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Digital restoration of signals in fiber optic transmission systems

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ABSTRACT

The high-performance methods of multi-stage digital processing of linear signals of fiber optic transmission systems in the spectral and time domain with the use of Fourier transform methods are proposed. Based on the proposed methods of signal processing, a digital device for restoring of linear signals in fiber-optic transmission systems is developed. The advantage of the device is high performance, which enables digital processing of linear signals in the spectral region without loss of information.

Keywords: fiber-optic transmission system, signal recovery device, spectral analysis, productivity, FFT, linear signals

1. INTRODUCTION

The development of communication technology is due to the growing demand for information exchange and advances in scientific and technological progress. The main role in this development belongs to optical communication means, which are based on fiber-optic communication lines (FOCL) and fiber-optic transmission systems (FOTS). The most important feature of the transmission of signals in FOTS is the possibility of linear signals (LS) restoring after their passage through the FOCL. In this case, there are specific problems associated with the peculiarities of the transmission of LS by the FOTS paths.

In the conditions of the modern development of digital telecommunication facilities, the problem of linear signals restoring in FOTS becomes of special urgency, because as a result of the introduction of new transmission methods that involve higher data transmission speeds, the distortion of the LS causes the appearance of bit errors, as well as uncontrolled slippage and synchronization violations. This, in turn, leads to a significant decrease in the stability of the functioning of telecommunication facilities, the deterioration of the quality of communication, and sometimes loss of communication[1]. Therefore, in the development and operation of telecommunication facilities, one of the most important quality indicators is the efficiency of linear signals restoring in FOTS.

In order to ensure the appropriate quality of the communication signals, the memory and playback of the LSon the output of each network interface, as well as each digital equipment or digital section of the FOTS, are performed.

Memory and restore devices LS are an integral part of the signals processing means in FOTS[2]. They are intended to memorize the frequency-time structure of the received LS, the issuance of data in the analysis means of these signals and the restoration at given time intervals of the processed LS[3].

Significant achievements in microelectronics and microprocessors have led to the creation of a fundamentally new class of devices for primary processing of LS - digital linear signal restoration devices (DLSRD). Such devices have significantly expanded the functionality of FOTS and improved the performance of their functioning[4].

2. STATE OF ART

The development of restoration means of linear signals in FOTS at the present stage is mainly due to the full use of the potential of evaluation parameters methods of the LS in the time domain by means of computer and microprocessor technology, as well as due to increased possibilities of hardware and software. However, known approaches do not

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provide significant and simultaneous improvement of the main functional indicators of linear signal recovery devices in FOTS, first of all, the productivity of their work. Consequently, there is an important scientific task, which is meant to increase the productivity of linear signal recovery devices in FOTS. Taking into account the general trends in the development of the telecommunication industry, it should be noted that the solution of this problem is relevant for the present time[5].

At the same time, it should be noted that a qualitative leap in improving the efficiency of linear signals regeneration in FOTS can be only provided by the application of new methods of LS processing and transforming, new methods of LS processing ways and new methods of DLSRD constructing[6].

The actual performance of the DLSRD does not reach its potential theoretical capabilities due to the low performance of digital signal processing (DSP) processes. Discrete Fourier Transform (DFT) procedures are widely used in DSPs in the spectral region. A number of methods for rapid calculation of the DFT are proposed, which allow to reduce the amount of computations compared with the direct execution of the DFT[6,7,8]. Such methods are associated with the implementation of fast Fourier transform algorithms (FFTs). But, as research has shown, there is a reserve for improving DSP performance in the DLSRD[9,10].

The given argument confirms the timeliness and urgency of the set scientific and practical task, the solution of which requires the creation of theoretical principles and practical provisions for the construction of the restoration means of linear signals in FOTS, the development of the processing and transformation methods of LS in the time and frequency domain, which are based on the theory of DSP.

Judging by the recent publications[7,8,9], despite the rich pre-history of DSP methods in the primary processing means of linear signals, the development of certain aspects of LS digital processing continues today and cannot be considered completed.

3. RESEARCH OBJECTIVES AND TASKS

The purpose of the work is the productivity increase of digital devices for the linear signals restoration in fiber-optic transmission systems by reducing the computational complexity of procedures for multi-stage digital signal processing.

The objectives of the study are the following:

- the choice and justification of memory and restoration methods of linear signals;
- the development of a high-performance mode of the output signal transferring of an analog-to-digital converter into a spectral region;
- the development of a high-performance mode of the linear signal transferring from the frequency to the time domain;
- the structure development of the DLSRD;
- the productivity analysis of the proposed DLSRD.

4. THE CHOICE AND JUSTIFICATION OF THE MEMORY AND RESTORATION METHOD OF LINEAR SIGNALS

Three main memory and restoration methods of LS are used in modern digital means of primary processing of linear signals. The first method is based on memorizing of the sequence of time-discretized and quantized by the level of instantaneous values of linear signals. The digital equivalent of LS is memorized, and then reproduced using a digital-to-analog converter (DAC)[3]. This method is characterized by narrow functional capabilities and low productivity of LS processing[10,11,12].

The second method is the amplitude-phase, which involves digital amplitude and phase representationof the LS. The memorization of the amplitude and phase reading is carried out in the operational storage device (RAM). An analogue copy of the signal is reproduced by amplitude and phase modulation of the high-frequency carrier signal of a highly stable heterodyne. The laws of amplitude and phase modulation are formed in accordance with the digital codes of amplitude and phase, calculated from the RAM[5]. Such a method has a number of disadvantages, namely: high hardware costs, low accuracy of the LS restoration and low performance of the LS reproduction devices.

The third spectral method is based on the representation of a linear signal $x(t)$ in the form of a spectral image $S(\omega)$ with the following digital processing. In this case, various FFT algorithms are used. In contrast to the two previous methods, the spectral method involves recording in the RAM of digital reference samples of the linear signal spectrum $S(k)$, and the restoration of analog LS is done with the help of an inverse DFT (IDFT)[10]. Thus, according to the spectral method of DSP in the DLSRD is carried out mainly in the frequency domain.

The advantages of spectral digital processing of linear signals are the possibility of rapid analysis of the LS spectra, the unlimited possibilities of digital signals synthesis through the procedures of rapid digital collapse, a significant reduction in the volume of computations in digital filtration. Therefore, in the work, a spectral method of the LS processing in the construction of the DLSRD will be applied[13-16].

The generalized structure of the processes of transformation and processing of linear signals in the DLSRD on the basis of the spectral method is presented in Fig. 1

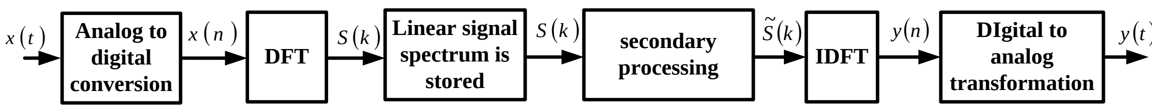

Fig.1 The structure of the processes of transformation and processing of linear signals in the DLSRD

Input linear signal $x(t)$ is the subject to analog-digital conversion into digital form $x(n)$. Further, using DFT methods, the signal $x(n)$ is transmitted from the time domain to the frequency domain $S(k)$. The formed signal counts in the frequency domain $S(k)$ are remembered in the RAM. In the next step, the secondary processing of the signal in the frequency domain is performed, for example, digital filtering, digital coil. Next, the signal is transmitted from the spectral to the time domain $y(n)$ using IDFT methods and, finally, the digital-to-analog transformation into a continuous form $y(t)$.

5. A HIGH-PERFORMANCE WAY OF THE OUTPUT SIGNAL TRANSFERRING OF THE ADC TO THE SPECTRAL REGION

The process of a digital signal transferring from the time domain to the frequency region takes the longest period of time when processing linear signals in DLSRD. Therefore, increasing the productivity of this process is an important stage in the development of DLSRD. The DFT and fast algorithms of its calculation assume that the input sequence is complex. But a valid digital signal is formed on the output of the analog-to-digital converter (ADC). The use of a valid FFT signal method leads, on the one hand, to excessive computing costs, and on the other hand, to an excess of RAM.

A number of FFT algorithms for actual sequences[5, 6, 8] have been developed, but they are characterized by irregularity of the structure and low values of the productivity coefficient. Therefore, it is necessary to develop a method for rapid transfer of the signal to the spectral region, which is specially adapted for the case of a real LS from the output of the ADC.

The sequence $x(n)$ in the form of two subsequences can be presented: $x_1(n)$ and $x_2(n)$. Each of these subsequences has the length of $0,5\cdot N$. These subsequences are formed from even and odd reference samples of the output signal of the ADC:

$$\begin{aligned} x_1(n) &= x(2n); \\ x_2(n) &= x(2n+1), \end{aligned} \tag{1}$$

where $n = 0,1,...,0,5\cdot N-1$.

Then the DFT of the output signal of the ADC $x(n)$ in the volume of N readings, can be written as follows:

$$S(k)=\sum_{n=0}^{0,5\cdot N-1} x(2n)\cdot e^{-j\frac{2\pi}{N}\cdot 2\cdot nk}+\sum_{n=0}^{0,5\cdot N-1} x(2n+1)\cdot e^{-j\frac{2\pi}{N}\cdot(2n-1)k}. \quad (2)$$

Taking into account (1) for even and odd counts, the expression (2) will look like this

$$S(k)=\sum_{n=0}^{0,5\cdot N-1} x_1(n)\cdot e^{-j\frac{2\pi}{0,5\cdot N}\cdot nk}+\left[\sum_{n=0}^{0,5\cdot N-1} x_2(n)\cdot e^{-j\frac{2\pi}{0,5\cdot N}\cdot nk}\right]\cdot e^{-j\frac{2\pi}{N}\cdot k}. \quad (3)$$

Thus, the time domain the signal restoration using IDFF and the direct FFT technique is carried out in three stages. At the first stage, the formation of a complex $S(k)$ conjugate sequence $S^*(k)$ is carried out. The second stage $x^*(n)$ is determined by means of FFT taking into account the multiplier $1/N$. At the last stage, the initial sequence of a linear signal $x(n)$ in the time domain from a complex-conjugated sequence $x^*(n)$ is formed.

6. THE STRUCTURE OF THE DLSRD

In recent years, some methods of constructing means of the linear signals restoration in FOTS, based on the use of both specialized analyzers and universal means, are developing intensively. In practical research of LS, analog, digital and hybrid hardware is applied. At the same time, the choice of the implementation principle is due to the specifics of the analyzed parameters of LS, the requirements for accuracy and resolution, the possibility of reconciling the equipment with the investigated telecommunication facilities and applied computer technology.

One of the main requirements that arise when solving the tasks of the linear signals restoration in FOTS is to ensure the rapid processing of LS. This processing mode allows to analyze the clock signals with the frequency of their income from the telecommunication means under study. The processing efficiency provides the mode of LS analysis, in which the evaluation of the LS parameters are obtained during the experiment without loss of information. Specialized devices function in real time and approach the analog devices of linear signal restoration in the FOTS, but at the same time maintain the accuracy of the processing inherent in the digital representation of information. Such devices are not universal LS analyzers, but these devices are characterized by high efficiency of signal processing, in which a large amount of similar computations must be performed.

When implementing the method of spectral evaluation of LS, the main underlying operations are FFT and convolution of the sequences. Various methods of hardware construction can be used for their execution. At the same time different variants of the core structure realization of the DLSRD are possible. The speed of the DSP modules in the frequency and time representation depends on the number of input signals, the duration of the summation and multiplication operations, the cycles of write-to-read RAM. But the main weight in the calculations of FFT and convolution belongs to multiplication operations in the time and frequency representation of linear signals. This important circumstance should be taken into account, since the multiplication operation in digital devices belongs to the "long" class.

The most optimal DLSRD operation mode is conditionally real. That is, analog-to-digital conversion and determination of the LS spectrum is carried out in real time without loss of information. And further secondary processing is carried out at a speed determined by the element base of the device. The block diagram of the DLSRD is presented in Fig. 2

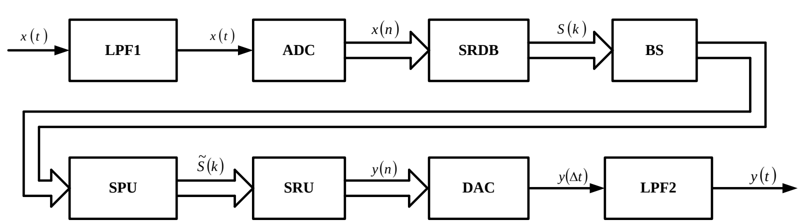

Fig. 2 The block diagram of the DLSRD

The linear signal $x(t)$ through the low pass filter (LPF1), which eliminates the effect of the spectra overlaying, is sent to the ADC input. From the ADC output, the digital equivalent of the signal $x(n)$ arrives at the spectrum rapid definition block (SRDB), in which the spectral readings of the LS $S(k)$ are formed. These readings are stored in a buffer storage

(BS). Further processing of the signal in the frequency domain is carried out in the secondary processing unit (SPU). From the SPU output, the spectral readings $\tilde{S}(k)$ are sent to the input of the signal restoration unit (SRU), where it is transformed into a time domain. The DAC transforms the digital signal $y(n)$ into an amplitude-pulse-modulated (APM) signal $y(\Delta t)$. On the output of the LPF2, which performs the functions of the APM demodulator, a reconstructed linear signal $y(t)$ is formed.

7. PERFORMANCE ANALYSIS

The efficiency criterion for the proposed DLSRD is the performance, which is conveniently estimated by the number of multiplication operations. The generalization of this criterion is the productivity coefficient, which demonstrates the gain in the number of required "long" multiplication operations in the application of the proposed methods of LS processing in relation to the processing methods of based on the traditional methods of FFT and IDFF[11]:

$$G_S = \frac{C_{FFT}}{C_{DSA}}, \tag{4}$$

where C_{FFT} – number of "long" multiplication operations with direct LS spectrum analysis on the basis of FFT; C_{DSA} – number of multiplication operations when applying the proposed methods.

Spectral analysis of LS based on the direct execution of FFT requires $0,5 \cdot N \cdot \log_2 N$ multiplication operations, and for the restoration of the signal in the time domain based on the classical IDFF fast algorithm requires $2 \cdot N \cdot \log_2 N$ multiplications[7]. For the implementation of these procedures for the LS processing in accordance with the methods proposed in the work, it is necessary to perform $0,25 \cdot N \cdot \log_2 (0,5 \cdot N) + N$ multiplication operations for spectral analysis and $N \cdot \log_2 N$ multiplication operations to restore the LS in the time domain. Then the productivity coefficient of the DLSRD is:

$$G_S = \frac{2,5 \cdot N \cdot \log_2 N}{0,25 \cdot N \cdot \log_2 (0,5 \cdot N) + N + N \cdot \log_2 N}. \tag{5}$$

Charts of the dependence of the productivity factor on the volume of the analyzed sample of the LS are presented in Fig. 3. The upper curve shows the dependence of the productivity factor on the sample volume for the proposed method of transferring the output signal of the analog-to-digital converter to the spectral region. The lower curve characterizes the process of through-wave transformation of signals from time domain to frequency one, from frequency domain to time one. As can be seen from the graphs, the productivity of the DLSRD, which operates on the basis of the proposed methods of the LS processing, improves with the increase of the sample volume and equals 1.45 ÷ 1.95.

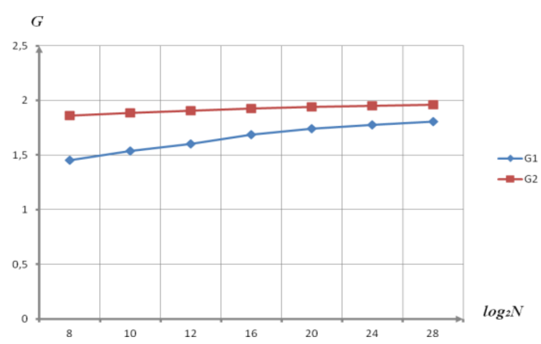

Fig. 3 Dependence of the productivity factor of the DLSRD on the sample volume of the LS

Thus, the proposed methods of transferring the LS from the time domain to the frequency domain and vice versa, based on multi-stage digital processing of the array of samples of the investigated linear signal, enable to significantly reduce the time to determine the spectral and temporal components of the signal and to provide the functioning mode of the DLSRD in the conditionally real time scale.

8. CONCLUSIONS

The research presents high-performance methods for digital spectral analysis of linear signals of fiber-optic transmission systems and inverse transmission of linear signals in the time domain, which are based on procedures for multistage digital processing of the sample matrix of the linear signals under study. The analysis of the efficiency of the proposed methods confirmed that, thanks to the developed methods, it is possible to increase the productivity of equipment for digital reconstruction of linear signals in 1.45 to 1.95 times, depending on the volume of the analyzed sample of the linear signal. The maximum increase in productivity is obtained for the volume of the analyzed sample of the linear signal equal to 2^{28}. A structure of devices for digital reconstruction of the linear signal that operates on a conditionally real scale without loss of information has been developed. The proposed device can be used in regenerative devices of fiber-optic transmission systems.

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