Smart Remote Nodes Fed by Power over Fiber in Internet of Things Applications

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***Abstract*—Smart IoT solutions integrated in power grid stations are important due to their high economic and social value. Power over fiber technology to remotely feeding sensors and control electronics is a good choice in these environments of high electromagnetic interference. A sensing system design for magnetic field monitoring, fire and temperature/presence detection and remotely fed by optical means is discussed. This design includes two types of nodes, smart and passive. Smart remote nodes have an energy manager to provide power on demand. Asymmetric splitting is proposed to optimize power distribution. Some tests on remote node power consumption, feeding, sensing and centralized monitoring in one type of those nodes are successfully performed and reported.**

***Index Terms*— Electromagnetic compatibility, Multimode optical fiber, Power-over-Fiber (PoF), Power distribution, Sensor network, Smart remote node, Internet of Things (IoT).**

I. Introduction

Internet of Things (IoT) is driving an increasingly demand in the extent and type of sensing technology deployments almost everywhere. Novel sensor types featuring low power, low cost, small size, and with high sensitivity and comprehensive functions can now be integrated as smart remote nodes into sensor networks for novel applications. These remote nodes comprise sensors, control electronics, transmission units and other electronic devices that all need to be powered somehow thus leading the method for a proper power supply to a key issue in this application scenario. This problem becomes critical in strong electromagnetic radiation areas with high electromagnetic interference (EMI) and other harsh and noisy environments such as those with risk of explosion due to sparks and/or fire [1]. If these areas are critical infrastructures, more attention is even required to improve their protection, security and resilience due to their high economic and social value. This is the case for power grid facilities. They are a source of localized high magnetic fields, close to urban centers, with the population concern about the potential electromagnetic field impact on human health [2]. It is important to monitor radiation levels as well as to detect either sparks due to short circuits from the high voltage lines or the generation of hot spots due to the deterioration of the insulators of the transformers; events that could start a fire. Sensing systems for fire and magnetic field detection can prevent those incidents.

In this framework, the use of Power over Fiber technology (PoF), firstly reported in 1978 [3], improves the reliability of any IoT solution by (safely) optically feeding the remote nodes. As this technique employs fibers as power supply lines instead of electrical counterparts, it provides inherent immunity to surrounding electromagnetic fields thus avoiding the use of any conventional EMI reduction technique for the power distribution network of the different spatially located remote sensing nodes and leading to cost savings. The use of optical fiber for remote powering also results in a lighter weight for this remote sensors' power distribution and becomes safer due to its dielectric nature avoiding the generation of any spark. Moreover it allows the provisioning of an alternative path to remotely power any sensing scheme with the aforementioned benefits. The PoF system at the remote node can also charge a battery to provide a self-sufficient sensor operation in case of unconventional disasters to assure service continuity and resilience as well as providing a monitoring or feedback channel to check and control the remote node status. Those features are aligned with current smart IoT solution demands. In any case, the electrical energy from the photovoltaic converter (PVC) can drive sensors, processors and other electronics comprising the smart IoT remote node.

PoF technology provides optical power delivery in applications covering multiple high-end fields that are compatible with IoT requirements. As in high-voltage and high EMI environments [4, 5], to optically power remote antenna units [6-9], in defense applications [10], for temperature measurements with optical fiber pyrometers in hazardous environments [11] or to feed a video surveillance system [12], but for mostly applied to a single remote sensor. PoF is also used to monitor and control the position of fiber optic connectors in passive optical networks (PONs) [13], in-service PON monitoring [14], as well as a solution for powering remote nodes for measurements of turbidity and acoustic in seafloor [15]. Some PoF designs include either multiple sensor feeding capabilities [16-18] or are able to provide a feedback data communication link to the PoF

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transmitter [19]. However, there is not an integrated approach for solving different problems in a specific scenario such as health and safety matters in electric power transmission lines with high reliability. There is not a proposal of a smart sensor with an embedded energy manager (EM) that is capable of simultaneously feeding the electronics in the remote node and charging an external battery. Finally, there is a lack of a full analysis for any PoF solution to operate different types of remote nodes with different power demands.

In this paper, the design of a smart centralized PoF system for IoT purposes in power grid stations and capable of addressing remote nodes fed by an optical fiber for harsh and noisy environment applications is discussed, extending the electronic designs reported in [20]. A smart remote node with both monitoring and power management functionalities is developed with autonomous operation enhancing at the same time the overall power transfer efficiency provided by the PoF system. A proof of concept is developed by optically feeding one node with monitoring and power management capabilities that comprises an array of integrated temperature sensors (presence sensor) and a spark/fire detector. In addition, we extent our experimental results by analyzing the scalability of the proposed centralized PoF system assuming an asymmetric power distribution network topology for nodes with different power consumption requirements.

II. PoF Network Technology

A schematic of the proposed centralized PoF system is shown in Fig. 1 for feeding N remote sensor nodes in a star topology. The system comprises a PoF transmitter at the central office (CO) that includes a high-power laser (HPL), an optical fiber of length L, a 1:N power splitter for remote node power distribution, N photovoltaic converters (PVC) and N remote devices/nodes. The latter within this work are assumed to be deployed for health, safety and control monitoring purposes in power grid stations and power lines. Either symmetric (same power is delivered to all remote nodes) or asymmetric topologies for the power distribution network are considered, as described in section 3.

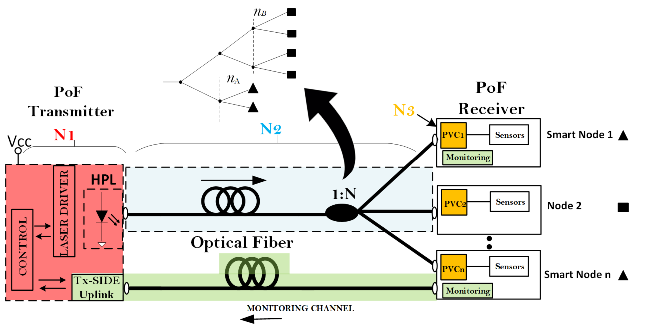

Fig. 1. Schematic of the generic PoF topology addressing N remote sensor nodes. HPL: High Power Laser. PVC: Photovoltaic converter. Some smart nodes (▲) with monitoring capabilities are shown. Inset: asymmetric topology.

The smart nodes have additional functionalities and thus demand more energy. They include an EM that allows feeding both the sensor module and a battery. It supports a self-sufficient remote node operation in case of power outage. There is also a monitoring optical channel for centralized battery status and control operation management.

The overall efficiency is a critical design factor in any PoF system. It directly depends on three fundamental efficiency terms: the electrical to optical conversion efficiency of the transmitter (N1), the transmission efficiency of the optical fiber (N2), and the optical to electrical conversion efficiency of the PVC at the remote node (N3). Previous studies [7] have defined the Energy Efficiency in a power over fiber System, SEE, as the product of N2 and N3. However, we define a Global Energy Efficiency (GEE) for the PoF system including the term N1 [20] thus yielding to a ratio between two electrical power magnitudes. The GEE figure of merit also includes the coupling efficiency between the laser and the optical fiber as well as the losses in the connectors in the term N2. The GEE is given by:

$$GEE = \frac{\text{Energy provided to REMOTE NODE}}{\text{Energy provided to HPL}} = N1 \times N2 \times N3 \qquad (1)$$

Because of the wavelength dependence of the optical fiber attenuation and the power conversion efficiencies of PVCs, the selected power signal wavelength depends on the distribution link length [7]. Maximum experimental values of 58 % for AlGaAs/GaAs PVCs at 808 nm [21] and 45 % for InGaAsP/InP PVCs at 1550nm [22] are reported. However, commercial available devices show lower conversion efficiency values.

III. Application Scenario and Power over Fiber Design

The safety and security in electric power distribution substations, see Fig. 2, within the power grid is essential to maintain vital societal functions as being a critical infrastructure. The increasing concern about the electromagnetic field impact on human health demands sensing systems to monitor those fields in a power substation. Also, the infrastructure security and protection demands specific sensing and surveillance systems to monitor flames or detect undesirable presences within the substation facility. Finally, infrastructure resilience issues require smart solutions to provide an alternative power supply as well as a smart autonomous operation against power outages due to possible criminal threats. Power over Fiber technology is a good choice for all these requirements with the following features:

- multiple sensors fed in a centralized fashion,
- flame detection, human body radiation and temperature measurement,
- remote feeding at hundredths of meters from CO,
- redundancy and an intrinsically safe feeding system (battery and PoF energy sources),
- monitoring channel to send the status of the different remote sensor nodes back to CO,
- on demand delivery, depending on battery status.

Current off-the-shelf low-cost and low power consumption sensors can improve both fire and intrusion detection systems. Their low power consumption make them compatible with PoF technology and fulfill IoT needs.

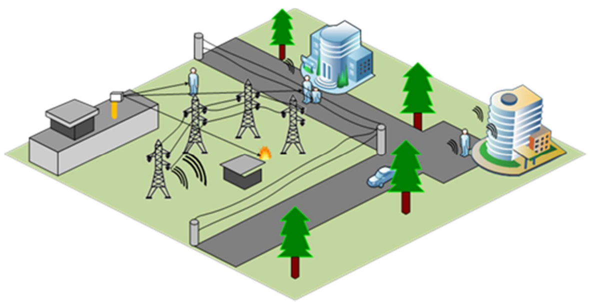

Fig. 2. Power distribution substation with IoT sensing solutions for emerging threats.

The selected sensors with power consumptions up to tenths of mW are shown in Table I, suitable for the target scenario.

In the following we discuss a generic PoF distribution network design with two types of remote nodes with different power consumption requirements. The first node type is a smart remote node with both fire detection and temperature/presence monitoring capabilities. It embeds an Energy Manager (EM) that provides energy delivery on demand by the PoF system to operate the remote node and to charge the battery at the same time or independently for security and resilience purposes. The smart remote node also provides an upstream optical link of 1 kbps data rate to transmit the measured information as well as the battery status to the CO. An experimental proof-of-concept of its operation is addressed in section 4. The second type of node, considered for our scalability analysis although not experimentally implemented, is a passive node for magnetic field sensing applications wherein the selected sensors that could be implemented, either LIS3MDL or ISM303DAC, have a magnetic field dynamic range of ±1.6mT and ±5mT, respectively [20]. They are able to detect the magnetic radiation levels harmful to health.

TABLE I
CONSUMPTION OF SELECTED SENSORS FOR THE TARGET SCENARIO

Devices	LIS3MDL	ISM303DAC	Flame Detector Module	AMG8833
Consumption [mW]	0.972	2.33	1.5	14.85
Sensor type	Magnetic	Magnetic	Flame	Temperature
Dimensions [mm]	2x2x1	2x2x1	36x50x12	78x10.9x4.3

A. PoF design

As part of the PoF transmitter, the HPL has a maximum optical output power of 1.5W. More details about the electronics in the transmitter are reported elsewhere [18]. On the other hand, the required link length considered for our application is 300m. From this length, the PVC efficiency term N3 in Eq. (1), becomes the dominant factor for the overall system efficiency GEE. Thus to maximize the PoF system efficiency a selected HPL operating wavelength of 808nm becomes an optimum choice. The optoelectronic converter employed at the PoF receiver is an AlGaAs/GaAs multi-junction compound semiconductor photovoltaic converter (PVC), model OPI-6G-FC from L2W Energy. The conversion efficiency of the chosen PVC, optimized at this wavelength, is around 40%. In our previous work [17], for PoF fiber spans beyond 1 km the fiber attenuation coefficient starts to be the most critical term, and PoF operating wavelengths around 1480nm would provide a better GEE. For the PoF distribution network we select a 200/225 µm core/cladding diameter step-index silica multimode fiber. This is for two main reasons compared to standard 62.5/125 µm silica fiber counterpart: a) to maximize the HPL source-to-fiber coupling efficiency, and b) to maximize the optical power limit that can be injected into the fiber before damage might occur. In both cases, greater values are obtained for the 200/225 µm fiber so more optical power can be injected into the system thus being the PoF system able to address a greater number of remote nodes. The selected fiber has an attenuation coefficient of 7dB/km at 808nm. With these numbers and assuming a 29% of electrical-to-optical power conversion efficiency of the HPL (extracted from the vendor's datasheet) we roughly estimate a GEE for the designed PoF system to be around 9.3% for a 300m-long point-to-point topology. This figure of merit is much better compared to the commercially PoF solution available in [23] where a GEE of around 1.3% is achieved for a 10m-long 62.5/125 µm silica multimode fiber.

B. Power distribution design

If a symmetric power distribution is considered the same optical power is distributed to each branch, with a 1:N optical splitter. But considering a generic case where two types of remote nodes with different power consumption requirements are deployed, an asymmetric topology provides a better performance to distribute the power among the remote nodes.

The proposed asymmetric architecture considers two types of nodes, node A and node B, and assumes power requirements on smart node A, $P_{NA_{\min}}$, greater than power requirements on passive node B $P_{NB_{\min}}$. The asymmetric architecture uses 1x2 splitters. As $P_{NB_{\min}} < P_{NA_{\min}}$, the splitting stages on node B, n_B, is greater than the splitting stages to reach a node A, n_A. Initially 50% of the electrical power at the remote site, P_T, is devoted to each type of nodes. In this scenario there is an even number of nodes A (N_A) with power P_{NA} and nodes B (N_B) with power P_{NB} given by:

$$N_A = 2^{n_A} \text{ with } P_{NA} = P_T / 2^{n_A+1} \quad (2)$$

$$N_B = 2^{n_B} \text{ with } P_{NB} = P_T / 2^{n_B+1} \quad (3)$$

Afterwards, nodes A are given priority for being fed. We allow creating M_A new nodes A by reallocating some power from M_B nodes B to nodes A, thus increasing the nodes $N_A^{'}$ with P_{NA} in detriment of the nodes $N_B^{'}$ with power P_{NB}.

The total number of nodes N is $N = N_A^{'} + N_B^{'}$ being:

$$N_A^{'} = M_A + 2^{n_A} \quad (4)$$

$$N_B^{'} = 2^{n_B} - M_B \text{ and } M_B = 2^{(n_B - n_A)} M_A$$
(5)

In this final scenario, the procedure to design the sensor network is following described. The number of nodes A fed by a minimum power $P_{NA_{\min}}$ is given by:

$$N_A^{'} = round\left[\frac{P_T}{2P_{NA_{\min}}}\right] \quad (6)$$

Then the minimum n_A and M_A values fulfilling Eq (4) are obtained. As an example, if $N_A^{'} = 5$ then $n_A = 2$ and $M_A = 1$.

The n_B splitting stages that provide a minimum power $P_{NB_{\min}}$ on nodes B is given by:

$$n_B = floor\left[\log_2\left(\frac{P_T}{2P_{NB_{\min}}}\right)\right] \quad (7)$$

with $n_B \geq n_A + 1$. Then the number of nodes B, i.e. $N_B^{'}$, is derived from Eq (5).

As an example, for $P_T = 1.0W$, $P_{NA_{\min}} = 100mW$ and $P_{NB_{\min}} = 50mW$, respectively, from Eq. (6) results in $N_A^{'} = 5$ nodes consuming 100mW thus yielding $n_A = 2$ and $M_A = 1$ from Eq. (4). From Eq. (7) $n_B = 3$ is obtained resulting in $N_B^{'} = 6$ nodes, from Eq. (5), consuming 62.5mW. Therefore, a total of 11 nodes could be fed, 5 nodes A consuming 125mW each and 6 nodes B consuming 62.5mW each, from 1x2 cascaded optical splitters.

A more realistic approach in a PoF system considers the excess loss, in natural units EL <1, of each splitting stage. The previous equations are valid but considering a new minimum power at both nodes, $P_{NA_{\min}}^{'}$ and $P_{NB_{\min}}^{'}$, respectively. If all splitting stages have the same excess loss they are given by:

$$P_{NA_{\min}}^{'} = P_{NA_{\min}} \Big/ \left(EL_{N_A}\right)^{n_A+1} \quad (8)$$

$$P_{NB_{\min}}^{'} = P_{NB_{\min}} \Big/ \left(EL_{N_B}\right)^{n_B+1} \quad (9)$$

IV. Experimental setup and results

The electronic design of the remote node and its power demand optimization is a key factor. Within this section we address the PoF receiver design and implementation at the smart remote node, the experimental measurements to test its functionality as well as its power consumption.

A. Setup

Fig. 3 shows the block diagram of the PoF system capable of remotely feeding different nodes at the remote site, although only the smart remote node with advanced functionalities is implemented as a proof-of-concept. This node (PoF receiver) provides smart functionalities for fire detection and temperature/presence sensing and embeds an Energy Manager (EM). It uses a flame detector module and an infrared array sensor based on MEMs technology in an 8x8 matrix topology. The receiver includes an AlGaAs/GaAs multi-junction compound semiconductor photovoltaic converter (PVC), the control electronics based on a 16-bit ultra-low power microcontroller with power consumption in active mode of 330µA at 1MHz and 2.2 V of operation, a VCSEL (Vertical-Cavity Surface-Emitting Laser) for upstream communications operating at 840nm with current demand of 1.5mArms, and an embedded EM. The EM integrates a 130mAh lithium ion battery (3.7V, 480mAh) for energy storage, a switch module to select between charging the battery and/or feeding the load and three DC/DC converters (two buck- and one boost-) to adapt different internal voltage values to the different sensing devices and electronics implemented for the smart remote node. The storing device, i.e. the battery, permits the node to operate in an autonomous way, in absence of the energy transmitted by the PoF system. The VCSEL transmits the sensors' data through the fiber to the CO where the PoF transmitter is located. The uplink fiber is a standard 62.5/125µm core/cladding diameter silica multimode fiber as there are no requirements for a high-power transmission on this link. At the PoF transmitter site a switchable gain photodetector receives the upstream data traffic at 840nm of wavelength prior to be converted into voltage by means of a transimpedance amplifying stage in the electronic domain. Finally, based on the status info received by the remote node, the control unit in the PoF transmitter operates the HPL accordingly. As previously discussed, the fiber lead deployed for the PoF link consists of a 300m-long 200/225µm core/cladding diameter silica multimode optical fiber.

The inset of Fig. 3 depicts the data received from the upstream communications channel described in next section.

B. Consumption and efficiency measurements

From the experimental measurements, both the GEE and the efficiency of the PVC module are obtained.

The optical incident power to the PVC is 925.5 mW and the converted electrical power is 340mW thus giving a PVC conversion efficiency of 37%, following [24]. I_{SC} (short-circuit current) and V_{OC} (open-circuit voltage) are measured and the PoF system GEE efficiency is of 9.83%. To determine the scalability or the maximum number of remote sensors that can be optically fed by the designed centralized PoF system, it is necessary to determine the consumption of each remote node type. From our estimations, the magnetic sensor LIS3MDL-based passive remote node could demand 24mW of power consumption including the required control electronics for a proper node's operation.

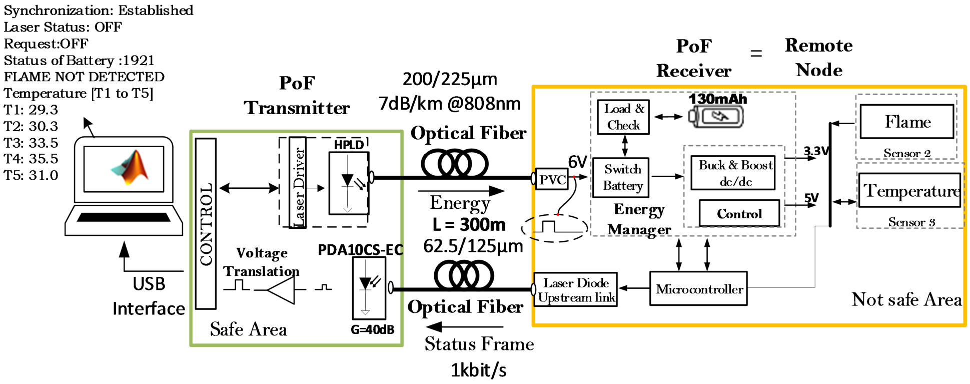

Fig. 3. Remote smart sensor node design with embedded Energy Manager. Smart Node comprises a fire detection system and a temperature/presence sensor. PVC: Photovoltaic Converter.

In contrast, the consumption of the smart remote node, where the flame detector module, the temperature/presence sensor, the energy manager and the optical uplink monitoring system are included, depends on its operation mode and status thus leading to different electrical current demands. This fact is shown in the set of figures comprising Fig. 4. Fig. 4(a) depicts the experimental setup to measure the power demands required from the smart node. Fig. 4(b) shows the measured electrical current demand depending on the node operation mode. We distinguish two operation modes, both fed by the PoF system: (A) namely <<charging+sensing>> where flame detection and temperature/presence sensing are performed with simultaneous battery charging; and (B) where only flame detection and temperature/presence sensing are performed with no battery charging, as it is fully charged. In both operation modes the monitoring uplink optical module always transmits information to the central office, where the PoF transmitter is located, regarding the measured data from both sensors as well as the battery status, see inset of Fig. 3. A custom-made communication protocol is implemented for this purpose, thus transmitting 25 bytes of data frames every 300ms at 1 kbps of bit rate. This communication protocol is established to reduce power consumption but could be even further improved.

From Fig. 4(b) when the battery is fully charged, i.e. operation mode (B), the average current demand of the smart node results in around 8mA thus leading to around 50mW of power consumption. This overall current consumption involves the current demands of the two sensor devices, the upstream data communication laser and the control electronics. The temperature/presence sensor demands 4.5mA of electrical current whereas the flame detector module operates at 0.3mA. The ultra-low power microcontroller demands 0.33mA. The monitoring uplink VCSEL is powered at 3.3V with average current demand (root-mean-square value) of 1.5mA$_{rms}$ as the output light is being modulated and the laser transmits every 300ms from a nominal current bias operation of 5mA.

Nevertheless, when the electrical power provided by the PVC is employed to simultaneously feed both sensor devices and charge the battery, the current demand results in a peak of 27mA, operation mode (A), thus leading to around 160mW of power consumption for the smart remote node.

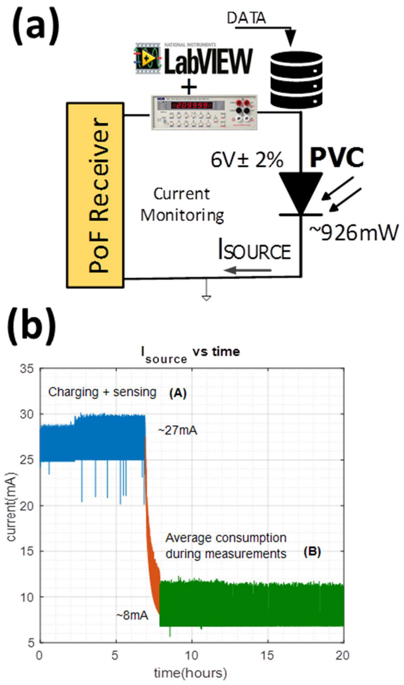

Fig. 4. (a) Experimental setup to characterize the smart remote node power demand; (b) Smart remote node electrical current demand depending on its operation mode.

The transient curve from operation mode (A) to operation mode (B), see Fig. 4(b), illustrates the process where the battery starts to be fully charged thus leading to a less electrical current (and power) demand from the PoF system, where only the operation of both flame and temperature/

presence sensors is required.

From these experimental values and assuming an ideal high-power handling 1:N symmetric optical splitter for energy distribution, the designed PoF system could feed either 14 passive remote nodes or 2 smart remote nodes (with both operation modes). These numbers increase by reducing the length L of the link or increasing the total output power provided by the HPL source. However, another option is to consider a 1:N asymmetric optical splitter topology for the power distribution network based on 1x2 cascaded splitting stages and targeting the two types of remote nodes addressed: smart- and passive-. We define N'_A and N'_B as the number of smart- and passive- nodes that can be addressed by the PoF system with 50mW, if only operation mode (B) is considered, and 24mW of power consumption, respectively. The total available power measured P_T is 340mW. From previous Eq. (2)-(7) and in the ideal case with no excess losses from the splitting stages it results in a figure of merit of $N'_A = 3$ *and* $N'_B = 2$ or $N'_A = 2$ *and* $N'_B = 4$ nodes, respectively. Even if using 1x2 3.5dB insertion loss optical splitters and considering Eq. (8) and (9), the same number of nodes can be remotely fed by the PoF system.

C. *Test on application scenario*

As a proof of concept, a smart remote node that includes the AMG8833 temperature/presence sensor, the flame detector module, the microcontroller-based control electronics, the energy manager (external battery included) and the monitoring optical uplink is developed. The AMG8833 sensing device consists of an infrared array of sensors that provide an 8x8 matrix (64 pixels) of thermal microsensors within the same package. It allows the detection of a temperature range from −20 °C to 100 °C. This range permits the detection of the thermal radiation produced from different entities, like human body, or an abnormal thermal radiation pattern due to an external cause. It is able to detect thermal radiation changes up to a distance of 7 m. The experiment, shown in Fig. 5, demonstrates the feasibility of remotely powering via PoF a smart remote node with the above mentioned characteristics. In addition to the remote sensor node, a set of development boards (mainly Arduino one module and I2C-1Wire converter) and a computer are used for debugging purposes that are not required in the final deployment and are electrically fed.
Experimental results on the different functionalities implemented within the smart remote node are shown in Fig. 6 as well as in the inset of Fig. 3 where an example of the data received at the PoF transmitter is shown. These data comprise the HPLD current status, the battery charge level, the readout from the flame detector and the measured temperature (in °C) from pixels 1 to 5 from the 8x8 temperature/presence sensor matrix. The readout provided by one pixel of the temperature/presence sensor is shown in Fig. 6(a). The temperature changes by the presence of a human body located 1.5m far away from the sensor's active area (see Fig. 5) are clearly identified.

On the other hand, the monitoring uplink system functionality is depicted in Fig. 6(b). While the HPLD at the PoF transmitter is in ON-state the electrical power converted by the PVC is employed for simultaneously feeding the entire smart remote node (including the sensor devices) and charging the battery. When the battery is fully charged, the uplink monitoring system sends a command to the control logic unit at the PoF transmitter to switch OFF the HPLD starting now the remote node being fed solely by the battery.

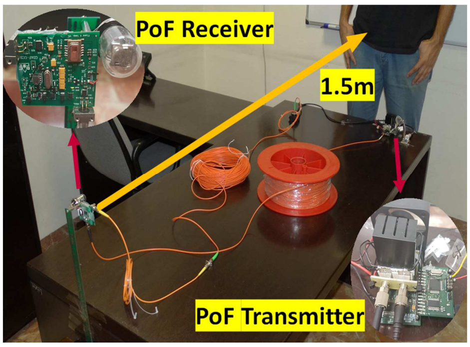

Fig. 5. Picture of the PoF system experiments carried out to feed a smart node that includes a temperature/presence sensor, a flame detector, microcontroller-based control electronics, an energy manager and an upstream optical data channel.

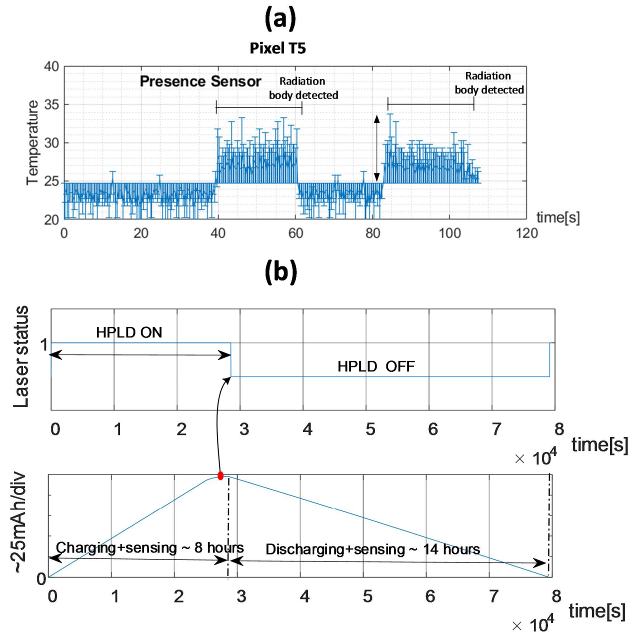

Fig. 6. (a) Experimental test of the temperature/presence sensor implemented in the smart node; (b) Experimental test of the battery status monitoring functionality implemented in the smart node. HPLD: High Power Laser Diode at the PoF transmitter.

D. *Discussion*

The PoF technique is now seen as a realistic option to remotely and optically feed some elements or sensing devices in harsh and noisy environments thanks to the recent advances in power-efficient innovative hardware, low-energy medium access control protocol and power consumption savings in electronics. New PoF applications are currently being explored, particularly within the future 5G framework where the reduction of the cell size of remote radio heads, where the antenna is located, forecasts a dramatic reduction of the overall RRH power consumption. Remotely powering the RRHs via PoF means may provide an "all-optical" solution once it is clear that the fronthaul topology to support the required data-rates for future 5G infrastructures needs to be deployed in the optical domain. Some work has been done introducing the concept of PoF pooling [25] which can make PoF scalable to outdoor small cell deployments. As well as for feeding a 100GHz photoreceiver operating in the millimeter-wave region with electrical power demand of 60mW [26], being similar to that of required to operate the developed smart remote node as a proof-of-concept of an IoT solution for power grid stations. Therefore, the upcoming 5G technology is envisaged as a potential new application niche and market for the PoF technology.

V. Conclusions

Optically powered smart electronic sensor nodes for IoT purposes are suited for harsh and noisy industrial environments that require electromagnetic immunity and high galvanic isolation solutions. An optimized PoF demonstrator for power grid stations capable of remotely feeding a smart IoT remote node that comprises a fire/flame detector, a temperature/presence sensor, microcontroller-based control electronics, an embedded energy manager and an optical uplink channel for data communications is successfully developed and tested. An external battery charged by the PoF system while operating the remote node provides an additional 10h of autonomy for resilience purposes. The optically-powered smart sensor node communicates with the central office, allowing power on demand depending on both battery and remote node status.

The PoF system has a link length of 300m and shows a global efficiency around 10%, greater than current off-the-shelf PoF solutions. The mathematical framework to analyze the scalability of the proposed PoF system in an asymmetric power distribution network topology is also addressed.

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