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INVESTIGATION OF THE POSSIBILITY OF REDUCING ERRORS IN DETERMINING THE COORDINATES OF OBJECTS INDOORS BY MULTI-FREQUENCY METHOD

Purpose. To investigate the influence of LOS/NLOS conditions on the radio signal propagation and the possibility of interference mitigation by using multi-frequency method of transmitting and receiving for positioning tasks in enclosed spaces. To check the difference in measurement accuracy when receiving a signal at one frequency from receiving a signal at four frequencies by combining the measurement results of individual frequencies into one reading. To check the influence of various obstacles on the signal passing.

Methodology. Design at the laboratory of UHF – generator and BLE – beacons with the ability to set broadcast frequencies and adjust transmission power. Application of a multi-frequency transmission and reception method.

Findings. The possibility of increasing the accuracy of positioning of objects in closed rooms, including mine workings, through the use of multi-frequency radio signals is investigated. It is shown that the influence of re-reflections of radio signals from the walls of structures, from obstacles of various origins, and the associated interference, can be reduced by using averaged values of attenuation at different frequencies. The use of radio emitters with many frequencies as "beacons" can provide new possibilities in solving the problem of positioning objects in closed rooms.

Originality. The work proposes a method for combining measurement results of individual frequencies into one reading, which will reduce interference. Multi-frequency transmission method and multi-frequency reception method are proposed to reduce the influence of interference caused at one frequency on the overall signal level.

Practical value. The experimental results obtained can be used at deploying positioning systems in closed rooms, including mine workings.

Keywords: *Bluetooth Low Energy – BLE, line-of-sight – LOS, non-line-of-sight – NLOS, received signal strength indicator – RSSI, beacon, USB – generator, spectrum analyzer*

Introduction. Indoor positioning is one of the main challenges in applications for underground construction, positioning robotic vehicles, rescue services, museum excursions. These and other tasks require precise positioning. To determine the location of an object, you can use Bluetooth, Wi-Fi, RFID, UWB, infrared radiation, inertial navigation systems, visible light, computer vision, micro-electromechanical systems, geomagnetic fields and pseudo-satellites [1]. In this article, Bluetooth Low Energy – BLE technology was used as a transmission technology. Not standard, but modified for research tasks beacons were designed based on this technology, as well as a device capable of broadcasting at frequencies from 0.025 to 6 GHz, which we will call the microwave beacon. By reading the signal level in dBm from these devices to the receiver, they need to be converted to a length scale in meters. Knowing the coordinates of transmitting devices and the distances to the receiver from them, based on the intersection of the circles, solving the equations, you need to find the location of the desired object. But in closed spaces, the location of the object will be determined with an error if you use only theoretical calculations. Beforehand, it is necessary to carry out practical detections to determine signal attenuation in line-of-sight and in the presence of obstacles. Experiments must be carried out multiple times and with an accurate reading device. In the article, a precision 5-channel spectrum analyzer and smartphone software are presented as the reader. A software application for smartphones was also used to compare the readings of signals by different means. BLE and microwave beacons transmitted signals at different frequencies. To eliminate interference, if a signal at one of the frequencies experiences interference, the rest of the signals during averaging will not greatly spoil the result. Thus, on the basis of practical results, the difference between the positioning method at one frequency and the method for determining the position at several frequencies is analyzed.

Literature review. According to GOST R 5515442012 [2] p. 6.3.9.2., there is a requirement that the subsystem must continuously in real time determine the location of each worker who has descended into the mine with a resolution of ±20 m. [3] proposes a complex for positioning personnel and transport with the function of alerting personnel "Argus-control". The purpose is to determine the position of the personnel in underground workings and in-mine transport; personnel notification. The presented technical characteristics indicate the frequency range of radio communication in 2.405–2.485 GHz, which is approximately the same as the used frequency range in our article, the maximum length of the cable segment to the repeater is 1200 m and the guaranteed detection distance of mobile objects is 100 m, which does not meet the requirements of the regulatory document [2]. It is necessary to increase the positioning accuracy to 20 m.

In [4], the authors point out that, taking into account the permitted movement of people in a coal mine with the maximum possible speed on a conveyor belt of 3.15 m/s, the period for updating data on the location of personnel should not exceed 1–3 s. It is noted that at large values of this period, the positioning accuracy parameter of 20 m will significantly expand and the system will lose its practical value. The rationale for using Bluetooth Low Energy (BLE) in our article over other technologies is justified by this remark, since BLE has a high scanning speed and the time between two events reaches 7.5 m·s. When choosing a technology for indoor positioning, one can be guided by article [5]. The authors of this article conducted a comparative analysis of these two technologies. BLE has a low power relative to mW – 1 dB (20 dB – Wi-Fi), high scanning speed – 30 Hz (1 Hz – Wi-Fi), low power consumption – 30 mW (1 W – Wi-Fi). In an indoor experiment, they showed that BLE has advantages over Wi-Fi. Three main advantages: frequency hopping – if there is interference on one of the channels, then a transition to another channel occurs; low transmission power – helps to avoid multipath effects, i.e., rays coming with reflection are heard only as noise; high scan rate – allows one to average possible spikes from interference or multipath. Also, when deploying Wi-Fi access points, they are guided by providing good coverage, rather than positioning tasks.

In [6], the authors reviewed positioning technologies suitable for deployment in underground mines. The authors point out the gaps that no one has overcome yet: accessibility; the presence of direct and indirect visibility conditions – LOS/NLOS; functional safety. These challenges must be overcome in a cost-effective manner. The authors point out that due to narrow tunnels and large vehicles in underground mines, LOS/NLOS conditions change frequently and quickly. It is often difficult to assess when an object is in LOS or NLOS conditions. Vehicles can also influence interference. The fading of the radio signal due to this can reach 50 % or even more, which in turn affects the accuracy of positioning. Our article empirically investigates these tasks. Influence of LOS/NLOS conditions, reduction of interference noise.

In [7], the authors presented their development of an underground navigation system based on the Bluetooth technology. The system monitors the exact location of each dump truck in an underground mine using sensors, analyzes a possible access road from the current location to the destination, and displays the path on a mobile device. The authors point out the disadvantage of the system in the time delay in determining the signal from one transmitter to the next. A possible solution is to install more transmitting devices at a short distance from each other and improve the software application to reduce the delay in signal detection. The authors point out that many positioning systems in mines are patented by companies. The article proposes its own development of Bluetooth Low Energy sensors, but the possibility of combining signals of different frequencies is not considered. The article does not contain the results of the conducted experiments to study the attenuation of signals from various obstacles.

In [8], the authors presented a warning system required to detect the approach of an object in mines. Experiments on signal detection by the receiver from BLE transmitting devices showed that the required average distance to the object was from 18.4 to 37.4 m. The accuracy depended on the location of obstacles, which justifies the importance of multipath propagation. By reducing the interference caused by this, one can approach the requirements of the normative document [1]. In [9], the authors suggested using the difference between the time of determining the first and the last beacons to determine the passage of a mobile object in underground mines. As suggestions for future research, the authors suggest paying attention to positioning methods to improve accuracy, since the article did not investigate the effects of obstacles and multipath propagation.

In [10, 11], the authors point out the need for more practical research.

In [12], based on the analysis of underground mines, the authors point out that before deploying systems based on BLE, it is necessary to take into account the structure of tunnels, frequent reflections and obstacles from various materials.

In [13], the authors point out that in underground mines, the positioning accuracy deteriorates due to reflections from the walls of the tunnels. They have developed an algorithm that determines the location of mobile objects, taking into account errors in reading distances. The disadvantage is the lack of experience in reading the signal in the presence of obstacles, such as space between floors and metal objects. The authors also point out the importance of solving the problem with interference.

In [14], the authors presented an indoor positioning method for dynamic RSSI correction by deploying a Bluetooth gateway. The authors conducted the experiment in a rectangular office space with many working people and office equipment and furniture. The authors point out that they did not consider special cases in the experiment, such as the corners of rooms and other complex electromagnetic regions. In [15], the authors propose an adaptive and reliable algorithm based on channel separation, on models with separate signal attenuation, on a distance selection strategy and a weighted algorithm for determining coordinates by intersecting circles using BLE sensors and well-known brands of smartphones. The authors emphasize that NLOS is a major factor that degrades RF distance estimation. In their NLOS measurement, cases were not fully considered to stabilize positioning. The authors propose to conduct additional studies with different station deployments to assess positioning errors. In [16], the authors point out that one of the interesting directions for future research is the development of new algorithms and the adaptation of existing algorithms for more complex indoor localization scenarios in complex NLOS environments. NLOS can significantly reduce localization accuracy, especially in cases where the surrounding configuration is unknown, i.e., where it is not known in advance which one is a LOS channel and which one is NLOS. Instead of allocating between LOS and NLOS channels and neglecting the NLOS channel, considering it as an incorrectly received signal, it is advisable to isolate the offset of the NLOS channel relative to the noise and use this opportunity to improve positioning accuracy in difficult environments. In [17], the authors propose a complete system for determining the location of people indoors. The authors propose to analyze the impact of the presence of people as obstacles to improve performance. The authors of [18] carried out the reading of the signal level in an empty room, with a small number of obstacles and in the presence of a large number of obstacles. In [19], the authors propose an algorithm for determining the location in a closed object using a smartphone using BLE sensors. Description of the algorithm of the authors of the article is as follows: it is required to find the location of the receiver. The receiver measures the level of the RSS signal from them separately for three channels. Then, these readings are smoothed. The polynomial regression model (PRM) determines the distance, and FP (fingerprinting) determines the location of the receiver. Using the average of all three broadcast channels, the confidence interval is determined by the outlier detection method. If any measured distances are outside the confidence interval, they will be discarded as outliers. The data goes through advanced

Kalman filtering. This is where the state vector and covariance matrix prediction process take place and is updated based on the measurement model. After that, outliers are detected again. These data are the final results. They are sent to the exit and to the FP printing base to improve the base. The polynomial regression model uses the nth degree polynomial as opposed to the simple PM (propagation model). The polynomial coefficients are found during the calibration process. The calibration process calculates the error of the difference between the estimated distance and the true distance. Then, according to the condition of minimizing the error in relation to the coefficients, the partial derivatives are taken and equated to zero. The optimal coefficients are found by solving the equations. The authors point out that the conventional propagation model is not suitable for use in closed sites, due to the large number of obstacles and the inability to distinguish LOS from NLOS. However, their proposed PRM polynomial regression model at finding the polynomial coefficients also did not take into account the combination of LOS and NLOS for indoor environments. At reading the RSS signal level by the receiver, it is necessary to take into account all possible scenarios of LOS, NLOS, obstacles, spaces between floors. Then, one should use the averaged data. This will give an acceptable result for rooms with complex geometries. Then, these signal level readings can be used to estimate the coefficients of the polynomial by the authors' method. The authors point out that, using the average of all three broadcast channels, the confidence interval is determined by the outlier detection method. If any distances read are outside the confidence interval, they will be discarded as outliers. But if three broadcast channels are combined in this block, then this method is similar to the channel sharing method. Practical results have shown that a sparse sensor configuration performed better than a similar multi-channel configuration. But, with a larger number of them, the accuracy of the algorithm of the authors of the article and the algorithm with channel combining is approximately the same. This way more sensors can be used.

Determining the location of an object in closed rooms is carried out by two methods: triangulation and an algorithm based on the use of distances. The triangulation method is performed by calculating the angles between three sensors with known coordinates and the direction of movement of the desired object. Using the method of complex numbers and solving the equation, we find the coordinates of the desired object. The distance-based method is performed by detecting the received signal strength indicator (RSSI) from three transmitters with known coordinates to the target. The readings of the power value are converted to a length scale, in meters, and by solving the equation, the coordinates of the desired object are determined.

Theoretical studies determine the coordinates of the object, but in practical applications, the coordinates of the object are determined with errors. This is due to the presence of noise in the surrounding area.

Experimental studies are needed to determine the practical values of the power readings from sensors. Applying this data, one can adjust the accuracy of the coordinates of the desired object.

Purpose. To investigate the influence of line-of-sight (LOS) and non-line-of-sight (NLOS) conditions on the radio signal propagation and the possibility of interference mitigation by using multi-frequency method of transmitting and receiving for positioning tasks in enclosed spaces.

Taking into account the current related literature review, we distinguish the main tasks of this paper.

Experiments are carried out to determine power level of signal of the UHF sensor at configurations, when transmitter and receiver are located:

1) at line-of-sight (LOS);

2) at non-line-of-sight (NLOS). Obstacle object made of iron material;

3) at non-line-of-sight (NLOS). Obstacle object is a wall;

4) at non-line-of-sight (NLOS). Obstacle object – space between floors; (*4^{th}–3^{rd}*, *4^{th}–2^{nd}*, *4^{th}–1^{st}*);

5) carrying out experiments at different frequencies: 1800, 2000, 2200, 2400 (MHz);

6) comparing results for single channels with the results for combined channels;

7) measurement of power level of Bluetooth Low Energy (BLE) beacon, when transmitter and receiver located at – line-of-sight (LOS) condition;

8) comparing results for single channels with the results for combined channels;

9) carrying out experiments with precise 5-channel spectrum analyzer and "BLE – scanner" standard software application for smartphones.

Methods and results. For practical purposes, two generators were designed. The first, connected via USB to a computer, is capable of broadcasting a signal at frequencies from 0.025 to 6 GHz. The second, also connected via USB to a computer, is a BLE beacon that broadcasts a signal in the standard frequency range for Bluetooth, but with a channel width of 2 MHz. For the tasks of determining the magnitude of the signal power, a spectrum analyzer was used, capable of operating simultaneously on five channels, designed by combining five USB-SA 124 B modules, capable of measuring signals at frequencies from 100 to 12.4 GHz. To compare the differences in accuracy and display capabilities, the signal from the BLE beacon was measured with a smartphone with the BLE scanner application installed. An image of the BLE generator is shown in Fig. 1.

Spectrum analyzer modules for five channels are capable of measuring signals from 100 kHz to 12.4 GHz. The modules have a relative accuracy of 0.25 dB.

Ultra-high frequency beacon specifications: microchip: HMC833LP6GE. It has low noise, wideband, uses a Fractional-N Phase-Locked-Loop (PLL) consisting of an Integrated Voltage Controlled Oscillator (VCO) with a fundamental frequency of 1500 to 3000 MHz and a built-in VCO external divider (divisible by 1/2/4/6.../60/62), which together allows the HMC833LP6GE to generate signals at frequencies from 0.025 to 6 GHz. This is its bandwidth. Built-in Phase Detector – Integrated Phase Detector (PD) and delta sigma modulation, capable of operating up to 100 MHz, provide a wider contour bandwidth with superior spectral performance. The lighthouse broadcasts sinusoidal frequencies. Very low phase noise: –110 dBc/Hz in Band Type; quality factor: –227 dBc/Hz; standard deviation: <180 fs; power change: 0 dB: –0.5 dB (step): –31.5 dB; frequency accuracy: 3 Hz; maximum signal power: at 1 GHz-17 dBm, at 2 GHz-16 dBm, at 3 GHz-12 dBm; power: 1 mW.

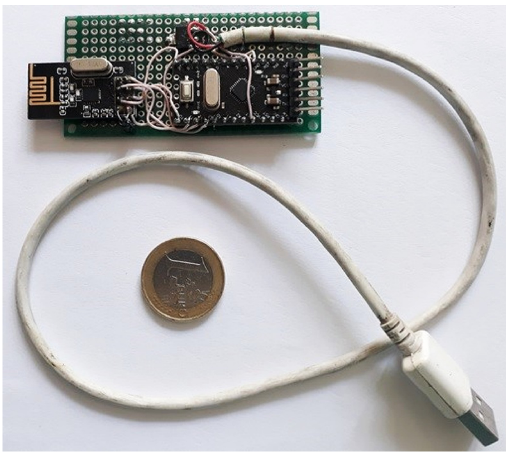

Fig. 1. BLE generator (beacon), which broadcasts signal in standard Bluetooth frequency, but with twice channel bandwidth

For practical tasks of determining coordinates using distances, a BLE transmitter designed for these tasks was used. The design office manufactured BLE transmitters based on the nRF24L01 chip and operate in the ISM – 2.4 GHz band. BLE transmitters have been designed for experiments and are similar to the standard specification. Standard Bluetooth equipment uses the ISM band and has a single channel bandwidth of 1 MHz. By programming the BLE transmitters, the channel bandwidth has been changed from 1 to 2 MHz. So, designed BLE transmitter has 40 channels. For the experimental purposes transmitters broadcasts data on 4 channels of 2405, 2423, 2429, 2477 (MHz) frequencies. Received signal strength RSS from these 4 channels measured by spectrum analyzer and with software application for smartphones "BLE scanner".

Below, in all the figures, the experimental results are presented: Reference path loss is the theoretical dependence of the signal power value from the distance (red curve). Intermediate lines of different colors are the quadratic fit of the curves to all measured data points. Blue data points are made by averaging all measured data at all frequencies. The blue curve is the quadratic approximation of these data points.

Received signal strength indicator (RSSI) at line-of-sight (LOS) condition in closed room. Reading the signal from the generator at various frequencies: 1800, 2000, 2200, 2400 (MHz).

To perform practical tasks, the generator is installed in the line-of-sight zone and its coordinates are recorded. The broadcast frequency is tuned. Measurement starts at 1800 MHz. Also, the measurement is repeated for other frequencies. At a distance of 1 meter from it, we place the spectrum analyzer to be sure that the wave is formed. We write down the analyzer reading. We move the analyzer by another 1 meter, again record the reading of the device. Thus, we take the analyzer reading every 1 meter. When the signal value does not stand out from the ambient noise value, we stop measuring. For practical tasks, the antenna length of the transmitting device was chosen the same for all given frequencies. The analyzer antenna length was chosen equal to its length and also did not change during the experiment [20, 21]. The location of the transmitting and receiving equipment for practical tasks of measuring the value of the received signal in line-of-sight is shown in Fig. 2. The results of reading the signal are shown in Fig. 3.

Received signal strength indicator (RSSI) at non-line-of-sight (NLOS) condition in the presence of obstacle from iron in closed room. Signal level measurement at various frequencies: 1800, 2000, 2200, 2400 (MHz).

Practical tasks began with setting the transmitting frequency of the generator and fixing its coordinates on the ground. The first stage of measurement began with a frequency of 1800 MHz. Then, we repeat the readout for frequencies 2000, 2200, 2400 (MHz). At a distance of 0.2 m from it, we set up an obstacle made of iron material. The spectrum analyzer is installed at a distance of 1 m from the obstruction. We move the analyzer away from the obstacle by 1 m. Obstacle size is 1.2 × 1.8 m. The rectangular shape does not cover the receiver, but covers part of the space between the broadcasting device and the analyzer. We write down the analyzer reading. We move the receiver by another 1 m, record the reading again. Thus, we take the reading of the receiving analyzer every 1 m. When the signal value does not stand out from the surrounding noise, we stop measuring. For practical tasks, the antenna length was chosen the same for all given frequencies. The length of the analyzer antenna was chosen equal to the length of the generator antenna and also did not change during the stages of the experiment. The preliminary location of the transmitting and receiving equipment, as well as obstacles between them for reading the received signal with no direct visibility, is shown in Fig. 4. The results are shown in Fig. 5.

Fig. 2. Experimental setup of generator and spectrum analyzer for measuring of received signal strength at line-of-sight (LOS)

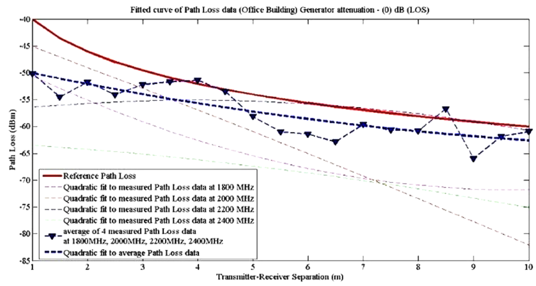

Fig. 3. Quadratic curve fitting of RSSI dependence on distance at LOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer

Fig. 4. Experimental setup of generator and spectrum analyzer for measuring of received signal strength at non-line-of-sight (NLOS) in the presence of obstacle from iron

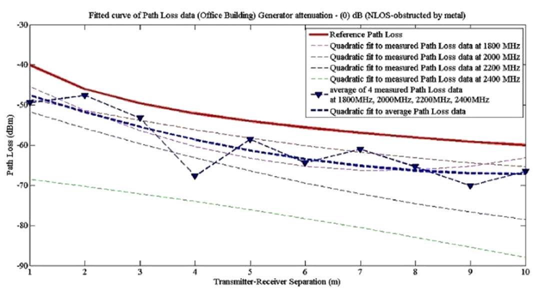

Fig. 5. Quadratic curve fitting of RSSI dependence on distance at NLOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer, obstacle material – iron

Received signal strength indicator (RSSI) at non-line-of-sight (NLOS) condition in the presence of obstacle – the wall in closed room. Measuring the signal from the transmitter. Signals were transmitted at the following frequencies: 1800, 2000, 2200, 2400 (MHz).

We begin the experiment by setting the transmitter and recording its coordinates. We adjust the broadcast frequency. We begin practical measurement tasks from a frequency of 1800 MHz. Then we repeat for frequencies 2000, 2200, 2400 (MHz). At a distance of 0.2 m from it there is an obstacle (the wall). The spectrum analyzer is installed at a distance of 1 meter from it on the other side. Then, with a step of 1 m, we move the analyzer away from the obstacle. We record the reading of the receiving analyzer. We move the receiver by another 1 m, record the reading again. Thus, we take a reading every 1 m. When the signal value does not stand out from the ambient noise value, we stop the practical measurement tasks. For the experiment, the length of the generator antenna was chosen the same for all specified frequencies. The antenna length of the receiving analyzer was chosen equal to its length and also did not change during the experiment. The location of the transmitting and receiving devices, the location of the obstacle between them before the start of the experiment on measuring the signal in non-line-of-sight can be seen in Fig. 6, and the graphs of the attenuation versus distance are shown in Fig. 7.

Received signal strength indicator (RSSI) at non-line-of-sight (NLOS) condition in the presence of an obstacle – space between floors in closed room. Measurement of the signal from the generator at various frequencies: 1800, 2000, 2200, 2400 (MHz).

To carry out the experiment, we install the generator on the *4th* floor and record its location. We adjust the broadcast frequency. We begin the measurement process at a frequency of 1800 MHz. Then we repeat the experiment for the remaining frequencies. One floor below it, we have a receiving spectrum analyzer. We measure the signal. We record the reading of the receiving analyzer. We move it along the corridor by 1 m and record the reading. We repeat the process and take a reading. When the magnitude of the received signal does not stand out from the level of the surrounding noise, we stop the measurement process. Further, according to the same scenario, we conduct an experiment on the lower floors up to the *1st* one. For the experiment, the length of the antenna of the broadcasting generator was chosen the same for all specified frequencies. The antenna length of the receiving analyzer was chosen equal to the length of its antenna and also did not change during the measurement work. The experimental setup of the generator and receiving analyzer for measuring the level of the received signal in line-of-sight is shown in Fig. 8. The experimental results are shown in Figs. 9–11.

Received signal strength indicator (RSSI) at line-of-sight (LOS) condition in closed room. The signal is broadcast by a projected BLE transmitter and measured by a spectrum analyzer.

Measurement of the signal from the generator at various frequencies: 2405, 2423, 2429, 2477 (MHz).

The transmitter coordinates are fixed. The receiver is installed at a distance of 1 m from it. The receiver moves in 1 m steps from the transmitter. Each power level reading measured by the spectrum analyzer is recorded on paper. Practical mea-

Fig. 6. Experimental setup of generator and spectrum analyzer for measuring of received signal strength at non-line-of-sight (NLOS) in the presence of an obstacle (the wall)

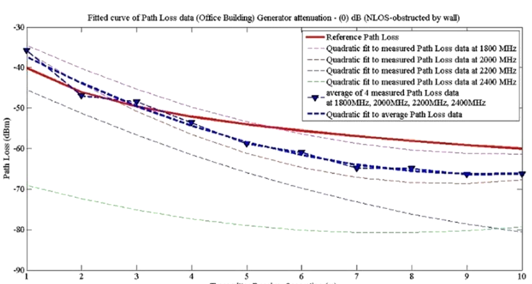

Fig. 7. Quadratic curve fitting of RSSI dependence on distance at NLOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer, obstacle material – wall

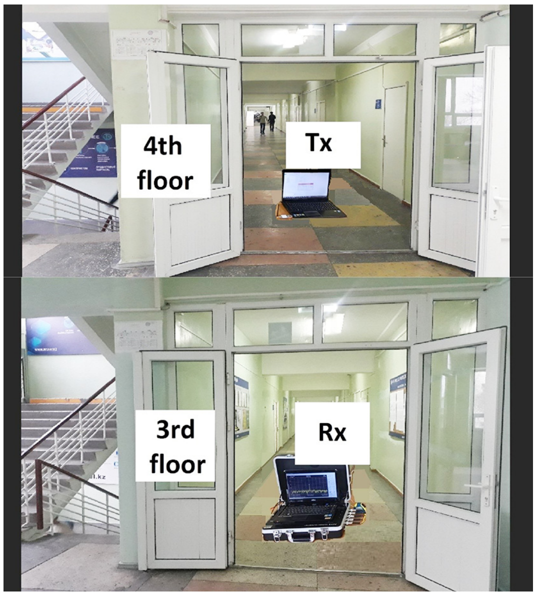

Fig. 8. Experimental setup of generator and spectrum analyzer for measuring of received signal strength at non-line-of-sight (NLOS) in the presence of an obstacle – space between floors (generator on the 4th floor, receiver is alternately located on the three lower floors)

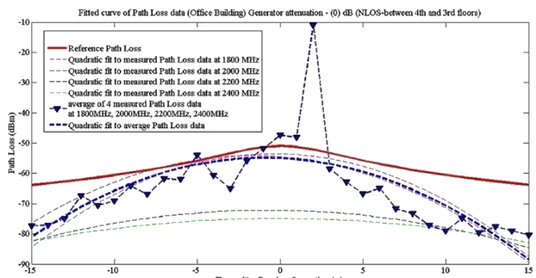

Fig. 9. Quadratic curve fitting of RSSI dependence on distance at NLOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer, obstacle material – space between the 4th and 3rd floors

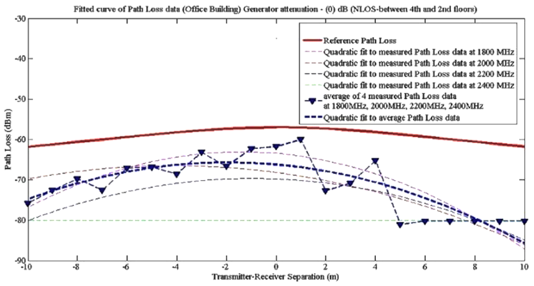

Fig. 10. Quadratic curve fitting of RSSI dependence on distance at NLOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer, obstacle material – space between the 4th and 2nd floors

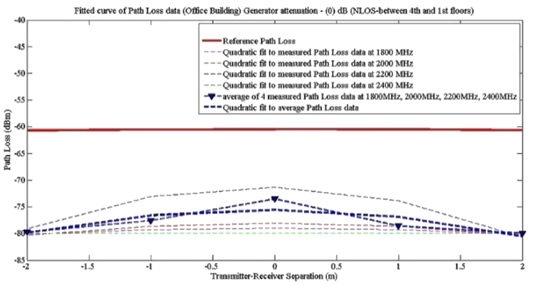

Fig. 11. Quadratic curve fitting of RSSI dependence on distance at NLOS on 1800, 2000, 2200, 2400 (MHz); signal of UHF beacon at power level attenuation of generator until (0) dB – measured by spectrum analyzer, obstacle material – space between the 4th and 1st floors

surement tasks continue until the received signal strength is indistinguishable from noise. The spectrum analyzer does not distinguish between power levels relative to mW below –80 dB. Thus, when the received power level from the transmitter reaches –80 dBm, it is indistinguishable from noise. BLE – beacon broadcasts a signal at frequencies 2405, 2423, 2429, 2477 (MHz). The experimental results are shown in Fig. 12.

Received signal strength indicator (RSSI) at line-of-sight (LOS) in closed room. The signal is broadcasted by a projected BLE transmitter and measured by the software application for the smartphone – "BLE scanner".

Measuring the signal from the generator at various frequencies: 2405, 2423, 2429, 2477 (MHz).

The software application does not indicate to which frequency its indication corresponds. The power level of the received signal is a single digit in dB relative to mW, which varies with distance.

The transmitter coordinates are fixed. The receiver is installed at a distance of 1 m from it. The receiver is moved in 1 m steps away from the transmitter. Each power level reading measured by the BLE scanner smartphone software is recorded on paper. Practical measurement tasks continue until the received signal power level is indistinguishable from noise. BLE – beacon broadcasts a signal at frequencies: 2405, 2423, 2429, 2477 (MHz). The BLE scanner software readings indicate one figure of attenuation in dB relative to mW, without indicating which frequency it refers to. To increase the accuracy, the experiment was repeated two times [22]. The experimental results are shown in Fig. 13.

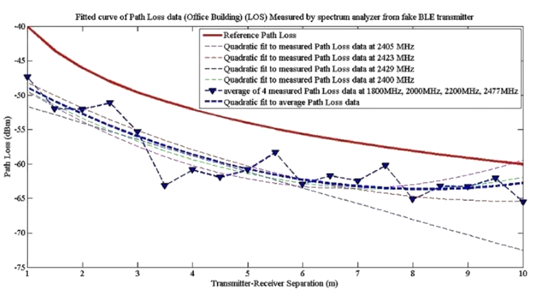

Fig. 12. Quadratic curve fitting of RSSI dependence on distance at LOS on 2405, 2423, 2429, 2477 (MHz); signal of BLE transmitter – measured by spectrum analyzer

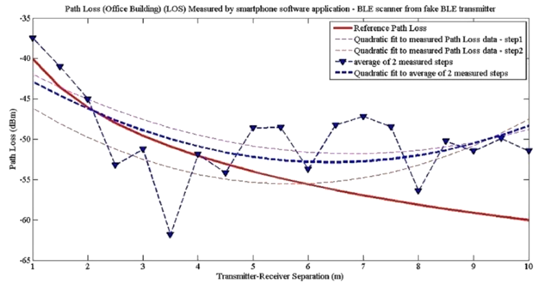

Fig. 13. Quadratic curve fitting of RSSI dependence on distance at LOS; signal of BLE transmitter – measured by software application for smartphone – "BLE scanner"

Conclusions. The article explores the possibility of increasing the accuracy of positioning objects in closed rooms, including mine workings. It is shown that the influence of multipath propagation of radio signals from the walls of structures, from obstacles of various origins, and the associated interference, can be weakened by using the averaged values of attenuation at different frequencies. The use of radio emitters with many frequencies as beacons can provide new possibilities in solving the problem of positioning objects in closed rooms. For the experiment, BLE was designed in the design bureau – beacons for research and measurement of signals in the standard frequency range for BLE and a UHF generator. The powers of the transmitters were chosen the same as for a standard BLE device. Experimental measurements have shown that theoretical and practical data are not the same at every point. Practical measurement tasks were carried out in the following configurations: line-of-sight – LOS, non-line-of-sight – NLOS in the presence of obstacles such as metal, walls and space between floors, as well as the use of a spectrum analyzer and software application for smartphones. Practical measurement tasks were carried out many times to average the results. These results can be used instead of theoretical data or to correct them in specific buildings or rooms. Frequencies 1800, 2000, 2200, 2400 (MHz) for experiments with a microwave transmitter and frequencies 2405, 2423, 2429, 2477 (MHz) for experiments with BLE beacons were chosen for averaging. This will eliminate interference. In this way, a multi-frequency transmitter and receiver can be used. Based on the results obtained by practical measurements, you can know at what distance you need to install beacons, where exactly you need to install sensors, taking into account the irregular location of obstacles, space between floors. The experimental results will assist in preliminary preparation for the deployment of positioning systems in enclosed spaces, including mines.

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Дослідження можливості зниження помилок визначення координат об'єктів у закритих приміщеннях багаточастотним методом

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Мета. Дослідити вплив умов LOS/NLOS на проходження радіосигналу й можливість зменшення шумових перешкод використання багаточастотного методу передачі та прийому для задач визначення в закритих приміщеннях. Перевірити відміну точності вимірювань при прийомі сигналу на одній частоті від прийому сигналу на чотирьох частотах, об'єднанням результатів вимірювань окремих частот в одне показання. Перевірити вплив різних перешкод на проходження сигналу.

Методика. Самостійне проектування UHF – генератора та BLE – маяків із можливістю встановлення частот мовлення й налаштування потужності передачі. Застосування багаточастотного методу передачі та прийому. Вимірювання точним п'ятиканальним аналізатором спектру та стандартним програмним додатком для смартфонів BLE – scanner.

Результати. Досліджена можливість підвищення точності позиціонування об'єктів у закритих приміщеннях, включаючи шахтні виробки, за рахунок використання багаточастотних радіосигналів. Показано, що вплив багатопроменевого поширення радіосигналів від стін споруд, від перешкод різного походження, і, пов'язану з ними інтерференцію, можна послабити, використовуючи усереднені значення затухань на різних частотах. Використання маяків із багатьма частотами може дати нові можливості у вирішенні питання про позиціонування об'єктів у закритих приміщеннях.

Наукова новизна. У роботі пропонується метод об'єднання результатів вимірювання окремих частот в одне свідчення, що дозволить зменшити інтерференційні перешкоди. Для зменшення впливу перешкоди, викликаної на одній частоті, на загальний рівень сигналу, пропонується багаточастотний метод передачі й багаточастотний метод прийому.

Практична значимість. Отримані експериментальні результати можуть бути використані при розгортанні систем позиціонування в закритих приміщеннях, включаючи шахтні виробки.

Ключові слова: *Bluetooth Low Energy – BLE, пряма видимість – LOS, поза прямої видимості – NLOS, індикатор рівня сигналу, що приймається – RSSI, маяк, мікрохвильова піч – генератор, аналізатор спектру*

Исследование возможности снижения ошибок определения координат объектов в закрытых помещениях многочастотным методом

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Цель. Исследовать влияние условий LOS/NLOS на прохождение радиосигнала и возможность уменьшения интерференционных помех использованием многочастотного метода передачи и приема для задач определения местоположения в закрытых помещениях. Проверить отличие точности измерений при приеме сигнала на одной частоте от приема сигнала на четырех частотах, объединением результатов измерений отдельных частот в одно показание. Проверить влияние различных преград на прохождение сигнала.

Методика. Самостоятельное проектирование СВЧ – генератора и BLE – маяков с возможностью установления частот вещания и настройки мощности передачи. Применение многочастотного метода передачи и приема.

Результаты. Исследована возможность повышения точности позиционирования объектов в закрытых помещениях, включая шахтные выработки, за счёт использования многочастотных радиосигналов. Показано, что влияние многолучевого распространения радиосигналов от стен сооружений, от препятствий различного происхождения и связанную с ними интерференцию, можно ослабить, используя усреднённые значения затуханий на разных частотах. Использование маяков со многими частотами может дать новые возможности в решении вопроса о позиционировании объектов в закрытых помещениях.

Научная новизна. В работе предлагается метод объединения результатов измерения отдельных частот в одно показание, что позволит уменьшить интерференционные помехи. Для уменьшения влияния помехи, вызванной на одной частоте, на общий уровень сигнала, предлагается многочастотный метод передачи и многочастотный метод приема.

Практическая значимость. Полученные экспериментальные результаты могут быть использованы при развертывании систем позиционирования в закрытых помещениях, включая шахтные выработки.

Ключевые слова: *Bluetooth Low Energy – BLE, прямая видимость – LOS, вне прямой видимости – NLOS, индикатор уровня принимаемого сигнала – RSSI, маяк, микроволновая печь – генератор, анализатор спектра*

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