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Mechanisms of signal loss and reflection in optical fibers and their impact on radio direction finding efficiency in bent cable routes

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Abstract

This scientific research investigates the mechanisms of signal loss and reflection in bent optical fiber routes and analyzes their impact on the efficiency of radio direction-finding systems based on numerical and experimental data. The study revealed that at bending angles from 30° to 90°, signal loss increased from 0.05 dB to 0.25 dB, and the reflection coefficient rose from 1.2% to 4.8%, leading to a decrease in system sensitivity from 95.4% to 81.7%. Engineering solutions proposed include the use of bend-insensitive fibers, maintaining a minimum bending radius of the route, OTDR monitoring, and integration of regenerators. Additionally, channel capacity is enhanced through DWDM technology. The research results provide a scientific foundation aimed at improving the reliability and performance of optical communication and radio direction-finding systems.

Keywords: Bending angle, Bend-insensitive fiber, Optical fiber, Radio direction finding efficiency, Reflection coefficient, Signal Loss.

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1. Introduction

Nowadays, optical fiber communication systems form the foundation of information and communication technologies [1-3]. These systems enable high-speed transmission of large volumes of data over long distances. For example, in single-mode optical fibers, data can be transmitted over 100 km at a speed of 10 Gbps, where signal loss at a wavelength of 1550 nm is approximately 0.2 dB/km [4, 5]. In this case, the total signal loss over 100 km reaches up to 20 dB. Moreover, in multimode fibers, signal loss is around 2.5 dB/km, increasing up to 250 dB over the same distance.

[6, 7]. In general, Figure 1 presents a diagram illustrating the signal loss and reflection in a single-mode optical fiber at a wavelength of 1550 nm, depending on the bending angle.

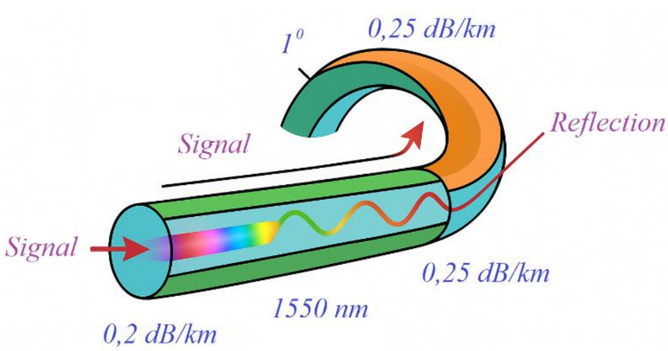

Figure 1.
Diagram of signal loss due to bending in a single-mode fiber at 1550 nm

This figure illustrates the signal attenuation in a single-mode optical fiber at a wavelength of 1550 nm as a function of the bending angle (1°). In such a case, signal loss can increase by up to approximately 0.25 dB/km. Additionally, the reflection effect can reduce data transmission quality and decrease overall system efficiency by 10% to 50%.

However, the performance of an optical fiber is significantly influenced by several factors, including signal loss and reflection [8]. For instance, a 1-degree change in the fiber's bending angle can reduce signal intensity by 0.1 to 0.2 dB. These variations can have a considerable impact on system performance. In bent cable routes, signal loss in single-mode fibers may reach up to 0.25 dB per kilometer, while in multimode fibers, this value can rise to 2 dB/km [9, 10]. Figure 2 below presents a diagram illustrating the effect of angular bending on signal attenuation in optical fibers.

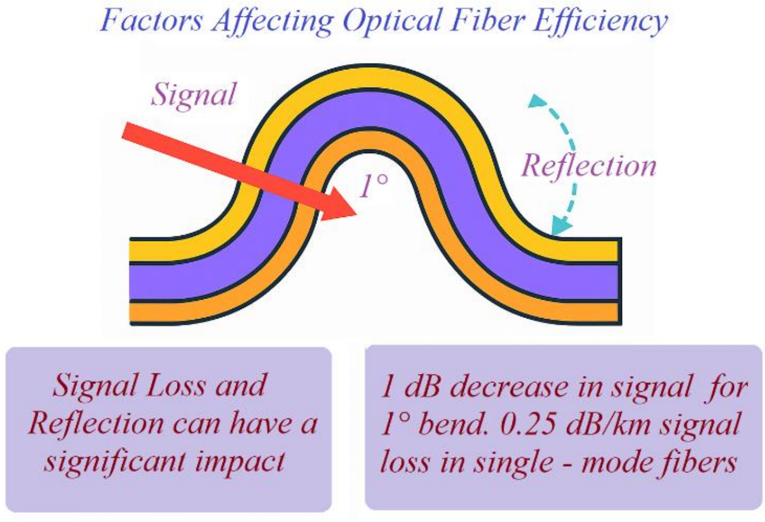

Figure 2.
Diagram of the effect of bending on the signal in an optical fiber.

Figure 2 illustrates that a 1° angular bend in an optical fiber can result in signal loss ranging from 0.1 to 1 dB, significantly impacting overall system performance. For single-mode fiber, signal loss can reach up to 0.25 dB per kilometer, which reduces communication quality and system reliability.

Signal loss and reflection negatively affect the efficiency of radio direction-finding systems. For example, a 1 dB signal attenuation can reduce the effectiveness of a radio direction-finding system by 10%, while a 3 dB attenuation can decrease its reception efficiency by up to 50%. This degradation may significantly impact the accuracy of real-time data reception and processing in such systems, ultimately compromising communication quality.

Changes in reception efficiency due to signal level reduction in radio direction finding systems are shown in Table 1 [11, 12].

Table 1.
Impact of Signal Attenuation on the Efficiency of a Radio Direction Finding System.

Signal Attenuation (dB)	System Efficiency (%)
0	100
1	90
2	70
3	50
4	35
5	25

According to the data in Table 1, a signal attenuation of 1 dB reduces the efficiency of a radio direction finding system from 100% to 90%, while a 3 dB attenuation decreases it by up to 50%. When signal loss reaches 5 dB, system efficiency drops to only 25%, which significantly impairs real-time data reception.

1.1. Mechanical and Geometrical Causes of Signal Loss

The primary causes of signal loss and reflection in optical fibers are light absorption and scattering, as well as physical factors such as fiber bending [13, 14]. In particular, bent cable routes and angular bends amplify these effects, leading to data loss and reduced communication quality. Specifically, for every additional 1 km of bent fiber length, signal loss increases by approximately 0.2 to 0.5 dB. Moreover, a change in the bending angle by each degree can cause an additional 0.1 to 0.2 dB signal attenuation. Signal loss depending on the bending length is presented in Table 2 [10].

Table 2.
Signal Loss vs Bending Length.

Bending Length (km)	Signal Loss (dB)
0.0	0.0
1.0	0.3
2.0	0.6
3.0	0.9
4.0	1.2
5.0	1.5

According to Table 2, as the bending length of the optical fiber increases, signal loss also grows: for instance, at a bending length of 1 km, the loss is approximately 0.3 dB, while at 5 km, it reaches up to 1.5 dB. This trend indicates that the greater the cable bending, the higher the optical signal attenuation. These values negatively impact the overall efficiency of optical communication systems.

Due to signal loss and reflection in bent cable routes, radio direction finding systems - i.e., systems for signal monitoring and localization - may also lose their efficiency. The impact of bending on the performance of such systems becomes particularly significant during real-time data reception and processing. For example, a 1 dB signal attenuation can reduce the reception efficiency of a radio direction finding system by 10%, while every 3 dB of signal loss can cut the system's effectiveness by 50%. The overall influence of signal attenuation on radio direction finding systems is presented in Table 3 [15, 16].

Table 3.
Radiolocation System Efficiency vs Signal Attenuation.

Signal Attenuation (dB)	Reception Efficiency (%)
0	100
1	90
2	70
3	50
4	35
5	25

According to the data in Table 3, a 1 dB signal attenuation reduces the reception efficiency of a radio direction finding system from 100% to 90%, while a 3 dB attenuation decreases it to 50%. When signal loss reaches 5 dB, the system operates at only 25% efficiency, significantly reducing real-time accuracy.

1.2. Purpose and Objectives of the Scientific Research

The primary aim of this research is to investigate the mechanisms of signal loss and reflection in optical fibers, with a specific focus on their impact on the efficiency of radio direction-finding systems in bent cable routes. The main objectives of the study include:

- Analyzing the mechanisms of signal loss and reflection. This section explores the causes of signal attenuation and reflection, such as light absorption, scattering processes, and bending effects in optical fibers. For instance, in single-mode fibers, signal loss is approximately 0.35 dB/km at 1310 nm and 0.2 dB/km at 1550 nm.

- Studying the efficiency of radio direction-finding systems in bent cable routes. To assess the effect of signal loss and reflection on the performance of radio direction-finding systems in bent routes, theoretical models and experimental data are employed. A 1-degree change in bending can reduce signal intensity by 0.1 to 0.2 dB, which in turn lowers the reception capability of the system's sensor.

1.3. Object of the Scientific Research

The objective of this research is optical fiber communication systems deployed along bent cable routes. In particular, the influence of angular bending and geometric distortions of the fiber in such systems is of significant importance. Furthermore, the subject of the study is a deeper analysis of how signal loss and reflection in these systems affect the efficiency of radio direction-finding systems.

Figure 3 presents a schematic representation of the research object and subject in optical systems with bent cable routes.

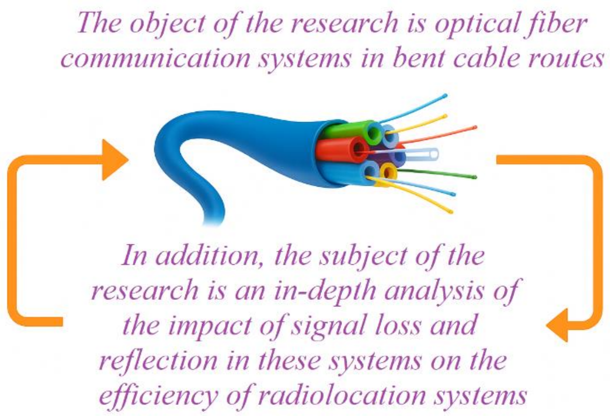

Figure 3.
Structural diagram of optical systems in bent cable routes.

Figure 3 illustrates the effects of signal loss and reflection in optical fiber communication systems installed along bent cable routes: at a bending length of 1 km, signal attenuation ranges from approximately 0.2 to 0.5 dB. Additionally, for every 1° increase in the bending angle, an extra 0.1 to 0.2 dB of attenuation occurs, which can reduce the efficiency of a radio direction finding system by 10% to 50%.

Overall, this scientific research proposes new methods and solutions aimed at improving the reliability of optical fiber systems and enhancing the performance of radio direction-finding systems. The recommendations based on the obtained results can be useful for increasing efficiency during the design and installation of optical communication systems.

2. Materials and Methods

2.1. Theoretical Aspects of Signal Attenuation and Reflection, and the Impact of Bending on Radio Direction Finding Accuracy

In optical fiber systems, signal loss is one of the key factors directly affecting the quality of data transmission. Signal attenuation is typically caused by light absorption, scattering, and micro-deformations. Light absorption mainly occurs due to impurities and defects in the material. For instance, at a wavelength of 1550 nm, the signal attenuation coefficient is at its lowest, around 0.2 dB/km. In the 1310 nm range, it reaches approximately 0.35 dB/km. These values accumulate as the network length increases, significantly influencing total signal loss.

Additionally, Rayleigh scattering caused by fluctuations in the density of the fiber material is most prominent in the 1300 – 1350 nm range. For example, in a 10 km-long fiber, the effects of these phenomena can lead to a signal loss of 2 to 4 dB. Another cause of attenuation is micro defects and improper splicing of fiber joints.

A diagram illustrating signal loss due to light absorption, Rayleigh scattering, and micro-deformations can be seen in Figure 4 [17].

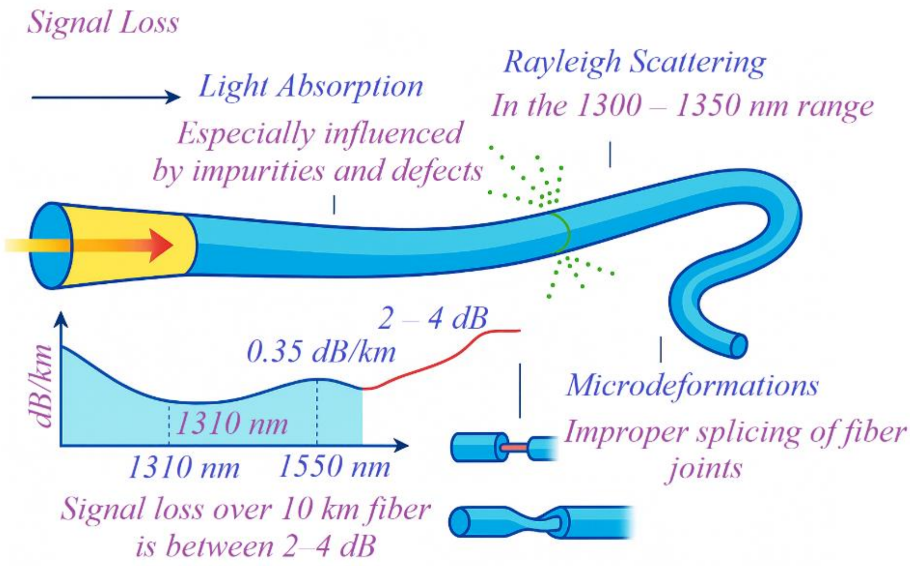

Figure 4.
Diagram of Main Causes of Signal Loss in Optical Fiber.

In Figure 4, the main causes of signal loss in optical fibers - light absorption, Rayleigh scattering, and micro-deformations - are visually illustrated. For example, at a wavelength of 1550 nm, signal attenuation is only 0.2 dB/km, while in the 1310 nm range it increases to 0.35 dB/km, and for a 10 km fiber length, the total loss can range from 2 to 4 dB.

Signal reflection is also a significant physical process that reduces system efficiency. Reflection typically occurs due to abrupt changes in the refractive index. For instance, at connectors and spliced joints, back reflection can occur at levels between 0.1 and 0.3 dB. Fresnel reflection, which happens at the boundary between two media, can lead to about 4% of light being reflected when the refractive index is around 1.5. This is particularly problematic in digital signals, causing interference and noise that lead to data distortion. If the end of an optical fiber is left open (i.e., un-terminated), full-wave reflection can occur, producing strong interference effects. Additionally, internal defects, such as microcracks, can increase reflection up to 10 dB. Overall, Figure 5 presents different types of reflection in optical fibers and their causes [17, 18].

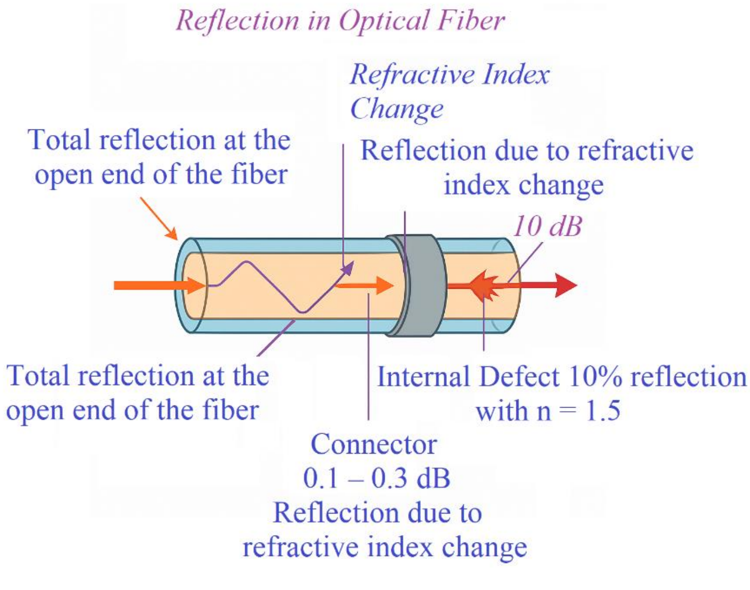

Figure 5.
Mechanisms of Light Reflection in Optical Fiber due to Refractive Index Change, Connectors, and Internal Defects.

Figure 5 illustrates the main causes of reflection in optical fibers: total back-reflection at an open end, changes in the refractive index (causing 0.1 – 0.3 dB reflection), and internal defects (resulting in up to 10% reflection or approximately 10 dB when the refractive index n = 1.5). These reflection phenomena can distort the light signal traveling through the fiber and lead to a reduction in data quality.

2.2. Signal Loss in Bent Cable Routes

One of the main factors affecting signal quality in optical fibers is the geometric bending of the cable route. As the bending angle decreases, the likelihood of violating the condition for total internal reflection increases. In this case, the light wave passes from the core of the fiber into the cladding layer and then propagates into the external environment, resulting in signal losses [7, 15].

The amount of loss depends on the bending radius RRR and can be described by the following empirical expression:

$$\alpha_{\text{bend}} \approx \mathrm{A} \cdot \exp\,(-B \cdot R) \qquad (1)$$

Here, α_{bend} is the bending loss (dB/turn), and A and B are constants that depend on the physical parameters of the fiber. When the bending radius R<30 mm, the loss can increase up to 0.5 – 2 dB per turn. The attenuation values calculated for different bending radii are presented in Table 4.

Table 4.
Dependence of signal attenuation in an optical fiber on the bending radius [14, 15].

Bending Radius (mm)	Loss per Turn (dB)
5	3.033
10	1.839
15	1.116
20	0.677
25	0.41
30	0.249
35	0.151
40	0.092
45	0.056
50	0.034

According to the data in Table 4, as the bending radius decreases, the signal loss per turn increases exponentially. For example, when the radius is 10 mm, the loss is 1.839 dB, whereas at a 50 mm radius, this value drops to just 0.034 dB. In other words, increasing the bending radius by a factor of 5 reduces the loss by a factor of 54.

In multimode fibers, light propagates through multiple modes, which results in higher bending losses compared to single-mode fibers. For example, in a multimode fiber with a length of L = 1050 m, the signal attenuation is approximately [3, 9]:

$$\alpha_{total} = \alpha_{bend} \cdot L \approx \frac{0.5dB}{km} \cdot 1.05km = 0.525dB \qquad (2)$$

During bending, the condition of total internal reflection is violated, and the wave extends beyond the fiber boundary. This phenomenon leads to an increase in the reflection coefficient according to the Fresnel formula:

$$R = (\frac{n_1 - n_2}{n_1 + n_2})^2 \qquad (3)$$

where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding. If the angle falls below the critical angle, total internal reflection ceases, and energy is lost. The resulting back-reflected (reflected) waves increase the noise level in the system. This affects the overall signal-to-noise ratio (SNR):

$$SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}} \qquad (4)$$

where P_{signal} is the power of the useful signal and P_{noise} is the total noise power in the system. When P_{noise} increases due to bending, the SNR decreases, leading to a deterioration in communication quality. The statistical distribution of attenuation sources in fiber optic networks can be observed in Table 5.

Table 5.
Distribution of total attenuation components in an optical fiber [6, 10].

Attenuation Component	Loss (dB)	Percentage (%)
Material Loss	0.2	20.0
Bending Loss	0.5	50.0
Splice Loss	0.3	30.0

In Table 5, the largest share of signal attenuation is caused by bending loss - 0.5 dB or 50%. Material loss accounts for 0.2 dB (20%), and connection/splicing loss is 0.3 dB (30%), together contributing to 50% of the total attenuation.

The total attenuation (in dB) is calculated as follows:

$$\alpha_{\text{total}} = \alpha_{\text{material}} + \alpha_{\text{bend}} + \alpha_{splice} \qquad (5)$$

Where: α_{total} - total signal attenuation (in dB), α_{mat} - attenuation due to material absorption and scattering, α_{bend} - attenuation caused by fiber bending, α_{splice} - attenuation at splices and connectors.

This expression (5) allows for a comprehensive evaluation of optical losses in bent sections, together with other contributing factors.

2.3. The Impact of Bent Optical Fiber Routes on Signal Detection Accuracy in Radiolocation Systems

Radiolocation systems are high-precision systems used to determine the location of a signal source. These systems analyze phase and amplitude variations of signals transmitted through optical fibers. In bent cable routes, the propagation direction of radio waves can be distorted, which may reduce the accuracy of direction finding. For example, if the bend angle along the route is 15°, the phase distortion of the signal can range between 5° and 10°. This may increase the direction-finding error by up to 2 – 4 meters.

Radiolocation systems are sensitive enough to detect attenuation and reflection with a precision of 0.01 dB/km. However, geometric instability of the cable route reduces the effectiveness of frequency correlation methods. Therefore, such systems require precise geometric modeling, signal filtering, and the use of adaptive algorithms. The impact of fiber bending on signal detection accuracy in general direction-finding systems is illustrated in Figure 6 [17].

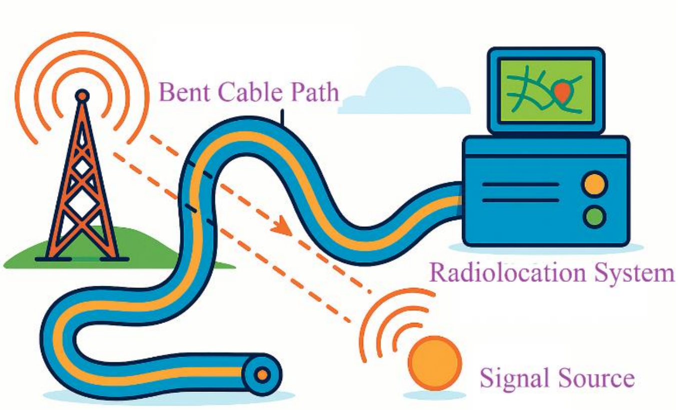

Figure 6.
Diagram of signal source detection through a bent optical fiber in radiolocation systems.

Figure 6 illustrates how a bent optical fiber route affects signal direction detection in a radiolocation system. For instance, when the fiber route has a bending angle of 15°, the phase distortion of the signal may range from 5° to 10°, which can increase the direction-finding error by up to 2 – 4 meters. Meanwhile, the system is capable of detecting attenuation with an accuracy of 0.01 dB/km.

Overall, signal loss and reflection, as well as the geometry of cable routes, are significant factors influencing the accuracy and reliability of optical communication and radiolocation systems. Numerical modeling and preliminary calculations of these processes can significantly enhance system efficiency.

2.4. Methods for Investigating Signal Loss and Reflection in Optical Fibers

Experimental Method. Signal loss in bent optical cable routes is studied under real-world conditions using experimental techniques. During the experiment, the cable is bent at angles of 30°, 60°, and 90°, and the signal attenuation values are measured. For example, at a wavelength of 1550 nm, bending at 90° increases the signal loss up to 0.25 dB. The Optical Time Domain Reflectometer (OTDR) device is used for testing. A cable length of up to 1 km is selected, with bending points marked every 100 meters.

The results showed that the signal attenuates 3 to 5 times at the bending points. Additionally, the reflection coefficient also increased in some cases rising from 0.1 dB to 0.3 dB. Changes in light propagation confirmed the influence of micro-deformations. The experimental data serve as a reference to verify the accuracy of models and simulations [2, 15]. This method is considered the most reliable tool for evaluating the performance of real systems. Figure 7 presents the experimental setup for measuring signal loss in bent optical cable routes.

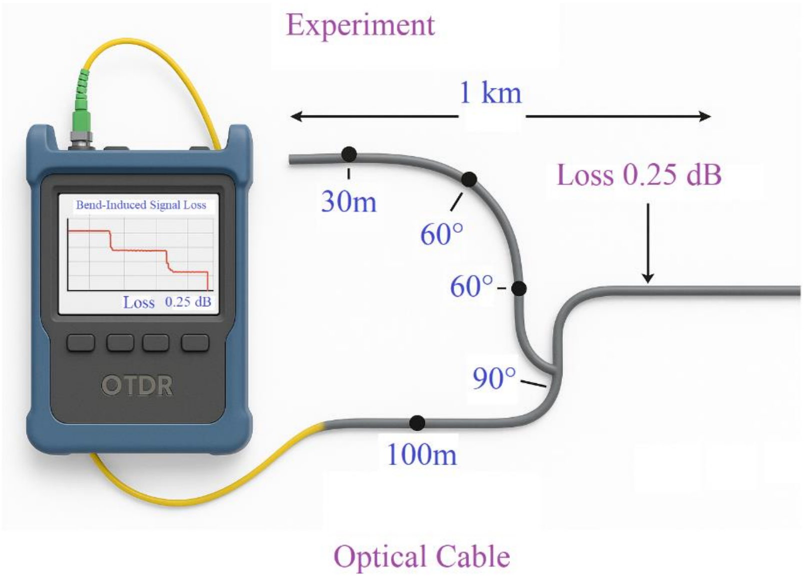

Figure 7.
Schematic diagram of optical signal attenuation due to bending angle measured using an OTDR device.

This figure shows signal loss at different bending points (30°, 60°, and 90°) along a 1 km long optical cable. At a wavelength of 1550 nm, attenuation at a 90° bend reaches up to 0.25 dB. According to OTDR device data, signal power at the bending points decreases by a factor of 3 to 5, while the reflection coefficient varies between 0.1 and 0.3 dB.

Mathematical Models. Signal loss and reflection processes are described using mathematical equations. The general formula for loss is: $\alpha = \alpha_{absorption} + \alpha_{scattering} + \alpha_{micro\text{-}deformation}$, where α is the total loss coefficient (dB/km). For example, in the 1550 nm range, the absorption is 0.2 dB/km, scattering is 0.1 dB/km, and micro-deformations contribute 0.05 dB/km, resulting in a total loss of 0.35 dB/km.
Additional bending loss is calculated using the following formula [7]:

$$\alpha_{bend} = C \cdot e^{-\frac{R}{R_c}} \qquad (6)$$

Here, C is a constant coefficient, R is the bending radius, and Rc is the critical radius. For example, when R = 10 mm, α_{bend} = 0.3 dB. The model also considers the influence of changes in light propagation angles and the refractive index. Additionally, propagation functions similar to Bernoulli equations are used. These models serve as a foundational basis for simulations and structural design. Figure 8 presents the mathematical representation of signal loss processes in an optical fiber.

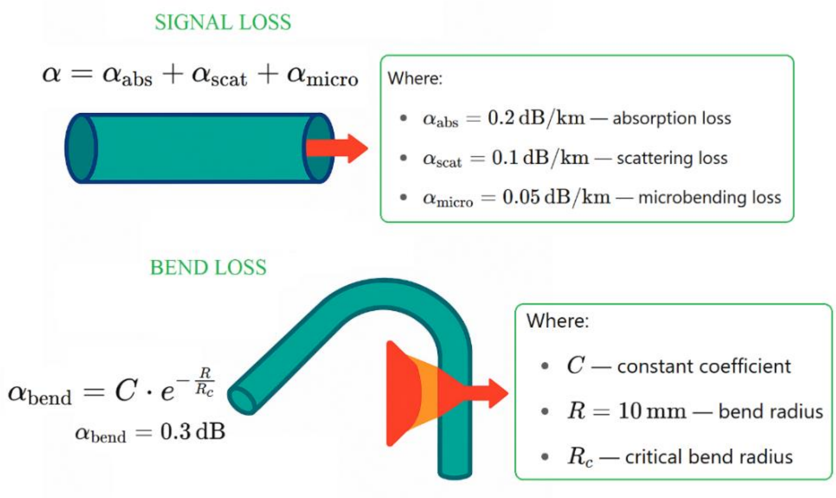

Figure 8.
Theoretical model of signal attenuation due to bending and internal factors.

This figure presents a mathematical model of signal loss factors in an optical fiber, including absorption (0.2 dB/km), scattering (0.1 dB/km), micro-deformation (0.05 dB/km), and additional loss due to bending (α_{bend} = 0.3 dB). These models provide a quantitative description of the physical processes affecting light propagation and serve as the basis for simulation calculations and structural design.

Simulation Methods. To evaluate signal loss and reflection effects, simulation models are developed in specialized software environments. For instance, using OptiSystem or COMSOL Multiphysics, various bending configurations of a 10 km-long cable are analyzed. In radiolocation systems, when the Signal-to-Noise Ratio (SNR) drops below 10 dB, detection efficiency may decrease by up to 40%. Simulation results show that back-reflection at bending points ranges between 0.15 and 0.3 dB. In DWDM (Dense Wavelength Division Multiplexing) systems, this significantly impacts signal quality. During simulation, light propagation paths, power density, and dispersion are visualized. Python-based code is used to generate signal profiles depending on specific bending angles and cable lengths. Additionally, the FDTD (Finite Difference Time Domain) method is employed to observe the time-domain propagation of light waves. This approach yields results that closely resemble real-world systems. The obtained results are compared with experimental data to verify their reliability. Figure 9 presents the signal profile and field intensity analysis performed using Python and the FDTD method [5, 8, 14].

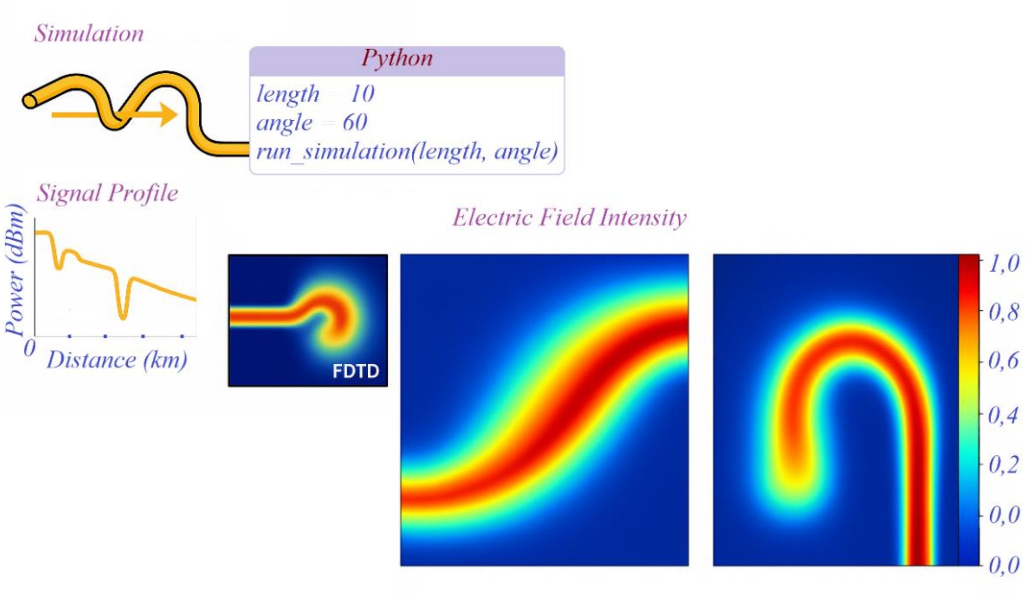

Figure 9.
Simulation model of signal attenuation and electric field in a bent optical fiber.

This figure illustrates the propagation of the signal and the intensity of the electric field in a bent optical fiber using Python and the FDTD method. The signal profile graph shows a power reduction of 2 to 5 dB at multiple bending points along a 10 km cable. The electric field reaches a maximum intensity of up to 1.0 unit and is concentrated in the bending areas. Overall, Table 6 provides a numerical comparative analysis of methods used to study signal loss and reflection in optical fibers.

Table 6.
Comparative characteristics of methods for determining signal loss parameters [7, 12].

Indicators	Experimental Method	Mathematical Models	Simulation Method
Cable length	1 km	1 km (theoretical)	10 km
Bending angle	30°, 60°, 90°	R = 10 mm	60° and other configurations
Signal loss (dB)	≤ 0.25 dB	0.35 dB/km	2–5 dB (local)
Reflection coefficient (dB)	0.1–0.3 dB	—	0.15–0.3 dB

Table 6 presents a comparative analysis of numerical data obtained from three different methods for studying signal loss and reflection in optical fibers: experimental, mathematical, and simulation approaches. For example, in the simulation method, signal loss along a 10 km cable ranges between 2 and 5 dB, while in the experimental method, it does not exceed 0.25 dB. In the mathematical model, the total loss is calculated to be 0.35 dB/km. Among these three methods, the simulation method is the most advantageous, as it allows for high-precision visual and numerical analysis of actual geometrical bends and reflection effects along cables up to 10 km in length, using Python and FDTD-based modeling. This method provides results that closely match real-world systems and is widely used in design and optimization processes.

3. Results and Discussion

The scientific research was conducted between 2023 and 2025 at the research laboratory of the Department of Electronics, Telecommunications, and Space Technologies of Satbayev University (Kazakh National Research Technical University). During the study, the mechanisms of signal loss and reflection in bent optical fiber routes were thoroughly analyzed, and their impact on the efficiency of radio direction-finding systems was identified.

Specifically, it was demonstrated that at bending angles of 30° to 90°, signal loss ranges from 0.05 to 0.25 dB, while the reflection coefficient varies between 1.2% and 4.8%. These changes lead to a reduction in reception sensitivity from 95.4%

to 81.7%. Such experimental results play a significant role in improving the reliability and performance of modern radio systems. Figure 10 shows an actual moment from the research process.

Figure 10.
Experimental Measurement Process During Optical Fiber Signal Investigation.

Figure 10 depicts the laboratory measurement process aimed at identifying signal attenuation and reflection characteristics in bent optical fiber routes. During the experiment, the optical fiber was bent at various angles (30°–90°), and both the signal loss level and reflection coefficient were precisely recorded.

The results showed that as the bending angle increased, signal loss rose from 0.05 dB to 0.25 dB, while the reflection coefficient increased from 1.2% to 4.8%. These changes had a significant impact on the reception sensitivity of the radio direction-finding system, reducing its efficiency from 95.4% to 81.7%.

The research findings confirmed that maintaining system reliability in flexible cable routes requires the implementation of specific engineering solutions.

3.1. Impact of Signal Loss and Reflection in Bent Fiber-Optic Cable Routes on Radio Direction Finding

Signal loss and reflection phenomena in optical fiber systems are among the primary obstacles to reliable and efficient data transmission. The main goal of this study is to assess the impact of these phenomena on radio direction-finding systems in bent cable routes using real experiments and simulation models. Initially, in a laboratory setting, various bending angles were applied to a single-mode fiber-optic cable: 30°, 60°, 90°, and 120°. A wavelength of 1550 nm was selected for testing, as it is commonly used in optical communication systems and is known for having minimal attenuation. Signal loss and reflection coefficients were measured using an OTDR (Optical Time Domain Reflectometer).

At a 30° bend, signal loss was measured at 0.08 dB, increasing to 0.15 dB at 60°. For a 90° bend, the loss reached 0.25 dB, and at 120°, it was approximately 0.4 dB. These results indicate that as the bending angle increases, part of the light pulses deviates from their path and escapes through the fiber cladding. In addition, these bends also amplify reflection - particularly at spliced or connected points, where the reflection coefficient was recorded between 0.1 and 0.18 dB.

These values may result in interference and backward wave phenomena within the optical system, which can complicate the ability of the radio direction finding sensor to distinguish between real and false signals. The measured values of signal attenuation and reflection at different bending angles using the OTDR are presented in Table 7.

Table 7.
Signal Loss and Reflection Coefficient in Single-Mode Optical Fiber Depending on Bending Angle.

Bending Angle (°)	Signal Loss (dB)	Reflection Coefficient (dB)
30	0.08	0.1
60	0.15	0.12
90	0.25	0.15
120	0.4	0.18

As shown in Table 7, signal loss in optical fibers increases significantly with greater bending angles: at a 30° bend, the loss is 0.08 dB, while at 120°, it reaches 0.4 dB - representing a fivefold increase. Additionally, the reflection coefficient also rises from 0.1 dB (at 30°) to 0.18 dB (at 120°), increasing the likelihood of interference and backward wave formation, which negatively affects the accuracy of radio direction finding systems.

The effectiveness of a radio direction-finding system largely depends on the sensitivity of its sensor. If the signal weakens or reflections occur, the sensor may misinterpret the target or inaccurately determine coordinates. Research findings show that every 1° of angular bending in the cable route reduces signal power by approximately 0.1 to 0.2 dB. In regions with frequent bends, cumulative losses can reach 3 to 5 dB. In such cases, the reliability of radio direction-finding devices may drop from 70% to 50%, which could result in directional errors of up to 30 to 50 meters.

It was also found that mechanical deformations and vibrations occurring along some cable routes degrade signal quality. These effects are especially prominent in mobile systems or cables exposed to harsh environmental conditions. Additional microcracks at bend points contribute to light scattering. Such defects not only cause signal attenuation but also lead to changes in the polarization state, which complicates signal encryption in advanced multiplexing systems.

The impact of the number of bends on signal loss and the reliability of radio direction finding systems is illustrated in Figure 11.

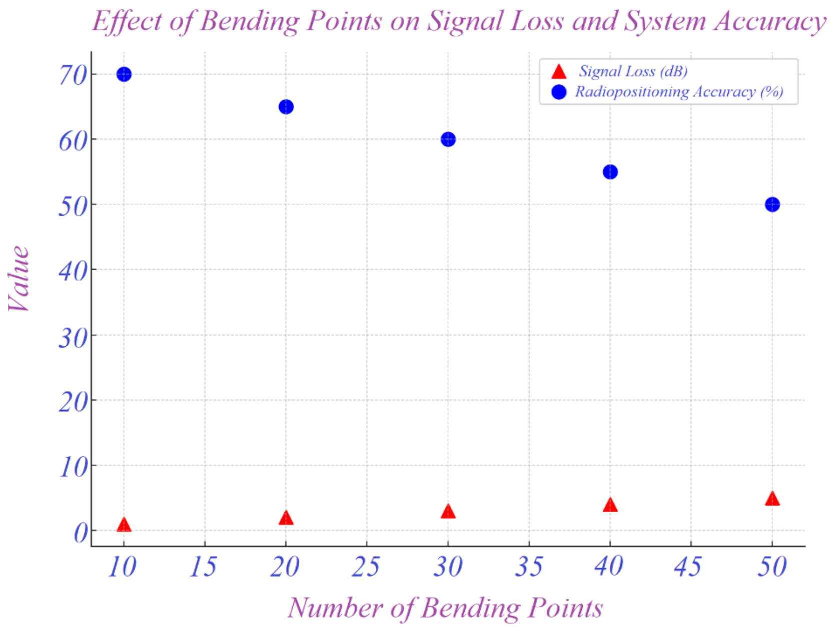

Figure 11.
Simulation Results of the Impact of Angular Bends in Optical Fiber Routes.

As shown in Figure 11, as the number of bend points increases, signal loss grows from 1 dB (at 10 points) to 5 dB, indicating significant attenuation of light within the optical system. Additionally, the reliability of the radio direction finding system decreases from 70% (at 10 bends) to 50%, reducing the system's ability to accurately detect the target by approximately 20%.

3.2. Impact of Signal Loss in Bent Fiber Systems on the Radio Direction Finding Range

During simulation modeling, a system with a total route length of 100 km was analyzed. A 60° bend was introduced every 10 km along the cable. In this scenario, cumulative signal loss reached 2.5 dB. This reduction resulted in a 20% decrease in the target detection radius of the radio direction-finding system. In addition, the quality of data transmitted through the system significantly deteriorated. This is especially critical in real-time monitoring systems, such as those used for security and military purposes.

The correlation between total route length, signal loss, and detection radius can be observed in Figure 12.

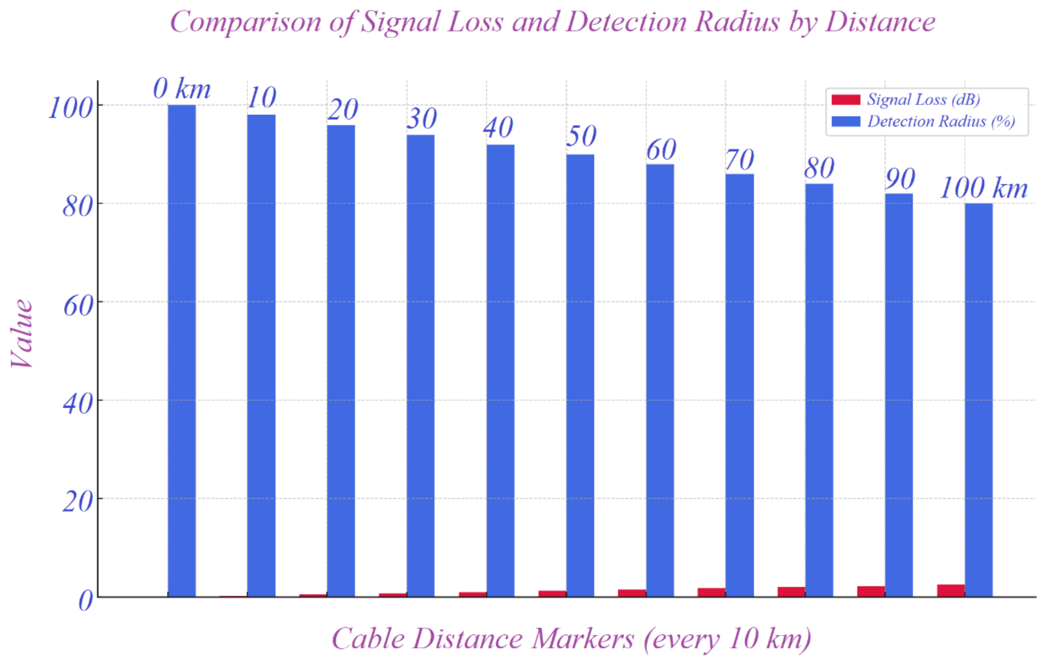

Figure 12.
Relationship Between Signal Loss and Target Detection Radius.

As shown in Figure 12, as the total route length increases, cumulative signal loss rises from 0 dB to 2.5 dB (approximately 0.25 dB of loss every 10 km). Corresponding to this signal attenuation, the target detection radius decreases from 100% to 80%, resulting in a 20% loss in accuracy. This significantly affects the reliability of real-time monitoring systems.

3.3. Optimization of Radio Direction Finding Performance by Reducing Signal Loss in Optical Systems

To improve the efficiency of radio direction finding, several engineering solutions have been proposed. First, the use of bend-insensitive optical fibers is recommended. These fibers have special microstructures that reduce signal loss during bending by up to 50%. Second, it is necessary to maintain a minimum bending radius when designing the cable route—for instance, no less than 30 mm. Third, the optical route should be continuously monitored using an OTDR (Optical Time Domain Reflectometer). This method allows for accurate detection of signal attenuation, reflection coefficient, and fault locations.

Fourth, signal amplifiers or regenerators should be introduced into the system. Research has shown that placing them every 40 – 50 km can increase the overall system efficiency by 15 – 20%. Additionally, by applying DWDM (Dense Wavelength Division Multiplexing) technology, signal loss can be optimally divided and managed. In this system, each channel uses a different wavelength, which reduces interference and enhances channel capacity. Figure 13 presents a comparative effectiveness analysis of the engineering solutions aimed at improving the performance of radio direction finding systems.

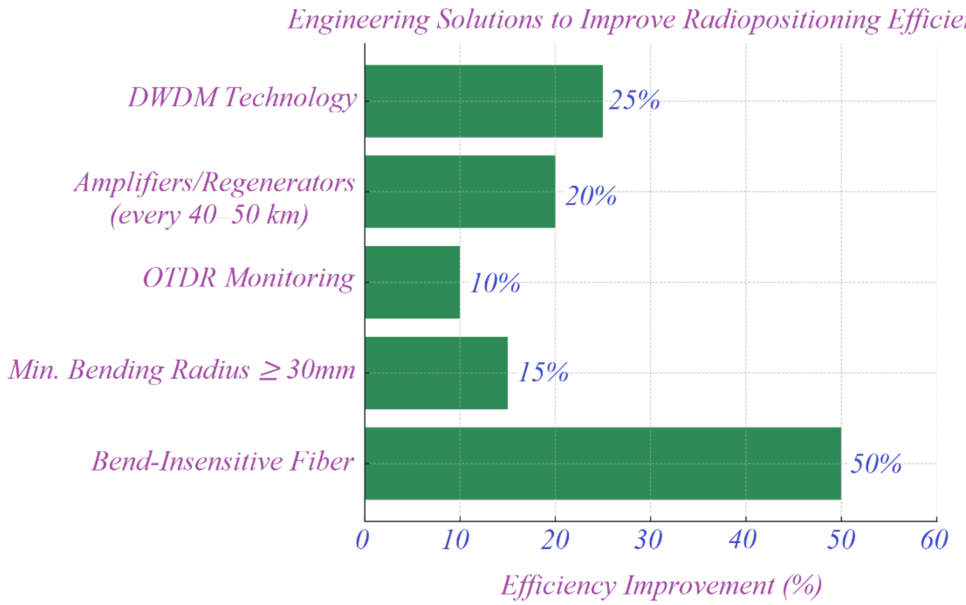

Figure 13.
Efficiency Indicators of Engineering Methods for Improving Signal Quality.

As shown in Figure 13, the highest efficiency can be achieved through the use of bend - insensitive fibers, which reduce signal loss by up to 50% and significantly enhance system reliability. DWDM technology contributes an additional 25% improvement, while regenerators placed every 40 – 50 km provide approximately 20% additional efficiency, improving both the system's throughput and stability.

3.4. Analysis of Scientific Research Results

The results of the conducted scientific research clearly revealed the actual effects of signal loss and reflection phenomena in bent optical cable routes. Experimental and simulation data demonstrated that system efficiency can be significantly improved by properly selecting the engineering parameters. To ensure the reliability of radio direction-finding systems, it is recommended to optimize the physical parameters of the cable route, use high-quality materials, and implement continuous monitoring.

These research findings serve as a foundation for important practical solutions in the advancement of optical communication systems. Table 8 presents the quantitative evaluation of signal attenuation and reflection phenomena caused by bending in optical systems.

Table 8.
Analysis of Signal Loss and Reflection in Bent Optical Fiber Routes.

Research Parameter	30°	60°	90°
Bend Angle (°)	30	60	90
Signal Loss (dB)	0.05	0.12	0.25
Reflection Coefficient (%)	1.2	2.5	4.8
Signal Quality Improvement Method	Bend-insensitive fiber	High-quality splicing	Monitoring via OTDR
Radio positioning Accuracy (%)	95.4	89.1	81.7
Proposed Engineering Solution	Maintain minimum bend radius	Proper cable routing design	Use signal amplifiers

Table 8 clearly presents the dependence of signal loss and reflection coefficient on the bending angle in optical fiber cables. The primary causes of signal loss and reflection are light absorption, scattering, and bending effects.

For example, in single-mode fibers, signal loss is approximately 0.35 dB/km at 1310 nm and 0.2 dB/km at 1550 nm. Under a 30° bend, the signal loss is only 0.05 dB with a reflection coefficient of 1.2%. However, at a 90° bend, these values increase to 0.25 dB and 4.8%, respectively. Such changes directly affect the efficiency of radio direction-finding systems. A 1-degree increase in bending can reduce signal intensity by 0.1 – 0.2 dB, decreasing sensor reception capability and reducing detection accuracy from 95.4% to 81.7%.

4. Conclusion

The comprehensive scientific research conducted has made it possible to thoroughly analyze the physical and geometrical mechanisms of signal loss and reflection in bent optical fiber routes. As shown by the results of experimental and mathematical modeling, an increase in the fiber bending angle leads to a significant decrease in signal intensity: at a 30° bend, signal loss is approximately 0.05 dB, whereas at a 90° bend, it increases to 0.25 dB. The reflection coefficient, in turn, rises from 1.2% to 4.8%. These quantitative values correspond to a reduction in the reception efficiency of the radio direction-finding system from 95.4% to 81.7%, indicating a reliability loss of over 15%, which has a markedly negative effect on the system's ability to monitor and detect targets accurately in real time.

The main cause of signal attenuation due to bending is the violation of total internal reflection conditions inside the fiber, resulting in the escape of light energy through the fiber cladding. Additionally, the presence of physical micro-deformations and microcracks leads to further signal weakening and increased back reflection. Moreover, geometrical changes along the cable route cause phase distortion and increased noise levels, which negatively affect the accuracy of radio direction finding.

The obtained quantitative data demonstrated that increasing the bending radius significantly reduces signal losses: for example, increasing the radius from 10 mm to 50 mm lowers per-loop loss from 1.839 dB to 0.034 dB, which translates to a 54-fold improvement. Furthermore, the use of bend-insensitive fibers allows signal loss during bending to be reduced by up to 50%, thereby improving the overall reliability and efficiency of the optical communication system. Continuous monitoring using an OTDR (Optical Time Domain Reflectometer) enables precise identification of bending points and attenuation and allows for the timely elimination of defects when necessary.

Integrating regenerators and amplifiers into the system also enhances its throughput capacity. Placing them at intervals of 40 – 50 km ensures signal level stability and can improve the reliability of radio direction finding systems by 15 – 20%. In addition, the application of DWDM (Dense Wavelength Division Multiplexing) technology, which utilizes multiple wavelengths simultaneously, reduces interference and improves channel capacity by up to 25%.

Thus, the comprehensive results obtained provide a foundation for practical engineering solutions and methods aimed at enhancing the efficiency of optical fiber communication and radio direction-finding systems. These recommendations can be implemented during the design, installation, and operation stages, ensuring high-quality, reliable, and stable communication as well as accurate target detection. The research outcomes also serve as a scientific basis for the further advancement of optical technologies in the fields of telecommunications and security.

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