WSN Coverage Improvement with ROF in Bus Topology for Smart Cities

Raphael M. Assumpção, Indayara B. Martins, Frank H. Behrens, Omar C. Branquinho and Fabiano Fruett

Abstract— **This work proposes an experimental coverage evaluation of a Wireless Sensor Network (WSN) connected with Radio-over-Fiber (RoF) network operating as system backhaul that can be implemented in WSN under the Internet of Things (IoT) context. The RoF is assembled in a bus topology and has a radio repeater for signal distribution to the WSN. Impairments present in RoF systems that degrade the RF signal are analyzed. The main parameter used to evaluate the WSN coverage of this system is distance by Packet Error Rate analysis. The results show that the radio repeater device brings benefits to signal quality, improving the area coverage of a WSN. The bus topology used for RoF reduces equipment cost.**

Keywords— WSN, RoF, Radio Repeater, Bus Topology, Smart Cities, IoT.

I. Introduction

The Internet of Things (IoT) is a recent communication paradigm aimed at connecting objects of everyday life equipped with sensors, microcontrollers and transceivers for digital communication that make them able to communicate with one another bringing new data and functionalities to the users through the Internet [1].

The application of the IoT paradigm to an urban context is of particular interest nowadays, as it permits the adoption of the information and communications technology (ICT) solutions to be used in the management of public affairs, thus realizing the concept known as Smart City [2].

In 2008, over 50 % of the world's population was already living in cities, and this number is expected to rise to 80 % by 2020. Cities have become important economic units in the global economy, where innovation takes place. The structure of cities has been radically transformed by the recent introduction of ICT network infrastructure, an important component to leverage cities into the digital age and e-economy. Ambient intelligence is embedded in the fabric of the city, wherein various sensors are widely and densely deployed to gather all sorts of information (traffic, pollution, temperature, etc.) which is then transported by wireless and wired access networks to data centers for analysis in order to optimize the use of resources [1].

Wireless sensor network (WSN) is a great area of applications currently under development. The monitoring and control of process in the context of Internet of Things (IoT) – where everything is connected – is becoming a great business for wireless communication. A WSN can be described as a network composed of sensor nodes that are highly distributed, small, and lightweight, that wirelessly monitors the environment or system through physical measurements. The topology of a WSN system design depends significantly on the application [3].

A known problem with WSN is its short-range coverage under low-power consumption restriction. In some applications, the sensor nodes need to operate in low power mode to preserve battery charge and extend its operating lifetime, thus limiting the WSN coverage by its restricted transmission power when sending monitored data. However, this limitation can be mitigated by using an optical fiber communication network as system backhaul [3, 4]. With the Radio over Fiber (RoF) backhaul, it is possible to increase the distance between a WSN cluster, comprised of several sensor nodes and a local coordinator node, and the Management Center by several kilometers if needed [5]. It is noteworthy that the path loss in free space is orders of magnitude higher than in the optical domain on a RoF based backhaul system, that is what makes it viable to transmit packets between the Management Center and WSN clusters as a single wireless hop, instead of multiple hops wireless links, which are lossy and have high latency.

A WSN topology for smart cities is shown in Figure 1.

An important fact to be noted is that fiber is abundantly available because of great implantation of fiber in the last 30 years and the development of the WDM technique that uses only one pair of fibers to transport many streams of data [6].

Considering there is a fiber surplus, it can be used to create a robust WSN with RoF network with low delay and high reliability [3].

Although advantageous, the utilization of RoF as a backhaul for WSN implies that additional impairments have to be considered. The conversion from radio to light and then from light to radio inserts a great amount of noise and also has its gain highly associated to laser modulation, demodulation, and optical attenuation.

RoF links are often used in a point-to-point topology [2,5,7,8,9,10], which would lead to a central site with several RoF equipment connected to the clusters equipment. In order to reduce equipment cost it is proposed using the system in a bus topology, as in [3,4], this way connecting all the distant clusters RoF under only one RoF equipment on the central site.

This study extends the results obtained on another works [3], analyzing the coverage improvement on WSN brought by the use of RoF bus network backhaul connected back-to-back to the radio repeaters. In the proposed testbed, the sensors nodes operate at 915 MHz, using FSK modulation, and are connected to the RoF bus network through a radio repeater. The packet loss and received signal strength were measured at the sensor. The results show that it is possible to use RoF in a WSN implementation. The impact of the penalty introduced by the RoF on the cluster coverage distance was mitigated with the use

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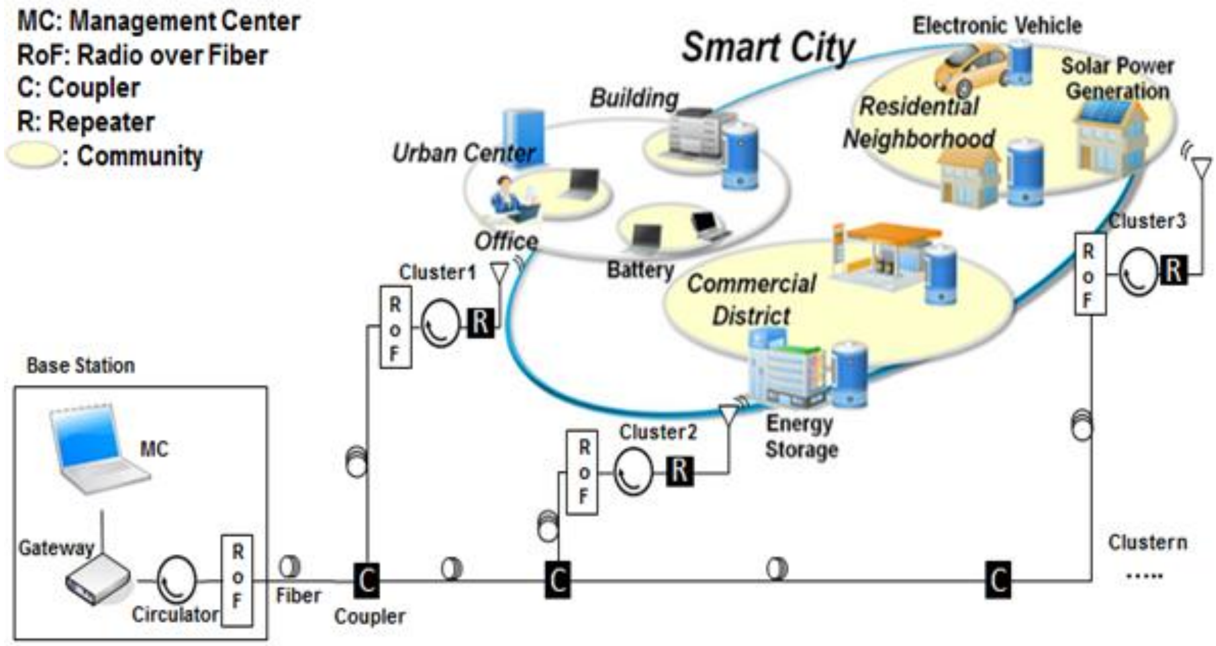

Fig. 1. Wireless Sensor Network with RoF in bus topology for Smart Cities

of the radio repeater, achieving a good performance for the RoF architecture proposed.

The paper is organized as follows. Section 2 describes some basic concepts about RoF and WSN. In section 3 the proposed set up model is described, as well as its bus topology configuration and radio repeater. In Section 4 the results are presented and discussed. In Section 5 we show our conclusions and a perspective of future works.

II. RoF and WSN Architecture

This section focuses on discussing aspects of the RoF and WSN architecture and their requirements.

A. Radio over Fiber

The main elements of RoF systems are shown in Figure2.

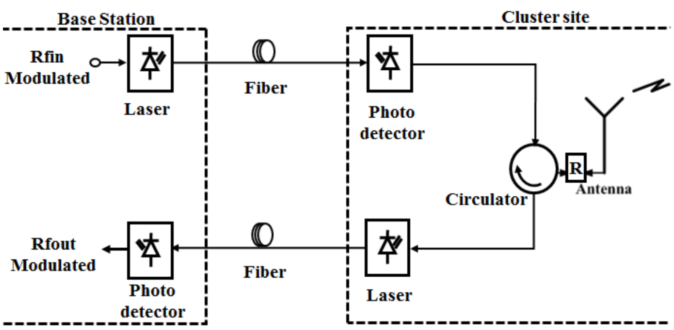

Fig. 2. RoF system architecture

The RoF transmit the RF signal by modulating a laser analogically as a mean to convert the electrical RF signal to an optical signal. The laser can be directly or externally modulated [5]. The RoF applied in this work uses direct modulation, and it's gain can be calculated by [7]:

$$G = S_l(f)^2.\alpha^2.S_d(f)^2.\frac{R_d}{R_l} \qquad (1)$$

Where G is the gain, S_l the laser slope, α the attenuation, S_d the detector slope, and R_l and R_d the laser resistance and detector load resistance, respectively. RoF systems' noise figure comes from both generation and detection of the optical signal. Considering signal and link analysis, the most relevant noises in a direct modulation scheme are the laser relative intensity noise (RIN), the shot noise, and the thermal noise. Most direct modulated systems are RIN limited. The noise figure from a direct modulation RoF link can be calculated by Eq. (2) [8], [9].

$$NF = 10.\log\left[1 + \frac{I_D^2.RIN.R_d}{k.T.G} + \frac{2q.I_D.R_d}{k.T.G} + \frac{1}{G}\right] \qquad (2)$$

Where I_D is the current at the photodetector output, R_d the detector load resistance, k the Boltzmann constant, T the temperature in kelvin, G the RoF gain, and q the charge of an electron.

Generally, commercial systems have their noise figure contribution presented in the form of equivalent input noise (EIN). The EIN represents the sum of all noise contributions and is given by Eq. (3) [10].

$$EIN = N_{RIN} + N_{SHOT} + N_T \qquad (3)$$

Where N_{RIN} means the noise detected at the receiver, N_{SHOT} the noise influenced by the photoreceptor current, and N_T the thermal noise, which depends on the temperature. *EIN* is usually presented in dBm/Hz units. Equation (3) is valid when the RoF link is composed of only one RoF as head end unit and another RoF as remote antenna unit (RAU). In this case, this system is considered to have a single cluster. For multi cluster systems, where more than one RAU is present, the EIN should consider the noise components from all the clusters. Thus, the EIN for a multi cluster system is given by Eq. (4), where the noise from all the clusters is considered.

$$EIN = \sum N_{RIN} + N_{SHOT} + N_T \qquad (4)$$

It is important noticing that the RIN perceived and shot noise, both, are influenced by all the clusters in the system, while the thermal noise is dependent only on the two RoFs included in the link that is being analyzed.

From this, it is shown that noise figure analysis is case specific and has to be done for each link.

B. Wireless Sensor Network

The WSN consists of sensor nodes that are connected to each other through a wireless network.

For the analysis of the wireless signal propagation, an additive white Gaussian noise channel may be considered. The signal-to-noise ratio (SNR) vs bit error rate (BER) curve for the modulation used can be calculated, aiming determine the necessary SNR required for any defined packet error rate (PER). The error probability for FSK-NC, considering Noncoherent (NC) frequency shift keying (FSK) modulation is given by Eq. (5) [11]:

$$P_{e,FSK} = \frac{1}{2} e^{\left(-\frac{E_b}{N_0}\right)} \qquad (5)$$

Where $P_{e,\,FSK}$ is the error probability for FSK-NC, E_b the bit energy, and N_0 the noise power spectral density. As the data rate used and the bandwidth necessary for the transmission are known, the SNR is given by Eq. (6):

$$\frac{S}{N} = \frac{E_b}{N_0} \cdot \frac{R}{B} \qquad (6)$$

Where R is the data rate and B the bandwidth. With the BER and the transmission packet size, it is possible to obtain the PER value equivalent to the BER as shown in Eq. (7) [12].

$$PER = 1 - (1 - BER)^n \qquad (7)$$

Where n is the packet size. The PER versus SNR for FSK-NC modulation with 38.4 kbps bit rate, 406.25 kHz bandwidth and 496 bits packet, was considered.

The WSN's link budget is calculated seeing the RoF link as a gain, or attenuation, and a noise source. In this way the link budget equation considering the RoF gain is shown in Eq. (8).

$$P_{Rx} = P_{Tx} + G_{Tx} - L_{PL} + G_{Rx} + G_{RoF} \qquad (8)$$

Where P_{Rx} is the reception power, P_{Tx} the transmission power, G_{Tx} the transmission antenna gain, L_{PL} the path loss, G_{Rx} and G_{RoF} the gains from reception antenna, and RoF, respectively. The path loss can be calculated by various methods, but for further calculations, the log-distance path loss model was used in Eq. (9) [11].

$$L_{PL} = 20.\log_{10}\left(\frac{4.\pi.d_0}{\lambda}\right) + 10.\beta.\log_{10}\left(\frac{d}{d_0}\right) \qquad (9)$$

Where L_{PL} is the path loss, d_0 the reference distance, λ the RF wavelength, β the path loss exponent and d the total distance.

The path loss exponent is dependent on the environment where the signal is propagated and, in this experiment, it was defined as 3.41, which is the exponent for an open area for WSN in 915 MHz [13].

C. WSN + RoF

The union of WSN and RoF result in some impairments for the radio communication. Since RoF system introduce a large amount of noise, it makes necessary to increase the signal power on the receiver to guarantee the same error rate.

The reception power can be defined as a function of the noise power, the SNR defined by the modulation, and the PER as given in Eq. (10).

$$P_{Rx} = EIN_{dBm/Hz} + 10.\log_{10}(B) + SNR_{dB} \qquad (10)$$

Where P_{Rx} is the reception power necessary for a given PER, $EIN_{dBm/Hz}$ the EIN as shown in Eq. (4) in dBm/Hz, B the signal bandwidth, and SNR_{dB} the SNR that is defined by a chosen PER given the modulation scheme.

Motivated by the huge degradation on distance coverage encountered in previous works [3], we decided to experiment using a multi-hop like scheme to mitigate the problem with the noise and coverage distance. For this, it was proposed a repeater formed by 2 sensor nodes, connected through a serial bus and containing a firmware which retransmitted in one radio what was received in the other. This repeater was then connected in one side directly to the RoF backbone and on the other side feeding the antenna system.

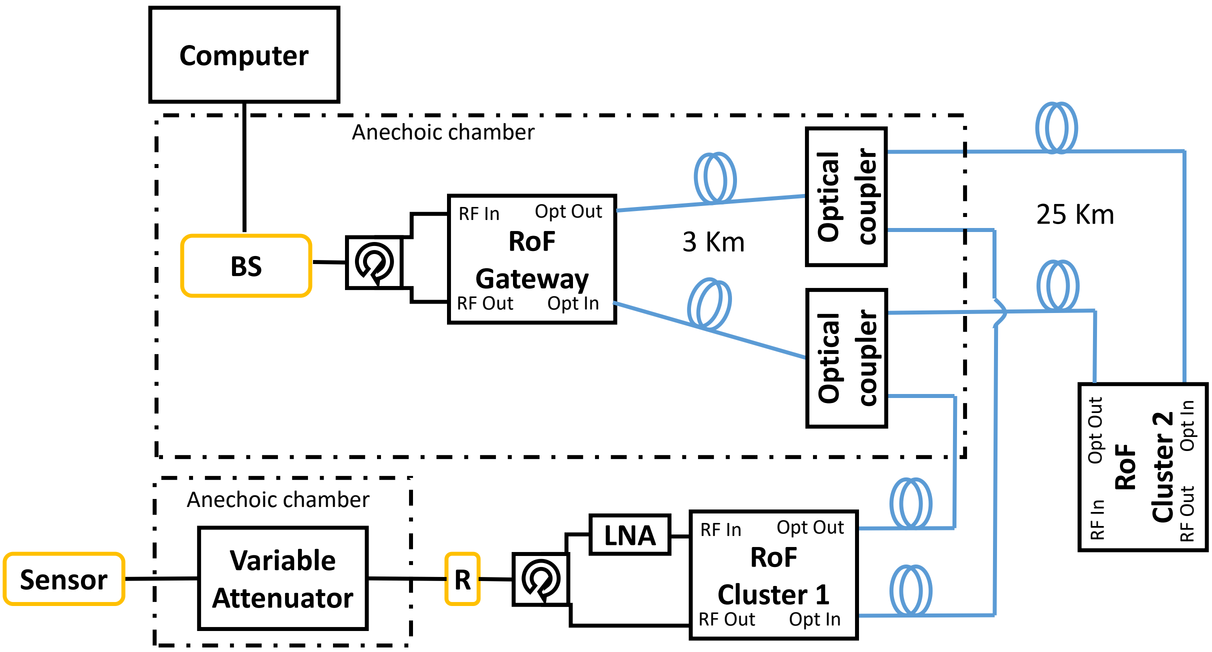

Fig. 3. Experimental Setup

III. Experimental Setup

The experimental setup was designed for testing the radio coverage adding a repeater to decouple the cluster coverage from the RoF backhaul impairments as shown in Figure3.

The WSN with RoF testbed layout is modular and can be reorganized to match the proposed tests scenarios. The testbed is composed of a sensor node acting as the remote node, a variable attenuator to emulate the radio channel, a radio repeater, antenna duplexers, three commercial RoF equipment, two optical couplers, a sensor node working as base station, and a computer for data processing and logging.

To minimize uncertainties on radio propagation, such as multipath propagation, the testbed was cabled and a variable attenuator was used to emulate the sensor being carried away from the RAU toward the cluster boundaries.

The Radiuino platform [14] was used to configure the radio module parameters for the WSN's nodes such as channel frequencies, modulation, transmission rate, transmission power, serial baud rate and net address.

Each experiment round consisted of a set of data transmissions. While the attenuation was slowly raised, PER and RSSI data were collected. For each point of data 10,000 packets were transmitted from the sensor to the base station.

From the curves of PER vs RSSI obtained we collected the RSSI where 5% PER is observed and used it to calculate the theoretical coverage distance.

The modulation used was FSK with data rate of 38.4 kbps. The filter bandwidth was 406.25 kHz. The packets used in the transmission were 62 bytes long. The packet architecture used is similar to the one shown in [3], with a payload 43 bytes longer. Although CRC was included in the transmitted packet, correction code was not used. The RoF system used is a commercial unit [15]. It works in 1310 nm and has an optical output of 3 dBm and a typical RF gain of 0 dB without optical attenuation (back to back). The EIN presented in the datasheet is -134 dBm/Hz and the RIN given by the manufacturer is -140 dB/Hz. The testbed has an optical attenuation of 6.5 dB between RoF clusters and RoF base station (BS). This was reflected as a measured RF gain of -15 dB in the performed tests.

The tests of this work were realized in three rounds as follow:

A) In the first experiment round, the BS was connected back-to-back to the repeater without any RoF. The repeater was connected to variable attenuator (radio channel emulator).The results from this experiment were used as a reference for the other tests.

B) In the second experiment round, the RoF from the BS and the first cluster were introduced in the test.

C) In the third experiment round, a second RoF (cluster 2) was connected to the testbed. As we just wanted to measure the degradation caused by adding the cluster, no sensor was connected to it (i.e., the RoF equipment on cluster 2 emitted a continuous-wave signal).

Using the repeater connected directly with the RoF makes it possible to guarantee that the necessary power is received at the radio receiver. Since the packet is received and retransmitted on the repeater the cluster is thus decoupled from the RoF backbone transmission.

These tests were proposed to verify the feasibility of such arrangement for future use on a real case scenario.

IV. Results and Comments

The results of the experiments (A, B and C) described in the last section are presented in Figure 4.

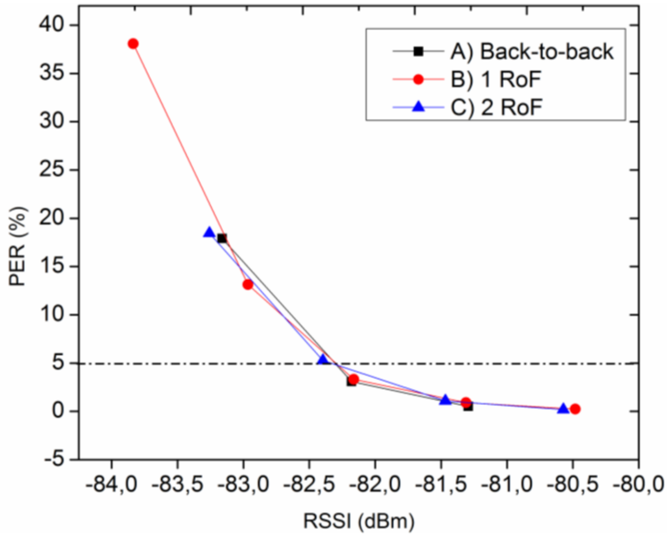

Fig. 4. PER versus RSSI

These results show that in all tests the WSN network performed the same in PER x RSSI, with the 3 curves overlapping each other.

From these results, taking the practical RSSI values for the links to perform with a PER of 5%, the coverage distances radius were calculated using Eq. (7).

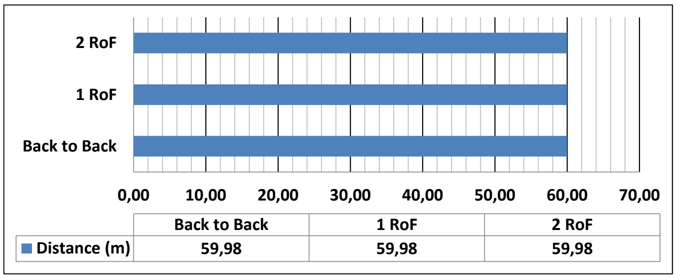

Fig. 5. Calculated Coverage

The results show that the cluster coverage was not affected by the insertion of the RoF backhaul or even the insertion of other cluster to the backhaul.

It is important to note that in previous work [3], where there were no repeaters in the setup, the coverage distances obtained in the experimental setup were very inferior in tests with 1 and 2 RoFs, besting at approximately 21% when there was only 1 RoF and attenuation was compensated with a low-noise amplifier.

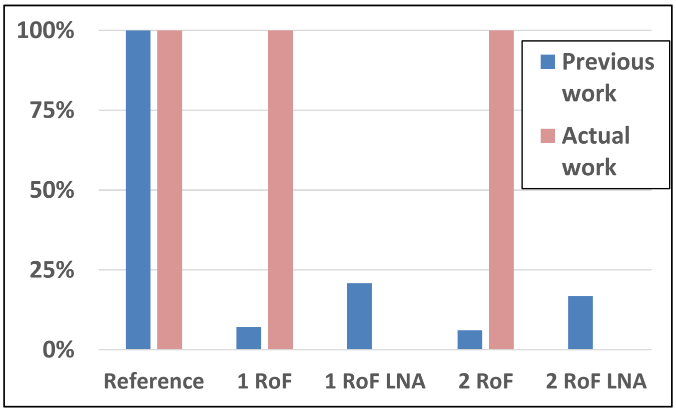

Fig. 6. Comparison between reference and other scenarios

Figure 6 shows a comparison in percentage of coverage radius in both works. Note that the radio parameters like transmission rate, packet size, filter bandwidth, etc. from this work are not the same as in previous work [3], preventing direct comparison on coverage distance.

By using the radio repeater, the RF signal is re-formatted before being sent to the WSN cluster, thus having no reduction in coverage area when using 1 and 2 RoFs, making it a suitable strategy to the smart cities context.

V. CONCLUSIONS

The main proposal of this work is an experimental evaluation of the coverage of a Wireless Sensor Network with Radio-over-Fiber bus network backhaul that can be implemented in Smart City applications under the Internet of Things (IoT) context. The proposal was a RoF backhaul assembled in a bus topology using a radio repeater for signal distribution to the WSN.

The results show that the radio repeater device mitigate the impairments imposed by the RoF to signal quality by decoupling the wireless cluster from the RoF backhaul. The improvement in the coverage area of the WSN enables the system to be used in Smart Cities applications.

The bus topology in the RoF network is proposed as a new contribution for RoF usage, maintaining performance, reduced attenuation and strong electromagnetic immunity while reducing infrastructure cost.

For future works, we intend to extend this experiment using more RoF clusters and implementing this setup in a real use case for further tests.

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