Position control for mobile nodes in wireless sensor network based on the IEEE 802.15.4 protocol by link quality estimation*

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Abstract

The paper describes a method for position control for mobile nodes in wireless sensor network, based LQI indicator provided by the IEEE 802.15.4 standard. Experimental measurements were carried out. The optimal performance parameters of the regulator have been obtained.

1 Introduction

Wireless Sensor Networks (WSN) based on the IEEE 802.15.4 standard [1] - low-speed personal distributed networks are currently the subject of many researches. This is due to their use in many relevant technical areas, such as monitoring of disturbed parameters (fire sensors, seismic monitoring, radioactivity, etc.), rapid deployment of the network in order to gather the information in the area (for military or rescue purposes). In such cases WSNs of aggregation network type are use: collecting data from disturbed sensors using a single root device (sink), forming a tree-like structure of wireless routes with a root in the sink. In this case, the transmission range of each node can be limited by several neighbors that act as repeaters from this node to the sink. This allows you to reduce the power of transmitter and increase the lifetime of nodes for safe battery. At high levels of the OSI model one of protocols for PAN networks is used: 6LowPAN - a protocol which uses IPv6 addresses for PAN networks [1], ZigBee - a protocol for devices with simple automation purposes (IoT, Smart Home, etc.) [2].

Wireless communication allows you to realize the ability of sensors to move. It's can increase the efficiency of the system by increasing the coverage of the area an optimal way. The initial location of nodes may be a priori unknown (if nodes were placed in its initial positions randomly, for example, by dropping from an airplane, or they begin to move from one common place). One of the most common optimization problems is the problem of optimal coverage of the field with sensors. Each point of the field should be in the coverage area of sensors of at least one node, and the total number of nodes in WSN should be minimal. Such mobile sensor networks are used both for tasks of dynamically coverage of certain area with a sensor network, and for more complex algorithms accompanied with movement (perimeter protection by patrolling, sweep coverage, etc.). A review of possible applications and the most typical algorithms was made in [3]. Several approaches are applied to this problem: methods based on the virtual force algorithm [4], graph-oriented methods [5], algorithms with the possibility of gap closing [6].

The problem described above is based on methods for determination and control of relative position of nodes by distance estimation between nodes. From location and distances to its neighbors the node can calculate its necessary movement dynamically. Currently, there are many approaches to determine the position of nodes: from expensive and accurate (GPS) to cheap, but with low accuracy. It is obviously that small WSN nodes require accurate, but cheaper methods for distance estimation. Several approaches have been developed for this task: by received signal strength (RSSI), by time of arrival (TOA), by time difference of arrival (TDOA), and by angle of arrival (AOA).

API though the problem of distance estimation has been observed in many papers, the close task of position control based on this data is much worse highlighted. However, since any values used by the regulator of object (in this case, the motor subsystem of sensor node) should be predictable and reliable, it is necessary to focus on practical aspects of control system implementation based on the feedback distance estimation signal.

According to this information, remainder of the article contains the following sections: section 2 shows an overview of existing methods for distance estimation from LQI value, in section 3 we discuss the probabilistic nature of the measured LQI values and propose a method for distance estimation, in section 4 gives a technique for position control of node using the measured LQI value has been proposed, experimental results of performance measurements has been shown in section 5, section 6 contains analysis of the results and a conclusion.

2 First Level Heading Existing methods for distance estimation based on signal strength and link quality

The paper of [7] provides an overview of existing methods for localization of nodes throw characteristics of radio signal. There are two main groups of algorithms: algorithms with distance estimation (ranged based) and with no distance estimation (ranged free). A key aspect of distance estimation algorithms is to obtain the distance from the current node to several nearest nodes and to find its position using the trilateration method. In ranged-free algorithms, node position can be estimated from the fact that the nearest beacon node with known coordinates is placed near the one. We assume that our node has approximately the same coordinates as the reference one. If there are several beacon nodes nearby, a more accurate estimation of node position can be performed by combining known coordinates of beacon nodes.

Ranged-based algorithms use one of following parameters of the received radio signal for this task:

- RSSI
- Time of Arrival
- Difference Time of Arrival
- Angle of Arrival

The most universal method is the first one. It is caused by complexity of due to the complexity of small time intervals measuring in ToA and DToA methods, and design of the antenna configuration for measuring in AoA method.

During measuring distance in RSSI based method the power of transmitted signal, the power of received signal and attenuation model must be taken into account. The formula is

$$P_R(t) = P_T - 10\eta \log(d) + X(t) \tag{1}$$

where P_T and $P_R(t)$ –powers of transmitted and received signals; η – an empirically selected parameter; d – distance between transmitting and receiving nodes; $X(t)$ – random component that depends on interference, attenuation in medium properties.

This equation can be solved with respect to variable d. Then the distance can be calculated by known values of the remaining parameters.

However, this technique has several disadvantages:

- the logarithmic law the attenuation is not always performed in real cases. This may be caused by both signal effects and anisotropy of signal propagation in different directions. The paper of [8] provides an estimation of error in calculated distance of ± 50% even for the stationary case.

- the presence of obstacles in the line of sight causes uncontrolled changes in the RSSI signal due to reflections from obstacles

- the determination of coefficient η and distribution law of random variable $X(t)$ requires calibration of the system before taking measurements, which is not always possible with dynamic deployment of network.

These shortcomings have been investigated in many papers where methods for overcoming them by hardware or software signal processing have been proposed. Part of these papers in this area is devoted to refinement and modification of model (1) [9, 10]. In research of [11] it is proposed to use an adaptive algorithm that dynamically determines actual current value of RSSI as a weighted sum of instantaneous measured values. Recent works focus on non-classical RSSI signal calculation: for example, the paper of [12] proposes distance estimation with the help of fuzzy logic. One of the hardware improvements is a combination of radio and ultrasonic transceivers [13]. However, this will require the installation of additional equipment on the mobile platform. In the case when sensor field can be prepared in advance, it is possible to orient nodes in space according to pre-arranged tags or anchor nodes, with known location [14].

However, it must be noted that the disadvantages cannot be completely by proposed methods. In networks based on IEEE 802.15.4-2003 standard, the quality of received signal can be estimated using the link quality indicator (LQI). The standard proposes to calculate LQI value with the help of the received signal, or signal-to-noise ratio, or a combination of both values. The LQI value should be between 0 and 255, where 0 is the worst received signal quality and 255 is the best. The dependence of LQI on the distance between the nodes is covered in the literature in only few articles [15] (indoors and outdoors), [16] (indoors). The difficulty of such task is that LQI calculation algorithm is selected individually by each chip manufacturer. Thus, the published data on this topic mainly concerns the Chipcon CC2420 chip and cannot be extrapolated on chips from other manufacturers. However, based on the information available in papers [15, 17], it can be assumed that the dependence of distance d_{ij} between nodes i and j on LQI indicator, which shows the link quality between them, can be interpolated by simple piecewise linear function:

$$d_{ij} = f\left(LQI_{ij}\right) = A \cdot LQI_{ij} + B \tag{2}$$

where coefficients A and B depend on specific chip manufacturer.

A comparison of RSSI and LQI indicators versus the distance between receiver and the transmitter in [18] shows that the relationship between LQI and distance is more monotonic and less susceptible to interference, especially for outdoor cases. This is consistent with the authors' data obtained during experiments with chips from another manufacturer [17].

3 Determination probability distribution parameters of LQI measurements values

Because measured value of LQI indicator is based on RSSI value, we can assume that distribution laws of random LQI values and RSSI values are the same as was shown in [11] the measured RSSI is the Gaussian random variable.

To determine the standard deviation, a number of measurements was carried out for various LQI values. The experimental setup consists of a pair of modules (transmitter and receiver), the distance between which can vary from 0 to 85m. The tests were carried out outdoors, with no people around and in conditions of direct visibility between modules. As a payload, a packet with length of 100 bytes was used (the maximum packet length in ZigBee protocol). The total number of measurements for each LQI value is 100.

Experimental results are presented in Fig. 1 and 2. It is seen that the average LQI values in the absence of obstacles on the line between receiver and transmitters decrease monotonously with increasing distance. Unlike LQI, the Packet Delivery Ratio (PDR) decreases non-monotonously, which can be caused by the fact that LQI is calculated by the first eight received bytes of the frame, while the PDR depends on bytes of whole frame, which can be dropped because errors in frame checksum.

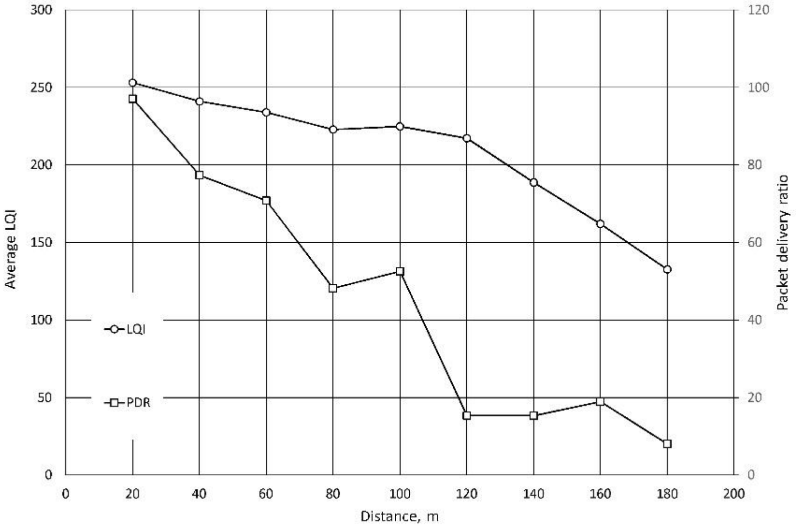

Fig.1. Influence of the distance between nodes on measured average LQI and PDR for outdoor

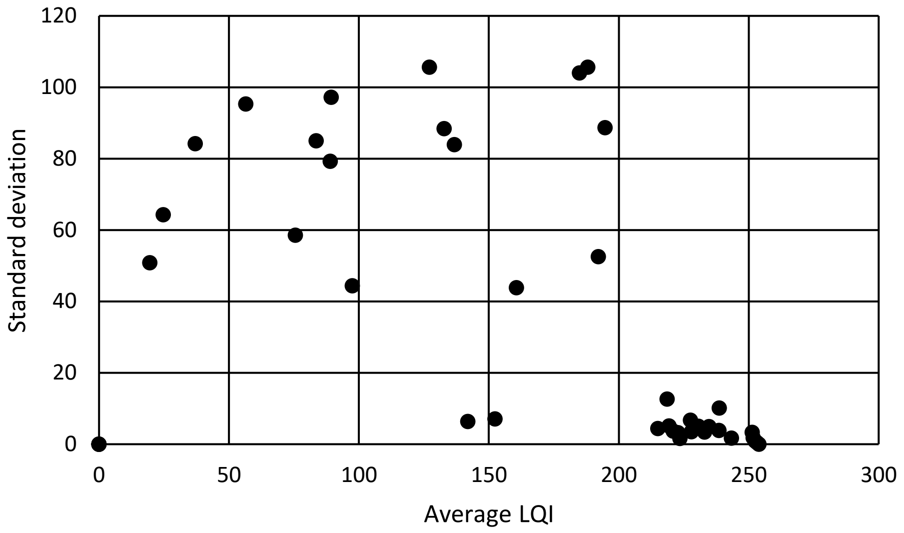

Fig. 2. Standard deviations of LQI values.

From Fig. 1 we can interpolate the relationship between distance d and measured LQI value: Small distances (<20m) do not cause a systematic change in LQI values. After reaching d = 20m, LQI value begins to decrease linearly. The dependence d (LQI) which we are interested in, can be obtained for distances greater than 20 m and has the form:

$$d = f(LQI) = -1{,}75 \cdot LQI_{ij} + 420{,}25 \quad (3)$$

From Fig. 2, we can conclude that for LQI range [200; 255] the RMS value does not exceed 6.7 (except for two measurement misses in region of 11-12). For LQI values less than 200, the standard deviation is stepwise and significantly increase. This limits the operating range for control the moving node: LQI = [200; 255]. Taking a lower value of LQI as the operating point will make control process of the node position difficult due to the noisy feedback signal for the regulator.

The probability of measurement miss can be estimated from the value of the standard deviation and known distribution law. According to [11], we can assume the distribution law of the obtained LQI values is the Gaussian law.

Suppose that measured LQI is a random variable with the mean value LQI_{set}. In this case, for a normally distributed variable, we estimate the probability p^* of obtaining value beyond a given range $(LQI_{set} - \Delta LQI_{set}; LQI_{set} + \Delta LQI_{set})$, which will be used in deadband for the regulator:

$$p(LQI_{set} - \Delta LQI_{set} \leq LQI \leq LQI_{set} + \Delta LQI_{set}) = F(LQI_{set} + \Delta LQI_{set}) - F(LQI_{set} - \Delta LQI_{set}) \ (4)$$

Where

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{(\lambda - LQI_{set})^2}{2\sigma^2}} d\lambda \quad (5)$$

is probability distribution function.

The probability p^* can be calculated:

$$p^* = 1 - p(LQI_{set} - \Delta LQI_{set} \leq LQI \leq LQI_{set} + \Delta LQI_{set}) \quad (6)$$

Having upper limit of 6.7 as the standard deviation (from fig.2), we get a graph for determining the probability p* and regulator deadband ΔLQI_{set}.

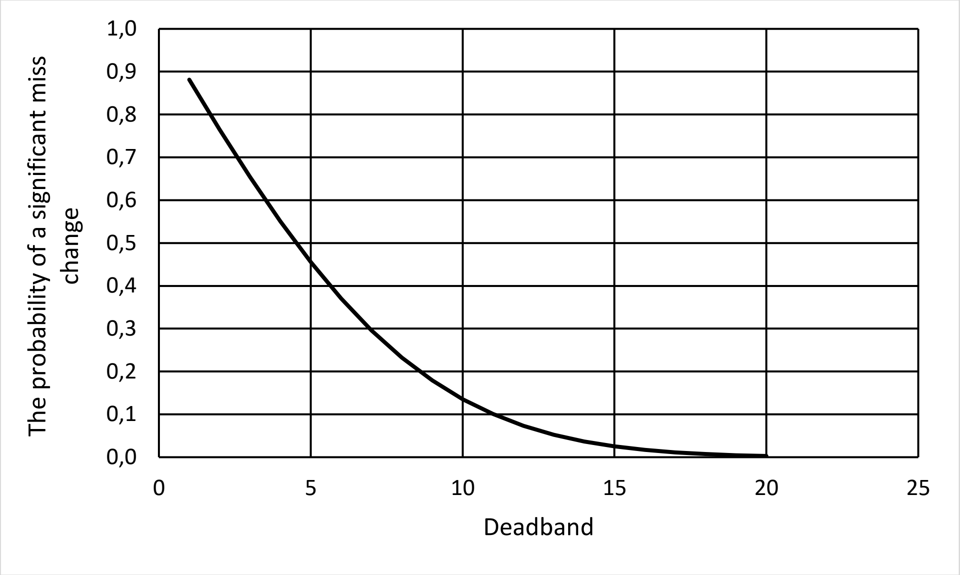

Fig. 3 The relationship between probability of miss and regulator deadband range.

4 Position control of mobile node

The research task is to automatic the distance between the fixed sink node and mobile autonomous WSN node. The equipment of model is shown in Fig. 4.

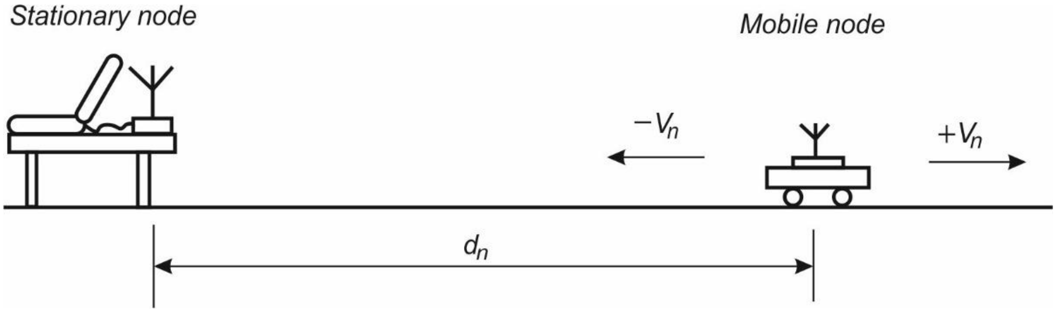

Fig. 4. The experimental setup.

Problem statement: it is required to automatically control the distance d_{set} from mobile unit to the base station by controlling the motors of the wheel platform of the unit.

As a mobile node WSN, a model based on AVR ATmega328 microcontroller was constructed. The mobile part consists of a four-wheeled platform with DC motors mounted on each wheel. The digital engine control circuit can select the direct and reverse direction of the wheels rotation at a constant speed. The experimentally established speed of the wheel rotation is 10.5 rad/s, while the linear velocity of the platform is 0.34 m / s. As a transceiver for wireless communication we use XBee S2C module with ZigBee protocol. The core of the module is Ember EM357 chip.

Such characteristics of the equipment led us to consider the position control system as a three-position digital regulator. This regulator has input parameters: 1) Set point distance between the mobile and fixed nodes d_{set}; 2) value of deadband of the controller Δd_{set}; 3) feedback signal - measured random value of LQI and the value of the distance $d(LQI)$obtained according to formula (3); and output parameter 4) a signal to DC motors of the wheels, which can take three states - back, stop, forward.

Node speed v is determined by the expression:

$$v = \begin{cases} +V_n, & d(LQI) < d_{set} - \Delta d_{set} \\ 0, & d_{set} - \Delta d_{set} \le d(LQI) \le d_{set} + \Delta d_{set} \\ -V_n, & d(LQI) > d_{set} + \Delta d_{set} \end{cases} \tag{7}$$

Because the distances $d(LQI), d_{set}, \Delta d_{set}$ are determined by values of LQI, $LQI,\ LQI_{set},\ \Delta LQI_{set}$, expression (7) can be reformulated as follows:

$$v = \begin{cases} +V_n, & LQI > LQI_{set} + \Delta LQI_{set} \\ 0, & LQI_{set} - \Delta LQI_{set} \le LQI \le LQI_{set} + \Delta LQI_{set} \\ -V_n, & LQI < LQI_{set} - \Delta LQI_{set} \end{cases} \tag{8}$$

The experiment equipment includes: 1) stationary base node; 2) mobile node (see Fig. 4). By determining the distance to sink, mobile node controls switch direct-stop-reverse directions of platform wheels. For operational measurement of LQI values, the node must receive ZigBee packets addressed for it or broadcasts. Based on performance of the MC, the frequency of broadcast packets of 1 Hz was selected on the stationary node. The time-lag of the control object in this case will be determined by the frequency of updating LQI value, and, therefore, the frequency of receiving frames from the base station. Parameters of three-position controller used in the experiment: 1) setpoint value LQI_{set}, which can be converted into a distance according to an empirically obtained formula; 2) the value of deadband of the regulator ΔLQI_{set}, inside which the position of node is recognized as satisfactory and does not require its movement to another place.

The choice of LQI_{set} was made basing on the obtained in Figs. 1 and 2 relationships. It can be seen in Fig. 1 that LQI values from the interval [222; 255] are of practical interest. At lower values, distance estimation is not possible due to the increasing influence of interference. Another criterion for choosing a setpoint is the standard deviation of a random variable LQI shown in Fig. 2. This parameter limits the range of setpoint values to the range [215,255]. The number of LQI_{set} values was chosen: $\{230, 240, 250\}$.

Deadband value was chosen on basis of probability p^* in Fig. 3. In addition, it must be noted that chosen value $\Delta LQI_{set} = 20$ is the upper limit of this parameter based on the restrictions discussed in the previous paragraph. When choosing, not only the probability of missing LQI value is important, but also the probability of such value, which forces node to move, p_{out}. This probability depends not only on p^*, but also on driver subsystem of the platform's (its speed and updating period of the LQI values). The probability of a node moves out the deadband is defined as the probability of obtaining N consecutively measured LQI values that exceed ΔLQI_{set} limit. Here N depends on the node speed v_{node} and the measurement period τ_{node} according to the formula:

$$p_{out} = \left(\frac{p^*}{2}\right)^N = \left(\frac{p^*}{2}\right)^{d(\Delta LQI_{set})/(v_{node} \cdot \tau_{node})} \tag{9}$$

These consideration sets a number of deadband $\Delta LQI_{set} = \{2,4,5,10,15\}$.

The experiment was conducted under conditions of line of sight between nodes outdoor, which minimized reflections, interference and attenuation from obstacles.

5 Measurement results

Performance measurement parameters are:

- Setting t_{set}; This value depends on the speed of node, which takes a place for gather sensor information.

- Average value of distance between nodes in the steady state d_{avg}; It allows to evaluate the offset error of the position.

- Standard deviation σ of distance d from the set point d_{set}. This parameter shows the accuracy of position control for node over time. The start point of parameter measuring corresponds to the time when the node reaches the point with $d = d_{set}$

- Total time τ_{move} of motors turning on. This parameter helps to calculate the degree of use of motor subsystem in transient process and after. Movements a node around setpoint cause fast depletion of node battery.

Measured results for chosen cases of initial parameters are collected in table 1.

№	d_{set}, m	Δd_{set}, m	LQI_{set}	ΔLQI_{set}	t_{tot}, m	t_{set}, s	d_{avg}, m	σ, m	τ_{move}, s
1	45	3,5	250	2	500	442	45,9	0,8	344
2	45	6	250	4	220	166	-	-	104
3	60	8,8	240	5	500	212	64,9	4,81	368
4	60	17,5	240	10	500	160	63,7	3,63	248
5	75	17,5	230	10	500	224	77,6	3,1	338
6	75	26,3	230	15	500	198	81,2	3,08	294

Typical dependences of the distance on time for experiments 1, 4, 6 are shown in Fig. 5-6.

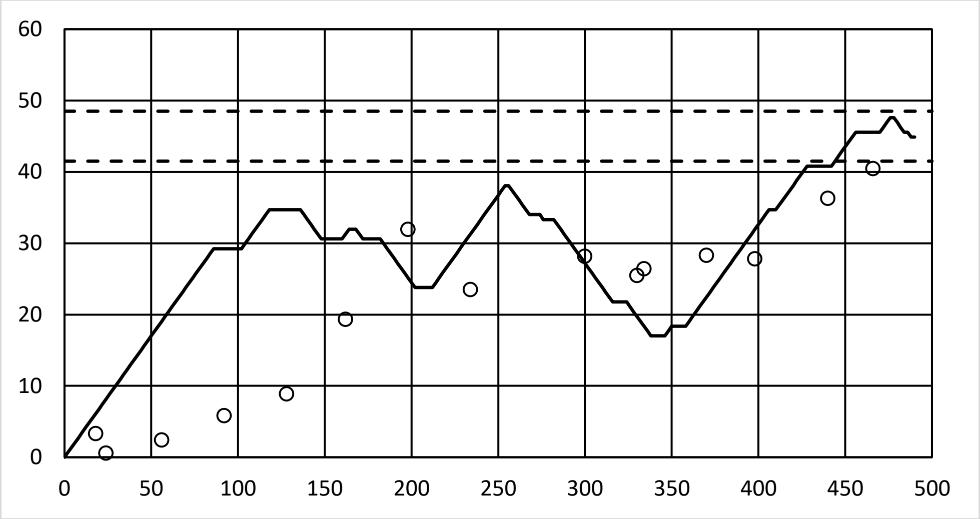

Fig. 5. Time dependence of the distance between mobile node and the sink at $d_{set} = 45\ m\ (LQI_{set} = 250), \Delta d_{set} = 6\ m$

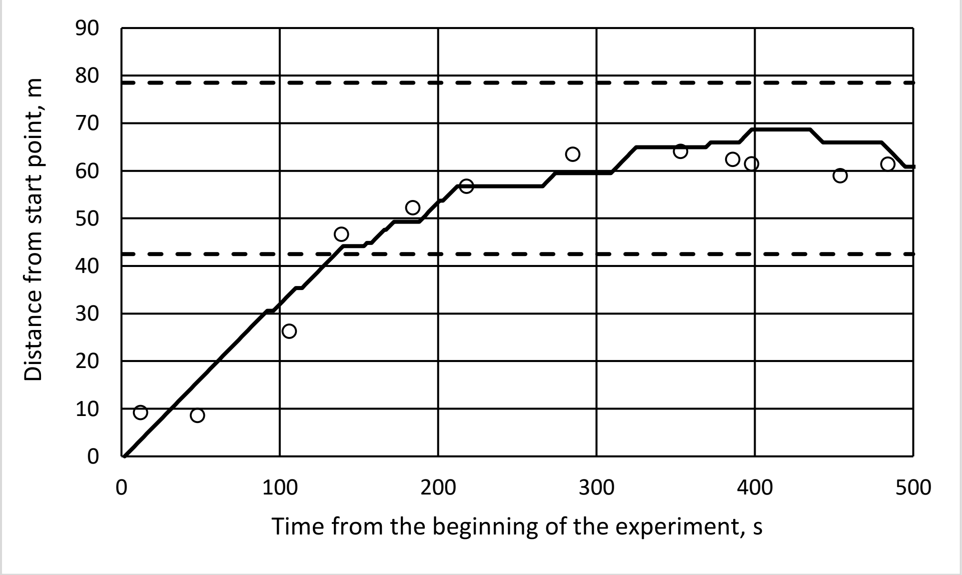

Fig. 6. Time dependence of the distance between mobile node and the sink at $d_{set} = 60\ m\ (LQI_{set} = 240)$, $\Delta d_{set} = 17{,}5\ m$.

The corresponding time dependences of measured LQI parameter are shown in Figs. 7-8.

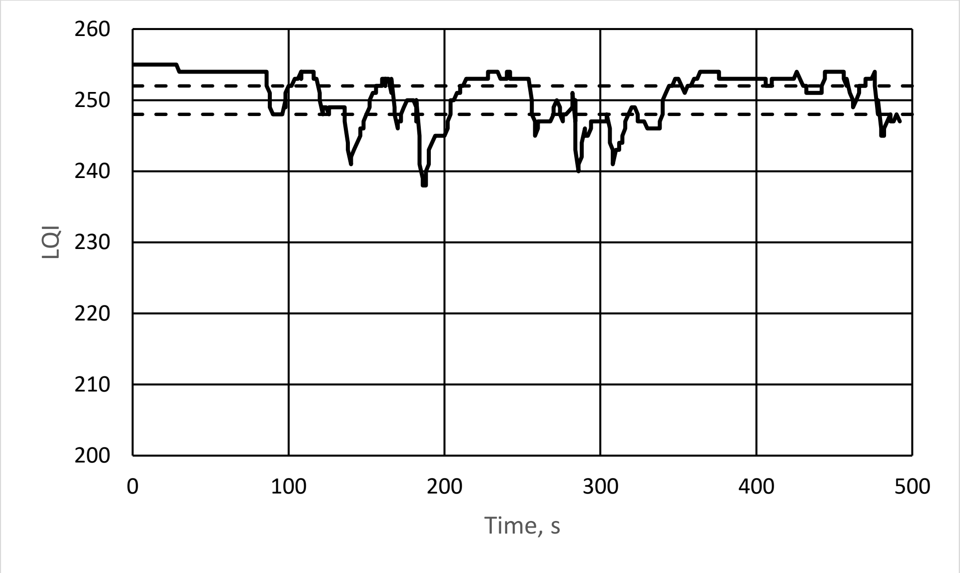

Fig. 7. Time dependence of the distance between mobile node and the sink at $d_{set} = 45\ m\ (LQI_{set} = 250)$, $\Delta LQI_{set} = 2$.

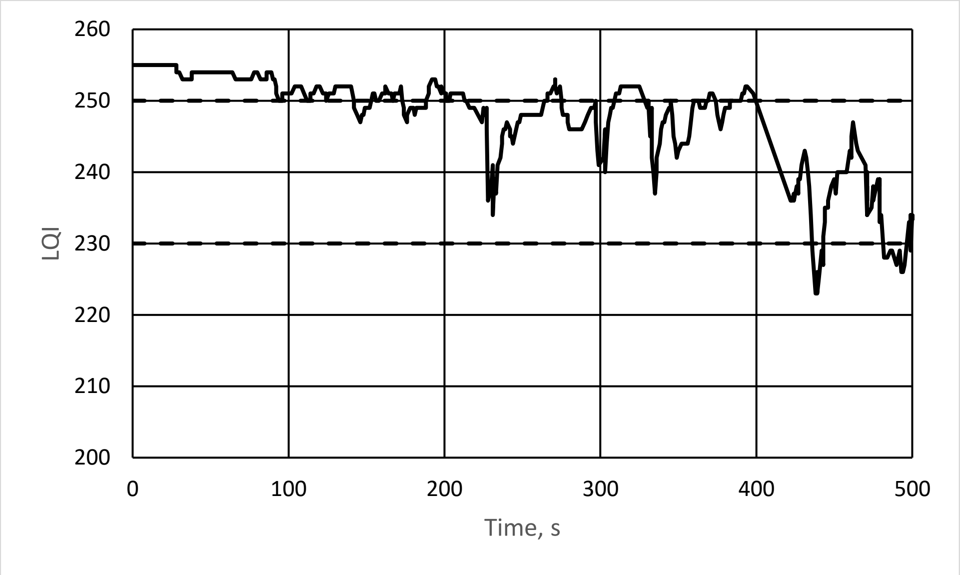

Fig. 8. Time dependence of the distance between mobile node and the sink at $d_{set} = 60\ m\ (LQI_{set} = 240)$, $\Delta LQI_{set} = 10$.

5.1 Setting time, required for node takes place

According to the table 1 the fastest way to the set point was shown in cases 2 and 4. This is can be explained by reasons: a small target distance (d_{set} = 45 m in experiment 2) and a wide deadband (Δd_{set} = 17.5 m in the experiment 4). The small target distance allows node to reach the operating point with high LQI values in short time, but at the same time, by reducing average distance between nodes, the total network coverage area is reduced. On the other hand, considering the random values LQI in feedback and small values of the deadband, the probability of a measurement miss is high, that leds to often pauses in the platform engine moving and increases the time to reach the error bound (as, for example, in experiment 1). Thus, considering the setting time, the optimal combination is: average distance between nodes (60-70m) and average deadband (10-20m).

5.2 The accuracy of node B position control

In experiments 1,3,5 the setpoint distance was increased from 45 to 75 m. The accuracy of position of the motor subsystem of the mobile node decreases with increasing required distance. This is due to the fact that with increasing distance, the probability of LQI misses increases, which makes the control process more complicated. It is seen that in experiment 6, small changes in the position of the node lead to significant changes in LQI value, which reduces the control quality, but can be compensated by an increase of deadband (up to 26.3 m). The magnitude of standard deviation for the distance does not increase significantly. This fact proves data shown in Fig. 2. So, we can conclude that for considered combinations of setpoint distance and deadband, all experiments show required control quality.

5.3 Efficiency of motor subsystem using

Mobile nodes in wireless sensor networks have autonomous power supply for both the control and drive parts. Therefore, an optimal movement strategy is required both for moving to set point and for maintaining the position. In this paper, this parameter can be indirectly estimated as the total time, when the platform moves. The shortest moving time was demonstrated in experiment 4 ($d_{set} = 60\ m, LQI_{set} = 240$ и $\Delta d_{set} = 17{,}5m$).

Thus, summarizing the analysis of measured results we can describe each of experiments in terms of one of performance indicators: experiment 1 demonstrated the poor quality of regulation due to small deadband. This drawback does not allow the node to reach setpoint in the shortest time (time was spent on stopping due to missed measurements of LQI value); experiment 2 with small setpoint distance shows a short settled time. During experiment 3 we set deadband and the platform also reaches the setpoint point in a long time. Experiment 4 shows the optimal combination of parameters ($d_{set} = 60\ m, LQI_{set} = 240$ и $\Delta d_{set} = 17{,}5m$), in which the node holds on the distance, while spending a small amount of energy on moving. Experiments 5 and 6 test the system for low LQI values, when probability of measurement misses increases. This disadvantage can be compensated by wide deadband (Experiment 6). However, this set of parameters is not efficient in term of battery usage.

6 Conclusions

In this paper, we research practical aspects of mobile node position control in wireless sensor network using the measured LQI signal values. A number of experiments was conducted to obtain an optimal combination of control parameters. Existing methods for distance estimation do not take into account properties of position regulator (type of regulation, control parameters, random values of feedback and so on).

We propose to estimate distance from measured LQI values in wireless communication. The dependence of LQI value on the distance, and standard deviation for LQI values has been measured. Based on the normal distribution law of a random variable, an estimation of the measurement error probability, which can be led to harmful position changes of node. These researches allows to obtain a number of control parameters for three-position regulator, which controls the motor subsystem of node: setpoint ($d_{set} = 40..100$m) and deadband (Δd_{set} = 3..25m).

The experimental model was assembled on a wheeled platform with DC motors controlled by the ATmega328 MC. As a communication module, the ZigBee XBee S2C module was used, which provided the physical standard IEEE 802.15.4.

Measured results show the optimal combination of control parameters $d_{set} = 60m, LQI_{set} = 240$ и $\Delta d_{set} = 17{,}5m$ for chosen conditions. When distance setpoint exceeds the optimum, link quality decreases, and accuracy of node position control worsens. Reducing the deadband causes the platform to make unnecessary movements, because misses of measurement LQI quickly move the platform away from optimal place. Increasing the deadband $\Delta d_{set} > 20$ m reduces the accuracy of position control near the operating point.

Future research will be aimed at increasing the number of mobile nodes to obtain a coverage area by sensors network. The question of optimal control law also remains open, and PI or PID regulator may be interesting.

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