Implementation of PoF-powered IoT Sensing Systems for Industry 4.0

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***Abstract*– We propose and experimentally investigate two distinct power-over-Fiber (PoF) approaches, aiming to remotely power Internet-of-Things (IoT) sensing systems for Industry 4.0 environments. The first proof-of-concept is focused on demonstrating a 1-W optical power transmission through a 50-m-fiber-optic link for powering an Arduino Uno, a temperature sensor (DS1820B), and a 433-MHz transceiver (FS1000A). The designed PoF link is able to provide up to 280 mW with power transmission efficiency (PTE) of 28.9%. The second implementation is based on a 100-m PoF link capable of transmitting over 0.6-W optical power and delivering 140-mW electrical power with PTE of 23%. In this scheme, an Arduino Pro Mini, another temperature sensor (LM35), and a 2.4-GHz transceiver (nRF24L01+) are employed. A voltage stability analysis enables to demonstrate that our PoF system is capable of delivering stable output voltage at 8.5 V and 5 V, with only 0.6% and 0.2% voltage fluctuations. In addition, an industrial oven is employed to evaluate the sensor performance considering temperature measurements from both sensing systems. The obtained results demonstrate that PoF might be considered as a potential technology to optically-power IoT wireless sensing systems for Industry 4.0 scenarios.**

***Index Terms*–** Industrial Internet of Things (IIoT), Industry 4.0, Power-over-fiber (PoF), sensor nodes.

I. Introduction

The rapid development of electric/electronic devices, information and communication technologies has driven a fundamental paradigm shift in industrial production, leading to a fourth industrial revolution, namely Industry 4.0 [1], [2]. The concept of using Internet of Things (IoT) technologies in manufacturing, known as Industrial IoT (IIoT), has enabled the interconnection of engines, power grids, and sensors to the cloud over a wireless network [3]. One of the foundation technologies of IIoT is the wireless sensor network (WSN), which aims to collect data from different sensors in industrial environments, aiming to achieve an intelligent and reliable process management in industrial production lines. Therefore, the data obtained from sensors are analyzed to generate valuable information for factory operation and control devices [4]. In addition, the use of wireless communications technologies in industrial environments is a potential solution to reduce installation costs and provide scalability, flexibility, intelligent-processing capability, and high mobility, compared to conventional wired solution [5]. The most commonly employed communication protocols are Wi-fi, Zigbee and Bluetooth, which generally operate at 2.4 or 5 GHz [6], [7]. On the other hand, the LoRa protocol has been considered for short-range industrial applications operating at 433, 868 or 915 MHz [8].

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Industrial monitoring systems face challenges in terms of operating conditions, as the industrial environment is characterized by higher temperatures, humidity, vibration, dust, and/or electromagnetic interference [7]. In addition, the increasing number of devices in an IIoT system may lead to a considerable energy consumption. Therefore, energy efficiency is one of the most important challenges that needs to be addressed by using different techniques in different layers of the system, from the physical to the upper layers [9]. In addition to providing solutions to reduce the components consumed power, it is critical to find energy-efficient techniques to power WSNs and improve the industrial systems reliability and safety [10]. In this context, the use of power-over-fiber (PoF) technology may be a promising solution to improve the safety and reliability of IIoT systems [11]. This technique, firstly reported in 1978 [12], employs a high-power laser diode (HPLD) that emits light through an optical fiber to a photovoltaic power converter (PPC), which performs the optical-to-electrical conversion, transporting electrical power to remote applications. Optical fibers provide electrical isolation and are immune to electromagnetic interference, short circuits, sparks, corrosion, and moisture [13], [14]. As a consequence, the use of optical fibers in the industrial power distribution network becomes a potential enabler to remotely power sensing nodes, specially in hazardous environments.

PoF has already been considered for powering sensor networks for hazardous applications. For instance, the Authors in [15] reported optically-powered smart nodes based on magnetic field monitoring, fire, and temperature/presence sensors aiming at IoT-based solutions for power grid stations. Moreover, a PoF-based system designed to power IoT temperature and humidity sensors was presented in [16]. Another previously reported PoF-based sensor system focused on powering remote transceivers, which are responsible for receiving and transmitting the acquired data to a base station through an optical fiber. Additionally, the Authors fed the wireless sensing nodes employing battery units, which may present safety risks in hazardous environments [17]. Regarding industrial applications, few works report the use of PoF for powering remote sensors. Budelmann *et. al.* demonstrated a cost-effective PoF approach based on standard light-emitting diodes (LEDs) and photodetectors (PDs) to power a base station which can handle up to four sensor nodes [18]. Nevertheless, one may note most works are aimed at general IoT or hazardous environments.

In this paper, we propose PoF-powered IoT sensing systems applied to Industry 4.0 scenarios, as depicted in Fig. 1. Aiming to demonstrate the feasibility and potential of the PoF technology, we develop two PoF-based sensing system architectures employing DS18B20 temperature sensor and 433-MHz wireless transceiver and LM35 temperature sensor and 2.4-GHz wireless transceiver. Both sensing systems performance is analyzed by compiling the sensors temperature measurements over time in a temperature controlled environment. In addition, the PoF systems performance is evaluated in terms of delivered electrical power, power transmission efficiency (PTE), and voltage stability. This paper is organized as follows. Section II presents the PoF-powered 433-MHz wireless sensing system design and experimental results. Section III reports the implementation and performance evaluation of the PoF-powered 2.4-GHz wireless sensing system, whereas Section IV presents the paper conclusions and future works.

II. PoF-powered 433-MHz IoT Wireless Sensing System

Fig. 2(a) depicts the block diagram of the first implemented PoF-based wireless sensor system. In this setup, a 1-W feed light was generated by a 975-nm HPLD and transmitted over a 50-m multimode fiber

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(MMF). The main fiber parameters are 4 dB/km attenuation at the HPLD center wavelength, core and clad diameters of 100 μm and 140 μm, respectively. Afterwards, two 3-axis micropositioners XYZ have been employed to properly couple the feed light into the PPC (YCH-L300, MH GoPower Company Limited), which presents approximately 32.5% conversion efficiency. The converted electrical power has been used to drive an Arduino UNO microcontroller, a low-power temperature sensor (DS18B20), which measures temperatures from -55ºC to +125ºC, and a 433-MHz radio-frequency (RF) transceiver, as presented in Fig. 2(b). At the remote station, the transceiver (FS1000A) is responsible for transmitting the acquired temperature data over a 21.7-m wireless link to an identical transceiver, operating as receiver (XY-MK-5V). The signal propagated through 4 walls in indoor and outdoor environments, characterizing a non-line-of-sight (NLOS) propagation, as depicted in Fig. 2(d). The transmitter has maximum output power and data rate of 16 dBm and 10 kbps, respectively, and employs amplitude shift keying (ASK) modulation. At the reception side, shown in Fig. 2(c), the received data is decoded by an electrically fed Arduino MEGA and displayed by a computer, which are only required for debugging purposes. The detailed system specifications are listed in Table I.

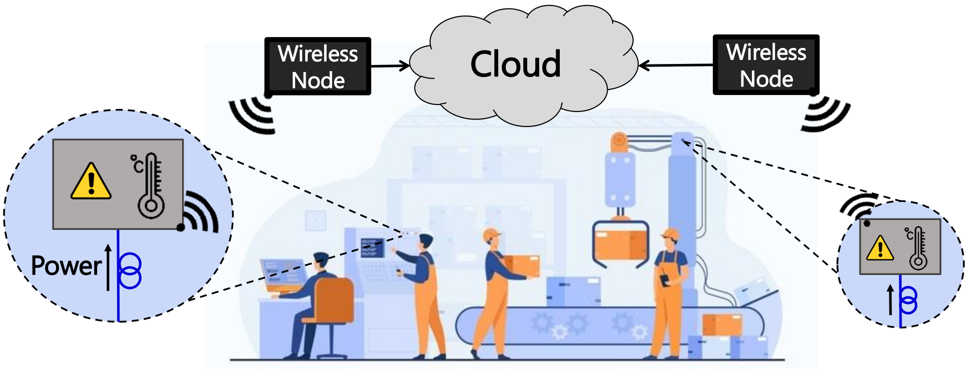

Fig. 1. PoF-powered sensing system applied to Industry 4.0 scenarios.

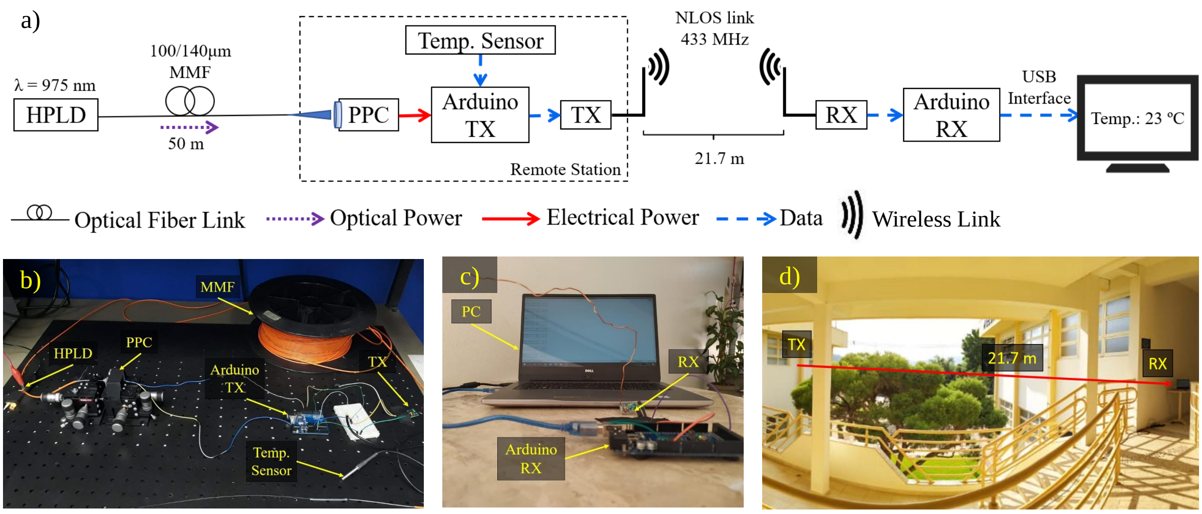

Fig. 2. First implemented PoF-based wireless sensor system: a) Block diagram, b) Experimental setup photograph of the PoF system, Arduino Uno, temperature sensor, and 433-MHz transmitter, (c) Experimental setup photograph of the reception side, including the Arduino Uno, receiver and computer, (d) The NLOS propagation environment. HPLD - high-power laser diode; MMF - multimode fiber; PPC - photovoltaic power converter; TX - transmitter; RX - receiver; PC - personal computer; NLOS - non-line-of-sight.

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TABLE I. PoF-powered 433-MHz IoT Wireless Sensing System Specifications.

Component	Specifications
Fiber-coupled HPLD	Center wavelength: 975 nm/Max. output power: 30 W
Optical Fiber	Type: MMF/Length: 50 m 100 μm/140 μm core/cladding diameters
PPC (YCH-L300 with Passive Heatsinking)	Operating wavelength: 915 - 980 nm Output voltage: up to 8.5 V Max. incident power: 3 W Conversion efficiency: 32.5% @ 975 nm
Arduino UNO	Operating voltage: 6 - 20 V/Current consumption: <40 mA
Temperature Sensor (DS18B20)	Operating voltage: 3 - 5.5 V Current consumption: 1 mA (active)/ 750 nA (standby)
Transmitter (FS1000A)	Operating frequency: 433 MHz Operating voltage: 3.5 - 12 V/Max. current consumption: 28 mA Transmission power: 10 dBm
Receiver (XY-MK-5V)	Operating frequency: 433 MHz Operating voltage: 5 V Current consumption: 4 mA (standby) Sensitivity: -105 dB

An efficiency analysis has been carried out for illustrating the PoF system feasibility. We have estimated the total link attenuation by measuring the PPC output converted electrical power. Considering that approximately 0.97 W was generated by the laser and 280 mW was measured at the PPC output, we estimate that the total link attenuation was around 0.5 dB. We have also estimated that around 0.86 W was injected into the PPC, since its conversion efficiency is typically 32.5%. In order to evaluate the PoF system overall power efficiency and consumption, we have also estimated the end-to-end electrical efficiency, which is calculated as the electrical power delivered to the driven electronics divided by the electrical power consumed by the laser. The HPLD has typical electrical-to-optical (E/O) conversion efficiency of 50%. In this context, we have obtained over 14% of electrical efficiency. Afterwards, we calculated the system PTE, which is the most prevalent PoF system metric, defined as the total electrical power delivered by the PPC divided by the HPLD output power [19]. Thereby, PTE of around 28.9% could be achieved with this configuration. This result is far more superior compared to a commercial PoF solution available in [20], in which the achieved PTE is approximately 10% for a 3-m-long 62.5/125 μm MMF. The overall PoF PTE might also be improved by employing HPLDs and PPCs with higher conversion efficiencies as well as low-loss MMFs.

Stable supply voltage and current are mandatory to ensure reliable and accurate industrial sensing systems. Therefore, the first system characterization consisted in measuring the PoF system output voltage over a 60-minute period, aiming to analyze its stability, as presented in Fig. 3. We have measured approximately 8.5-V nominal output voltage from the PPC. Thereby, one may note that the voltage supplied by the PoF system is feasible, presenting only slight variations. Nevertheless, a zoom-in-view enables to properly quantify the voltage fluctuations. An average fluctuation of 0.05 V is observed i.e. only 0.6% of the nominal voltage (8.5 V). In addition, only one voltage peak ranged to 0.1 V over the entire analyzed time period. The EN 50160 voltage standard defined acceptable voltage fluctuations ranging between 5% and 15% of the nominal voltage, depending on the device or application [21]. Therefore, our proposed PoF system accomplished the standard with plenty of margin in terms of stability, validating its applicability to properly supply IoT sensor nodes.

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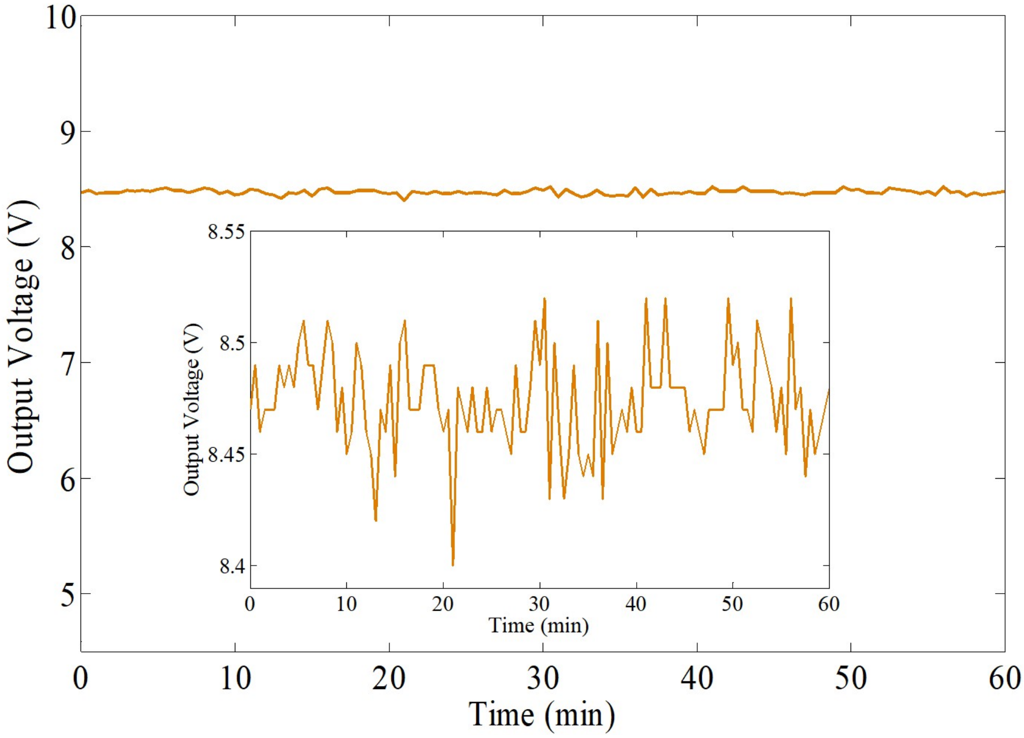

Fig. 3. PoF system output voltage measurements over a 60-minute period.

Subsequently, an experimental investigation regarding the PoF use for remotely powering the proposed sensing system has been carried out. Basically, we have varied the temperature in a controlled environment and analyzed the data acquired from the PoF-powered 433-MHz sensing system. A didactic plant was employed in order to emulate an industrial oven, in which the temperature sensor (DS18B20) was placed. In order to control the temperature inside the oven, a proportional-integral-derivative (PID) embedded in a programmable logic controller (PLC) was employed. The PLC is a computer-based device commonly designed to control industrial systems [22]. In particular, the PID controller algorithm performs the closed-loop control based on a temperature set-point, defined by the user. In this case, we have employed a temperature set-point of 50 ºC. Fig. 4 reports the obtained temperature measurements provided by the PoF-powered sensor over a 3-minute period. In this experiment, the room temperature was around 23.5 ºC and the employed sensor was able to measure temperatures up to 47.75 ºC. One may observe a slight temperature oscillation mainly caused by the environment external disturbance. Nevertheless, the sensor operated properly throughout the entire analysis, demonstrating the PoF feasibility to remotely supply IoT sensor nodes.

III. PoF-powered 2.4-GHz IoT Wireless Sensing System

Fig. 5(a) depicts the block diagram of the second implemented PoF-based wireless sensor system. In order to evaluate the PoF technology potential, we have improved the PoF link distance by adding a second 50-m MMF spool, corresponding to a 100-m fiber link, as reported in Fig. 5(b). Nevertheless, we have employed the same PoF components, namely 975-nm HPLD and PPC. The PoF system was designed to power a control board, temperature sensor and transceiver module. The control board is composed of an Arduino Pro Mini, which presents lower power consumption compared to Arduino Uno, and a conversion module (FTDI FT232R), which performs the universal serial bus (USB) to

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transistor-transistor logic (TTL) serial conversion. Both boards operate at 5 V. For that reason, a step-down DC/DC converter (LM2596) was required to reduce the voltage generated by the PPC from 8.5 V to 5 V. The employed temperature sensor (LM35) is able to measure values ranging from 0 ºC to 120 ºC. The transceiver module (nRF24L01+) operates at 2.4 GHz and employs Gaussian frequency-shift keying (GFSK) modulation with programmable data rate of 250 kbps, 1 Mbps, and 2 Mbps, and transmission output power of 0, -6, -12, and -18 dBm. Table II lists the detailed system specifications.

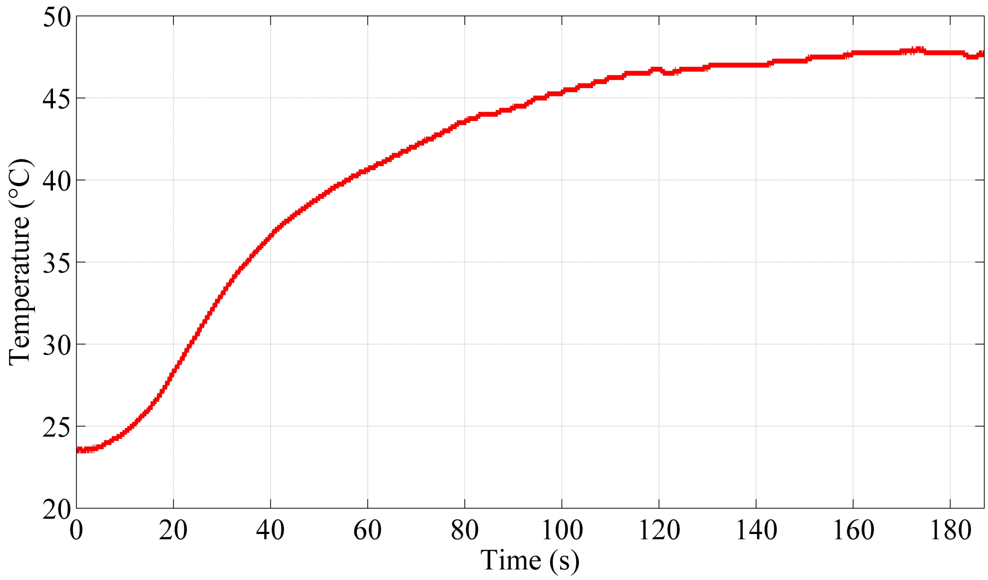

Fig. 4. Temperature measurements acquired from the PoF-powered 433-MHz wireless sensing system over 3 minutes.

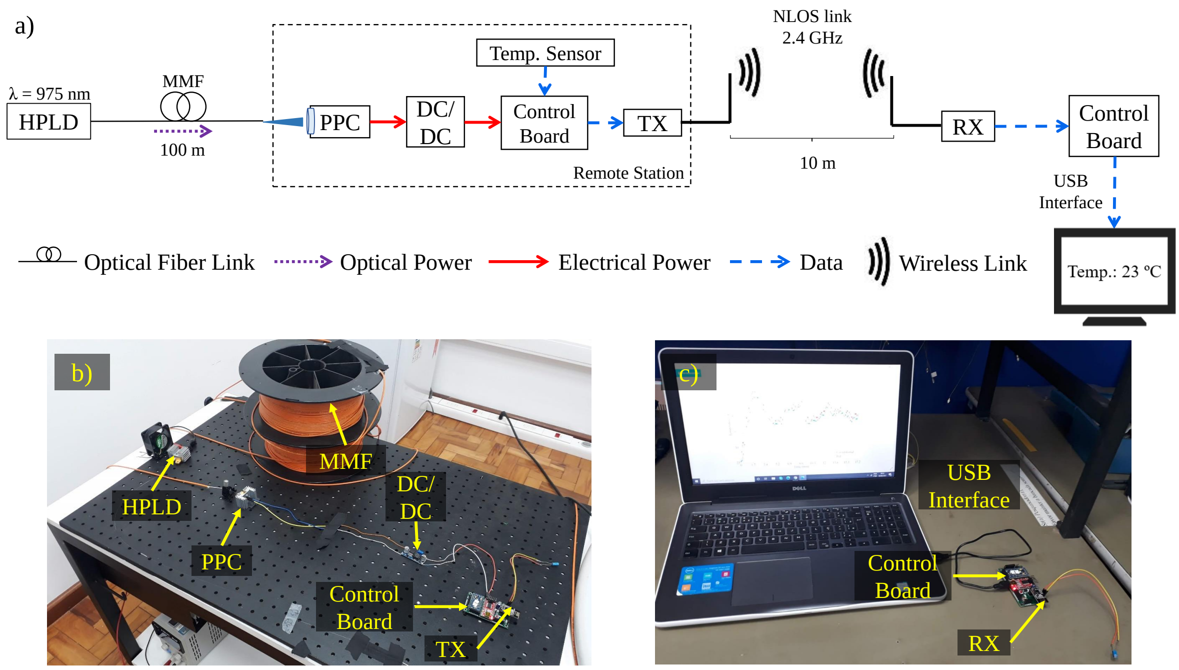

Fig. 5. Second implemented PoF-based wireless sensor system: a) Block diagram, b) Experimental setup photograph of the PoF system, control board, and 2.4-GHz transmitter, (c) Experimental setup photograph of the reception side, including the control board, receiver and computer.

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TABLE II. PoF-powered 2.4-GHz IoT Wireless Sensing System Specifications.

Component	Specifications
Fiber-coupled HPLD	Center wavelength: 975 nm/Max. output power: 30 W
Optical Fiber	Type: MMF/Length: 100 m 100 μm/140 μm core/cladding diameters
PPC (YCH-L300 with Passive Heatsinking)	Operating wavelength: 915 - 980 nm/ Output voltage: up to 8.5 V Max. incident power: 3 W/ Conversion efficiency: 30% @ 975 nm
DC/DC Converter step-down (LM2596)	Input/output voltage: 3.2 - 40 V/1.5 - 35 V Conversion Efficiency: 92%
Arduino Pro Mini	Operating voltage: 5 V/ Current consumption: <5 mA
Conversion Module (FT232R)	Operating voltage: 5 V/ Current consumption: 15 mA
Temperature Sensor (LM35)	Operating voltage: 4 - 30 V/Current consumption: <60 μA
Transmitter (nRF24L01+)	Operating frequency: 2400 - 2525 MHz Operating voltage: 1.9 - 3.6 V/ Current consumption: 11.3 mA at 0 dBm Transmission power: 0 dBm
Receiver (nRF24L01+)	Operating frequency: 2400 - 2525 MHz Operating voltage: 1.9 - 3.6 V/Current Consumption: 13.5 mA at 2 Mbps Sensitivity: -82 dBm at 2 Mbps

The acquired temperature data is processed by Arduino Pro Mini and sent to the transmitter, which was set with 0-dBm output power and 2-Mbps throughput. The wireless transmission was performed at 2.4 GHz over a 10-m link in an indoor NLOS environment. The temperature data was transmitted every 100 ms. At the reception side, depicted in Fig. 5(c), the data was received and decoded by an identical transceiver and control board, respectively. The Arduino Pro Mini is connected to a computer via serial interface and the temperature data is displayed in real-time. It is worth mentioning that all equipment at the reception side were powered by the computer USB port. In this scheme, the HPLD generated approximately 0.6-W optical power, which was attenuated by 1 dB, considering the fiber and splice losses. Consequently, the PPC was able to convert 0.5-W optical power into 152-mW electrical power, considering efficiency of 30%. The DC/DC conversion efficiency is 92%, resulting in 140-mW total delivered electrical power. Consequently, end-to-end electrical conversion efficiency and PTE of around 12% and 23%, respectively, could be achieved with this configuration. One may note that this system consumes less power than the first implementation. This divergence is due to the employed components and equipment, i.e. microcontroller, temperature sensor, and transceiver, which consume approximately half less then the ones employed in the first system.

We have also compiled the DC/DC converter output voltage measurements over a 60-minute period in order to evaluate the PoF system stability in this case. Fig. 6 presents the results. An average fluctuation of 0.01 V is observed, corresponding to 0.2% of the nominal voltage (5 V), which is far less than the one obtained with 8.5 V in the first implementation (see Fig. 3). This contrast occurs mainly due to the DC/DC converter regulator device, which maintains a stable output voltage. Consequently, by employing a DC/DC converter, our proposed PoF system met the EN 50160 standard requirements in terms of voltage stability with over 4.9% of margin.

Regarding the 2.4-GHz PoF-powered sensing system performance investigation, we have employed the same industrial oven from the first implementation and the temperature set-point has also been configured to 50ºC. Correspondingly, the temperature sensor (LM35) has been placed inside the in-

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dustrial oven. Fig. 7 reports the temperature measurements obtained from the PoF-powered 2.4-GHz sensing system. In this case, the room temperature was around 21ºC and the employed sensor was able to measure temperatures up to 47.5ºC. By comparing the curves from Fig. 4 and Fig. 7, one may note that the temperature measurements performed with the PoF-powered 2.4-GHz solution are noisier than the ones obtained with the 433-MHz. This is due to the differences between the temperature sensor models. The DS18B20 model, which was employed in the first solution, has higher resolution and is more reliable than the LM35, which was employed in the second solution. Nevertheless, one may note good agreement between the curves from Fig. 4 and Fig. 7, demonstrating that both PoF-based systems, i.e. operating at 433 MHz and 2.4 GHz, functioned as expected.

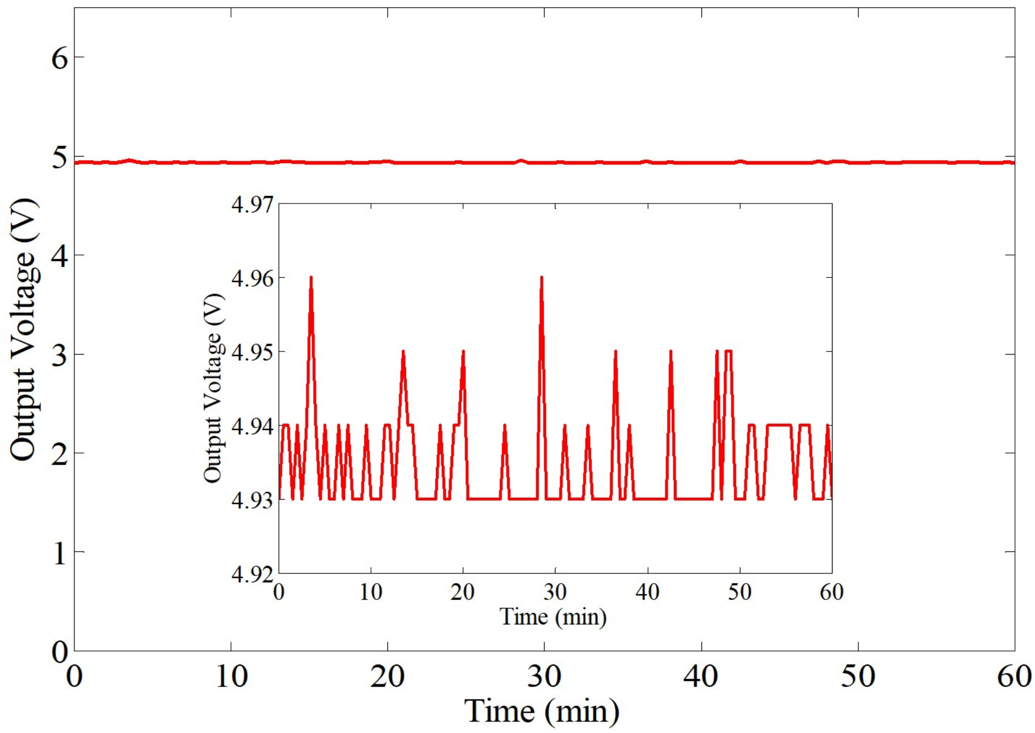

Fig. 6. PoF system output voltage measurements over a 60-minute period using a DC/DC converter.

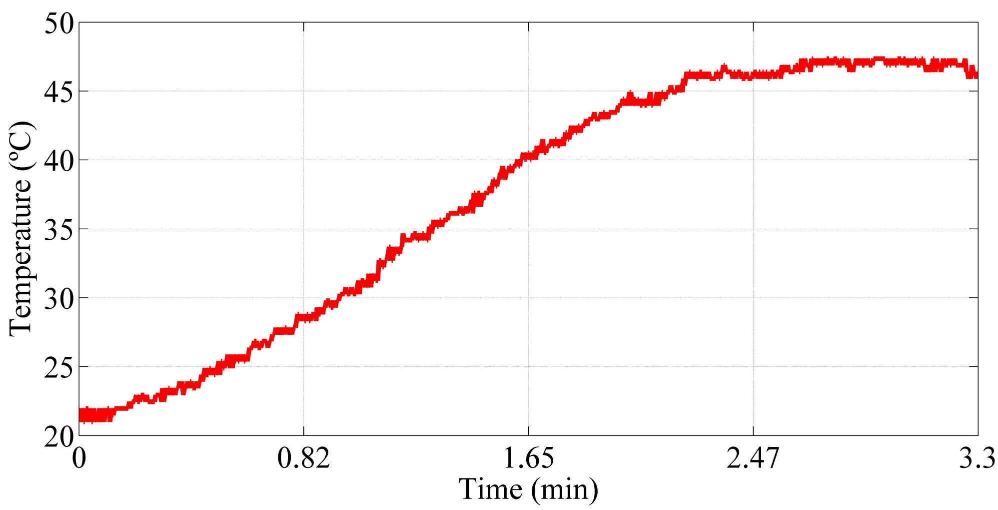

Fig. 7. Temperature measurements acquired from the PoF-powered 2.4-GHz wireless sensing system over 3 minutes.

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IV. Conclusions

This paper has successfully demonstrated the use of the PoF technology for powering IoT wireless sensing systems for Industry 4.0 applications. The proposed PoF system consisted of a 975-nm HPLD, a MMF link, and a 30-% efficiency PPC. In the first implementation, a 50-m PoF link could provide up to 280 mW for simultaneously powering an Arduino Uno, a temperature sensor (DS18B20) and a 433-MHz transceiver (FS1000A) with PTE of 28.9%. In the second implementation, we have improved the PoF link distance to 100 m and we were able to achieve 140 mW of delivered electrical power with PTE of 23%. In this scheme, we have implemented an Arduino Pro Mini, another temperature sensor (LM35), and a 2.4-GHz transceiver (nRF24L01+). In addition, a DC/DC converter was required to reduce the PoF system output voltage, as the Arduino Pro Mini operates at 5 V.

In order to evaluate the PoF system applicability for powering IoT wireless sensing systems, we have carried out a voltage stability analysis. Our PoF system was able to deliver stable voltage for both applications, i.e. 8.5 V and 5 V, respectively, with 0.6% and 0.2% voltage fluctuation of nominal voltage, respectively, meeting the EN 50160 standard requirements with plenty of margin. In addition, an industrial oven was employed to evaluate the sensor performance considering temperature measurements over a 3-minute period. Experimental results demonstrated that the PoF technique could be useful to feed sensing and other systems in hazardous industrial environments.

Future works include the implementation of IoT transceivers using commercial protocols, such as Zigbee, Bluetooth or Wi-fi, as well as further increasing the PoF link distance and power transmission efficiency. Further experimental evaluations regard increasing the number of deployed sensors and exploring different sensing measurements, such as humidity, air pressure, and gas. In addition, we envisage the implementation of a PoF-powered sensing architecture based on optical data transmission using media converters.

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