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Method for improving the coverage efficiency of wireless sensor networks based on UAVs

Abstract. The purpose of this study was to adaptively optimise sensor networks using unmanned aerial vehicles to reduce information losses and ensure the minimum possible technical performance of information transmission channels in the face of a considerable number of architectural obstacles. In this study, experiments were conducted on data transmission via a wireless channel using Wi-Fi technology, where the access point was placed on an unmanned aerial vehicle. The study was conducted in complex architectural settings, using the 2.4 GHz and 5 GHz frequency bands to investigate the behaviour of radio channels and assess their effectiveness in real-world conditions. As a result of the study, a new method for estimating and optimising the energy parameters of radio channels was proposed, which accommodates the influence of a range of factors to improve the coverage efficiency of wireless sensor networks based on unmanned aerial vehicles. This method helped to partially solve the problem of information losses through adaptive optimisation of network coverage

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when influencing factors occur. The experimental models developed in this study allow estimating the signal distribution in space for sensor networks based on unmanned aerial vehicles, considering the influence of external factors, using fluctuation coefficients. The study also developed a mechanism for using a control device that allows measuring signal strength at any distance from the base station, providing flexibility and accuracy of assessment. The results showed a prominent level of measurement accuracy, with 95% reliability for an observation period of 20 seconds and an error of up to ±0.5 dBm. The total error of the methodology does not exceed 5%, which confirms the high reliability of the results and their compliance with real operating conditions. Thus, the findings of this study contribute to improving the efficiency and reliability of wireless sensor networks based on unmanned aerial vehicles, providing stable and high-quality connection in various operating conditions

Keywords: wireless sensor networks; wireless channel; energy parameters; throughput; model; UAV; statistical analysis; information loss

INTRODUCTION

Wireless Sensor Networks (WSNs) play a significant role in technological systems, enabling continuous monitoring and data transmission in a variety of environments. The introduction of unmanned aerial vehicles (UAVs) into these networks opens new opportunities to increase their efficiency and flexibility. As a result, UAVs can serve as mobile base stations, enabling rapid network deployment in areas where the installation of fixed infrastructure is difficult or uneconomical. The use of unmanned aerial vehicles to create coverage for wireless sensor networks provides added benefits, such as the ability to respond quickly to changing conditions and reduce the cost of network maintenance and deployment. However, the introduction of UAVs into wireless sensor networks faces a range of challenges that limit coverage efficiency and connection stability. One of the main problems is the presence of architectural obstacles that affect signal propagation. Multi-storey buildings, walls, and other structures can considerably degrade signal quality, making it difficult to ensure reliable and stable connection between sensors and base stations. A method to improve the coverage efficiency of UAV-based wireless sensor networks can significantly help solve the problem of architectural interference. Thanks to the adaptive tuning capability of unmanned aerial vehicles, signal transmission routes can be optimised to avoid interference and minimise data loss (Seidaliyeva *et al*., 2024). This approach also accommodates the impact of external factors, which helps ensure stable and reliable connection. The use of special algorithms to optimise the parameters of radio channels allows for efficient use of resources and high-quality coverage even in difficult conditions.

Internet of Things (IoT) devices have become widespread for offline data exchange and storage. The architecture of such networks is based on the use of various types of sensors or sensors to track and convert certain physical quantities into information signals for further processing. P. Karlin (2021) examined the impact of architectural solutions on the performance of IoT networks by investigating a modified method of interaction between IoT nodes. A. Sangaiah *et al*. (2020) also investigated the possibilities of optimising data exchange in IoT networks, considering the use of different types of sensors and sensors. V. Kryzhanovsky & S.P. Sergienko (2020) focused on the investigation of energy-efficient devices and their impact on the Internet of Things. However, despite the progress made, further research in this area is needed to further improve IoT networks and ensure their stable and efficient operation.

Considering the widespread use of wireless network technologies such as Wi-Fi, Bluetooth, and 4G/5G massive data systems, it is important to consider their diversity and application possibilities. M. Mollah *et al*. (2020) investigated the effectiveness of various wireless technologies in terms of their bandwidth, transmission range, and interference resistance, showing their advantages and disadvantages. Y. Zhuang *et al*. (2022) analysed the use of Bluetooth technologies in home automation systems, where it is important to ensure stable connection and low energy consumption. Q. Khanh *et al*. (2022) explored the potential for 4G/5G technologies to connect smart transport systems and infrastructure, confirming the significance of ensuring high data rates and low latency. However, it should also consider integrating other wireless technologies to create integrated and efficient data collection and processing systems that will ensure more efficient use of resources.

Another important factor is that wireless technologies can be used in various industries and households. P. Malik *et al*. (2021) considered the effectiveness of wireless technologies in production processes and their impact on increasing the productivity of industrial plants. A. Utsav *et al*. (2021) experimented with the implementation of wireless monitoring systems in military operations to optimise command and control processes and respond to military threats. S. Routray *et al*. (2020) also explored the possibilities of using wireless technologies for military purposes, to improve monitoring systems on the battlefield. At the same time, it is vital to continue research to improve the efficiency of wireless technologies in various areas, which will facilitate their rapid development and spread, as well as improve their functionality and reliability in general.

The purpose of this study was to develop and implement a new method for optimising sensor networks using UAVs to reduce information losses and increase data transmission efficiency in the face of a considerable number of architectural obstacles. The main objective of this study was to develop adaptive algorithms for estimating and optimising the energy parameters of radio channels, which accommodate the influence of various factors, to improve network coverage, and ensure stable connection. Another important task of the study is to develop experimental models for estimating the signal distribution in space and studying the influence of external factors, which will improve the accuracy of the estimation and ensure the reliability of the results in real-world operation.

MATERIALS AND METHODS

A range of experimental studies were conducted to develop a method for estimating and optimising the energy parameters of radio channels. This study developed a methodology that involved the organisation of wireless information transmission channels using Wi-Fi technology. This technology was chosen as the main tool for data transmission due to its popularity among drone manufacturers thanks to its low power consumption and high efficiency.

Within the framework of the experiment, the Wi-Fi access point was placed on a UAV and acted as a model of an intermediate base station, which is important for creating an effective wireless network. During the research, a mobile measuring device was used, which moved within the network coverage area and simulated the sensor field. This helped to investigate the behaviour of radio channels in real conditions. To ensure maximum representativeness of the experiment, the study was conducted in two frequency bands: 2.4 GHz and 5 GHz, which made it possible to assess the efficiency of data transmission in different scenarios. Based on the findings obtained, two types of data transmission channels were created: between two unmanned aerial vehicles (UAV-UAV) and between an unmanned aerial vehicle and a sensor (UAV-sensor).

The studies were conducted in areas with complex architectural buildings, where significant architectural obstacles, such as buildings, walls, and other structures, could affect signal propagation. This helped to investigate the behaviour of wireless channels under real architectural constraints, which is important for the further development of networks that should function effectively in urban or similar environments. Furthermore, a variety of equipment for the channel between unmanned aerial vehicles was used for research. This included testing with different types of devices to get generalised results on the behaviour of the signal on different surfaces. This approach made it possible to detect signal fluctuations depending on the type of equipment used. Analysing such fluctuations helps to better understand the impact of different devices on the stability and quality of connection, which can be useful when planning and deploying networks.

Based on the proposed methodology, a series of studies of signal coverage from the intermediate base station used on UAVs were conducted, which provided important data on the efficiency of data transmission in real conditions involving unmanned aerial vehicles. To evaluate the properties of the radio channel in different frequency bands, the study first considered the results in the 2.4 GHz frequency band, which is typical for further analyses due to its general significance and analogous nature to other bands. Analogous studies were also conducted in the 5 GHz frequency band, including its upper 5.8 GHz part, which made it possible to examine the properties of the radio channel at higher frequencies in greater detail and assess its ability to ensure connection stability.

RESULTS

The architecture of sensor networks can be represented as a four-tiered model that includes the sensor layer, data links, data processing layer, and application layer (Fig. 1).

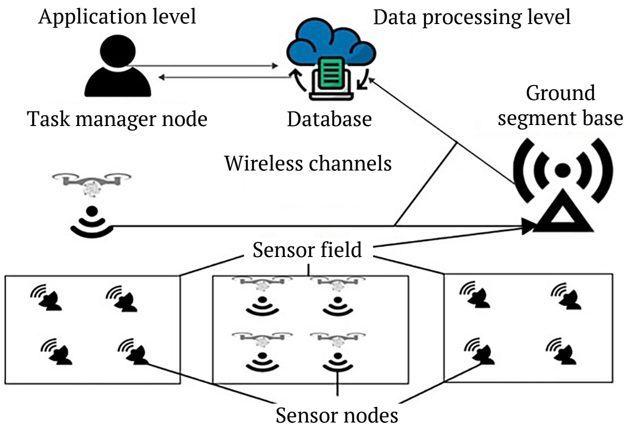

Figure 1. Structure of the sensor network
Source: developed by the authors of this study

The first is the sensor layer, which is responsible for monitoring certain environmental parameters. This layer consists of a variety of sensors combined into sensor nodes that can measure various physical quantities such as temperature, humidity, pressure. The capabilities and parameters of these sensors determine the purpose and type of the entire network. The next level is the information transmission channel, where the collected data is transferred from sensor nodes to central nodes or base stations. These channels can be either wireless or wired, depending on the specifics and requirements of the network. It is important to ensure the reliability and speed of information transmission for the effective functioning of the entire system (BenSaleh *et al.*, 2020).

The data processing layer is also a vital component of sensor network architecture, where the collected data is processed and analysed for further use. This involves filtering, aggregating, and interpreting data to extract useful information from raw measurements. Data can be processed both on-site, in sensor nodes, and in centralised computing systems (Cai & Shi, 2020). The fourth layer is the application layer, which is responsible for creating various services based on the processed data. Thus, the basic component of sensor networks is the sensor layer, which combines various sensors as part of sensor nodes. Sensor nodes form a so-called sensor field, which can be autonomous, directly subordinated to ground stations, or use intermediate base stations to collect and transmit data. Such stations can be either stationary or mobile. Fixed stations are usually located in fixed locations and provide continuous data collection and transmission. However, mobile stations that can be deployed on unmanned aerial vehicles offer much greater flexibility and efficiency (Kopetz & Steiner, 2020; Laghari *et al.*, 2021).

UAV-based mobile stations act as repeaters, allowing for efficient coverage of large and hard-to-reach areas. This approach is known as clustering, where unmanned aerial vehicles act as mobile network nodes. Due to their mobility, unmanned aerial vehicles can quickly change their position, providing the optimised location for data collection and transmission. This is crucial in environments where a rapid response is required, such as natural disasters or military conflict zones. Additionally, the integration of sensors directly on the UAV opens new opportunities for monitoring. Such sensors can be used to create an entire UAV-based sensor field that can move and adapt to changes in the environment. In military applications, UAVs with sensors can be used for reconnaissance, battlefield surveillance, detection of enemy movement, and other important tasks (Tertyshnik *et al.*, 2024). Mobile sensor networks based on UAVs allow for rapid deployment and reconfiguration of the network depending on the operational situation, which considerably increases the efficiency of military operations.

After converting the physical value into a digital code, the sensor transmits the information to the base station via a wireless channel created by the transceiver pair. This channel has several key parameters that determine its effectiveness. The main ones are the signal strength of the transmitters of both the sensor and the base station. Power defines coverage areas, with radii denoted as r_1 for the sensor and r_2 for the base station. To ensure efficient and symmetrical data transmission, the signal strength at the receiving end, denoted as Pm, must be sufficiently high. This is to avoid asymmetries that could lead to data loss or connection failures. A channel with a bandwidth of V must be available within the coverage area (denoted as ABh) to allow the transmission of data frames without delay to the base station of the terrestrial segment. The average value of the parameter Pm can be estimated by the following formula (1):

$$P_m \approx \frac{1}{T}\int_0^T P_m(t)dt \approx \frac{1}{n}\sum_{i=1}^{n} P_{m.i}, \tag{1}$$

where T – the observation period; n – the number of monitoring cycles.

The process of estimating V_{pl} can be expressed as follows (2):

$$V_{pl} \approx \frac{1}{T}\int_0^T V_{pl}(t)dt \approx \frac{1}{n}\sum_{i=1}^{n} V_{pl.i}, \tag{2}$$

where $V_{pl.i}$ – the measurement of throughput during one monitoring cycle; n – the number of monitoring cycles during the observation period T to obtain the required reliability.

A range of experimental studies have been conducted to develop a method for estimating and optimising the energy parameters of radio channels with regard to influencing factors. A special methodology was created for this purpose. Wireless information transmission channels are often organised using Wi-Fi technology. This technology is popular among drone manufacturers because of its low cost and low power consumption of radio modules (Ertam *et al.*, 2020). The use of Wi-Fi can substantially reduce the material costs of manufacturing UAVs, while maintaining high efficiency. Wi-Fi provides high-performance data links with low latency video streaming, high image quality, and interference resistance, which are critical requirements for special purpose networks (Chen *et al.*, 2020). Within the framework of the experiment, the access point was placed on a UAV and served as a model of an intermediate base station. A mobile measuring device that moved within the coverage area simulated the sensor field, allowing for a detailed study of the behaviour of radio channels in real-world conditions. Two frequency bands were used for the research: 2.4 GHz and 5 GHz. This allowed for two types of data links to be created: one between two UAVs (UAV-UAV) and one between a UAV and a sensor (UAV-sensor), as presented in Figure 2.

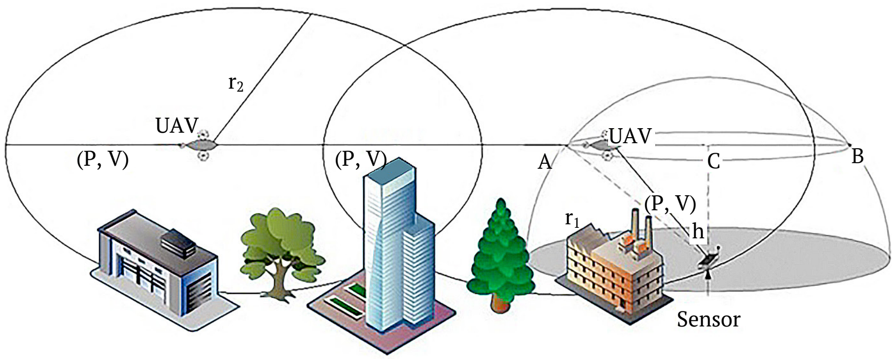

Figure 2. Structure of experimental studies of UAV-based network coverage in conditions of complex architectural obstacles

Source: developed by the authors of this study

Based on the proposed methodology, a series of studies of signal coverage from an intermediate base station based on unmanned aerial vehicles were conducted. The results of the studies in the 2.4 GHz frequency band should be considered first, since they are typical for other bands and have an analogous nature. The signal power distribution for the channels between the UAV and the sensor, as well as between the two UAVs, is presented in Figure 3.

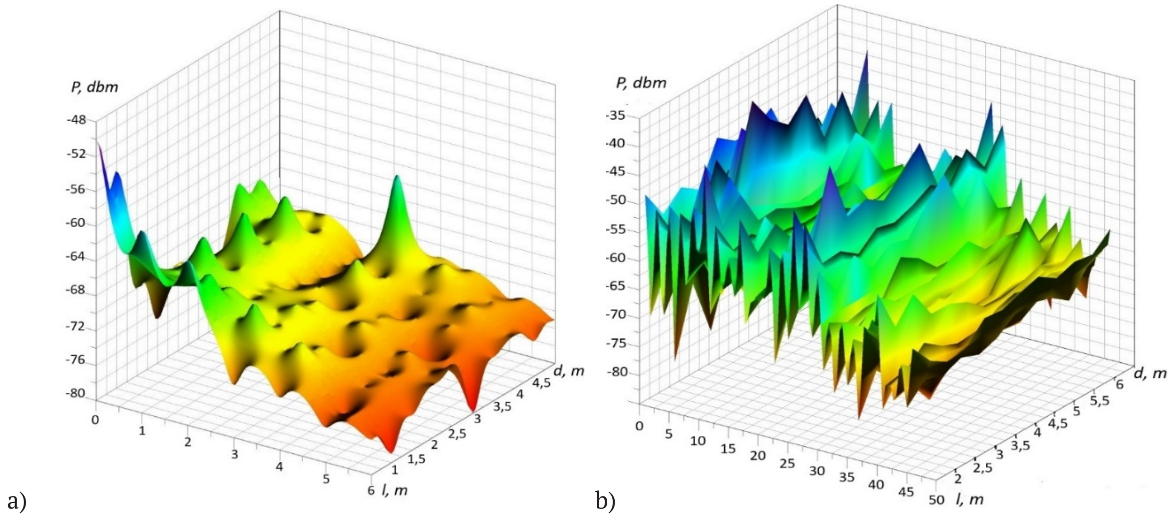

Figure 3. Signal power distribution for the 2.4 GHz frequency band
Note: a) UAV-sensor channel; b) UAV-UAV connection diagram
Source: developed by the authors of this study

As Figure 3a shows, the UAV–sensor channel shows characteristic signal peaks and troughs near architectural obstacles. That is, when the signal crosses any architectural elements such as walls or poles, it can experience a considerable increase or decrease in power. For instance, when a signal passes through a building wall, it can lose some of its power due to absorption by the wall material or reflection. On the other hand, when a signal passes through an open area, its power can increase. As for Figure 3b, there is a difference between the different devices in terms of the constant attenuation factor. This means that different devices can have different levels of signal loss when passing through the same architectural obstacles. Such a difference in attenuation coefficients can lead to an increase in the jitter interval of up to 15 dBm. In some places, the signal may be significantly weaker or stronger than in other places, creating uneven connection quality. Analogous studies have also been conducted in the 5 GHz frequency band, specifically, its upper 5.8 GHz. Studies in this range allow examining the properties of the radio channel at higher frequencies, which can affect the ability to transmit data in demanding conditions and ensure connection stability. The data obtained are presented in Figure 4.

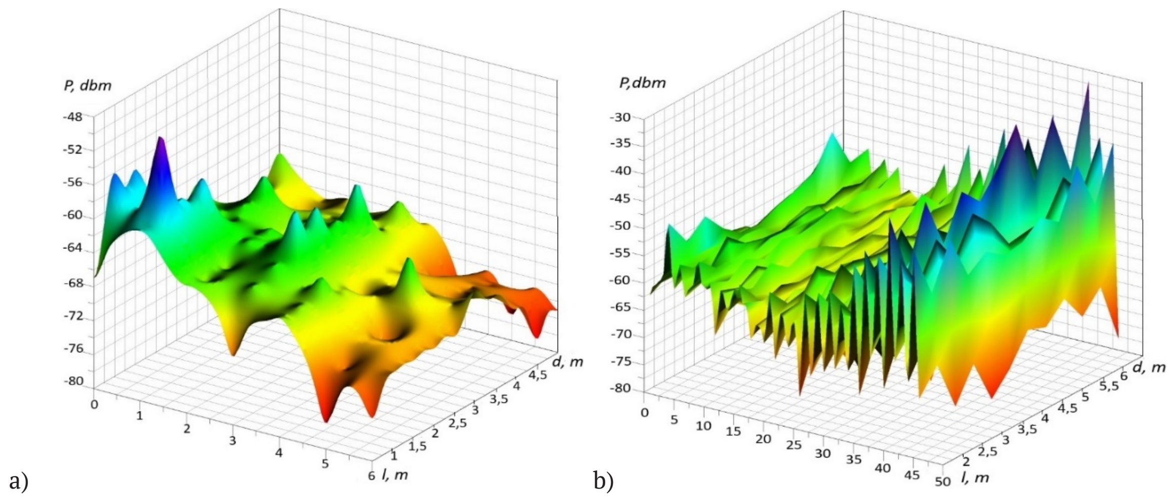

Figure 4. Signal power distribution for the 5 GHz frequency band
Note: a) UAV-sensor channel; b) UAV-UAV connection diagram
Source: developed by the authors of this study

In this case, there is a different distribution of signal peaks and troughs compared to the previous results, as well as a higher attenuation coefficient, which may be due to the physics of wave propagation in this particular frequency range. Furthermore, for the UAV-UAV channel, there is a significant maximum between the two stations, where signal fluctuations can reach up to 20 dBm. Such indicators may indicate intensive interaction between devices and possible interference in the signal path, which affects its stability and reliability of data transmission (Saeed *et al*., 2021). As such, channels in the 2.4 GHz band are proving to be more appropriate in terms of stability and range, due to their ability to penetrate obstacles such as walls and ceilings with less signal loss than higher frequencies. They can provide reliable connection at a distance and in conditions of limited line of sight between devices. However, 2.4 GHz channels have a rather narrow bandwidth, which can limit the data transfer rate, especially when there are many connected devices. Furthermore, this frequency band is also subject to significant interference and noise from other wireless devices, microwaves, Bluetooth devices, and other sources, which can result in signal loss and reduced data transmission efficiency.

The 5 GHz frequency band has a wider frequency spectrum compared to 2.4 GHz, which opens the possibility of creating a much larger number of frequency channels. These channels can be continuous or have a wide bandwidth, making them attractive for high-performance multimedia transmissions with minimal chance of architectural interference. The use of the 5 GHz band can be recommended for data exchange between UAV intermediate stations, where high bandwidth and reliability are important. However, one should consider the possibility of architectural interference, which can lead to signal loss and reduced data transmission efficiency. If sensor networks are used for bandwidth-constrained tasks, such as low-intensity data collection, it is more appropriate to use the 2.4 GHz band with narrowband channels. This can provide greater connectivity stability and less vulnerability to architectural interference and interference, which can be critical for data reliability in such scenarios (Shahraki *et al*., 2020; Abdulsahib *et al*., 2024).

To obtain an experimental model of the signal power distribution, it is important to consider the spatial aspect, which can be represented by two coordinates: l and d. However, in this case, a simplified model was used, where only the l coordinate corresponding to the line of sight was used. This simplification can introduce a certain error in the results, as it does not accommodate other factors, such as the distance d from the signal source. The results of the signal power distribution studies for the 2.4 GHz and 5 GHz frequency bands are presented in the form of graphs presented in Figure 5.

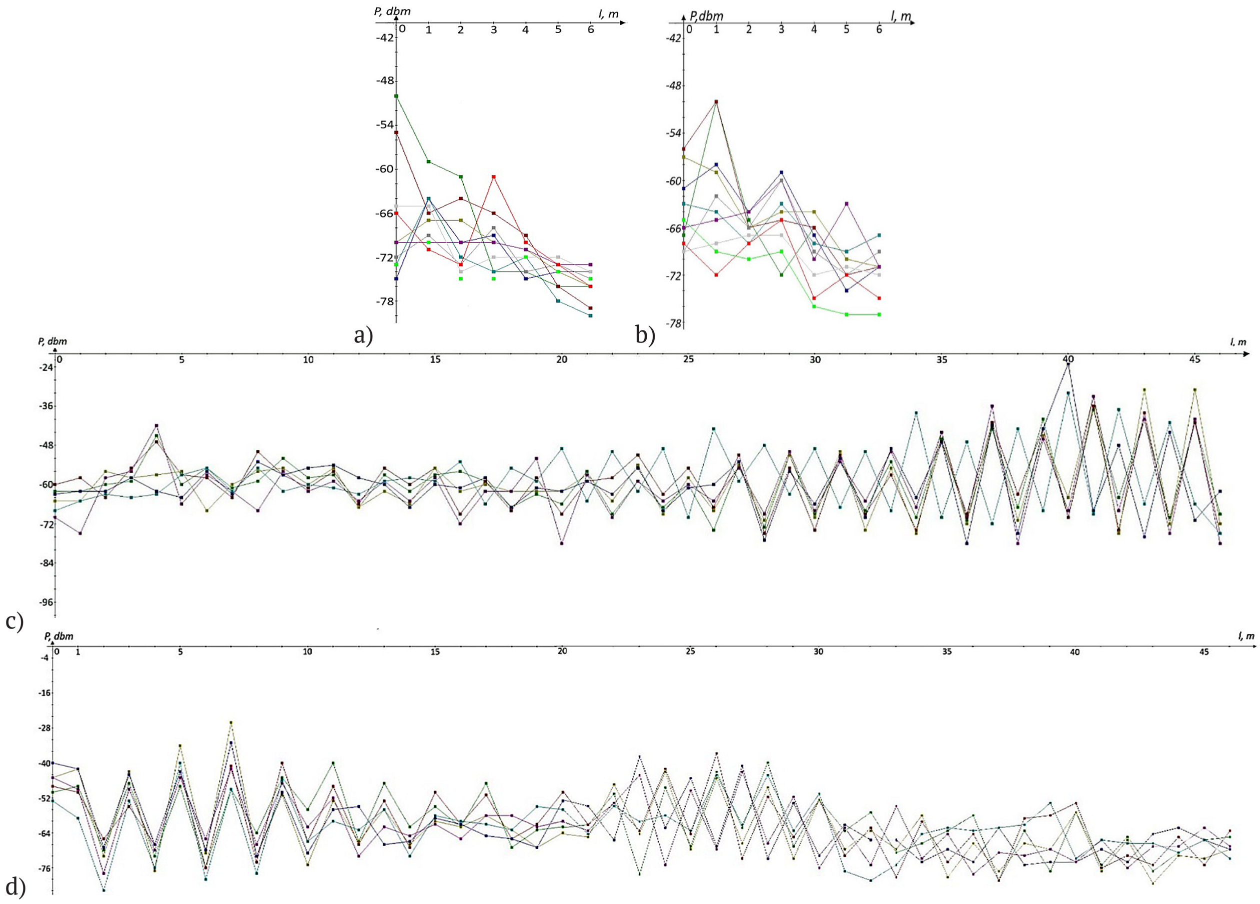

Figure 5. Research results for the 2.4 GHz band by line-of-sight coordinate
Note: a) 2.4 GHz "UAV-sensor"; b) 2.4 GHz "UAV-UAV"; c) 5 GHz "UAV-sensor"; d) 5 GHz "UAV-UAV"
Source: developed by the authors of this study

The analysis of Figure 5 suggests that the UAV-sensor channel is characterised by a quadratic fading law, which is typical for channels with a considerable influence of external factors. Specifically, this may include obstructions or other sources of interference that may cause harmful interference to signal transmission. To build a model of the signal power distribution (3) in space for the UAV-sensor channel, a regression analysis based on the line-of-sight coordinates can be used:

$$P_{US} = (a \pm \Delta a)l^2 + (b \pm \Delta b)l + k \pm \Delta k, \qquad (3)$$

where a, b – the signal attenuation coefficients along the line-of-sight coordinate; k – the initial level; Δa, Δb, and Δk – the fluctuation parameters of the respective attenuation coefficients.

When analysing the UAV-UAV channel and separating the results into individual devices, it can be established that the signal power distribution model can be simplified to a linear nature as follows (4):

$$P_{UU} = (d \pm \Delta a)l + k \pm \Delta k, \qquad (4)$$

where d – the signal attenuation coefficient along the line-of-sight coordinate.

By applying statistical analysis to the results presented in Figure 5, the attenuation and fluctuation coefficients for formulas (3) and (4) were determined, which indicate how the signal changes with distance or depending on other factors of influence. The obtained values of the attenuation and fluctuation coefficients were summarised and presented in Table 1.

Table 1. Attenuation coefficients

	UAV-sensor						UAV-UAV			
Coefficient	a	Δa	b	Δb	k	Δk	d	Δd	k	Δk
2.4 GHz	0.002	**±0.002**	-0.2	**±0.1**	-65	**±5**	0.13	**±0.03**	62	**±2**
5 GHz	0.005	**±0.003**	-0.5	**±0.3**	-55	**±5**	0.3	**±0.5**	55	**±2**

Source: developed by the authors of this study

Thus, formulas (3) and (4) provide a means to assess and predict the level of signal coverage, accommodating a range of factors of influence, by using fluctuation intervals. They allow accommodating the influence of various variables, such as the distance between devices, architectural obstacles, and other factors that can affect signal stability. Based on models (3) and (4), which reflect the signal distribution in space for the sensor field and the intermediate station, a new method for estimating and optimising the energy parameters of radio channels was developed, considering the influence of a range of factors. This method includes several stages, which will be discussed in greater detail below.

At the first stage, the software and hardware of the receiving device are used to estimate the signal power at the receiver input (P_m). The evaluation is carried out based on the average statistical value of the parameter P_m, which is calculated according to formula (1). To obtain this value, an observation period of 5 seconds and a monitoring cycle of 1 second are used. This stage allows collecting data on signal strength and creating a basis for further analysis and optimisation of radio channel parameters.

At the second stage, the network coverage area is determined based on mathematical models (3) and (4), which consider the signal distribution in space. For this, a control sensor is used, which is placed at a certain distance from the base station, but within the coverage area. This distance can be set arbitrarily and is denoted as l_0. The control sensor records the signal strength it receives when it is located at a certain distance from the base station. The data received from the control sensor allows applying mathematical expressions to describe the distribution of the signal in space, making it possible to accurately determine the zone where the signal values fluctuate from minimum to maximum, and providing the necessary signal strength for stable and reliable connection. The resulting formula (5) based on model (3) allows quantifying the network coverage area, considering the factors of influence:

$$P_{US} = (a \pm \Delta a)(l^2 - l_0^2) + (b \pm \Delta b)(l - l_0) + P_m + \Delta P, \qquad (5)$$

where ΔP – the level of signal power fluctuations, which is defined as follows (6):

$$\Delta P \approx \frac{1}{2}\left(\frac{1}{n}\sum_{j=1}^{n} \max\{P_{m.i}\}_j - \frac{1}{n}\sum_{j=1}^{n} \min\{P_{m.i}\}_j\right), \qquad (6)$$

where n – the number of observation periods for obtaining experimental characteristics $P_m(l)$.

For instance, the calculations for the UAV-sensor channel based on the measurement of the control sensor are considered. A fragment of the calculation is presented in Figure 6. Thus, one can analyse the level of maximum and minimum signal values based on fluctuation intervals, which allows predicting the impact of various factors on the signal. This approach involves the use of a prebuilt database, which helps to predict and analyse the impact of factors on radio communications more accurately.

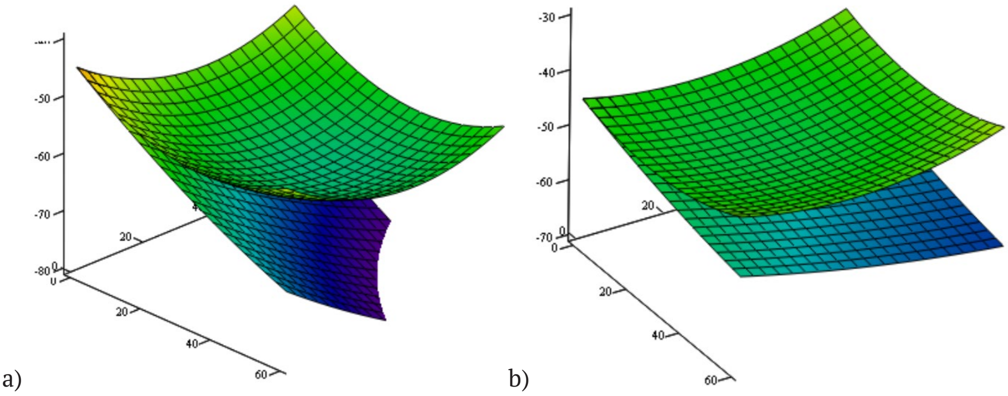

Figure 6. Fragment of network coverage based on reference measurement for the UAV-sensor channel
Note: a) for the 2.4 GHz band; b) for the 5 GHz band
Source: compiled by the authors of this study

The third stage involves assessing the bandwidth, which is a key indicator of the radio channel's efficiency. For this, one can use statistical matching coefficients, which reflect the degree of correspondence between the estimated and factual channel capacity. Statistical coefficients accommodate a range of factors such as interference, signal fading, and other specific channel characteristics. The use of statistical relationships makes it possible to make predictions about the possibility of data transmission in specific conditions and to adjust the radio channel to achieve optimised throughput (Mykhalevskiy, 2020). The static relationship can be expressed as follows (7):

$$V_{pl}(l) \approx K(P_{БС} \pm \Delta P) + S_0 \pm \Delta V, \tag{7}$$

where K – the correlation coefficient between the signal power at the receiver input and the bandwidth; S_0 is the initial coefficient; ΔV – the bandwidth fluctuation interval, which is defined as follows (8):

$$\Delta V \approx \frac{1}{2n}\sum_{i=1}^{n}\left(\max\{V_{m.i}\}_j - \min\{V_{m.i}\}_j\right), \tag{8}$$

The results of experimental studies of the throughput for the UAV-sensor channel are presented in Figure 7.

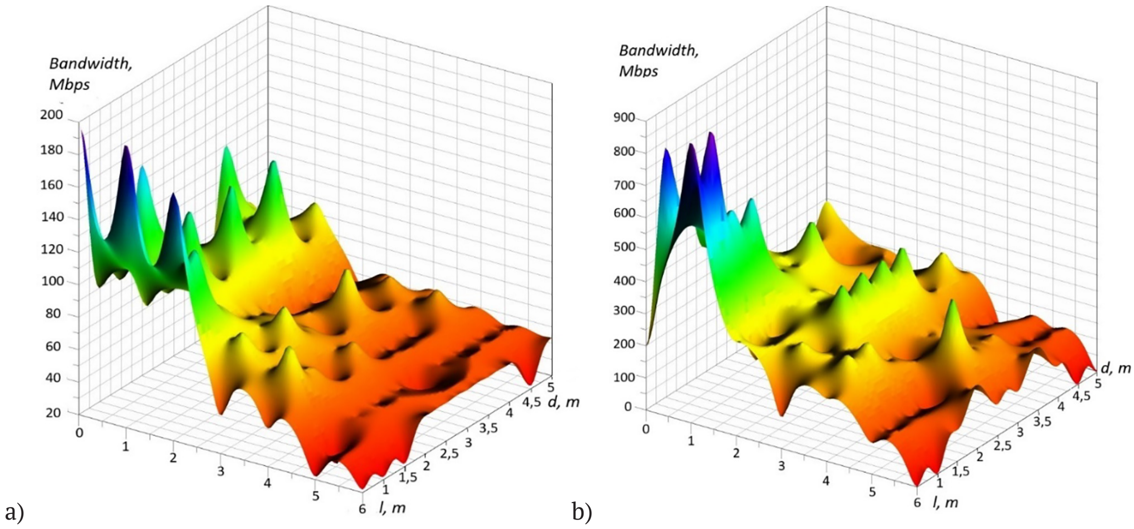

Figure 7. Measurement results of throughput values for the UAV-sensor channel
Note: a) for the 2.4 GHz band; b) for the 5 GHz band
Source: developed by the authors of this study

The obtained results and the expression of the statistical relationship (7) allow establishing a correspondence between the radio channel bandwidth and the required minimum signal power level.

This process is carried out considering the fluctuation interval, which is allocated to ensure that information loss in the network is minimised. This analysis helps to determine exactly what signal power values are required to ensure optimised channel throughput under different connection conditions, which allows for efficient radio channel management and minimises data loss during transmission.

At the fourth stage, the need to adjust the coverage area to ensure the minimum required channel capacity is assessed, including an analysis of the signal power fluctuation intervals (ΔP) and bandwidth (ΔV). The correction interval, denoted as Δl, is defined as the minimum signal power value that allows maintaining the required channel bandwidth. This stage involves detailed signal modelling and analysis to identify the points where changes need to be made to ensure stable and efficient connection. Based on the data obtained, the coverage area can be optimised to minimise signal loss and provide the required throughput even in areas with high fluctuations. An example of determining the correction interval Δl is presented in Figure 8.

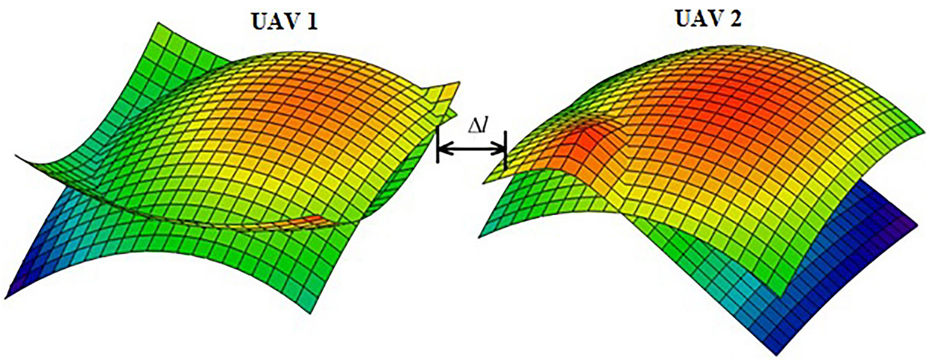

Figure 8. Estimating the adjustment interval
Source: developed by the authors of this study

As Figure 8 shows, between the coverage areas created by UAV1 and UAV2, there is an area with insufficient signal strength, denoted by the length Δl, where the signal strength is lower than the minimum required. In this zone, information losses may occur, such as delayed video stream transmission, errors in information frames, added transmission cycles, and other problems. Therefore, in such a situation, it is necessary to adjust the coverage area to ensure a stable signal strength and minimise information loss, which is crucial for maintaining the efficient operation of the network.

The fifth stage involves deriving the estimation results, considering the fluctuation intervals specified in formulas (6) and (8), as well as measurement errors. At this stage, the error minimisation operation and coverage optimisation are performed. This is achieved by adjusting the Δl parameter, which defines the area with insufficient signal strength. Due to the mobility of UAVs, their position can be adjusted to ensure that the minimum required channel capacity is set (Meng *et al.*, 2022). Thus, this stage involves the dynamic adjustment of the position of unmanned vehicles to achieve optimised network coverage and ensure stable and reliable data transmission, minimising the impact of negative factors.

The proposed method is relatively simple and affordable, since it is based on the control measurement of the energy parameter Pm using the sensor's software and hardware or a subscriber device. The parameter P_m is estimated within the range of coverage from the UAV, using the parameter l_0 within the sensor field. This involves placing sensors at different points in space to measure the strength of the signal reaching them from the base station to the UAV, enabling the creation of a detailed picture of the signal distribution in space. The reliability of the results used to create the experimental surfaces with an observation period of 20 seconds is 0.95 with an error of up to σP±0.5 dBm, confirming their accuracy and reliability. Even when the observation period is reduced to 5 seconds, the error stays within σP±1 dBm, which ensures an error of no more than 5%. This level of accuracy is sufficient for most practical applications. The accuracy of the measurement of the parameter P_m also depends on the characteristics of the sensor receiver and the parameter database of the statistical connection model V_{pl} for different devices, which indicates the significance of having such a base for correct evaluation and optimisation. Thus, this method allows collecting reliable data on the energy parameters of radio channels used in the network and ensure their optimisation, accommodating the influence of a range of factors. This helps to increase the efficiency of the wireless sensor network by ensuring stable and high-quality data transmission, minimising losses, and improving overall system performance.

DISCUSSION

Research in the field of wireless sensor networks based on unmanned aerial vehicles is of significant importance for technological development. Such networks are critical to ensure continuous monitoring and data collection in a variety of environments, from small urban areas to remote areas. The detailed investigation of wireless sensor networks can make a considerable contribution to the development of modern technologies, allowing to optimise the efficiency and reliability of such networks, and ensuring stable connection even in challenging conditions. The development of new methods for assessing and optimising the energy parameters of radio channels will help reduce information losses and ensure efficient data transmission (Lavdanskyi *et al.*, 2022). In addition, new advances in this area may contribute to the development of innovative technologies that will automate and optimise processes in these industries. They will improve data collection and processing, which will open new opportunities for efficient use of resources and provide generally more accurate and prompt decisions.

The experiment carried out within the framework of this study drew attention to the study of radio channels in real conditions. The access point placed on the UAV acted as a model of an intermediate base station, creating unique conditions for connection analysis. Particular attention was paid to the use of two frequency bands – 2.4 GHz and 5 GHz, which made it possible to obtain comprehensive data on the efficiency of signal transmission in different frequency spectra. Comparing the results in both bands helped to understand how frequency affects the quality of connection and helped us determine the optimised parameters to improve network efficiency. Z. Al Aghbari *et al*. (2020) also addressed significant aspects of the efficiency of wireless sensor networks, including their adaptive optimisation and reduction of information loss. T. Vaiyapuri *et al*. (2022) focused on improving methods for analysing radio channels in different operating conditions, which ultimately contributed to increasing the reliability and stability of connection. J. Bhola *et al*. (2020) developed new network optimisation strategies to maximise performance and speed, which proved to be a major step in the development of wireless sensor networks. However, when comparing the findings of the cited studies with the results of the present study, it should be noted that the latter allowed considering a wide range of factors, including the impact of different frequency bands, external interference, and other factors affecting the quality of connection. Quick progress has also been made in developing new methods for assessing and optimising the energy parameters of radio channels, which makes it possible to increase the network's resilience and efficiency (Sabibolda *et al*., 2022). This analysis opens new prospects for further research and development of wireless sensor networks based on UAVs.

It should also be emphasised that the experimental results indicate that the channels in the 2.4 GHz band are more appropriate in terms of stability and wave propagation range. Their ability to penetrate obstacles such as walls and ceilings with less signal loss than higher frequencies enables reliable connection over distance and in conditions of limited line-of-sight between devices. However, 2.4 GHz channels have limited bandwidth, which can limit data rates and increase vulnerability to interference from other wireless devices. At the same time, the 5 GHz frequency band has a wider frequency spectrum, which opens the possibility of creating more frequency channels. Such channels can be either continuous or have a wide bandwidth, making them attractive for high-performance multimedia transmissions with minimal architectural interference (Kabdoldina *et al*., 2022). The use of the 5 GHz band is recommended for data exchange between UAV intermediate stations, where high bandwidth and reliability are significant. However, considering the possibility of architectural interference that can affect the quality of connection, it is important to choose this range with special attention. H. Khan *et al*. (2020) also analysed the impact of various data transmission parameters on the performance of wireless sensor networks depending on the selected frequency range, which revealed key factors for optimising parameters to achieve maximum data transmission efficiency in concrete operating conditions. K. Qureshi *et al*. (2020) investigated the impact of network configuration and node location on connection efficiency in wireless sensor networks, allowing to identify optimised strategies for node location and network configuration to achieve the best performance and reliability of connection. Thus, the findings of these studies can complement the present study, expand its scope, and improve the understanding of the processes occurring in wireless sensor networks based on UAVs, accommodating various aspects of their operation and optimisation.

As a result of the present study, the proposed method proved to be effective and easy to use. It is based on the control measurement of the energy parameter P_m, which is important for evaluating the performance of radio channels in wireless sensor networks. The use of sensor hardware and software or a subscriber device simplifies the process and allows measurements to be carried out without significant difficulty. The estimation of the parameter P_m takes place within the range of coverage from UAVs, which ensures the reliability and accuracy of the obtained findings. The use of the l_0 parameter within the sensor field, which allows obtaining detailed information about the distribution of the signal in space, should be highlighted. Placing sensors at separate locations allows detecting variations in signal strength and identifying optimised solutions to improve network efficiency, making it possible to accommodate real-world conditions and adapt the system to changes in the environment. S. Chatterjee *et al*. (2021) also investigated the impact of adaptive network coverage optimisation on the resistance to interference from other wireless devices, which revealed valuable findings for reducing the impact of interference and improving connection reliability. J. Akram *et al*. (2022) focused on the use of adaptive sensors to optimise target coverage in wireless sensor networks, helping to determine the optimised configuration of the network and its parameters to maximise performance and minimise signal loss. Comparison of the findings of the present study with the results of the cited studies suggests that the proposed method is effective in comparison with other strategies for optimising a network based on unmanned aerial vehicles. The identified differences in approaches and results offer a better insight into how different parameters and strategies affect network performance in different operating conditions. This analysis helps us to determine the optimised parameters and optimisation methods to improve connection quality and ensure network reliability.

It is also worth emphasising the reliability of the findings of the present study, which helped to draw significant conclusions to ensure the reliability and accuracy in assessing the energy parameters of radio channels. Based on the data obtained during the observation period of 20 seconds, it was found that the reliability is 0.95, with an error of up to ±0.5 dBm. This demonstrates the high accuracy and reliability of the findings obtained, which makes them credible for further use in practical applications. Even when the observation period is reduced to 5 seconds, the error stays within ±1 dBm, which ensures an overall error of no more than 5%. This elevated level of accuracy is important given the wide range of applications for this data. Notably, the accuracy of the measurement of the Pm parameter also depends on the characteristics of the sensor receiver and the availability of a database of parameters of the model of statistical connection V_{pl} for various devices. This indicates the significance of having and using such a database correctly to ensure adequate evaluation and optimisation of radio channels. Correctly selected parameters of the statistical link model play a key role in ensuring high accuracy of energy parameter estimation, which is an essential aspect for ensuring the efficiency and reliability of wireless networks (Bloshchynskyi & Klyatchenko, 2023). M. Nguyen *et al*. (2021) examined the process of data collection using UAVs in wireless sensor networks, opening new opportunities for understanding the interaction between radio channels. M. Nomikos *et al*. (2020) investigated the dynamics of changes in energy parameters during the movement of sensor devices, which provided valuable information on the adaptation of wireless networks to changes in operating conditions. However, the findings of the present study, in comparison with the cited research, helped to analyse the impact of external factors on the parameters of radio channels in greater depth and develop effective strategies to optimise their operation in a changing environment.

Thus, achievements and developments in this area are important for the development of wireless sensor networks based on unmanned aerial vehicles, helping to understand and optimise energy parameters and dynamics of changes in different conditions. They contribute to the creation of more efficient and reliable data transmission systems, which is of significant importance in the digital world, ensuring high performance and resilience of such technologies to external influences.

CONCLUSIONS

As a result of this study, a new method for estimating and optimising the energy parameters of radio channels was proposed, which accommodates the influence of a range of factors to improve the coverage efficiency of wireless sensor networks based on UAVs. This method is aimed at partially solving the problem of information loss by adaptively optimising network coverage when influencing factors occur. During the research, experimental models were obtained that allow estimating the signal distribution in space for sensor networks based on UAVs. These models accommodate the impact of external factors using fluctuation coefficients. Specifically, a mechanism was developed to use a control device that allows measuring signal strength at an arbitrary distance from the base station, providing flexibility and accuracy of assessment.

The reliability of the findings was confirmed by the prominent level of measurement accuracy. For an observation period of 20 seconds, the reliability is 95%, with an error of up to ±0.5 dBm. For shorter observation periods, such as 5 seconds, the error increases to ±1 dBm. The total error of the methodology does not exceed 5%, which ensures high reliability of the findings and their compliance with real operating conditions. This approach ensures efficient optimisation of sensor network coverage, considering both spatial and energy parameters, which significantly improves connection quality and reduces information loss. Thus, the new method helps to increase the efficiency and reliability of wireless sensor networks based on UAVs, providing stable and high-quality connection in various operating conditions. Notably, the study focused mainly on standard environmental conditions, which may not consider all possible variations in real field conditions. Furthermore, the use of specific UAV models and sensors may affect the universality of the results obtained, which also requires added attention and study.

Areas for further research could include extending the analysis to more diverse environmental conditions and further investigating the impact of different UAV models and sensors on the findings. It is also worth exploring the possibilities of applying the methods to a wider range of applications, including security, environmental monitoring, and intelligence, which will allow for further improvement of unmanned vehicle systems and wireless sensor networks for more accurate and efficient use in various industries.

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CONFLICT OF INTEREST

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REFERENCES

[1] Abdulsahib, G.M., Hassan, H.J., & Khalaf, O.I. (2024). A modified bandwidth prediction algorithm for wireless sensor networks. *Journal of Information Science and Engineering*, 40(1), 177-188. doi: 10.6688/JISE.202401_40(1).0011.

[2] Akram, J., Munawar, H.S., Kouzani, A.Z., & Mahmud, M.P. (2022). Using adaptive sensors for optimised target coverage in wireless sensor networks. *Sensors*, 22(3), article number 1083. doi: 10.3390/s22031083.

[3] Al Aghbari, Z., Khedr, A.M., Osamy, W., Arif, I., & Agrawal, D.P. (2020). Routing in wireless sensor networks using optimization techniques: A survey. *Wireless Personal Communications*, 111, 2407-2434. doi: 10.1007/s11277-019-06993-9.

[4] BenSaleh, M.S., Saida, R., Kacem, Y.H., & Abid, M. (2020). Wireless sensor network design methodologies: A survey. *Journal of Sensors*, 2020, article number 9592836. doi: 10.1155/2020/9592836.
[5] Bhola, J., Soni, S., & Cheema, G.K. (2020). Genetic algorithm based optimized leach protocol for energy efficient wireless sensor networks. *Journal of Ambient Intelligence and Humanized Computing*, 11, 1281-1288. doi: 10.1007/s12652-019-01382-3.
[6] Bloshchynskyi, B.V., & Klyatchenko, Y.M. (2023). Efficiency of computer means for automatic antennas direction in wireless data transmission systems. *Information Technologies and Computer Engineering*, 58(3), 33-40. doi: 10.31649/1999-9941-2023-58-3-33-40.
[7] Cai, Z., & Shi, T. (2020). Distributed query processing in the edge-assisted IoT data monitoring system. *IEEE Internet of Things Journal*, 8(16), 12679-12693. doi: 10.1109/JIOT.2020.3026988.
[8] Chatterjee, S., Abdel-Rahman, M.J., & MacKenzie, A.B. (2021). A joint optimization framework for network deployment and adaptive user assignment in indoor millimeter wave networks. *IEEE Transactions on Wireless Communications*, 20(11), 7538-7554. doi: 10.1109/TWC.2021.3085563.
[9] Chen, W., Jeong, S., & Jung, H. (2020). WiFi-Based home IoT communication system. *Journal of Information and Communication Convergence Engineering*, 18(1), 8-15. doi: 10.6109/jicce.2020.18.1.8.
[10] Ertam, F., Kilincer, I.F., Yaman, O., & Sengur, A. (2020). A new IoT application for dynamic WiFi based wireless sensor network. In *2020 International Conference on Electrical Engineering (ICEE)* (pp. 1-4). Istanbul: IEEE. doi: 10.1109/ICEE49691.2020.9249771.
[11] Kabdoldina, A., Ualiyev, Z., Smailov, N., Malikova, F., Oralkanova, K., Baktybayev, M., Arinova, D., Khikmetov, A., Shaikulova, A., & Bazarbay, L. (2022). Development of the design and technology for manufacturing a combined fiber-optic sensor used for extreme operating conditions. *Eastern-European Journal of Enterprise Technologies*, 5(5-119), 34-43. doi: 10.15587/1729-4061.2022.266359.
[12] Karlin, P.Y. (2021). *A modified method of interaction between nodes of the Internet of Things network*. Kyiv: National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”.
[13] Khan, H., Hassan, S.A., & Jung, H. (2020). On underwater wireless sensor networks routing protocols: A review. *IEEE Sensors Journal*, 20(18), 10371-10386. doi: 10.1109/JSEN.2020.2994199.
[14] Khanh, Q.V., Hoai, N.V., Manh, L.D., Le, A.N., & Jeon, G. (2022). Wireless communication technologies for IoT in 5G: Vision, applications, and challenges. *Wireless Communications and Mobile Computing*, 2022, article number 3229294. doi: 10.1155/2022/3229294.
[15] Kopetz, H., & Steiner, W. (2022). Internet of things. In *Real-time systems: Design principles for distributed embedded applications* (pp. 325-341). Cham: Springer International Publishing. doi: 10.1007/978-3-031-11992-7_13.
[16] Kryzhanovsky, V.G., & Sergienko, S.P. (2020). *Energy efficient devices of the Internet of Things (IoT)*. Vinnytsia: Vasyl Stus Donetsk National University.
[17] Laghari, A.A., Wu, K., Laghari, R.A., Ali, M., & Khan, A.A. (2021). A review and state of art of Internet of Things (IoT). *Archives of Computational Methods in Engineering*, 29, 1395-1413. doi: 10.1007/s11831-021-09622-6.
[18] Lavdanskyi, A., Faure, E., Tynymbayev, S., & Skutskyi, A. (2022). System for secure information exchange of text data through the radio channel of the ism band. *Bulletin of Cherkasy State Technological University*, 27(3), 41-48. doi: 10.24025/2306-4412.3.2022.267786.
[19] Malik, P.K., Sharma, R., Singh, R., Gehlot, A., Satapathy, S.C., Alnumay, W.S., Pelusi, D., Ghosh, U., Nayak, J., & Nayak, J. (2021). Industrial Internet of Things and its applications in Industry 4.0: State of the art. *Computer Communications*, 166, 125-139. doi: 10.1016/j.comcom.2020.11.016.
[20] Meng, K., Wu, Q., Ma, S., Chen, W., Wang, K., & Li, J. (2022). Throughput maximization for UAV-enabled integrated periodic sensing and communication. *IEEE Transactions on Wireless Communications*, 22(1), 671-687. doi: 10.1109/TWC.2022.3197623.
[21] Mollah, M.B., Zeadally, S., & Azad, M.A.K. (2020). Emerging wireless technologies for Internet of Things applications: Opportunities and challenges. In *Encyclopedia of wireless networks* (pp. 390-400). Cham: Springer. doi: 10.1007/978-3-319-78262-1_328.
[22] Mykhalevskiy, D. (2020). Devising a technique to evaluate fluctuations in the main parameters of a wireless channel of the 802.11 standard. *Easten-European Journal of Enterprise Technologies*, 6(108), 18-24. doi: 10.15587/1729-4061.2020.218720.
[23] Nguyen, M.T., Nguyen, C.V., Do, H.T., Hua, H.T., Tran, T.A., Nguyen, A.D., Ala, G., & Viola, F. (2021). UAV-assisted data collection in wireless sensor networks: A comprehensive survey. *Electronics*, 10(21), article number 2603. doi: 10.3390/electronics10212603.
[24] Nomikos, N., Michailidis, E.T., Trakadas, P., Vouyioukas, D., Karl, H., Martrat, J., Zahariadis, T., Papadopoulos, K., & Voliotis, S. (2020). A UAV-based moving 5G RAN for massive connectivity of mobile users and IoT devices. *Vehicular Communications*, 25, article number 100250. doi: 10.1016/j.vehcom.2020.100250.

[25] Qureshi, K.N., Bashir, M.U., Lloret, J., & Leon, A. (2020). Optimized cluster-based dynamic energy-aware routing protocol for wireless sensor networks in agriculture precision. *Journal of Sensors*, 2020, 9040395. doi: 10.1155/2020/9040395.
[26] Routray, S.K., Javali, A., Sahoo, A., Sharmila, K.P., & Anand, S. (2020). Military applications of satellite based IoT. In *2020 Third international conference on smart systems and inventive technology (ICSSIT)* (pp. 122-127). Tirunelveli: IEEE. doi: 10.1109/ICSSIT48917.2020.9214284.
[27] Sabibolda, A., Tsyporenko, V., Tsyporenko, V., Smailov, N., Zhunussov, K., Abdykadyrov, A., Baigulbayeva, M., & Duisenov, N. (2022). Improving the accuracy and performance speed of the digital spectralcorrelation method for measuring delay in radio signals and direction finding. *Eastern-European Journal of Enterprise Technologies*, 1(9-115), 6-14. doi: 10.15587/1729-4061.2022.252561.
[28] Saeed, U., Jan, S.U., Lee, Y.D., & Koo, I. (2021). Fault diagnosis based on extremely randomized trees in wireless sensor networks. *Reliability Engineering & System Safety*, 205, article number 107284. doi: 10.1016/j.ress.2020.107284.
[29] Sangaiah, A.K., Hosseinabadi, A.A.R., Shareh, M.B., Bozorgi Rad, S.Y., Zolfagharian, A., & Chilamkurti, N. (2020). IoT resource allocation and optimization based on heuristic algorithm. *Sensors*, 20(2), article number 539. doi: 10.3390/s20020539.
[30] Seidaliyeva, U., Ilipbayeva, L., Taissariyeva, K., Smailov, N., & Matson, E.T. (2024). Advances and challenges in drone detection and classification techniques: A state-of-the-art review. *Sensors*, 24(1), article number 125. doi: 10.3390/s24010125.
[31] Shahraki, A., Taherkordi, A., Haugen, Ø., & Eliassen, F. (2020). Clustering objectives in wireless sensor networks: A survey and research direction analysis. *Computer Networks*, 180, article number 107376. doi: 10.1016/j.comnet.2020.107376.
[32] Tertyshnik, E.M., Potapov, O.I., Mishok, A.A., & Andrushko, A.M. (2024). Analysis of the possibilities of using IoT for military purposes. *Collection of Scientific Works of the State Research Institute for Testing and Certification of Arms and Military Equipment*, 19(1), 140-146. doi: 10.37701/dndivsovt.19.2024.17.
[33] Utsav, A., Abhishek, A., Suraj, P., & Badhai, R.K. (2021). An IoT based UAV network for military applications. In *2021 Sixth International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)* (pp. 122-125). Chennai: IEEE. doi: 10.1109/WiSPNET51692.2021.9419470.
[34] Vaiyapuri, T., Parvathy, V.S., Manikandan, V., Krishnaraj, N., Gupta, D., & Shankar, K. (2022). A novel hybrid optimization for cluster-based routing protocol in information-centric wireless sensor networks for IoT based mobile edge computing. *Wireless Personal Communications*, 127(1), 39-62. doi: 10.1007/s11277-021-08088-w.
[35] Zhuang, Y., Zhang, C., Huai, J., Li, Y., Chen, L., & Chen, R. (2022). Bluetooth localization technology: Principles, applications, and future trends. *IEEE Internet of Things Journal*, 9(23), 23506-23524. doi: 10.1109/JIOT.2022.3203414.

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Метод підвищення ефективності покриття безпровідних сенсорних мереж на базі БПЛА

Анотація. Дане дослідження спрямоване на адаптивну оптимізацію сенсорних мереж із використанням безпілотних літальних апаратів для зменшення інформаційних втрат і забезпечення мінімально можливих технічних показників каналів передачі інформації в умовах значної кількості архітектурних перешкод. В ході роботи було проведено експерименти з передачі даних через безпровідний канал за допомогою технології Wi-Fi, де точка доступу була розміщена на безпілотному літальному апараті. Дослідження проводилися в умовах складної архітектурної забудови, з використанням частотних діапазонів 2.4 ГГц та 5 ГГц, щоб детально вивчити поведінку радіоканалів та оцінити їх ефективність у реальних умовах. В результаті дослідження було запропоновано новий метод оцінювання та оптимізації енергетичних параметрів радіоканалів, який враховує вплив різних факторів для підвищення ефективності покриття безпровідних сенсорних мереж на основі безпілотних літальних апаратів. Даний метод дозволив частково вирішити проблему інформаційних втрат через адаптивну оптимізацію покриття мережі під час виникнення впливових факторів. Експериментальні моделі, розроблені в ході дослідження, дають можливість оцінювати розподіл сигналу в просторі для сенсорних мереж на базі безпілотних летальних апаратів із врахуванням впливу зовнішніх факторів, завдяки використанню коефіцієнтів флуктуацій. Також в роботі було розроблено механізм використання контрольного пристрою, що дозволяє вимірювати потужність сигналу на будь-якій відстані від базової станції, забезпечуючи гнучкість та точність оцінювання. Отримані результати показали високий рівень точності вимірювань, з достовірністю 95 % для періоду спостереження в 20 секунд і похибкою до ±0.5 дБм. Загальна похибка методики не перевищує 5 %, що підтверджує високу надійність результатів та їх відповідність реальним умовам експлуатації. Таким чином, результати дослідження сприяють підвищенню ефективності та надійності безпровідних сенсорних мереж на базі безпілотних летальних апаратів, забезпечуючи стабільний і якісний зв'язок у різних умовах експлуатації

Ключові слова: безпровідні сенсорні мережі; безпровідний канал; енергетичні параметри; пропускна здатність; модель; БПЛА; статистичний аналіз; інформаційні втрати