International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:4, No:3, 2010

RF Link Budget Analysis at 915 MHz band for Wireless Sensor Networks

Abdellah Chehri, *Member, IEEE,* Hussein Mouftah, *Fellow, IEEE,* Paul Fortier, *Senior, IEEE,* and Hasnaa, Aniss, *Member, IEEE*

Abstract—Wireless sensor network has recently emerged as enablers of several areas. Real applications of WSN are being explored and some of them are yet to come. While the potential of sensor networks has been only beginning to be realized, several challenges still remain. One of them is the experimental evaluation of WSN. Therefore, deploying and operating a testbed to study the real behavior of WSN become more and more important. The main contribution of this work is to analysis the RF link budget behavior of wireless sensor networks in underground mine gallery.

Keywords—Sensor networks, RF Link, path loss.

I. INTRODUCTION

WIRELESS sensor network (WSN) consists of a large number of low-size, low-complex and locally powered sensor nodes that detect events and communicate wirelessly via multi-hop routing [1]. WSNs are continuing to receive an increasing research interest, largely due to the wide range of suitable applications, including environmental [2], precision agriculture [3], health monitoring [4], and smart building [5].

However, most of these researches have only been evaluated in simulations and under many unrealistic assumptions, such as a perfect communication, spherical radio range, an unlimited memory and processing resources, etc. One of the tough challenges facing the WSN applications now is translating theoretical investigations into deployable ones.

Wireless Sensor Networks have not yet reached the required state of maturity to make them practical for a large number of applications. There is still much research going on in the areas of channel modeling, the physical layer, and energy efficient routing protocols. Hence there is need for research facilities to support experimentation.

Test beds are vital tools to fill this need as they support the development of communication networks by replicating elements of the communication environment, replicating or simulating real-life processes, and providing the researcher with tools that support programming, data analysis, and evaluation of various variables [6],[7].

The motivation of our work has been the design of a protocol for an optimal deployment of wireless sensor network. We concentrate on stationary networks, i.e., where the nodes are not mobile. In the course of designing and implementing a low-power sensor network prototype, we have been able to isolate key questions in testbed protocol design.

The scope of this paper is limited to one of the most basic of those questions: How to measure and characterize wireless link quality. We have conducted experiments on our prototype to obtain insights to answer this question.

In this paper, we discuss the challenges and requirements of developing efficient WSN in mining industry. For this reason, we introduce a prototype WSN testbed, which has been developed for performance evaluation of WSN in harsh environments such as underground tunnel. The experimental setup was designed for continuous monitoring of a wireless link between a transmitter and receiver for a long time with respect to channel variation.

The remainder of this paper is organized as follows. Section II contains the related work. Section III defines the proposed architecture, we describes also the node hardware and software used in this work. Section IV deals with the measurements setup and the methodology. In Section V, we describe experimental data collected from the sensor node and make some general conclusion about radio link behavior. Finally, we will conclude with Section VI.

II. RELATED WORK

The impact of radio link on network performance can be investigated through a real measurement. Many researchers have been pursued this direction [8] - [20].

For example, Zhao and Govindan provide one of the first works that offered experimental measurements that shows that a wireless link is unreliable but they do not give any explanation of its findings [9].

Srinivasan et al., discuss the indoors and outdoors evaluation of 802.15.4 radio for static sensing platforms through a characterization of the RSSI (received signal strength indicator) and LQI (link quality indicator) for different distances [10], [11]. In [12], [13], the authors state that the antenna orientation greatly impacts the RSSI and the incidence of the asymmetric links.

In [14], the authors show that multipath fading is another important cause of indoor performance degradation. In [15], the authors present a detailed study of communication limitations for static sensor networks including findings associated with grey areas and link asymmetry.

In [16], the authors discuss the radio irregularities in wireless sensor networks and show that the battery level of a node impacts the signal strength at the receiver.

M. Chehri and H. Mouftah are with the School of Information Technology and Engineering(SITE), University of Ottawa, 800 King Edward Avenue, Ontario, K1N 6N5, Canada, e-mail: achehri@uottawa.ca.

P. Fortier is Department of Electrical and Computer Engineering, Université Laval, Québec (Québec), G1V 0A6, Canada.

H. Aniss was with LRCS laboratory Télébec in underground communications of Québec University in Abitibi-Temiscamingue (LRTCS-UQAT), 450, 3e Avenue, Local 103, Val-d'Or (Québec), J9P 1S2, Canada.

In [17], it is reported that the radio irregularity has a big influence on the routing protocols and they propose the Radio Irregularity Model that takes into account the non-isotropic properties of the antenna and the heterogeneous properties of node hardware.

In [18], the authors show an empirical results of extensive link layer measurements with the eyes nodes but they do not provide any channel model.

Petrova et al., analyzed the impact of 802.11 on the Zigbee radio [19]. The impact of the human body and mobility on 802.15.4 radio communication has been also studied in [20].

Lal et al. presented an experimental study of wireless link quality variation over a period of several days in a sensor network placed in two different indoor office environments [21].

III. WIRELESS SENSOR NETWORKS TESTBED

The wireless sensor network follows a two-layer hierarchy, with lower layer wireless sensor nodes, sample and collect the heterogeneous data from the sensor and the data packets are transmitted to the upper layer. The upper layer aggregates the data and forwards it to the central node kept at the deployment site.

When choosing deployment of WSN in underground mine, it should be necessary to make a compromise between conflicting requirements. In the design of WSN, the priority is to insure that the global network will be robust and also the nodes must be battery-operated, with a long autonomy. Therefore, the network was developed with the following goals in mind. Firstly, the node must be able to communicate with other notes via a highly reliable radio module compatible with the IEEE 802.15.4 standard. Secondly, the network should be robust to work for long time.

In this section, an overview on the hardware implementation and the software protocol are given. The testbed consists of the following components:

- Sensor unit;
- Sensor application software;
- Network architecture.

A. *Sensor Unit*

The sensor unit (ZMD44102 node) is a fully integrated system-on-chip CMOS transceiver providing license-free multichannel operation in the 902 MHz to 928 MHz ISM bands. This low-power RF transceiver is optimized for data rates up to 40 kbit/s and incorporates direct sequence spread spectrum technology (DSSS) to ensure reliable data transfer in hostile RF environments. The high level of integration, includes a thin Media Access Control (MAC) layer, resulting in a minimum of external components and lower application costs [22].

The sensor unit contains also an A/D converter for converting analog sensor signals into a digital format. The hardware MAC contains a 128 byte transmit FIFO (TxFIFO), a 256-byte receive FIFO (RxFIFO), the frame composition and decomposition, automatic acknowledge generation, the CRC generation and check, and a MAC controller together with several support timers. The MAC controller provides different operating modes, such as transmitting, receiving, beacon tracking.

For a radiated power of 0 dBm (corresponding to 1 mW) and with a supply voltage of 3.3 V, the transmit mode draws a current of 28 mA, corresponding to 92.4 mW, whereas in the receive mode, 27 mA current are drawn, corresponding to 89.1 mW. In the sleep mode, only 1.3 μA are drawn. A number of 10 sub-bands are available, which can be freely selected. In all bands, DSSS is used. A pseudo noise sequence of 15 chips is used for every bit. The data are Binary Phase Shift Keying (BPSK)-modulated.

A ZMD's TSic$^{\mathrm{TM}}$ temperature sensor is integrated to the sensor mote with temperature range (-40 °C to +85 °C). The transmission range is more than 250 m for LOS. Some basic data are summarized in Table I.

B. *Sensor Application Software*

During testbed a ZMD44102 kit bundle has been employed. The ZMD44102SKB enables detailed evaluation of the sensor unit using a Graphical User Interface (GUI) and provides basic communications software for application development.

In fact, the starter kit bundle comprises the SiLabs$^{\mathrm{TM}}$ development tools and debug adapter for code compilation and installation. The starter kit bundle GUI includes the configuration tool to control the nodes and establish a star network [22]. This application provides automatic display of network formation, topology changes, and router and coordinator state changes allowing rapid detection of incorrect network behavior and identification of device or network failures.

Network performances were be assessed using metrics, including LQI, RSSI, and packet success rate. LQI is a metric introduced in IEEE 802.15.4 that measures the error in the incoming modulation of successfully received packets.

C. *Network Architecture*

Wireless sensor network is used to transfer the sensor data frames from the sensor unit over a radio interface to the central node. If a radio link can be established between these modules for peer-to-peer communication, the radio modules put each sensor data frame into a radio message, send the message over the radio link, and extract the sensor data frame from the received radio message.

The network organizes itself and is self-healing, i.e. network nodes automatically establish and maintain connectivity among them.

For practical deployment, a sensor network only concerned with itself is insufficient. The network rather has to be able to interact with other information devices, for example, a miner equipped with a PDA moving will be able to read the temperature sensors even this node is located in different mine galley. To this end, the WSN first of all has to be able to exchange data with such a mobile device. This schema can be generalized to other important security parameter (carbon monoxides, or smoke concentration, for example).

TABLE I
SYSTEM PERFORMANCE SUMMARY [22]

Parameter	System Specifications
Standard Basis	IEEE Std. 802.15.4$^{\text{TM}}$
Frequency (MHz)	902-928
RF Bandwidth (KHz)	1200 kHz
Nb of channel	10
RF Channel Spacing	2 MHz
Data Rate Burst	40 kbit/s
Modulation Type	Binary Phase Shift Keying (BPSK)
Spreading Technique	Direct Sequence Spread Spectrum (DSSS)
PN Code	15-chip m-sequence
Tx Output Power	0 dBm (to 50 Ω)
Rx Sensitivity	-98 dBm
Typical Supply Current (Tx)	28 mA
Typical Supply Current (Rx normal, frame reception)	27 mA
Typical Supply Current (Off Mode)	1.3 μA
Transmit range	$\leq$ 250m (0 dBm, LoS)

Therefore, for the proposed WSN monitoring system, the performance and interoperability of sensor network with various network such as 802.11g (WiFi) and IEEE 802.11s (wireless mesh network) have been evaluated. In this schema, the nodes communicate with the central node, which is connected with a laptop on site. This last one has the capability of communicating wirelessly with other computers located in a monitoring room via IEEE 802.11 networks (or wireless mesh network). The number of access points of both WiFi and wireless mesh network are sufficient to ensure a total coverage of mine gallery.

The system is connected to Internet through a gateway. Gateways play the role of communication between WSNs and Internet access. A single board computer with public IP address as gateway in a WSN has been used. So the ambient temperature of a mine gallery can be measured and displayed in real time no matter where we are. The global schema of WSN mine gallery temperature monitoring is shown in Figure 1.

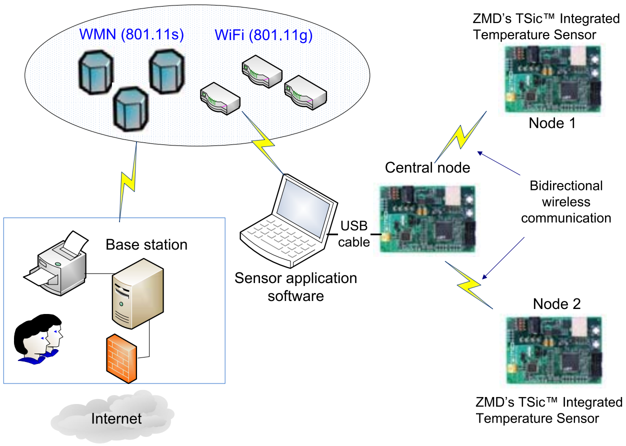

Fig. 1. *Block diagram of the wireless network's deployment.*

IV. MEASUREMENT SETUP AND METHODOLOGY

It is well known that designing an optimal topology in wireless sensor network requires the use of a cost metric based on wireless link quality. to be used precludes on-the-fly calculation of an accurate link quality estimate. However, there is an increasing interest in evaluating and measuring the actual link behavior and its effect and influence for WSN.

The measurements were carried out in an underground gallery of the MMSL-CANMET[1] laboratory mine located 540 km north of Montreal, QC, Canada [23]. The measurements have been performed at the 70 m level. Figure 2 show an example the node placement in the mine gallery for LOS (line-of-sight).

In this measurement campaign, the transmitting node remained at a fixed position whereas the receiver node was moved at different distances going from 1m up to 105 m (for LOS) and from 5 m to 77 m (NLOS) with a one meter step between two measurements. For each point, three measurements (center, left and right) have been taken. The received node was fixed at one meter above the ground, while the transmitted node was placed two meters above the ground. The radio transmission power is programmed at 0 dBm (1 mW).

Fig. 2. *Gallery mine (CANMET).*

---

[1] Canadian Center for Minerals and Energy Technology (CANMET) experimental mine

V. RESULTS AND DISCUSSIONS

In this section, we discuss the methodology we follow for experimentation and the results derived from the measurements.

A. Propagation Loss

The use of radio in underground mines has been frustrated due to relatively complex propagation characteristics associated with mine tunnels [24]. Researchers have modeled the underground tunnel as an imperfect waveguide whose walls partially absorb and partially reflect incident electromagnetic radiation. Propagation, therefore, is a function of both the tunnel dimensions and the surrounding material comprising the tunnel floor, ribs, and roof.

Measurements of radio propagation characteristics along straight tunnels correlates to what one would expect of such as waveguide. Attenuation expressed in dB, varies linearly with distance and exhibits large losses around corners, bends, or any deviation from a straight path. Surface irregularities of the walls also contribute to path loss [25].

Figure 3.(a) plots the average received signal strength versus the distance recorded follow the gallery long. The received power is measured at uniform distance step from the node emitter following a route located at the gallery center, a route following the right lateral wall and the route following left lateral wall of the gallery. For each point, the averaged value of this three reference points have been taken.

One can observe two regions of path loss. In the first region (1 to 36 m), signal attenuation is about 28 dB between 1 m and 36 m. However, the second region (from 37 m to 105 m) is characterized by small signal attenuation.

This small attenuation is due to the topology of the gallery. In fact, this region of the gallery is represented as a narrow corridor in which the multipath adds; therefore the signal can travel a long distance with a small attenuation. This is known as the *"waveguide propagation phenomenon"*.

From figure 3, we can show that the path loss referenced to a distance d_0 can be modeled as a function of distance with two different slopes (before and after a breakpoint d_p) using:

$$Pl(d) = \begin{cases} Pl_{0,1} + 10n_1 \log_{10}\left(\frac{d}{d_0}\right) + S_1(d), \ d \leq d_p \\ Pl_{0,2} + 10n_2 \log_{10}\left(\frac{d}{d_0}\right) + S_2(d), \ d > d_p \end{cases} \quad (1)$$

where d_0 is the reference distance, in our case d_0 = 1 m for LOS (d_0 = 5 m, for NLOS) and Pl_0 is the interception point, n is referred to as the path loss exponent, and S is the shadow fading parameter that varies randomly form one location to another location at the environment. It is a zero-mean Gaussian distributed random variables in dB with standard deviation σ_S.

Equation (1) was used to compute path loss for all measurements data. Using linear regression analysis, the minimum mean square error (MMSE) line is calculated for the dependence of average power (dB) on the logarithm of the distance for each measurement. The slope of the regression line gives the experimental values of n.

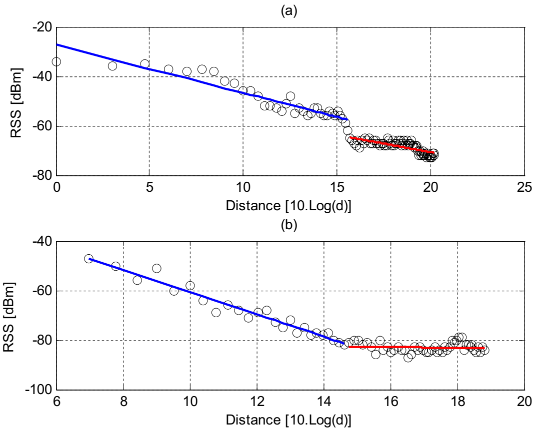

Fig. 3. *Scatter plot of average received signal vs. Tx/Rx separation distance, (a) LOS, (b) NLOS.*

TABLE II
LARGE SCALE CHANNEL PARAMETERS.

Scenario	n_1	n_2	$Pl_{0,1}$	$Pl_{0,2}$	σ_{S1}	σ_{S2}	d_p
LOS	1.94	1.38	-27.28	-42.90	1.99	1.59	36
NLOS	4.49	0.11	-15.76	-81.10	1.86	1.66	29

B. Shadow Fading Statistics

The shadow fading statistics deals with the remaining variation after removal of the signal-level distance dependence depicted by the best fit line from a mean signal. This is useful in estimating the coverage and cochannel interference. It is found that the shadow fading in many other radio propagation environments follows the log-normal distribution.

Analysis of our measurements shows that they basically follow the log-normal distribution. This can be seen from Figure 4; the solid and dot curves represent the normal and experimental distributions with the zero mean and standard deviation of 1.99 dB (region 1) and 1.59 dB (region 2) for LOS scenario; while these values for NLOS scenario are 1.86 dB for region 1 and 1.66 dB for region 2.

The obtained large scale parameters are given in Table (II).

C. Signal Quality

In wireless communication systems, small-scale fading describes the fluctuation due to constructive and destructive interference of the multipath components at the receiver when sub-wavelength changes are made in the receiver position. Such a definition can be extended to the received signal strength as the constructive and destructive interferences of the multipath components at the receiver node due to a change in its position.

In order to quantify the effect of the variations of the received signal let us consider signal quality defined by:

$$Q_{i,j} = E_{i,j} - E_0 \quad (2)$$

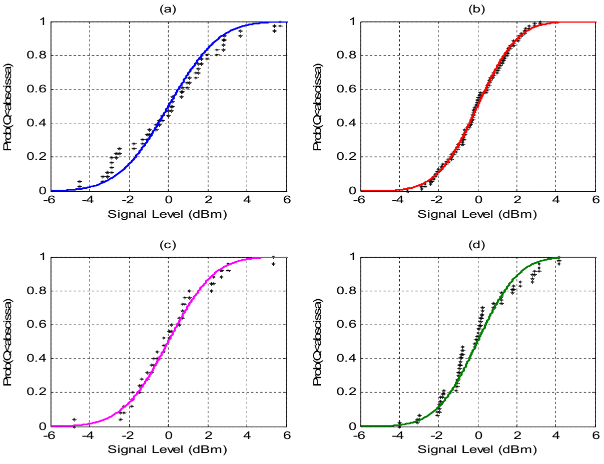

Fig. 4. *Cumulative distribution of signal levels of shadow fading variations, (a) LOS (region 1), (b) LOS (region 2), (c) NLOS (region 1), (d) NLOS (region 2).*

where E_0 is the average of the received signal strength at a fixed distance, and $E_{i,j}$ is the measured received signal strength over the grid (7×10 rectangular grid with 9 cm spacing).

The distance between the transmitter node and the receiver node was fixed at 40 m. The measurement results are illustrated in Figure 5.

One can observe in Figure 5 that the maximal variations of the received signal at different points on the grid are 13 dBm for LOS and 19 dBm for NLOS. These huge signal variations are due to the specific characteristic of the environment. This can be explained by multipath destructive or constructive combinations of the signal at different positions on the grid.

We can conclude that for a specific location and for fixed Rx/Tx separations, the topology of the gallery has a significant impact on the received signal strength.

These results indicate that the RF link budget should include a safety margin of several dBs to ensure reliable communications in an underground mine environment.

D. Signal Fluctuations vs. Time

The remaining experiments were performed with stationary nodes. Still, the RSSI values have a tendency to fluctuate. Figure 6 shows the RSSI values during a typical 120 seconds experiment. This variation can be explained by the radio transceiver of the motes.

We can also observe that the variations in the NLOS case are more important than what is observed in the LOS case.

VI. CONCLUSION

In this paper, an experimental deployment of a WSN in underground mine gallery has been described. The results of RF link budget analysis at 915 MHz band for wireless sensor networks over real measurements campaigns have been presented. From these experimentations, we have seen that the received signal strength is largely random; two slopes lognormal path-loss channel model is observed. This model is useful for future simulations because it's more realistic than the spherical radio patterns. The objective is to obtain more accurate channel models to feed realistic simulation and for future optimal deployment of sensor nodes in underground mines.

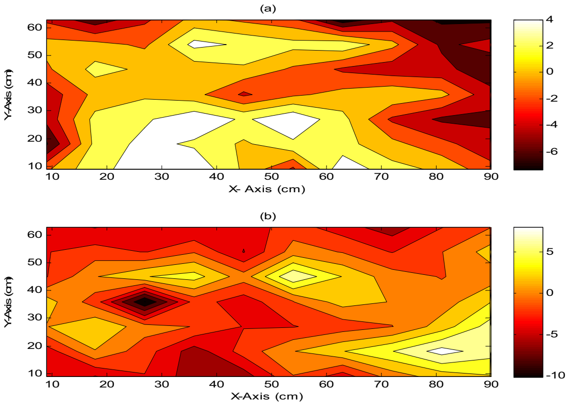

Fig. 5. *The received signal at a node for fixed distance and over 70 spatial sample points, (a) LOS, (b) NLOS case.*

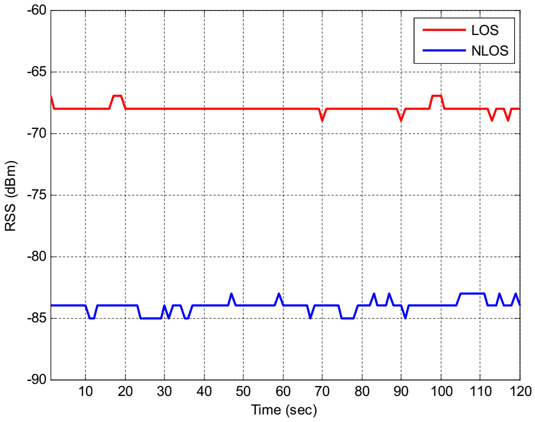

Fig. 6. *Signal fluctuations vs. time.*

ACKNOWLEDGMENT

This work was done with support of Université du Québec en Abitibi Témiscamingue (UQAT). The author would like to acknowledge the continuing guidance of LRCS laboratory. The authors also wish to thank the personnel of MMSL-CANMET (Mining and Mineral Sciences Laboratories - Canadian Center for Minerals and Energy Technology) experimental mine. The authors would like to thank the anonymous reviewers for their helpful comments which have significantly improved the quality of the paper.

REFERENCES

[1] F. L. Lewis, "Wireless sensor networks", In D. J. Cook and S. K. Das, Editors, Smart Environments: Technologies, Protocols, and Applications, New York, 2004. John Wiley.

[2] L. Kejie, Q. Yi, D. Rodriguez, W. Rivera, M. Rodriguez, “Wireless Sensor Networks for Environmental Monitoring Applications: A Design Framework”, IEEE Global Telecommunications Conference, pp. 1108 - 1112, 27 - 30 novembre 2007.

[3] D. Anurag, S. Roy, S. Bandyopadhyay, “Agro-sense: Precision agriculture using sensor-based wireless mesh networks”, First ITU-T Kaleidoscope Academic Conference, pp. 383 - 388, 12 - 13 may 2008.

[4] S. Bapat, W. Leal, K. Taewoo, W. Pihui, A. Arora, “Chowkidar: A Health Monitor for Wireless Sensor Network Testbeds”, 3^{rd} International Conference on Testbeds and Research Infrastructure for the Development of Networks and Communities, 21 - 23 may 2007.

[5] K. Tsai, J. Sung, M. Jin, “An Environment Sensor Fusion Application on Smart Building Sensor Networks”, IEEE International Conference on Ubiquitous and Trustworthy Computing, pp. 291 - 295, 11 - 13 june 2008.

[6] G. Werner-Allen, P. Swieskowski, M. Welsh, “MoteLab: A Wireless Sensor Network Testbed”, in Proceedings of Information Processing in Sensor Networks, pp 483 -4 88, 2005.

[7] V. Shnayder, M. Hempstead, B. Chen, G. Werner-Allen, M. Welsh,“Simulating the power consumption of large-scale sensor network applications”, in Proc. the 2^{nd} International Conference on Embedded Networked Sensor Systems (SenSys2004), Nov. 2004.

[8] A. Martinez-sala, E. Egea-lopez, L. Juan-llacer,J . Garca-haro, “Channel Model at 868 MHz for Wireless Sensor Networks in Outdoor Scenarios”, int. Workshop on Wirless Ad Hoc Networks, London, UK, 2008.

[9] J. Zhao, R. Govindan, “Understanding Packet Delivery Performance in Dense Wireless Sensor Networks”, In: Proc. of SenSys 2003, Los Angeles, CA, USA, November 5 - 7, 2003.

[10] K. Srinivasan, P. Dutta, A. Tavakoli, P. Levis, “Understanding the Causes of Packet Delivery Success and Failure in Dense Wireless Sensor Networks”, Technical Report SING-06-00.

[11] K. Srinivasan, P. Levis, “RSSI is Under Appreciated”, Proc. of the Third Workshop on Embedded Networked Sensors, EmNets 2006, Boston, MA, May. 2006.

[12] D. Lymberopoulos, Q. Lindsey, A. Savvides, “An Empirical Characterization of Radio Signal Strength Variability in 3-d IEEE 802.15.4 Networks using Monopole Antennas”, LNCS, Springer, vol. 3868, pp. 326 - 341, 2006.

[13] M. Yarvis, K. Papagiannaki, M. S. Conner, “Characterization of 802.11 Wireless Networks in the Home”, In: Proc. of Winmee 2005, Riva del Garda, Italy (April 2005).

[14] J. Werb, M. Newman, V. Berry, S. Lamb, D. Sexton, M. Lapinski, “ Improved Quality of Service in IEEE 802.15.4 Mesh Networks”, In: Proc. of the International Workshop on Wireless and Industrial Automation, San Francisco, California, USA , March 2005.

[15] A. Woo, T. Tong, D. Culler, “Taming the Underlying Challenges of Reliable Multihop Routing in Sensor Networks”, In: Proc. of SenSys, Los Angeles, CA, USA , November 5 - 7, 2003.

[16] G. Zhou, T. He, S. Krishnamurthy, J. A. Stankovic, “Models and Solutions for Radio Irregularity in Wireless Sensor Networks”, ACM Transactions on Sensor Networks, 2006.

[17] G. Zhou, T. He, S. Krishnamurthy, J. A. Stankovic, “Impact of Radio Irregularity on Wireless Sensor Networks”, In Proc. ACM MobySys, Boston (USA), June 2004.

[18] N. Reijers, G. P. Halkes, K.G. Langendoen, “Link Layer in Sensor Networks”, IEEE International Conference on Mobile Ad-hoc and Sensor Systems, Florida (USA), October 2004.

[19] M. Petrova, J. Riihijarvi, P. Mahonen, S. Labella, “Performance Study of IEEE 802.15.4 Using Measurements and Simulations”, In: Proc. of WCNC 2006, Las Vegas, USA, 2006.

[20] E. Miluzzo, X. Zheng, K. Fodor, A. T. Campbell, “Radio Characterization of 802.15.4 and Its Impact on the Design of Mobile Sensor Networks, In Proc. of Fifth European Conference on Wireless Sensor Networks (EWSN 2008), Bologna, Italy, Jan. 30/31 - Feb 1, 2008.

[21] D. Lal, A. Manjeshwar, F. Herrmann, E. Uysal-Biyikoglu, A. Keshavarzian , “Measurement and Characterization of Link Quality Metrics in Energy Constrained Wireless Sensor Networks”, in Proc. of IEEE Global Communications Conference (GLOBECOM), Vol. 1, pp. 446-452, San Francisco, USA, Dec. 2003.

[22] www.zmd.biz

[23] http://www.nrcan.gc.ca / mms / canmet-mtb / mmsl-lmsm / mines / mech / mineexperimental / experimental-f.htm

[24] P. Mariage, Martine Liénard, P. Degauque, “Theoretical and experimental approach of the propagation of high frequency waves in road Tunnels”, IEEE Trans. antennas propagation, Vol. 42, No. 1, pp. 75 - 81, January 1994.

[25] L. Deryck, “Natural propagation of electromagnetic waves in tunnels”, IEEE Transaction on Vehicular Technology, Vol.27, No. 3, pp. 145 - 150, 1978.