Methods and Means of Ensuring Information Security in Fiber-Optic Communication Lines

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Abstract. This paper considers the problem of protection against an unauthorized access and presents the results of comparing different methods for extracting data from optical fiber. This paper provides classification of methods of information receiving, physical principles of leakage channels formation, as well as methodology as to how to send a share of the optical radiation outside the propagation medium. The simplest of the analyzed methods is the bending of the optical fiber when the conditions of full internal reflection are broken. In this case, the monitoring system controls the introduced losses to detect fiber bends. This work outlines the structure, principles of operation, as well as the trends in the development of monitoring systems.

Keywords. Fiber-optic communication line, information protection, monitoring system, reflectometry, bending, unauthorized access, leakage channel.

1. Introduction
The technological advances increase the potential vulnerability of fiber-optic networks. This is primarily explained by the economic efficiency of equipment and accessories required to connect to the optical line, and as a result such equipment becomes more affordable. With the progress unauthorized connection is more feasible for the increased number of hackers. In most cases the economic feasibility determines the probability of unauthorized connection which is due to the relationship between the expenses for connection. For example, intruders can easily get free access to cable TV in the case of home PON networks, but they would not do it, since regular subscription access is cheaper in this case. The information from corporate or departmental networks is different.
Such information is usually confidential, and may be of significant value to a certain category of entities. Then, we should not exclude the risk of unauthorized connection. So, it is essential to develop identification algorithms and principles which would help to control information leakage channels in fiber-optic transmission systems.

2. Problem Statement
Solving the problem of protecting information transmitting in the fiber optical communication lines (FOCLs) has developed in two main line: to protect the content of the transmitted signals (e.g. to use cryptography, white noise deterministic chaos, and encryption) and to protect the propagating optical
signal (to monitor of unauthorized access to fibers of the FOCL – detection of the information leakage channels).

Security methods which are based on the content component protection of signals in the FOCL are reliable. However they impose high demands on the hardware and the whole organization of the infocommunication system (e.g., the use of cryptography methods requires key exchange). Moreover, with these methods do not provide data about unauthorized connection attempts.

Methods which are based on monitoring can be more available both from the point of view of organization and due to their technical features. They are cost-effective and independent of the structure and the transmission speed of the digital signal. These methods can be used in networks of different hierarchy levels (local, subscriber, zonal) and provide the ability to detect attempts of the unauthorized connections.

3. The theory

At the moment, the following methods of unauthorized access in optical fiber (OF) networks are well known [1]:

Mechanical influence on the optical fiber. The critical angle of the optical wave at the interface boundary (“core-cladding”) is changed. If the optical wave falls on the border “core-cladding” at an angle greater than the critical angle, then there is a direct exit of a certain part of the optical radiation from the OF.

We can determine the losses in OF during bending ($\alpha$) by the formula:

$$\alpha = \alpha_{\text{trans}} + \alpha_{\text{rad}},$$

where $\alpha$ is the resulting loss at the bend;

$\alpha_{\text{trans}}$ is transient losses;

$\alpha_{\text{rad}}$ is radiated power losses.

Transient losses are determined by the formula [2]:

$$\alpha_{\text{trans}} = 0.271 \frac{V^4 n_2^2}{(R/\alpha)^2 (n_1 - n_2)^2} \left( 0.65 + \frac{1.62}{\sqrt{V^5}} + \frac{2.88}{V^6} \right)^6,$$

where $\alpha$ is the radius of the core

$n_1$ and $n_2$ are indexes of the core refraction and the cladding refraction respectively;

$R$ is the bending radius of the OF;

$V$ is the normalized frequency.

The refractive index, in its turn, depends on the wavelength. This suggests that transient losses depend directly proportional on the wavelength and are in inverse dependence on the radius of bends [1 – 3].

The loss of radiated signal through the side surface of the OF can be calculated using the following formula [3]:

$$\alpha_{\text{rad}} = -10 \log(1 - 10^{-0.1 A_{\text{out}}/k_{\alpha}}) \text{ [dB]},$$

where $A_{\text{out}} = 10 \log(\rho_{\text{out}}/\rho_{c})$ [dB] are losses on the OF segment – the input terminal of receiving optical devices;

$k_{\alpha} = \rho_{\text{out}}/\rho_{c}$ is the ratio between the power on the side surface of the optical fiber and the power at the output terminal of the receiver;

$\rho_{c}$ is signal intensity in the core of the fiber;

$\rho_{\alpha}$ is signal intensity lost during radiation extraction;

$\rho_{\text{out}}$ is signal intensity at the output terminal of the receiver.

Formation of the leak channel by external influence on refractive indexes of the core and cladding.
Acoustic impact on the OF can also changes in the conditions of optical wave propagation at the “core-cladding” boundary. A diffraction lattice (periodic structure) can be created under the influence of the acoustic impact. This grating would make changes of the refractive index (RI). Because of this, the optical beam deviates from the main path, and some of the radiation penetrates into the cladding and further beyond the OF. Diffraction occurs under the Bragg condition:

$$\frac{\lambda L}{A^2} > 1,$$

where $\lambda$ and $A$ are lengths of optical and acoustic waves respectively; $L$ is the size of the acousto-optic interaction area.

We can directly observe the diffraction maximum power of the optical signal if the angle of incidence is equal to two Bragg angles.

Deformations that are made in the OF as in an elastic medium under the impact of the hyperacoustic wave, cause periodic changes in the fiber RI. The impact of the changes the cladding’s RI ratio to the core RI. When the mechanical strain of the OF occurs, there are some small changes in the refractive indexes of the fiber core (the value is $\Delta n_1$) and fiber cladding (the value is $\Delta n_2$).

We can determine reflection angles by the following formula:

$$\sin Q'_r = \left(1 - \frac{\Delta n_1}{n_1} + \frac{\Delta n_2}{n_2}\right) \sin Q_r,$$

where $Q_r$ is angle of internal reflection before exposure;
$Q'_r$ is angle of internal reflection after exposure;
$n_1$ is core RI;
$n_2$ is cladding RI;
$\Delta n_1$ is change in RI of the fiber core;
$\Delta n_2$ is change in RI of the OF cladding.

We can easily create leakage channels with considered methods, however they have a common shortcoming which named the backscatter of the high power optical signal in the leakage places.

**Leakage during optical tunneling.** This method involves soldering or gluing an additional OF. These captures a share of the optical signal which goes beyond the OF core and takes the advantage of not causing noticeable losses and backscatter.

The coupling of radiation into the intercepting OF occurs when the incidence angles are greater than the value of the critical angle. As a result, a small part of the optical radiation passes from the medium with RI $n_1$ to the medium with $n_3$ through the layer with $n_2$.

4. Methods for Detecting Unauthorized Connections to Optic Fibers

Any external influence on the OF results in changes in local fiber parameters and characteristics of the whole FOCL. Thus we can monitor unauthorized connections [3 – 6]. Up-to-date specialized monitoring systems monitor changes in the above parameters [5 – 12].

These systems must provide:

- detection the exact location of unauthorized access;
- remote monitoring of unauthorized connection to the active OFs;
- timely reporting;
- monitoring and managing the warning system of unauthorized access to OFs;
- manual control of the unauthorized access.

Functionally, the system of monitoring should consist of following important components [4]:

- module of the control;
- module for analysis of changes in the physical state of fibers;
- module for changes documentation about states of the FOLC.
A module of the control is designed to control and synchronize the work of other modules. The state diagnostics system (SDS) is the basis of the module for fixing state changes in fibers of the FOLC. The basis of the module for fixing changes in the state of is the state diagnostics system of the communication line. The signals of Rayleigh backscatter, Fresnel reflection and Mandelstam – Brillouin backscatter is analyzed in SDS.

Advantages of SDS with the analysis of the passed signal are [5]:
– possibility to measure optical radiation characteristics continuously;
– possibility to measure any branch of telecommunication systems.

Moreover, the simple is analyzed SDS based on the analysis of error coefficients can be designed using regular SDS devices. More complex characteristics based on the transfer of several optical signals over the OF are informational and control ones. Signals of the control are usually transferred at a slightly longer wavelength relative to the information signal, and it allows to enhance the system sensitivity.

More complex and functional system is the SDS on the basis of impulse reflectometry. It can determine the coordinate of unauthorized connection, calculated by the formula [6]:

\[ L_x = \frac{\Delta t c_0}{2 n_g} \]  \hspace{1cm} (6)

where \( L_x \) is the measured coordinate of unauthorized connection;
\( \Delta t \) is the time difference between the input and back-reflected pulses;
\( c_0 \) is the light speed of the vacuum equal to 300,000 km/s;
\( n_g \) is the valid group refractive index of the core glass.

The systems allow to accurately measure the changes made by unauthorized connections losses. This is achieved by approximating the sections of the reflectogram before and after connection using the mathematical apparatus of regression analysis. In the case of approximation by a linear dependence of the form

\[ Y = a + bx \]  \hspace{1cm} (7)

Coefficients \( a \) and \( b \) are calculated by the formulas:

\[ a = \frac{\sum_{i=1}^{n} \hat{X}_i \hat{Y}_i - \left( \sum_{i=1}^{n} \hat{X}_i \right) \left( \sum_{i=1}^{n} \hat{Y}_i \right)}{n \left( \sum_{i=1}^{n} \hat{X}_i \right)^2 - \left( \sum_{i=1}^{n} \hat{X}_i \right)^2} \]

\[ b = \frac{\sum_{i=1}^{n} \hat{X}_i \hat{Y}_i - \left( \sum_{i=1}^{n} \hat{X}_i \right) \left( \sum_{i=1}^{n} \hat{Y}_i \right)}{n \left( \sum_{i=1}^{n} \hat{X}_i \right)^2 - \left( \sum_{i=1}^{n} \hat{X}_i \right)^2} \]  \hspace{1cm} (8)

where \( \hat{X}_i \) is the estimation of mathematical expectations of the measured coordinated \( L_i \); \( \hat{Y}_i \) is the estimation of the mathematical expectations of measured losses values in coordinates \( L_i \); \( n \) is the number of readings at the approximation area [12].

The maximal distance to the coordinate of the unauthorized access can be calculated by the formula:

\[ L_{max} = \frac{D}{a_i} \]  \hspace{1cm} (9)

where \( D \) is the dynamic range of optical reflectometer, \( a_i \) is the kilometric losses of optical fiber.
High spatial resolution is required at a length of FOLC more than 20 km, and the pulse sensitivity may be insufficient. We can significantly improve the metrological characteristics of systems of the monitoring with the use of complex probing pulses, such as frequency-modulated ones [12]. The data concerning the evolution of the probing signal is contained in the spectrum of beats formed as a result of mixing two signals [7].

Along with its undoubted benefits, a method of the optical reflectometry, has a number of limitations that may complicate using it under certain conditions. Probing signals of refractometer can become the sources of interference to the information signal. When working at a wavelength other than the information signal wavelength, there may be cases when reflectometers do not detect external influences when they are purposefully manifested only at the information signal wavelength. The method of optical reflectometry cannot be used in branched networks and telecommunication lines that use directional erbium amplifiers. Moreover, the reflectometer is a costly precision device. It is not designed to be used continuously, which is essential for institutional communication systems, particularly for those that are deployed in emergency conditions [8, 12].

Inhomogeneities are known to occur in the OF due to thermal fluctuations of atoms. Hyperacoustic waves are always occur in the OF like infrared radiation. A light scatter on mobile inhomogeneities of the core RI caused by acoustic waves is referred to as Mandelstam – Brillouin backscatter (MBS). The resulting inhomogeneities move which makes the main difference between Rayleigh scatter and Brillouin backscatter. Thus, the frequency of the backscattered light signal is different from the probing one and, as a result, from the Rayleigh scatter. To diagnose the state of the OF and evaluate the nature of external impacts, we must measure the value of the Brillouin frequency displacement along the light-guide. To estimate the physical state of the OF and types of external impacts based on measuring the displacement of the light signal carrier frequency, we should include in the technical control tools a spectrum analyzer.

Regardless of the method of analysis of optical radiation, we can perform monitoring both in relation to the OF, that transmits information directly, and the optical sensor (a special OF) combined in protective elements. For the latter, the cable consists of special OFs which have increased sensitivity to external impacts. These are used for transmitting control signals, increasing the technology cost and reliability [9, 12].

After fixing the change in the FOLC state, data from the SDS is transferred to the analysis module. This module is responsible for data processing and accumulation. Changing the value of a controlled parameter is a condition to carry out an analysis and make a decision about the reasons of its occurrence. Appropriate commands are given on the basis of the identified reasons (e.g. stop transmitting data and send an alarm).

The system for detecting channels of the information leakage should solve the monitoring problems of the monitoring of the FOLC in real time, and the data transmission in this case not interrupt at the time of diagnosis.

It functions in cyclic automatic or semi-automatic (at the command of operators) mode [1 – 3].

5. Experimental results

Experimental tests to assess the level of losses on macro-bends of a single-mode optical fiber were conducted at the Siberian State University of Telecommunications and Informatics. They were carried out using single-mode patch-cords, optical radiation sources “Photom 352, 353” (Japan) and a power meter “Photom 211” (Japan), as well as rods for creating turns.

The results are shown in Fig. 1 and Fig. 2.

From the results of the experimental dependence analysis, it follows that the losses on the macrobends of the optical fiber progress with increasing wavelength and decreasing bending radius.
Figure 1. Losses with a bend diameter of 12 mm  Figure 2. Losses with a bend diameter of 7 mm

Experimental verification of the effectiveness of detecting unauthorized connection of the proposed pulse-reflectometric method was carried out using the “AQ7918B” optical reflectometer. The results are shown in Fig. 3. (“1” – bending of the OF; “2” – microcrack in the OF.)

Figure 3. Reflectogram of the optical fiber with a bend and a microcrack

To make sure that point “1” is a bend in the OF, and not a normal welded joint, we need to change the carrier wavelength. If the insertion loss increases with increasing wavelength, then it can be unambiguously stated that there is a bend at point “1”. There is no such dependency on a welded joint.
6. Conclusions
As a recent trend, a neural network-based analysis system is proposed in order to detect unauthorized connections more accurately.

The computer network summarizes and processes the data, obtained by different methods of diagnostics, analyzes, identifies and output summary data on the reasons of changes in the state of the FOLC and possible attacks on the protected network. So we can enhance the system’s efficiency by careful and deep analysis and reduce the probability of false responses [10, 12].

The analysis results of different methods of unauthorized access to the OF may be used in the project development and technical exploitation of the optical access networks. Researches of the increase in losses of information signals and the radiated power level can serve as the basis of the forming of algorithms for detecting unauthorized access in optical networks.

The intensity of the signal radiation through the side surface of the OF depends on the output coefficient. The dependence of the power level radiated through the side surface of the OF makes it possible to assess the requirements for the sensitivity of the optical receiver used for data acquisition, and take measures to timely detect possible channels of information leakage.

Most informative is the OF state diagnostics system based on pulse reflectometry [11, 12].

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