Adaptive Distance Estimation Based on RSSI in 802.15.4 Network

Miroslav BOTTA, Milan SIMEK

Dept. of Telecommunication, Faculty of Electrical Engineering and Communication,
Brno University of Technology, Brno, Czech Republic

botta@phd.feec.vutbr.cz, simek@feec.vutbr.cz

Abstract. *This paper deals with the distance estimation issue in 802.15.4 wireless sensor networks. On a basis of signal strength of received frames a distance between two sensor nodes is estimated. Estimation is done by using the log-normal shadowing radio propagation model (LNSM). Basic problems of signal strength based systems are variation of RSSI parameter and correct calibration of coefficients for the LNSM model. For distance estimation in wireless networks, static and dynamic methods of calibration have been already introduced. Static calibration has significant drawback in adaptation to the dynamical environment changes. The proposed work deals with an experimental validation of dynamic calibration method for distance estimation in wireless sensor networks. This method for dynamic estimation of radio environment parameters for LNSM results in the significant improvements in the distance estimation accuracy in comparison with the known static methods.*

Keywords

WSN, IEEE 802.15.4, RSSI, variance, dynamical calibration, LNSM, TinyOS, node localization, positioning.

1. Introduction

Wireless sensor networks (WSNs) are networks of specific character and usability with a wide scope of applications. WSNs have taken important place at information systems in last years, they are characteristic for their properties such as ultra-low energy consumption, low price and scalability.

Today the very popular standard for these networks is IEEE 802.15.4. It defines the physical (PHY) and medium access control (MAC) layer, but it does not define any specifications for upper layers, which depend on the used application.

Distance estimation in WSN is a very popular research topic, because it is a cheap way of localization in indoor environments where high accuracy is not needed. It has wide scope of applications such as medical, healthcare monitoring as proposed in [1]. The next suitable applications are surveillance, intrusion detection applications and automatic tracking or location estimation systems.

In systems for distance estimation two types of devices are used. These are devices with a fixed known position, so called reference nodes, and the others are mobile devices with unknown position. One can estimate absolute or relative positions of these mobile nodes against the reference ones.

The main idea of ranging technologies in WSN systems is transmitting of the signal from a node with unknown position to a node or a group of nodes with fixed known position or vice-versa. These fixed nodes can process radio signal many different ways on the basis of the received radio waves properties. For example time difference between transmitted and received radio signal (ToA - Time of Arrival), angle of arrival (AoA) and on the received signal strength (RSS) basis.

In this paper we have proposed and analyzed two RSS based methods for distance estimation between two wireless nodes. Nowadays, this method is very popular thanks to its simplicity and low implementation price because no additional hardware is required. The first method uses static calibration of LNSM parameters for distance estimation, where the best parameters are chosen after measuring the whole interval of distances. This means that the environment has to be known for the first and then its properties have to be estimated. There is also assumption that environment will have constant properties for the whole time. On the other hand, the second proposed method uses dynamic calibration performed during the measurement, which means that environment can change its properties.

The rest of the paper is organized as follows: Section 2 presents a brief description of other methods and approaches to this issue. In Section 3 we focus on the RSSI fundamentals and briefly describe its essential properties. Section 4 is devoted to the introduction of the propagation model used in this work. Within this section, the RSSI application for distance estimation purposes is also investigated. In Section 5 the proposed communication model and algorithm for dynamic calibration of the needed coefficients used in LNSM formula is introduced. This section is the main contribution to this experimental work. Subsection 5.2 with the results from indoor environment is also provided. Conclusion and future work is provided at the end of paper.

2. Related Work

Some of the related works deals with processing of the RSSI parameter with approximation methods [2] and filters [3]. In [2] statistical mean values, distances between the fixed nodes and Gaussian model to avoid the instability of RSSI were used. They conclude that the approximation with Gaussian model has the best performance. In [3], performance of Grey model, Kalman and Gradient filter within contemplating the holes of signal coverage inside the covered area were tested. Also [4] and [5] discuss the application of RSSI for distance measurements. They conclude that it is not an appropriate metric for localization systems because it lacks reliability between RSSI within increasing distance in different directions from a transmitter.

Some of the related works were devoted to the static calibration of parameters that are needed for LNSM formula. The main idea of these “static” systems is that the coefficients for LNSM are estimated at “configuration” time, when the network is created. Individual parameters for LNSM formula are statically estimated and used during the whole time of WSN application, even if the environment is dynamically changed, which is a significant drawback of this method. In [6] authors investigate also the adaptive method at small distances, where they were using not average values but the minimum, median and 25% quantile of all measurements at the same place. For adaptation they were using the artificial neural networks with back propagated error, where they achieved average estimation error of 50 cm at 3.5 m x 4.5 m area.

In many systems at short distances, the reference distance is given as 1 m. Parameter $RSSI_{d0}$ is measured at reference distance in every direction from a transmitter and then averaged. Path loss exponent η expresses how much radio signal strength decreases with distance. This can be estimated through measurement of radio signal propagation environment or it can be usually defined as constant for indoor or outdoor environment. In [7] the authors present more sophisticated way of defining the path loss exponent.

We have also investigated the energy efficiency of localization method based on the RSS indicator, the results of these measurements can be found in [8]. Because the ISM band is widely used and affected by other systems, we conducted another measurement [9], where we tested the coexistence of low-PAN network with home microwave appliances in laboratory and home environments in order to analyze its impact on the performance of the communication system.

3. Received Signal Strength Indicator

Received signal strength is measured from each received frame as average value measured during the first eight symbols (preamble) and converted to the RSS indicator. This conversion is variable for every type of radio chip [10]. With properly modeled path loss in a given environment, it should be possible to formulate a relation between distance and RSSI value. Problems arise with dynamical changes in environment because of radio signal unstable properties.

In this section we have introduced the results from the experiments with the human based interferences where we analyzed the variation of parameter *RSSI* in time and impact of movement of human being in the signal path. Two measurements were conducted, the first one with and the second one without violating the signal path in indoor inter-level environment. As can be seen from Fig. 1, we used three approximation methods for suppressing the instability of the RSSI.

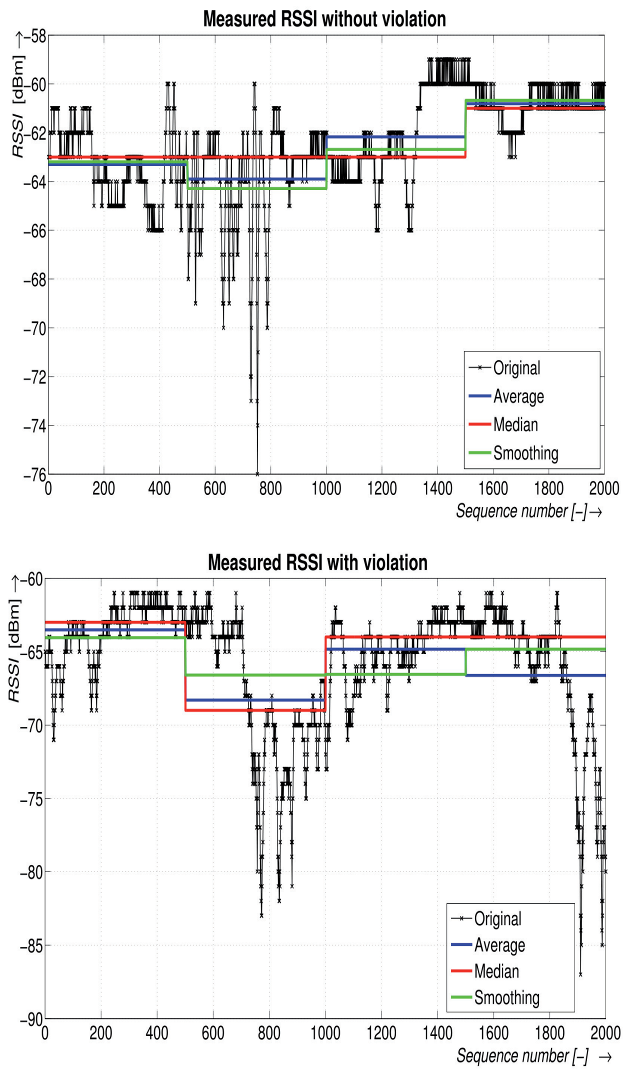

Fig. 1. Dependence of the RSSI during 2000 samples of radio signal in inter-level environment with 5 m distance between radio nodes.

Statistical mean value, median, and smoothing filter approximation method were every time applied on 500 samples. Smoothing filter ensures that a large difference between RSSI values will be smoothed, so peak values or noise can be suppressed.

Measurement accuracy of RSSI of the most today's radio chips used in sensor nodes is about ±4 dBm [11] and RSSI is also rounded to integer values. This means that notable uncertainty is brought to the estimation of distance.

Another uncertainty is caused by the signal propagation environment, like reflection, diffraction, scattering or penetration of the radio signal through the objects. Therefore, there are three types of sources of errors in RSS measurements: Errors caused by hardware, signal propagation environment and errors caused by method for approximation of the RSSI value.

4. Radio Propagation Model

The whole idea of distance estimation by means of RSSI is based in ideal case on the assumption that the received signal strength (RSS) is a function of the transmitted power and distance on the path between two radio devices, which is shown in Fig. **2**.

Equation (1) represents the path loss model proposed in [12], which is commonly used at small distances such as in buildings.

$$\frac{P_r(d_0)}{P_r(d)} = \left(\frac{d}{d_0}\right)^{\eta} \quad (1)$$

where $P_r(d)$ is- RSS in distance d [mW], $P_r(d_0)$ is RSS in the reference distance d_0 [mW], η is path loss exponent [−], d is the distance between transmitter and receiver [m], and d_0 is the reference distance [m].

$$RSSI = 10 \cdot \log \frac{P}{0{,}001} [\text{ dBm}] \Rightarrow P = 10^{\left(\frac{RSSI-30}{10}\right)} [\text{mW}],$$

$$\log P(d_0) - \log P(d) = \eta \cdot \log\left(\frac{d}{d_0}\right) \quad / \cdot 10,$$

$$\frac{RSSI_{d_0} - RSSI}{10} = \eta \cdot \log\left(\frac{d}{d_0}\right),$$

$$RSSI = RSSI_{d_0} - 10 \cdot \eta \cdot \log\left(\frac{d}{d_0}\right) \quad [\text{dBm}], \quad (2)$$

$$d = d_0 \cdot 10^{\left(\frac{RSSI_{d_0} - RSSI}{10 \cdot \eta}\right)} \quad [\text{m}]. \quad (3)$$

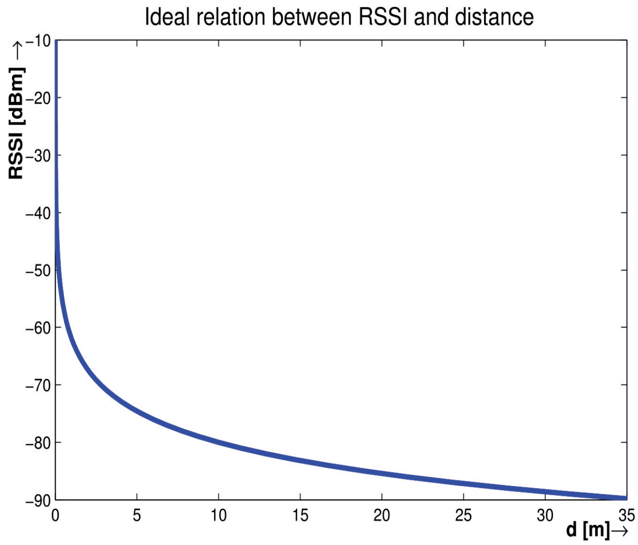

Fig. 2. Ideal RSSI over distance

RSSI value and reference $RSSI_{d0}$ are in dBm units. The relationship between the distance in (3) and RSSI value in (2) can be obtained with adjusting of (1). Equation (2) is so-called simplified log-normal shadowing model. Parameters $RSSI_{d_0}$, d_0, η are the main parameters for LNSM formula and they define the properties of radio propagation environment.

4.1 Distance vs. Measured RSSI

In this section we have tested the relation between the *RSSI* and distance shown in Fig. **3** in indoor environment. The experiment was conducted within constant transmitting power of 3.2 dBm between two IRIS XM2110 radio devices communicating in free space without obstacles.

Method	η [-]	d_0 [m]	$RSSI_{d0}$ [dBm]	δ [%]
AVERAGE	6.53	18.18	-72.19	10.12
MEDIAN	6.54	17.12	-75.73	11.71
SMOOTHING	6.42	12.18	-71.80	10.10

Tab. 1. The most efficient coefficients for Tx = 3.2 dBm.

In Tab. 1 the most efficient coefficients and mean distance estimation error are shown. These coefficients were obtained with simulation of the static calibration method in MATLAB environment. Static calibration algorithm uses every sample of the *RSSI* measured at a particular distance. Coefficients d_0, $RSSI_{d_0}$ and η are sequentially applied to the LNSM formula.

The most efficient coefficients are selected when applied in the LNSM equation to show the least estimation error for the whole interval of distance (in our case 21 m).

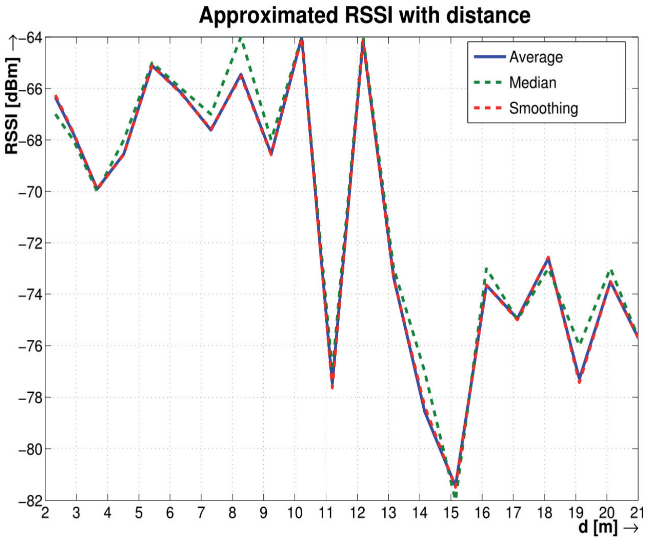

Fig. 3. Real RSSI over distance.

5. Adaptive Calibration of the LNSM Coefficients

As can be seen from the previous results, *RSSI* is the very unstable parameter that can be affected by various factors. So properties of this parameter bring uncertainty into precision of distance estimation techniques.

Many research papers describe distance estimation as a static process, when for the first, coefficients for LNSM formula are calibrated in a particular environment and then they are used for a whole time of measurement. Values of *RSSI* are environment dependent, which brings another problem, since we cannot guarantee that properties of environment stay constant. As can be seen in Fig. 3, there is not visible any notable relation between *RSSI* and distance in indoor at the whole interval of measured distance.

The proposed method tries to take all of these factors into account. This ranging system consists of fixed nodes that are suitably placed and continually sense the radio propagation environment, so they can dynamically evaluate coefficients for LNSM formula. Sensing the environment, respectively acquisition of RSSI value is performed at the background of communication between fixed devices.

5.1 Description of Method

Statistical mean value is used as the approximation method for suppressing the disturbance that occurs during sensing of RSSI.

In Fig. 4 there is an example of which information are sensed and computed for estimation of coefficient for LNSM formula. Calibration (fixed) nodes regularly process the received packets and gather information about $RSSI_{d0}$. This is performed on the background of useful communication.

$$P_r = P_t \cdot \left(\frac{1}{d}\right)^{\eta} \quad [\text{mW}], \tag{4}$$

$$\eta = \frac{\log\left(\frac{P_r}{P_t}\right)}{\log\left(\frac{1}{d}\right)} \quad [-]. \tag{5}$$

Parameters that are characteristic between two fixed nodes like reference distance d_0 and $RSSI_{d0}$ are known. Reference distance, which is in this case distance between calibration nodes, is known at the initial configuration. Then during the measurement, the value of $RSSI_{d0}$ is gathered from packets exchange between calibration nodes. *RSSI* is the value measured between mobile and fixed nodes.

Using these coefficients, the path loss exponent η of radio propagation environment is computed and defined with (5) proposed in [13]. P_r is the received power, P_t is the transmitted power in mW and d is the distance between two devices.

For distance estimation between mobile and fixed node Equation (3) is used. These values of estimated distance can be used for such other purposes like defining the position of the node in space with any kind of lateration technique as in [14].

Calibration of $RSSI_{d0}$, d_0 and η coefficients is performed only between a pair of calibration (fixed) nodes, which means that this method works correctly only when the pair of calibration nodes is located in a given area. One of the most important factors in this method is selection of the "appropriate" calibration node pair, so potential dynamic changes in given environment can be suppressed.

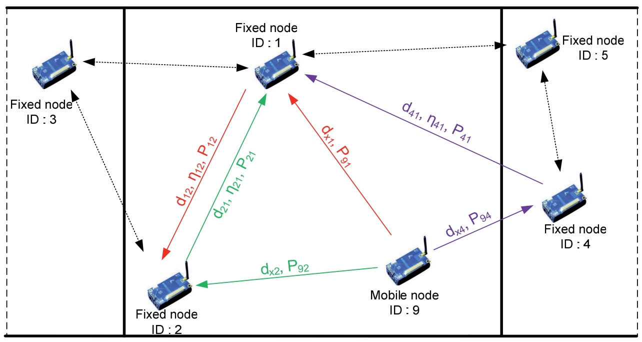

Fig. 4. Selection of the calibration node pairs.

Value of $RSSI_{d0}$ is very important for utilization of introduced dynamical calibration method. Interferences, other systems working in the same band, obstacles and movement of humans directly affect this value, what allows us to adjust the coefficients for LNSM formula. Calibration nodes regularly gather information with each other about $RSSI_{d0}$ that is affected by dynamical changes in radio propagation environment. Mobile nodes also regularly broadcast information to all fixed nodes in range. The value of RSSI between mobile and fixed node is then used for distance estimation.

The proposed adaptive algorithm selects the appropriate node pair for calibration process in a few steps. The example of sample topology is shown in Fig. 4, where selected nodes are differentiated by their color. This adaptive calibration process is performed for every fixed node that receives signal from the particular mobile node. Whole distance estimation in this implementation is performed at server database, where all sensed information is collected.

The first step in the proposed algorithm is selection of the mobile and fixed node pair, where the distance will be estimated. In the second step searching for every possible fixed node with which the mobile node communicates at same time is performed. One part of this step is finding the set of fixed nodes that are communicating with each other for calibrating purposes. At the end there will be selection of the neighbor calibration node that satisfies condition of direct communication simultaneously with the pair of mobile and fixed node. Another condition is that the new calibration node had to have the best value of received signal strength from the mobile node, so these nodes will be formed in triangle topology with minimum link cost at all line segments. With fulfillment of all these conditions there is assumption that mobile node is situated in the same environment as the calibration node. So for distance estimation only actual adjusted values of coefficients specific for given environment are used.

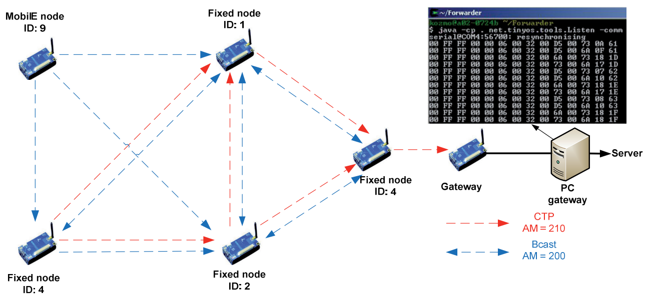

Fig. 5. Scheme of communication in sensor network

Communication architecture of this system is shown in Fig. 5. A data packet between the pair of mobile and fixed nodes includes only necessary information like address of the broadcasting mobile node and transmitted power. This packet is same when calibration between fixed nodes is in progress.

The gateway collects packets from every fixed (calibration) node, which contain source and destination addresses, transmitted power and received signal strength indicator. The gateway sends these values to the server that processes all incoming information to estimate distances between mobile and fixed nodes.

For communication the CTP (Collection Tree) protocol is used which is implemented in TinyOS. This network can consist of multiple gateways that are the roots of the communication tree. CTP is suited for low data rate WPAN's (Wireless Personal Area Networks). This type of communication is characteristic for WSN.

5.2 Experimental Measurement

For verification of performance of this system, six reference nodes attached to the ceiling in research laboratory and hall were used. The beginning of the coordinate system is in the left bottom corner on the ground plan shown in Fig. 6. The adaptive distance estimation method that does not meet the line of sight (LOS) condition was evaluated with this measurement. Therefore, this system could be used in various types of environments, where obstacles and dynamical changes are present. Every measurement was carried out on the marked points (cross 1-25) shown in Fig. 6.

Node ID	Position X [m]	Position Y [m]	Position Z [m]
103	11,7	9,8	3,3
106	11,7	2,1	3,3
126	0,34	1,1	3,3
127	0,34	4,73	3,3
128	7,52	4,73	3,3
129	7,52	1,1	3,3

Tab. 2. Node positions

Fig. 6. Ground plan of measured environment.

In the following graphs in Fig. 7 the ideal curves (black dashed line) of the distance estimation and maximal accepted variation (red dashed line) that was specified as ±1.5 m are shown. The distance estimation error from the original 10% achieved with static calibration shown in Tab. 1 was reduced to 4%. Therefore, our method for adaptive estimation of radio environment parameters results in the significant improvements in the distance estimation accuracy in comparison with the known static method.

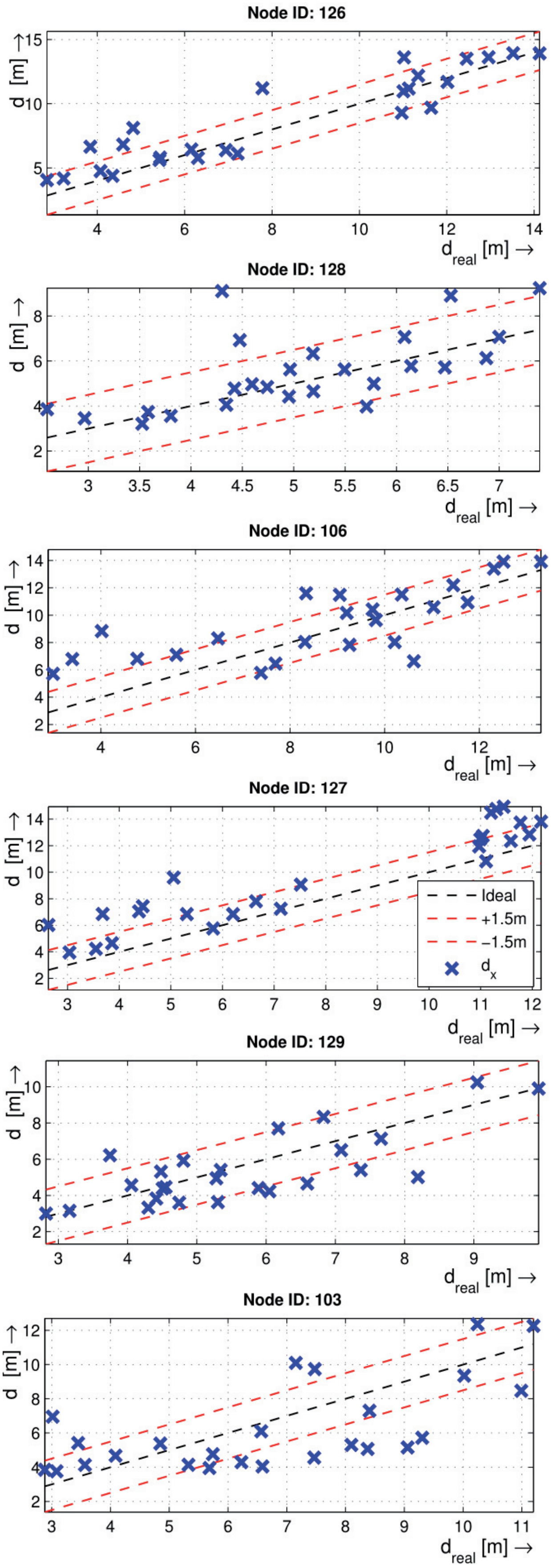

Fig. 7. Comparison between real and measured distance.

6. Conclusion and Future Work

The methods for distance estimation that can be used in indoor environment are very up-to-date topics. They have wide scope of applications like monitoring or surveillance of human beings or objects.

WSN devices used for RSS based method are not suitable for distance estimation with high precision. But they can be used at applications where this is not the main condition. With dynamical method we can estimate distance using LNSM formula without manual calibrating of every parameter. Errors from the original 10% achieved with static calibration shown in Tab. 1 were reduced to 4%. Inaccuracy that can be seen from the graphs in Fig. 7 could be caused by environment itself, where human beings, electronic devices in laboratory and other wireless systems working in the same 2.4 GHz ISM band were present.

Future work will be aimed to investigate the maximal count of reference nodes and distances between them. There will be also interests to use lateration techniques for estimation of position in space and choosing the "right" reference nodes for improving the method. Optimization of communication architecture with considering of energy consumption will also be a future topic.

Acknowledgment

This paper was prepared within the framework of grant project No.FRTI2/571 of the Ministry of Industry and Trade of the Czech Republic.

The described research was performed in laboratories supported by the SIX project; the registration number CZ.1.05/2.1.00/03.0072, the operational program Research and Development for Innovation.

References

[1] SILVA, R., SILVA, J., SILVA, A., PINTO, F., SIMEK, M., BOAVIDA, F. Wireless sensor network in intensive care units. In *Proceeding of IEEE ICC Communications Workshops*. Dresden (Germany), 2009, p. 68–72.

[2] JIANWU, Z., LU, Z. Research on distance measurement based on RSSI of ZigBee. In *ISECS International Colloquium on Computing, Communication, Control, and Management*, CCCM 2009. Aug. 2009, vol. 3, p. 210–212.

[3] SUZ, A., ELBATSH, K. A., MAC, E. Gradient RSSI filter and predictor for wireless network algorithms and protocols. *Network Protocols and Algorithms*, 2010, vol. 2, no. 2, p. 1–26.

[4] PARAMESWARAN, A. T., HUSAIN, M. I., UPADHYAYA, S. *Is RSSI a Reliable Parameter in Sensor Localization Algorithms.* An experimental study. New York, 2009.

[5] NAGY, Ľ., KARÁSEK, J., VYCHODIL, P., HOLEŠINSKÝ, P. Lokalizácia senzorov založená na RSSI (Localization based on

RSSI method). *Elektrorevue,* 2010, vol. 2010, no. 55, p. 1-6. [Online] Available at: http://www.elektrorevue.cz. (In Slovak).

[6] AWAD, A., FRUNZKE, T., DRESSLER, F. Adaptive distance estimation and localization in WSN using RSSI measures. In *10th Euromicro Conference on Digital System Design Architectures, Methods and Tools DSD 2007.* Aug. 2007, p. 471-478, doi: 10.1109/ DSD.2007.4341511

[7] MAO, G., ANDERSON, B., FIDAN, B. Path loss exponent estimation for wireless sensor network localization. *International Journal of Computer and Telecommunications Networking*, Jun. 2007, vol. 51, no. 10, p. 2467-2483.

[8] MORAVEK, P., KOMOSNY, D., SIMEK, M., GIRBAU, M., LAZARO, A. Energy analysis of received signal strength localization in wireless sensor networks. *Radioengineering*, 2011, vol. 20, no. 4, p. 937–945.

[9] SIMEK, M., FUCHS, M., MRAZ, L., MORAVEK, P., BOTTA, M. Measurement of lowpan network coexistence with home microwave appliances in laboratory and home environments. In *The 6th International Conference on Broadband and Wireless Computing, Communication and Applications*. August 2011.

[10] ATMEL. *AT86RF230 Datasheet*, Feb. 2009. Revision E.

[11] FARAHANI, S. *ZigBee Wireless Networks and Transceivers*. Newnes/Elsevier, 2008.

[12] KANG, J., KIM, D., KIM, Y. RSS self-calibration protocol for WSN localization. In *The 2nd International Symposium on Wireless Pervasive Computing ISWPC '07*. 2007. San Juan (Puerto Rico), Feb. 2007.

[13] XU, J., LIU, W., LANG, F., ZHANG, Y.Y., WANG, C.L. Distance measurement model based on RSSI in WSN. *Wireless Sensor Network*, 2010, no. 2, p. 606–611.

[14] HOLEŠINSKÝ, P., KOMOSNÝ, D., ŠIMEK, M. Lokalizační techniky bezdrátových senzorových sítí (Localisation algorithms of wireless sensor networks). *Elektrorevue,* 2009, vol. 2009, no. 66, p. 1-9. [Online] Available at: http://www.elektrorevue.cz. (In Slovak).

About Authors ...

Miroslav BOTTA received the M.Sc. degree in Electronics & Communication and Teleinformatics from Brno University of Technology (BUT), Brno, Czech Republic, in 2011. His research interests include optimization of communication in the low power wireless sensor networks.

Milan SIMEK received his M.Sc. degree in Electrical Engineering in 2006 and Ph.D. in Localization for Wireless Sensor Networking in 2010. His doctoral thesis was focused on anchor-free localization and boundary recognition for wireless sensor networks. Now he works as an assistant at the Department of Telecommunications, Brno University of Technology, Czech Republic. He is mainly interested in the research on the localization algorithms, investigation of the low-PAN energy consumption and 802.15.4 wireless channel measurements. His publications were presented in the international conferences (EWSN, WCSP, TSP) and journals (Springer-New York) and he also works as the expert for the European Committee for the ICT-Framework Program 7.