Radio Channel Models for Wireless Sensor Networks in Smart City Applications

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Abstract— **In this paper we present the measurements at three different carrier frequencies, i.e. 400 MHz, 868 MHz and 2.4 GHz, in two different propagation environments, namely an open area and tunnel. They are compared to empirical path loss models suitable for the particular environment. In an open area the plane earth model fits the measurements better than two slope model. The measurements performed in tunnel environment were evaluated by four slope empirical path loss model. The comparison confirmed the adequacy of the empirical model for performing the path loss calculation and communication range estimation in tunnels and street corridors.**

Keywords—four slope model, path loss, plane earth model, TETRA, two slope model, wireless senzor networks

I. Introduction

Wireless sensor networks (WSNs) have been identified as one of the most important technologies for the 21st century [1], [2], [3]. WSN consists of spatially distributed autonomous sensor nodes, which are via wireless or wired links connected in a powerful monitoring and control systems. WSN is expected to find application in smart homes, agriculture, water and waste water monitoring and monitoring of industrial applications [3], [5], [6]. They are applied to prevent natural disaster, in environmental monitoring and in many other applications. Several constrains, in particular the limited power resources at the sensor nodes, have to be considered, when WSNs are deployed. The radio part of sensor node and some sensors for environmental monitoring consume enormous amount of energy. The solar and battery powering, widely applied at sensor nodes, are not capable to provide sufficient power to such sensor nodes. In smart city applications the problem can be partially solved by placing sensor nodes on the light poles, which are equipped with permanent source of electrical energy. In addition, the light poles are nearly uniformly spread across city center as well in suburban areas which provide potential to monitor the complete city area. Recently even some highways are illuminated giving potential for monitoring rural areas as well. The light poles can also be used as gateways for broadband vehicular access to the internet. At the beginning the sensor nodes are mounted on the top of the light poles guaranteeing line of sight communication channel between nodes. Recently, the deployment and maintenance costs force the designers of WSNs to place the sensor nodes at the height reached without special purpose vehicle equipped with sky lifts, i.e. slightly above the height of the average person. Such sensor node placement also does not require additional wiring for sensors monitoring the environmental condition at the street levels.

Connecting each light pole to the internet via wired links, either fiber or cooper is feasible, but considering the cost of additional wiring is not acceptable. The power line communications can be applied for sensor nodes connection when the expected system throughput between sensor nodes and gateways is low. However, at the moment due to flexibility and throughput the wireless communication is foreseen as the main technology which will interconnect sensor nodes and WSN gateways. In order to design and deploy WSN in city environment an empirical propagation model is necessary. Each empirical propagation model requires tuning to the particular environment and communication system, which is usually attained using received signal strength measurement results in environment of the interest.

In this paper we present results of the measurements for communication systems which are according to our knowledge best candidates for interconnecting sensor nodes, i.e. TETRA at carrier frequency of 400 MHz and IEEE 802.15.4 at two carrier frequencies namely 868 MHz and 2400 MHz. Terrestrial Trunked Radio (TETRA) [7], a professional mobile radio, is widely used in practice by disaster relief forces across Europe and in many countries worldwide. It is expected that, the observations achieved by sensors worn by disaster relief forces will be transferred via TETRA radio interface to the control center either using infrastructure mode of TETRA operation or TETRA Direct Mode Operation (DMO), when there are no TETRA infrastructure. IEEE 802.15.4 [8] is a standard which specifies the physical layer and media access control (MAC) layer for low-rate wireless personal area networks. It is design primarily for device to device communication. It is adopted in majority of WSNs for physical and MAC layer, while for upper layers there exist several specification such as ZigBee or 6LoWPAN, etc. We limit our measurements to ISM frequency bands, namely 868 MHz and 2400 MHz.

The paper is organized as follows. After this introduction, the methodology of measurements including measurement equipment and scenarios are described. The next section contains the results of measurements in the environment of the interest, i.e. open street environment and tunnels, which are becoming frequent building elements in urban areas. In conclusion we provide some guideline for particular model usage and plans for future work.

II. Received Signal Measurements

The received signal strength measurements were taken in two different environments at three different carrier frequencies.

A. Measurement Equipment

Measurements at 868 MHz and 2.4 GHz were performed using VESNA sensor nodes (platform) [9]. VESNA is an embedded system developed at Jožef Stefan Institute with a modular design which provides support and flexibility for different applications. VESNA sensor nodes were equipped with wireless transceiver module from Texas Instruments. For the 868 MHz measurements cc1101 modules were used while for 2.4 GHz nodes were fitted with cc2500 modules.

To investigate radio signal propagation at lower frequencies used by the TETRA as a relay technology to control center the signal measurements at 400 MHz were performed. The received signal level was measured by EADS handheld (THR 880i) and mobile TETRA terminals (TMR 850) in Direct Mode Operation (DMO) with the dynamic sensitivity of the -103 dBm and omnidirectional antennas.

Distance between individual measurements was automatically logged using especially developed device mounted on the handcart. It is designed for counting the spins of a wheel and calculates the driven distance based on its radius. Measured distances are output over a serial interface on demand or periodically and collected with the computer running dedicated software for automatic signal strength measurements.

B. Measurement Methodology and Scenarios

The measurement setup using VESNA sensor nodes is depicted in Fig. 1. The output power for 868 MHz sensor node was set to 12 dBm while for 2.4 GHz node the 1 dBm output power was used. Receivers and transmitters were equipped with omnidirectional antennas with 2 dBi and 4.7 dBi gain for 868 MHz and 2.4 GHz nodes, respectively. Receiver sensor node and the distance measurement device are connected to the laptop via serial port. The dedicated software is applied for automatic RSSI measurements logging. The VESNA Tx node transmits data packed every 100 ms. At the receiver site the measurements are triggered by distance measurement device with the maximum resolution of 13 cm. Therefore, every 13 cm the RSSI value is extracted from the last received packed by Rx node and together with the distance between transmitter and receiver is logged into the ascii file for further processing.

Setup for RSSI measurements at 400 MHz using TETRA technology is depicted on Fig. 2. In order to measure RSSI at the receivers the DMO communication channel must be open by the transmitter with 1 W output power and omnidirectional antenna. Distance measurement device at predefine distance intervals (13 cm) triggers the handheld and mobile TETRA terminals connected to computer via serial ports to perform RSSI measurement on open DMO channel using standard AT commands.

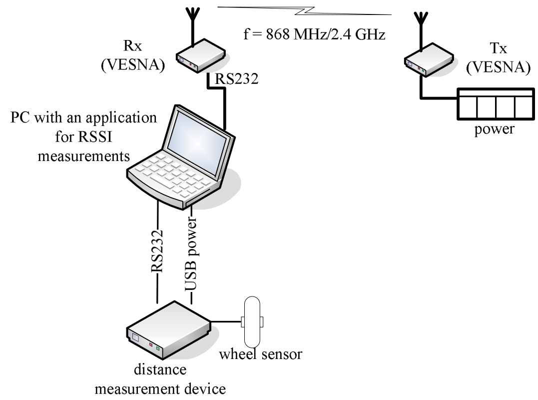

Fig. 1. Measurement setup – sensor system

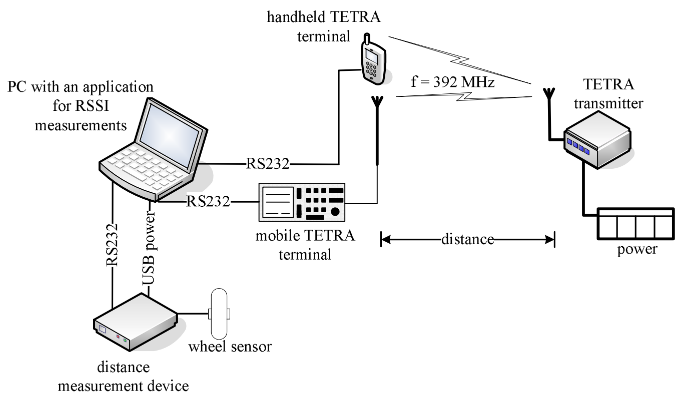

Fig. 2. Measurement setup – TETRA system

First set of measurements was performed on open straight 700 m long asphalted polygon without any obstacles, buildings and vegetation in the area. Transmitter was mounted on the tripod at a height of approximately 1.5 m. Receiver placed on a handcart equipped with the distance measurement device was located 1.5 m above the ground. The measurements were performed in a straight line from the transmitter at constant distance interval determined with the distance measurement device.

The second set of signal strength measurements was taken in the tunnel originally engineered for railway. The tunnel, which length is 520 m was closed and now it is used by pedestrians and cyclists. The shape and the dimensions of the tunnel are depicted on Fig. 3. The tunnel has an arched cross section and is 4.7 m wide and 4.5 m high. The walls and ceiling are of stone while the floor is asphalted. It is slightly curved at the entrance and exit and straight in the middle. Small niches are located every 100 m and the illumination is provided by lighting along the topmost line of the ceiling arch. The transmitter was located on the tripod placed in the middle of the tunnel, 20 m from the entrance, at a height of 1.5 m.

Receivers were placed on a handcart equipped with the distance measurement device. They were located 1.5 m above the ground. The measurements were taken along the path in the middle of the tunnel triggered by distance measure device at the maximum resolution.

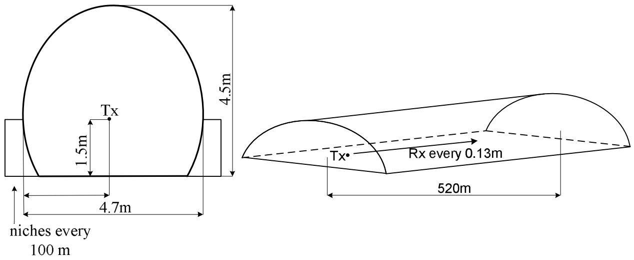

Fig. 3. Tunnel geometry and dimensions

III. MEASUREMENT RESULTS AND RADIO CHANNEL MODEL ANALYSES

After the extensive field measurements in two different environments at three different carrier frequencies, the results are graphically represented and compared to the suitable empirical model.

A. Radio Signal Propagation in an Open Area

In the first set of measurement in open flat polygon the results are compared with two empirical models, namely: plane earth model and two slope model [10].

The field measurements and simulation results of two empirical models for 400 MHz are graphically presented in Fig. 4. For the two slope model the break point is set according to the $d_b=(4h_Rh_T)/\lambda$, where h_R and h_T represent receiver and transmitter heights above the ground and λ is the signal wavelength. For 400 MHz the break point distance is set to 12 m. The constant values defining the slope of the individual segments n_1 and n_2 are set to 4 and 3.7, respectively. It is shown good coincident between measurements and the plane earth model as well as with the two slope model. The measured communication range of the system is 4100 m.

Measurements at 868 MHz using VESNA sensor nodes are depicted in Fig. 5. They are compared with the plane earth and two slope models. The measurements are in excellence agreement with the plane earth path loss model. For optimal fitting of the two slope path loss curve with the measurements the break point was according to the break point definition set to 26 m and values of n_1 and n_2 to 1.8 and 3.7, respectively. In the region before break point the model curve differs from the measurements while after the break point the model follows the measurements better.

The third set of measurements and simulations for open flat area done at 2.4 GHz are shown in Fig. 6. Measurement results in first 100 m perfectly suits to plane earth model while the simulation curve further away slightly deviates from measurement curve due to slow fading. The assumption could be proven with measurements at higher distances but the range of the system was reached. The disagreement with the two slope model with the slopes set to 1.8 and 3.1 increases at higher distances from the transmitter particularly after the break point set to 72 m the attenuation slope decreases to optimistic.

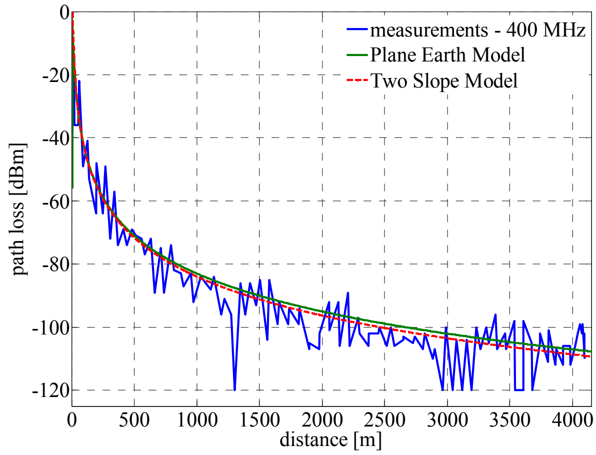

Fig. 4. Comparison of measurement results and path loss models for open area; f= 400 MHz

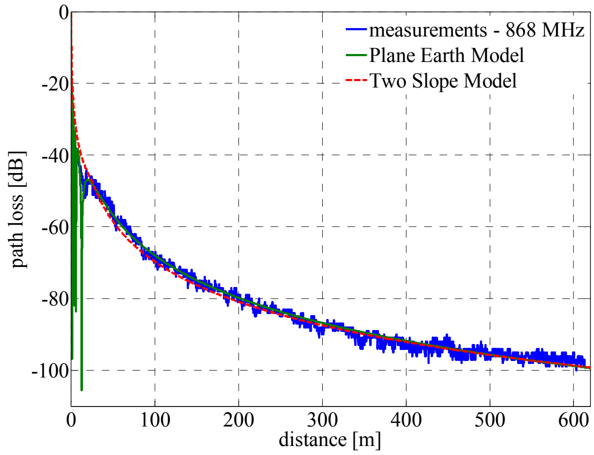

Fig. 5. Comparison of measurement results and path loss models for open area; f= 868 MHz

For the wireless sensor applications the connectivity between adjacent sensor nodes must be provided. Therefore, the expected communication range must be determined. In open flat area the range for 868 MHz and 2.4 GHz sensor systems with transmitter and receiver parameters given in previous section is measured. Sensitivity of 868 MHz sensor nodes is -100 dBm and the range of the system is approximately 600 m. Considering lower output power, sensitivity of -92 dBm and higher frequency the communication range at 2.4 GHz is considerably shorter. The communication between nodes was undisturbed and reliable up to 220 m.

Results for open flat area show good agreement between measurements and the empirical plane earth model which performs better compared to the two slope model. According to the [11] and [12] the latter one is suitable for very low antenna heights (less than λ) and if the part of the first Fresnel zone is obstructed by ground. In this case the break point is environment depended and cannot be calculated based on antennas heights and signal wavelength

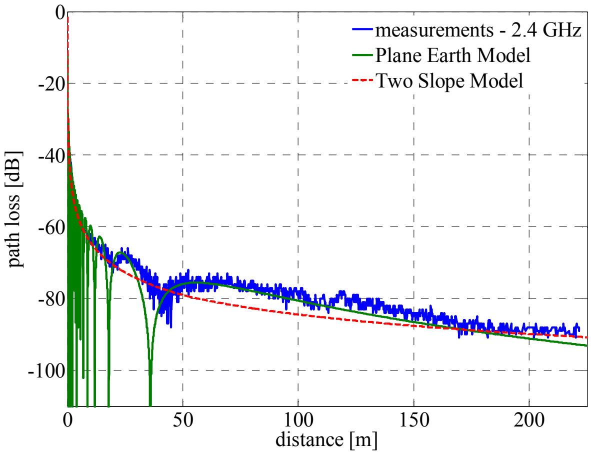

Fig. 6. Comparison of measurement results and path loss models for open area; f= 2.4 GHz

B. Radio Signal Propagation in Tunnel

In the second measurement campaign the radio signal propagation characteristic inside the tunnel environment was investigated. The measurements at 400 MHz, 868 MHz and 2.4 GHz are compared with four slope model proposed in [13]. While standard multi slope models consist only of two propagation regions with one break point and they are inappropriate for the estimation of the communication range, the four slope channel model consists of four regions separated by three break points. It was originally developed for 400 MHz frequency band and its validity for frequencies above 1 GHz is verified with measurements using sensor nodes.

In Fig. 7 measurements and simulation results of four slope model at 400 MHz are compared. The measured path loss curves for mobile and handheld terminals coincide with the model quite well. In the first 12 m path loss follows the free space attenuation. After the first break point gradient of the curve falls to 0.25 dB/m. When the distance between the transmitter and receiver exceeds 50 m the slope of the path loss decreases significantly. This is the distance where the additional reflected rays constructively contribute to the received signal strength. Thus, the effect of waveguide appears which considerably extends the communication range. The attenuation rate in the third part of the path loss curve is 0.1 dB/m. Since the tunnel is too short, the range of the communication cannot be determined by measurements. However, it is estimated to around 700 m by four slope model.

The measured values and simulation results gained with four slope model for 868 MHz are shown in Fig. 8. Four slope path loss curve fits measurement results well. After the free space region the path loss attenuates with 0.14 dB/m. In the third region started at the second break point of 120 m where waveguide effects appears the slope is reduced to 0.031 dB/m. Lower attenuation rate compared to 400 MHz confirms stronger waveguide effect at higher frequencies. Therefore, also the communication range is considerably extended and is estimated to 1700 m.

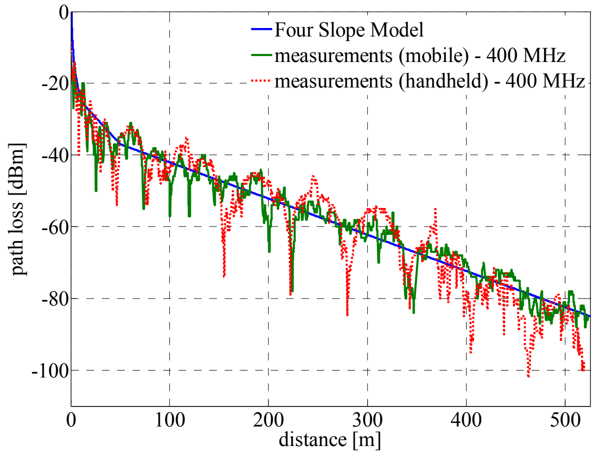

Fig. 7. Comparison of measurement results and path loss model for tunnel; f= 400 MHz

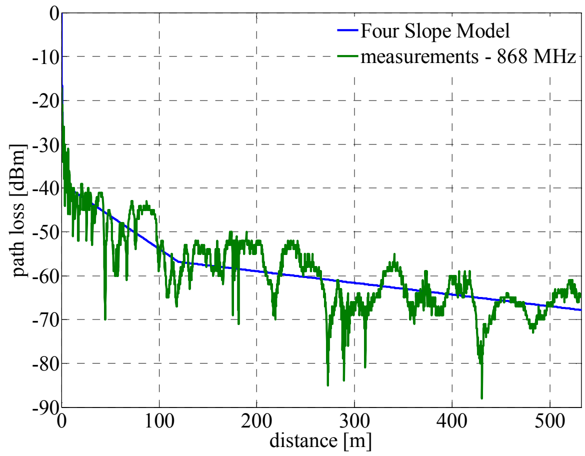

Fig. 8. Comparison of measurement results and path loss model for tunnel; f= 868 MHz

Fig. 9 shows measurement results and path loss model at 2.4 GHz. In the free space region and after the first break point at 12 m where the second region begins the model coincidence rather well with measurements. The attenuation slope in the second region is 0.1 dB/m. The waveguide region starts at approximately 130 m from the transceiver. A small disagreement between the model and measurements is observed. While the attenuation rate calculated by the model is 0.01 dB/m the attenuation rate estimated from the measurements is 0.015 dB/m. However, values confirm the presence of waveguide effect which is the result of constructive contributions of reflected rays. The waveguide effect is increasing by increasing the frequency. Therefore, compared to open outdoor environment the communication range is considerably extended and is approximately 1500 m.

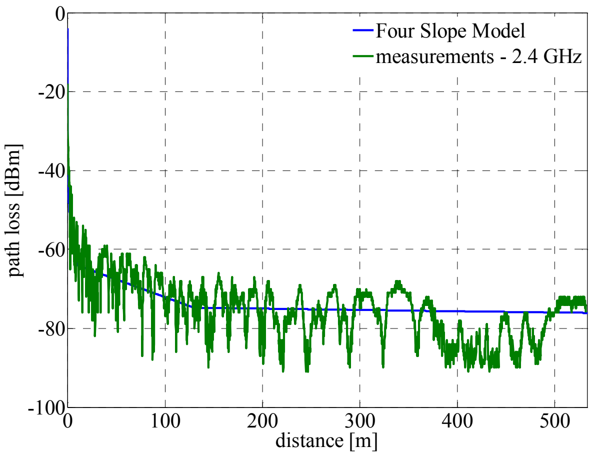

Fig. 9. Comparison of measurement results and path loss model for tunnel; f= 2.4 GHz

The validity of the four slope model is evaluated by measurements at 868 MHz and 2.4 GHz. In particular, the model is valued for the first three propagation regions while the tunnel length prevents the validation of the fourth part. Therefore, also the communication range of the individual systems essential for the network deployment is determined only theoretically. The measurements confirms present of the waveguide effect which occurs on certain distance from the transmitter and significantly extends communication range. Some disagreement between measurements and the model are also results of the tunnel shape and rough wall structures causing signal scattering.

IV. CONCLUSION

Radio channel characterization is an essential issue in design and deployment of any wireless communication systems. We analyze two wireless propagation channels suitable for wireless sensor networks, which at least for our opinion are appearing in smart city applications where the sensor nodes and sensor network gateways can be mounted on light poles due to permanent source of electrical energy. It was found out that the plane earth model perfectly model plane areas, and the four slope model can be applied for tunnels and street corridors for all three frequency bands suitable for wireless sensor nodes interconnection, namely, 400 MHz, 868 MHz and 2400 MHz. The model coefficients strongly depend on particular environment.

The proposed channel models can be extended also for street with vegetation, which may at least for high frequencies attenuate the signal significantly. Also the path loss dependence on transmitter and receiver height will be studied in future.

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