Wireless Sensor Network for Monitoring Infrastructure Adjacent to Metro de Medellín Railway System

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ABSTRACT
Structural Health Monitoring (SHM) systems using Wireless Sensor Networks (WSNs) are common nowadays in infrastructure such as tunnels, buildings and highways. Information gathered from in-situ deployed sensors is useful for maintenance purposes, evaluating infrastructure response before particular situations and preventing catastrophic events, among others. The design and implementation of a wireless sensor network for monitoring infrastructure adjacent to Metro de Medellín railway system is presented. A wireless network constituted by a set of nodes involving 8-bit microcontrollers uses the IEEE 802.15.4-compliant MiWi Protocol for communications within the Personal Area Range. Measurement data can be retransmitted over longer distances, within the local area or metropolitan area range, through communication gateways connected to network coordinator.

CCS Concepts
• Networks→Network types • Hardware→ Communication hardware, interfaces and storage.

Keywords
Structural Health Monitoring; Wireless Sensor Networks; MiWi Protocol; 8-bit Microcontroller; IEEE 802.15.4 standard.

1. INTRODUCTION
Wireless sensor networks exhibit features that greatly favor the requirements of structural health monitoring systems. Continuous measurement derived from the sensors deployed over infrastructure works such as tunnels, railways, bridges, and buildings, among other, can be achieved by means of wireless networks grouping sensor nodes according to the selected topology [1]. Connecting wireless personal area networks with other communication networks, both wired and wireless, covering the range of local area, metropolitan area or wide area network by using gateway elements provides the reliability needed in order to provide a continuous service.

In Colombia few experiences are found regarding structural health monitoring, but some events and accidents occurred during the last years, such as building and bridge collapses, have shown the need for the implementation of solutions involving continuous-monitoring capabilities.

2016 8th Euro American Conference on Telematics and Information Systems (EATIS), Cartagena de Indias – Colombia. April 27 - 29

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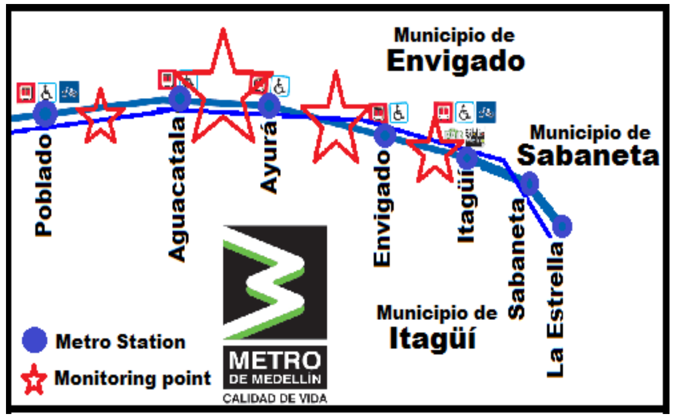


Figure 1. Metro de Medellín line-A railway system (blue) and selected points for structural health monitoring (red stars).

The railway system of the line A of Medellín Metro runs along a distance of about 20 kilometers in the Valley of Aburrá, Antioquia-Colombia. Most of the line A of this metro system goes parallel to Medelllín River. In order to monitor infrastructure adjacent to railway system to prevent landslide or similar events which could result in risk for metro passengers or stopping operation of this massive transportation system, a pilot project is currently under execution. This project is aimed at complementing current monitoring systems by installing a set of sensor nodes in points considered to be critical according to previous analysis derived from site inspections and historical data registers.

This structural health monitoring application requires unattended operation of nodes over long periods of time because of the conditions of places to be monitored and the restrictions to enter the areas adjacent to railway system during normal operation of trains. Commercial off-the-shelf elements such as batteries and photovoltaic modules are to be used in order to provide maintainability and scalability to the proposed solution regarding power supply requirements. Sensors and instrumentation boxes containing nodes circuitry are to be placed outdoors, therefore some considerations, such as NEMA and IP ratings, must be observed to fulfill these requirements when choosing these elements. According to the performed analysis both wall inclinometers and borehole inclinometers will be installed to monitor the retaining walls adjacent to line A railway system and the ground surrounding them.

Figure 2 shows the site of the line A selected to install the first nodes in order to conduct monitoring tests.

Figure 2. Inspecting a selected monitoring place before installing the sensors for the structural health monitoring application.

This work is ordered as follows: first MiWi protocol is presented, then the adopted architecture for this particular application is described, network nodes design, code development and primary testing issues are also described. Finally we discuss preliminary results and present conclusions

2. THE MIWI PROTOCOL

2.1 Protocol Overview

The MiWi protocol is proprietary from Microchip [2], this protocol is IEEE 802.15.4-compliant and among their main features we have their ease of implementation on 8,16 or 32 bit microcontrollers, their light footprint regarding to program memory usage and the topology and variants (MiWi P2P, MiWi pro) offered to the developers of applications. MiWi variants like MiWi P2P offer different choices to application developers related to network topologies, maximum number of nodes and routing mechanisms.

Table 1. Program Memory MiWi vs Zigbee [3]

Protocol		**MiWi**	**Zigbee**
Program Memory (Kbyte)	Coordinator	<16 Kbyte	37-96 Kbyte
	Router	<16 Kbyte	30-64 Kbyte
	End Device	2-8 Kbyte	18-40 Kbyte

2.2 MiWi P2P

This variant of MiWi protocol works in star and peer-to-peer topologies [4]. MiWi P2P function in single hop networks, therefore the maximum distance for connecting nodes is determined by the range of transceivers. Similarly to IEEE 802.15.4 Standard, we have in MiWi protocol Reduced Function Devices (RFD) and Full-Function Devices (FFD). The PAN Coordinator must be a FFD and, depending on the MiWi P2P topology, end devices can be either RFD or FFD. In star topology the end devices only can establish communication with the PAN Coordinator and this can establish with all the network nodes. Peer-to-Peer topology in MiWi P2P is more flexible than star topology, end devices can establish connection with other devices as shown in Figure 3.

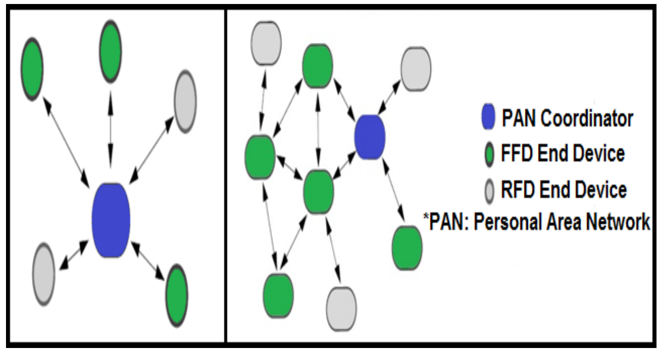


Figure 3. Star (left) and Peer-to-Peer (right) topologies under MiWi P2P protocol

2.3 Network Addressing and Message Format in MiWi P2P

For networks under MiWi P2P protocol we have eight-field 64-bit addresses, starting with the number one for the PAN coordinator (for example 11-22-33-44-55-66-77-01), end devices continues the numeration (11-22-33-44-55-66-77-02, and so forth).The personal area network also have an identifier called PAN ID, the default is 1234. Short addressing is used only for broadcast messages [4].

3. ADOPTED ARCHITECTURE

3.1 Architecture description

A three layer architecture, based on the proposal of Dexternet [5], has been adopted and some changes are proposed in order to develop an application of continuous structural health monitoring. This architecture allows accessing collected data at any of the layers: at the lower layer, which is called Field Datasink, at the intermediate level (Local Datasink) or at the upper level (Global Datasink). Accessing data at any of the three layers makes easier conducting tests while implementing the network, network maintenance becomes also easier because datasinks are not centralized and provides some flexibility to the monitoring application in aspects such measurement visualization, storage, analysis and processing.

The lower layer, called Sensor Node Layer, is based on a wireless sensor network which uses MiWi P2P protocol to collect data from the field sensors deployed on the infrastructure adjacent to railway system. The PAN coordinator belongs to the intermediate level, and it combines the management of sensor node communications with linking connection towards the so-called Ground Station which will be located at a distance around 1 to 2 kilometers. This network coordinator uses gateways which transfer on-field collected data to other data sinks by using other personal area networks protocols, such as IEEE 802.15.1, or Local Area Network protocols (IEEE 802.11 or M2M wireless protocols). At the upper level connection to metropolitan, local or wide area network is available by using GSM modems, TETRA standard radio modems [6], Ethernet gateways or similar devices.

Figure 4 shows an overview of the adopted architecture. Details are given regarding communication protocols and technologies used at each layer.

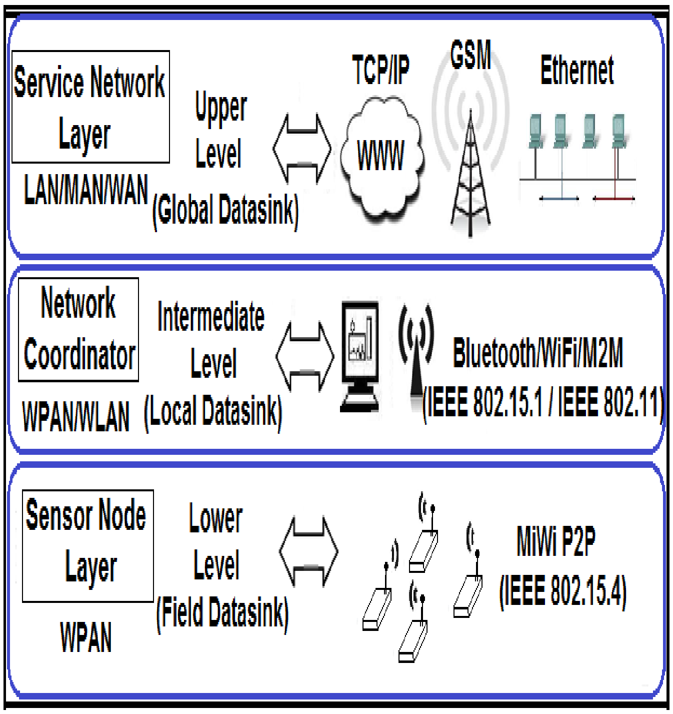


Figure 4. Three-layer architecture adopted for developing an application of structural health monitoring over infrastructure adjacent to railway

Two major concerns arise when planning this application: energy consumption and outdoor long-term functioning

3.2 Energy consumption

Long term energy autonomy is a required performance feature when developing an application like the above described. However achieving low consumption of sensor nodes depends on many factors like circuit design, electronic component specifications and firmware programming strategies. For the proposed architecture energy consumption is critical at the lower and at the intermediate layer, therefore traditional energy harvesting means like solar-photovoltaic are to be used in order to increase sensor nodes and coordinator operating time. Mean solar radiation for Medellín city, according to national climatic and energy Agencies IDEAM and UPME ranges between 4,0 to 4,5 KWh/m^2 daily [7].

3.3 Outdoor long-term functioning

Outdoor applications involving wireless sensor network pose some challenges for engineers. Weather, environmental and external agent (human beings or animals) influence must be considered in order to achieve continuous and reliable operation over long term time periods. Sun, rain, dust, moisture, vibration and similar factors could affect node performance. Circuit component performance could become degraded because the influence of temperature changes, furthermore rain and similar weather conditions could affect communications, mainly for sensor nodes operating in the 2.4 GHz ISM band. Sensor placement and enclosure selection must be conceived considering extreme conditions and favoring maintainability issues and potential extern agent damage or operation interference. This issue mainly is crucial for communication elements belonging to the lower and intermediate layer of the proposed architecture. IP66 rating, 4-4X NEMA rating enclosures are to be evaluated for field tests.

4. NODE DESIGN

The nodes for the personal area network are based on Microchip's PIC18F4620 microcontroller [8]. The PIC18F4620 is an 8-bit microcontroller which can execute the code to perform MiWi communications and additionally perform data logging/acquisition tasks.

4.1 Network Coordinator

Because of the number of nodes to be deployed over the field star topology has been adopted, therefore the coordinator will initialize the network and sensor nodes can only communicate with it. The coordinator operates continuously in order to collect the data sent from sensor nodes, and eventually it transmits alarms and reports data to the ground station

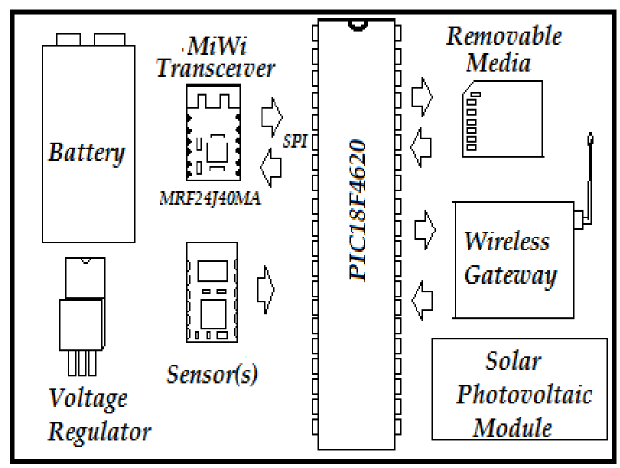


Figure 5. Elements constituting the network coordinator to be deployed on the measurement field

The elements constituting the network coordinator are listed in Table 2. Actual costs in Colombian local market are shown with the price expressed in United States dollars ($USD).

For some monitoring points TETRA-complaint radios are to be used. In this particular case we will use a MTP3200 portable radio which cost, including basic accessories, is about $1000 USD. The costs of this radios have been not included in the table because the Metro de Medellín already have a number of this units. They have provided us a pair which do not represent additional costs for them.

Table 2. Network Coordinator Elements

Element	Main Features	Cost (USD)
MiWi transceiver MRF24J40MA [9]	Operates in the channels 11 to 26 of the 2.4GHz band. Range of about 120 m with line of sight. SPI driven	10
Battery	12 V rechargeable dry battery	16
3.3 Voltage regulator [10]	DC-DC step-down low consumption	10
Sensor	Wall inclinometer	165
Datalogger	serially driven SD card	25
Wireless Gateway [11]	RS232 interface radio modem	185
Solar Photovoltaic Module (plus charge controller)	12V, 40 watt	126
TOTAL COST		$537

4.2 Network Nodes

On the field we will have sensor nodes and the PAN Coordinator (Network Coordinator). Sensor nodes have a structure similar to that shown in Fig. 5, but they do not include the wireless gateway. The solar photovoltaic module and the removable media could be present or not depending of particular application requirements. Sensors like inclinometers are common in structural health monitoring applications [12][13]. We also show in Figure 6 the mediating node that provides connectivity towards service networks. At the ground station we have the opportunity to use 120 Vac power supply and eventually connection points to IEEE 802.11-based networks.

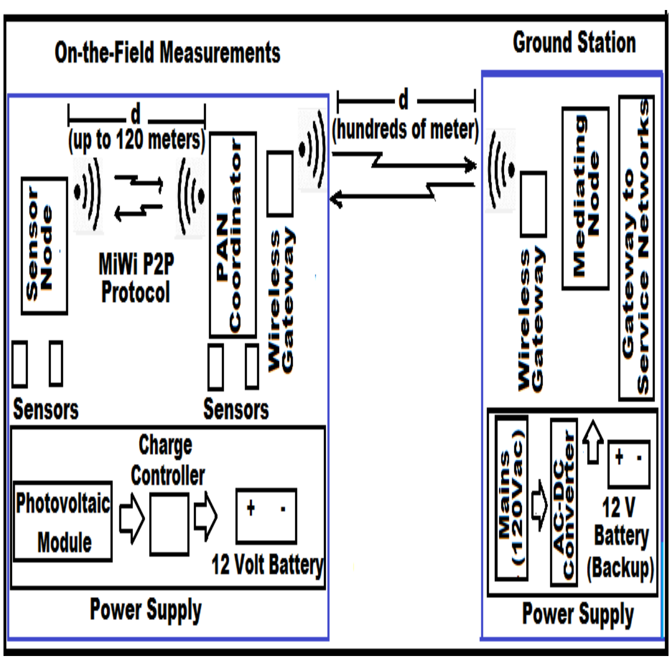


Figure 6. Overview of the network nodes to be deployed on the field and of the network node at the intermediate layer.

5. CODE DEVELOPMENT AND PRIMARY TESTING

Two MPLAB projects were developed in order to perform tests involving at least a sensor node and the network coordinator. Microchip's MiWi Application Programming Interface (MiApp) [14] functions were included into sensor node firmware in order to get better performance results from energy consumption point of view. Sleep mode was enabled for both transceiver and microcontroller, the payload of transmitted packets was formatted in order to make easier received data visualization and organization. Application developer can also use Microchip MiWi Media Access Controller (MiMAC) [15] functions to access special features at a lower level.

In order to illustrate the overall structure of the code executed by the network coordinator, Figure 7 shows the flowchart of the source file containing the main routine in the MPLAB project.

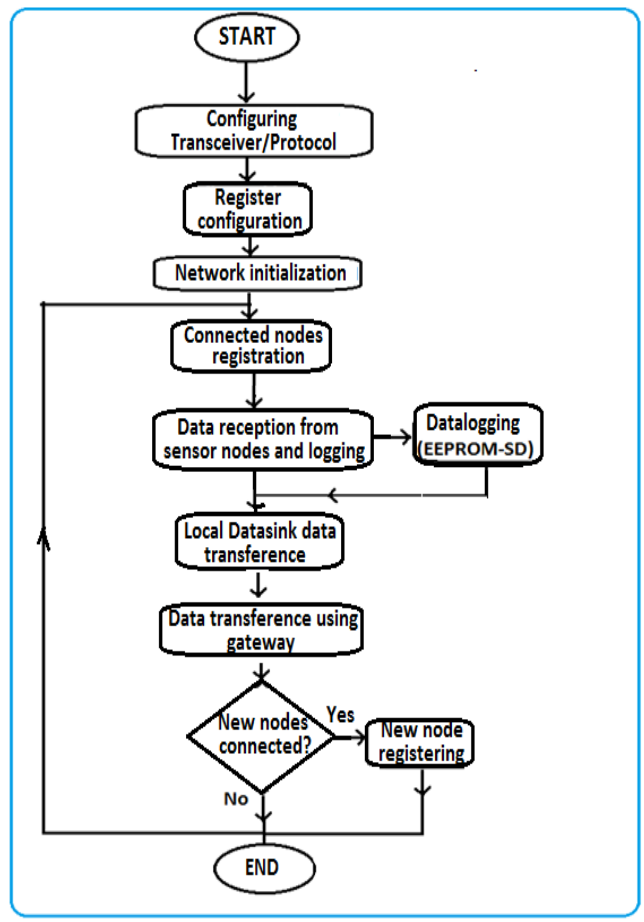


Figure 7. Flowchart of the source file containing the main routine for the Network Coordinator.

Programming nodes for this structural health monitoring application was successfully achieved by customizing MiWi stack reference libraries and files provided by Microchip. Complementary for-free available resources like MPLAB IDE and C18 compiler from this manufacturer were also used for developing the code and compiling the firmware to be executed by the microcontroller governing the nodes.

5.1 Battery Testing

In order to verify the performance of the nodes having the proposed design, a set of tests must be conducted. As we have already mentioned, one of the major concerns is that the nodes must have enough energy autonomy during operation. Continuous operation tests allow estimating the operating time of sensor nodes when powered by different types of rechargeable batteries. During the tests the sensor node only receives power from the tested battery and the network coordinator is powered from mains supply, as shown in Figure 8, in order to continuously count packet reception

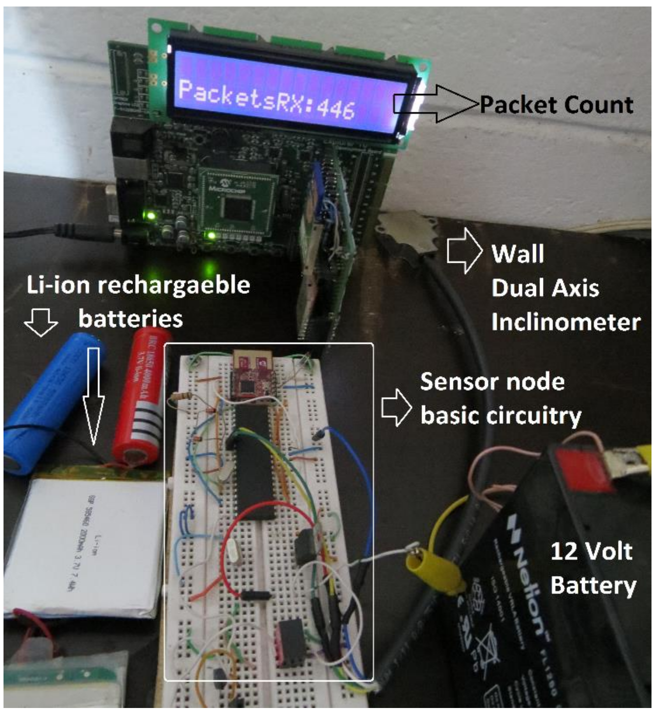


Figure 8. Sensor node and the mains-powered specially developed PAN coordinator to conduct continuous operation tests

Three types of batteries are to be tested while a sensor node periodically sent inclinometer data during several hours until packet transmission stops because of battery run out. The rechargeable batteries chosen to be tested are 8.4 volt Ni-MH, 3.7 volt Li-ion, and a traditional 12 volt lead-type (Pb) battery. The sensor node tested has a current consumption of about 15mA during transmissions and 6 mA during standby periods when both, transceiver and microcontroller, are put into sleep state.

Previous tests conducted under similar conditions have shown continuous operation for about six days when using the same 12 volt lead (Pb) battery, while NiMH and Li-ion batteries operated for time periods shorter than 10 hours [16].

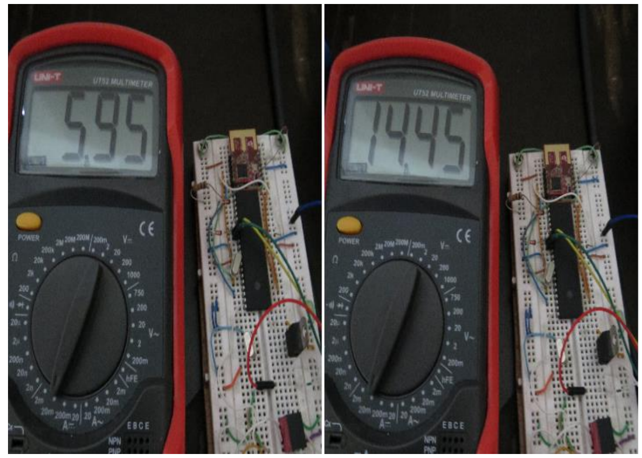
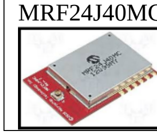


Figure 9. Current measurement for sensor node. During stand-by periods (left) with sleep function activated and during packet transmission (right).

5.2 Sensor Node Range Tests

Range tests were also conducted in order to establish the maximum distance reached by the MRF24J40MA transceiver, which was the choice made for communications at the lower layer of the proposed architecture. Other transceiver options such as MRF24J40MB and MRF24J40MC were considered but performance, technical and economic issues were not enough advisable taking into account project particularities.

Table 3. MiWi Transceivers Comparison

Transceiver	Advantages	Constraints
MRF24J40MA 	Widely available in local market Economical (10 dollar approx.)	Range is limited to about 120 meter
MRF24J40MB 	Range is about 1.2 kilometers Printed antenna	Discontinued (end of life declared by manufacturer) Unstable functioning when paired with MRF24J40MA
MRF24J40MC 	Range is about 1.2 kilometers	Higher cost Requires external antenna Higher power consumption

During tests conducted in the University campus, two nodes having MRF24j40MA reached links with distances of about 100 meters. A maximum distance of about 100 meters was also reached during a test in the field where the network is to be deployed. As shown in Figure 10, two persons verified the transmitted packets arrival. Passing trains do not seem to have influence on packet reception during the performed tests.

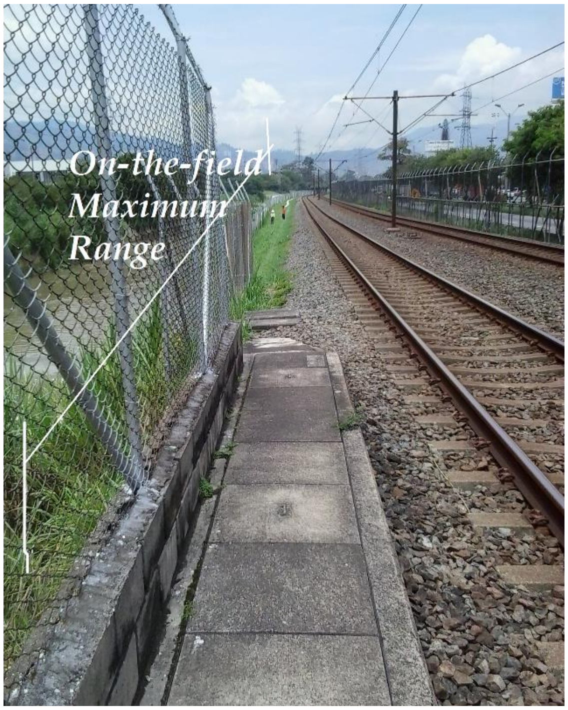


Figure 10. Range measurement test, for MRF24J40MA transceiver, conducted in the field place selected for deploying the structural health monitoring network

5.3 Mediating Node Communication Tests

In order to test the communications between the PAN coordinator, located in the measurement site, and the mediating node located at the ground station, data was sent through the 900 MHz gateways trying to establish a link between two points separated by a distance of about 800 meters.

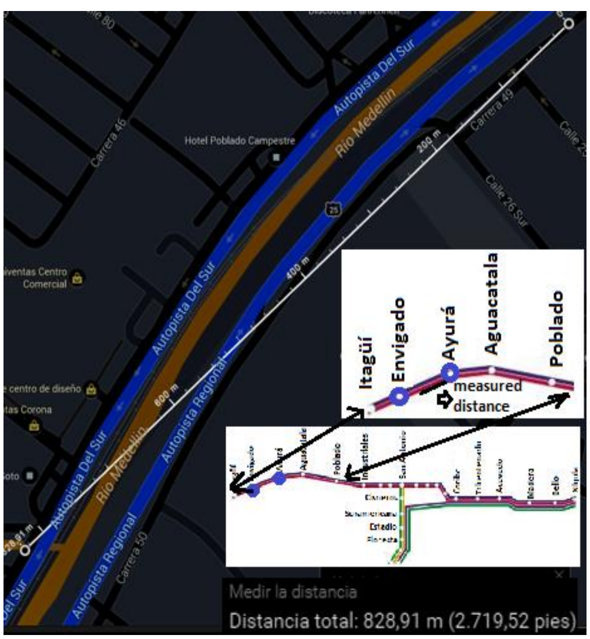


Figure 11. Distance to be covered between the site and the ground station

Because of the high trees located along the riverside there was no direct line of sight between the showed points, therefore communication was not possible by using the antennas provided with the CL4790 900MHz-radiomodems. Data was recovered only for link distances lesser than 400 meter. After analyzing terrain conditions it was found that it was necessary to use different antennas at the two ends of the communication link. In addition to this, 900 MHz radio modems must be located in poles to gain some meter height in order to establish a reliable Fresnel zone.

To gain access to wireless metropolitan area networks, and as a redundant element to cover critical communications additional, Terrestrial Trunked Radio TETRA-compliant transceivers will be installed both at the measurement site and at the ground station. By adding these TETRA transceivers we will take advantage of the existing communication infrastructure used by trains and Metro de Medellín technical staff. Current consumption increases by using TETRA radios.

6. RESULTS

A generic printed circuit board, shown in Figure 12, has been designed to be used either as sensor node or PAN coordinator. This printed circuit board includes connectors for different sensors, power supply (battery-solar photovoltaic), serial communications, serial debugging and datalogging. Current consumption of the electronic components of this printed circuit board, with a wall inclinometer connected, ranges from 21.2mA to 44.7 mA during tests performed with the transceiver shown. The current consumption of the TETRA radio used (MTP3200) can reach the scale of Amperes during transmissions.

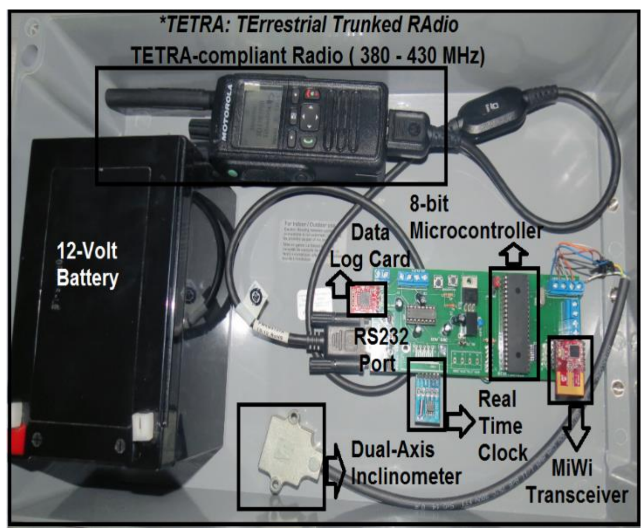


Figure 12. Printed circuit board and basic node setup

Communication on-the-field tests have been performed in order to verify data transmission from the place selected to install sensors. A 900 MHz serially-driven radio modem was tested but the distance separating the monitored place and the ground station was not fully covered. Environmental elements and railway infrastructure represented major interference for the signals. By using patch antennas distances ranging from 500 to 600 meter was covered, not enough for the application requirements.

After these tests the communication with the ground station was successfully performed by using AT commands serially sent to a TETRA-compliant radio operating in the 380-430 MHz band. The code executed by the PAN coordinator microcontroller was specially modified to send SDS (Short Data Service) messages.

Figure 13. On-the-field tests to verify communications of network node prototype with the ground station

Figure 14 shows the message content for a packet transmitted to the ground station containing inclinometer data.

Figure 14. Inclinometer data received for TETRA-compliant radio located at the ground station

The adoption of TETRA communications provide higher reliability for the system but power consumption considerably increases depending on the periodicity of the reports send from the PAN coordinator to the ground station. The power consumption of the TETRA radio used ranges from 1 to 1.8 Watts. The maximum power consumption of the 900 MHz radio modem tested is 1 about Watt.

Currently we have all the elements to start validation tests on the field by installing sensors on the contention walls and other infrastructure to be monitored and adapting enclosures and energy harvesting elements to the site requirements. A 20-Watt solar panel is to be used to support PAN coordinator node operation.

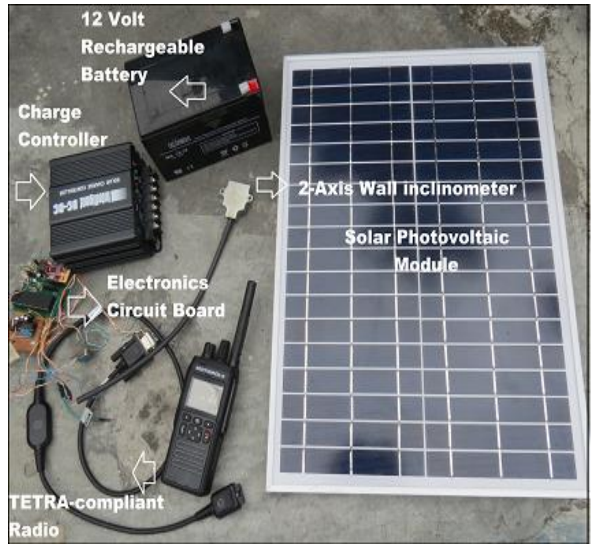


Figure 15. Basic set of elements to start on-the-field continuous operation test in order to validate prototypes

Some tests have been performed regarding the logging of sensor data into a removable media, as shown in Figure 16. Offline analysis involving huge quantity of acquired data over continuous time periods could provide valuable information for engineers and Metro staff. The personnel in charge of the security and operation of the Metro-de-Medellín system could get valuable information from offline analysis.

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 Prueba de registro fecha y hora  en medio extraible micro SD
EjeX Canal0:  755
EjeY Canal1:  756
 anyo:  16  mes:  2  dia:  22  hora:  15  minuto:  23  segundo:  13
-
 Prueba de registro fecha y hora  en medio extraible micro SD
EjeX Canal0:  756
EjeY Canal1:  756
 anyo:  16  mes:  2  dia:  22  hora:  15  minuto:  23  segundo:  17
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Figure 16. Datalogging of dual-axis inclinometer measurements. Time and date are included.

7. CONCLUSIONS

An approach is presented regarding the development of an application of structural health monitoring for the infrastructure adjacent to line-A railway of the Metro de Medellín. This approach is supported in the adoption of a three-layer architecture, with a wireless sensor network at the lower level which is based on the IEEE 802.15.4-compliant MiWi protocol. This protocol can be implemented on 8-bit, cheap and easily available microcontrollers without requiring paying royalty fees for network functioning.

After some tests performed both in laboratory and field conditions, the performance of different batteries and node's gateways has been first evaluated. The 12-volt powered node tested transmitted about 1200 packets a day and can operate during several days without battery charging. Further testing must be conducted with the full system deployed over the field in order to identify additional performance features. An approximate cost estimation has been performed in order to project the overall cost of developing network nodes for this monitoring application. Installation and maintenance costs are to be estimated as the project evolves.

Although the 900 MHz radio modems first used as gateways for transmitting data from the monitored site were supposed to cover kilometer distances, field tests demonstrated major obstacles for proper functioning which were solved by adopting higher performance devices like TETRA-compliant radios. TETRA radios allowed communication in the metropolitan range with high reliability and, in addition, they make easier integrating monitoring data to Metro de Medellín SCADA system. Radio modems operating in the 900 MHz have shown proper functioning for links not having many obstacles. They will be used to monitor other infrastructure points.

The tests performed with the first set of printed circuit boards have shown that some modifications must be included in their design. Some changes will be made regarding gateway communication, battery-level energy monitoring and real-time clock and datalogging circuit stages. Additional modifications will be made to improve component placement and in order to search a better functional performance and maintenance. Automated messages with measurement data have been successfully sent and received with TETRA radios separated by several kilometers.

8. ACKNOWLEDGMENTS

We wish to thank to the Metro de Medellín Ltda. and to the University of San Buenaventura Medellín for supporting this project, code CN20150040. The engineer Valerio Quintero Arboleda of the Research and Development Department of Metro de Medellín Ltda. supported much of this work

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