators do not need to directly interrogate HSN nodes during the normal mode of operation. This approach is particularly useful for battery-operated devices, since it allows HT nodes to stay most of the time in sleep mode (e.g., the IEEE 802.15.4 radio transceiver is kept OFF) and to wakeup only in case of emergency. More in detail, the MA registers itself as an observer to the CoAP resources exposed by HT nodes and to the RFID reader-related resources exposed by 6LRR nodes scattered in the hospital. In such a way, when a patient enters within the coverage region of 6LRR node, all the information stored into the user memory of the Monza X-8K RFID Gen2 chip can be read and delivered to the MA for a further analysis. At the same time, the use of conditional observation methods allows the MA to be notified only when the value of patient's physiological parameters fit outside a specified range, thus substantially reducing the number of notification messages in the network. In case of medical emergency, the MA is also able to send PN to the mobile devices of medical staff using Google Cloud Messages (GCMs). It is worth noting that the use of the GCM instead of other technologies (e.g., GSM) allows the SHS to directly interface with the mobile app and, therefore, to provide all the information about the patients stored into the database. In particular, we resorted to the Amazon SNS cloud service, since it can seamlessly scale and add an abstraction level allowing programmers to use the same APIs for sending notifications on different platforms (e.g., iOS and Android). In order to monitor hospital's environmental conditions, the MA also observes important environmental parameters (i.e., the temperature in the intensive care unit) and maintains specific control rules defined by the network operators (e.g., if the temperature rises above 28°C the air conditioner is turned ON).

3) Secure Access Manager and User DB: The Secure Access Manager (SAM) application ensures privacy and data protection. It coordinates all communication between end users and IoT smart gateway, providing access to stored information only to authorized users, i.e., registered on the User DB.

C. User Interfaces

Authorized users can interact with the system through user interfaces, accessible via web browser by both fixed workspaces and mobile devices. Specifically, such interfaces implement RESTful services, which allow user to communicate with the HSN through the two-way Proxy. The developed user interfaces offer two main functionalities depending on two possible client profiles: 1) network operators and 2) medical staff.

1) Operator Interface: This interface allows network operators to register to the SHS in order to manage current and historical information from environmental sensors, set rules and alarm notifications. It is also used to easily and remotely configure new nodes identified using the RD server implemented in the two-way Proxy.

2) Medical Interface: Similar to the operator interface, the medical interface allows medical staff to register to the SHS, configure the HT nodes assigned to new hospitalized patients, visualize, and eventually change the historical patient
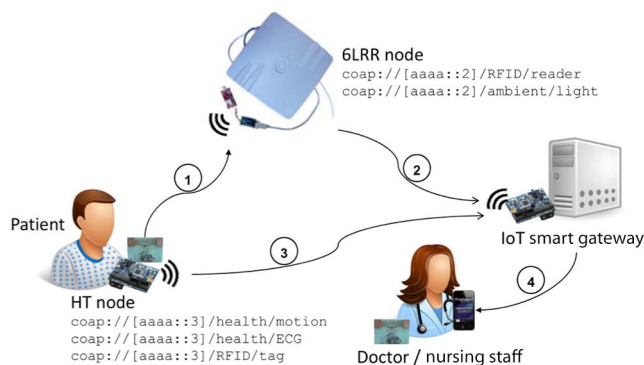
Fig. 7. SHS validation scenario.

data stored into the control DB. Furthermore, this interface allows doctors to directly access to the health sensor data of each patient wearing an HT node. Doctors can interact remotely with the system using the Medical App, a customized Android application. As previously described, the Medical App also allows doctors equipped with an RFID-enabled smart phone to directly retrieve and manage patient's data stored into the Monza X-8K user memory during the daily medical inspection. Finally, the Medical App provides PNs in case of emergency.

VI. PROOF-OF-CONCEPT

In this section, a prototype implementation of the proposed SHS is described and validated by means of a simple proof-of-concept representative of the main functionalities, capabilities, and aspect of novelty of our system compared to similar state-of-art solutions available in the literature.

A. Functional Validation

In the prototype SHS implementation, the ADXL345 digital three-axis accelerometer connected to the multisensor board of the HT node has been exploited to evaluate a patient fall and generate an alert. Especially for hospitalized elder, these accidents could give rise to serious consequences if aid is not given in time. Although many solutions in the literature propose sophisticated mechanisms to detect and prevent falls, a simple threshold-based approach has been considered in this work. Thresholds have been set on the basis of empirical data obtained through several tests carried out in our laboratory. It is worth noting that the aim of this paper is to demonstrate the feasibility of just one of the several possible use-case scenarios where the proposed SHS could find adoption. Therefore, the definition of specific, optimum algorithms to detect patient falls is outside the scope of this work. Moreover, procedures similar to those described in this section for the fall-detection case can be easily replicated to handle also different emergency situations, e.g., related to the violation of critical heartbeat thresholds.

The considered SHS validation scenario and all the components involved are depicted in Fig. 7. As shown, each node can

expose a variety of resources which the IoT smart gateway connected to the 6LBR can manipulate through CoAP methods. Specifically, the two main actors of the system are: 1) the HT node, in charge of monitoring the patient's health status and detecting potential patient's falls and 2) the 6LRR node, in charge of reading and delivering to the IoT Smart Gateway data retrieved from the user memory of the Monza X-8K RFID chip equipping the HT node. To this end, in the considered example, the HT node exposes the following resources:

coap : //[aaaa :: 3]/RFID/tag
coap : //[aaaa :: 3]/health/motion
coap : //[aaaa :: 3]/health/ECG
while the 6LRR exposes:
coap : //[aaaa :: 2]/RFID/reader
coap : //[aaaa :: 2]/ambient/light

The RFID Gen2 tag embedded into the HT node contains, in addition to environmental and patient's physiological information, the electronic product code (EPC), used to univocally identify the patient within the hospital. Note that conventional identification-only Gen2 tags could be also used to identify and track the nursing staff and biomedical devices.

In the considered scenario, the control DB stores information about the location of each 6LRR node in the hospital (e.g., the 6LRR #1 is placed in Room #21) and data about the employed doctors while a Nexus 4 mobile phone running Android 4.4.3 "KitKat" connected to the BlueBerry RFID Gen2 reader from TERTIUM Technology is used as handled reader. The Medical App is installed on the Nexus 4 and uses the Wi-Fi or 3G Internet access. When a patient-fall event is detected the application receives the PN sent by the MA and notifies the doctor with a sound. The Medical App also allows the doctor to retrieve from the IoT Smart Gateway further details on the occurred event and the last registered patient location (i.e., the last location where the patient's HT node has been successfully read by a 6LRR).

In order to ensure the proper operation of the designed SHS, an initial setup phase is required. During this phase an authorized medical operator registers the new hospitalized patient to the SHS. Specifically, as shown in some exemplifying screenshots in Fig. 8, the operator accesses the system via the web application and requires the MA to observe the health sensor resources coap : //[aaaa :: 3]/health/motion and coap : //[aaaa :: 3]/health/ECG by sending a CoAP message to the HT node assigned to the patient. We assume that the MA is already registered as observer of the coap : //[aaaa :: 3]/RFID/reader resource exposed by the 6LRR node. The 6LRR and the HT nodes maintain a list of active subscriptions, while, in the MA, an event handler is installed at run-time and associated to receive notification messages. In this simple proof-of-concept, we consider that MA requires the HT node to be notified only when the acceleration values along the three axes, measured by the accelerometer, exceed predefined thresholds (representative of a potential fall event) by means of conditional observation methods.

To demonstrate the efficiency of the proposed SHS, the functional validation has been conducted considering two different use cases: 1) patients' monitoring and 2) emergency
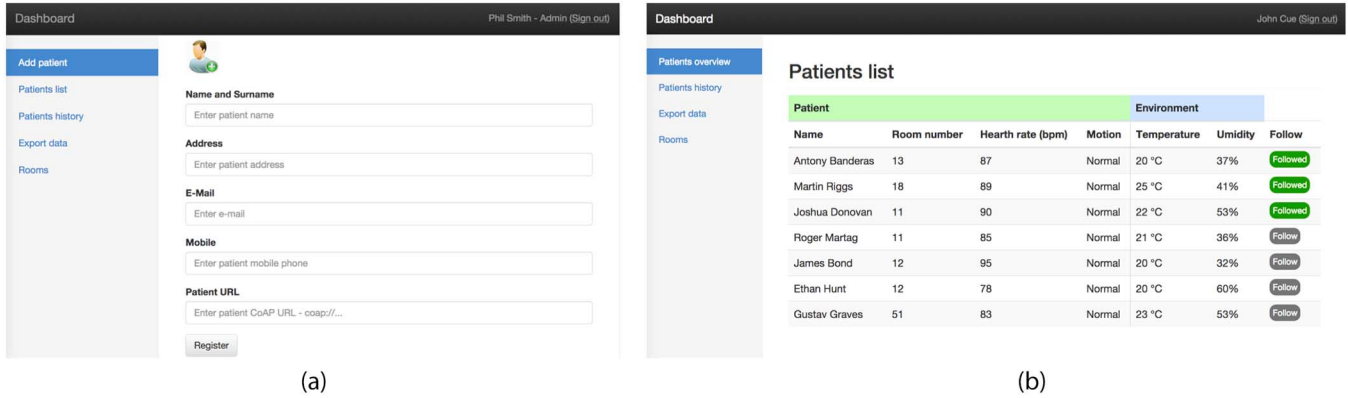
Fig. 8. Screenshots of the prototype SHS in action. (a) Operator registers the new patient. (b) Operator requires the MA to observe important physiological parameters of the hospitalized patient.

event handling. In the former, the following operations are performed.

1) The 6LRR identifies the patient by means of his/her unique EPC and retrieve his/her current and historical health status by accessing the user memory of the Monza X-8K RFID chip equipping the HT node.

2) The 6LRR node sends a notification message containing the read data to the MA using a CoAP method. The MA application running on the IoT smart gateway analyze the received data and store them into the control DB.

In the latter, the following procedure is used to handle emergency situations.

1) The HT node detects the patient fall and activates its IEEE 802.15.4 radio transceiver to send a notification message to the MA.

2) The MA retrieves from the database information about the nearest doctor/nurse in the hospital (e.g., the mobile phone number) and sends him/her a PN. The doctor/nurse receives on the Medical App the emergency notification [Fig. 9(a)] and visualizes the actual location of the patient [Fig. 9(b)]. Note that the location refers to the room where the patient is hospitalized or, alternatively, to the last position where the RFID tag has been read.

3) The doctor visualizes details about the patient fall and promptly provides to handle the emergency.

As shown in Fig. 9(c), the Medical App is also able to retrieve all the information stored in the control DB concerning hospitalized patients.

B. Architecture Comparison

As highlighted by the state-of-the-art analysis proposed in Section II, only few attempts to combine UHF RFID and WSN technologies in the healthcare application scenario have been proposed in the literature. With respect to such work, the main advantage of our solution consists in its intrinsic scalability to large-scale deployment. Furthermore, as clarified in Sections III and V, the proposed SHS is able not only to track and monitor medical devices and hospitalized patients but also to provide medical staff with advanced features and services. First of all,
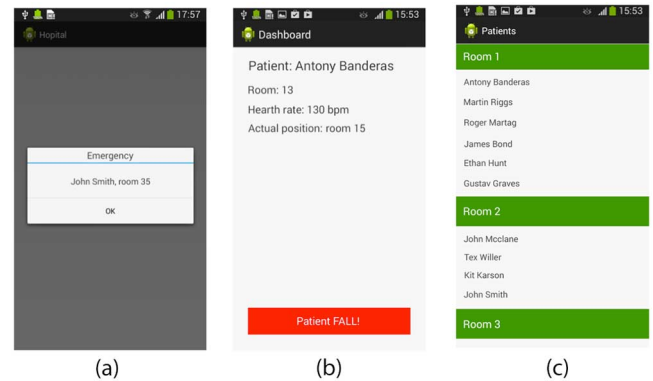

Fig. 9. Screenshots of the Medical App. (a) PN on the mobile phone. (b) Visualization of details about the emergency situation. (c) List of patients and their location.

the integrated use of UHF RFID and WSN allows HT nodes to maintain their IEEE 802.15.4 transceiver in deep sleep mode for most of the time, thus substantially reducing their power consumption, which represents one of primary challenges in WSN contexts. In fact, different from the classical approach relaying on the IEEE 802.15.4 RF interface (see [16], [17], and [22]), the HT nodes are able to transmit both environmental and patient's physiological parameters via the energy-efficient RFID Gen2 interface. As reported in Table III, such a strategy provides a current consumption roughly three orders of magnitude less than that observed in WSN-only systems (i.e., not exploiting the RFID Gen2 interface for sensor data transmission).

At the same time, in the proposed SHS, doctors, equipped with a smart phone connected to a portable RFID Gen2 reader, can use a customized mobile application to check, at any time, patients' status by reading the health sensor parameters logged on the user memory of the HT node worn by the patient.

Finally, the adoption of IoT protocols and solutions, such as REST, 6LoWPAN, and CoAP, makes the designed architecture easily extensible and interfaceable with different standards and technologies. A comparison overview between our SHS and some of the most relevant systems in the literature is presented in Table IV.

TABLE III
COMPARISON BETWEEN THE RFID-ENABLED HT NODE AND IEEE 802.15.4-BASED SENSOR NODES ADOPTED
IN HEALTHCARE SCENARIOS

Reference work	Sensor node	Available sensors	RF interface current consumption
[14]	TelosB using the TI CC2420 IEEE 802.15.4 transceiver	Ambient light, temperature, humidity	RX: 18.8 mA TX: 17.4 mA
[15]	Customized M2M device using the TI CC2420 IEEE 802.15.4 transceiver	PPG	RX: 18.8 mA TX: 17.4 mA
[20]	Customized mode using the Digi XBEE IEEE 802.15.4 transceiver	Body temperature, heart beat	RX/TX: 40 mA
Proposed SHS	HT node transmitting sensor data via the RFID Gen2 interface	Acceleration, light, pressure, temperature, ECG	RX/TX fully-passive mode: 0 mA RX/TX BAP mode: 0.025 mA

TABLE IV
COMPARISON BETWEEN THE PROPOSED SHS AND SIMILAR ARCHITECTURES PRESENTED IN THE LITERATURE

Reference work	Technologies			Services provided				IoT interoperability	
	RFID	WSN	Mobile	Patient Tracking	Staff Tracking	Remote Patient Monitoring	Alert Notification	6LoWPAN	CoAP
[1]		√	√	√		√			
[3]	√		√			√	√		
[4]	√			√	√				
[14]		√		√		√			
[15]		√	√			√		√	
[19]	√	√	√	√			√		
[20]	√	√				√			
Proposed SHS	√	√	√	√	√	√	√	√	√

VII. CONCLUSION

In this paper, a novel, IoT-aware, SHS architecture for automatic monitoring and tracking of patients, personnel, and biomedical devices within hospitals and nursing institutes has been proposed. With the IoT vision in mind, a complex network infrastructure relying on a CoAP, 6LoWPAN, and REST paradigms has been implemented so as to allow the interoperation among UHF RFID Gen2, WSN, and smart mobile technologies. In particular, taking advantage of the zero-power RFID-based data transmission, an ultra-low-power HSN has been implemented. It is able to collect the real-time variation of any critical patients' physiological parameter as well as of the environmental conditions. The sensed parameters are delivered to a control center where they are made easily accessible by both local and remote users via a customized REST web service. Two different use cases have been implemented to validate the proposed SHS. The former deals with patients' monitoring, the latter with the management of an emergency situation caused by patient falls promptly detected by three-axis acceleration measurements. The achieved results demonstrate the appropriateness of the proposed system to perform not only identification and tracking of patients, nursing staff, and biomedical devices within hospitals and nursing institutes, but also to provide power-effective remote patient monitoring and immediate handling of emergencies.

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