

PROJECT WIRELESS SENSOR NETWORK ARCHITECTURE FOR TUNNEL MONITORING

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Abstract: This paper presents an architecture for wireless sensor networks (WSN) operating in the 2.4GHz RF band for implementation in environments of small tunnels. The study begins with an objective description of the RF architecture and with the implementation of a RSSI analysis in real scenarios. The designed modules are using directional and omnidirectional antennas for each test scenario. In initial experiment is included a test on the 433MHz band. The developed WSN architecture provides a higher degree of reliability at environments with denser structures (tunnels) and enables the use of directional and omnidirectional antennas for better signal behavior considering the structure of environment to propagation.

1 INTRODUCTION

At present, the need to preserve the environment is vital to our planet. The continual degradation of the environment has triggered terrible environmental disasters converting public places in areas of risk of disaster such as the flooding of towns, overflow in tunnels and others, representing a high risk to city inhabitants.

The technology presents itself as an important tool helping at these numerous issues that need to be answered, how to watch extensive forests [1], prevent fires [2], floods [3] landslides and avalanches. One way to prevent these disasters could be based on a continuous monitoring of nature and its phenomena through a wireless sensor networking (WSN) capturing real-time information that would serve to predict or anticipate the outcome of natural phenomena of catastrophic impact [4]. This monitoring provides a simple and instant response to any change in the environment considering parameters such as temperature, acceleration or CO₂ concentration, providing objective and constant

information to a diagnostic center [5] enabling on time decision-making to prevent significant damage and loss of human life. However, despite these statements and the numerous advantages of the architectures of RSSF, it is necessary to efficiently determine the type of architecture to be used for each environment to be monitored, considering the power consumption, robustness of the sensors hardware and suitable frequency range to operate in the most diverse and aggressive environments for monitoring [6].

In this respect, the present work aims to present a sensor-nodes architecture followed by a specific study based on received signal strength (RSSI) at 2.4GHz for application in small tunnels considering technical characteristics needed to ensure the quality and reliability of wireless communication at such environment.

This paper is organized in the following topics: initially, is presented, the justifications for this work. In Section 2, details are given of RF

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communication and the various frequency bands. In Section 3, there is an approach to communication in tunnels and its technical fundamentals. In section 4, are described the previous steps to the execution of the experiments, such as settings, hardware and test scenarios. Finally in section 5, the conclusions are presented.

2 RF COMMUNICATION

The growth of RF communication and its application in various technological fields have resulted in a rapid saturation of the communication bands, in some cases in an irregular manner, however, it is necessary to argue that even though the free frequencies do not require licenses, the devices used at these frequency bands are ruled by laws and regulations that vary from country to country. The regulations specify aspects of radio such as the allowed spectrum and power for RF systems which falls in the technical specifications of the equipment.

2.1 Overcrowding at the free bands

The exponential growth of electronic devices with wireless communication has resulted in a great diversity of its use and as a consequence the congestion of most bands of free use, grouped as follows:

a) **Frequency band 433MHz**; free Band in Europe and several other countries as a result it presents the problem of band congestion to be considered. This is considered a narrowband [7] and is not designed to have interference resistance to adjacent or coexistent channel. The use of this frequency is subject to a special regulation [8] where the equipment using this frequency must follow certain requirements with the main objective of reducing its congestion.

b) **Frequency band 868MHz**; its use is more restricted or the same as the standard norm, as a consequence it has a lower level of interference and or congestion. The 868MHz band is divided into several sub-bands which are strictly reserved for particular functions [9].

c) **Frequency band 2.4GHz**; this band has become quite popular and the requirement is that all devices using it should consider coexistence in its construction; it must have the ability to function in the presence of other devices operating in the same frequency. The 2.4GHz band, due to the features mentioned above, is much more congested than any

other free frequency band which has caused the performance, quality and reliability of the transmissions to be questioned.

The free use of this frequency eventually ended up demanding the application of some technical specifications to reduce its congestion and its problems of interference, in general, the devices manufactured to operate in this band should meet the regulation [7] considering additional features such as Signal Filtering and Frequency Hopping (FHSS).

2.2 RF Regulation

The operation of the RF communications and electromagnetic compatibility are a new, modern and technical field that has experienced rapid growth in the Brazilian telecommunications scenarios well as internationally possibly as a result of the high complexity of the electronics telecommunication designs in which electromagnetic compatibility (CEM) is present.

The standard EN 301 783 corresponds to the European standard while approved in Brazil, which standardizes the use of frequency bands amateur radio bands from 420MHz up to 440MHz and 2.3GHz to 2.4GHz. RF devices used within this band must meet the technical requirements described in this standard [7].

3 COMMUNICATION IN TUNNELS OF SMALL AND LARGE SIZE

The design and choice of RF hardware for specific applications should always follow a meticulous study of the characteristics of the environment as well as of the objectives of the application becoming quite often a difficult task because of fact that the propagation phenomena adopt distinct characteristics in each environment.

This paper considers the architecture for wireless sensor, firmware and analysis of RSSI, a clarification of the technical details a RF communication in tunnels to small or large size.

The communications in small and large tunnels features peculiar characteristics and behavior. To model the path loss is not a trivial task, being necessary to consider for this work some of the mechanisms that regulate the propagation of radio signal, which can be grouped into three categories: reflection, diffraction and scattering. The first occurs when the electromagnetic wave reaches the surface

of an object with dimensions much larger than the wavelength. The second occurs when there is an object with sharp edges between the transmitter and receiver. And finally the third occurs due to multiple objects of small size between transmitter and receiver.

Some of the basic models for "path loss" follow:

a) **Free Space model:** used to predict the propagation of radio signal when the path loss between the transmitter and receiver is free and unobstructed (1).

$$Pr(d) = \frac{PtGtGr\gamma^2}{L d^2(4\pi)^2} \quad (1)$$

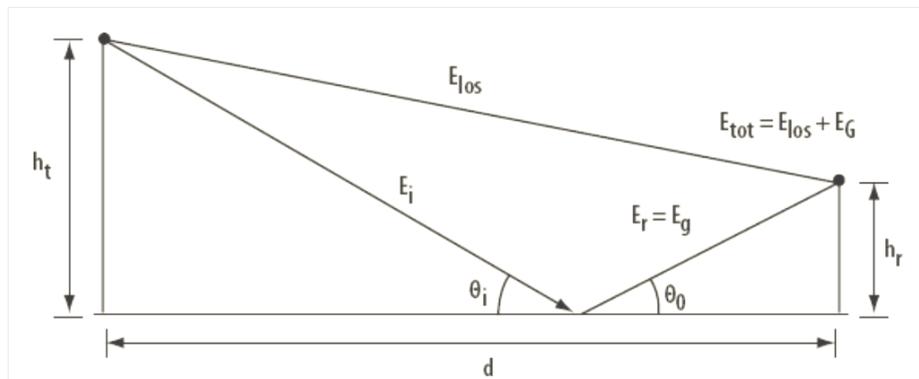


Figure 1: Representation model of 2 rays

In the testing scenario is referenced model (Figure 1) where the received power distribution is given as a function of distance by the following formula (2):

$$Pr = PtGtGr \frac{ht^2hr^2}{d^4} \quad (2)$$

where ht is the height of the transmitter antenna and hr the height of the receiver antenna. If the distance between the transmitter and the receiver is relatively large ($d \gg \sqrt{ht hr}$), the characteristics of the radio modules are abstracted by the following simplified formula (3):

$$Pr(d) = Ct \frac{pt}{d^4} \quad (3)$$

Where Ct (t for "two-ray") is a constant and depends on the characteristic of the radio.

c) **Estimation of losses in indoor environments:** Indoors propagation, such as in tunnels, large or small are much more complex than in the open because of an increased number of obstacles which commonly have dimensions that are closer to the length of the propagated signal

Being $Pr(d)$ the power of signal received by receiver placed at a d distance from the transmitter, Gt is the gain of the transmitter, Gr is the receiver gain, L is loss factor of the system not related to propagation, and the wavelength in meters. This model illustrates the case where there is only the direct path between the transmitter and receiver, as a result ends up being in most cases, inaccurate.

b) **Radius Model:** It is a more accurate model for which considers the direct and the reflected path in the floor space between the transmitter and receiver [10]. (Fig. 1).

wave and at the same time the presence of walls and floors having various features combined to be consider in the complexity of the calculations in each of the propagated test signal. This work considered not only the average loss calculus, but also a description of various attenuation components which combined impact on the propagated waves and on the power level (4).

$$Ltotal = 20 \log(f) + N \log(d) + Lf(n) - 28dB \quad (4)$$

Where N is the rate of power decay, f the frequency in MHz, $Ltotal$ The value of total losses, (d) distance in meters ($d > 1$ m), $Lf(n)$ is the loss factor due to ground penetration and (n) is the number of floors between transmitter and receiver. For a zero value of Lf the transmitter and receiver are considered on the same level. And for $N = 20$, this model is identical to a free space model for outdoor environments. Indoors studies requires $N = 18$ for a path with losses between transmitter and receiver (an exponent of "path loss" equal to 1.8). Propagation

around corners and walls require $N = 40$. In the case of long distances, the reflected paths can interfere again and result in $N = 40$.

3.1. Tunnels of small Dimensions (radius <2.5m)

The propagation of electromagnetic waves in small underground tunnels have been being modeled as a large and imperfect waveguide, whereas basically a waveguide is a structure with conductive walls that support transverse electric waves (TE) and transverse magnetic (TM). These waves create electric and magnetic fields perpendicular to the direction of propagation. The reinforced concrete of the tunnel, however, does not maintain the theory that the walls behave as nearly as perfect conductors, in practice, the wall acts more like an insulation than as conductor.

At the characterizing of the propagation scenario of a tunnel, it is necessary to consider that the dominant mode of the waveguide will have the lower cutoff frequency [11]. When no energy is propagated throughout the system a standing wave exists below this cutoff frequency. For a circular waveguide, the cutoff wavelength is the diameter multiplied by 1.71 for the dominant mode TE₁₁. At tunnels used for this purpose, the inner diameter was 1.61 m. Considering primarily a circular waveguide, the cutoff frequency is approximately $(3 \times 10^8 \text{ m/s}) / (1.06\text{m} \cdot 1.71)$ or 165.5 MHz, expanding to the exterior concrete and assuming a dielectric constant of value 6, the tunnel frequency cut-off is reduced by a factor of 16 to 67.5 MHz. Using the waveguide model is expected that losses follow the propagation model of a hybrid tunnel, increasing losses with increasing distance between the transmitter and receptor.

3.2. Tunnels to Large Dimensions (radius > 2.5m).

The propagation characteristics described for small tunnels are not different for large tunnels [12] where to determine which type of RF architecture to implement a RSSF is necessary to know the

behavior for each type of frequency within the tunnel.

4 EXPERIMENTS

4.1. Initial Considerations

It is increasingly common to need to conduct experiments in real scenarios in order to be able to capture the phenomena and errors that occur in the iteration of the wireless transmitter hardware (RF) and the propagation scenario.

In this paper two real scenarios have been used for the experiments yielding great accurate results that can serve as aid in future implementations of wireless communication systems in restricted environments such as small tunnels.

a) **Hardware RF:** The prototypes built for the experiments in real scenarios base on the use of Receiver / Transmitter FM-TRX2-24G modules of Quasar-UK. [13], it contains a CC2500 RF chip from Texas Instruments which is an RF module for low power consumption [14], consistent with other RF transmitters operating on the ZigBee stack using the same frequency band. The baud rate used oscillates between 1.2 and 500 Kbps according to the type of modulation used. The transmitter operates between 2.4 - 2.483 GHz with a sensibility on receptor of up to -104 dBm. (Fig. 2) (Fig. 3).

It should be noted that the choice of the Transceiver modules was not solely based on economic factors, but also in technical characteristics which should be considered indoors with very dense structures (reinforced concrete). These specifications should consider the phenomena in signal propagation communication offered by the environment, a relevant feature was to considered the FHSS (Frequency Hopping Spread Spectrum) that not only makes the signal more resistant to interference, but also enables the sharing of bandwidth with many other types of conventional transmitters with minimum interference, which is an essential feature in the 2.4GHz band due to factors of signal sensitivity and high congestion.



Figure 2: Developed prototypes 2.4GHz



Figure 3: Prototypes - Omnidirectional antenna

In addition in the A scenario (described in section 4.2) a hardware operating at the frequency of 433MHz, the hardware produced by Miteos Company is composed of a radio chip from Texas C1150 [15], and a 8-bit and 2 kb of programmable

flash memory microcontroller Atmel ATtiny2313 / V [16]. The base station is composed of processor ATmega 1280v [17] with 4 kb of EEPROM. The radio base station chip is also a C1150 Texas Instruments (Fig 4)(Fig. 5).

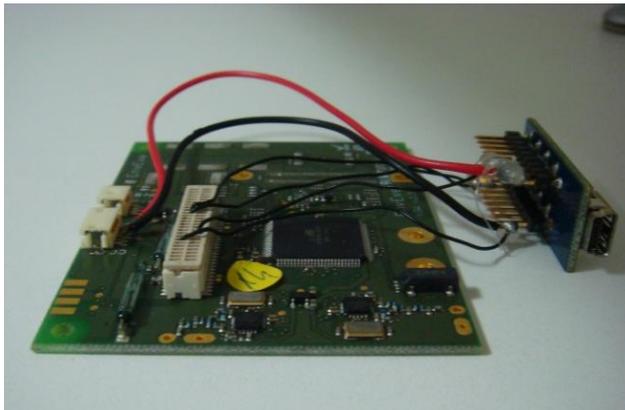


Figure 4: Station Base Device - 433Mhz

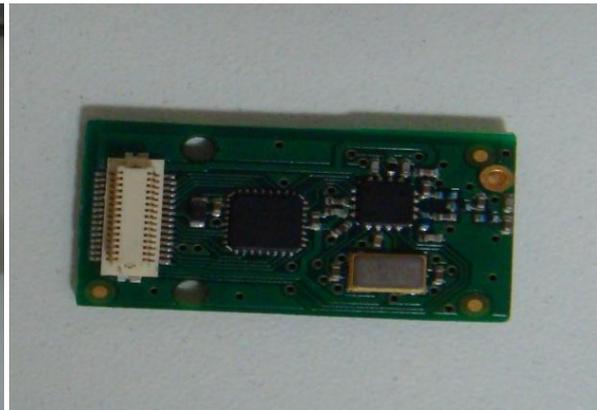


Figure 5: Device Sensor 433Mhz

b) **Vivaldi Antenna:** This antenna belongs to the family of aperiodic radiators, continuously scaled by an exponential curve. One can say that in theory a Vivaldi antenna has a characteristic semi-uniform irradiation over an ultra-wide frequency range [18][19][20][21]. Based on these characteristics, it was decided to choose the Vivaldi antenna, which can be defined as a small planar antenna consisting of a microstrip line transition (*Micro Transition Line - MTL*) and a radiator in exponential opening (*Exponential Line Slot Radiator*

- *ESLR*) respectively detailed in the following sections:

- **Microstrip transition line:** We can define the MTL as a impedance transition line constituted by a separate tape conductor, electrically isolated from a conducting surface (ground plane) by means of a structural substrate as illustrated in Figure 7. This substrate usually has a high dielectric constant ($\epsilon > 2$) and separates the ground plane from the conductor tape, both consisting of thin-copper-film [21]. (Fig 6).

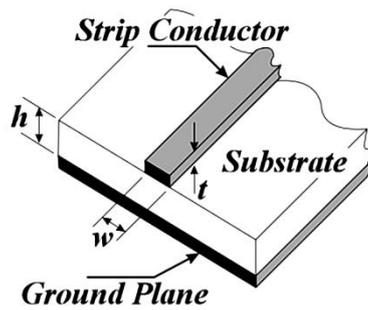


Figure 6: Microstrip Transition Line where h and t are the substrate and strip conductor thickness respectively, and w is the strip conductor width [21].

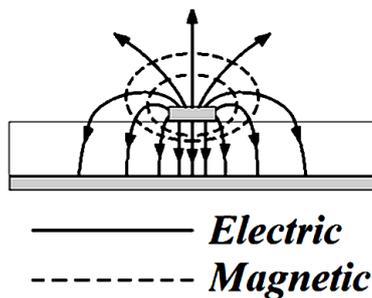


Figure 7: Illustration of the analysis of cross-sectional view of an MTL with detail propagating quasi-TEM [21]

In a structure of the type microstrip line can be seen that the field lines are not contained entirely inside the substrate (Fig. 7), as would happen in a waveguide, so that the mode of propagation on the microstrip line is not purely transverse electromagnetic (TEM), thus defines the propagation as quasi-TEM [21].

According to studies conducted by [21], if the relation between w/h is greater than 1, the characteristic impedance (Z_0) and the effective dielectric constant (ϵ_{eff}) of a microstrip transmission line can be calculated by:

$$Z_0 = \frac{120 \pi / \sqrt{\epsilon_{eff}}}{w/h + 1.393 + 0.667 \ln(w/h + 1.444)} \quad (5)$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 h/w\right)^{-1/2} \quad (6)$$

• **Irradiation in opening exponential;** After performed the calculations and studies to ensure the best impedance matching between the circuit, connectors, cables and MTL, the goal was to design the best radiator between the MTL and the

propagation medium (air) in a manner in which is possible to ensure a naturally smooth transition of the signal throughout the RF link. Thus it was considered using a radiator with exponential opening, which is able to ensure an impedance bandwidth relatively large [20][21][22].

Figure 8 illustrates the exponential aperture and its respective function registered in the (x, y) as well as the start and end points of the curve for the design of this opening that forms the proposed electromagnetic radiator.

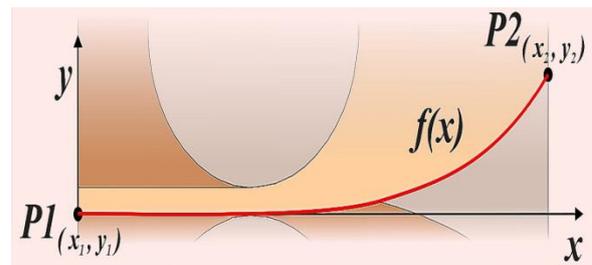


Figure 8: Detail of the exponential curve of Vivaldi Antenna [DE OLIVEIRA ,2012].

The curve of opening exponential radiator of the Vivaldi antenna can be obtained according to [20], using an exponential function given by equations (7), (8) and (9), having as its start and end points $P1_{(x1,y1)}$ e $P2_{(x2,y2)}$.

$$f(x) = c_1 e^{Rx} + c_2 \quad (7)$$

where

$$c_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}} \quad (8)$$

and

$$c_2 = \frac{y_2 e^{Rx_2} - y_1 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \quad (9)$$

c) **Firmware:** The work and experiment are not limited solely to the development of a prototype for testing, but also the development of an embedded microcontroller firmware for the wireless modules. The firmware in question was developed entirely in C language with a total of 50 pages of code, and can be considered the brain of the modules (prototypes). It should be noted that the flexibility of firmware code allows modifying settings like: Transmission frequency (2.4Ghz - 2.43Ghz), output power (T_x) throughput bit, parameters that must change in each application environment. The code segment responsible for setting up some of the mentioned parameters is shown in figure 9.

```

typedef struct wi_utx_cc_setup_s {
    uint8_t address;
    uint8_t value;
} wi_utx_cc_setup_t;

volatile uint8_t wi_utx_cc_field_fifo_rx[4]; /* Received field message */
volatile uint8_t packet_received = 0;

#define WI_UTX_CC_SETUP_VALUES 32 /* How many values we have to set */
static const wi_utx_cc_setup_t
wi_utx_cc_setup_values[WI_UTX_CC_SETUP_VALUES] = {
    /* RF output power */
    { WI_UTX_CC_PATABLE, 0xFB },
    /* RF frequency */
    { WI_UTX_CC_FREQ2, 0x5D }, /*set the frequency at 2438MHz*/
    { WI_UTX_CC_FREQ1, 0x93 }, /**/
    { WI_UTX_CC_FREQ0, 0xB1 },
    /* Data rate */
    { WI_UTX_CC_MDMCFG4, 0x2D },
    { WI_UTX_CC_MDMCFG3, 0x3B },
    { WI_UTX_CC_MDMCFG2, 0x73 },
    { WI_UTX_CC_MDMCFG1, 0x22 },
    { WI_UTX_CC_MDMCFG0, 0xF8 },
    { WI_UTX_CC_CHANNR, 0x00 },
    { WI_UTX_CC_DEVIATN, 0x01 },
    { WI_UTX_CC_FREND0, 0x10 },
    { WI_UTX_CC_FREND1, 0xB6 },
    { WI_UTX_CC_MCSMD, 0x18 },
    { WI_UTX_CC_FOCCFG, 0x1D },
    { WI_UTX_CC_BSCFG, 0x1C },
    { WI_UTX_CC_AGCCTRL2, 0xC7 }, /* c7 */
    { WI_UTX_CC_AGCCTRL1, 0x00 },
    { WI_UTX_CC_AGCCTRL0, 0xB0 },
    { WI_UTX_CC_FSCAL3, 0xEA },
    { WI_UTX_CC_FSCAL2, 0x0A },
    { WI_UTX_CC_FSCAL1, 0x00 },
    { WI_UTX_CC_FSCAL0, 0x11 },
    /* Frequency synthesizer calibration control */
    { WI_UTX_CC_FSTEST, 0x59 },
    /* Set packet length */
    { WI_UTX_CC_PKTLEN, 0x04 },
    /* Various test settings */
    { WI_UTX_CC_TEST2, 0x88 },
    { WI_UTX_CC_TEST1, 0x31 },
    { WI_UTX_CC_TEST0, 0x0B },

```

Figure 9: Firmware code segment for setting communication parameters.

4.2. Configurations

The experimental network (Figure 10) consists of two RF modules (transmitter / receiver) with the characteristics described above, and a programmable gateway with a sensitivity of -101 dBm, transmission rate of up to 250 kbps connected to a base station (Used for collecting and filtering data).

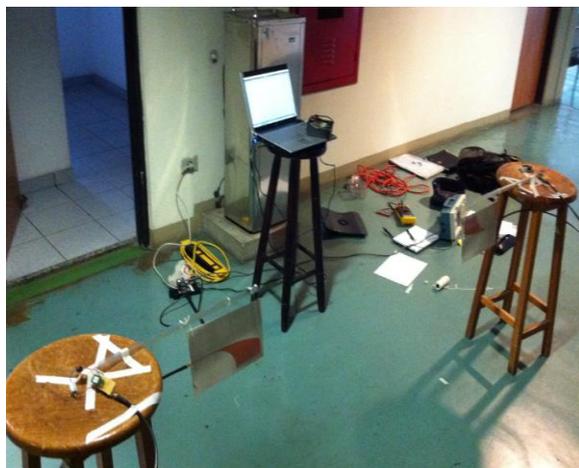


Figure 10: Distribution of modules in scenario B - Vivaldi Antennas

In each of the network modules (transmitter - Gateway) is used a micro-controller unit to command the RF module embedded. The microcontroller used is ATTINY26 [23] which has

characteristics of high performance, low power consumption, advanced RISC architecture, programmable EPROM 128 \ 256 \ 512 Bytes, among other technical features that maximize the performance of the prototypes developed for this work. Additionally is used a module AVR RISP kII [24] for programming the microcontrollers ATTINY26.

4.3. Scenario of Experiments and Results

The scenario - A, corresponds to an area of approximately 100m² belonging to the company Miteos-Italy in a narrow corridor to simulate the conditions of a tunnel, the performed tests corresponds to RSSI values for modules over 2.4Ghz in conditions with obstacles. The distance between the transmitter and receiver module is 15m, for this test is included an antenna RUBBR DUCK (omnidirectional) [25] coupled to the transmitter and at the receiver an antenna PCB 2.4 Ghz. The test was carried out to check the efficacy of the antenna coupled to the circuit (the nominal gain was equal to the actual gain), the measures being made with all the same parameters, just adding to the antenna to the circuit (Fig. 11).

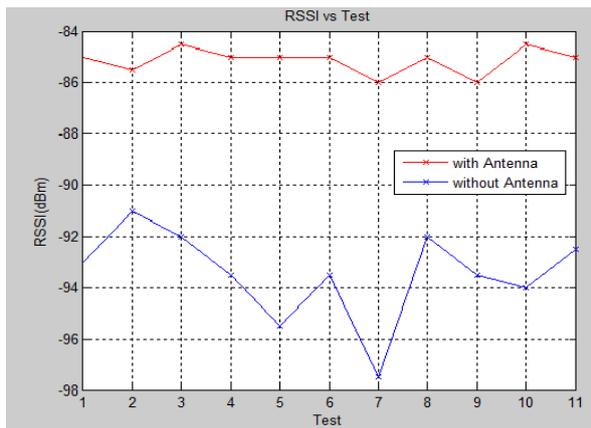


Figure 11: Graphic - RSSI signal with antenna and without antenna. 2.4GHz

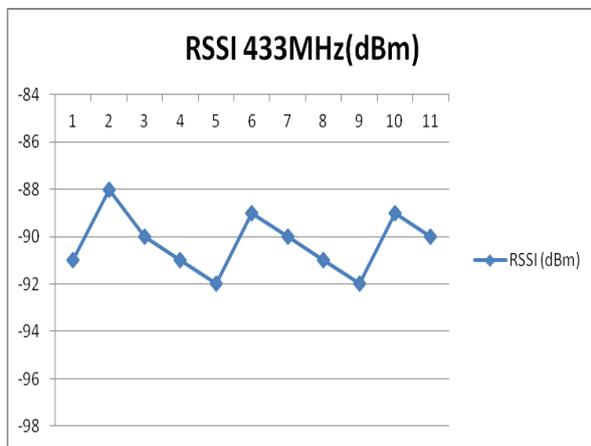


Figure 12: Graphic - RSSI signal, Frequency of 433MHz.

The test verified the proper functioning of the circuit and coupling of the antenna, since the real gain is equal to the nominal. It is also proved that the RSSI signal power at 2.4GHz (Figure 11) was greater than the transmission at 433MHz (Fig. 12) under the same conditions. This result proves the premise of this study, in which the transmission made at higher frequencies have better efficiency when the mediums of transmission are small tunnels or places with the same geometrical conditions.

The scenario – *B*, corresponds to an area of 100m², comprising one of the corridors of the building of the electrical engineering department from the Polytechnic School of the University of São Paulo - Brazil, the modules are distributed randomly with a separation distance of 10m between the modules and

concentrator (gateway) and with a distance of 1m from the ground. For this test was used the Antipodal Vivaldi UWB antenna (Fig.13) developed by the group PAD in the Laboratory of Integrated Systems of the Polytechnic School - USP.

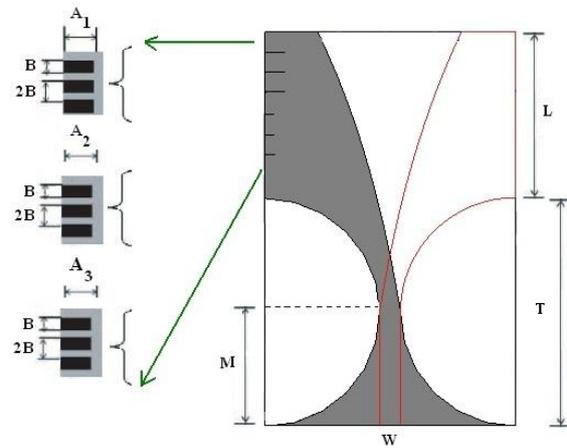


Figure 13: Geometry proposed of antipodal Vivaldi antenna – Frequency 2.4Ghz

In figure 13, *B* = Width of opening, *L* = Width of the irradiation plan, *W* = Width of the transmission line or microstri, *M* = Length of Transmission microstrip and *T* = Major axis of the ellipse.

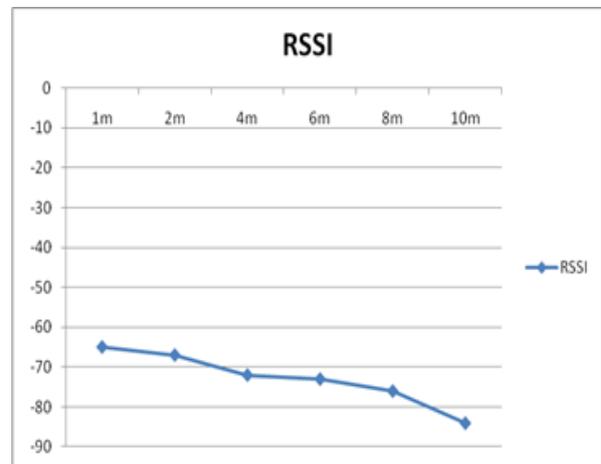


Figure 14: Graphic - RSSI signal with directional Vivaldi antennas and without obstacles

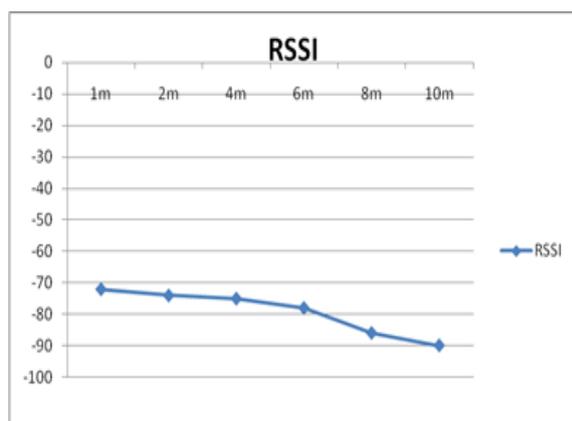


Figure 15: Graphic - RSSI signal with directional Vivaldi antennas and with obstacles

The results of the tests (Figures 14 and 15) verifies a considerable variation of the received power when obstructions are introduced between the receiver and transmitter. At the same time it was demonstrated the possibility of hardware circuit to be optimized so that the losses are reduced, higher gains and a longer range to be obtained being able to reach a power of -110dB at a distance of approximately 80m.

5. CONCLUSIONS

This article began with a study on characteristics of the transmission utilizing frequency bands free for use in Europe: 433MHz and 2.4GHz. The study aimed to identify the frequency to bring better results in transmissions in small tunnels to develop a product with the best results. After studies and initial tests it was decided for the frequency of 2.4GHz, which was more appropriate for this medium in a way in which it behaves as a waveguide within the structure of the test scenarios. After selecting module the firmware was developed. The experiments indicated successful transmission at 2.4 GHz, and the at the tests within the company Miteos-Italy, a higher power received in the case of 433MHz, confirming the initial hypothesis of the study.

2.4 Ghz tests proved very effective considering the RSSI value obtained for scenarios that use omnidirectional antenna (DUCK RUBBR) and directional (Vivaldi) for the second type of antenna as there is great need for communication over-sight throughout the longitudinal path of the tunnel, the Vivaldi antenna was chosen, since it has the favorable characteristics for the link-sight application applied at communications in tunnels,

namely: simple geometry (a plate of composite insulator with the faces covered with conductive film), low weight, high bandwidth, high efficiency, small size and high gain [20][26] and showed favorable results in scenarios with and without obstacles, leaving open the possibility to tailor-off the Firmware developed to ZigBee modules for this type of directional antennas.

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