An IoT-based measurement system for aerial vehicles

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***Abstract*—In this paper we present an innovative monitoring system, namely *TLSensing*, that can be integrated in future aerial vehicles for supporting the development of advanced health management systems. Based on the revolutionary Internet of Things paradigm and emerging open standards for low-power and short-range wireless technologies, it intends to enable pervasive monitoring services through the diffusion of a large number of sensors around the aircraft, which continuously capture critical and non critical parameters from on-board equipments and the environment and deliver them to the remote monitoring devices through wireless communication links. In summary, *TLSensing* is composed by a number of constrained devices equipped with sensing and wireless communication capabilities, a central system coordinator that controls data acquisition processes through a dedicated monitoring software, and a web server application that collects data coming from the network and makes them available to the user and to external software entities belonging to the health management system. Starting from the description of the technological background that motivated the development of the presented platform, we will carefully describe both hardware and software components integrated in *TLSensing*, alongside their interaction and the most important features they cover. Moreover, to provide a further insight, we will also present how *TLSensing* works by showing some measurements collected with an experimental testbed deployed in our research laboratory.**

***Keywords*—Health management systems, IoT-based monitoring system, experimental testbed**

I. INTRODUCTION

In avionics, *health management systems* are massively used for controlling the status of on-board electronic devices, identifying service disruptions, monitoring critical and non-critical parameters (i.e. temperature of both engines and cabins, vibration of wings and wheels, cabins' pressure, fuel consumption, and so on), thus preventing dangerous events [1][2]. To this end, they generally integrate sophisticated measurement techniques that continuously capture data from a number of sensors deployed around the aircraft (i.e., inside the cabins, outside the body aircraft, in the hold, etc.) [3]-[7]. In conventional solutions, such sensors are connected to monitoring devices through a wired communication infrastructure. As a consequence, the presence of a high amount of cables (for instance, the monitoring system in the Airbus A380 adopts over 300 miles of cables consisting of approximately 98000 wires and 40000 connectors) frequently brings to the growth of the aircraft's weight, thus making impossible the realization of *pervasive monitoring services* [8].

In this context, a change of perspective, which intends to replace *heavy* cables with *weightless* wireless communications, is extremely required for solving this challenging issue.

During the last few years, the Internet of Things (IoT) paradigm has gained worldwide the attention of academia and industrial research fields, thanks to its main idea to deploy a network composed by a potentially large number of constrained devices, that communicate each other by means of *low-power and short-range wireless links* [9]. From the literature review, we learned that the IoT already offers impressive opportunities for developing pervasive services in different domains, like health care, smart city, energy management, military, environmental monitoring, and industry-automation [10]. Furthermore, recent studies also proposed to integrate IoT-based solutions within monitoring systems in both aircrafts or smaller aerial vehicles [8],[11]-[16]. From these preliminary contributions, it emerges that the IoT could really represent a key enabling technology for conceiving advanced (and pervasive) measurement methodologies in future aerial vehicles.

In line with these premises, we developed an IoT-based measurement system, namely *TLSensing*, which can be integrated in advanced health management systems for offering pervasive monitoring services in future aerial vehicles. It is composed by a number of constrained devices equipped with sensing and wireless communications capabilities, a central system coordinator that controls data acquisition processes through a dedicated monitoring software, and a web server application that collects data coming from the network and makes them available to the user. The communication among the central system coordinator and constrained devices is enabled by low-power and short-range wireless technologies based on IEEE 802.15.4 and IEEE 802.15.4e standards. At the application layer, instead, the interaction between involved entities is handled through a client-server paradigm, built on top of open standards emerging from IETF standardization bodies. The web server, that runs on the same machine hosting the monitoring software application, exposes collected data to users and external softwares belonging to the health management system by using a web-based/user-friendly interface and a dump of the database structured according to the JavaScript Object Notation (JSON) syntax. Indeed, after having carefully described the main features offered by the developed *TLSensing* platform, we will also present how TLSensing works by showing some measurements collected with an experimental testbed deployed in our research laboratory.

The rest of the paper is organized as follows: Sec. II introduces the protocol stack adopted for reaching reliable short-range wireless communications in the aircraft; Sec. III depicts the *TLSensing* network architecture and gives more details on both hardwares and softwares used to build up the entire system; Sec. IV shows how to interact with *TLSensing* and advantages deriving by the adoption of an IoT-based monitoring system in the aircraft and, finally, conclusions are reported in Sec. V.

II. A ROBUST PROTOCOLS STACK FOR LOW-POWER AND SHORT-RANGE WIRELESS COMMUNICATIONS IN THE AIRCRAFT

Without loss of generality, we can assume that an aircraft is a real crowded scenario, where a number of electronic devices generating electromagnetic emissions and several on-board wireless systems (e.g., aircraft communication, navigation, surveillance radio, etc.) coexist into the same environment [17][18]. In this really challenging scenario, a pervasive measurement system must take care about of several issues, like synchronization, security, and real-time and reliable wireless communications.

At the time of this writing, IEEE 802.15.4 and IEEE 802.15.4e standards are widely recognized as the most successful enabling technologies for low-power and short-range wireless communications [19][20]. Based on these specifications, IETF standardization bodies are dedicating many efforts to the definition of standard protocols for IoT systems [9][21]. The resulting protocol stack is composed by (see Fig. 1):

- IEEE 802.15.4-2011 PHY: low-power physical layer based on the Direct Sequence Spread Spectrum (DSSS) modulation scheme and operating at the 2.4 GHz of the ISM band [19];
- IEEE 802.15.4e-2012 MAC: powerful MAC layer based on the Time-Slotted Channel Hopping (TSCH) protocol, which ensures reliability and energy efficiency in challenging wireless PAN [20];
- IETF 6TOP: adaptation layer that enables the integration between higher-layers protocol and the novel IEEE802.15.4e standard through management and data interfaces and organize the transmission of a IPv6 packet over a TSCH protocol [22];
- IETF 6LoWPAN: adaptation layer to let IPv6 datagram to fit the small payload size (up to 127 bytes in IEEE 802.15.4) by means of advanced header compression techniques [23];
- IETF RPL: gradient based routing protocol that can ease the formation and the management of multi-hop topologies based on short-range low-power links. It supports multiple roots and is highly flexible thanks to the possibility to optimize the topology based on parametric optimization functions [23];
- IETF CoAP: application protocol which easily translates to HTTP for integration with the web, while meeting specialized requirements such as: multicast support, very low overhead, and simplicity for constrained environments [24].

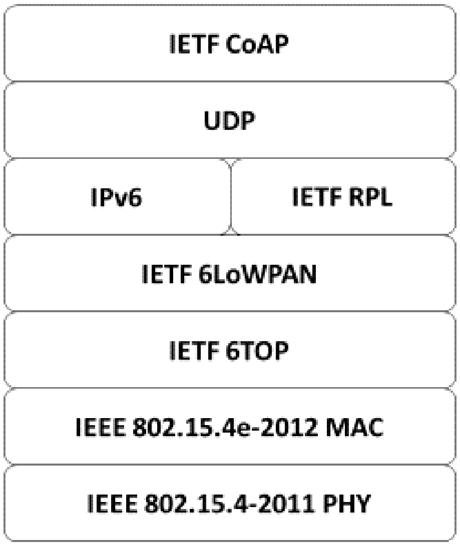


Fig. 1. Communication stack integrated in the *TLSensing* platform.

It is very important to note that the TSCH protocol, integrated at the MAC layer of the aforepresented protocol suite, is able to build robust wireless communications in challenging wireless environments. Based on both Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) schemes, it assumes that all the nodes are synchronized on a slot-frame basis, i.e., a pre-defined group of time-slot that repeats over time. Of course, the duration of a single time-slot allows the transmission of a given MAC frame and the reception of the corresponding acknowledgement. In order to mitigate the impact of both narrow-band interference and multi-path fading, as well as increasing the aggregate network capacity, TSCH adopts multiple physical frequencies, each one identified by a specific channel offset. Finally, a TSCH schedule is introduced for orchestrating the communication among devices (e.g., by defining the set of time-slots and physical frequencies that each couple of devices should use for exchanging packets) and for managing the duty cycle of the radio activity, thus avoiding idle listening and extending batteries' lifetime.

In conclusion, we believe that the aforementioned protocol stack has all the potentials for supporting the development of robust and a reliable communication infrastructure enabling advanced health monitoring systems in future aerial vehicles. Hence, it has been fully integrated within the *TLSensing* platform for enabling the communication among sensing devices and the data collection process handled by the central network coordinator.

III. TLSENSING IN A NUTSHELL

As already anticipated in the Introduction, *TLSensing* is based on the revolutionary IoT networking paradigm and integrates the emerging open standards developed by IETF standardization bodies.

The core of *TLSensing* is a wireless sensor network made up of a number of constrained devices, having both sensing and communication capabilities, deployed around the aircraft. They are in charge of gathering data from the environment (like temperature, humidity, luminosity, and acceleration) and make them available to the rest of the monitoring platform. In line with the protocol stack described in the previous Section, the communication technology is based on IEEE 802.15.4 and IEEE 802.15.4e standards and the adopted protocol stack. Moreover, in each constrained device is installed the OpenWSN stack [25], which is an open source implementation of the protocol suite reported in Fig. 1. In order to guarantee confidentiality and authenticity services, messages are exchanged at the layer-2 in a secure fashion. In particular, the layer-2 payload is encrypted and authenticated by using security functionalities already defined in the IEEE 802.15.4 and IEEE 802.15.4e specifications; the whole network works in the *Fully Secured* configuration [27], and link keys are negotiated among nodes by using the lightweight key management protocol proposed in [28]. In general, *TLSensing* does not impose any constraint to the network topology and extension, thus fully supporting (just to make an example) star, chain, binary, and mesh configurations. The whole wireless sensor network is coordinated by a central node, namely *PAN coordinator*, which is connected to the central system coordinator through an USB interface. Indeed, it acts as a border router between the IoT domain and the external Local Area Network (LAN). The central system coordinator runs a monitoring software that controls data acquisition processes by adopting a client-server communication paradigm. The software is the client that periodically generates requests to send towards remote constrained devices. On each constrained device, instead, runs an application server that processes such requests, queries on-board sensors, and delivers measurement data back to the central system coordinator. As it will be better explained in the sequel, messages are encapsulated into the Constrained Application Protocol (CoAP) protocol and the *PAN Coordinator* just acts as a relay between the client and the server. Data retrieved by the monitoring software are finally delivered to the web server application that will make them available through a web-based/user-friendly interface. This means that the user may visualize the outputs of the measurement process on a web-page by using any device connected through the LAN. The history of captured data is continuously stored within the database, whose dump is exposed through a specific JSON-based data structure. This makes easier the integration of *TLSensing* in complex and general health management systems.

To summarize, the *TLSensing* network architecture has been shown in Fig. 2.

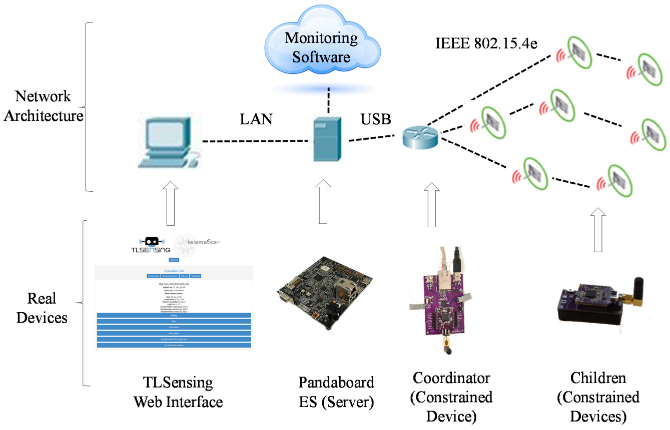
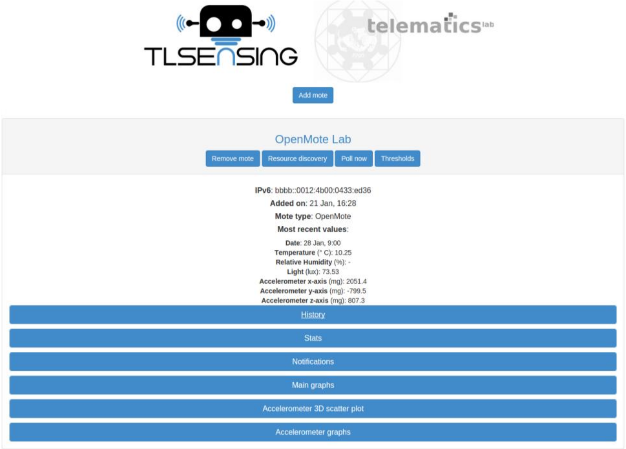


Fig. 2. Network architecture.

The web server application also allows the user to interact with the measurement system (i.e., by observing the set of measured data or forcing an update of information acquired in the past). Once the network is deployed, the user may discover the list of constrained devices that are available in the aircraft by clicking on the *resource discovery button* available on the web page of the application. From this moment on, data can be retrieved by means of two mechanisms: from one side, the monitoring software polls remote devices every 10 s, thus triggering them to provide an answer with a message containing the current value of variables measured by their sensors; from another hand, the user can use the *poll now button* to force the poll of remote nodes, thus capturing any measured parameter at a desired time instant. Received measurements are then processed and visualized on the web page of the application. In summary, the following sections can be seen from the web page (see for example Fig. 3):



IPv6: bbbb::0012:4b00:0433:ed36
Added on: 21 Jan, 16:28
Mote type: OpenMote
Most recent values:
Date: 28 Jan, 9:00
Temperature (° C): 10.25
Relative Humidity (%): -
Light (lux): 73.53
Accelerometer x-axis (mg): 2051.4
Accelerometer y-axis (mg): -799.5
Accelerometer z-axis (mg): 807.3

Fig. 3. TLSensing web page.

- history section, which stores the latest values polled from a specific device (as default it reports the latest 10 values);
- statistics section, which reports the maximum, the minimum, and the mean values of aforementioned values;
- notification section, which reports possible error messages (e.g., the retrieved data exceeds a pre-defined threshold);
- graphs section, which graphically shows the trend of retrieved measurements;
- accelerometer 3D scatter plot, which draws the scatter plot related to a given remote device;
- accelerometer graphs, which details the values provided by the accelerometer, both in x, y and z directions.

Details on hardware, firmware and software components used to build up the *TLSensing* architecture will be described in what follows. Furthermore, softwares, firmwares, and deploying instructions are freely available from *http://telematics.poliba.it/tlsensing_tool*.

A. Hardware details

The central system coordinator has been installed on the Pandaboard ES platform, which is a low-power and low-cost single-board computer development platform. It is an open-source development platform which integrates dual-core 1.2

GHz ARM Cortex-A9 MPCore CPU, 384 MHz PowerVr SGX540 GPU, IVA3 multimedia hardware accelerator with a programmable DSP, and 1GiB of DDR2 SDRAM, as well as SD Card slot, 10/100 Ethernet, Wi-Fi, and Bluetooth interfaces, output video signal via DVI and HDMI interfaces, and two USB ports.

Constrained devices are, instead, provided by the OpenMote technologies[1]. In particular, each node is made up of three elements, that are the OpenMote-CC2538 (which is the portion of the constrained device that integrates computational capabilities), the OpenBase (that is used for configuring both firmware and software of the aforementioned element), and the OpenBattery (that contains a set of sensors). At the time of this writing, OpenBattery includes four types of sensors, that measures temperature, relative humidity, ambient light, and acceleration. Their most important characteristics have been summarized in Tab. I.

B. Firmware and software details

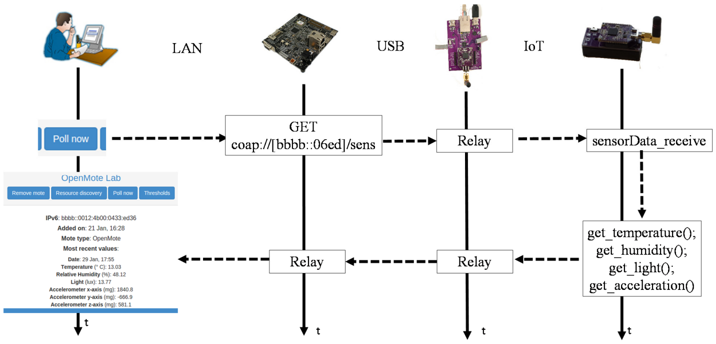
All the functionalities of the proposed *TLSensing* are enabled thanks to a set of applications implemented in both constrained devices and central system coordinator.

From one hand, a CoAP server application, namely *SensorData*, has been developed in the firmware of the constrained devices. In particular, it has been implemented starting from the OpenWSN protocol stack (we considered version 1.9.0 as a reference). *SensorData* starts in the initialization phase of the protocol stack and continuously waits for GET requests directed to the */sens* path. Moreover, GET requests may also contain a specific set of arguments, through which generating customized queries (i.e, poll all sensors vs poll a single sensor directly).

From another side, the monitoring software integrates an open-source library, namely *OpenCoAP*, that is used to interact with remote devices by means of CoAP messages. The possibility to generate GET requests with customized queries is enabled by the URI-Query options, already integrated within the aforementioned library. Finally, the web server application is written in Python, is built on top of the well-known Django framework[2], and it makes use of the non relational MongoDB database[3].

IV. TLSENSING AT WORK

With the aim of describing how does *TLSensing* work, an example showing the interaction between user and constrained device has been reported in Fig. 4. From the illustration, it is possible to observe that the user generates requests by clicking on the *Poll Now* button. The web server application contacts the monitoring software that triggers the generation of a CoAP GET request to send towards a specific constrained device. Such a request is delivered via the *PAN Coordinator* to the destination node, that takes required data from on-board sensors and generates a CoAP response to send back to the client (i.e., the monitoring software). Once the requested data are received, they are then processed and visualized on the web page.



IPv6: bbbb::0012:4b00:0433:ed36
Added on: 21 Jan, 16:28
Mote type: OpenMote
Most recent values:
Date: 29 Jan, 17:55
Temperature (° C): 13.03
Relative Humidity (%): 48.12
Light (lux): 13.77
Accelerometer x-axis (mg): 1840.8
Accelerometer y-axis (mg): -666.9
Accelerometer z-axis (mg): 581.1

Fig. 4. Interaction between the user and the measurement system.

In addition, to demonstrate how *TLSensing* works in a practical scenario, we deployed an experimental testbed in our research laboratory, thus allowing any user to see, in real-time, local measurements. The testbed is available from *http://telematics.poliba.it/tlsensing*.

For example, Figs. 5 and 6 summarize temperature and relative humidity measurements gathered during a single day by motes located indoor and outdoor, respectively. As expected, values provided by the indoor mote do not significantly change during the time. The mote placed outside, instead, reports variable values that strictly depend on external conditions.

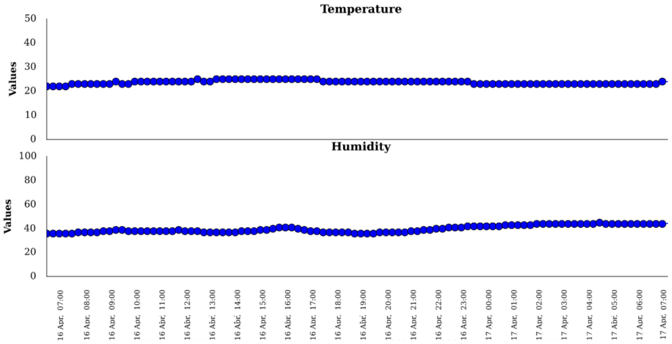


Fig. 5. Temperature and relative humidity acquired in an indoor environment during a single day.

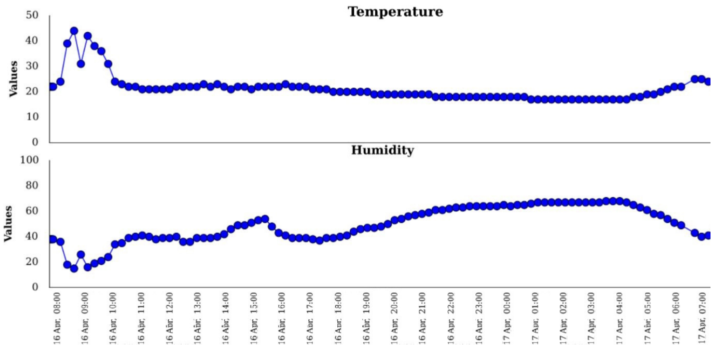


Fig. 6. Temperature and relative humidity acquired in an outdoor environment during a single day.

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[1] http://www.openmote.com/

[2] https://www.djangoproject.com/

[3] http://www.mongodb.org/

TABLE I. SENSORS ALREADY AVAILABLE ON THE OPENBATTERY.

Sensor	**Model**	**manufacturer**	**Main characteristics**
Relative humidity	SHT21	Sensirion	Resolution: 0.04 %RH @ 12 bits; 0.7 %RH @ 8bits Accuracy tolerance: ± 2 %RH (typical); ± 3 %RH (maximum) Response Time: 8 s Long Term Drift: $<$ 0.25 %RH/years
Temperature	SHT21	Sensirion	Resolution: 0.01 $^{\circ}$C @ 14 bits; 0.04 $^{\circ}$C @ 12bits Accuracy Tolerance: ± 0.3 $^{\circ}$C (typical); ± 1.6 $^{\circ}$C (maximum) Operating Range: from -40 $^{\circ}$C to 125 $^{\circ}$C Response Time: from 5 s to 30 s Long Term Drift: $<$ 0.02 $^{\circ}$C/years
Light sensor	AX44009	Maxim	Maximum Lux Sensitivity: 0.045 Lux/LSB Saturation Ambient Lux Level: 188000 Lux Total Error: 15 % Signal Integration Time: 800 ms (maximum); 6.25 ms (minimum)
3-axis accelerometer sensor	ADXL346	Analog Devices	User selectable Measurement Range: $\pm 2g \pm 4g, \pm 8g, \pm 16$ g Output Resolution: 10-bit Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$: 256 LSB/g Scale Factor: 3.9 mg/LSB

V. CONCLUSIONS

In this paper we have presented an innovative monitoring platform, namely *TLSensing*, which is based on the revolutionary IoT networking paradigm and emerging open standards for low-power and short-range wireless technologies. It provides a number of powerful functionalities that can be used for developing advanced (and pervasive) health monitoring systems for future aerial vehicles. In the future, we plan to experimentally evaluate the performance, scalability, and feasibility of the proposed platform in more realistic scenarios.

ACKNOWLEDGMENTS

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