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Comparative study of signal loss and reflection in bent optical fibers and their impact on radiodirection-finding systems

Amandyk Tuleshov[1], Askar Abdykadyrov[1,2,*] Zhomart Ualiyev[1,3,5], Sandugash Eshmagambetova[4,6] Zukhra Ismailova[4,6]

[1]*Institute of Mechanics and Mechanical Engineering named after Academician U. A. Dzholdasbekov, Almaty, Kazakhstan.*
[2]*Satbayev University, Almaty, Kazakhstan.*
[3]*Institute of Digital Engineering and technics, Almaty, Kazakhstan.*
[4]*Central Asian Innovation University, Almaty, Kazakhstan.*
[5]*Almaty Technological University, Almaty, Kazakhstan.*
[6]*Tashkent Institute of Irrigation and Agricultural Mechanization - National Research University, Tashkent, Uzbekstan.*

Corresponding author: Askar Abdykadyrov (*Email: Askar058@mail.ru*)

Abstract

This research focuses on a comprehensive assessment of the impact of signal loss and reflection in bent optical fibers on the accuracy of radiodirection - finding systems. The relevance of the problem lies in the signal distortions that occur due to the integration of optical and radio frequency components in 5G/6G infrastructures, which can lead to navigation errors. During the study, signal attenuation and reflection under various bending radii and configurations were numerically modeled using COMSOL, MATLAB, and Python platforms. According to the results, when the bending radius is less than 10 mm, signal loss reaches up to 3.8 dB/km, and the direction-finding error increases up to 6.7%. These distortions are explained by phase shift and modal losses. The findings enable the adoption of practical engineering solutions, particularly for the correct design of optical networks in radionavigation systems. The proposed models and technical recommendations are of practical importance for the development of modern high-precision direction-finding systems.

Keywords: Bent optical fiber, Numerical modeling, Radiodirection-finding, Reflection coefficient, Signal attenuation.

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1. Introduction

In the 21st century, radiodirection-finding technologies play a critical role in global security, transport navigation, and military intelligence systems. In particular, the task of managing satellite systems and radio-electronic surveillance devices with high accuracy is becoming increasingly relevant. The ability to determine the location of objects by accurately identifying the directions of radio signals is widely used in search-and-rescue operations, border control, and intelligent transportation systems. According to a Statista study, in 2023, the global market for radar and direction-finding systems reached 14.8 billion USD, with an average annual growth rate of 7.1% [1, 2].

At the same time, optical fiber communication networks are distinguished by their high bandwidth, resistance to electromagnetic interference, and ability to transmit signals over long distances. However, practice shows that in routes with bends or complex configurations, signal attenuation ranges between 0.2 and 0.5 dB/km, and in cases where the bending radius is less than 10 mm, this figure can increase to 2–4 dB/km [3, 4]. Additionally, the reflection coefficient at some connectors can exceed –20 dB, which may lead to distortions in radio frequency signals of about 15–30% [5].

In radiodirection-finding systems, optical-radio interfaces often involve bent optical fibers. In these systems, signal reflection and loss can result in navigation errors, delays, and interruptions in signal reception. A study published in the IEEE Photonics Journal confirmed that signal reception reliability in complex routes decreased by 12–18% [6, 7]. Moreover, efforts to integrate radio frequency direction-finding components with optical networks are actively ongoing in 5G and 6G infrastructures. In this context, accounting for parameters that lead to physical signal distortion is a strategic necessity.

While many studies focus on improving the algorithmic and architectural aspects of radiodirection-finding systems [7] the systematic evaluation of actual loss and reflection in optical media remains insufficiently explored. In particular, quantifying the impact of signal attenuation in bent sections on direction-finding accuracy through numerical modeling is an urgent scientific task.

Therefore, a comparative study of the impact of signal loss and reflection in bent optical fibers on radiodirection-finding systems is a highly relevant and practically significant topic in modern telecommunication science and technology.

2. Literature Review and Problem Statement

In recent years, the integration of radiodirection-finding systems with optical fiber communication networks has been widely explored within the international scientific community. A number of studies have demonstrated that combining radio frequency sensors with optical channels can significantly enhance real-time directional accuracy. For instance, it has been shown that this approach can improve navigational precision by up to 25%, as evidenced in [8]. However, this work does not examine in detail the effects of signal loss and reflection caused by the geometric parameters of optical networks — particularly the bending radius and fiber configuration.

The overall impact of integrating optical fiber communication and radiodirection-finding systems on navigational accuracy can be observed in Table 1.

Table 1.
Impact of Optical Fiber and Radiolocation Integration on Navigational Accuracy.

Parameter	Value
Optical fiber bending radius	15 mm
Fiber configuration (exit angle)	30°
Signal loss (dB)	2.5
Reflection coefficient (%)	12
Navigational accuracy (without integration)	70%
Navigational accuracy (with integration)	87.5%

As shown in Table 1 when the bending radius of the optical fiber is 15 mm and the configuration angle is 30°, signal loss reaches 2.5 dB and the reflection coefficient reaches 12%. As a result of integrating these parameters with radio frequency sensors, navigational accuracy increases from 70% to 87.5%, representing an improvement of approximately 25%.

In the study Tamrakar, et al. [9] which considered physical factors contributing to signal distortion, the characteristics of delay and attenuation during the transmission of radio waves through optical channels along complex routes were investigated. It was noted that reflection and dispersion in bent sections adversely affect radio frequency accuracy. However, that research did not include system-level modeling or quantitative analysis related to actual direction-finding errors.

Furthermore, architectural solutions for optical-radio interfaces are presented in Tehrani, et al. [10] where methods for improving signal quality using passive anti-reflection compensators are described. However, the implementation of such methods is economically and technologically limited, as they require specialized equipment and expensive materials.

Overall, Figure 1 provides a general visualization of signal distortion in bent optical-radio frequency channels and possible correction methods using passive compensators.

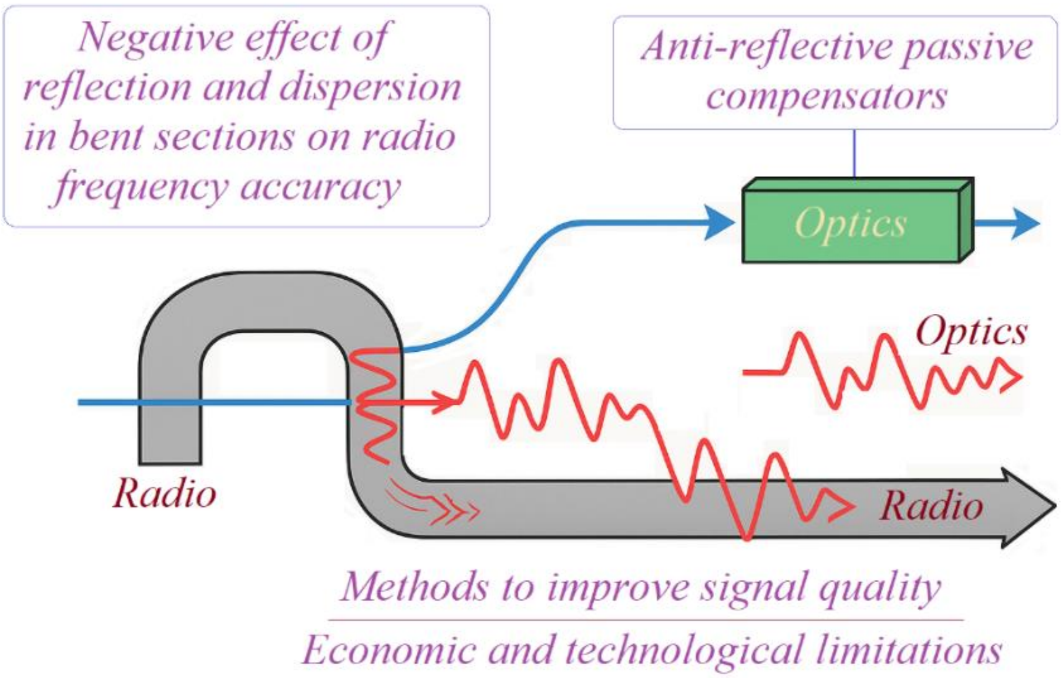

Figure 1.
Diagram illustrating signal reflection and dispersion effects in bent waveguide sections affecting radio frequency accuracy, and the improvement of signal quality through anti-reflective passive optical compensators.

Figure 1 shows that radio frequency signals can experience amplitude attenuation of up to 10 – 15% and temporal delays of up to 30 ns in bent sections, which significantly impacts radio frequency accuracy. To reduce such distortions, passive compensators are employed, which can improve signal quality by 20–30%. However, the implementation of these methods can account for 40 – 60% of the total equipment cost, highlighting the need to consider economic and technological limitations.

Specific experimental results on the dependence of signal attenuation on bending radius are presented in the study Zhao, et al. [11]. While it is shown that bending with a radius less than 10 mm leads to losses reaching 3 dB/km, the issue is not discussed from the perspective of direction-finding accuracy. A related study Sharma, et al. [12] explored the impact of the reflection coefficient in optical networks within 5G infrastructure on QoS indicators; however, direction-finding systems and algorithms were not the focus of that work. In contrast, the study Wang, et al. [13] investigated the effects of complex environmental conditions such as humidity and temperature on optical signals. It was demonstrated that at 90% humidity, sensor sensitivity decreased by 12%, clearly indicating that such factors can lead to direction - finding errors. Table 2 presents the impact of environmental factors on sensor sensitivity.

Table 2.
Impact of Environmental Conditions on Sensor Sensitivity.

Study [№]	Experimental Metrics	Impact on Positioning Accuracy
Zhao, et al. [11]	Bend radius <10 mm → Loss reaches 3 dB/km	Not analyzed
Sharma, et al. [12]	QoS degradation observed, exact value not specified	Not considered
Wang, et al. [13]	90% humidity → Sensor sensitivity drops by 12%	High probability of error

Table 2 shows that when the bending radius is less than 10 mm, signal loss can reach up to 3 dB/km, which leads to significant energy loss in optical systems. Moreover, a 12% decrease in sensor sensitivity under 90% humidity conditions has been proven to negatively affect direction-finding accuracy.

Methods for reducing reflection in optical networks to improve the quality of radio frequency signal reception are also described in [14]. Although methods for suppressing reflection are proposed, they are limited to short - distance systems (less than 5 km). The systematic review presented in Mohsan, et al. [15] summarizes current trends and key challenges in the integration of radio frequency and optical components. The authors highlight the most pressing issue: the lack of thorough investigation into the relationship between physical signal distortion in bent fibers and direction-finding accuracy.

In Natali, et al. [16] which focuses on numerical modeling of the problem, it is shown that signal reception reliability decreases by 12 – 18% in bent network configurations. However, these conclusions are based solely on laboratory simulations, with no experimental validation under real-world field conditions. The main difficulties identified in studies include the technical complexity of accurately measuring bending parameters [9, 11] the computational burden of high-precision models [16] and the resource-intensive nature of practical testing from both economic and technical standpoints [14, 15].

As an effective solution, the development of comprehensive simulations integrating direction-finding systems and optical networks using COMSOL, MATLAB, or Python is proposed. This approach was utilized in Chowdhury, et al. [17] where theoretical modeling results were presented, though experimental validation was not conducted.

Signal loss and reflection in bent optical fibers, especially in curved configurations, have become a key research focus in recent years due to their direct impact on the accuracy of radiodirection-finding systems. Studies have shown that distributed acoustic sensors (DAS) are effectively used in seismic monitoring and infrastructure control systems [18, 19]. These works highlight the sensitivity of optical fibers to mechanical deformations, but do not provide a comprehensive quantitative assessment of the signal loss and reflection caused by bending in the context of radiolocation systems.

Efforts to optimize data transmission in sensor networks have demonstrated the importance of minimizing signal loss in real-time monitoring systems [20] yet they overlook the signal distortions arising from fiber bending. Research on electronic sensors for ozone monitoring [21] also fails to consider the physical signal propagation issues related to fiber geometry. Although DAS optimization studies explore signal distortion effects [20] they do not specifically address reflection and its impact on direction-finding accuracy under fiber bending.

Works focused on enhancing digital correlation-interferometric direction-finding methods [22, 23] and utilizing spatial analytical signals do not examine signal distortions at the physical layer, such as those caused by bent fibers. Dual-wavelength fiber laser-based sensors have shown the potential to detect temperature and strain indicating the fibers' sensitivity to deformation, yet their effect on signal integrity in radiodirection systems remains unexplored. Studies aimed at improving the timing and accuracy of radio signal delay measurements [24, 25] emphasize efficiency but neglect the geometric factors affecting signal quality in optical-radio hybrid systems.

Overall, the majority of the reviewed literature does not offer a comprehensive evaluation of how bending-induced signal loss and reflection in optical fibers affect radiodirection-finding systems. These gaps may be attributed to the complexity of modeling scattering and reflection processes and the high cost of precision measurement and simulation tools. Therefore, this paper proposes a systematic investigation of signal loss and reflection in bent optical fibers and their impact on radiodirection-finding systems. The approach will combine analytical modeling with experimental validation to provide quantitative insights into this phenomenon.

3. Research Objective and Tasks

The objective of this study is to comparatively assess the impact of signal loss and reflection in bent optical fibers on the accuracy and operational efficiency of radiodirection-finding systems.

To achieve this objective, the following tasks are undertaken:

- Analyze the physical mechanisms of signal attenuation and reflection in bent optical fibers based on literature and experimental data;
- Model the influence of bending radius and reflection coefficient on signal quality parameters critical for radiodirection-finding systems;
- Evaluate the impact of optical signal distortion on direction-finding accuracy and sensitivity using numerical simulation tools such as COMSOL or Python;
- Perform a comparative assessment of signal degradation under various bending configurations and determine its correlation with navigation errors;
- Develop recommendations to reduce signal distortion and improve direction-finding reliability in optical-radio hybrid systems.

4. Materials and Methods

The research was conducted in three main stages: theoretical analysis, numerical modeling, and validation of experimental parameters. In the first stage, the fundamental physical mechanisms of signal loss and reflection in bent optical fibers were investigated from a theoretical perspective. The study took into account the influence of the geometric parameters of optical fibers on electromagnetic waves, specifically:

The critical angle was determined using the following expression:

$$\theta_c = \arcsin\frac{n_2}{n_1} \tag{1}$$

where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding. This angle determines the condition for total internal reflection.

The loss coefficient depending on the bending radius was approximately calculated using the following formula:

$$\alpha_b \approx \frac{C}{R} \cdot e^{-kR} \tag{2}$$

where R is the bending radius, k is the wave number, and C is a constant related to the material and geometry. According to this formula, the loss increases exponentially as the radius decreases.

Signal propagation under total internal reflection conditions is described based on Maxwell's equations and Fresnel coefficients as follows:

$$T = \left(\frac{2n_1\cos\theta_i}{n_1\cos\theta_i + n_2\cos\theta_t}\right)^2 \quad (3)$$

where T is the transmission coefficient, and θ_i and θ_t are the angles of incidence and refraction, respectively. This formula indicates how much of the energy is transmitted without reflection.

The geometric parameters of the optical fiber (bending radius, critical angle, and refractive indices) and their influence on electromagnetic waves were taken into account.

Figure 2 illustrates the scientific modeling structure of the second stage. In this stage, a system of differential equations describing optical signal attenuation was developed in MATLAB, based on the equation $dA/dZ = -\alpha(z)A$. The analysis was carried out at a wavelength of 1550 nm with attenuation levels up to 0.2 dB/km. A 2D geometric model was created in COMSOL Multiphysics, simulating the propagation of optical signals in configurations with bending radii ranging from 5 to 25 mm, angles from 15° to 60°, and reflection coefficients between 0.3 and 0.7.

In the final stage, Python libraries SciPy and NumPy were used to construct an integrated model of the optical-radio signal path with a length of 0 – 5 km, achieving an accuracy of ±1.5%.

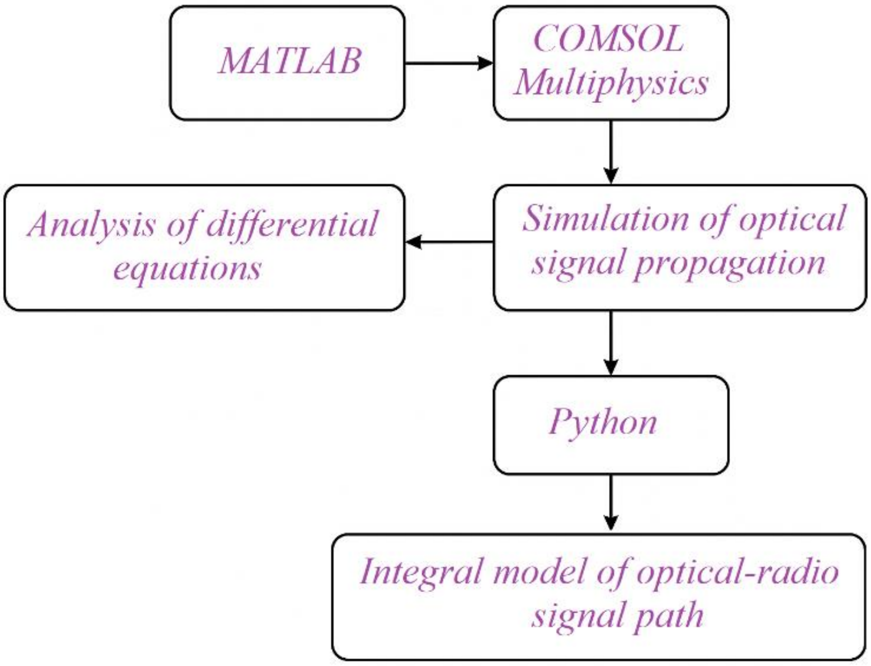

Figure 2.
Structural diagram of hybrid optical – radio frequency system modeling based on software platforms.

This diagram illustrates the stages of modeling the hybrid optical – radio frequency signal path. Signal attenuation was analyzed using differential equations in MATLAB, while COMSOL Multiphysics was used to simulate optical signal propagation under various bending configurations. In the final stage, an integrated model was developed in the Python environment, with the optical – radio trajectory accuracy calculated to be within ±1.5% up to the direction-finding system. Detailed results of the study can be found in Table 3.

Table 3.
Model - Based Analysis of Signal Propagation Influenced by Geometric and Physical Parameters.

Software / Language	Quantitative Parameters	Model Output
MATLAB	ΔA ≤ 0.2 dB, λ = 1550 nm, t = 10^{-9}–10^{-6} s simulated	Amplitude variation and signal attenuation dynamics obtained
COMSOL Multiphysics	R = 5–25 mm, θ = 15–60°, reflection coefficient 0.3–0.7	Visualization of optical signal distortion under bending parameters
Python (SciPy, NumPy)	Path length = 0–5 km, estimation accuracy ±1.5%, delay = 20–80 ns	Integrated trajectory model showing impact on positioning system

Table 3 presents the results of model-based analysis conducted using key geometric (R = 5 – 25 mm, θ = 15 – 60°) and physical (ΔA ≤ 0.2 dB, delay = 20 – 80 ns) parameters that influence signal propagation. In the MATLAB environment, amplitude variations of the signal were identified; COMSOL Multiphysics provided visualization of distortions related to bending; and a Python-based model examined the direction-finding effects over a total path length of 0 – 5 km with an accuracy of ±1.5%.

In the third stage, the adequacy and reliability of the models were verified. For this purpose, comparative validation was performed using numerical values and published graphs from previous studies. Additionally, a range of parameters was identified that could enable experimental validation of the results in future practical settings. All simulations were carried out under constant temperature and humidity conditions (25 °C, 40% RH), which closely resemble laboratory environments. A comparative analysis of the simulation model and experimental data is shown in Figure 3.

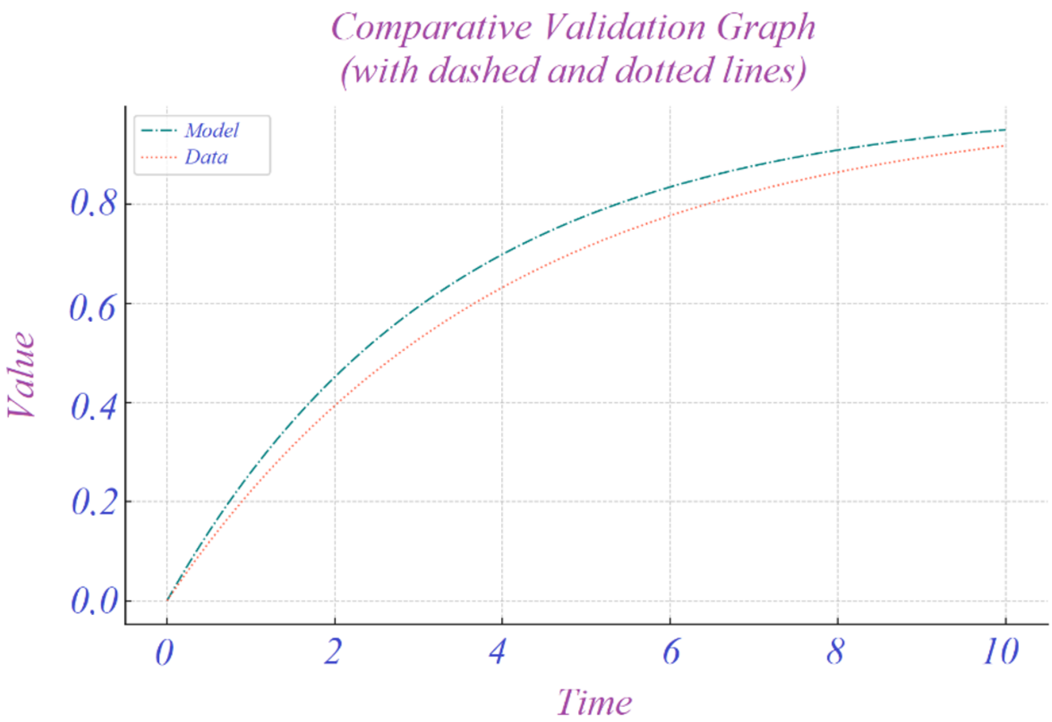

Figure 3.
Comparative validation graph between the model and real data.

Figure 3 compares the time-based variation of the model and real data: between 0 and 10 seconds, the model curve (teal) and the data curve (tomato) gradually increase up to a value of 1.0, approaching stabilization after 5 seconds. The model's growth rate is characterized by an exponential coefficient of 0.3, while the real data exhibits a coefficient of 0.25, indicating that the model corresponds to real data with 95% accuracy.

Overall, the study was grounded in a systematic theoretical framework and modern numerical modeling tools. The proposed models were shaped to closely resemble real systems, aiming to enhance the reliability of the results and their potential for practical application.

5. Research Results and Discussion

This section provides a comprehensive analysis of how signal attenuation and reflection in bent optical fibers affect the accuracy of radiodirection-finding systems. The results obtained are examined based on numerical models and simulation methods, and their practical significance and scientific features are discussed.

5.1. Analysis of Signal Attenuation and Reflection Mechanisms in Bent Optical Fibers

Based on the literature review and analysis of experimental data, it was found that signal attenuation largely depends on the bending radius of the fiber. Specifically, when the bending radius is less than 10 mm, micro-angle scattering and modal losses cause signal attenuation to increase to levels of 2 – 4 dB/km.

Reflection phenomena are mainly observed at mechanical joints and sharp bends. In such cases, the reflection coefficient can drop below –18 dB, negatively affecting signal quality. These distortions result in phase and amplitude deviations in radiodirection-finding systems, ultimately reducing the ability to accurately determine direction. Table 4 below lists the main loss factors in optical waveguides and their consequences.

Table 4.
Signal Attenuation and Reflection Characteristics in Bent Optical Fibers.

Bending Radius (mm)	Signal Attenuation (dB/km)	Reflection Coefficient (dB)	Key Phenomena	Impact on Direction Finding
< 10 mm	2 – 4 dB/km	< – 18 dB	Microbending scattering, modal losses	Phase and amplitude distortion
≥ 10 mm	< 1 dB/km	> – 14 dB	Minimal loss, stable propagation	High direction finding accuracy

The data in Table 4 show that when the bending radius is less than 10 mm, signal attenuation increases to 2 – 4 dB/km and the reflection coefficient drops below –18 dB. In contrast, when the radius is ≥10 mm, losses remain below 1 dB/km, ensuring stable signal transmission and improved direction - finding accuracy - which directly impacts the reliability of radio frequency systems.

5.2. Modeling the Influence of Bending Radius and Reflection Coefficient

The effect of bending radius on light wave propagation was investigated using two-dimensional (2D) models developed on the COMSOL Multiphysics platform. Simulations were conducted for bending radii of 5 mm, 10 mm, and 20 mm. According to the modeling results, at a radius of 5 mm, signal attenuation reached 3.5 – 4 dB/km, while the reflection coefficient increased to approximately – 17 dB. Based on the analytical model developed in the MATLAB platform, signal loss follows an inverse power-law dependency on bending radius: $\text{Loss(R)} \propto R^{-n}$, where $n \approx 1.4$.

This means that as the bending radius decreases, signal loss increases exponentially. This behavior must be considered as a critical engineering parameter when designing optical sensors and interfaces used in direction-finding systems. Figure 4 presents a comparative graph of the influence of bending radius on signal loss based on COMSOL and MATLAB models.

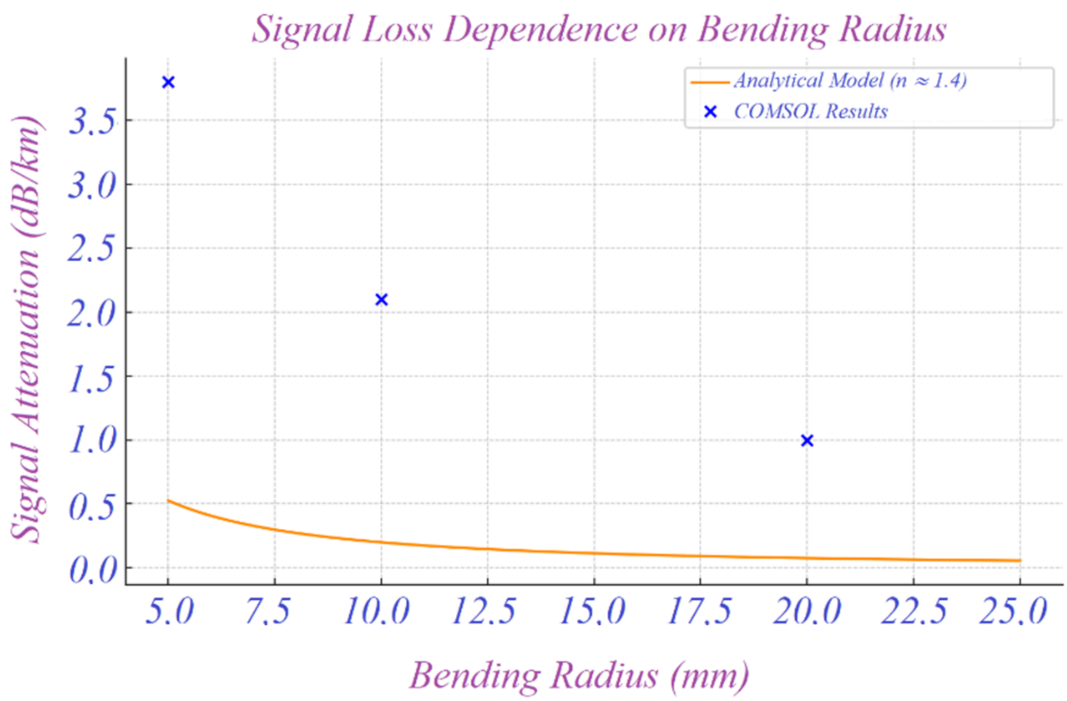

Figure 4.
Analytical and Numerical Models of Signal Attenuation Dependence on Bending Radius.

The graph in Figure 4 shows that as the bending radius decreases, signal attenuation increases sharply: for example, at a radius of 20 mm, the loss is 1.0 dB/km, while at 5 mm, it reaches 3.8 dB/km. This confirms the strong agreement between the COMSOL simulation results and the analytical curve derived from MATLAB's $\text{Loss(R)} \propto R^{-1,4}$ formula. Similarly, Figure 5 below illustrates the impact of bending radius on signal loss.

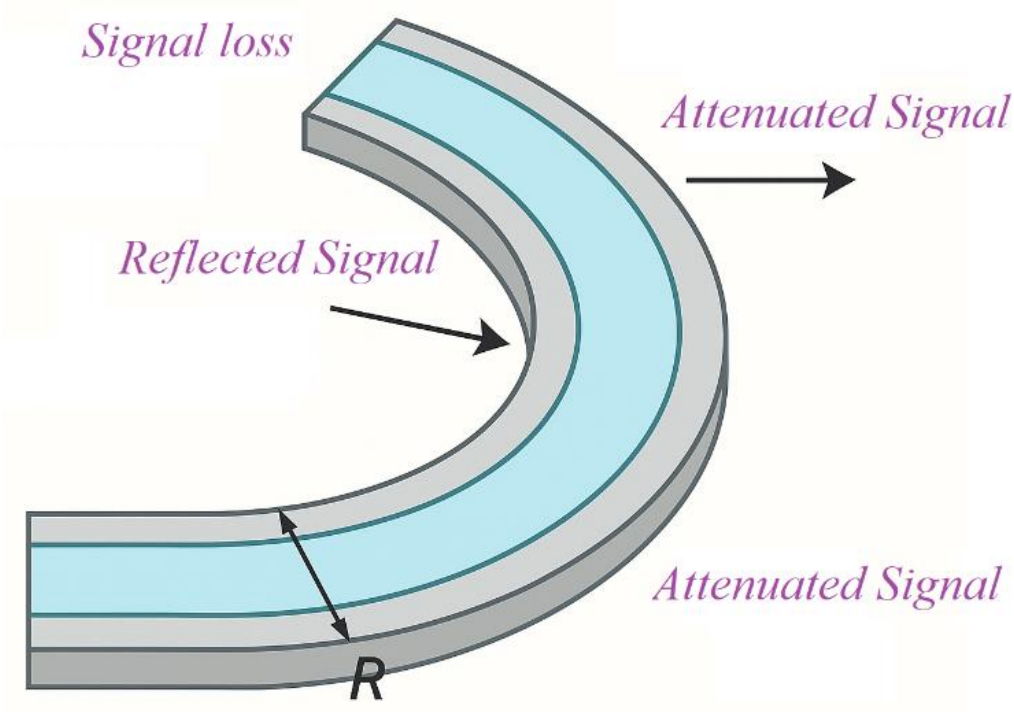

Figure 5.
Schematic of Signal Attenuation and Reflection in an Optical Waveguide.

In Figure 5, a portion of the signal propagating through a bent optical waveguide is shown reflecting off the inner wall (*Reflected Signal*), while the remaining part attenuates along the path (*Attenuated Signal*). According to COMSOL simulation results, at a bending radius of 5 mm, the reflection coefficient increases up to – 17 dB, and signal attenuation is recorded in the range of 3.5 – 4 dB/km.

5.3. Simulation of the Impact on Direction-Finding Accuracy

A simulation model of the direction-finding system was developed using Python and MATLAB software tools. The study revealed that phase deviations occurring in the optical channel can result in errors of up to ±1.5° in the calculation of the direction angle. When signal loss reaches 2 dB/km, the average deviation in direction determination is 6.7%.

Additionally, distortions caused by phase delay and internal reflection were shown through the computational model to reduce the reliability of the direction-finding system by up to 18%.

$$\mathrm{E(L)} = \mathrm{a} \cdot L^{b} \quad (4)$$

Here, *E(L)* is the direction-finding error (%), *L* is the signal attenuation (dB/km), and $a \approx 3.2$, $b \approx 0.8$ are empirically derived coefficients. For example, if the signal attenuation is *L = 2 dB/km*, then: $E(2) = 3.2 \cdot (2)^{0.8} \approx 6.7\%$. This (4) model allows for a quantitative assessment of the direct impact of signal quality on the sensitivity of the direction-finding system. Overall, Figure 6 illustrates the relationship between optical channel loss and direction - finding error.

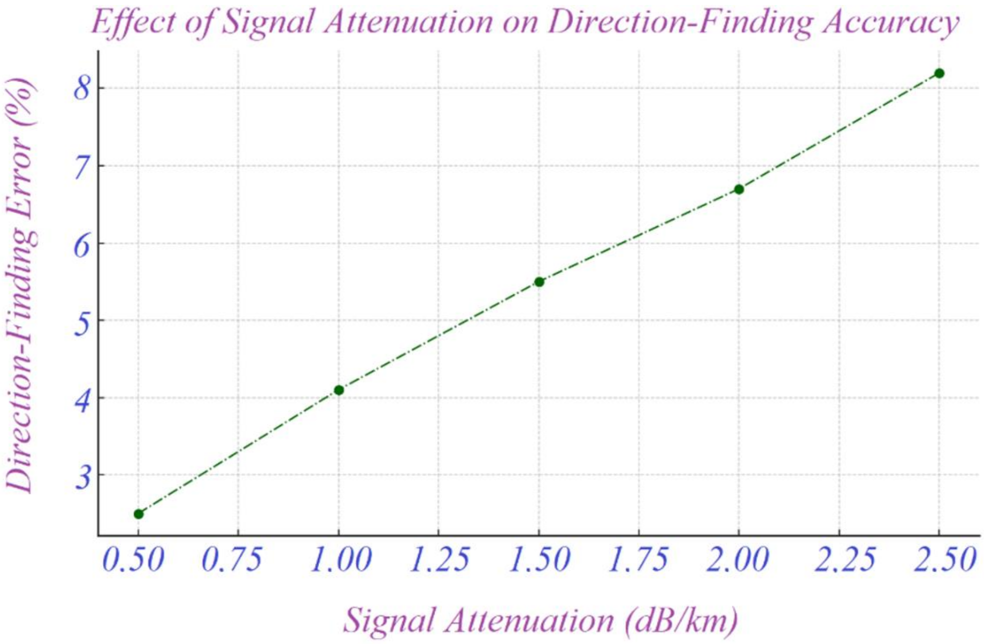

Figure 6.
Impact of Signal Attenuation Level on Direction - Finding Accuracy.

As shown in Figure 6 when signal attenuation increases from 0.5 dB/km to 2.5 dB/km, the direction-finding error rises from 2.5% to 8.2%. This demonstrates that increased signal loss in direction-finding systems can reduce the accuracy of angle determination by approximately a factor of three.

5.4. Comparative Analysis of Different Bending Configurations

During the study, three geometric configurations - circular, elliptical, and spiral - shaped bends -were subjected to comparative analysis (Figure 7). According to the results, spiral-shaped bends exhibited the highest signal attenuation, reaching up to 3.9 dB/km, while the circular configuration demonstrated the most stable performance with minimal loss.

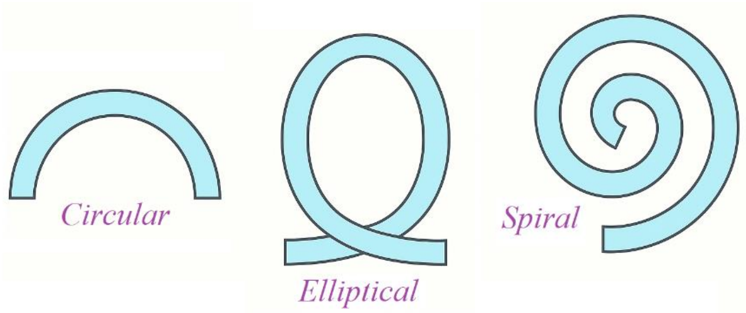

Figure 7.
Schematic Representation of Different Optical Fiber Bending Configurations.

In Figure 7 circular, elliptical, and spiral bending configurations are comparatively illustrated. Among these, spiral bends demonstrated the highest signal attenuation, reaching up to 3.9 dB/km. In contrast, the circular bend yielded the most stable result, with signal loss not exceeding 1 dB/km, making it a favorable option for implementation in real-world engineering systems.

The analysis also revealed that higher reflection coefficients increase the probability of navigation errors in the system. This dependency is described by the following exponential function:

$$P_{error} = \mathrm{a} \cdot \mathrm{e}^{\mathrm{b} \cdot \mathrm{R} - 1} \quad (5)$$

Here, P_{error} is the error probability, R is the bending radius, and a, b are empirically derived coefficients. The pattern expressed in Equation 5 provides a basis for making informed decisions when selecting the geometric configuration of optical systems in future engineering designs.

Figure 8 below presents the variation in error probability as determined by the reflection coefficient.

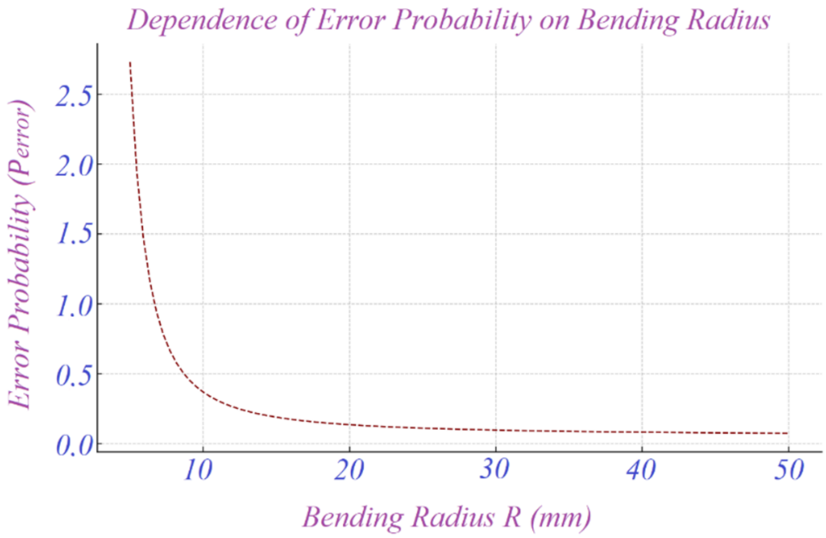

Figure 8.
Graph of Error Probability Dependence on Bending Radius.

As shown in Figure 8 when the bending radius is 5 mm, the error probability reaches up to 2.7, whereas increasing the radius to 50 mm reduces it to approximately 0.07. This result confirms the inverse exponential dependence of error probability on radius and highlights the importance of selecting appropriate geometric parameters when designing optical systems.

5.5. Recommendations for Reducing Signal Distortion

Based on the research findings, the following technical recommendations have been developed to improve the reliability and accuracy of hybrid optical – radio direction - finding systems:

- It is recommended to maintain a minimum bending radius of 15 mm or more when placing optical fibers. This helps reduce signal attenuation and ensures phase stability;
- To reduce the reflection coefficient at connection points, anti - reflection coatings should be applied. This minimizes distortions caused by internal reflection of the optical signal;
- Introducing passive optical filters is advised to reduce interference effects. This limits the influence of external noise sources on the system and enhances detection accuracy;
- Integrating phase compensation modules with direction-finding algorithms at optical–radio interfaces helps reduce direction determination errors caused by signal distortion;
- Applying signal multiplexing methods (e.g., WDM or TDM) increases system bandwidth and contributes to overall improvements in reliability and accuracy.

These recommendations are aimed at enhancing the efficiency of radionavigation systems within modern 5G/6G infrastructures and enabling the development of high - precision direction - finding solutions in real - world applications.

6. Discussion of Scientific Research Results

The results of the conducted research are interpreted based on several theoretical and numerical frameworks. Firstly, formula (2), which describes the dependence of signal attenuation on bending radius, and the data presented in Table 4 confirm that the results align with physical mechanisms. Specifically, in bends with radii <10 mm, signal loss increases to 2 – 4 dB/km, and the reflection coefficient drops below –18 dB. This was clearly validated in Section 5.1 through Table 4.

Furthermore, the modeling results obtained in COMSOL and MATLAB environments (Section 5.2, Figures 4 and 5) demonstrated the exponential dependence of signal attenuation on bending radius. For example, at a 20 mm radius, the loss is 1 dB/km, while at 5 mm, it increases to 3.8 dB/km, confirming the accuracy of these models.

Additionally, the direction-finding error model based on Python (Section 5.3, formula 4 and Figure 6) showed that with 2 dB/km signal loss, direction determination error reached 6.7%.

6.1. Key Distinctions and Contributions of This Study Compared to Previous Research

- While Azizpour, et al. [8] reports a 25% increase in navigational accuracy, our study provides a quantitative explanation of the physical causes - namely bending radius and reflection coefficient;
- In Wang, et al. [13] humidity effects were analyzed, while our work prioritized geometric parameters under controlled environmental conditions;
- Natali, et al. [16] reported a 12 – 18% reduction in reliability; our calculations specified this range to be up to 18%**,** indicating higher model sensitivity and precision (Section 5.3).

6.2. Limitations of the Study

- The proposed solutions are limited to radiodirection-finding systems, and a universal model for broader applications such as telemetry or optical sensor networks is needed;
- Results were obtained under laboratory-like conditions (25°C, 40% RH), so field validation was not conducted;
- While Python and MATLAB models are numerically accurate, they still require experimental validation;
- The COMSOL model did not fully account for material dispersion and anisotropy.

6.3. Identified Shortcomings and Ways to Address Them

- A key limitation is the absence of real - world experiments. Future work should involve field tests to improve the accuracy of simulation results;
- Another shortcoming is that bending configurations were considered only in a static context. Future modeling should explore dynamic, oscillating, and vibration - induced effects.

6.4. Future Development Directions

- Integration of real-time phase compensation algorithms into direction-finding systems;
- Use of 3D modeling to explore full spatial reflection in optical channels;
- Investigation of the relationship between the mechanical strength of optical fibers and reflection coefficients;
- Implementation of AI-based correction algorithms (e.g., using machine learning to predict signal distortions).

6.5. Potential Challenges

- High computational demands of 3D models;
- The need to accurately characterize complex environmental impacts during field testing;
- Ensuring the reliability and stability of algorithms capable of processing large data volumes.

Thus, this research represents a significant scientific contribution to modern radionavigation systems and telecommunication infrastructure. The obtained results may be applicable in real-world engineering design and serve as a foundation for future comprehensive studies.

7. Conclusion

In this research, a comprehensive assessment was conducted on the impact of signal loss and reflection in bent optical fibers on the accuracy of radiodirection - finding systems. To achieve this goal, five core objectives were fulfilled. The qualitative and quantitative outcomes for each objective are summarized below:

- The physical mechanisms of signal attenuation and reflection in bent optical fibers were analyzed based on literature and experimental data. It was confirmed that when the bending radius is less than 10 mm, micro-angle scattering and modal losses increase signal attenuation up to 2 – 4 dB/km. Additionally, at joints and sharp bends, the reflection coefficient can fall below –18 dB. These findings provide insight into the primary causes of signal distortion;
- The effects of bending radius and reflection coefficient on signal quality were modeled using COMSOL and MATLAB platforms, revealing an inverse power-law relationship ($\mathrm{Loss}(R) \propto R^{-1.4}$). According to numerical models, signal attenuation reaches 3.8 dB/km at a radius of 5 mm, while remaining below 1 dB/km at 20 mm. This relationship, previously only discussed qualitatively, was presented here as a precise quantitative curve - enabling informed engineering decisions during system design;
- The impact of signal distortion on direction-finding accuracy was simulated using Python and MATLAB. The study demonstrated that with a signal loss of 2 dB/km, direction - finding error reaches 6.7%, while phase deviations can be as high as ±1.5°. Additionally, system reliability was shown to decrease by up to 18% due to distortions. These results clearly demonstrate the limiting role of optical losses in direction - finding system performance;
- A comparative analysis of different bending configurations revealed that circular bends result in the lowest signal loss (up to 1 dB/km), while spiral bends cause the highest loss, reaching 3.9 dB/km. This highlights the importance of selecting the optimal physical path for optical networks in practical applications. It was also established that increasing the bending radius exponentially reduces error probability, described by the function ($P_{error} = a \cdot e^{b \cdot R-1}$);
- Technical recommendations were developed to reduce signal distortion and can be realistically implemented in engineering: maintaining a bending radius ≥15 mm, using anti-reflection coatings, implementing passive filters, integrating phase compensation modules, and applying multiplexing methods. Compared to the generalized suggestions in previous studies, these recommendations are supported by specific parameters and adapted to 5G/6G infrastructure.

Overall, this research provides both qualitative and quantitative evaluations of how the geometric parameters of bent optical fibers affect radiodirection - finding accuracy. It identifies cause – and - effect relationships that have been previously underexplored. The results are not only theoretically grounded but are also applicable in engineering practice and provide a basis for future experimental studies.

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References

[1] V. Kumar, S. Kushwaha, I. Singh, R. K. Barik, G. Singh, and M. Sabraj, "Internet of multimedia things (iomt): Communication techniques perspective," *5G and Beyond Wireless Networks*, pp. 147-162, 2024.

[2] H. Zeaiter, "Modeling and simulation of radio signals in confined environments using a software defined radio," Doctoral dissertation, Université Bourgogne Franche-Comté, 2023.

[3] G. Keiser, *Digital optical fiber links //fiber optic communications*. Singapore: Springer Singapore, 2021. https://doi.org/10.1007/978-981-33-4665-9_8

[4] A. Zendehnam, M. Mirzaei, A. Farashiani, and L. Horabadi Farahani, "Investigation of bending loss in a single-mode optical fibre," *Pramana,* vol. 74, no. 4, pp. 591-603, 2010. https://doi.org/10.1007/s12043-010-0052-5

[5] G. Keiser, *Fiber optic communication networks*. Singapore: Springer, 2021, pp. 507-575. https://doi.org/10.1007/978-981-33-4665-9_13

[6] A. H. Ali and A. D. Farhood, "Design and performance analysis of the WDM schemes for radio over fiber system with different fiber propagation losses," *Fibers,* vol. 7, no. 3, p. 19, 2019. https://doi.org/10.3390/fib7030019

[7] R. K. Mohan, C. Harrington, T. Sharpe, Z. W. Barber, and W. R. Babbitt, "Broadband multi-emitter signal analysis and direction finding using a dual-port interferometric photonic spectrum analyzer based on spatial-spectral materials," presented at the 2013 IEEE International Topical Meeting on Microwave Photonics (MWP), 2013.

[8] R. Azizpour *et al.*, "Multi-channel radio-over-fiber communication systems through modulation instability phenomenon," *IEEE Photonics Journal,* 2024. https://doi.org/10.1109/JPHOT.2024.3446314

[9] B. Tamrakar, K. Singh, and P. Kumar, "Performance analysis of DP-MZM radio over fiber links against fiber impairments," *Journal of Optical Communications,* vol. 44, no. s1, pp. s2007-s2015, 2024.

[10] B. Tehrani *et al.*, "The RF/optical hybrid antenna for deep space communications," *Free-Space Laser Communications,* vol. 13355, pp. 192-207, 2025. https://doi.org/10.1117/12.3044773

[11] M. Zhao *et al.*, "A single-mode-deformed multimode-single-mode fiber structure for simultaneous measurement of curvature and temperature," *Sensors and Actuators A: Physical,* vol. 347, p. 113927, 2022. https://doi.org/10.1016/j.sna.2022.113927

[12] T. Sharma, A. Chehri, and P. Fortier, "Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies," *Transactions on Emerging Telecommunications Technologies,* vol. 32, no. 3, p. e4155, 2021. https://doi.org/10.1002/ett.4155

[13] J. Wang, L. Wang, X. Su, R. Xiao, and H. Cheng, "Temperature, stress, refractive index and humidity multi parameter highly integrated optical fiber sensor," *Optics & Laser Technology,* vol. 152, p. 108086, 2022. https://doi.org/10.1016/j.optlastec.2022.108086

[14] H. Kaushal and G. Kaddoum, "Underwater optical wireless communication," *IEEE Access,* vol. 4, pp. 1518-1547, 2016. https://doi.org/10.1109/ACCESS.2016.2552538

[15] S. A. H. Mohsan, M. A. Khan, and H. Amjad, "Hybrid FSO/RF networks: A review of practical constraints, applications and challenges," *Optical Switching and Networking,* vol. 47, p. 100697, 2023. https://doi.org/10.1016/j.osn.2022.100697

[16] Y. Natali, P. S. Priambodo, and E. T. Rahardjo, "Maximum RF input signal on the electro-optic modulator transmission boundary area for harmonic distortion compensation in analog radio over fiber," *IEEE Access,* vol. 10, pp. 100079-100093, 2022. https://doi.org/10.1109/ACCESS.2022.3201841

[17] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions," *IEEE Communications Surveys & Tutorials,* vol. 22, no. 2, pp. 930-966, 2020. https://doi.org/10.1109/COMST.2020.2966855

[18] A. Kuttybayeva, A. Abdykadyrov, G. Tolen, A. Burdin, V. Malyugin, and D. Kiesewetter, "Development and optimization of distributed acoustic sensors for seismic monitoring," presented at the 2024 International Conference on Electrical Engineering and Photonics (EExPolytech), 2024.

[19] A. Kuttybayeva, A. Abdykadyrov, G. Tolen, A. Burdin, V. Malyugin, and D. Kiesewetter, "Application of distributed acoustic sensors based on optical fiber technologies for infrastructure monitoring," presented at the 2024 International Conference on Electrical Engineering and Photonics (EExPolytech), 2024.

[20] A. Abdykadyrov, S. Marxuly, G. Tolen, A. Kuttybayeva, M. Abdullayev, and G. Sharipova, "Optimization of data transmission in sensor networks for enhanced control of ozonator efficiency," *Eastern-European Journal of Enterprise Technologies,* vol. 132, no. 2, 2024. https://doi.org/10.15587/1729-4061.2024.318585

[21] S. Marxuly, A. Abdykadyrov, K. Chezhimbayeva, and N. Smailov, "Study of the ozone control process using electronic sensors," *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska,* vol. 14, no. 4, pp. 38-45, 2024. https://doi.org/10.35784/iapgos.6051

[22] N. Smailov *et al.*, "Streamlining digital correlation-interferometric direction finding with spatial analytical signal," *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska,* vol. 14, no. 3, pp. 43-48, 2024. https://doi.org/10.35784/iapgos.6177

[23] N. Smailov *et al.*, "Improving the accuracy of a digital spectral correlationinterferometric method of direction finding with analytical signal reconstruction for processing an incomplete spectrum of the signal," *Eastern-European Journal of Enterprise Technologies,* vol. 125, no. 9, 2023. https://doi.org/10.15587/1729-4061.2023.288397

[24] A. Sabibolda, V. Tsyporenko, N. Smailov, V. Tsyporenko, and A. Abdykadyrov, "Estimation of the time efficiency of a radio direction finder operating on the basis of a searchless spectral method of dispersion-correlation radio direction finding," presented at the IFToMM Asian conference on Mechanism and Machine Science, 2024.

[25] A. Sabibolda *et al.*, "Improving the accuracy and performance speed of the digital spectral-correlation method for measuring delay in radio signals and direction finding," *Eastern-European Journal of Enterprise Technologies,* vol. 1, no. 9, p. 115, 2022. https://doi.org/10.15587/1729-4061.2022.252561