From the revolution to the evolution: the change in the character of development of fiber optic communications technology

And the record performance of 100 Gbit/s systems as a marker of this change

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***Abstract*—The performance of fiber optic communication systems reached its maximum several years ago with the introduction of 100 Gbit/s systems (100G). The further development of communication systems is going in such directions as complicating the formats of modulation, increasing the flexibility of tuning the occupied spectrum and increasing the speed of transmission over the carrier. This is advantageous for short lines, but leads to a significant reduction in transmission range and performance. Thus, the record performance of the 100G systems can be considered a marker for the transition from the revolutionary stage of the development of fiber-optic communication technologies to the evolutionary stage of their development.**

Keywords—100G; DWDM; fiber optic communications; performance; spectral efficiency; transmission reach

I. INTRODUCTION

The rapid development of technology fascinates the observer. Rate of data transmission over single optical carrier in commercial DWDM systems reached 10 Gbit/s in 1995, 40 Gbit/s in 2002 [1], 100 Gbit/s in 2010 [2], and 200 Gbit/s in 2015. DWDM systems with optical carrier data rates up to 600 Gbit/s are on the way; their soon introduction is shown in roadmaps of main vendors. Laboratory experiments go even further up to 1.2 Tbit/s per single carrier [3]. There is a feeling of continuous development (and even exponential, in the opinion of optimists), which is supported by a common stable opinion about the constant technical progress of mankind.

We do not want to upset the optimists. But historians of science and technology are well aware that any technology goes through a number of stages in its development, and after the revolutionary leap of technical characteristics, a stage of the evolutionary process comes that is aimed at increasing economic returns. The marker of this transition is the achievement of limiting characteristics by basic indicators.

In the aviation, for example, the period of rapid development of aerodynamic schemes ended in the 1970s. Then the industry focused on on-board electronics (avionics), increasing passenger comfort and improving economic performance, as well as solving related problems (for example, reducing the visibility for radars). But the basic parameters of the airplane as a flying object that is heavier than air – i.e. maximum speed, flight range, specific load on the wing, specific load on power – have almost not changed for 40 years.

Thus, in order to adequately analyze and evaluate the development of fiber-optic communication technologies, it is necessary to define a basic indicator that enables correct comparison of communication systems among themselves.

II. COMPARISON OF TECHNOLOGIES

A. *Choosing the basic indicator*

What is a basic indicator of a fiber optic communication line? Technically, the task of a communication system is to transmit in the optical fiber the maximum data stream to the maximum distance with a minimum use of the spectral resource (range). If we introduce the concept of spectral efficiency (SE), that is the transfer rate of useful data divided by the spectral range used, the basic criterion for estimating the degree of development of a fiber optic communication system can be expressed as SE * L, where L is the transmission range. The product SE * L is known as the performance of a communication system.

Thus, in order to compare communication systems, we need to compare their performances [4].

The spectral efficiency (SE) of communication equipment is usually known or easily calculated. The main difficulty in comparing the performance of various fiber optic communication technologies is the calculation of the maximal transmission distance (L) that a particular communication system can provide.

B. *Calculation of L (transmission range)*

The "transmission range" in backbone DWDM systems means the maximal transmission distance in the multi-span line based on amplifiers (i.e. without the signal regeneration in intermediate points). The more this range, the less often it is necessary to put the receiving-transmitting equipment (transponders) on the line; consequently, the cost of the solution is lower.

The transmission range of the multi-span fiber optic communication line depends on many characteristics. They includes (but not limited to) the following parameters: the lengths of the spans; attenuation in the fiber; noise factor of amplifiers; nonlinear coefficients (that are expressing the influence of nonlinear effects on signal propagation); input optical powers in each span; number and type of transmitted channels; the used frequency plan and guard intervals; required operating margin for OSNR (optical signal to noise ratio); threshold sensitivity of the transponder OSNR_T (the minimum signal-to-noise ratio

978-1-5386-3537-7/17 $31.00 © 2017 IEEE
DOI 10.1109/EnT.2017.17

at the receiver input that is required to receive a signal in a short line without nonlinear effects).

The values of the input powers in the line can be chosen differently depending on the line optimization method used (minimization of BER, maximization of the OSNR margin, etc.). The optimization methods for systems with coherent signal detection differ from the methods used in systems with direct detection [5].

To compare different technologies, all experimental or calculated ranges should be brought to a single set of input parameters (line characteristics). Table 1 shows a set of parameters that we used to compare different fiber optic transmission technologies (the length of all spans of the multi-span line was assumed to be the same; the transmission of one channel was investigated).

TABLE I. PARAMETERS USED FOR THE COMPARISON

Description	Symbol	Value
Length of the span	L	100 km
Attenuation in the fiber	A	0.18 dB/km
Noise factor	NF	5,5 dB
Nonlinear coefficient[a]	H	$12*10^{-5}$ mW^{-2}
Margin for the exploitation	_	0 dB

a. For systems 100G and higher with coherent detection

An optimization of multi-span coherent communication lines were based on the BER minimization method, that coincides with the OSNR margin maximization method for the maximal achievable line length [5]. An optimization of multi-span incoherent communication lines was based on empiric rule stating that the sum of input optical powers in all spans should not exceed 30 mW.

C. *Results of comparison*

Several types of fiber optic communication systems were compared with data rates over single carrier from 2.5 Gbit/s to 400 Gbit/s. Spectral efficiency (SE) of communication systems is constantly growing, that is often considered as an indicator of constant development of fiber optic communication technologies. So the SE was chosen as a parameter of the horizontal axis. Results of the comparison are shown on Fig. 1.

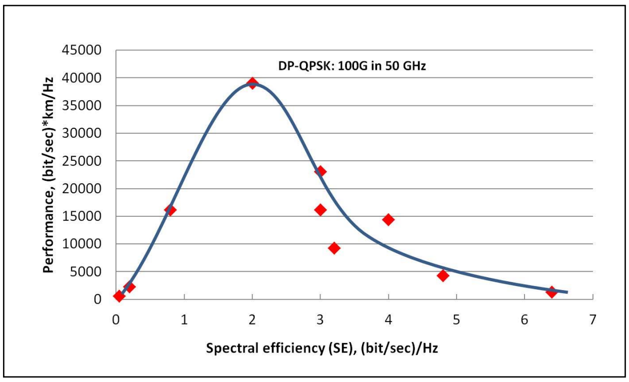

Figure 1. Dependence of the performance of fiber optic communication systems on their spectral efficiency.

III. DISCUSSION

The analysis shows that DP-QPSK technology with a signal transmission rate of 100 Gbit/s in the 50 GHz band may have become a turning point in the development of backbone fiber-optic links. Prior to its appearance, the data rate in fiber optic communication lines increased with the preservation of the occupied spectral bandwidth (2.5 Gbit/s, 10 Gbit/s, 40 Gbit/s, 100 Gbit/s – all in the 50 GHz grid) and with the preservation of the transmission range. Accordingly, the performance of the fiber optic communication systems also constantly increased. The transmission range was kept high with the help of various technical methods – primarily through the use of additional degrees of freedom of light radiation and the development of error correction technologies. At the transition from 2.5 Gbit/s to 10 Gbit/s, the transmission range was retained due to the use of the forward error correction (FEC); at the transition from 10 Gbit/s to 40 Gbit/s – due to the use of phase modulation DPSK and SuperFEC; at the transition from 40 Gbit/s to 100 Gbit/s – due to coherent detection, use of two polarizations (DP-QPSK modulation format) and soft-decision FEC (Soft FEC).

As a result, telecom operators became to perceive the growth in the performance of communication systems as a natural process. When making a decision on the transition to a new generation of fiber optic communication systems, they get used to consider the cost of implementing the same capacity by different type of equipment as the main criterion. Systems 10 Gbit/s began to replace 2.5 Gbit/s when the cost of the transponder 10 Gbit/s became approximately equal to the cost of four transponders 2.5 Gbit/s (with the same transmission distance due to FEC). 100 Gbit/s systems became massively introduced by operators when the cost of the 100 Gbit/s transponder became approximately equal to the cost of ten 10 Gbit/s transponders (with the same transmission distance due to coherent reception and Soft FEC). However, with the advent of 100G systems, trends have changed – and the habit of comparing only the capacity of systems today can lead to a distorted evaluation of the characteristics of new high-speed systems.

100 Gbit/s systems with coherent detection probably reached the limiting efficiency of using independent parameters of light radiation (phase and polarization). Also, the appearance of the 100 Gbit/s systems was probably coincided with the cease of the fast increase of symbol rate. 32-45 Gbod is a standard level for the existing element base, 64 Gbod systems are still on development. The speed of the electronics will probably slowly increase with the further improvement of technology, but it will hardly be an explosive development as before.

The further development of fiber-optic communication systems, as can be seen from the trends of 2014-2017, will be based on the use of complex modulation formats (DP-16QAM, DP-64QAM, etc.). These formats enable significant increase of the spectral efficiency and, accordingly, the data transmission capacity in the operator's usual spectral bandwidth (it is the reason for the "record" headlines of articles and press releases). However, the complication of the modulation format inevitably leads to a significant drop in the data transmission range. The performance also decreases noticeably, as seen from Fig. 1.

IV. CONCLUSION

Thus, it can be assumed that there has been a transition in the development of equipment for fiber optic communication systems from a revolutionary to an evolutionary development. The achievement of maximal performance in the 100 Gbit/s systems was a mark of this transition. It seems that telecommunications operators will now have to revise their usual economic criteria for comparing fiber optic communication systems. Comparison of capacity alone is no longer capable of answering the question of the cost-effectiveness of implementing a particular technology, since increasing the capacity can now be associated with a significant reduction in the transmission range (and the need for additional intermediate signal regeneration points). In particular, even under the condition of equal cost (for the same capacity), it is unprofitable for a communication operator to use complex modulation formats on long communication lines, since for transmitting the same amount of data at the same distance, these formats will require more signal regeneration points than for 100 Gbit/s DP-QPSK.

There is practically no doubt that the 100G technology will remain the main "workhorse" of backbone fiber optic communication lines in the foreseeable future due to its record performance and, accordingly, maximum economic efficiency for long lines. At the same time, new technologies with "high" modulation formats give noticeable gains for short lines, where, with the same spectral band, they can achieve a much higher speed. The record performance of 100 Gbit/s systems is not used on short lines, and therefore is not an important factor for the operator when choosing a solution. The basic parameter for short lines, in fact, is the spectral efficiency (SE) itself: the more SE is better. Therefore, in metro networks, we can expect the rapid introduction of 200 Gbit/s and 400 Gbit/s systems, which are now commercially available from several manufacturers.

The increase in speed at short distances will continue in the regions of the United States, Europe, China, Japan and other countries with a dense location of large cities, where the need for an increase in the speed of short lines is very high. Undoubtedly, network management systems will also develop. For example, today the FlexGrid concept is actively implemented – i.e. flexible control of the occupied spectral bandwidth and transmission speed by variation of the signal modulation format through the control system. The option is also possible that the cost of systems with high modulation formats will drop with time so significantly that their use will be more profitable than the application of "long-range" 100 Gbit/s systems even on long communication lines.

However, our analysis shows that the 100 Gbit/s systems with the DP-QPSK modulation format represent the top of development of fiber optic backbone technologies by the basic technical parameter – performance. And this peak was reached several years ago.

Well, "Concord" also once made its last flight across the Atlantic ... Modern passenger airliners are not as fast as supersonic record-holders of the past – but it turned out that this is not the main thing for their users.

ACKNOWLEDGMENT

We are thankful to our colleagues from the T8 company (Dr. Prof. Oleg Nanii, Dr. Vladimir Treshchikov and Dr. Rustam Ubaydullayev) for their useful comments, and also to Dr. Yury Kuzmin from the S. I. Vavilov Institute for the History of Science and Technology of the Russian Academy of Sciences for his valuable consultations about the history of aviation.

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