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Evaluation of a Wireless Sensor Network with Low Cost and Low Energy Consumption for Fire Detection and Monitoring

Xavier Silvani, Frédéric Morandini and Eric Innocenti, Laboratory Sciences Pour l'Environnement CNRS UMR 6134, University of Corsica, Campus Grimaldi, 20250 Corte, France*

Sylvestre Peres, EDF – Systèmes Energétiques Insulaires, Ancienne Centrale d'Aspretto, 20090 Ajaccio, France

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Abstract. Wireless sensor networks (WSNs) may offer the opportunity to eliminate most of the extension cables and wires in digital systems, allowing operation far from any infrastructure. This opportunity coincides with a great increase in cost-effectiveness in an overall fire detection and monitoring system for forests, buildings or industrial sites. Our purpose is to evaluate this opportunity. After presenting the three main technologies for wireless communications to non experts, we retained the Zigbee protocol for this study. We then investigated whether the use of a WSN with this protocol is valuable for measuring heat quantities during a fire spreading over a vegetation fuel bed. Experiments are performed under both lab scale indoor and real outdoor conditions. The method consists of comparing temperatures and radiant heat fluxes gained with the wireless technology with those recorded at the same location through a wired data acquisition system. Delays due to the wireless radio communications are identified and explained. We also observe information loss for measurements performed in the fire front. Finally, we highlight that fires can be detected satisfactorily by WSN equipment in indoor and outdoor conditions. However, we also show that measurement accuracy obtained from wired systems cannot be obtained with the present wireless technology, and we do not recommend their use at the present time for fire monitoring and mitigation.

Keywords: Fire metrology, Wireless sensor network, Lab scale experiments, Outdoor experiments

1. Introduction

In the case of fire engineering, the metrology for detection, mitigation, and monitoring at the field scale is complex and expensive, as far as large structures are concerned (forests and industrial sites with fuel storage, ships, and buildings). This metrology is complex because the phenomena involve nonlinear physics of mass,

* Correspondence should be addressed to: Xavier Silvani, E-mail: silvani@univ-corse.fr

momentum, and energy transport in real geometries with tubes, corridors, walls, doors, floors, or paths through vegetation cover. Metrological systems are also expensive because the devices must be resistant to a real fire, and usually long wires are used, which have to be insulated and/or buried, with the sensors and the data acquisition/control systems.

For scaling with these constraints, let us consider the cost of a wired fire detection or measurement system in two field-scale applications, namely, a large area of fuel storage and a fire experiment over real vegetation cover. These are representative of respectively industrial and wildland fire safety problems. For industrial areas of fuel storage, the average length of wire for the fire safety of a 11,000-m^3 tank of liquid oil fuel is 500 m, with a wire cost of approximately $300 to $6,000 per metre [1]. The latter cost is attributed to the indispensable innocuousness of electrical devices operating in explosive atmospheres. The overall cost of wiring scales to $500,000 for a single fuel storage tank. However, in wildland fire experiments, one metre of wire costs approximately $1 to $10, as in [2, 3]. However, the total length of extension wire also depends on the size of the vegetation plot, requiring more technical staff for experiments over large areas. The overall cost finally includes the cost of materials for wiring, insulation, and/or burying wires and the cost of the technical staff (approximately $1,000 per day per person). Finally, in an outdoor wildfire experiment, the range of the overall cost due to wires versus area ranges from $2,250 for three sensors [4] over 200 m^2 when two researchers are concerned. Additionally, the cost reaches $325,000 for 100 sensors over 7,500 m^2 [2] with six researchers. In the largest experiment, the wiring cost was approximately $500,000. These amounts span over several orders of magnitude, and strong differences can exist between large-scale fire situations [5]. Regardless, one can reasonably assert that by eliminating wires, the use of wireless technology could reduce the overall cost of fire engineering by approximately $500,000. Furthermore, wired technologies are today well known as suffering from a crude lack of flexibility, when the display of sensors must be momentarily adapted in both industrial or wildland configurations. This induces additional costs in the management of industrial installations or wildland areas subject to fire hazards. Despite these cost limitations, wired data acquisition systems (WDASs), i.e. digital recorders related to sensors through wires, strongly demonstrate the reliability of their measurement capability in fire science. One can cite examples of fire experiments in full-scale conditions where WDASs are used in a non-exhaustive list [4, 6–11]. Recent investigations with wired systems with high sampling rates demonstrate the promising outlook of WDASs for the measurement over very short timescales of turbulent fluctuations in fire data [6].

Finally, beyond the cost-effectiveness to replace wired communications by radio communications, the advantages of eliminating wires in digital systems for confined or outdoor fires must be evaluated in terms of accuracy for fire detection and monitoring for mitigation. Consequently, a question about wireless capability which arises for people accustomed to working with wired digital systems in the difficult context of fire scenarios is whether a wireless system is able to efficiently record physical quantities as standard wired data loggers do during a fire. In this paper, we attempt to address this issue, with fire experiments at a lab scale in outdoor conditions. For several reasons described below, we chose the Zigbee protocol among three standards for wireless communication. Hereafter, the acronym WSN will therefore represent wireless sensor network systems based on the Zigbee protocol. Fire spread experiments are performed by igniting a fire in a spanned vegetation cover, and we measure the gas temperature at the top of the fuel bed and, in some cases, the radiant heat flux outside of the plot. The heat measurements were performed with the use of two heat sensors, thermocouples or fluxmeters, positioned at the same location, one using a wired data logger and the other using a WSN. Wired and wireless heat measurements are then compared and discussed.

The paper is organised as follows: in Sect. 2, we provide a short overview of wireless technology to readers familiar with fire safety science in order to justify the choice of the Zigbee protocol in the present work. In Sect. 3, we present the experimental protocol used to evaluate the performances of both wired and wireless DASs in outdoor fire experiments. The comparisons concern the measurement of gas temperatures in a flaming fire. In Sect. 4, we present the results, which we discuss in Sect. 5. The conclusion and outlook end the paper in Sect. 6.

2. Overview of Wireless Technologies

The question arises of choosing a wireless technology for replacing wired communications in fire experiments. People with experience performing heat measurements in fire science may ignore the differences which exist between several approaches for transporting digital information through radio waves. For this reason, we summarise the features and skills of wireless technologies in this section. The basic principle of wireless communication consists of an emitter which sends a signal via radio waves to a receiver located at a certain distance away. A radio wave is an electromagnetic wave oscillating without any material support in a large spectral range from 3 kHz to 300 GHz. Mobile and sensor networks use microwaves, with frequencies in the range of 400 MHz to 30 GHz. Wireless technologies for networks have been persistently developed for decades. Indeed, in the recent years, WiFi (IEEE 802.11-wireless local area networks (WLANs)) and Bluetooth technologies (IEEE 802.15 wireless personal area networks (WPANs)) have been under strong development and have mainly been used in homes and large commercial offices. These are general public wireless technologies and have found limited usage in industrial installations because of harsh environments, electromagnetic compatibility, and interference issues. Since the middle of the year 2000, the Zigbee technology (IEEE 802.15.4) has corresponded to a standard wireless communication protocol based on the use of a microcontroller. This differs from Bluetooth or WiFi hardware, which are based on the use of micro central processing units (CPUs). The Zigbee technology for wireless communications therefore leads to low energy and financial costs in devices, making them answerable to a set of industrial/environmental needs and challenges. The use of the Zigbee system in place of wired or WLAN/WPAN data acquisition systems coincides with several advantages and but also with drawbacks. As previously mentioned, the advantages include the low cost and low energy consumption of the Zigbee technology, which allow the display of a large number of measurement points, greater compactness, and greater autonomy than WiFi/Bluetooth devices. Indeed, WiFi requires nearby infrastructure to collect and process the data, whereas Bluetooth is limited to eight units in a network. On the contrary, Zigbee allows the design of ad hoc networks, i.e. networks that are distant from any installation. This feature offers the ability to sense a large isolated area in an industrial or outdoor environment with a reliable autonomous system. Furthermore, Zigbee offers commercially available products, which enable the design of home-made solutions dedicated to specific industrial or outdoor scenarios. They are easy to use for even nonexperts in wireless communications. That explains the numerous attempts to edit wireless solutions on the basis of Zigbee. In [12], the authors presented the most recent development of a Zigbee WSN optimised for an industrial environment, as in warship industries, where multisensory systems are needed [13]. Concerning their main limitations, one can argue that wireless solutions based on Zigbee architecture first coincide with communications over a short distance, namely, shorter than 10 m between two nodes of the network. Additionally, several works such as [12] have established that the Zigbee technology is optimal for a star-like topology.

Table 1 lists the different criteria for comparing the most adapted wireless solutions to wired systems in fire tests. From this brief overview of wireless technologies, we find strong relevant arguments to select Zigbee rather than Bluetooth or WiFi for a fire study. However, regardless of the results we find for Zigbee, every fire study with Bluetooth or WiFi remains valuable and interesting.

Until now, for every protocol (WiFi, Bluetooth, and Zigbee), the ability of a WSN to offer a cost-effective and accurate alternative to wired solutions is already illustrated in agricultural science [14–17] or in indoor environments [18]. More peculiarly, in a measurement and instrumentation strategy, wireless technology can be used as a DAS, mainly regarding the gain and loss in terms of flexibility,

Table 1
Relevancy of Wireless Protocols for Fire Detection and Monitoring Strategy Over Large Span Areas. Most Favourable Items are Underlined Italic

Category	Zigbee	Bluetooth	Wifi
Distance	<10 m (wall sensitive)	10 m	50 m
Extension	Automatic	None	Depends on the existing network
Power supply	Years	Days	Hours
Complicity	Simple	Complicated	Very complicated
Transmission speed	250 kps	1 Mbps	1–54 Mbps
Network nodes	65535	8	50
Linking time	30 ms	Up to 10 s	Up to 3 s
Cost of terminal unit	Low	Low	High
Integration level and reliability	High	High	Normal
Prime cost	Low	Low	Normal
Ease to use	Easy	Easy	Hard

cost, and transfer rate in wireless architecture [19], [20], [21]. Other evaluations of wireless technology for a remote DAS focus on the maximum achievable data acquisition [22]. In the last decade, WSNs have been adopted in several fire applications in order to detect forest fires [23–27]. Despite these pioneering works, no comparison with wired systems is available.

The present paper proposes to address this issue by comparing the data acquisition of heat quantities with a wired DAS and a WSN based on the Zigbee protocol.

3. Experimental Protocol

The paper reports on seven scenarios of a fire spreading over a fuel bed of pine wood while temperature and radiant heat flux measurements are performed. The scenarios are described as two lab-scale and five field-scale conditions. They are summarised in Table 2.

3.1. Fire Scenarios and Heat Measurements

3.1.1. Experimental Plot. The lab-scale experiment (LabS) consists of igniting a fire line at the edge of a 1-m^2 area of pine needles. The fire spread on the 0°-slope and 20°-slope conditions. These conditions without aid by wind allowed for selecting a process of fire spread purely driven by heat radiation (0°) and a mixed heat convection-radiation drive process (20°) [28].

Field-scale experiments concern two different sets of fire experiments in no-slope conditions: the first experiment was performed in Winter 2012 (W'12) in a sunny and dry cold atmosphere (8°C), whereas the second experiment was performed in Summer 2013 (S'13), under a dry and hot atmosphere (33°C). In both cases, the incident wind flow was weak (<4 m/s), when measured by the use of a manual anemometer located 2 m off the ground.

3.1.2. Fuel Properties. The fuel bed for lab-scale conditions was formed with dead pine needles: the fuel bed depth was measured at three random locations on the 1-m^2 area. The surface-to-volume ratio and density of the fuel were 7,112 m^{-1} and 603 kg/m^3, respectively. The fuel load was equal to 400 g for the 1-m^2 area. Each outdoor plot was covered with pine excelsior. The fuel bed depth was measured at three random locations per square metre. The surface-to-volume ratio and density of the fuel were 4,730 m^{-1} and 780 kg/m^3, respectively. A constant fuel load, fuel homogeneity, and fuel bed bulk density were maintained during the experiments. The fuel load varied from 1 kg/m^2 to 8 kg/m^2 $\pm$ 10% for the entire set of experiments. The fuel samples were not conditioned in an oven before the fire tests, and their moisture content was approximately 10%. Before the fire experiments, the fuel load (aerial fuel and litter) and vegetation height were measured from three samples in the 1-m^2 area.

All fuel parameters are reported in Table 2 (Fig. 1).

Table 2
Experimental Parameters: w'12-exp. 3 and s'13-exp. 7 (*Grey*) are Destructive for the Wired System

Set number	LabS	LabS	W'12	S'13	S'13	S'13	S'13
Experiment number	1	2	3	4	5	6	7
Experimental conditions	Lab 1 m^2	Lab 1 m^2	Outdoor 30 m^2	Outdoor 20 m^2	Outdoor 20 m^2	Outdoor 20 m^2	Outdoor 20 m^2
Slope wind	0° no wind	20° no wind	0° <4 m/s	0° <3 m/s	0° <3 m/s	0° <3 m/s	0° <3 m/s
Average fuel load (kg/m^2)	0.4 ± 0.01	0.4 ± 0.01	13 ± 1	1 ± 0.1	2 ± 0.2	4 ± 0.4	8 ± 0.8
Average fuel bed height (cm)	1	1	88	16	30	39	46
Max temp. °C	1148	987	1115	543	563	992	N/A
Max radiant heat flux Φ (kW/m^2)	10	4.6	33	8	25	30	34
Time during which $\Phi > 5\ kW/m^2$ (s)	72	0	233	31	48	217	250
Flame height (m)	0.25	0.15	4	0.7	2.3	1.7	2.9
Rate of spread (cm/s)	0.3	0.9	15.3	7.6	20.6	11.3	16.7

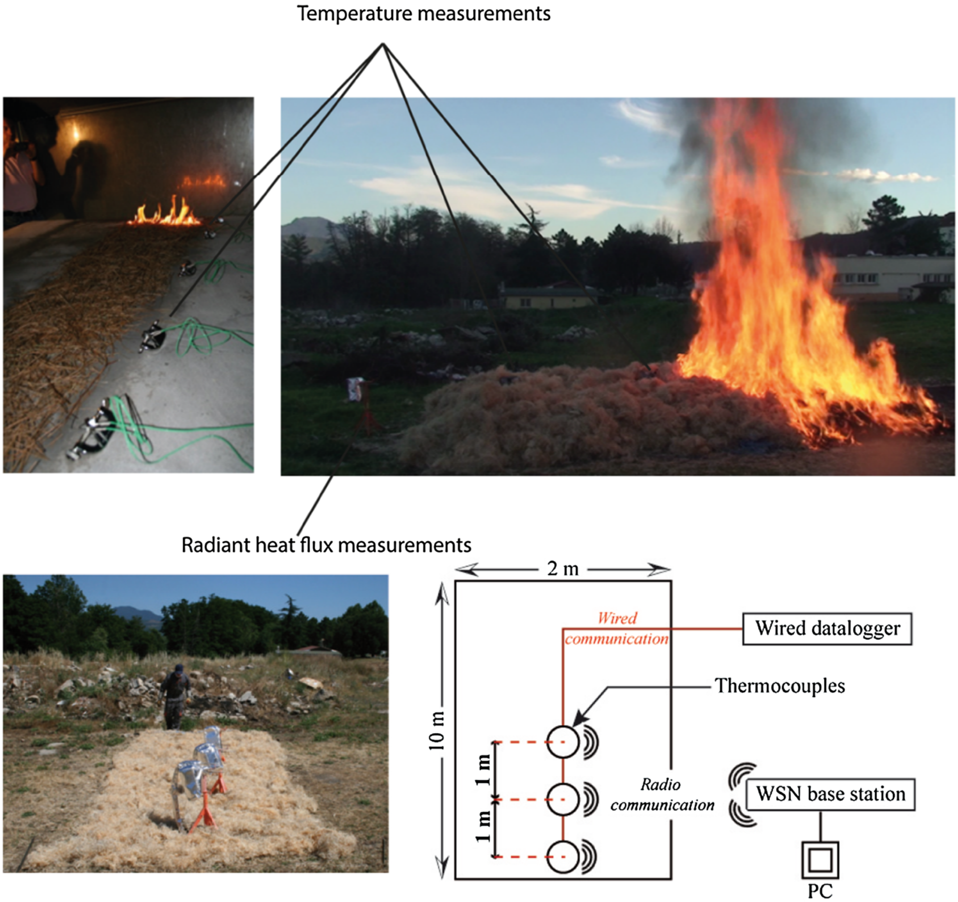

Figure 1. Overview of the experimental plot: LabS and W'12 (*top*)/ S'13 (*bottom*)—schema for summer configuration (*bottom right*). Length and thickness change for.

3.1.3. Heat Measurements. In each case, a measurement point involves two sensors. The first is plugged into a wired DAS, whereas the other is plugged into a node belonging to the wireless network. For temperature measurement, the sensor is a K-type thermocouple (TC) with a 250-μm-diameter grounded junction (50-μm wires). We notice that when using the frequency response of an electrically compensated thermocouple to measure temperatures in turbulent flames, changes in the time constant may occur. These are due to the temperature and the velocity dependences of the TC time constant. A study [29] emphasised the ability of the 250-μm-diameter thermocouple to capture the flame pulsations up to a rate of 10 Hz. This means that the effective time constant of the TC in flames is lower than 0.1 s. Furthermore, when using thermocouples in flames, some errors may be due to the radiative heat losses. Finally, according to [4], the errors due the radiative gain or loss do not exceed 10% inside and outside the flame front. Both wired and wireless intrusive sensors measured the gas temperature during the fire spread experiments. Each sensor was thermally insulated and designed to be fast and easy to set up (less than 30 min in the present conditions, regardless of the mode of communication). A protective sleeve fabricated from several layers of ceramic felt and radiation shield materials thermally insulated the wireless nodes. We observed that the internal temperature never exceeded 70°C. All experimental measurements were performed at a constant height. Images of the wireless and wired devices are provided in Fig. 2, for the lab-scale and field-scale experiments.

The maximal temperature in the flame is provided for each experiment in Table 2 as recorded on the wired system. The value for experiment 4 is not reported because it is inaccurate as a result of the partial or complete destruction of wires by the most intense fire in the set.

In order to measure experimental heat quantities in relation to the fire intensity and its dependence on the fuel load, we also obtained the radiant heat flux Φ by the use of a Medtherm Gardon gauge, as in previous fire experiments [4, 9, 10] displayed outside the plot, facing the approaching fire front. This indication of the dependence of fire intensity on the fuel load is provided through the maximal value of Φ and the time interval during which Φ is greater than 5 kW/m^2 (reported in [30] as the first level of significant damages and injuries for a 20-s exposure). All these quantities are also reported in Table 2.

3.2. Data Acquisition Systems

The aim of the seven experiments is to evaluate the ability of the WSN to capture heat signals from a fire in comparison with a reference standard wired data logger. Both are presented below.

3.2.1. Wired Data Acquisition System (WDAS). On the wired network, the temperature was recorded using a portable Campbell Scientific© data logger CR 3000 model. We have already used this DAS to collect data in large-scale fire spreading experiments [4, 9, 10]. The CR 3000 is equipped with 14 differential analogue channel inputs. Each channel has a maximum scan rate of 100 Hz and can measure the voltage levels with 16-bit resolution. Five voltage ranges from ± 50 mV to ± 5 V can be selected. In this study, the channels were configured at ±50 mV

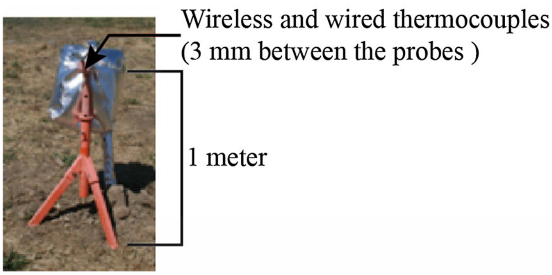

Figure 2. The measurement system for outdoor conditions.

(analogue resolution: 1.5 μV per digit), and a 1-Hz sampling rate is selected. The data are stored on a 4 MB of memory. The dimensions and the weight of the rechargeable battery are respectively 24.1 × 17.8 × 11.9 cm^3 and 4.8 kg. The experimental setups with several measurements points spaced far apart, as in environmental studies, generally involve a long extension cable from the sensors to the data logger. In the present study, the cables are buried into the ground. The off-ground section of the data logger was protected as a result of thermal insulation. This protection should guarantee that the wires will be resistant to fire, except in the two experiments with a heavy fuel load (13.5 kg/m^2 for W'12 experiment 3 and 8 kg/m^2 for S'13). These resulted in the most powerful fires.

3.2.2. Wireless Sensor Network (WSN). The WSN is composed of thermocouples plugged into radio communication nodes (five in lab-scale experiments, three in field-scale experiments). Another node is used for a heat fluxmeter. Because of their small size in the Zigbee architecture, a node is often called a 'mote'. The WSN modules are MEMSIC© devices (previously Crossbow). For the tests, commercially available products were used. Their choice may not reflect the preferences of the author. No recommendation is connected with their use.

The WSN nodes are MICAz motes with mote data acquisition boards (MDA 300). The dimensions and weight of the assembled device were respectively 5.76 × 1.2 × 4.6 cm^3, and 18 g, excluding the battery pack, as shown on Fig. 3. That illustrates the great advantages which fire scientists and engineers can expect from Zigbee WSN technology in terms of device compactness. We explained in Sect. 2 that these skills are mainly due to the microcontroller-type hardware of Zigbee technologies. The MEMSICS devices were from 2010: they are not the most recent devices of the Zigbee protocol. However, there has been no significant upgrade for fire applications in IEEE in the last 4 years. The advantages and limitations presented here remain generic and mainly a result of microcontroller technology.

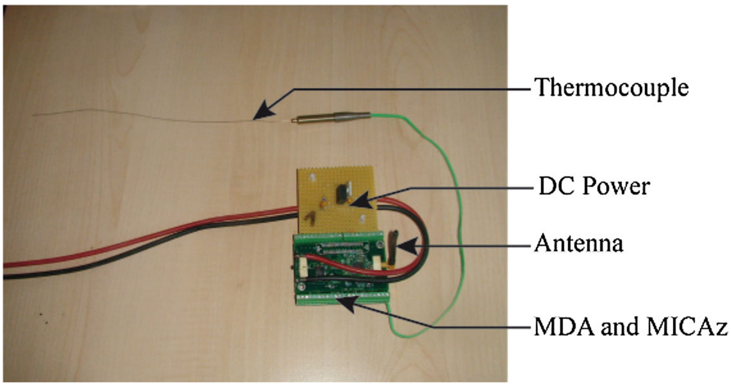

Figure 3. A WSN mote: MICAz node and its MDA board.

According to the manufacturer specifications [31], the node is a 2.4-GHz IEEE 802.15.4 tiny wireless measurement system. The communications between the nodes are based on the ZigBee protocol, which is known to be adapted in embedded applications requiring low data rates and low power consumption. These last two features make the Zigbee protocol useful for experiments in outdoor conditions, where large areas and long observation periods require numerous and autonomous sensors. A WSN may work according to a 'flat' protocol where the data may pass through every neighbour up to the base station. In the case of breakdown or communication loss, a Zigbee node is able to reroute the data through another active neighbour: this is called the resilience property. It is a fundamental skill for sensing large areas far away from any maintenance or infrastructure. In certain cases, the WSN topology can also allow direct communication between the nodes and the base station, as in the current experiments. This is a star-like topology, for which Zigbee is optimal. We selected this configuration in the present work.

The main disadvantage of this system is the low power of the radio transmission signals between nodes, which does not allow for long distances. The outdoor and indoor communications scales are theoretically 75–100 m and 20–30 m, respectively. However, real communication scales are less than 10 m, as we observed in previous WSN studies in shrub land vegetation [26].

In the present study, communications between the Zigbee nodes and the base station are direct—radio antennas are all at an equal distance—and supported by the Xmesh high-power protocol. We use this mode because it enables a theoretically higher data rate with the present technology. In the high-power mode, every node is an emitter-receiver at any time, i.e. it is at the fastest data rate reachable by each unit. Each node is set to its theoretical maximal value, which is 300 ms, with an accompanying higher energy consumption. However, this consumption is not considered in the present study.

The MICAz node is associated with an MDA 300 board with 12-bit resolution. This board offers four differential-precision channel inputs for signals with a dynamic range of ±12.5 mV using a sensor frontend with a gain of 100 (bit resolution: 6 μV per digit). These precision channels are used for the TCs and heat radiation gauges of the experiments. Each node transmits a message to its neighbours with a 300-ms data rate in its default factory configuration.

4. Results

In this section, we present four distinct quantities: the rate of fire spread (ROS), the flame height, the time evolution of the temperature, and the time evolution of the radiant heat flux, when available. These are summarised for the three sets of experiments, namely, LabS, W'12 (both with heat flux), and S'13.

4.1. Flame Height and Rate of Fire Spread (ROS)

Regardless of the scale, the flame height is measured on averaged images of the fire front viewed from a lateral position. Instantaneous images are recorded with a visible HD digital camera (Sony HandyCam) at a 25-Hz frame rate and averaged over 20 s. This procedure has already been used in previous similar works for several scales of fire [4, 9, 10, 28]. The ROS is measured using the evolution of temperature profiles through the different measurement points. The flame height, width of the fire front, and ROS are also reported in Table 2.

4.2. Heat Flux Measurement

This measurement is nonintrusive: the Gardon gauge radiometer is located outside the plot; regardless of the scale, the thermal sensor does not pass through a propagating flame front. This choice allows observing the transmission of heat information without a strong influence of the fire on radio communication.

The heat flux measurements are available in three experiments, i.e. two LabS experiments and one W'12 outdoor experiment. Their time evolution is reported in Fig. 4a (LabS) and Fig. 4b (W'12). As shown in the figures, the heat flux gained with the WSN network is close to that gained using the wired data logger. However, two main differences occur: the WSN heat flux signal is damped from the wired signal and delayed by approximately 2 (lab scale) to 10 s (field scale). The differences in signal amplitude can be explained by the differences in bit resolution for each equipment: the WSN has 12-bit resolution, whereas the CR3000 has 16-bit resolution. Digital signals are therefore more resolved in the wired system, allowing greater accuracy in the presence of strong temporal variation. The WSN also introduces a different temporal resolution for the wireless data. We recall that the wired system samples signals at a stable rate of 1 Hz. Because the data flow in the radio channel is different than in the wired channel, the WSN imposes different time sampling, even if the MDA 300 scans the analogue channel every second. Indeed, WSN data resolves the signal every 2 s relative to the wired DAS because of the time interval required by radio communication and noted $\Delta t^{WSN}_{communication}$. (see Appendix for details). Because of that difference in effective time sampling between WSN and wired signals, the WSN appears as under-resolved. As a result, some local fluctuations are not captured, leading to a form of damping. That contributes to the difference in heat flux amplitude between wired and WSN signals.

This radio time interval $\Delta t^{WSN}_{communication}$ also explains the observed shifts in the WSN signal of heat flux from the wired signal on the time axis (Fig. 4a, b). The corresponding delay is measured by a level-crossing algorithm. Only temperature is reported in Table 3. For the heat flux, this retard is approximately 2 s for LabS and can exceed 10 s for W'12.

4.3. Temperature Measurement

This measurement is intrusive: the sensor is located inside the vegetation plot, and the fire spreads over wired and wireless equipment. This choice allows observation of the transmission of heat information by radio waves through the fire.

We present several temperature measurements: five in the LabS scenarios and three in every field-scale fire. The time evolution of temperature measurements is reported in Fig. 5a for LabS and in Fig. 5b. One can observe in the LabS temper-

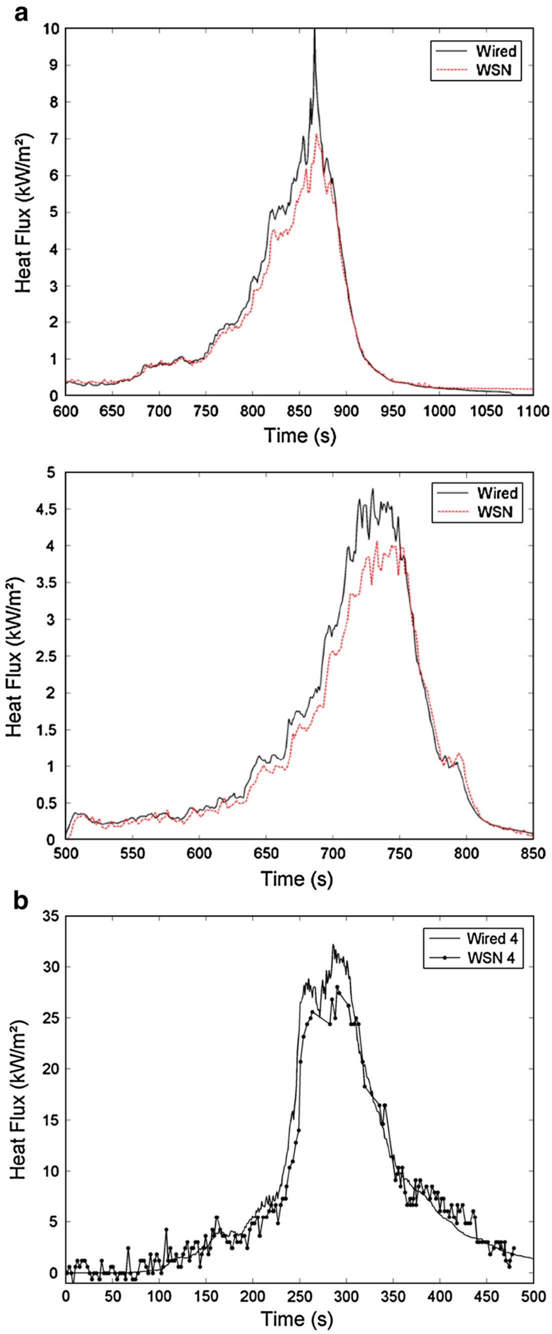

Figure 4. (a) Experiment 1–2 (Labscale): temporal evolution of the heat flux—no slope (*top*) and slope (*bottom*) cases. (b) Experiment 7 (winter outdoor): temporal evolution of the heat flux.

Table 3
Average Delays Between Temperature Rises With Wired and Wireless TCS: Delays are Measured as the Time Difference Between Instants of T = 100 = 100°C Padding

	TC 1	TC 2	TC 3	TC 4
Δt (s) in exp. N°1	6	9	**2**	3
Δt (s) in exp. N°2	4	6	**2**	7
Δt (s) in exp. N°3	Destructive	Destructive	Destructive	
Δt (s) in exp. N°4	−13	9	−5	
Δt (s) in exp. N°5	**2**	**2**	21	
Δt (s) in exp. N°6	12	6	**23**	
Δt (s) in exp. N°7	Destructive	Destructive	Destructive	

Bold font is used for minimum (2 s) and maximum (23 s) delays

ature measurements that the wireless system respects the dynamics of the wired system, even if some fluctuations disappear because of differences in time resolution, as we explained above for heat fluxes. It also appears that some delays are approximately 2 s because of the data flow through the WSN. At a larger scale (S'13), this delay may increase to 23 s (see Table 3).

There is another important feature in the temperature signal gained by the WSN at field scale. One can clearly observe a loss of data in experiments 3, 4, and 5 (see TCWSN 1 in experiment 3 in Fig. 6 at t = 40 s and TCWSN3 in experiment 5 in Fig. 7 at t = 70 s). This concerns measurements which are performed inside the fire by intrusive measurement systems. We assume that these losses are related to the complex interaction with the radio communication protocol and the electromagnetic environment of the fire. Indeed, packet loss usually results from radio interference among several sources. It is significant when the IEEE 802.15.4 protocol coexists with other radio communication protocols (approximately 92% of the packet loss with WiFi according to the Steinbeis Transfer Centre coexistence tests). Unfortunately, there is a paucity of literature on the electromagnetic properties of fires, especially in the range of microwaves, where WSN radio waves are emitted and received. However, a single study reports on the ability of fire to emit electromagnetic waves from UV up to microwaves: [32] presents a fire detection system based on the record of the microwave emissions by a burning fire, in closed as well as open environments. That study identifies fire as potentially a significant source of radio waves, which may interact with a WSN, causing packet losses. The energy of radio waves due to the fire is an extensive thermodynamic quantity: it could increase with the fire size. That would explain the reason that fires of increasing size increasingly alter radio transmission in WSNs. Furthermore, changes in the refraction index or temperature gradients due to the fire may strongly alter the radio transmission of the WSN data. Finally, optimal radio communication through a burning fire and its scale dependency must be extensively studied before providing any quantitative conclusion about the response of a radio network in a flame front. Regardless of the large-scale fire scenario, these

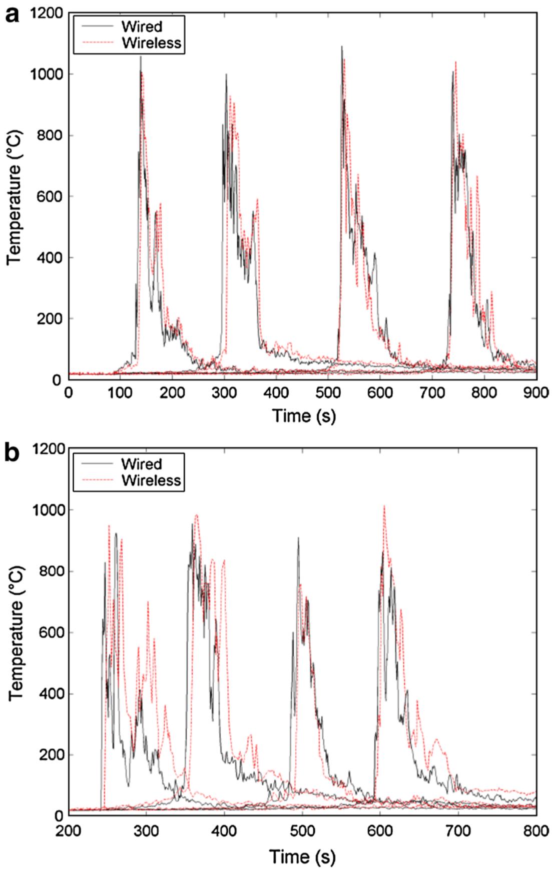

Figure 5. Experiment (a)–(b) (labscale): temporal evolution of the temperature—no slope (*top*) and slope (*bottom*) cases-.

losses only occur during the immersion of the sensor inside the flame front (Fig. 6).

At the end of the experiments, both W'12 and S'13 lead to the complete destruction of the wired network and partial destruction of the WSN. Temperature signals fell to zero or diverged when the corresponding wires burned. This case corresponds to a fire performed in summer (or winter for W'12) conditions with a heavy load (8 kg/m^2 and 13 kg/m^2, respectively). Such behaviour illustrates the way in which the high compactness of wireless solutions exposes them less to fire destruction than wired solutions, especially after cumulative thermochemical aggressions by successive fires. This emphasises that beyond the reduction of financial cost for installation and maintenance, wireless technology also offers to increase the overall robustness of an outdoor sensing system by reducing its spatial span with wire suppression (Fig. 7).

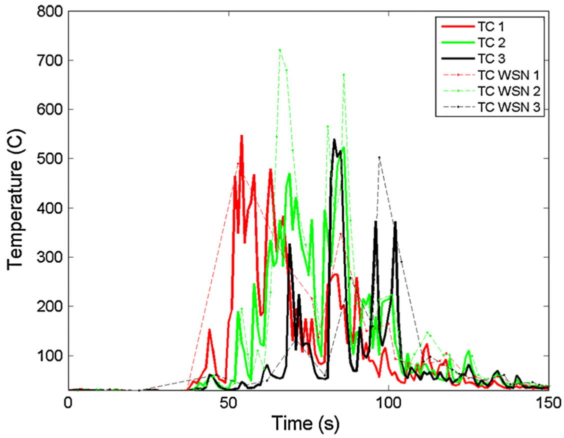

Figure 6. Experiment 3 (summer outdoor): temporal evolution of the temperature.

5. Discussion

The present study aims to observe the behaviour of radio transmission of thermal data in the presence of forest fires in comparison with that of wired transmission. The results exhibit the main differences between wired and wireless systems: wireless signals are delayed relative to wired signals regardless of the scale of the fire. They also suffer from information loss at the field scale, when sensors are immersed in the fire. These results are discussed below in terms of the ability to detect and monitor fires (Fig. 8).

5.1. Delays

The delays between wired and wireless systems are observed in every fire scenario, at every scale, and in indoor and outdoor environments. We already explained the results from the examination of the time interval needed to convert an analogue signal to a digital signal, package the information, and make several attempts at radio transmission. From a common instant t_0, when the information is recorded, a time shared by both wired and wireless systems, the WSN introduces a time delay Δt due to the treatment of the information for radio transmission. The time delay is strongly related to the wireless technology: WiFi or any other IEEE 802 wireless standard may have a shorter time interval, but it also strongly depends on the fire application. Furthermore, with Zigbee, it could be possible to control data flow with systems which allow for parameter changes in the medium access control layer. That is not the case for the proprietary system used in the present study. The delay also depends on the working cycle and the time synchronisation of every node on the network with the coordinator. Commercial systems without

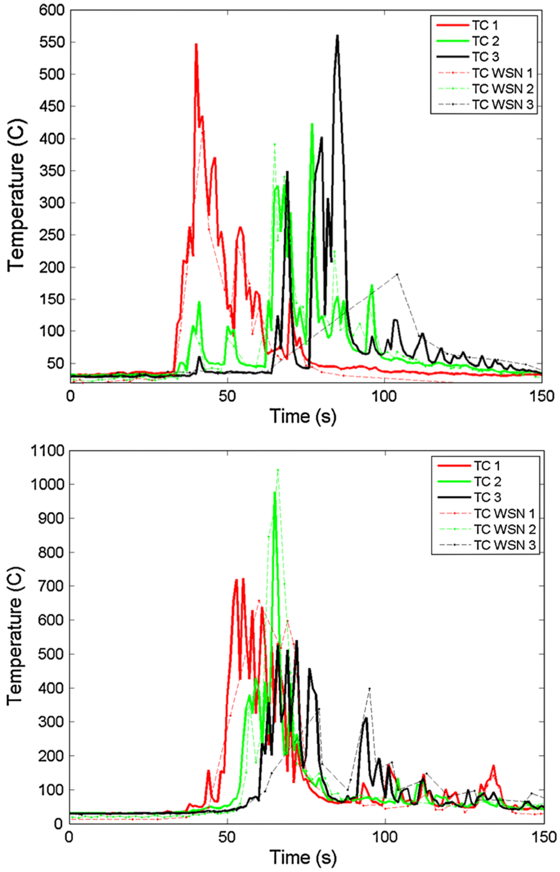

Figure 7. Experiments 5 (*top*) and 6 (*bottom*) (summer outdoor): temporal evolution of the temperature.

open-source code are not often good candidates for such high-level parameterisation. The OCARI project [12] for Zigbee could fill these requirements.

The WSN demonstrates in every case its ability to detect fires with an overall average delay of 12 $\pm$ 10 s relative to the 1-Hz sampled wired solution. In every following study [27, 33–35], the fire detection seems effective with a delay in the range of 30 s to 180 sin after ignition. The present wireless system therefore seems promising in terms of performance. It is sensitive to a significant rise in temperature and heat flux in every configuration, despite a slight damping of the maxima due to the time resolution. Because the Zigbee standard leads to devices with low cost and low energy consumption, we consider that Zigbee is a good candidate for establishing a wireless fire detection system for large-span areas in vegetation, agricultural settings, or industrial settings, given the present results in fire detection.

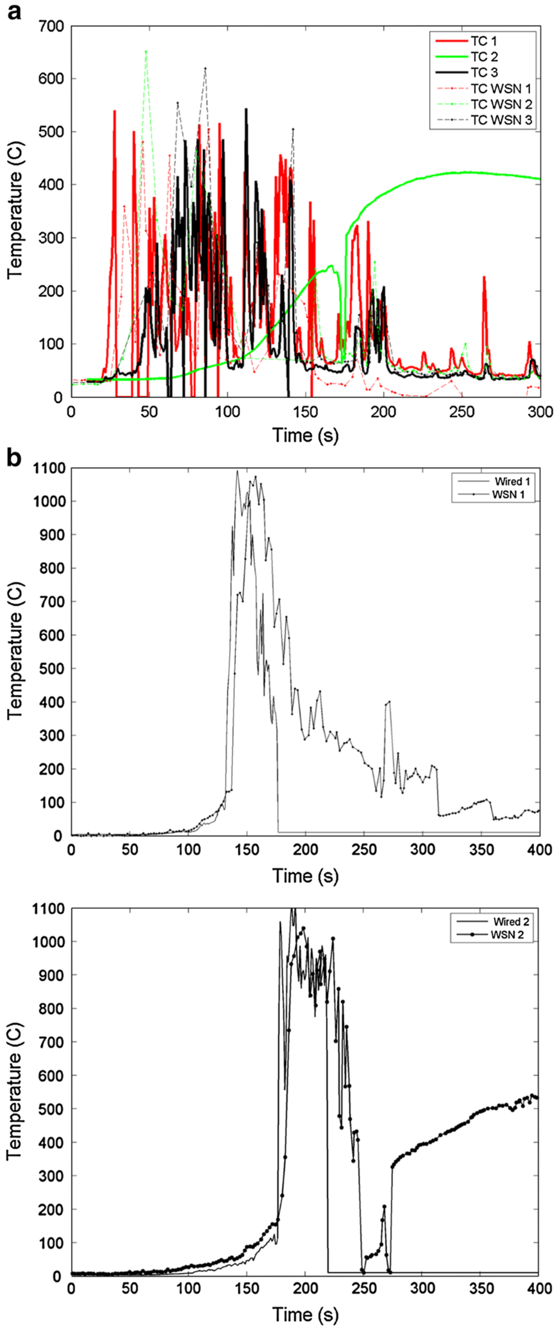

Figure 8. (a) Experiment 7 (summer outdoor destructive case): temporal evolution of the temperature. (b) Experiments 3 (winter outdoor destructive case): temporal evolution of the temperature.

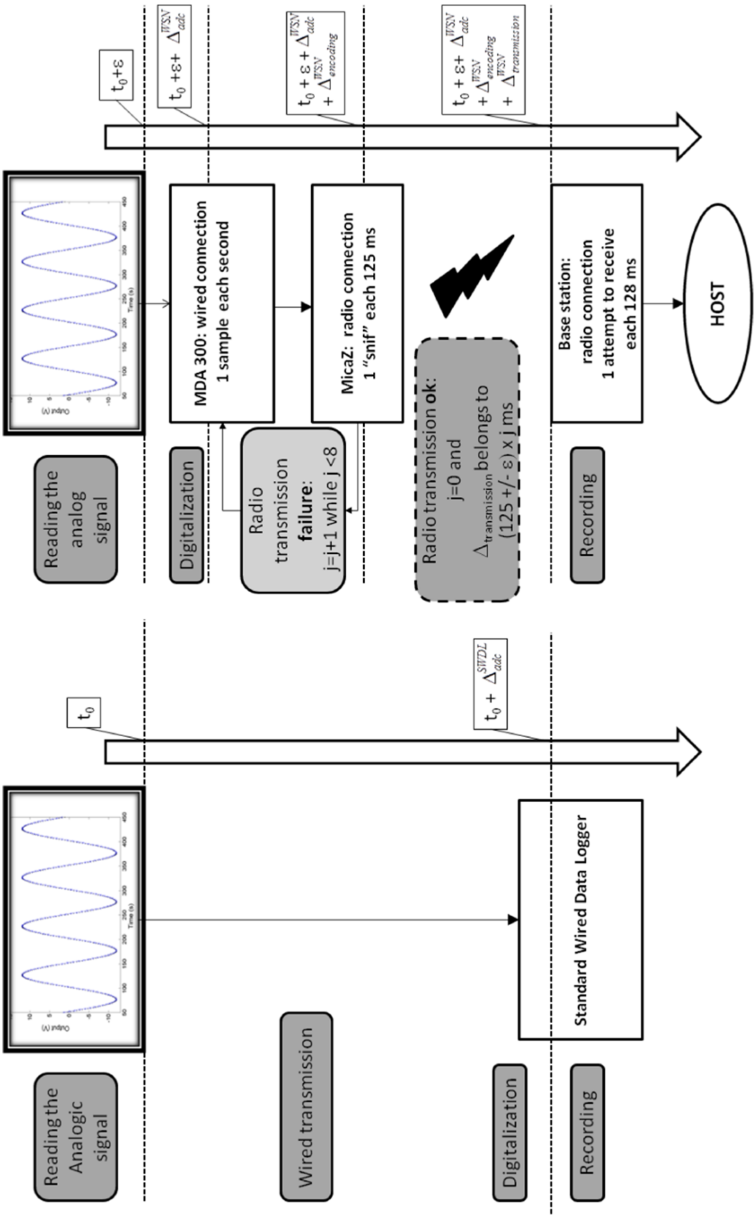

Figure A. 1. The time history of data processing in wired and wireless systems: from the same absolute instant t_0, contrary to the wired system, the wireless system introduces a non negligible delay modeled by Eq. (A.1) due to conversion analogue-to-digital, signal packaging, signal radio emission/reception and recording by the host.

5.2. *Losses*

Data losses are significant in large-scale outdoor fire scenarios. The wireless solution lost information mainly when sensors were immersed in the fire front. As we explained, this is probably a consequence of radio wave interference with a fire which behaves as a source of microwaves; however, this issue remains poorly addressed in the literature, and hence, data transmission by radio waves through fire becomes central according to the present results. One can assume that a more powerful protocol such as WiFi could overcome the present difficulty by generating more powerful radio waves. However, this must be demonstrated and will coincide with increased financial and energy costs regardless of the outcome.

We therefore consider that the Zigbee protocol is not able to capture data with the same accuracy as a wired system. The delay is the first drawback for in a monitoring system. However, we think that this can soon be controlled on new operating systems. For instance, the new IEEE 802.15.4e standard should upgrade the existing protocol in particular with a communication class for fast 'real-time' communications. This will help to solve the problem of low time resolution in the WSN solution. On the contrary, avoiding the loss of information is a great challenge. This problem could be systematic regardless of the radio communication protocol and must be studied. Only scientific studies quantifying the attenuation of radio waves and packet loss through well-documented fires will answer that challenging question.

6. Conclusion

The paper presents a comparison of a WSN system with low cost and low energy consumption with a standard wired network in fire experiments. The wired system is based on the use of a Campbell Scientific© CR 3000 data logger, sampled at 1 Hz, for temperature and heat flux measurements. The wireless system is based on a commercial Zigbee protocol, where radio communication nodes duplicate the wired measurement points. We conclude that there are delays between the WSN and the wired network. They are due to the time interval required on a WSN to convert analogue information into recordable digital information for radio transmission. The retard might be common to every wireless system: there was no investigation found in the literature, and this topic is of varying importance according to the radio communication protocol. The retard is not prohibitive for using a WSN as a fire detector and is sufficient when the performance is compared to that of a wired system in fire detection applications. These time delays could probably be eliminated by the next generation of the Zigbee standard. However, packet and data losses due to interaction between fire and radio waves remain as difficult technical obstacles. Until there have been further complementary studies on these interactions, and the future developments of the Zigbee technology are known, the results do not allow us to recommend a wireless system for monitoring fires with accuracy comparable to a wired system.

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Appendix: The Timing of the Data Flow in Wired and Wireless Systems

The present appendix details for nonexperts the processing of information gained by a sensor through wired and wireless communication systems. In particular, it explains the differences in the time interval between wired and wireless solutions existing at each stage in the digital processing of analogue data.

Let us therefore consider the different stages in the sampling and recording of an analogue signal on a digital data logger for both DASs considered. In a wired system, the analogue signal coincides with a voltage of 0–12 mV inputted into the digital system by wires. It was converted into digital data by an analogue-to-digital converter (ADC) at a given sampling rate. In the case of a standard wired data logger (SDWL) such as the CR3000—the digital recorder of the WDAS solution—the time scale for converting the value of an electrical voltage is 96 ns when one value is read each second. This conversion rate is therefore extremely short compared to the sampling interval of the data (see figure A.1).

Let us now consider the process for the WSN system. The acquisition board MDA 300 reads a value in the continuous analogue signal each second. The sampling rate of each acquisition system in the ADC is therefore the same. However, in the WSN, after an ADC delay Δt_{adc}^{WSN} (approximately 50 ms) [36], the data is then encoded for security and converted into a message involving packets. This occurs over a timescale of $\Delta t_{encoding}^{WSN}$ (approximately 20 ms). Next, the data is ready to be transmitted to the base station. At this instant, the data is timestamped by the MicaZ mote at the instant $t = t_0 + \Delta t_{adc}^{WSN} + \Delta t_{encoding}^{WSN} + \varepsilon$, where ε is the error due to the clock synchronization from a mote and the base station (ε cannot exceed 0.36 s in the Xmesh HP communication protocol because it is set to zero every 36 s). The process then involves a call from the mote to the base station each 125 ms (8 Hz). The base station listens to its neighbours at the same frequency. The data read by the MDA 300 remains the same as long as the transmission process fails, i.e. for eight attempts. Then, this data is erased and replaced by the new data flowing from the MDA 300 board. This process is summarised in figure A.1. The XMesh mapping is therefore set up to ensure stable communications between motes, ideally before the MDA reads the new following analogue value. The time scale during which the transmitter attempts to send its message is $\Delta t(j)_{transmission}^{WSN}$. This value depends on the number of attempts j for communicating with the base station $\Delta t(j)_{transmission}^{WSN} = j * 125ms$, where j = (1,2,…,8) is the number of attempts for radio transmission from a node to the base station. Finally, according to these processes, one can consider that the timestamp associated with an analogue record by the WSN MDA 300 acquisition board obeys the following model provided by the following equation:

$$\Delta t^{WSN}_{communication} = \Delta t^{WSN}_{adc} + \Delta t^{WSN}_{encoding} + \Delta t(j)^{WSN}_{transmission} \pm \varepsilon \quad (A.1)$$

It is important to observe that the maximal transmission rate of a single node (time of 300 ms in Xmesh HP mode) is therefore estimated on the assumption that the radio transmission cannot fail more than two consecutive times ($j = 2$ leads to $t = t_0 +$ 300 ms). However, this assertion is incorrect in real conditions, where interference may occur and force the number of attempts to be greater than two. As a theoretical distance for data transmission, one can observe that the radio transmission rate in the WSN cannot be set up with the present commercial system.

The model in Eq. (A.1) will be exact for a single node-to-base-station communication when it is evaluated on the record of each packet and when the process of decoding information and the flow to host are also described. In a multiple-node configuration, this model remains reliable, but another time interval $\Delta t^{WSN}_{multiplexing}$ appears. This is due to the multiplexing of incoming data at the base station. The network of an efficient WSN is able to transmit data 'continuously', with a base station which starts to read a new message, segmented in packets, before the end of the transmission of previous packets. This will delay the delivery of the acknowledgement, which completes the arrival of a full message at the base station.

This model explains why a delay of approximately 2 s to 23 s may exist between wired and wireless signals in the present experiments.

Incoming upgrades of the Zigbee protocol IEEE 802.15.4e should introduce a fast communications class, where $\Delta t^{WSN}_{communication}$ is expected to approach $\Delta t^{SWDL}_{communication}$, which will allow us to use a WSN as a data logging system.

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