Internet of Things for Environmental Monitoring based on Radio over Fiber

Carlos A. Astudillo, Tiago P. C. de Andrade, Eduardo S. Gama,
Luiz F. Bittencourt, Leandro A. Villas, Edmundo R. M. Madeira
and Nelson L. S. da Fonseca
Institute of Computing - State University of Campinas, Brazil
{castudillo, tiagoandrade and eduardogama}@lrc.ic.unicamp.br, {bit, leandro, edmundo and nfonseca}@ic.unicamp.br

***Abstract*—Radio over Fiber (RoF) is one of the main technologies for the next-generation access networks due to its immunity to electromagnetic interference, low latency, low power consumption and high transmission capacity. RoF enables the processing of several radio frequency (RF) signals in a centralized location, reducing both capital expenditures (CAPEX) and operating expenditures (OPEX). This paper describes a testbed of Internet-of-Things (IoT) for environmental monitoring based on RoF that is under development in the framework of the H2020 FUTEBOL project. Moreover, we assess the impact of RoF on network performance by using a new methodology oriented to real environments.**

Keywords—Radio-over-Fiber, Internet-of-Things, Experiments, ZigBee and Arduino

I. Introduction

Radio-over-fiber (RoF) is one of the main technologies for the next-generation access networks due to its high transmission capacity, low attenuation, immunity to electromagnetic interference, low power consumption and multi-service operation [1]. Moreover, one of the most attractive advantages of RoF is the enabling of the processing of several radio frequency (RF) signals in a centralized location while reducing the complexity of access nodes at the cell site [1]. It allows moving the entire signal processing, intelligence and control to a central entity, for instance at a central office (CO) or even in the cloud. It reduces both capital expenditures (CAPEX) and operating expenditures (OPEX) of wireless access networks while providing low overhead as well as scalability and transparency. Thus, a RoF-based access network is a cost-effective solution to meet the ever increasing user's demands.

RoF integrates wireless and optical networks. Unlike traditional optical communications networks, in which a baseband signal is transmitted into the optical fibers, in RoF systems one or multiple analog carriers are transported into the fibers. In such networks, RoF links are at the physical layer of wireless networks, being an extension of the radio access domain.

The advantages of employing RoF are attractive for wireless sensor network (WSN)-based Internet-of-Things (IoT) for environmental monitoring applications such as those in smart cities, agriculture, university campuses, mines, to name a few. Even though customized and open experimental research testbeds have been built to assess the performance of new protocols and applications for the IoT [2]–[4], none of these proposals covers use cases employing RoF. Moreover, one of the main advantages of IoT testbeds running in real environments is that interference caused by spectrum sharing and physical phenomena due to environmental changes and weather conditions can be captured. However, this also poses new challenges on the methodology used in the performance evaluation in the face of variability of the results under uncontrolled conditions [3].

Motivated by the advantages of the RoF technology and the ubiquity enabled by the Internet of Things (IoT), an experimental testbed has been proposed under the framework of the H2020 Futebol project for developing an efficient RoF-based environmental monitoring system at the University of Campinas (UNICAMP) by using underutilized optical fibers already deployed. In this paper, we briefly describe the proposed experiment on integrated fiber-wireless networks for IoT for environmental monitoring based on RoF. We propose and validate a methodology for assessing the impact of employing RoF in the physical layer on network performance. Preliminary results obtained by using the deployed testbed are presented. These results focuses on the impact of RoF on the performance of IEEE 802.15.4-based networks.

This paper is organized as follows. Section II presents related work on the impact of RoF on IEEE 802.15.4-based networks. Section III briefly describes the proposed testbed on IoT for environmental monitoring based on RoF. Section IV shows preliminary results on the impact of employing RoF on the network performance derived using the testbed deployed at UNICAMP campus. Finally, Section V concludes the paper.

II. Related Work

This section presents previous work related to the impact of RoF systems on the performance of IEEE 802.15.4-based networks, such as ZigBee and 6LowPAN.

A. Impact of RoF systems on performance

The performance of RoF systems for different wireless technologies has been studied in the past decade [5]–[12]. The review in this subsection focuses on the IEEE 802.15.4 technology, which is the IoT wireless technology employed in our testbed.

Sodré *et al.* [7] demonstrated the performance of RoF systems employing the IEEE 802.15.4 standard. The performance of the RoF systems was assessed on a geographical-distributed, research-oriented network called Kyatera at the 2.4 GHz industrial, scientific, and medical (ISM) band. Even though authors present the performance of the RoF system, they fail to

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compare with networks that do not employ RoF. Moreover, the two scenarios evaluated in the study are uncommon. In the two scenarios a signal generator equipment was employed at the transmitter side. The first scenario is a fixed scenario in which actual wireless transmission is not present, while the second has the wireless component, but it is used for delivering data, i.e., a downlink use case scenario. However, typical use cases of most of IoT applications are wireless and uplink oriented.

The first application level comparison of RoF and wireless-only scenarios was presented by Assumpção *et al.* in [8], [13], [14]. They performed a laboratory experiment to evaluate the impact of RoF on wireless coverage by deriving empirical Packet Error Rate (PER) as a function of the received signal strength indicator (RSSI). They employed an IEEE 802.15.4-like transceiver at the 900 MHz band and emulated the wireless channel by using a variable attenuator to modify the RSSI value. Results show a decreasing coverage area due to the degradation of the channel quality imposed by the RoF system. Lona *et al.* [9] assessed the performance of two different RoF devices, showing their impact on coverage by following the same methodology and experimental setup as did Assumpção *et al.* [13].

Finally, Li *et al.* [10] studied an RoF system which supports simultaneous transmission of multiple wireless services over the same RoF infrastructure. They demonstrate the simultaneous transmission of WiFi and ZigBee on the 2.4GHz band, and RFID on the 900 MHz band. They investigated the coexistence of the three technologies in the same RoF system supported by a single fiber link. It was shown that the RoF system is able to transport both 2.4 GHz signals (WiFi and ZigBee) with negligible impact on network performance. They show that the WiFi throughput decreases up to 20 %, depending on the fiber length. They also show that performance is not jeopardized by the transmission of ZigBee and WiFi signals on the same fiber.

B. Methodological approaches for assessing the RoF impact

As evinced in the previous subsection, the comparison of wireless and RoF-based systems for IEEE 802.15.4-based applications has been primarily carried out in laboratories. To avoid wireless interference and impairments when assessing real wireless communications, RoF environment emulation with variable attenuators is employed and in some cases an RF isolation chamber is used for electromagnetic isolation in laboratories [8], [9], [13]. The approach typically used is to perform the measurement campaigns for the wireless-only experiment and the RoF experiment in different time periods. This approach, which we called herein the *temporal-based* approach, is currently the only one reported in the literature for both laboratory and outdoor/indoor testbeds. This approach fits well for laboratory experiments, but not for real environments, in which external wireless interference cannot be controlled. This approach is highly prone to bias due to the temporal RSSI and link quality information (LQI) properties evinced in operational IEEE 802.15.4-based networks [15]. This happens because of the spectrum sharing with other unlicensed technologies such as WiFi or Bluetooth, environmental changes or even weather conditions. For instance, radio channel conditions in the university campus in the morning are different from those in the evening. There are also differences between measurements on different weekdays [15]. This is mainly due to the high number of interference sources in the 2.4 GHz band, in which many other technologies and devices are co-located in university campus, mall center, building, stadium and at home [15]. A straightforward way of minimizing this effect is to execute the experiments at late night or over the weekend, when the interference is usually reduced. However, this does not eliminate the possibility of having unpredictable results.

III. FUTEBOL RoF-BASED IoT TESTBED

The experiment focuses on the setup of a robust and flexible environmental monitoring system in the UNICAMP campus, using several IoT wireless sensor devices over an RoF system employing optical infrastructure already deployed in the campus. A high level overview of our proposed testbed is illustrated in Fig. 1 and the main objectives of the experiment are as follows.

Suitable transmission process – The RoF system is responsible for transporting the RF signals on the optical fibre as well as transforming the optical signals received through the fibre into RF signals. Such process can be analogue (RoF) or digitized (D-RoF). While in the latter RF signals are converted to digital serial bit stream (digital baseband in-phase and quadrature stream) before transmission over optical fiber link, the former transmit the analog modulated RF signal through the fiber. Thus, we aim at comparing the performance of RoF and Digitalized RoF (D-RoF) systems describing the advantages and drawbacks of each system in order to use the most suitable system for our specific application in term of latency, energy consumption and system performance degradation.

Efficient data reporting – IoT devices are responsible for gathering and measuring environment-related data as well as for sending the collected data to a central entity for further processing and analyzing. As the IoT devices can use wireless technologies such as ZigBee to transmit this data, multi-hop protocols may be employed because of its short-range communication interface. We aim at providing various multi-hop routing protocols to the experiments.

Real-time remote reconfiguration – the IoT devices gather and measure different environment-related data, but not all IoT devices have to report the same data and these measurement values do not need to be reported at the same time, i.e., different devices can measure different environment-related data and each measurement value can be reported with a different periodicity. Moreover, given that some applications and experimenters may not have interest in specific measurement values, they can avoid reporting such unwanted data. To enable an easy reconfiguration for each application according to specific needs, we aim at providing a real-time remote configuration mechanism.

Data analysis – measurement values reported by each IoT device, according to each profile, is stored in a database for further analysis. In this way, each profile will be capable of accessing and visualizing specific measurement reports in real-time. Moreover, historical data can be provided and filters can be applied to improve the data analysis.

IV. IMPACT OF RoF TECHNOLOGY ON PERFORMANCE OF IEEE 802.15.4-BASED IoT APPLICATIONS

In this section, as a preliminary result obtained with the above described experiment, the impact of the RoF system on

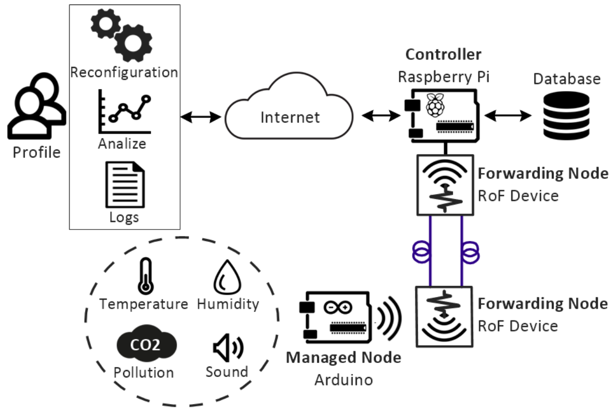


Figure 1. Overview of the FUTEBOL RoF-based IoT enviromental monitoring testbed

IEEE 802.15.4-based IoT monitoring applications is assessed. We propose a new methodology oriented to real outdoor/indoor environments.

A. Methodology

We present two approaches to address the methodological problems identified in Section II for assessing the impact of RoF technology on the network performance: the *splitter-based* and the *spatial-based*. The *splitter-based* approach uses an RF splitter, being more accurate to measure the impact of the RoF system on the system performance. In this approach, the wireless and RoF systems are simultaneously assessed. This avoids the bias introduced by the *temporal-based* approach since the RF signal transmitted on the RoF system and the one received by the wireless-only receiver at the antenna location is exactly the same. However, it introduces a loss of at least 3 dB, since the power is divided evenly among the two systems. This reduces the coverage area of the system being tested and impacts on the power consumption of the wireless nodes since this loss needs to be compensated by increasing the transmit power [15].

To overcome these problems, we also introduces the *spatial-based* approach, in which the RF signal is received separately by two identical antennas located close to each other. In this case, the splitter is not used, instead another antenna is co-located with that used by the receiver of the RoF system. The distance between the antennas must be less than half the operation wavelength (λ_0) in order to maintain a high correlation between the signals received by the antennas. In the case of the 2.4 GHz band, λ_0 is 12.5 cm. In this way, all drawbacks of the *splitter-based* and *temporal-based* approaches are addressed. Thus, the *spatial-based* approach was the one used in this paper to analyze the impact of RoF systems on IoT applications in our testbed.

B. Experimental Setup

Our experimental setup is illustrated in Fig 2. Two directly-modulated-based OZ810 RoF transceivers from OpticalZonu working at 1310 nm with a 3 GHz bandwidth were employed. One device (RoF 1) is located inside of a small data center in Building 1 and the other (RoF 2) is located in Building 2, where there are lab rooms as well as faculty and administrative offices. These equipment are interconnected by a 300 m single mode fiber (SMF) with attenuation of 0.33 dB/km and negligible dispersion at the working wavelength. This setup allows us to assess the performance of IoT applications under real environment conditions in both the wireless and the optical part. For instance, ZigBee networks share the 2.4 GHz ISM band with other technologies such as WiFi and Bluetooth. With this setup we are able to capture the effect of cross-technology interference on the network performance.

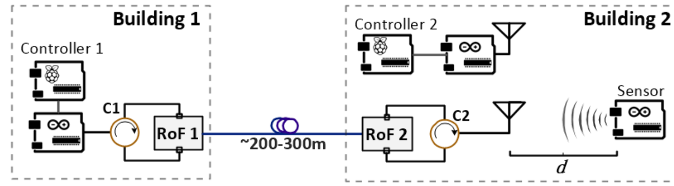


Figure 2. Experimental setup for the spatial-based methodology.

The RoF 2 device serves a sensor node by employing an 8 dBi indoor omnidirectional dipole antenna located at Bulding 2, in the middle of a corridor. An RF circulator (C2) featuring 20 dB isolation between ports and 0.2 dB insertion loss is employed to connect the antenna to the RF in and out coaxial ports of RoF 2 device.

The sensor node is implemented on an Arduino UNO which communicates via an XBee-Pro S1 802.15.4 RF module at 2.4 GHz from Digi international. The Arduino and XBEE module are connected by their serial interface. This module has an internal zero-gain printed circuit board (PCB) antenna, -100 dBm receiver sensibility, and international certification with the following transmit power levels: -3 dBm, 2 dBm, 8 dBm and 10 dBm.

In Building 1, a controller node (Controller 1) is placed inside the data center for centralized processing of the IEEE 802.15.4 signals transmitted by the RoF system. The controller node is implemented on a Raspberry Pi 3 Model B, which communicates with the sensor node via an Arduino/XBEE device with similar characteristics as the one used at the sensor side and connected via an USB port. However, in order to connect the XBEE module to the RF in and out ports of RoF 1 device, the module used at the controller side features an RP-SMA antenna connector. Another circulator (C1) with same characteristics as the one used in the Building 2 is employed to connect the XBEE module to RoF 1 device. We used an Arduino at the controller side due to the facility provided by its library for getting information of the RSSI value from the received frames. To avoid interference, acknowledgement (ACK) messages were disabled in all modules used in this experiment.

The proposed *spatial-based* methodology requires a second receiving system co-located at Building 2 for processing the IEEE 802.15.4 signals locally. This wireless-only system is passive (i.e., just hearing) and is composed of an antenna identical to and co-located with that used in the RoF system, and a second controller node (Controller 2), whose XBEE module is directly connected to the antenna. This antenna is located about 5 cm from the one used in the RoF system.

Synchronization between the devices involved in the experiments are needed. The Controller 1 coordinates the exper-

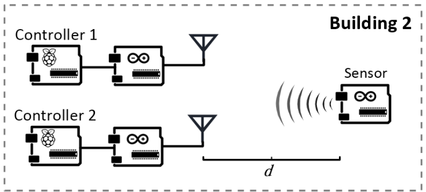


Figure 3. Experimental setup for the methodology validation.

iment execution out-of-band by sending commands to the Sensor Node and Controller 2 via a private WiFi network available in Building 1 and Building 2. In order to enable the out-of-band control of the Sensor Node, a Raspberry was connected to it. These commands includes change of the power levels and initiation of transmission.

Two different instances of the experiment were executed. In a first setup, the distance d between the Sensor Node and the antennas was 8 m and the height between the ground and the Sensor Node 1.5 m in a semi-NLOS scenario, whereas in the second setup the distance was 11 m and the the height 2.5 m in a non-line-of-sight (NLOS) scenario, in which there are an ordinary brick wall between the antennas and the Sensor Node.

In each experiment the sensor node transmits $1,000$ messages of 25 bytes every 100 ms for each power level within the set $\{10\,\text{dBm},\ 8\,\text{dBm},\ 2\,\text{dBm},\ \text{-}3\,\text{dBm}\}$. This round robin fashion is employed to reduce the impact of temporal changes in the environment between power levels as well as to avoid dependencies between measurement values of the same power levels. One hundred replications of each experiment were performed, lasting in total about 16 hours each setup.

To assess the impact of the RoF technology on IEEE 802.15.4-based IoT applications, we compare the performance of the RoF and wireless-only systems in terms of packet success ratio and RSSI values. To calculate these metrics, every packet successfully received at the controller-side (in both controllers) is logged along with their RSSI value and arrival time. Note that for the XBEE modules used here, the RSSI value is only an indication of the RF energy detected at the antenna port. Its value is accurate between -40 dBm and the receiver sensitivity. However, the RSSI value could contain not only the energy from the desired signal but also from background noise and interference. Thus, it is possible to get consistently high RSSI values but still have communication errors.

C. Validation of the methodological approach

We made the experiment illustrated in Fig. 3 to validate the proposed methodology. In this experiment, both controller nodes were placed in Building 2 and they were directly connected to their respective antennas, which were co-located in the Building 2 corridor. The sensor node was located at 8 m from the antennas. This experiment aimed at validating the *spatial-based* methodology, which simultaneously assesses the performance of the RoF and the wireless-only systems by employing different hardware. This experiment highlights the differences that may exist.

The RSSI values and packet success ratio (PSR) for the methodological validation setup are shown in Fig. 4(b) and Fig. 4(a), respectively. Even though the median (for -3 dBm, 2 dBm)

TABLE I. RESULTS FROM STATISTICAL TEST

Test	Metric	Setup	Data Set	P-value -3dBm	P-value 2dBm	P-value 8dBm	P-value 10dBm
Indep. t-test	PSR	valid.	C1xC2	0.7042	0.2058	0.7773	0.4744

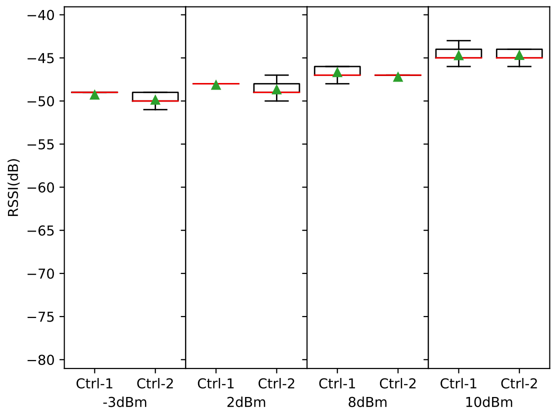
and interquartile range (the difference between the third and first quartile in the boxplot for -3 dBm, 2 dBm and 8 dBm) of the RSSI values slightly vary between the two devices, both give similar mean values under all transmit power levels. These slight differences were already expected due to hardware and spatial differences of the XBEE modules and antennas.

The independent samples t-test was applied for assessing equality of means of the packet success ratio obtained with the two devices (Controller 1 and Controller 2) for each power level with 5 % significance level. This test verifies the impact of the RSSI differences on the the packet success ratio metric. We found that there is no statistical difference ($p > 0.05$) between the packet success ratio values obtained by the two devices (Table I). Therefore, the *spatial-based* methodology is statistically valid to analyze the impact of RoF systems on network performance.

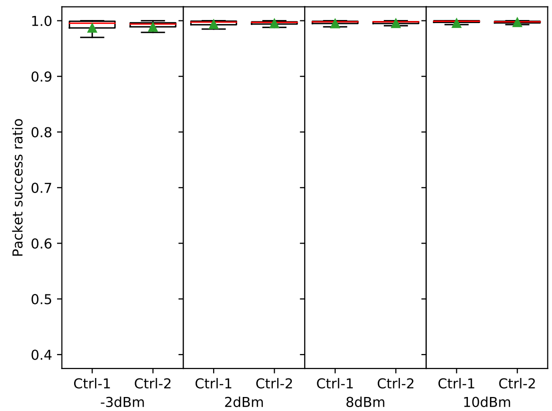
D. Experimental results and discussion

Figure 5 and 6 show a comparison of the RoF system and the system without RoF (wireless-only) systems for the semi-NLOS and NLOS setups, respectively. On average, the RSSI values given by the two systems slightly increases as the transmit power level increases (Fig 5(a) and Fig. 6(a)). However, the increment of the RSSI value is not proportional to the increment in the transmit power, i.e., the gain between transmit power levels of -3 dBm and 10 dBm is much less than 13 dB. The non-RoF system yields RSSI values about 23 dB (Semi-NLOS) and 15 dB (NLOS) higher than those of the RoF system. This well-known effect of the RoF systems is caused by distortion and non-linearity of the optical components [16]. Results for the Semi-NLOS agrees with those already obtained in laboratory under a controlled RF environment, which avoids RF interference and wireless impairments [14]. Actually, the decreasing impact of the RoF system under NLOS scenarios has never been reported so far. Moreover, the variation of the RSSI values (measured by the interquartile range) for the RoF systems slightly differs from those of the wireless-only system. This could be caused by several factors. First, as previously stated, the optical components impact the signals transmitted through the optical system, introducing noise and distortion. Second, since the two systems have different geographical location, they can be impacted differently by their environment (i.e., different radio interference in the XBEE antenna connector in Bulding 1 and Building 2). Even though a direct comparison between the Semi-NLOS and NLOS setups is not possible due to the temporal difference that exists between the two measurements, a degradation of about 10 dBm in the RSSI value for the non-RoF scenario is observed, which is consistent with the impact of a NLOS scenario.

The differences in the RSSI values are reflected on the packet success ratio (Fig 5(b) and Fig 6(b)). However, their impact is different, depending on the scenario considered. In the Semi-NLOS scenario, packet success ratio values produced by the RoF system are roughly 20 percent lower than

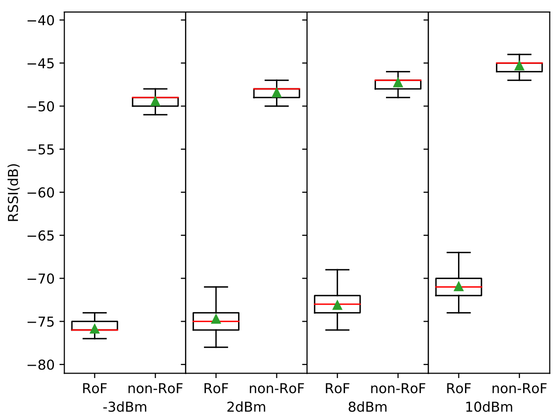


(a) RSSI values

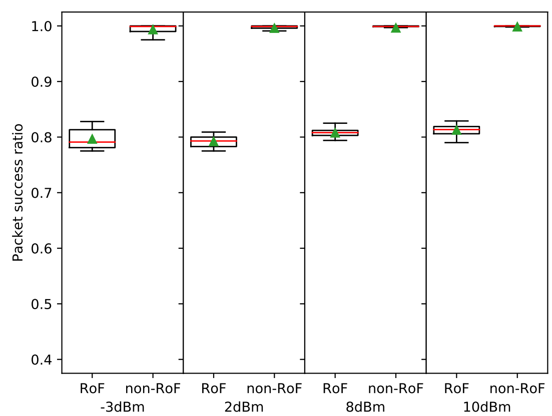


(b) Packet success ratio

Figure 4. Methodological validation results.

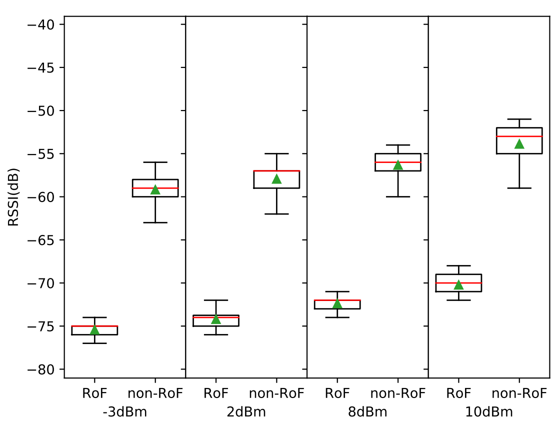


(a) RSSI values

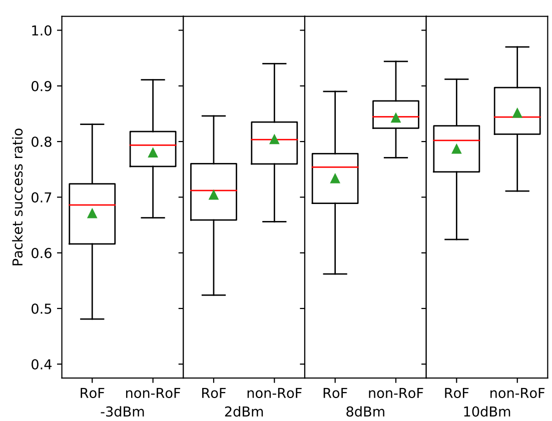


(b) Packet success ratio

Figure 5. Impact of RoF system on the network performance. Distance d between sensor node and antennas of 8m in a semi-NLOS scenario.



(a) RSSI values



(b) Packet success ratio

Figure 6. Impact of RoF system on the network performance. Distance between sensor node and antennas of 11 m in a NLOS scenario (wall on the middle).

those given by the non-RoF scenario under all power levels. Moreover, there is a very slight improvement in the packet success ratio as the power level increases. On the other hand, in a NLOS scenario, the RF signal suffers from fading which is a phenomenon induced by multi-path signal propagation, weather, and shadowing from obstacles (e.g., walls, people). In this scenario, the network performance can be severely impacted by interference and noise, which measurements come together with the desired signal power in the RSSI value provided by the XBEE modules. This phenomena leads to a wide varying of the combined multi-path signals degrading the receiver performance. This is the cause of the high variance observed in the packet success ratio for both systems in this scenario. The interquartile range of the packet success ratio for the RoF system is consistently lower than that of the non-RoF for all power levels. However, the medians are almost the same for transmit power of 10 dBm. The difference between the medians of both systems is about 10 percent for the other power levels.

Based on these observations, we conclude that the degradation introduced by the RoF system can partially be compensated by applying power control in a XBEE module following international regulation, which limits the transmit power to 10 dBm. As the single-hop coverage of the network decreases, multi-hop communication is required by the sensor nodes that become out of reach. However, note that the distance between the two end-side devices (Sensor node and Controller) in the RoF system is much larger than that in the non-RoF system in our setup; while in the non-RoF scenario the distance between the Sensor Node and the Controller is 8 m, in the RoF scenario this distance is approximately 300 m and it can be up to 600 km with low additional penalty [7].

Despite the impact of the RoF system on RSSI and packet success ratio, RoF is still attractive for IoT environmental monitoring given its advantages of low latency and centralized processing. This includes scenarios in which the distance from the antenna to the central location is long since wide-coverage just relying on multi-hop communications (without a backhaul network) is unreliable and costly in terms of delay and energy consumption. Moreover, the RoF system is also attractive in scenarios in which the optical infrastructure is already available. For instance, when there is another wireless technology (such as WiFi or cellular networks) already using the optical network.

V. Conclusion

In this paper, we have described a testbed proposed under the H2020 Futebol project. It focuses on the demonstration of the suitability of RoF technology for IoT environmental monitoring. We have proposed and validated a methodology to measure the impact of RoF on network performance. As a preliminary result, we have analyzed the impact of RoF systems on the performance of IoT environmental monitoring by using the proposed methodology. Future work includes the comparison of RoF and wireless-only scenario with multi-hop capabilities in term of delay, packet success ratio and sensor-node energy consumption as well as the study of the Digital RoF and its comparison with the results obtained here.

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