INTERNATIONAL JOURNAL OF COMMUNICATIONS
Issue 4, Volume 7, 2013

Analysis of Radio Propagation Models for Smart City Applications

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Abstract—In this paper we give a thorough study of radio propagation models suitable for smart city applications and select two channel models for coverage prediction of wireless sensor networks for two typical propagation environments often occurs in smart city applications, namely the open area plane earth model for open areas and the four slope channel model for street canyons and tunnels. The measurement campaigns performed at three carrier frequencies applied for wireless sensor networks in Europe i.e. 400 MHz, 868 MHz and 2.4 GHz, reveals, that in open areas the plane earth model fits the measurements better than two slope model and four slope channel model gives sufficiently high accurate path loss prediction in tunnels and street corridors.

Keywords— four slope model, GRASS RaPlaT, path loss, plane earth model, RSSI measurements, TETRA, two slope model, wireless sensor networks, WSN testbed.

I. Introduction

The natural resources on Earth is limited, thus people have to use them efficiently as much as possible. The efficient usage of natural resources will also reduce pollution; consequently this will improve the people living conditions. In order to reach this aim the human environment has to be monitored, to provide sufficient and accurate information to decision process controlled the usage of natural resources, such as energy, water resources, soil protection by exaggeration in using fertilizer in agriculture, etc. The process has already been started and today, we are witnessing a rapid increase in the number of devices with sensing capabilities connected to the internet. In future the number of sensing capability devices connected to the internet will definitely grow. The technology which supports inexpensive interconnection of sensing capability device to internet is wireless sensor networks (WSNs). That’s why WSNs have been identified as one of the most important technologies for the 21st century [1]–[3].

WSN consists of spatially distributed autonomous sensor nodes, which are via wireless or wired links connected into a powerful monitoring and control systems. WSN is expected to find applications in smart homes in particular energy consumption control, agriculture i.e, fertilization monitoring, water and waste water monitoring with special emphasize in quality of water monitoring and monitoring of industrial applications [4]–[6]. They are applied to prevent natural disaster, in environmental monitoring and in many other applications.

Among constrains, which prevent more rapid deployment of wireless sensor nodes is the limited power resources at the sensor nodes. 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

Manuscript received November 10, 2013.

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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, 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 communications. 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 the Section II containing related work, the communication systems used in the experiments are briefly described. Methodology of measurements including measurement equipment and scenarios are described in Section IV. The next section contains description of the radio channel models potentially suitable for measurement analyses in chosen environments. 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, are presented and analyzed in Section VI. In conclusion we provide some guideline for particular model usage and plans for future work.

II. Related Work

As stated above, for sensors monitoring the environmental condition at the street levels nodes should be mounted slightly above the height of the average person. In the literature there are some near-ground (less than 50 cm) measurements which are used for the channel characterization and empirical channel models verification while for the heights around 1.5 m the lack of measurements and their comparison with the channel models is observed.

In [9] a practical radio signal propagation model – Free-space Outdoor Model – suitable for WSN is proposed. The model is based on combining four path loss factors, which cause distortion and diminishingof the radio signal, i.e. free-space path loss, ground reflection path loss, RSS uncertainty and antenna pattern irregularity. The proposed model is verified with actual measurements at 2.4 GHz .

Low-computational cost, two slope, log-normal path loss outdoor channel model is validated by extensive real hardware measurements obtained in different scenarios at 868 MHz [10]. The model is compared with the well-known one slope path-loss model and shown that provides more accurate WSN results compared to the single slope one. It is also shown that the radio propagation characterization heavily depends on the adjusted model parameters for a target deployment scenario. Similar finding were presented in [11] where path loss values for three near-ground scenarios were captured through extensive measurements at 2.4 GHz, and then a least-square linear regression was performed. The results indicates the log-distance-based model is suitable for path loss modeling in near-ground scenarios, and the prediction accuracy of the two-slope model is superior to that of the one-slope model.

In [12] lognormal shadowing model is used to represent near-ground path loss characteristics for three naturally occurring environments (open fields, woods and wooded hills) at 915 MHz. Based on field measurement data the parameters of the model were obtained. The model is incorporated into a network simulation for randomly distributed transmitting sensors. The effects of the various environments on coverage area are explored for various power transmission levels.

A novel signal propagation model of wireless sensor network (WSN) for outdoor open environments is presented in [13]. The new VSR (Variable Soil Reflectivity) is based on the existing double path propagation model (two-ray), but it takes into account the distance of antennas from the soil, their directivity and the soil reflection properties. The proposed model is applicable in outdoor open scenarios, as agricultural fields and parking areas.

The suitability of the existing empirical foliage loss models for WSN planning and deployment in agricultural fields and gardens have been evaluated with the measured path loss at 2.4GHz [14]. The poor prediction of the Early ITU vegetation and Weissberger models is due to the low antenna height and the use of low transmitter power. The COST 235 model is suitable for near-ground WSN planning and deployment in agriculture fields and gardens.

In [15] signal propagation studies for WSN planning in aquaculture environment for water quality and changes in water characteristics monitoring is analyzed. The two-ray model has been found to provide high accuracy for signal propagation over water where there are no objects in close proximity to the propagation path. Vegetation in close proximity causes the temporal and spatial signal variations therefore additional frequency selective fading characteristics has to be taken into account.

III. Communication Systems

A. TETRA System

TETRA (Terrestrial Trunked Radio) is a set of standards developed by the European Telecommunications Standards

Institute (ETSI) aimed to meet the needs of public safety and security organizations like police, fire and rescue forces, ambulance services, frontier guards and other professional mobile users [7]. It has a scalable architecture, allowing economic network deployments ranging from single site local area coverage to multiple site wide area national coverage.

The physical and MAC layer specifications are optimized for operation between 150 MHz and 900 MHz. Most of the TETRA systems operate in 380-400 MHz band. The TETRA system was designed for reliable, spectral efficient and safe voice communications offering push to talk functionality and also data transmission. Two main operating modes are defined in the TETRA standard, namely:

- Trunked Mode Operation (TMO) – TETRA V+D; enables basic voice and data transmission in a circuit switched mode using network infrastructure and
- Direct Mode Operation (DMO); enables direct mobile-to mobile communication without the support of the network infrastructure and mobile-to-repeater communication, where range extension is needed.

In addition to the voice communication services, the TETRA V+D mode provides three different data transmission services; (i) Short Data Service (SDS), (ii) Packet Mode Data and (iii) Circuit Mode Data. To increase data rates, ETSI defined TETRA Enhanced Data Service (TEDS) as part of the TETRA Release 2 standard, which contains specifications for improved air interface, speech coding, interworking, roaming, and development of the USIM module. TEDS offers higher data rates of up to 150 kbit/s, however it needs significantly more radio spectrum and wider channels than TETRA V+D.

B. IEEE 802.15.4

IEEE 802.15.4 specifies the physical and media access control for low rate wireless personal area networks [8]. It was released in 2003 and updated in 2006. Standard adopted a wideband physical layer using a Direct Sequence Spread Spectrum technique (DSSS). The three frequency bands are specified in standard, namely the 868 MHz band, available in Europe, the 915 MHz band, available in US, and the 2400 MHz ISM band, available worldwide. A frequency division multiplexing has been foreseen to enable coexistence of several networks: i.e. one channel in 868 MHz band, 10 channels in 915 MHz band and 16 channels in 2.4 GHz band. In the standard released in 2006, the low data rate per channel, 250 kbits/s, can be achieved in all three specified frequency bands. Two classes of devices are specified in standard: (i) Full-Function Devices (FFD) and Reduced-Function Devices (RFD). All network functionalities are implemented in FFD device, while in RFD device has only reduced network functionality. As a consequence only the FFD devices can work as Personal Area Network coordinator, while RFD devices can only join to existing network.

Two basic network topologies are supported in IEEE 802.15.4 standard namely (i) star topology, in which all communications are via Personal Area Coordinator and (ii) peer-to-peer topology in which FFD devices communicate directly to each other while RFD devices communicate via coordinator. The peer-to-peer topology allows construction mesh networks. A combination of random access, usually in communications towards the network coordinator, and scheduled access in direction from network coordinator is adopted in standard. The random access is based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA).

The layer above the physical and MAC layer are not specified in the standard. In order to build a wireless network the specification such as 6LoWPAN or ZigBee are used for higher layers. The IEEE 802.15.4 standard is typically applied for wireless sensor networks.

IV. Received Signal Strength 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) [16]. VESNA is an embedded system developed at Jožef Stefan Institute with a modular design which provides support and flexibility for different applications. Hardware solutions typically consist of:

- Sensor Node Core (SNC) module based on a powerful ARM microprocessor with Cortex-M3 core.
- Sensor Node Radio (SNR) module supporting in different implementations a variety of communication interfaces, technologies and operating frequency ranges.
- Sensor Node Expansion (SNE) module enabling the realization of application-related functionality, additional power supply solution and/or gateway functionality in order to connect to other communication networks.

Through a set of digital and analog interfaces the platform supports a wide range of sensors and actuators. The core and radio modules of the VESNA platform are shown in Fig. 1.

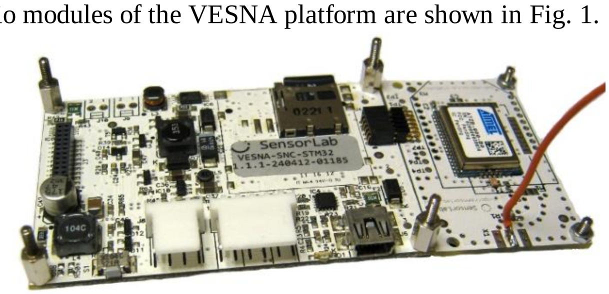

Fig. 1. VESNA platform SNC and SNR modules

For the purpose of the field measurements 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. the computer running dedicated software for Measured distances are output over a serial interface on demand or periodically and collected with automatic signal strength measurements.

Distance measurement device is developed on the ITLPC2138 development system with the embedded Philips LPC2138 microcontroller. The concept of device is illustrated in Fig. 2. The phototransistor placed on the wheel is illuminated by the IR diode through the evenly spaced holes. The output of the phototransistor is connected to the digital input of the microcontroller. When the interruption is detected the counter is increased and the logic in the microcontroller calculates the driven distance based on the following parameters: wheel radius, number of holes and interruptions. The result can be accessed via the serial interface which is also used to control the device and to enter correct parameters.

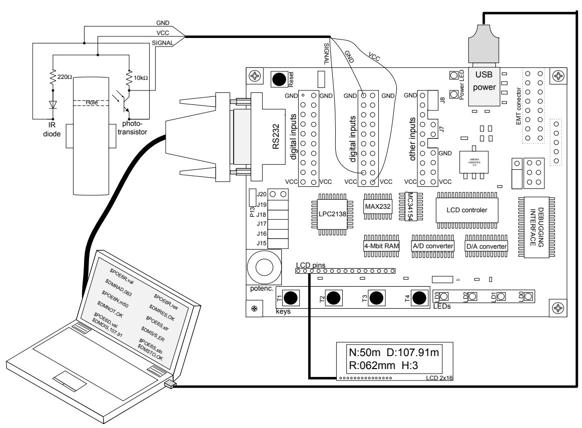

Fig. 2. Distance measurement device block scheme

B. Measurement Methodology and Scenarios

The measurement setup using VESNA sensor nodes is depicted in Fig. 3. 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. The measurements are triggered by distance measurement device with the maximum resolution of 13 cm at the receiver site. 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.

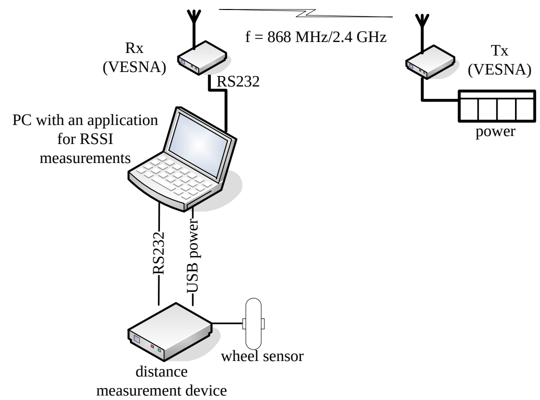

Fig. 3. Measurement setup – sensor system

Setup for RSSI measurements at 400 MHz using TETRA technology is depicted on Fig. 4. 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.

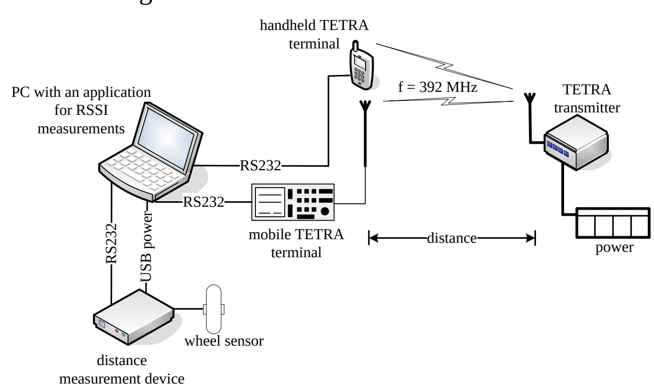

Fig. 4. Measurement setup – TETRA system

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 transmitter on the tripod and receiver mounted on the handcart together with the distance measurement device and power supply are illustrated on Fig. 5.

Fig. 5. Photograph of the measurement setup

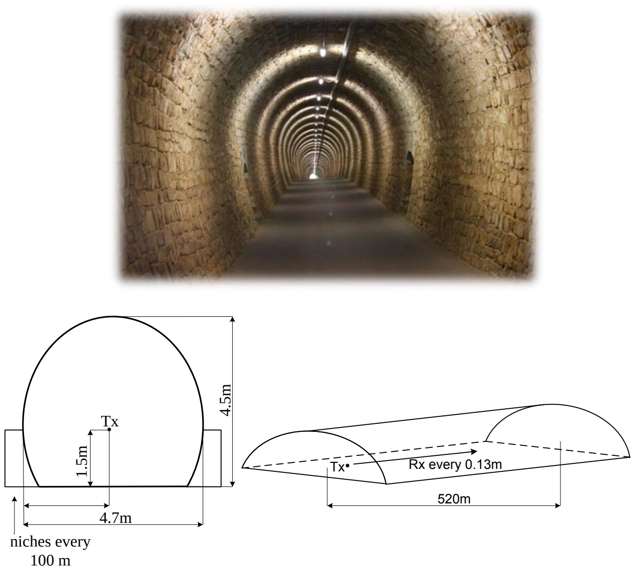

Fig. 6. Railway tunnel

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. 6. 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.

V. Radio Channel Models

After the preliminary analyzes of the measurements the appropriate radio channel models for analyzed environments were chosen. Plane earth model and two slope model were used for an open environment while four-slope model was selected to analyze measurements performed in the railway tunnel.

A. Plane Earth Model

Plane earth channel model (PEL) presumes that the transmitter and the receiver are situated above a flat reflecting ground (plane earth), at heights h_T and h_R, respectively [17]. The propagation takes place via both a direct path between the antennas and a reflection from the ground. These two paths sum at the receiver with a phase difference related to the difference in length between the two paths. Assuming the antenna heights are small compared with the total path length *d*, the difference between two paths can be expressed as

$$\Delta d = \frac{2h_T h_R}{d} \quad (1)$$

Therefore the plane earth propagation equation can be simplified and written as

$$L = 40\log d - 20\log h_T - 20\log h_R \quad (2)$$

From the previous equation it is evident that the path loss is independent of the carrier frequency and is increasing with the fourth power of the distance which is due to the assumption that the transmitter and receiver heights are small compared to the distance between them and that the flat ground provides a perfect reflection of the radio ray.

B. Two Slope Model

In two slope model two separate path loss exponents are used to characterize the propagation, together with a breakpoint where propagation changes from one regime to the other [18]. In this case the path loss is modeled as

$$L = \begin{cases} L(d_b) + 10n_1 \log\left(\dfrac{d}{d_b}\right) & d < d_b \\ L(d_{b+1}) + 10n_2 \log(\dfrac{d}{d_b}) & d > d_b \end{cases}, \quad (3)$$

where the $L(d_b)$ and $L(d_{b+1})$ are selected as the reference path losses before and after the breakpoint at the distance d_b, respectively. The n_1, and n_2 are the path loss exponents which indicate the attenuation rate before and after the break point. Typical values for the path loss exponents are found by measurement to be around $n_1=2$ and $n_2=4$, with breakpoint distances of 200-500 m, but it should be emphasized that these values vary greatly between individual measurements.

C. Four Slope Model

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 [19]. It was originally developed for 400 MHz frequency band and its validity for frequencies above 1 GHz is verified with measurements using sensor nodes.

The model consists of four regions separated by three break points. In the first region propagation follows free space channel model (FSL) [17] which can be applied if the first Fresnel zone is free of obstacles. Assuming h_R and h_T represent receiver and transmitter height above the road in meters and λ is the signal wavelength, first break point is defined as

$$d_0 = \frac{4h_R h_T}{\lambda} \tag{4}$$

In the next region the received signal is composed of several reflected rays, but due to high reflection loss the waveguide channel model cannot be applied. The path loss can be modeled as [20]

$$L[\text{dB}] = L_0[\text{dB}] + \alpha(d - d_0) \tag{5}$$

whereat L_0 is attenuation at d_1 and α is the slope of the curve and d is the distance between transmitter and receiver. The second break point representing the end of the near region is calculated from the size of antenna array seen from the receiver point $N(d_1)$ and tunnel width a

$$d_1 = aN(d_1). \tag{6}$$

Second break point denotes the beginning of the far region where waveguide phenomenon is apparent. Waveguide propagation model is given by

$$L[\text{dB}] = L_1[\text{dB}] + 4.343\lambda^2 \left(\frac{\text{Re}\left\{ \frac{\varepsilon_r}{\sqrt{\varepsilon_r - 1}} \right\}}{a^3} + \frac{\text{Re}\left\{ \frac{1}{\sqrt{\varepsilon_r - 1}} \right\}}{b^3} \right)(d - d_1) \tag{7}$$

where $L_1[dB]$ is the attenuation at distance d_1, a and b are width and height of the tunnel and ε_r is the relative permittivity.

At extremely far distances effect of waveguide vanishes out, due to the attenuation at each reflection and the slope of the path loss obeys the free space loss attenuation, with occasional deep fades caused by a single reflected ray from the walls of the tunnel. The last break point which determines the end of the waveguide region occurs at 1200 m and is defined from measurements.

VI. Measurements 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.

The field measurements and simulation results of two empirical models for 400 MHz are graphically presented in Fig. 7. For the two slope model the break point is set according to (3). 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. 8. 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.

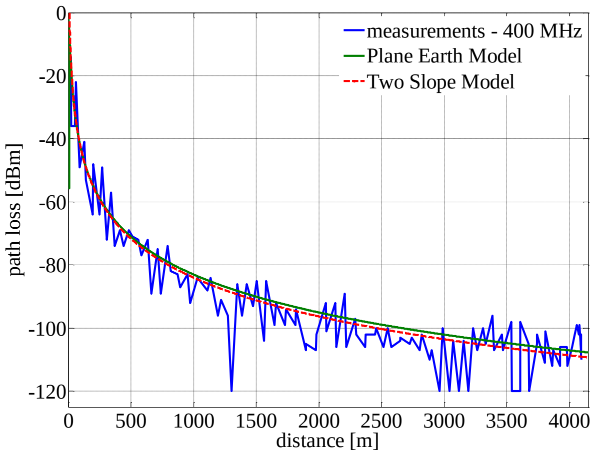

Fig. 7. Comparison of measurement results and path loss models for open area; f= 400 MHz

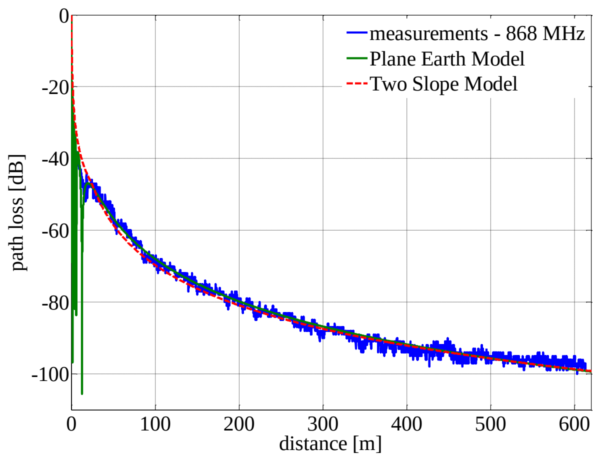

Fig. 8. Comparison of measurement results and path loss models for open area; f= 868 MHz

The third set of measurements and simulations for open flat area carried out at 2.4 GHz are shown in Fig. 9. Measurement results in first 100 m perfectly fits 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.

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. The communication range at 2.4 GHz is considerably shorter due to using lower output power, receiver sensitivity of -92 dBm and higher frequency. The communication between nodes was undisturbed and reliable up to 220 m.

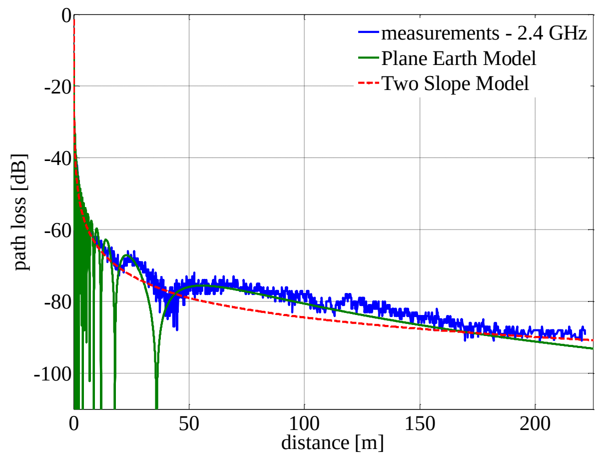

Fig. 9. Comparison of measurement results and path loss models for open area; f= 2.4 GHz

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 [10] and [11] 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.

Additional coverage computational using GRASS RaPlaT tool [21] were performed for outdoor experimental sensor network LOG-a-TEC which is deployed on the public lighting infrastructure in the city of Logatec in Slovenia. The testbed consists of six nodes operating at 868 MHz and sixteen nodes operating at 2.4 GHz. In the city environment various obstacles are present causing additional signal attenuation. Therefore, the distance between neighborhood nodes must be less that the measured communication range in open flat area.

Fig. 10 presents radio signal coverage from nodes operating at 868 MHz. The transmit power was set to 12 dBm and the omni-directional antenna with 2 dBi was used. The radio signal coverage map, computed using hataDEM [21] propagation model, presenting the area of 800 m by 530 m clearly shows that each sensor can communicate at least with its nearest neighbor.

Coverage for the same area with the wireless sensor nodes with the 1 dBm transmit power and 4.7 dBi antenna gain operating at 2.4 GHz is shown in Fig. 11. Because of the reduced range caused by higher operating frequency, lower transmit power and poorer sensitivity the density of the nodes must be higher. Coverage maps also shows rapid signal strength attenuation in the directions away from the testbed which is more evident for the higher frequency case.

Fig. 10. Coverage of wireless sensor testbed in the city environment; f=868 MHz

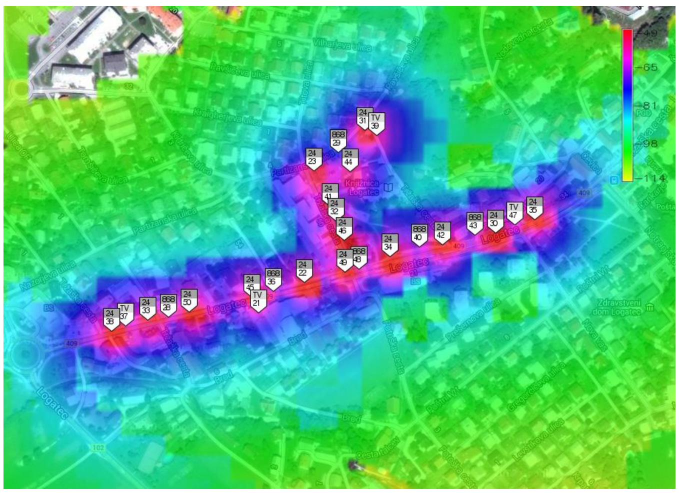

Fig. 11. Coverage of wireless sensor testbed in the city environment; f=2.4 GHz

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 [19].

In Fig. 12 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.

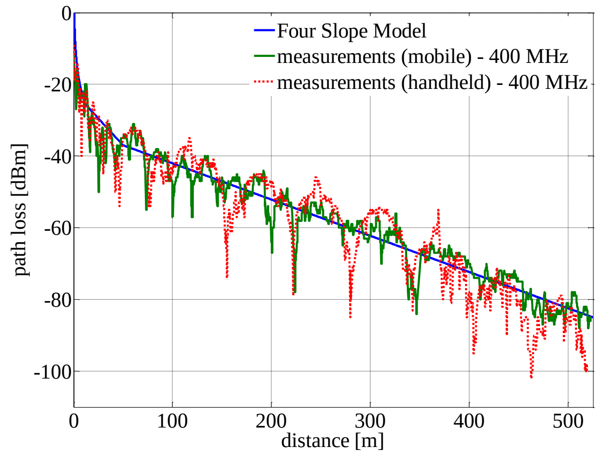

Fig. 12. Comparison of measurement results and path loss model for tunnel; f=400 MHz

The measured values and simulation results gained with four slope model for 868 MHz are shown in Fig. 13. 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.

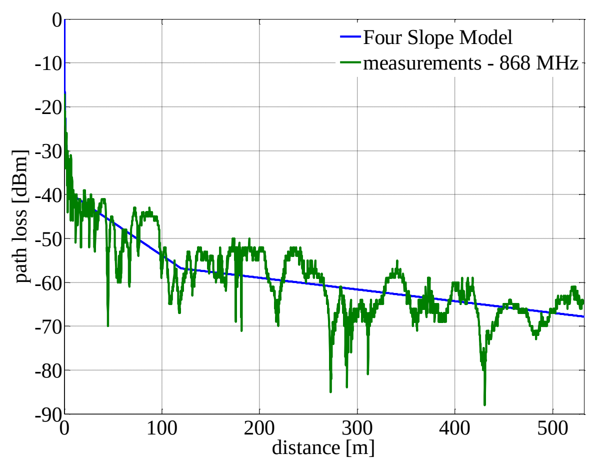

Fig. 13. Comparison of measurement results and path loss model for tunnel; f=868 MHz

Fig. 14 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.

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.

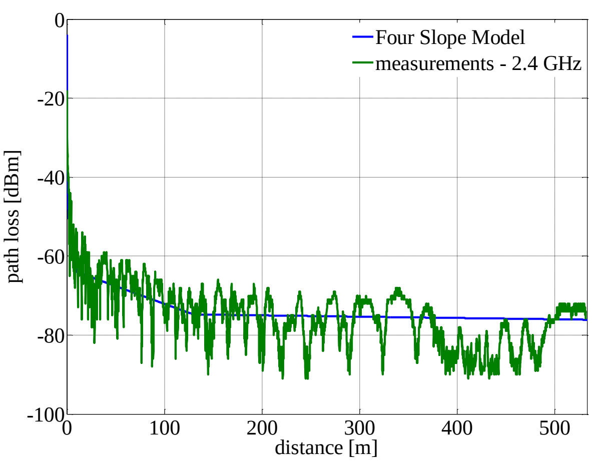

Fig. 14. Comparison of measurement results and path loss model for tunnel; f= 2.4 GHz

VII. Conclusion

Design and deployment of any wireless communication system requires proper radio channel characterization. In the paper we analyzed two wireless propagation channels suitable for wireless sensor networks, which are appearing in smart city applications. It is expected that the sensor nodes and sensor network gateways will be mounted on light poles due to permanent source of electrical energy. Because of the cost of mounting and wiring for sensors monitoring the environmental condition at the street levels the nodes should be placed at heights slightly above the average people.

The measurement set-up was designed and extensive field measurements in open flat area and in tunnel at three different carrier frequencies, namely 400 MHz, 868 MHz and 2.4 GHz were carried out. It was shown that in open flat area empirical plane earth model slightly outperforms two slope model, particularly at higher frequencies. According to the literature the two slope model is more suitable for near-ground channel modeling. Measurements from the tunnel environment confirm suitability of the four slope model also for frequencies higher than 1 GHz. With the additional adaption of the model coefficient it can be also applied for street corridors.

The proposed channel models should be also validated by measurements in dense urban environment. Particularly, the two slope and four slope models parameters should be studied. The models can be extended also for street with vegetation, which may at least for high frequencies attenuate the signal significantly. Moreover the path loss dependence on transmitter and receiver height will be studied in future.

Acknowledgment

This paper is based on the work, partially funded by the European Community through the 7th Framework Programme ICT projects CREW (FP7-ICT-258301) and ABSOLUTE (FP7-ICT-2011-8-318632). We would like to thank all our colleagues in SensorLab (http://sensorlab.ijs.si/) who contributed VESNA sensor nodes used in measurement campaigns.

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