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RSSI Performance of Maturity Sensor Based on LoRaWAN Network

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Abstract. *This paper aims to evaluate the quality of wireless communication via LoRa protocol in maturity sensors BDM-1 of the author's design. The object of the study is the characteristics of continuity of a given measurement interval and the power of the data transmission signal. Experimental studies with immersion of a maturity sensor in a concrete sample and monitoring of its hardening temperature for 16 days were conducted. From 11 days of curing, the concrete sample was transported and held at different distances from the base station, divisible by a 30 m interval, in order to measure the signal strength of the data transmission. For this experiment, two trajectories for transporting the concrete sample in an urban environment were determined – with and without obstacles. The results of the monitoring confirmed the variability of the measurement intervals, as well as determined the signal strength at different distances and the signal range. Analysis of these results allowed expressing the relationship between the signal strength and distance for the maturity sensor BDM-1, applicable in practice on construction sites.*

Keywords: *LoRa, IoT, RSSI, maturity sensor, signal strength, obstruction.*

Introduction

Construction is one of the few areas where the introduction of new technologies is proceeding at a rapid pace. Many of them are focused on restructuring the organization of economic and technological processes. The ultimate goal of all these implementations is to form a product that will eliminate the need for human involvement in some of the activities and operations. This concept is reflected in the term Internet of Things (IoT). It was first formulated and applied by Kevin Ashton, the founders of the Auto-ID research group at the Massachusetts Institute of Technology (MIT). The new direction began to rapidly gain momentum in the early 2000s; the first extensive articles and publications in academia began to appear [1-3]. As time passed, IoT technologies conventionally split into many groups and subgroups (Table 1) [4].

This article discusses the technological capabilities of the author's development belonging to the subgroup Building and home automation of IoT classification. The development represents a maturity sensor BDM-1, designed for wireless temperature monitoring and concrete strength control by the maturity method [7]. When developing it, one of the important components was the choice of wireless communication technology. Such technologies as LoRa, SIGFOX, NB-IoT, and Weightless P were considered. WiFi and Bluetooth were ignored due to negative experiences with foreign analogues of maturity sensors [8-10].

The widespread use of radio-frequency identification for the interaction of objects requires a stable and reliable connection between themselves and with the external environment. For this reason, there are a large number of Low Power Wide Area Networks (LPWAN) [11]. One of them is LoRaWAN (or LoRa), a product of the fast-growing LoRa Alliance. The developers of this technology justify the obvious advantages of this system compared to Wi-Fi and Bluetooth [12]. The existing Machine-to-Machine (M2M) interconnection between boards allows a range of up to 20 km at about 50 kbit/s with minimal power consumption [13]. Another private company, SIGFOX, has focused its LPWAN development on the creation of a worldwide network. This network has a similar infrastructure to GSM and GPRS using 3G and 4G connections, but is more energy efficient and less expensive. The third LPWAN technology called NB-IoT is characterized by the ability to implement rapid upgrades to existing networks and a 10-year warranty on battery life. Ubiik's Weightless standard has made it a leader in LPWAN networks by clearly separating the protocol for its different user segments. Weightless: H, W, P – designed for oil and gas, operational-one-way and two-way communications, respectively [14]. The latter protocol covers a greater number of devices than the previous two. It is worth noting that the range of all networks is distorted in urban areas, so in the example of SIGFOX technology, the coverage area in rural areas is 30-50 km, and in urban areas is reduced to 3-10 km [11]. More detailed characteristics of the considered wireless technologies are shown in Table 2 below.

Thus, the technical characteristics listed above form the value of each device working on the concept of IoT [4]. However, as can be seen from the table above, only LoRa technology is suitable for the Asian region in terms of frequency, which was the choice for the design of the maturity sensor.

The next step was to validate the adequacy of the signal strength received from the BDM-1.

Table 1 – Classification of IoT [4]

№	Applications	№	Sub-Applications
1	Consumer applications	1	Smart home
		2	Elder care
2	Organizational applications	3	Medical and healthcare
		4	Transportation
		5	V2X communications
		6	Building and home automation
3	Industrial applications	7	Manufacturing
		8	Agriculture
		9	Food
		10	Maritime
4	Infrastructure applications	11	Metropolitan scale deployments
		12	Energy management
		13	Environmental monitoring
5	Military applications	14	Internet of Battlefield Things
		15	Ocean of Things
		16	Product digitisation

Table 2 – Comparison of technical characteristics of LPWAN networks [11]

№	Parameter	Технологии беспроводной связи			
		LoRa	SIGFOX	NB-IoT	Weightless P
1	Modulation method	CSS	–	OFDMA/DSSS	FDMA/TDMA
2	Diapason	ISM	ISM	Licensed	ISM
3	Speed	0,3–50 kbps	100 kbps	UL: 1–144 kbps DL: 1–200 kbps	0,2–100 kbps (adaptive)
4	Band	Wideband up to 500 kHz	Narrowband up to 100 kHz	Narrowband up to 200 kHz	Narrowband up to 12,5 kHz
5	Autonomy time	> 10 лет	–	До 10 лет	3–5 лет
6	Frequency	868,8 MHz (Europe) 915 MHz (USA) 433 MHz (Asia)	868,8 MHz (Europe) 915 MHz (USA)	700 / 800 / 900 MHz	169 / 433 / 470 / 780 / 868 / 915 / 923 MHz
7	Safety	AES-64 & 128 bit	AES, HMACs	–	AES-128 / 256
8	Range	Up to 2.5 km in the city, up to 45 km outside the city	Up to 10 km in the city, up to 50 km outside the city	–	Up to 2 km in the city
9	Support	LoRa Alliance, IBM, Cisco…	SigFox, Samsung	3GPP, Nokia, Huawei, Intel…	Ubiik Weightless SIG

Terminologically, the signal strength is commonly referred to as the «Received Signal Strength Index» (RSSI). Its classical scheme of behavior is shown in Figure 1 [15-19]. RSSI results reflect the strength of the received signal measured in dBm relative to 1 mW, and in the case when the power is below 1 mW, the RSSI in dBm takes a negative value. And for this reason, the closer its value to zero, the better the signal (Figure 2) [20].

To test the signal strength, the authors recreated the field conditions under which the maturity sensors are operated. Since the operating conditions of the maturity sensors involve immersion in concrete, in order to test their signal strength at different distances, it was decided to embed BDM-1 in a small cubic sample for its mobility. In addition to the distance, the signal strength can also be affected by various obstacles in the urban infrastructure, which presumably can also affect the loss of signal at a certain point in time. In other words, a given measurement interval of 30 minutes for the BDM-1 may be disrupted. In this regard, the purpose of this study is to evaluate the quality of wireless communication via LoRa protocol in the BDM-1 maturity sensors. The object of the study is the data transmission interval and signal strength.

Materials and methods

The experimental part of the study covered several locations: the monitoring station, the laboratory and the urban environment. The following components had to be prepared for the experiment (Table 3).

The computer and the base station were located in a monitoring station that had a stable and constant

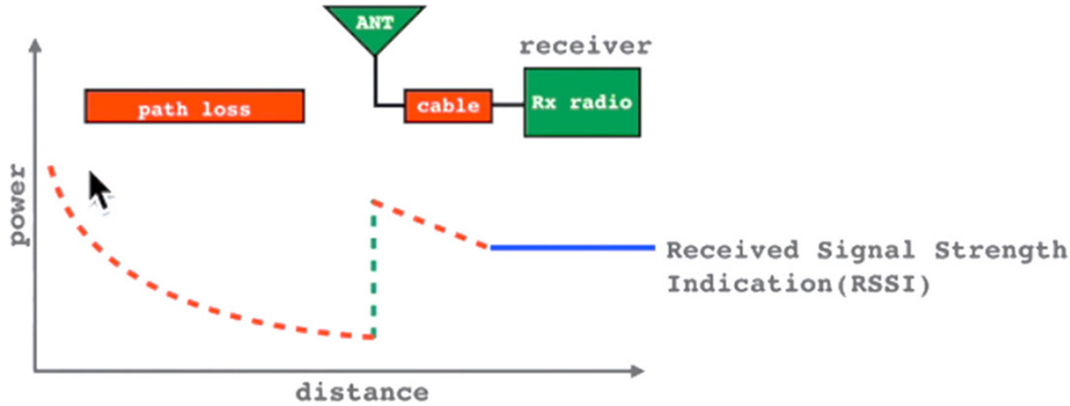

Figure 1 – RSSI behavior [15]

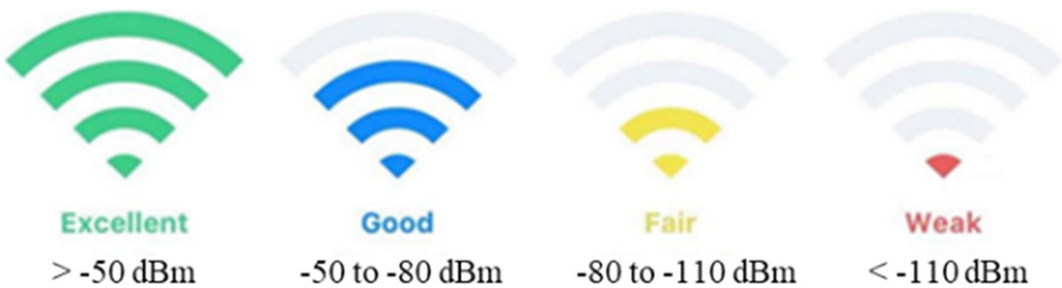

Figure 2 – RSSI range [20]

Table 3 – Equipment for the experiment

№	Materials and equipment	Unit	Quantity
1	Computer	pcs	1
2	BDM-1 maturity sensor	pcs	1
3	Base station	pcs	1
4	Concrete (B25 M350)	m3	0,008
5	Formwork (20x20x20 cm)	pcs	1
6	Vibrating table	pcs	1

electrical and Internet connection (Figure 3). Since the monitoring data coming from the BDM-1 to the base station was visualized on the computer through the server software, which is accessed through an Internet browser. To establish communication between all three components, a virtual project was created in the server software, in which the serial number of the experimental BDM-1 was entered. Next, by activating the maturity sensor, a communication verification was performed. The measurement data successfully passed through the base station and was visualized in the software (Figure 3).

In order to simulate realistic operating conditions of the BDM-1, the dimensions of the 20x20x20 cm formwork for making a concrete sample in the laboratory were selected so that the distance from the LoRa chip inside the BDM-1 body to the walls of the sample exceeded 5 cm. Since foreign manufacturers recommend immersing their maturity sensors no deeper than 5 cm [8-10]. Installation of the sensor in the center of the formwork was carried out by fixing it to the reinforcing bar with a tying wire (Figure 4).

After installing the sensor in the design position, the entire cycle accompanying the concrete work at the construction site was executed (Figure 5), i.e. batching the concrete mixture, followed by laying and compaction. But a vibrating table was used to compact the mixture in the sample. For the experiment, it was important to achieve the density and strength of the concrete in the sample, which is achieved in commercial concrete B25 M350, used on construction sites on a large scale. Because the density also affects the strength of the transmitted signal, and BMD-1 was designed specifically for heavy commercial concrete with a density of 1800 to 2500 kg/m^3. It was also important to test the performance of the BDM-1 under the influence of vibration loads: the reliability of groove joints of various components inside the casing of the BDM-1, tightness and durability of the casing. And in this regard, vibro-compacting was an integral part of this experiment (Figure 5).

The point of reference for monitoring the temperature of concrete curing in the sample with the BDM-1 was taken as the moment of completion of vibration compaction. From this point, the sensor successfully transmitted data for 16 days. The first 11 days, of which the sample was stored in the laboratory at 20°C and natural humidity. The remaining 5 days the sample was kept in ambient conditions (in summer) and transported at different distances from the monitoring station in order to determine signal strengths in the presence and absence of urban

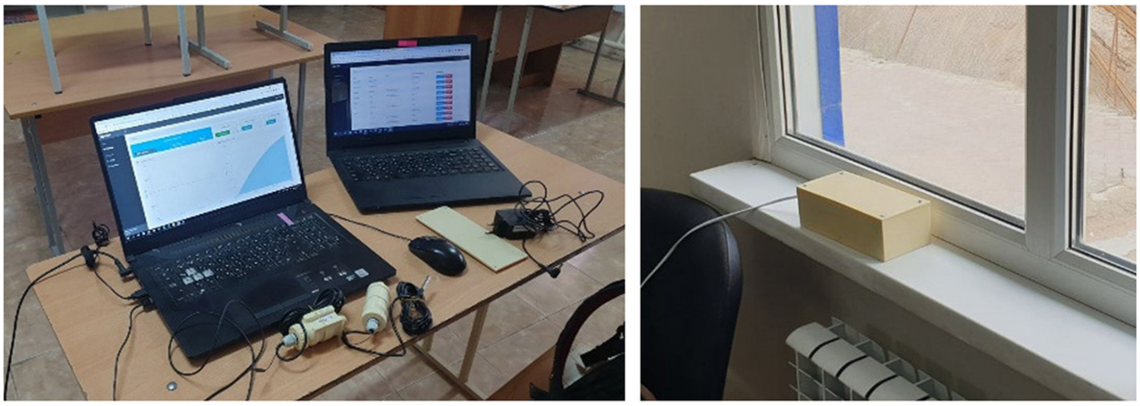

Figure 3 – Monitoring station

Figure 4 – Installation of the maturity sensor in the formwork

obstacles. The interval of distances at which the signal strength was measured was 30 m. And the distance was increased until the final loss of signal for both conditions (with and without obstacles) occurred.

When analyzing the result of monitoring the concrete curing temperature obtained from the experiment, special attention was paid to the time and interval of the received data (equivalent to the signal transmission interval), which was naturally disrupted. Apparently, this was due to the weakening of the signal strength at one or another point in time. Based on the results of the signal strength analysis, distance and signal strength relationships were obtained for conditions with and without obstacles.

Results and Discussion

Figure 6 shows the result of monitoring the curing temperature of concrete in a cubic sample.

As can be seen in the graph, there is a certain dynamics of curing temperature values associated with the transition from daytime to nighttime and vice versa. There are also small jumps and uniform drops associated with the exothermic process occurring in the body of concrete. During the first 11 days, the temperature fluctuated within 20±1°C. With the transition to the urban environment there is a sharp rise in curing temperature up to 29°C and fluctuates depending on the time of day by 2-3°C. This is understandable, since the experiments were conducted in the summer, when the temperature during the day could reach 30°C. In the figures on the right one can notice an identical temperature graph obtained from the server temperature monitoring software.

By calculating the difference between each subsequent and previous time value, the signal arrival intervals for each fact of data transmission are estimated (Figure 7).

According to the graph of intervals, it can be seen that the initially set interval of 30 minutes deviated on average by 200 seconds and is in the range of 33 minutes 20±10 seconds. Also, large deviations from 1 hour and above are noticed. If neglecting deviations of 200 seconds, the rest can be classified into 4

Figure 5 – Concrete pouring into the formwork and vibro-compacting

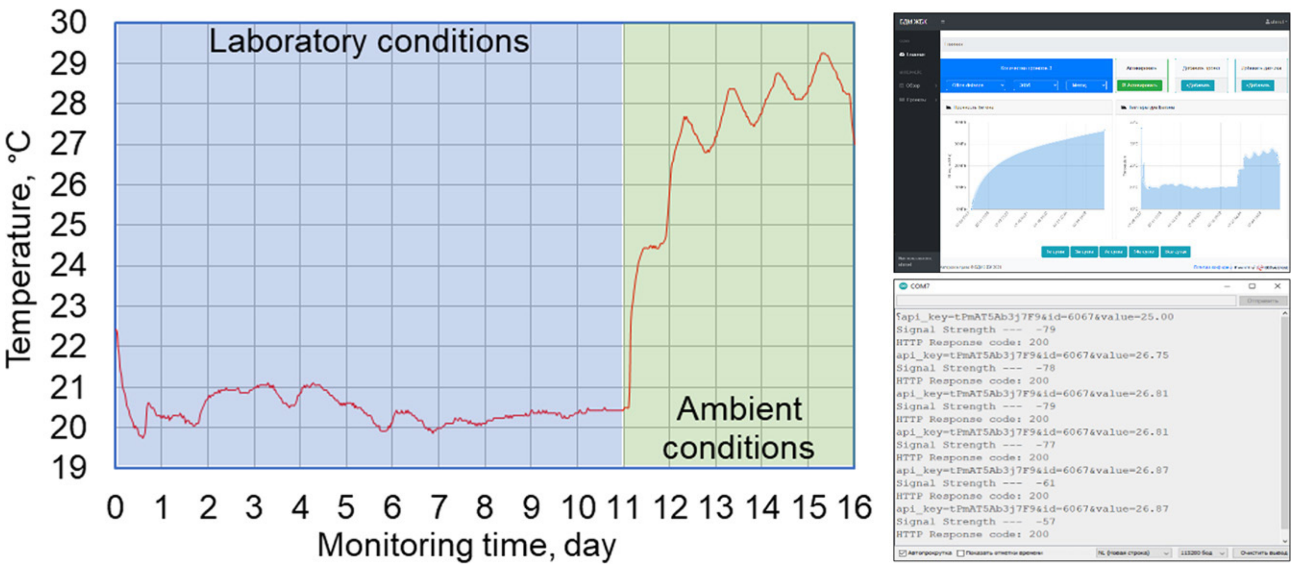

Figure 6 – Curing temperature monitoring

categories with deviations greater than 0.5, 1, 2, and 2.5 hours, respectively (Figure 8).

The pie chart shows that most of the data (93.9%) were transmitted in the normal time interval. 4.7% were transmitted more than 0.5 hours late, 0.6% by 1 hour, 0.2% and 0.3% by 2 and 2.5 hours respectively. Deviations occurring on day 11-12 of concrete curing can be explained with the transportation of the concrete sample from the laboratory to the urban environment. However, the question arises about the deviations that occurred before 11 days. This may be due to the exothermic reaction occurring in the body of the concrete sample. For instance, comparing Figures 6 and 8, a certain pattern of deviations in the measurement intervals can be observed, especially on days 2-5 of curing, in which there is a consolidation of interval deviations by more than 0.5 hours. Also, it can be assumed that the activation energy of the reaction in some way affects the radiocommunication, and thus on the interval of measurements.

The results of the study of the transmitted signal strength from the maturity sensor embedded in the concrete sample are shown in Figure 9.

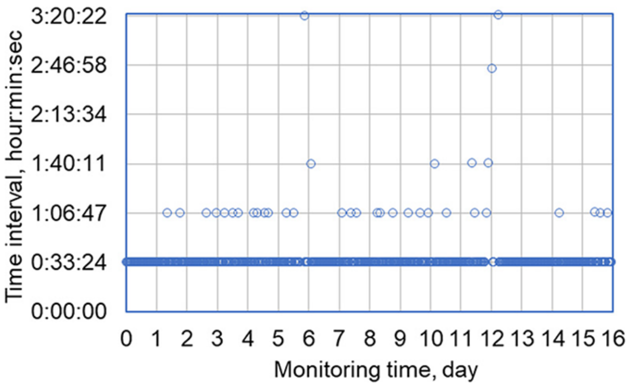

Figure 7 – Data arrival intervals

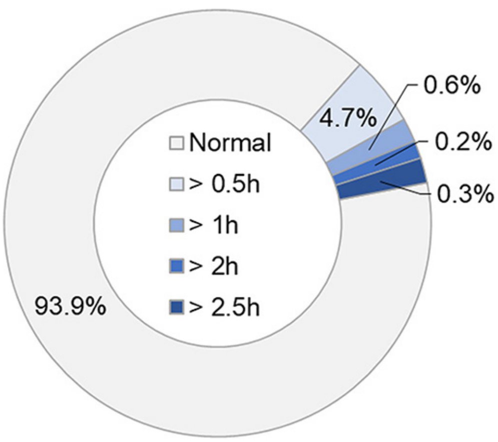

Figure 8 – Percentage of deviated reading interval

In the figure above, the left part of the map shows the trajectory of transporting a concrete sample through obstacles, and on the right without obstacles. The maximum signal ranges reached 270 m without obstacles and 90 m with obstacles, respectively. In the graph below different colors are used to show which of the intervals on the RSSI scale belong to which particular distances from which signal strengths were measured. As it turned out, being embedded in the concrete and taking into account the obstacles, a reliable connection is held only at a distance of 30-60 meters. In the realities of the construction site, this means that the base station, which collects data from the maturity sensors, will need to be installed, not exceeding this distance interval.

For the purpose of practical determination of the signal strength of BDM-1 its dependencies on the distance in conditions of obstacles and without were expressed (Figure 10).

The expressed dependencies are represented by a polynomial quadratic function and have high coefficients of determination close to one, which indicates their reliability.

The results obtained in the study have prompted the need for further research in this direction and will be aimed at studying the effect of activation energy of the reaction on radio communication and the quality of the transmitted signal of maturity sensors. It is also planned to further upgrade the technical capabilities of the wireless communication module of maturity sensors by strengthening the antenna and electronic circuitry.

Conclusion

This paper presents the results of experimental studies of the quality of the transmitted signal of the maturity sensor of the author's development BDM-1, implementing wireless LoRa communication technology.

Monitoring of the concrete curing temperature using the BDM-1 revealed unevenness in the interval of measurement data receipt, due to the regular signal losses; more than 6% of the data were transmitted with a delay of 0.5 to 2.5 hours.

A study of RSSI at different distances revealed signal ranges of the BDM-1 with obstacles up to 90 m and without obstacles up to 270 m. At the same time, satisfactory range intervals were 30-60 m and 60-240 m, respectively.

Expressed the dependence of RSSI-Distance for the conditions of data transmission with and without obstacles, applicable in practice on construction sites when selecting a place to install a base station.

It was decided to strengthen (improve) the antenna of BDM-1 and the base station in order to increase the strength of the transmitted signal.

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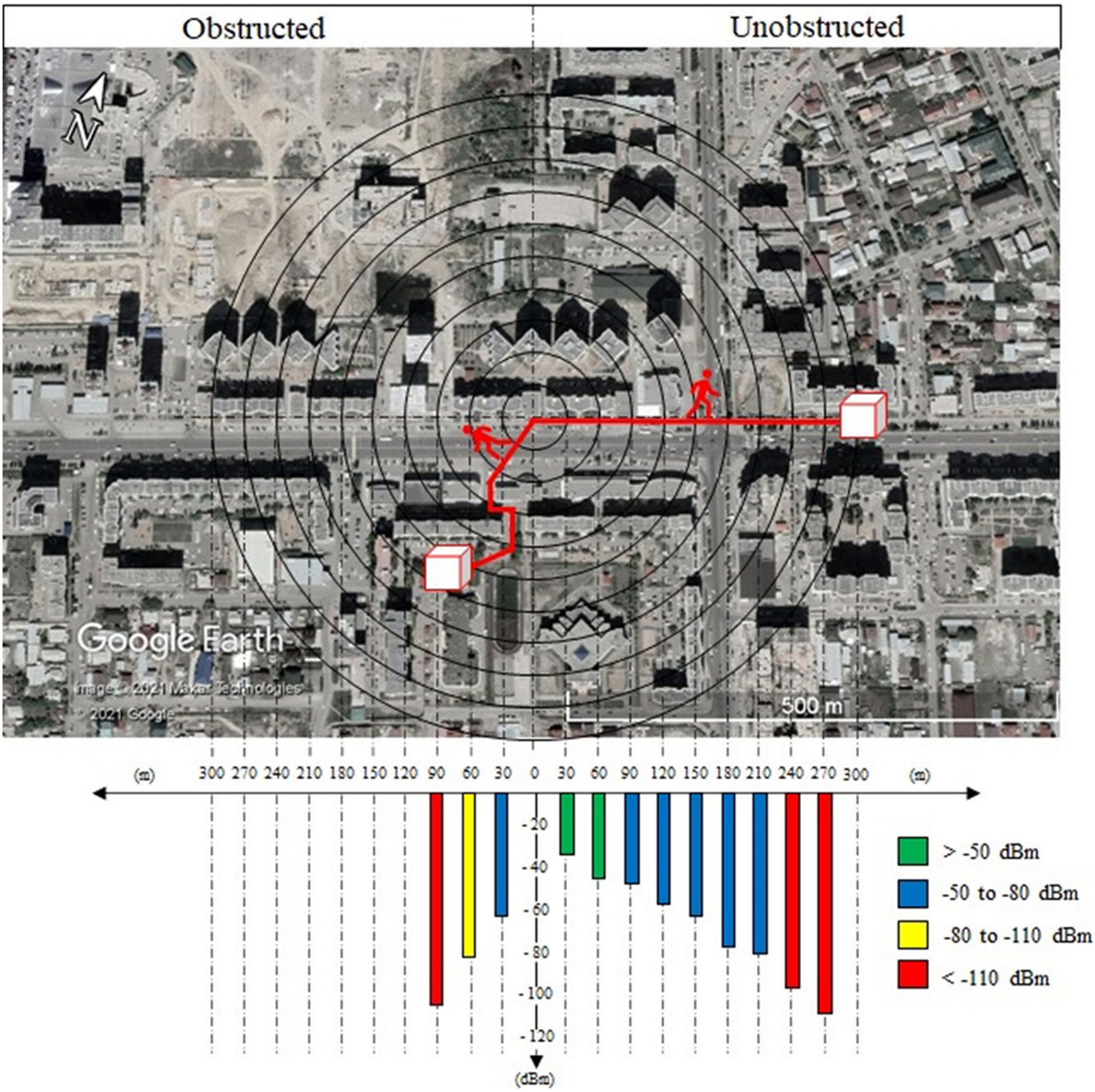

Figure 9 – RSSI vs Distance

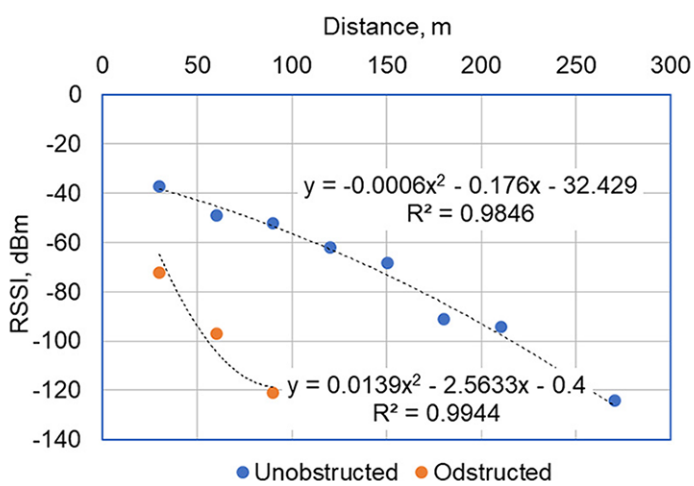

Figure10 – RSSI-Distance relationships

REFERENCES

1. Kranenburg R. The Internet of Things. Amsterdam, The Netherlands, 2008. 1-61 p.
2. Vimala T., Rajaram U. Analysis of RSSI in diverse field // International Conference on Information Communication and Embedded Systems (ICICES2014). Chennai, INDIA: IEEE, 2014. P. 1-3.
3. NIC. Disruptive Civil Technologies. Six Technologies With Potential Impacts on US Interests Out to 2025. 2008. 27-31 p.
4. Gershenfeld N., Krikorian R., Cohen D. The Internet of Things // Sci. Am. 2004. Vol. 10. P. 76-81.
5. Utepov Y. et al. Prototyping an embedded wireless sensor for monitoring reinforced concrete structures // Comput. Concr. 2019. Vol. 24, No. 2. P. 95-102.
6. Utepov Y. et al. DURABILITY TESTING OF THE CONCRETE MATURITY SENSOR HOUSING MADE OF TWO-COMPONENT PLASTIC // Eurasian Phys. Tech. J. 2021. Vol. 18, No. 3.
7. ASTM C1074. Standard Practise for Estimating Concrete Strength by the Maturity Method. 2019.
8. Walsh D. IoT Hero from Giatec Develops "SmartRocks" with Bluetooth [Electronic resource] // Giatec Scientific. 2015. URL: https://www.silabs.com/community/blog.entry.html/2016/01/18/iot_hero_from_giatec-Av1P (accessed: 28.07.2021).
9. Giatec. The World's Leading Wireless Sensor for Temperature and Strength Monitoring [Electronic resource] // Smart Construction Testing Technologies. 2021. URL: https://www.giatecscientific.com/products/concrete-sensors/smartrock-maturity-meter/ (accessed: 28.07.2021).
10. Hilti. Help finish projects faster and under budget with Hilti Concrete Sensors [Electronic resource] // Hilti Concrete Sensors. 2018. URL: https://www.hilti.com/content/hilti/W1/US/en/services/tool-services/internet-of-things/concrete-sensors.html (accessed: 27.07.2021).
11. Kumaritova D., Kirichek R. Overview and comparative analysis of LPWAN network // Telecom IT. 2016. Vol. 4, No. 4. P. 33-48.
12. Cabrera-Goyes E., Ordóñez-Camacho D. Indoors positioning with Android, Bluetooth and RSSI // Enfoque UTE. 2018. Vol. 9, No. 1. P. 118-126.
13. Basu S.S. et al. An End-To-End LwM2M-Based Communication Architecture for Multimodal NB-IoT/BLE Devices // Sensors. 2020. Vol. 20, No. 8. P. 2239.
14. Chaudhari B.S., Zennaro M., Borkar S. LPWAN Technologies: Emerging Application Characteristics, Requirements, and Design Considerations // Futur. Internet. 2020. Vol. 12, No. 3. P. 46.
15. Gualda D. et al. RSSI distance estimation based on Genetic Programming // International Conference on Indoor Positioning and Indoor Navigation. Montbeliard Belfort, FRANCE: IEEE, 2013. P. 1-8.
16. Zheng J. et al. The Study of RSSI in Wireless Sensor Networks // Advances in Intelligent Systems Research. Beijing, CHINA: AIIE, 2016. P. 207-209.
17. Yoppy, RH. Arjadi, H. Candra, HD. Prananto T.W. RSSI Comparison of ESP8266 Modules // Electrical Power Electronics Communications Controls and Informatics Seminar. Batu, INDONESIA: IEEE, 2018. P. 150-153.
18. M. Jusoh, T. Sabapathy, KNFK. Azir, MS. Shakhirul, CBM. Rashidi A.R. Adaptive Beam Steering: RSSI Performance // 2nd International Conference Computer Communications Control Technology / ed. HA. BinSulaiman. Kuching, MALAYSIA: I4CT, 2015.
19. Wattananavin T. et al. Reduction of RSSI variation and position estimation error caused by human movements in an RSSI-based indoor localization system // SURANAREE J. Sci. Technol. 2019. Vol. 26, No. 3. P. 266-277.
20. Tan Z.A. et al. Analysis on LoRa RSSI in Urban, Suburban, and Rural Area for Handover Signal Strength-Based Algorithm. // IOP Conf. Ser. Mater. Sci. Eng. 2019. Vol. 705. P. 012012.

LoRaWAN желісіне негізделген RSSI жетілу сенсорының өнімділігі

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Аңдатпа. *Бұл жұмыстың мақсаты BDM-1 авторлық датчиктеріндегі loRa протоколы бойынша сымсыз байланыс сапасын бағалау болып табылады. Зерттеу объектісі берілген өлшеу аралығының үздіксіздігінің сипаттамаларын және деректерді беру сигналының қуаты болып қабылданды. Тәжірибелік зерттеулер жетілу сенсорын бетон үлгісіне батыру және оның қату температурасын 16 күн бойы бақылау арқылы жүргізілді. Қатаюдың 11 күнінен бастап бетон үлгісі деректерді беру сигналының қуатын өлшеу үшін базалық станциядан 30 м аралыққа дейінгі әртүрлі қашықтықта тасымалданды және сақталды. Бұл эксперимент үшін бетон үлгісін қалалық ортада – кедергілері бар және кедергісіз тасымалдаудың екі жолы анықталды. Мониторинг нәтижелері өлшеу аралықтарының сәйкес еместігін растады, сонымен қатар әртүрлі қашықтықтардағы сигналдың қуатын және сигналдың әрекет ету радиусын анықтады. Осы нәтижелерді талдау құрылыс алаңдарында практикада қолданылатын BDM-1 жетілу сенсоры үшін сигнал қуатының қашықтыққа тәуелділігін білдіруге мүмкіндік берді.*

Кілт сөздер: *LoRa, IoT, RSSI, жетілу сенсоры, сигнал күші, кедергілер.*

Производительность RSSI датчика зрелости на основе сети LoRaWAN

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Аннотация. _Целью данной работы является оценка качества беспроводной связи по протоколу LoRa у датчиков зрелости БДМ-1 авторской разработки. Объектом исследования приняты характеристики непрерывности заданного интервала измерений и мощность сигнала передачи данных. Проведены экспериментальные исследования с погружением датчика зрелости в бетонный образец и мониторингом температуры его твердения в течение 16 суток. С 11 суток твердения бетонный образец транспортировался и придерживался на различных дистанциях от базовой станции, кратных интервалу 30 м, с целью замера мощности сигнала передачи данных. Для данного эксперимента были определены две траектории транспортировки бетонного образца в городской среде – с препятствиями и без препятствий. Результаты мониторинга подтвердили непостоянство интервала измерений, а также определили мощности сигнала на различных дистанциях и радиус действия сигнала. Анализ данных результатов позволил выразить зависимость мощности сигнала от дистанции для датчика зрелости БДМ-1, применимый на практике на стройплощадках._

Ключевые слова: _LoRa, IoT, RSSI, датчик зрелости, мощность сигнала, препятствия._

REFERENCES

1. Kranenburg R. The Internet of Things. Amsterdam, The Netherlands, 2008. 1-61 p.
2. Vimala T., Rajaram U. Analysis of RSSI in diverse field // International Conference on Information Communication and Embedded Systems (ICICES2014). Chennai, INDIA: IEEE, 2014. P. 1-3.
3. NIC. Disruptive Civil Technologies. Six Technologies With Potential Impacts on US Interests Out to 2025. 2008. 27-31 p.
4. Gershenfeld N., Krikorian R., Cohen D. The Internet of Things // Sci. Am. 2004. Vol. 10. P. 76-81.
5. Utepov Y. et al. Prototyping an embedded wireless sensor for monitoring reinforced concrete structures // Comput. Concr. 2019. Vol. 24, No. 2. P. 95-102.
6. Utepov Y. et al. DURABILITY TESTING OF THE CONCRETE MATURITY SENSOR HOUSING MADE OF TWO-COMPONENT PLASTIC // Eurasian Phys. Tech. J. 2021. Vol. 18, No. 3.
7. ASTM C1074. Standard Practise for Estimating Concrete Strength by the Maturity Method. 2019.
8. Walsh D. IoT Hero from Giatec Develops "SmartRocks" with Bluetooth [Electronic resource] // Giatec Scientific. 2015. URL: https://www.silabs.com/community/blog.entry.html/2016/01/18/iot_hero_from_giatec-Av1P (accessed: 28.07.2021).
9. Giatec. The World's Leading Wireless Sensor for Temperature and Strength Monitoring [Electronic resource] // Smart Construction Testing Technologies. 2021. URL: https://www.giatecscientific.com/products/concrete-sensors/smartrock-maturity-meter/ (accessed: 28.07.2021).
10. Hilti. Help finish projects faster and under budget with Hilti Concrete Sensors [Electronic resource] // Hilti Concrete Sensors. 2018. URL: https://www.hilti.com/content/hilti/W1/US/en/services/tool-services/internet-of-things/concrete-sensors.html (accessed: 27.07.2021).
11. Kumaritova D., Kirichek R. Overview and comparative analysis of LPWAN network // Telecom IT. 2016. Vol. 4, No. 4. P. 33-48.
12. Cabrera-Goyes E., Ordóñez-Camacho D. Indoors positioning with Android, Bluetooth and RSSI // Enfoque UTE. 2018. Vol. 9, No. 1. P. 118-126.
13. Basu S.S. et al. An End-To-End LwM2M-Based Communication Architecture for Multimodal NB-IoT/BLE Devices // Sensors. 2020. Vol. 20, No. 8. P. 2239.
14. Chaudhari B.S., Zennaro M., Borkar S. LPWAN Technologies: Emerging Application Characteristics, Requirements, and Design Considerations // Futur. Internet. 2020. Vol. 12, No. 3. P. 46.
15. Gualda D. et al. RSSI distance estimation based on Genetic Programming // International Conference on Indoor Positioning and Indoor Navigation. Montbeliard Belfort, FRANCE: IEEE, 2013. P. 1-8.
16. Zheng J. et al. The Study of RSSI in Wireless Sensor Networks // Advances in Intelligent Systems Research. Beijing, CHINA: AIIE, 2016. P. 207-209.
17. Yoppy, RH. Arjadi, H. Candra, HD. Prananto T.W. RSSI Comparison of ESP8266 Modules // Electrical Power Electronics Communications Controls and Informatics Seminar. Batu, INDONESIA: IEEE, 2018. P. 150-153.
18. M. Jusoh, T. Sabapathy, KNFK. Azir, MS. Shakhirul, CBM. Rashidi A.R. Adaptive Beam Steering: RSSI Performance // 2nd International Conference Computer Communications Control Technology / ed. HA. BinSulaiman. Kuching, MALAYSIA: I4CT, 2015.
19. Wattananavin T. et al. Reduction of RSSI variation and position estimation error caused by human movements in an RSSI-based indoor localization system // SURANAREE J. Sci. Technol. 2019. Vol. 26, No. 3. P. 266-277.
20. Tan Z.A. et al. Analysis on LoRa RSSI in Urban, Suburban, and Rural Area for Handover Signal Strength-Based Algorithm. // IOP Conf. Ser. Mater. Sci. Eng. 2019. Vol. 705. P. 012012.