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SPECTRAL AND ENERGY EFFICIENCY OF TRANSMISSION IN WDM OPTICAL NETWORKS

Summary of the Doctoral Thesis

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DOCTORAL THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF ENGINEERING SCIENCES (TELECOMMUNICATIONS) TO BE DEFENDED AT RIGA TECHNICAL UNIVERSITY

To be granted the scientific degree of Doctor of Engineering Sciences (telecommunications), the present Doctoral Thesis is to be defended publicly on 4 June 2015 — 4 p.m., at the Faculty of Electronics and Telecommunications, Riga Technical University, Azenes Str. 16/20, Room 215, Riga, Latvia.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences, is my own and does not contain any unacknowledged material from any source. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Aleksejs Udalcovs …………………………….

Date:

The Doctoral Thesis has been written in the Latvian language. It contains the introduction, 4 main chapters, conclusions, bibliography with 160 reference sources, 6 appendices. It has been illustrated by 81 figures and 18 tables. The volume of the Doctoral Thesis is 188 pages.

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LIST OF ABBREVIATIONS

2-POLSK	*Binary Orthogonal Polarization-Shift Keying*
3R	*Re-timing, Re-shaping, and Re-amplification (type of optical regenerators)*

A

ASE	*Amplified Spontaneous Emission*
AWG	*Arbitrary Waveform Generator*
AWG	*Arrayed Waveguide Grating*

B

B2B	*Back-to-Back*
BER	*Bit-Error Rate*

C

CD	*Chromatic Dispersion*
CW	*Continuous Wave*
CWDM	*Coarse (WDM)*

D

DCF	*Dispersion Compensating Fiber*
DCM	*Dispersion Compensation Module*
DFB (laser)	*Distributed Feedback (laser)*
DP-QPSK	*Dual Polarization QPSK*
DPSK	*Differential Phase-Shift Keying*
DQPSK	*Differential Quadrature PSK*
DSO	*Digital Storage Oscilloscope*
DSP	*Digital Signal Processing*
DSP	*Digital Signal Processor*
DWDM	*Dense (WDM)*

E

ECL	*External Cavity Laser*
EDFA	*Erbium Doped Fiber Amplifier*

F

FBG	*Fiber Bragg Grating*
FEC	*Forward Error Correction*
FOTS	*Fiber Optic Transmission System*
FWM	*Four-Wave Mixing*

G

GHG	*Greenhouse Gas*

H

HFLW	*High Frequency Linewidth*

I

IP	*Internet Protocol*
ITU	*International Telecommunication Union*

L

LO (laser)	*Local Oscillator (laser)*

M

MLR	*Mixed Line Rate*
MZI	*Mach-Zehnder Interferometer*
MZM	*Mach-Zehnder Modulator*

N

NRZ-OOK	*Non-Return-to-Zero On-Off Keying*

O

OLA	*Optical Line Amplifier*
OSNR	*Optical Signal to Noise Ratio*
OXC	*Optical Cross-Connect*

P

P2P	*Point-to-Point*
PIN (photodiode)	*Positive-Intrinsic-Negative (photodiode)*

Q

QoT	*Quality of Transmission*
QPSK	*Quadrature Phase-Shift Keying*

R

RZ	*Return-to-Zero*

S

SI	*Swedish Institute*
SLR	*Single-Line Rate*
SP	*Single Polarization*
SSMF	*Standard Single Mode Fiber*

T

TSP	*Transponder*

W

WDM	*Wavelength Division Multiplexing*

X

XPM	*Cross-Phase Modulation*

GENERAL DESCRIPTION OF THE THESIS

Topicality of the Subject Matter

Under the conditions of continuously growing and heterogeneous IP (Internet Protocol) traffic demands, operators of backbone optical networks should ensure a definite quality of service and its accessibility [7, 8]. To achieve this goal, it is necessary to find a compromise between the infrastructure development and the maintenance and operation costs, taking also into account possible impact on the environment (ecology) [26, 31, 32].

In the last ten years, in order to satisfy the demand for the data transmission amounts the frequency bandwidth used in fiber optic transmission systems (FOTSs) has been steadily growing. Every two years these bandwidths are at least doubled [33]. Therefore, the aggregated traffic transmitted via FOTS is increased by both at the cost of number of wavelengths (channels) and through the increase of data rate in them. As a result, it is observed that, for example, 10 Gbps channels are replaced by 40 Gbps or even by 100 Gbps ones [2, 10, 12, 29]. However, this can be considered a short-term solution [17], since a frequency band where wavelength channels could be placed even in the silica optical fibers is not infinite. It is limited either by the gain spectrum bandwidth of optical line amplifiers (OLAs) or by the operational range of dispersion compensation modules (DCMs) [3, 6]. In the backbone optical networks, this bandwidth is usually limited by the gain spectrum bandwidth of erbium doped fiber amplifiers (EDFAs), i. e., 1530–1565 nm or the conventional band (C-band) [12, 15]. Therefore, over the last five years the solutions have been investigated that allow increasing the total capacity of information transmitted per Hertz (Hz) of the frequency bandwidth, i. e., increasing the ***spectral efficiency (bps/Hz)*** [4, 10, 18, 27].

Increase in the spectral efficiency imposes requirements on the quality of the signal at the receiving node [10, 11]. In turn, the exacerbation of the linear and nonlinear optical effects results in a smaller distance by which these signals can be detected with a definite bit-error-rate (BER), i. e., ***transparent reach*** [5, 21, 23, 35]. Although optical signals can be regenerated in the optical domain but considering the dimensions of core networks it would be still necessary to use regenerators based on opto-electrical and electro-optical conversions, i. e., so-called 3R (Re-timing, Re-shaping, and Re-amplification) regenerators. This is directly related not only to large transmission distances (link lengths) but also to the spectral efficiency, modulation formats, routing algorithms, network topology, traffic matrices and traffic nature itself [34, 36, 37]. Therefore, for regeneration of optical signals in commercially used transport optical networks just 3R regenerators based on OEO conversion are mostly used, while all-optical regenerators are employed noticeably less. This can be explained by their complexity and quite recent commercial accessibility.

Due to smaller transparent reach, the spacing between two 3R regenerators is also reduced. This leads to their larger number in order to ensure the required signal quality at the receiving node if the length of fiber-optical link (FOL) remains the same. In turn, the use of extra infrastructure components (e. g., 3Rs and OLAs) leads to greater power consumption for transmitting 1 bit/s of aggregated traffic, i. e., ***lower energy efficiency (J/bit).*** As a result, in transport optical networks based on wavelength division multiplexing (WDM) the following trade-off exists between *(i)* spectral efficiency, *(ii)* length of fiber-optical link, and *(iii)* energy efficiency of transmission at the given requirements for the signal quality at the receiving node. Therefore, the mutual influence of these parameters needs to be investigated.

The Aim and Tasks of the Thesis

In the light of the above-mentioned facts, the **aim** set for the Doctoral Thesis **is to estimate analytically and experimentally the influence of spectral efficiency on the**

energy consumption required for the transmission of 1 bit in wavelength division multiplexing based optical transport systems.

To achieve the set aim, the following **main tasks** have been put forward:

1. To find out solutions that are used for transmitting ever-increasing data amounts between two backbone optical network nodes and to set off the main factors that limit the system reach and spectral efficiency of transmission.
2. To derive the power consumption models for evaluating the influence of modulation formats on the power consumption of transponders and 3R regenerators employed in the backbone optical networks in cases of 10 Gbps, 40 Gbps and 100 Gbps data transmission rates.
3. To estimate the power consumption values for the components of FOTS infrastructure and to compare the power consumption values of transponders and 3R regenerators obtained using derived power consumption models with such values from the scientific literature or manufacturers' specifications.
4. To determine experimentally the influence exerted by the parameters of radiation (such as the linewidth and the frequency noise spectrum) from a laser source contained in the most energy-efficient transponder (100 Gbps DP-QPSK) on the received signal quality in the coherent communication systems.
5. To determine the minimum allowable channel spacing and the sub-band spacing, which ensure detection of NRZ-OOK, NRZ-DPSK and DP-QPSK modulated signals with a definite BER value in the WDM FOTS with 10 Gbps, 40 Gbps and 100 Gbps data transmission rates, and to derive the analytical transmission models.
6. To analyze the influence of spectral efficiency on the transmission energy efficiency in single line rate (SLR) and mixed line rate (MLR) WDM systems depending on: *(i)* the distance between two optical line amplifiers, *(ii)* the maximum allowable transmission distance without 3R regeneration (system reach), and *(iii)* the overall transmission distance between two backbone optical network nodes.

The Methodology of Research

For fulfilment of the tasks set in the Doctoral Thesis and for analysis of the problems, mathematical calculations, numerical simulations and experimental measurements have been used. The values of power consumption by transponders and 3R regenerators as well as the system reach of modulation formats have been estimated using the derived power consumption models and analytical transmission models. Apart from the estimation of the influence exerted by linear crosstalk from the channels, several measuring methods have been employed, which comprise both numerical simulations and experimental measurements. In the numerical simulations, the non-linear Schrodinger equation is used that is solved in the time domain using the split-step Fourier method. The measurements of frequency noises from the laser source have been taken using two methods: *(i)* interferometric, and *(ii)* mixing of radiation from two lasers — the laser under test and the Local Oscillator (LO) laser. For the optical signal quality estimation, the measurements of power spectra, eye diagrams, IQ diagrams and BER values have been taken.

The Main Results of the Doctoral Thesis

The **scientific novelty** of the Doctoral Thesis is as follows.

1. An improved fixed DWDM grating has been worked out for central frequency separation of the transmission channels, which allows increasing the spectral efficiency of the frequency band used for transmission.

2. The influence of resonance peaks of transmitter laser frequency noise on the radiation linewidth has been determined experimentally using a coherent receiver; it was found out that the 224 Gbps DP-QPSK solution is more resistant against frequency noise than the corresponding 112 Gbps solution for coherent FOTS with optical fiber link length *(i)* L_{P2P} = 0 km (B2B transmission) and *(ii)* L_{P2P} = 500 km (the average link length in the COST-239 network topology).
3. By means of the proposed scheme for allocation of 10 Gbps, 40 Gbps and 100 Gbps transmission channels the relationship has been determined between the spectral efficiency (bps/Hz) in the frequency band, the average power consumption per bps transmitted (i. e., energy efficiency, J/bit) and the overall transmission distance in the 10-40-100 Gbps WDM-based FOTS.
4. Analytical models have been derived for calculation of power consumption by transponders and 3R regenerators, and it has been proved that in design of the most energy efficient transmission system the energy consumption is to be considered coherently for both transponders and 3R regenerators. Otherwise, at choosing the modulation format that is based only on the transponder energy consumption we would be unable to ensure the least energy consumption needed for 1 bit transmission between two optical network nodes with the maximum allowable spectral efficiency (e. g., 2 bps/Hz in the 100 Gbps DP-QPSK case).

Based on the results obtained during the Doctoral Thesis, and in collaboration with the Optical Networks Laboratory (ONLab) of the Royal Institute of Technology (KTH) a Visby programme grant has been given by the Swedish Institute (SI) for the R&D project “Green 3R Placement Strategies for WDM Networks with Mixed-Line-Rate”. In the working process, the author of the Doctoral Thesis has had the opportunity to perform some of the experimental measurements required for the Doctoral Thesis at *Finisar Sweden AB* and *Acreo Sweden AB* laboratories.

The **main conclusions** drawn in the course of the Doctoral Thesis are as follows.

1. The spectral efficiency of the frequency band can be increased up to two times if for channel separation in mixed line rate (MLR) WDM FOTS instead of the fixed DWDM grating described in the ITU-T recommendation the improved grating with unequal frequency intervals is used. The increase in spectral efficiency depends on the initial system configuration that determines the data transmission rate and modulation formats in different channels (at different wavelengths).
2. The quality of transmission in case of coherent modulation formats depends not only on the linewidth of transmitter laser but also on the shape of its frequency noise spectrum, which is determined by such parameters as carrier resonance frequency, K-factor and high-frequency linewidth (HFLW). The coherent FOTS using DP-QPSK for optical signal modulation with a higher baud rate is resistant against frequency noise from transmitter laser source than in the solution with a smaller baud rate.
3. The use of non-coherent modulation format (e. g., NRZ-OOK and NRZ-DPSK) in cases of 40 Gbps bitrate allows for saving up to 30 % from the energy that would be needed for transmitting 1 bit in the 100 Gbps DP-QPSK case, if the length of optical fiber link is 1000 km, while the distance between two consecutive 3R regenerators due to the spectral efficiency is 40 km span of standard single-mode optical fiber (SSMF). In turn, if the distance between two 3R regenerators is significantly greater than the length of used standard single-mode fiber span (L_{SSMF} = 40 km), then the 100 Gbps DP-QPSK provides the best spectral efficiency ($\gg$1 bit/s/Hz) in combination with the least energy consumption required for 1 bit transmission through a fiber-optical link.

4. Apart from the used configuration of the mixed 10–40–100 Gbps WDM FOTS, there is also “the point of equal energy efficiency” determined by the number of 10 Gbps NRZ-OOK channels, by the energy efficiency of 40 Gbps and 100 Gbps transponders and 3R regenerators, and by the length of fiber-optical link according to which a definite quality of the received signal must be guaranteed (e. g., $BER \leq 1 \cdot 10^{-9}$).

Practical value of the Doctoral Thesis:

1. The results of scientific research achieved within the Doctoral Thesis have been used in two international programmes (FP7 project GRIFFON (No. 324391) and ICT-DISCUS (No. 318137)) and in four Latvian programmes (ESF No. 2013/0012/1DP/ 1.1.1.2.0/13/APIA/VIAA/051, ESF No. 2009/0144/1DP/1.1.2.1.2./ 09/IPIA/VIAA/005, ERDF No. 2DP/2.1.1.2.0/10/APIA/VIAA/003, ERDF No. 2010/0270/2DP/2.1.1.1.0/ 10/APIA/VIAA/002) for implementation of R&D projects.
2. In cooperation with the team from the Optical Networks Laboratory (ONLab) of the Royal Institute of Technology (KTH), the Visby programme grant (No. 00228/2013) has been awarded by the Swedish Institute for the R&D project “Green 3R Placement Strategies for WDM Networks with Mixed-Line-Rate”.
3. In the framework of a cooperation agreement, the topicality of the energy efficiency improvement in the fiber optic transmission systems has been included in the “Assessment of the Basic Tendencies in the Long-haul Network Technologies and Their Projecting” prepared by the state joint stock company “Latvian State Radio and Television Center” (ERDF project No.3DP/3.2.2.3.0/12/IPIA/SM/001 “Development of Next Generation Electronic Communication Networks in Rural Regions”).
4. Application for the Latvian patent (No. P-12-15) is pending, which is related to the design of the wavelength division multiplexing communication systems of energy efficient mixed line rates at data rates of 10 Gbps, 40 Gbps and 100 Gbps .

The **thesis statements** to be defended are as follows.

1. In the mixed line rate (MLR) FOTS, the spectral efficiency of the frequency band is to be increased more than twice using the improved DWDM grating with the unequal frequency intervals that consider the data rate and modulation format in the neighboring channels.
2. The coherent FOTS with a greater baudrate are more resistant against the transmitter laser frequency noise than solutions with a smaller baudrate. (For example, the 224 Gbps DP-QPSK is more than by 3 dB resistant against the transmitter laser frequency noise than the corresponding 112 Gbps solution. This would allow using a laser source with the linewidth of up to 20 MHz, while the K-factor is below 0.5 ns, and the resonance frequency is below 3 GHz).
3. The highest energy efficiency of transmission will not be achieved in the WDM systems where the maximum transmission distance without optical signal regeneration is limited by one section of optical fiber link if the choice of modulation formats and bitrates is based on the power consumption of transponders as the only criterion. (For example, the use of 40 Gbps NRZ-DPSK modulation format provides up to 30 % lower energy per bit of transmission than the 100 Gbps DP-QPSK at a 1000 km long optical fiber line in cases when the optical signal restoration is to be done in every intermediate node).
4. In case of spectrally efficient 10-40-100 Gbps FOTS, there is also “the point of equal energy efficiency” at which the energy efficiency of transmission is the same for all mixed line rate communication systems and at this point the frequency band distribution between the 40 Gbps and 100 Gbps channels does not affect the energy efficiency of transmission.

Approbation of the Results of the Research

The main results of the Doctoral Thesis are presented in **23** international scientific conferences as well as are reported in **5** publications in scientific journals, **15** publications in the full-text conference proceedings, **9** publications in the conference books of abstracts, and 3 Latvian patents.

Publications in **scientific journals:**

1. **Udalcovs A.**, Monti P., Bobrovs V., Schatz R., Wosinska L. Power efficiency of WDM networks using various modulation formats with spectral efficiency limited by linear crosstalk// Optics Communications. — Elsevier Inc., 2014. — No. 318. — pp. 31–36.
2. **Udalcovs A.**, Bobrovs V., Trifonovs I., Celmins T. Investigation of maximum distance reach for spectrally efficient WDM system with mixed data rates and signal formats// Electronics and Electrical Engineering. — Kaunas, Lithuania: Kaunas University of Technology, 2013. — Vol. 19, No.1. — pp. 87–92.
3. **Udalcovs A.**, Bobrovs V., Ivanovs G. Investigation of differently modulated optical signals transmission in HDWDM systems// Journal of Computer Technology and Applications. — New York: David Publishing Company, — 2011. — Vol. 2, No. 10 — pp. 801–812.
4. Bobrovs V., Ivanovs G., **Udalcovs A**. Investigation of allowed channel spacing for differently modulated optical signals in combined HDWDM systems// Electronics and Electrical Engineering. — Kaunas, Lithuania: Kaunas University of Technology, 2011, Vol.112, No. 6. — pp. 19–24.
5. Bobrovs V., Spolitis S., **Udalcovs A.**, Ivanovs G. Schemes for compensation of chromatic dispersion in combined HDWDM systems// Latvian Journal of Physics and Technical Sciences. — Riga, Latvia: Institute of Physical Energetics, 2011. — Vol. 48, Issue 5. — pp. 13–27.

Publications in the **full-text conference proceedings**:

1. Olmedo M., Pang X., **Udalcovs A.**, Schtaz R., Zibar D., Jacobsen G., Popov S., Monroy I. Impact of carrier induced frequency noise from the transmitter laser on 28 and 56 Gbaud DP-QPSK metro links// Proceedings of Asia Communications and Photonics Conference (ACP). — Shanghai, China: OSA, 2014. — Paper ATh1E. — pp. 1–3. **(Best Student Paper Award)**
2. Bobrovs V., Gavars P., Trifonovs I., Ivanovs G., **Udalcovs A.** Transponder impact on power and spectral efficiencies in WDM links based on 10-40-100 Gbps mixed-line rates // Proceeding of Progress in Electromagnetic Research Symposium (PIERS). — Gaungdzhou, China: The Electromagnetics Academy, 2014. — pp. 1664–1668.
3. **Udalcovs A.**, Bobrovs V., Ivanovs G. Power efficiency vs. spectral efficiency and transmission distance in 2.5-10-40 Gbps backbone optical networks // International Symposium on Communications, Control & Signal Processing (ISCCSP). — Athens, Greece: IEEE, 2014. — pp. 202–205.
4. **Udalcovs A.**, Bobrovs V., Ivanovs G. Comparison between power efficiencies of mixed-line rate over single-line rate in spectral efficient WDM networks with signal quality guarantee// Proceedings of IEEE Latin-America Conference on Communications (LATINCOM). — Santjago, Chile: IEEE, 2013. — pp. 1–6.
5. **Udalcovs A.**, Monti P., Bobrovs V., Schatz R., Wosinska L., Ivanovs G. Spectral and energy efficiency consideration in mixed-line rate WDM networks with signal quality guarantee// Proceedings of International Conference on Transparent Optical Networks. — Cartagena, Spain: IEEE, 2013. — Paper Tu.D1.3. — pp. 1–7. **(Invited Paper)**

6. Bobrovs V., **Udalcovs A.**, Trifonovs I. Evaluation of nonlinear effect impact on optical signal transmission over combined WDM system// Proceedings of Progress in Electromagnetics Research Symposium (PIERS). — Taipei, Taiwan: The Electromagnetics Academy, 2013. — pp. 303–307.
7. **Udalcovs A.**, Bobrovs V., Porins J. Evaluation of SPM-induced optical signal distortions in ultra-dense mixed-WDM system// Proceeding of International Conference on Future Generation Communication Technology (FGCT). — London, United Kingdom: IEEE, 2012. — pp. 180–184.
8. Bobrovs V., **Udalcovs A.**, Parts R., Trifonovs I. Evaluation of the maximum permissible transmission distance for the mixed-HDWDM systems// Proceedings of the 9th International Symposium on Telecommunications (BIHTEL). — Sarajevo, Bosnia and Herzegovina: IEEE, 2012. — pp. 1–6.
9. **Udalcovs A.**, Bobrovs V., Ivanovs Ģ. Investigation of the maximum distance reach for the mixed-WDM systems with unequal frequency grid// Proceedings of International Symposium on Signals, Systems and Electronics. — Potsdam, Germany: IEEE, 2012. — pp. 1–5.
10. **Udalcovs A.**, Bobrovs V. Investigation of spectrally efficient transmission for unequally channel spaced WDM systems with mixed data rates and signal formats// Proceedings of the 8th IEEE, IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP). — Poznan, Poland: IEEE, 2012. — pp. 1–4.
11. Bobrovs V., **Udalcovs A.**, Trifonovs I. Investigation of spectrally efficient transmission in mixed WDM systems// Proceeding of Progress in Electromagnetics Research Symposium (PIERS). — Kuala Lumpur, Malaysia: The Electromagnetics Academy, 2012. — pp. 977–981.
12. **Udalcovs A.**, Bobrovs V. Proposed model of mixed-WDM systems resulting from development trends in optical transport and access networks// Proceedings of the 4th International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT). — Saint Petersburg, Russia: IEEE, 2012. — pp. 563–569.
13. Bobrovs V., **Udalcovs A.**, Trifonovs I. Investigation of maximum distance reach for spectrally efficient combined WDM systems// Proceedings of the 2nd Baltic Congress on Future Internet Communications (BCFIC). — Vilnius, Lithuania: IEEE, 2012. — pp. 52–55. **(Best Paper Award)**
14. Bobrovs V., Ivanovs G., **Udalcovs A.**, Spolitis S., Ozolins O. Mixed chromatic dispersion compensation methods for combined HDWDM systems// Proceedings of the 6th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA). — Barcelona, Spain: IEEE, 2011. — pp. 313–319.
15. **Udalcovs A.**, Bobrovs V. Investigation of spectrally efficient transmission for differently modulated optical signals in mixed data rates WDM systems//Proceedings of IEEE Swedish Communication Technologies Workshop (Swe-CTW). — Stockholm, Sweden: IEEE, 2011. — pp. 7–12.

Publications in the conference **book of abstracts**:

1. **Udalcovs A.**, Bobrovs V. Transponder impact on power efficiency in WDM-links based on 10-40-100 Gbps mixed-line rates// Book of Abstract of the 8th International Conference on Advanced Optical Material and Devices (AOMD-8). — Riga, Latvia: Insitute of Atomic Physics and Spectroscopy, 25–27 August 2014.
2. **Udalcovs A.**, Garkavcenko A. Impact of single-mode fiber dispersion coefficient on signal distortions for different data-rates and modulation formats// Book of Abstracts of the 9th International Young Scientists Conference on Developments in Optics and

Communications (DOC 2013). — Riga, Latvia: Institute of Atomic Physics and Spectroscopy, 10–12 April 2013. — pp. 40–41.
3. Karjakina O., **Udalcovs A.** Research of chromatic dispersion management strategies applied for fiber-optic transmission systems with wavelength division multiplexing// Book of Abstracts of the 9th International Young Scientists Conference on Developments in Optics and Communications (DOC 2013). — Riga, Latvia: Institute of Atomic Physics and Spectroscopy, 10–12 April 2013. — pp. 94–95.
4. **Udalcovs A.**, Bobrovs V. Evaluation of the maximum permissible transmission distance for mixed HDWDM systems// Book of Abstracts of the 8th International Young Scientists Conference on Developments in Optics and Communications (DOC 2012). — Riga, Latvia: Institute of Solid State Physics, University of Latvia, 12–14 April 2012. — pp. 84–85.
5. **Udalcovs A.**, Bobrovs V., Ivanovs G. Investigation of spectral efficiency for mixed data rates combined HDWDM systems// Book of Abstracts of the 7th International Young Scientists Conference on Developments on Optics and Communications (DOC 2012). — Riga, Latvia: Institute of Solid State Physics, University of Latvia, 28–30 April 2011. — pp. 40–41.
6. **Udalcovs A.**, Bobrovs V. Investigation of error-free transmission for high density combined WDM systems // Book of Abstracts of the 12th International Young Scientists Conference on Optics & High Technology Material Science (SPO 2011). — Kiev, Ukraine, 27–30 October 2011. — pp. 211–212.
7. **Udalcovs A.,** Bobrovs V. Research of combined transmission for high-speed WDM systems// Books of Abstracts of the 52nd International Conference of Riga Technical University. — Riga, Latvia: Riga Technical University, 13–14 October 2011. — pp. 12–12.
8. **Udaļcovs A.**, Bobrovs V. Minimāli pieļaujamā starpkanālu intervāla izpēte kombinētajās WDM sistēmās// 52. RTU Studentu zinātniskās un tehniskās konferences materiāli. — Rīga, Latvija: RTU Izdevniecība, 28. aprīlis, 2011. — 282.–282. lpp.
9. Bobrovs V., **Udalcovs A**. Estimation of combined NRZ-DUOBINARY-NRZ HDWDM system performance // Book of Abstracts of the 6th International Young Scientists Conference on Developments on Developments in Optics and Communications (DOC 2010). — Riga, Latvia: Institute of Solid State Physics, University of Latvia, 23–25 April 2010. — pp. 42–42.

It should be noted that all research results published in the full-text conference proceedings and conference book of abstracts were presented in the oral or poster sessions of specific international scientific conferences.

Latvian **patents**:
1. Bobrovs V., Ozolins O., Spolitis S., **Udalcovs A.**, Ivanovs G. Measurement scheme for evaluation of efficient bandwidth of wavelength filter // Latvian patent No. LV-14557.
2. Bobrovs V., Spolitis S., **Udalcovs A.,** Parts R., Ivanovs G. WDM-PON fiber optical access communication system with dispersion compensation// Latvian patent No. LV-14628.
3. **Udalcovs A.**, Ozolins O., Spolitis S., Parts R., Bobrovs V. Mixed line rate wavelength division multiplexing communication system// submitted Latvian patent application No. P–12–15.

The results of the Doctoral Thesis have been used for the implementation of **3** international and **4** Latvian scientific research **projects**:
1. The 7th framework programme of the European Commission ICT–DISCUS project under grant agreement No. 318137, 2007–2013.

2. The 7th framework programme of the European Commission GRIFFON project under grant agreement No. 324391, 2013–2017.
3. Swedish Institute (SI) Visby programme under grant agreement No. 00228/2013.
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6. European Regional Development Fund (ERDF) project: “Development of Riga Technical University International Cooperation, Projects and Capacity”, No. 2DP/2.1.1.2.0/10/APIA/VIAA/003.
7. European Regional Development Fund (ERDF) project: “Design of High-speed Optical Access Networks and Elements”, No. 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002.

The Volume and Structure of the Thesis

The volume of the Doctoral Thesis is 188 pages. It consists of the introduction, four main chapters, conclusions, bibliography and appendices.

Chapter 1 (Introduction): the topicality of the doctoral thesis is substantiated, and its directions are determined. The aim and tasks of the research are set, thesis statements to be defended are formulated; the main results are summarized.

Chapter 2: *(i)* the WDM technology is investigated and evaluated, *(ii)* the criterion is defined for the estimation of signal quality losses due to amplified spontaneous emission (ASE), Kerr’s nonlinearities, polarization mode dispersion (PMD), and crosstalk from wavelength filters, *(iii)* phase and frequency noises originated from laser sources are evaluated and *(iv)* the modulation formats are characterized, which are mostly employed for modulation of optical signals in commercial optical networks and which could be used for spectral efficiency improvement of frequency bands.

Chapter 3: *(i)* the model of backbone optical network is described, which will be used for estimation of transmission energy efficiency, *(ii)* estimation is given for the power consumption by the components of WDM-based FOTS. The values obtained are compared with those found in literature.

Chapter 4: *(i)* the improved model of Dense WDM (DWDM) grating is described, and its use for improvement of transmission spectral efficiency is estimated; *(ii)* Q-factor changes in the worst channel of the transmission system are determined depending on the channel spacing used for three different lengths of a single-mode optical fiber, i. e., 40, 80 and 120 km) and for the cases of used/unused forward error correction (FEC); *(iii)* the impact of ASE noise due to line amplifiers is analyzed from the viewpoint of the signal quality loss and the created transmission models are described, which in cases of NRZ-OOK, NRZ-DPSK and DP-QPSK modulation formats make it possible to determine the maximum allowable transmission distance without 3R regeneration of optical signal (i. e., system reach); and, finally *(iv)* it is experimentally verified how the phase and frequency noises of laser sources used in coherent FOTS influence the transmission quality in cases of single polarization QPSK (SP-QPSK) and dual polarization QPSK (DP-QPSK) modulation formats.

Chapter 5: the impact is clarified as to the spectral efficiency depending on the energy consumption when transmitting 1 bit of data between two nodes of the optical transport network while ensuring a definite signal quality at the receiving node.

Conclusions: the main conclusions based on the results of the Doctoral Thesis are substantiated and summarized. The appendices contain the lists of conferences, publications and projects as well as Latvian patent certificates, Erasmus training programme recommendation and the Visby grant offer by the Swedish Institute.

CONTENTS OF THE CHAPTERS

Chapter 1 (Introduction)

The determining factors of WDM network development are: *(i)* increase in the Internet traffic and in the number of users, *(ii)* possibilities for improvement of spectral efficiency, *(iii)* energy consumption in the world, and *(iv)* contribution of the ICT (Information and Communication Technology) sector to the global electricity consumption. Estimation of these factors has led to the conclusion that the operators of optical networks will choose the solutions that allow increasing the spectral efficiency at the same time not exceeding the energy consumption needed for transmitting 1 bit of information. Otherwise, not only operational expenditure will rise, but also environmental impacts will follow due to increased emissions of greenhouse gases (GHGs).

In compliance with the International Telecommunication Union (ITU) calculations, the ICT sector is responsible for at least 2–2.5 % of the total GHG emissions (or slightly less than 10^{12} kg in CO_2 equivalent) [40, 41]. Increasing energy consumption by the ICT sector — from the current 4 % up to forecasted 8 % in 2020 — this will have irreversible consequences for the global ecology [13, 26, 31, 32, 40, 41].

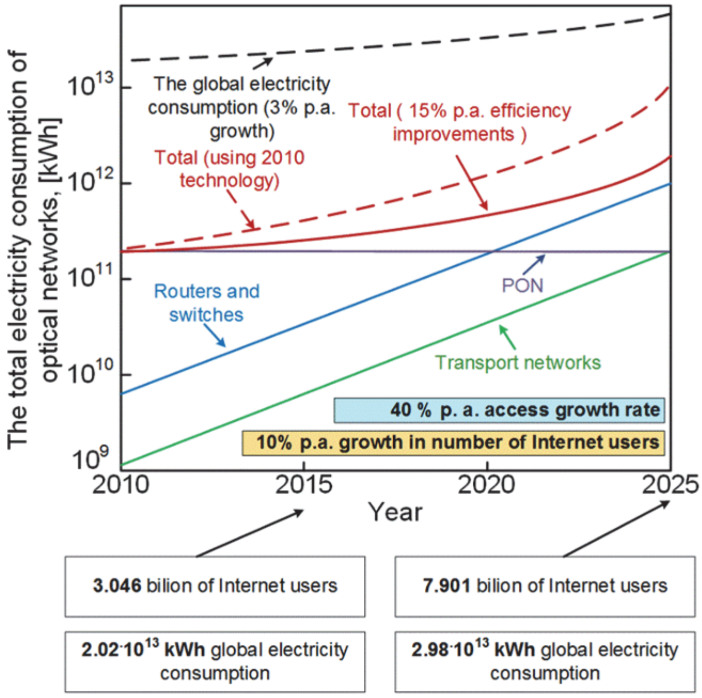


Fig. 1. The forecasted electricity consumption of the optical networks in the time span from 2010 to 2025 [28]

The telecommunication infrastructure of today consumes only ~ 1 % of the global generated electricity. However, taking into account the pace of IP traffic growth, this percentage will be only increasing in the nearest future, reaching by 2025 up to 10 % [16, 28], (see Fig. 1). Such a forecast is made assuming that *(i)* the infrastructure of transmission network model is based on the fiber-to-home; *(ii)* the average access growth rate to the Internet increases by 40 % per year; *(iii)* the number of Internet users increases by 10 % every year; *(iv)* the energy efficiency of the transmission network infrastructure components improves by 15 % per year; *(v)* the rate of global electricity generation will increase by 3 % per year.

From the forecasts it could be inferred that the energy consumption in the transport optical networks is as swift as by routers and switches, while the energy consumption in the passive access networks (PON) remains unchanged. Therefore, the improvement of energy efficiency in the transport networks is one of the main tasks being solved at the world's leading scientific laboratories and consortiums (see, e. g., [1, 3, 28, 33, 34]).

Chapter 2

In the WDM-based FOTS, five separate stages of the optical signal transmission could be set off: *(i)* generation of a carrier signal; *(ii)* multiplexing the optical signals; *(iii)* transmission of optical signals along a fiber-optical link (FOL); *(iv)* separation of optical signals according to the wavelengths (frequencies); *(v)* reception, demodulation and detecting of signals (see Fig. 2). The first and the fifth stages are linked to the chosen format of optical signal modulation. The second and the fourth stages are connected with the method that is used for assignment of channel central frequencies. The third stage is associated with the mechanisms of linear and nonlinear distortions that affect transmission of modulated signals in the optical fiber.

The assignment of central wavelengths (or frequencies) of the channels is based on two ITU-T recommendations: G.694.1 and G.694.2. The former recommendation describes the fixed and elastic DWDM gratings. In case of a fixed DWDM grating, the recommendation determines only and solely the central frequencies of channels at different channel spacing values, e. g., 200, 100, 50, 25 and 12.5 GHz, while in the elastic DWDM grating case this recommendation determines not only the channel central frequencies, but also the width of frequency slot. In this case for assignment of central frequency of the channels a 6.25 GHz step is used (see (1)), whereas for determination of the width of frequency slot twice as large step is taken, i. e., 12.5 GHz (see (2)).

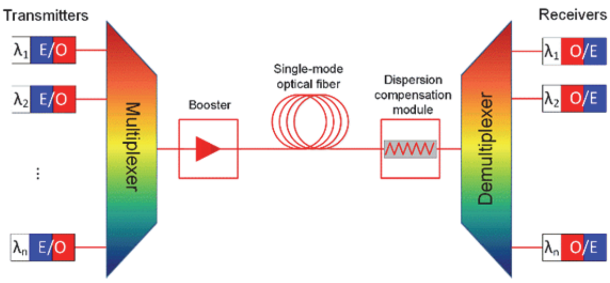


Fig. 2. A simplified block-diagram of the WDM-based FOTS [20]

It has been necessary to introduce the elastic DWDM since the fixed DWDM grating works well, while in the WDM system all transmission channels operate at one data transmission rate and/or for modulation of optical signals the same modulation format is used. In the opposite case, either overlapping of optical channels occurs or the frequency resources of optical fiber are employed inefficiently.

$$f_c = 193.100 + n0.00625\ [THz], n = 0, \pm1, \pm2, \pm3, \dots \quad (1)$$

$$\Delta f_{width} = 12.5m\ [GHz], m = 1, 2, 3, \dots \quad (2)$$

The latter recommendation (ITU-T G.694.2) describes the assignment of central frequencies of the channels in case of coarse WDM (CWDM). This recommendation comprises 18 CWDM channels, the central wavelengths of which are spaced with a 20 nm step in the range from 1271 nm to 1611 nm. Further studies of CWDM are not carried out, since this multiplexing is not considered an appropriate solution for present-day optical transport networks.

Analysis of the signal propagation along an optical fiber evidences that one of the main linear effects which significantly distort transmission of signals in the backbone optical networks is the ASE noise due to optical line amplifiers (OLAs), while the cross-phase modulation (XPM) is the main nonlinear optical effect. The level of ASE noise at the receiver's end directly depends on the noise factor of the EDFA used, on the gain itself determined by the distance between two OLAs, on the optical fiber attenuation coefficient and on the bandwidths of the electrical and optical filter used. This happens because the ASE noise after its reception and optical-to-electrical conversion appears as electrical noises. The XPM causes just increase in the amplitude noises that arise due to dispersion observed in optical fibers. Such dispersion converts the phase modulation into the intensity modulation. Therefore, the XPM-related amplitude noises can seriously affect the intensity-manipulated signal (e. g., NRZ-OOK) transmission and the BER value at the receiver's end. In the Doctoral Thesis, it has been found that in case of 10 Gbps NRZ-OOK transmission with the quality of received signal being Q = 7.3, the level of XPM-related nonlinear noises exceeds noises by more than 20 times due to four-wave mixing (FWM) [30].

Considering the degrees of freedom for the optical signal — the amplitude (intensity), phase and state of polarization — the modulation formats that manipulate with the given degrees of freedom have been determined (see Fig. 3). The non-return-to-zero encoded on-off Keying (NRZ-OOK) is a historical solution for 10 Gbit/s networks. The phase of the optical signal is already employed in the next stage of optical network development — namely, in the 40 Gbit/s channel. In this case, one of the common modulation formats is the NRZ encoded differential phase-shift keying (NRZ-DPSK). The differential quadrature phase-shift keying (DQPSK) and the optical duobinary format (ODB) are an alternative solution for a data rate of 40 Gbps in a single wavelength.

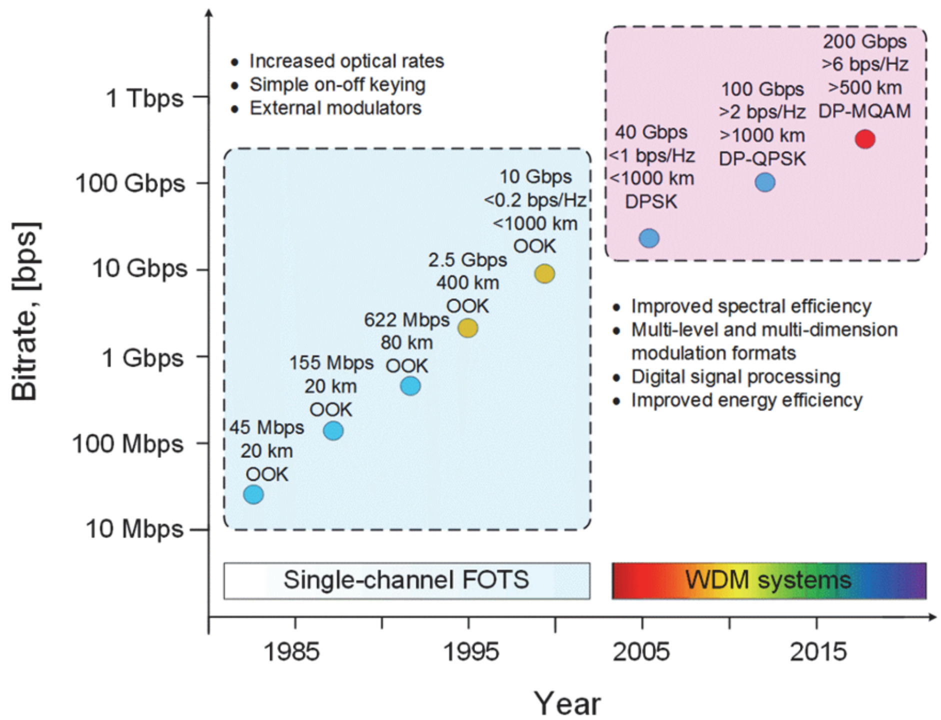


Fig. 3. The development of transmission rate and modulation formats used in optical primary networks in the time period from 1980 to 2015 [11]

As far as the optical signal state of polarization is concerned — even though this could also be applied to optical signal modulation (e. g., using the binary orthogonal polarization state keying (2-POLSK)) — in the backbone optical networks of today this state is employed for additional optical signal polarization division multiplexing (PDM). For example, in case of 100 Gbps DP-QPSK solution two 50 Gbps QPSK signals are multiplexed after they have been in the particular state of polarization, one of them having linear X-polarization while the other — linear Y-polarization. The optical signal polarization division multiplexing (PDM or PolMux) allows reducing the width of frequency band required for transmission and the baud rate. For demodulation of such multi-level and multi-dimension modulation formats it is necessary to apply the coherent detection methods and digital signal processing (DSP). Dealing with coherent optical signal modulation formats one more distortion source should be taken into account — phase and frequency noises from the transmitter and receiver laser sources. This is especially important, since for cost minimization semi-conductor lasers are employed to generate radiation.

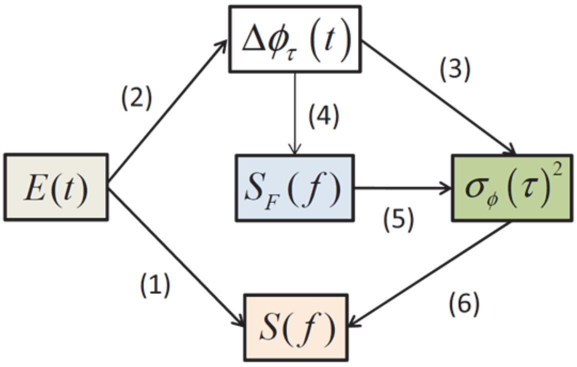


Fig. 4. Relations among the complex amplitude $E(t)$ of laser field, the phase difference $\Delta\phi_\tau(t)$, the field spectrum $S(f)$, the frequency noise spectrum $S_F(f)$, the phase difference spectrum $S_{\Delta\phi_\tau}(f)$ and the phase noise variance $\sigma_\phi^2(\tau)$ [42]

Several functions could be used for characterizing the laser field (see Fig. 4) — the phase and frequency noise spectra are one of them. Figure 4 shows the relations among the complex amplitude $E(t)$ of laser field, the phase difference $\Delta\phi_\tau(t)$, the field spectrum $S(f)$, the frequency noise spectrum $S_F(f)$, the phase difference spectrum $S_{\Delta\phi_\tau}(f)$ and the phase noise variance $\sigma_\phi^2(\tau)$. Mathematical expressions which are linking each of these parameters are given by equations (3)–(8) [42].

$$S(f) = \langle |F[E(t)]|^2 \rangle \tag{3}$$

$$\Delta\phi_\tau(t) = \phi_n(t) - \phi_n(t-\tau) \tag{4}$$

$$\sigma_\phi^2(\tau) = \langle \Delta\phi_\tau(t)^2 \rangle \tag{5}$$

$$S_{\Delta\phi_\tau}(f) = 4\left(\frac{\sin(\pi\cdot f\cdot\tau)}{f}\right)^2 S_F(f) \tag{6}$$

$$\sigma_\phi^2(\tau) = 4\int_0^\infty \left(\frac{\sin(\pi\cdot f\cdot\tau)}{f}\right)^2 S_F(f)df \tag{7}$$

$$S(f) = F\left[\exp\left(-\frac{\sigma_\phi^2(\tau)}{2}\right)\right] \tag{8}$$

Note that the Fourier transformation is represented as $F[*]$ while $\langle * \rangle$ is the ensemble average. These equations later on, in Chapter 4, will be used for obtaining the phase and frequency noise spectra through calculations in MATLAB (see Fig. 13, 14 and 17).

Chapter 3

For estimation of the transmission energy efficiency, the backbone optical network model has been employed, which consists of four different layers (see Fig. 4): *(i)* IP/MPLS; *(ii)* Ethernet; *(iii)* OTN and *(iv)* WDM ones. The energy efficiencies in IP/MPLS and Ethernet layers depend on the power consumption by corresponding core network routers, and, obviously, on the traffic between particular network nodes. It has been revealed that in the IP/MPLS layer the routers from only two producers are used: *(i)* CISCO, for example, CISCO CRS-3; *(ii)* Juniper Networks. Calculating the energy efficiency in this layer, it is assumed that such type of routers consume approx. 10 W per Gbps transmitted, or 10 nJ/bit.

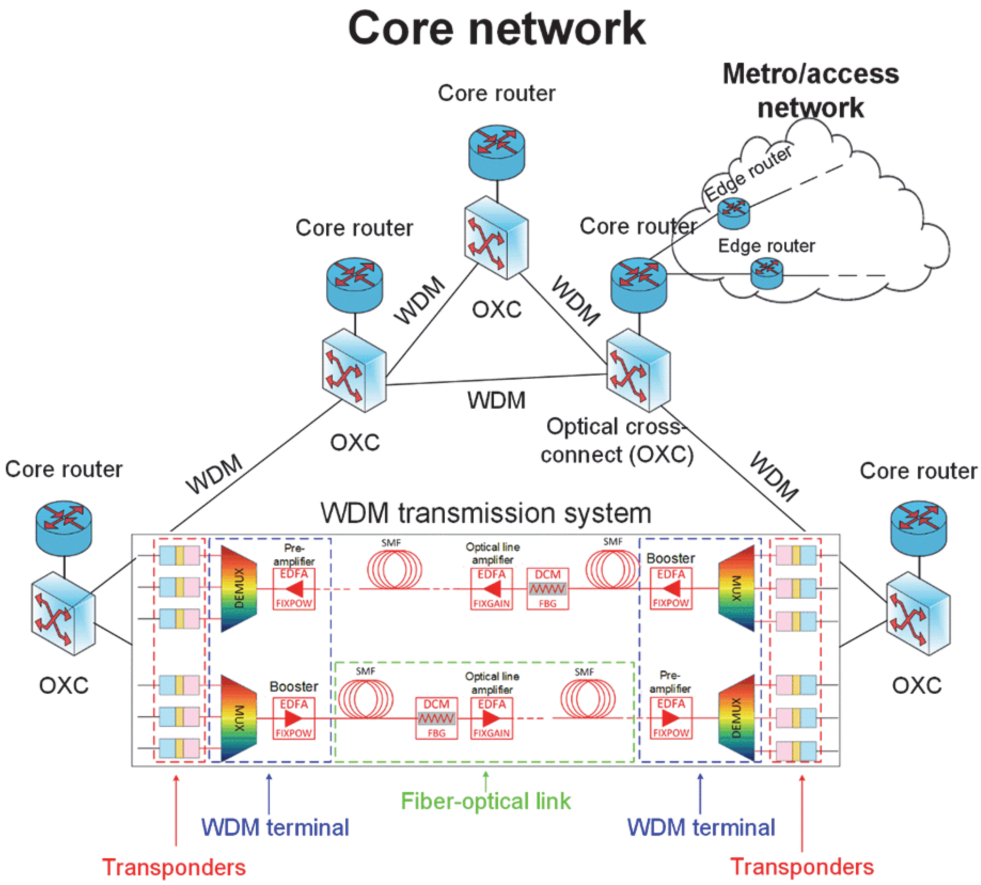


Fig. 5. General structure of the backbone optical network [25]

The power consumption in the Ethernet layer is composed of two systems used in a given manner for implementation of routing in commercial backbone optical networks. One of them is Cisco Nexus 7018 and the other — Juniper EX8216. It should be noted that in this case we operate with such a parameter as the power consumption by a particular port. For example, it is calculated that the power consumption by a 10 G port is about 38 W. The estimation of power consumption in the OTN layer is mostly based on confidential or limited-access information, which can be received if only there is close cooperation with producers. It should be noted that the difference between consumption in OTN and Ethernet layers is quite small. For example, 10 Gbps OTN ports consume about 34 W.

Table 1

Power Consumption by the WDM Components Whose Value Is Independent of the Used Modulation Format [13, 14]

Component	Description	Power consumption, [W]
OLA	2 km long SMF span, per fiber span	65
OLA	40 km long SMF span, per fiber span	65
OLA	80 km long SMF span, per fiber span	110
OLA	120 km long SMF span, per fiber span	120
WDM terminal	Up to 40 channels, per fiber span	230
WDM terminal	Up to 80 channels, per fiber span	240

As far as the power consumption in the WDM optical layer is concerned, this is mostly determined by two factors: *(i)* the algorithm chosen for routing; *(ii)* such transmission system parameters as the bitrate, optical signal modulation format, spectral efficiency of transmission, and, quite obvious, distance between network nodes where a pre-defined signal quality must be ensured. The components of a transmission system have been divided into two groups — the power consumption is *(i)* independent of and *(ii)* dependent on the optical signal modulation format used for transmission. The power consumption by optical line amplifiers and WDM terminals is independent not only of the optical signal modulation format but also of the bitrate employed (see Table 1). In turn, the power consumption by transponders and regenerators depends on the both above-mentioned parameters (see Table 2).

Table 2

The Calculated Power Consumption of Transponders (TSP) and 3R Regenerators (with and without FEC) and Comparison of TSP Values Most Often Met in the Literature

Bitrate, [Gbps]	Modulation format	TSP power consumption [W] (with/without FEC)	3R power consumption [W] (with/without FEC)	TSP power consumption found in references
10	NRZ-OOK	23.4/22.0	24.0/21.2	34.0 [31], 35.0 [39], 50.0 [13, 14]
40	NRZ-OOK	75.0/69.4	54.0/42.8	66.0 [24], 100.0 [13, 14]
10	NRZ-DPSK	23.8/22.4	24.8/22.0	20.5* [44]
40	NRZ-DPSK	75.4/69.8	54.8/43.6	85.0 [43]
10	DP-QPSK	42.0/40.6	61.2/58.4	–
40	DP-QPSK	126.0/120.4	156.0/144.8	113 [131]
100	DP-QPSK	292.8/278.8	345.6/317.6	351.0 [19], 139.0 [38], 188.0 [31]
		139.0/132.4	164.1/150.8	70.8* [9]

Notes: * The equipment specifications sometimes give not the nominal power consumption under normal operational conditions but just the maximum values. As far as the nominal values were concerned, it was assumed that the nominal power consumption is 75 % of the maximum value [13].

Based on the calculation and analysis of the power consumption values for different transponders and 3R regenerators, it should be concluded that at relatively small amounts of aggregated traffic (below 30 Gbps) the maximum energy efficiency could be achieved using 10 Gbps NRZ-OOK. In turn, if the aggregated traffic exceeds 80 Gbps, the minimum energy for 1 bit transmission is ensured precisely by 100 Gbps DP-QPSK. In case of 3R regenerators, the greatest energy efficiency at high aggregated traffic is provided just by non-coherent modulation formats (NRZ-OOK and NRZ-DPSK). The energy efficiency of 40 Gbps NRZ-DPSK transponders is almost twice as large as compared with that achieved by using the coherent DP-QPSK format for optical signal modulation, i. e., 1.9 nJ/bit and 3.2 nJ/bit, respectively.

Based on the values obtained for the power consumption by 10-40-100 Gbps mixed WDM transmission systems, the algorithm has been created, described, and studied which makes it possible to determine the number of 10 Gbps, 40 Gbps and 100 Gbps channels needed for transmission of particular aggregated traffic in order to ensure the least overall power consumption of transponders (see Fig. 6). If for choosing the modulation format the energy efficiency of a transponder itself is used as the only criterion, then independently of the aggregated traffic transmitted the number of 10 Gbps NRZ-OOK channels must not exceed three, and not more than one 40 Gbps NRZ-DPSK channel can be used for data transmission. Otherwise it would be possible to reduce the total power consumption by transponders.

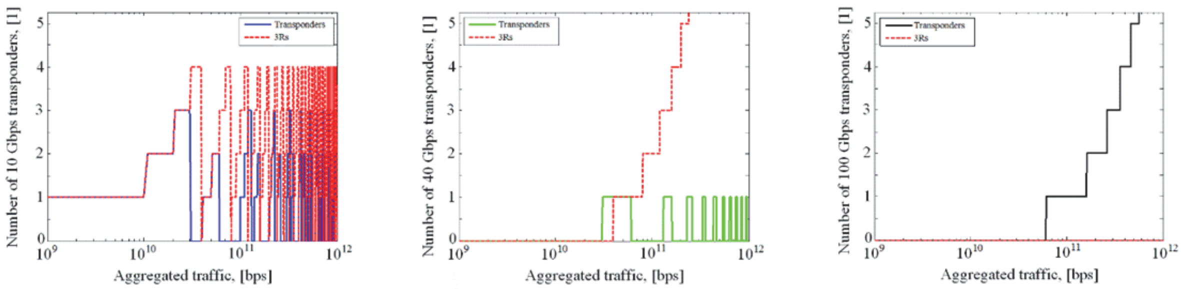


Fig. 6. The number of 10 Gbps NRZ-OOK (a), 40 Gbps NRZ-DPSK (b), and (c) 100 Gbps DP-QPSK transponders required for transmitting a given amount of data between two nodes of optical network in the MLR system

The total power consumption needed for transmitting a definite aggregated traffic along one section of fiber-optical link (see Fig. 7) is *(i)* as large as it would be in case of 10 Gbps SLR transmission if the aggregated traffic to be transmitted were smaller than 30 Gbps; *(ii)* smaller than in cases of choosing any other channels, if *30 Gbps < C < 60 Gbps*; *(iii)* not larger than in case of 100 Gbps SLR solution.

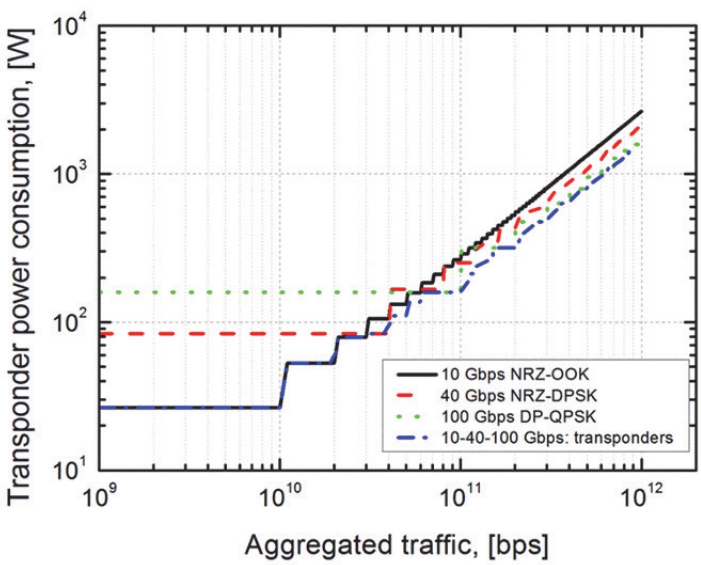


Fig. 7. Total power consumption of transponders versus the aggregated traffic

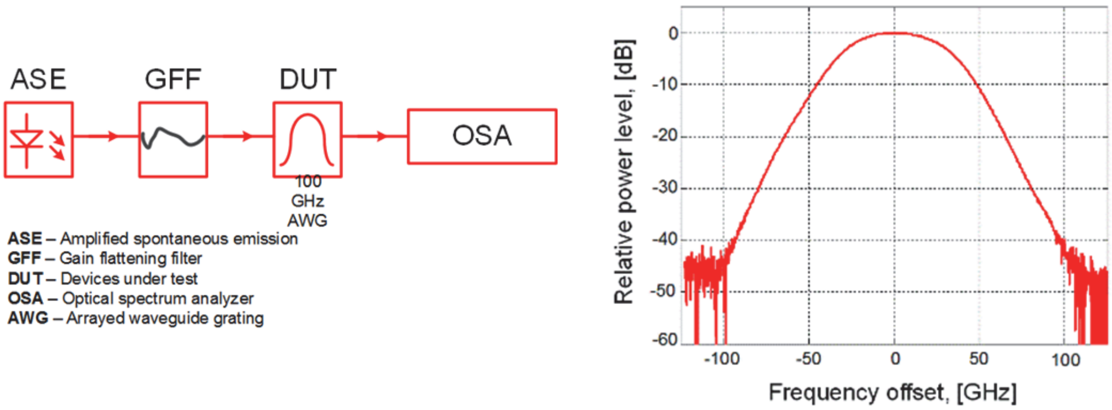
The situation changes if as the criterion the power consumption of 3R regenerators is chosen. In this case, the least total power consumption by transponders is ensured in the 10-40-100 Gbps MLR systems, in which independently of the aggregated traffic to be transmitted not more than four 10 Gbps NRZ-OOK channels are used, the number of 40 Gbps NRZ-DPSK channels is increasing with the transmitted amount of traffic, while 100 Gbps DP-QPSK channels are not employed at all. This could be explained by the high energy efficiency of 40 Gbps NRZ-DPSK 3R regenerators (~ 1 nJ/bit).

It should be noted that if transmission distances (length of fiber-optical link) or spectral efficiency values are large enough, it is not the transponders but the optical line amplifiers and the optical signal 3R regenerators that determine the power consumption needed for transmission.

Chapter 4

Optical signal distortions are explored due to their transmission over spectral efficient WDM fiber optic communication systems. First, the improved DWDM grating is described, which is intended for increasing the spectral efficiency. Then, using the proposed improvements of the DWDM grid, the dependence of signal quality on the channel spacing used in FOTS with/without FEC at the SSMF span lengths being 40 km, 80 km and 120 km is examined. Next, based on the Q-factor values after transmission over one section of the fiber optical link the system reach is determined. This was done using the derived transmission models, which enable the estimation of signal quality loss due to ASE noises. Finally, the signal quality loss is estimated depending on the phase and frequency noises from the laser source used on the transmitter side.

The proposed improved DWDM grating is based on the use of a smaller step at varying the channel spacing. While in case of fixed DWDM grating described in the ITU-T recommendation G.694.1, the value of each next channel spacing is obtained dividing by 2 the previous one. However, for spectral efficiency improvement it is proposed using intermediate values — in this case the mean arithmetic value is obtained taking the interval values of two adjacent channels from the ITU-T recommendation. Such an approach makes it possible to obtain as small as desired variation step for channel spacing. Obvious enough, a closer channel arrangement in the transmission spectrum would lead to greater linear crosstalk from adjacent channels.



a) *b)*

Fig. 8. Measuring scheme (a) used for determination of wavelength filter bandwidth and ASTF shape (b)

The level of linear crosstalk and its influence on the transmission quality to a great extent depend on the parameters of the wavelength filters used (e. g., the bandwidth and the shape of the amplitude square transfer function (ASTF). To define the closest distance between channels in the frequency spectrum without replacing already existing wavelength filters, a two-channel 10 Gbps NRZ-OOK WDM system with arrayed waveguide grating (AWG)has been applied, which according to the producer's specifications is meant for using in case of 100 GHz channel spacing. Therefore, first the bandwidth of a 100 GHz AWG filter and the ASTF shape have been defined with the help of the patented measuring scheme based on the use of ASE noise source (see Fig. 8).

As a result, it has been found that the two-side bandwidth of 100 GHz AWG filter at a level of −3 dB is equal to 58 GHz and to 130 GHz at a level of −20 dB. If such filters are placed in a WDM system, the quality losses due to linear crosstalk arise only at a 50 GHz channel spacing. Noticeable distortions that do not allow reception of signals with $BER \leq 1 \cdot 10^{-9}$ arise only at 37.5 GHz (see Figs. 8–9). Therefore, it could be concluded that the wavelength filter, which according to producer's data is intended for 100 GHz channel spacing, can also be employed in case of a half as large channel spacing without serious loss in the signal quality.

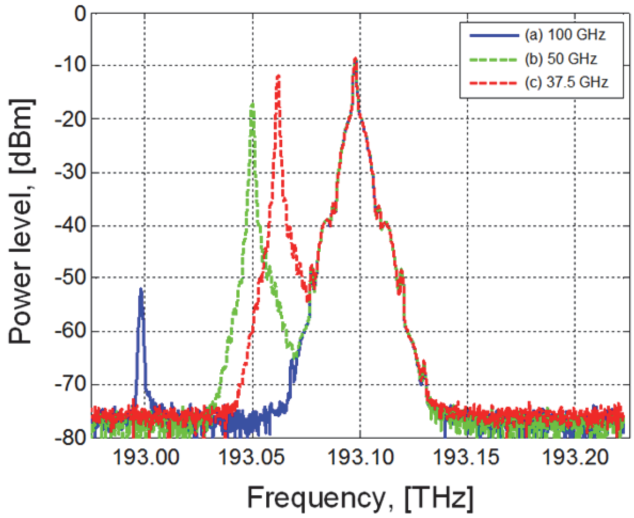


Fig. 9. The spectrum of 10–10 Gbps NRZ-OOK in case of B2B transmission at (a) 100 GHz, (b) 50 GHz and (c) 37.5 GHz channel spacing

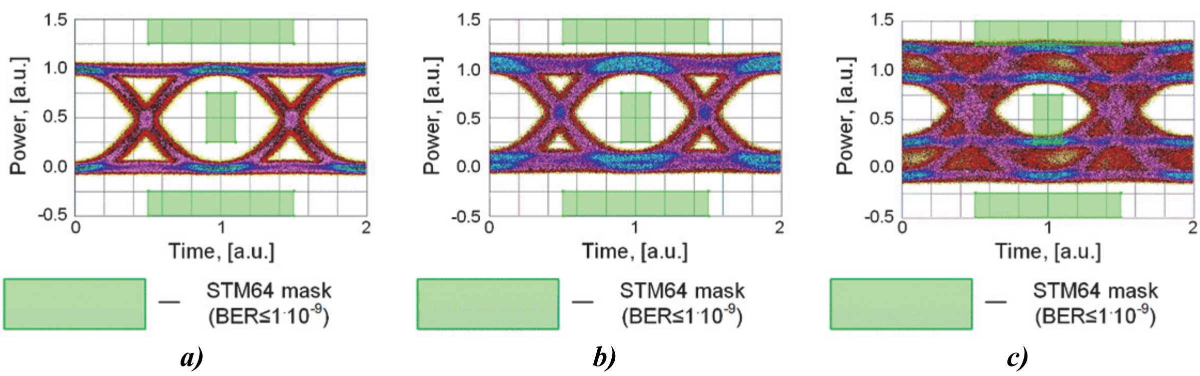


Fig. 10. The eye diagram received in 10–10 Gbps NRZ-OOK system after B2B transmission at (a) 100 GHz, (b) 50 GHz and (c) 37.5 GHz channel spacing

In order to estimate the spectral efficiency improvement achieved through the proposed improvements of the ITU-T recommendation G.694.1, a mixed WDM system has been chosen, whose configuration can be described as [10 Gbps NRZ-OOK in 1, 4, and 7 channels] — [10 Gbps 2-POLSK in 2, 5, and 8 channels] — [40 Gbps NRZ-DPSK in 3, 6, and 9 channels]. If for channel spacing an unmodified fixed DWDM grating is used, then the maximum achievable spectral efficiency is 0.20 bit/s/Hz. In turn, a modified grating would enable achievement of the efficiency of 0.27 bit/s/Hz or even 0.42 bit/s/Hz if for wavelength placing unequal channel spacing were used. This allows for an increase in the spectral efficiency by more than two times as compared with the ITU-T defined solution.

Next, using the improved DWDM grid, which is based on the ITU-T recommendation G.694.1, the channel spacing values have been determined that allow signal detection with $BER \leq 1 \cdot 10^{-9}$ and $BER \leq 2 \cdot 10^{-3}$ in sytems with and without FEC, respectively. These frequency intervals will be referred to as the minimum acceptable channel spacing. The BER threshold is sufficiently higher if the FEC is used. This is due to additional bits that increase a nominal bitrate up to 10.709 Gbps, 43.018 Gbps and 127.16 Gbps. As a result, the minimum acceptable channel spacing values have been determined for three optical signal modulation formats — *(i)* 10 Gbps NRZ-OOK, *(ii)* 40 Gbps NRZ-DPSK, and *(iii)* 100 Gbps DP-QPSK — and depending on the lengths of SSMF span used: *(i)* 40 km, *(ii)* 80 km, and *(iii)* 120 km. In total, 14 curves have been obtained that show the Q-factor values are used in the worst system channel as a function of the channel spacing (see Fig. 11). Later on, these curves have been used as input data in the derived transmission models for determination of the system reach (see Fig. 12).

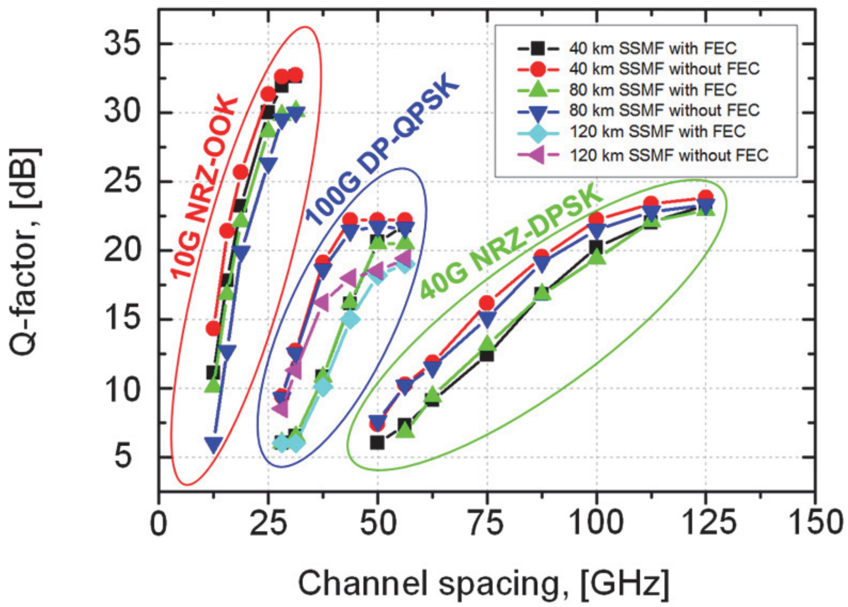


Fig. 11. The smallest Q-factor values detected as a function of the channel spacing in the SLR WDM FOTS with and without FEC

From the obtained Q-curves, it is seen that the largest Q-factor values are obtained in WDM systems with FEC and 40 km long SSMF spans. After exceeding particular values of channel spacing, Q-factor values do not rise anymore. Independent of the SSMF span length and FEC usage, this channel spacing is: *(i)* 31.25 GHz for the 10 Gbps NRZ-OOK systems, *(ii)* 150 GHz for the 40 Gbps NRZ-DPSK systems. However, for 100 Gbps DP-QPSK systems this value depends on both — SSMF span length and the presence or absence of FEC. In systems with FEC and 40/80 km long SSMF spans, it equals 43.75 GHz, while for the other cases it is 56.25 GHz. If wavelengths are separated with frequency intervals that are smaller than previously stated then the signal quality is defined mainly by the linear crosstalk.

In the WDM systems with FEC, the minimum allowable frequency intervals (channel spacing values) in 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK cases are 12.5 GHz, 75 GHz and 37.5 GHz, respectively, while in the systems without FEC these are 15.625 GHz, 87.5 GHz and 37.5 GHz. The minimum allowable channel spacing values have also been determined between different modulation formats (wavelengths) in the transmission band: *(i)* 10 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK; *(ii)* 10 Gbps NRZ-OOK and 100 Gbps DP-QPSK; *(iii)* 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK. Further, they have been taken for wavelength placement in the spectrum of 10-40-100 Gbps MLR system. As a result, it could be inferred that the minimum frequency interval to be used for spacing the mentioned wavelengths is *(i)* 62.5 GHz, *(ii)* 31.25 GHz and *(iii)* 75 GHz. If a smaller frequency interval were used for this purpose, this would cause greater linear crosstalk, thus not contributing to the compliance with the set requirement — namely, $BER \leq 1 \cdot 10^{-9}$.

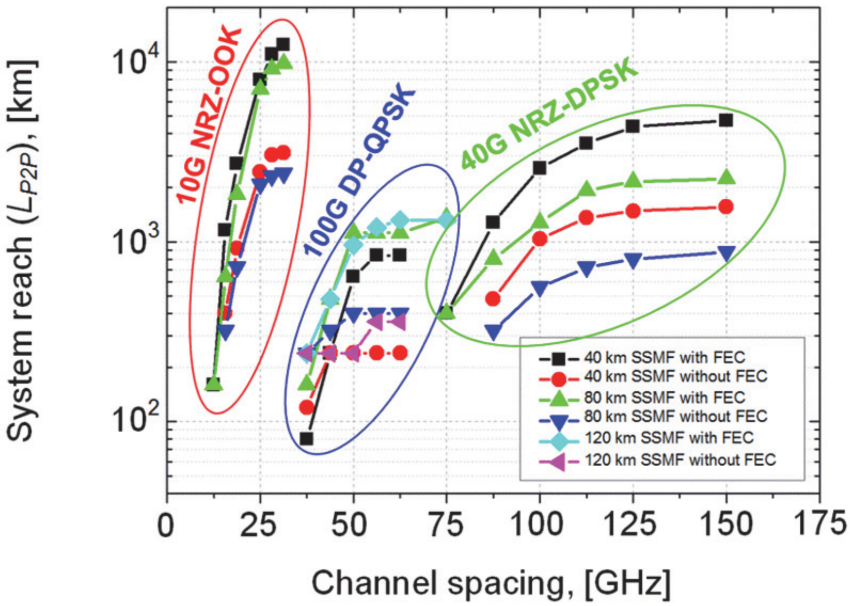


Fig. 12. The maximum allowable transmission distance without optical signal 3R regeneration (i. e., system reach) vs. the channel spacing and the length of point-to-points fiber-optical link

From the obtained Q-factor curves it has been possible to define the maximum transmission distance without 3R regeneration (i. e., the system reach) or the so-called length of regeneration section (see Fig. 12). This has been done using the derived transmission models, which allow for analytical determination of the Q-factor decrease depending on the number of optical line amplifiers, their gain and noise factor. As the input parameters, the following ones have been used: *(i)* the modulation format; *(ii)* the SSMF span length; *(iii)* the channel spacing; and *(iv)* the previously defined Q-factor after transmission along one section of fiber-optical link. Analysis of the maximum transmission distance curves demonstrates that the WDM system configuration using FEC and link consisting of 40 km long SSMF spans provides the greatest system reach just in case of non-coherent modulation format. In case of 100 Gbps DP-QPSK, it is necessary to use 80 km or even 120 km long SSMF spans. Otherwise a decrease in the regeneration section length by more than 30 % would occur. The maximum difference of regeneration section lengths is only 40 km, if for 100 Gbps DP-QPSK modulation format 80 km or 120 km long SSMF spans are used. It is clear that the least regeneration section in 100 Gbps DP-QPSK case is achievable for FEC-devoid systems and the SSMF span length is only 40 km. The greatest regeneration section length in the WDM systems with FEC and 80 km long SSMF spans exceeds *(i)* 9700 km, *(ii)* 2200 km and *(iii)* 1300 km in cases of 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK modulation formats, respectively.

If so far the main sources of transmission distortions have been considered the linear crosstalk or the linear crosstalk in combination with ASE noises or only ASE noises from optical line amplifiers, then here we study quite a different cause of signal quality loss — the phase and frequency noise from the laser sources used for transmission. This type of distortions arises exactly in case of coherent modulation formats that could be employed both for improving the spectral efficiency and for raising the transmission energy efficiency. First of all, the power spectral density of frequency noise of tunable DFB laser has been measured using the interferometric measurement method. The measurements have been taken for two output power levels: +5 dBm and +6 dBm. The spectra obtained are slightly different by shape in the low frequency range (see Fig. 13). Next, its influence has been estimated on the optical signal-to-noise ratio (OSNR) level required for reception of 28 Gbaud/s SP-QPSK and DP-QPSK signals with $BER \leq 2 \cdot 10^{-3}$ for two link lengths: *(i)* L_{P2P} = 0 km (i. e. B2B transmission) and *(ii)* L_{P2P}=880 km. The required level turned out to be not greater than 1 dB. Similarly, such a small difference between the required OSNR levels has been obtained by using the external cavity laser (ECL) at output power of +6 dBm instead of tunable DFB laser. Note that according to the producer's data the linewidth of the tunable DFB laser at a level of — 3 dB is not smaller than 20 MHz, while the ECL linewidth is not greater than 100 kHz. Thus, it has become clear that the linewidth only cannot be employed in order to characterize the influence of phase noise on the transmission quality. Therefore, it has been necessary, first, to find a way how to experimentally generate — under fully controlled laboratory conditions — different type of frequency noises from laser sources, and, second, to find a more convenient way for characterizing the frequency noises generated by these sources

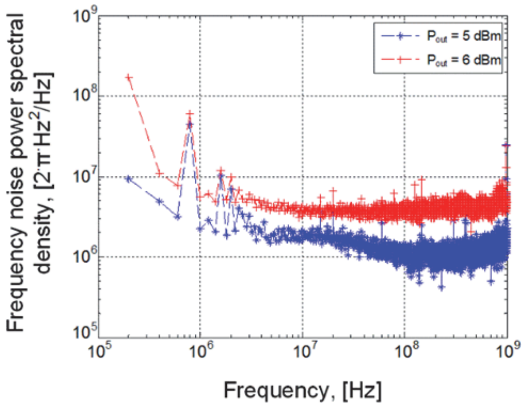


Fig. 13. Power spectral density (PSD) of Agilent 81689A tunable DFB laser frequency noise,

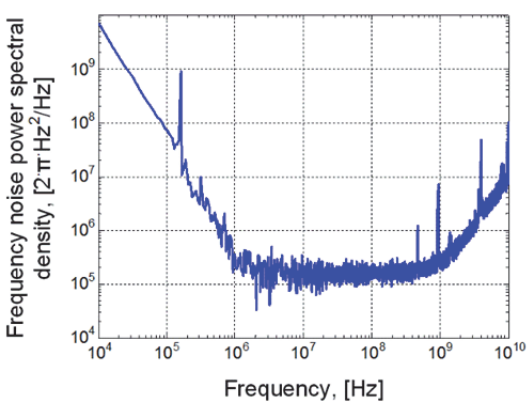


Fig. 14. ECL and LO laser frequency noise PSD obtained using a coherent receiver,

Since in case of DP-QPSK modulation also on the receiver side a laser source is used (i. e., Local Oscillator (LO) laser), which has a very narrow linewidth and is stable in time, it has been decided to characterize the frequency noises for two lasers at once. This could be done using this same coherent receiver and a digital storage oscilloscope (DSO). The electric signals Z_I and Z_Q from the coherent receiver output are fed to the DSO. In our case an *Agilent Technologies Digital Storage Oscilloscope DSO-X 93304Q* was used, which has a 33 GHz bandwidth and the sampling frequency of $80 \cdot 10^9$ samples per second (80 GSa/s). The Z_I and Z_Q signals are DSO-processed and stored for further processing by computer. The complex signal consisting of two measured Z_I and Z_Q signals/ones can be described as follows:

$$Z_k = Z_I(kT_0) + jZ_Q(kT_0) = \sqrt{P_S P_{LO}}\exp\{j\vartheta kT_0 + j\varphi_k\} + n_k \tag{9}$$

In this case, Z_k is the complex signal sample that is measured at the sampling frequency $R = 1/T_0$. The P_s and P_{LO} are the optical signal power values of the tested and LO laser, respectively. The term designated as $\Delta\vartheta$ is the frequency shift between the tested and LO laser radiation frequencies; φ_k is the sample of the optical signal phase with respect to the LO signal phase; n_k is the additive noise sample. It should be stressed that such a method of measurements allows simultaneous experimental estimation of combined characteristics of both lasers (the tested or signal and LO ones).

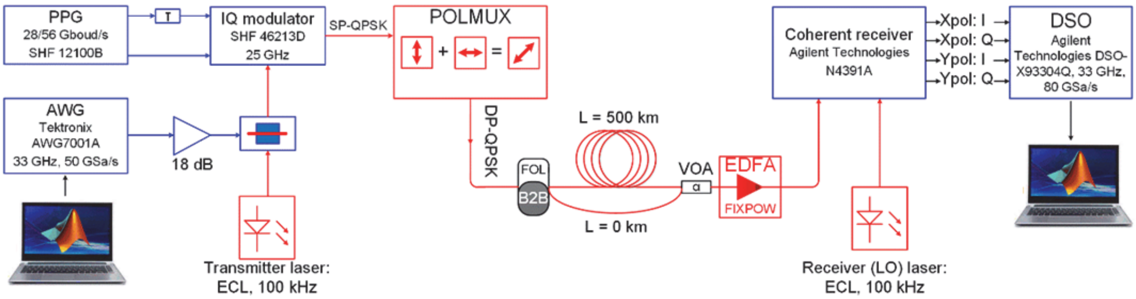


Fig. 15. Experimental scheme used for determination of the influence exerted by frequency noise with different characteristic values on the transmission quality in a coherent FOTS

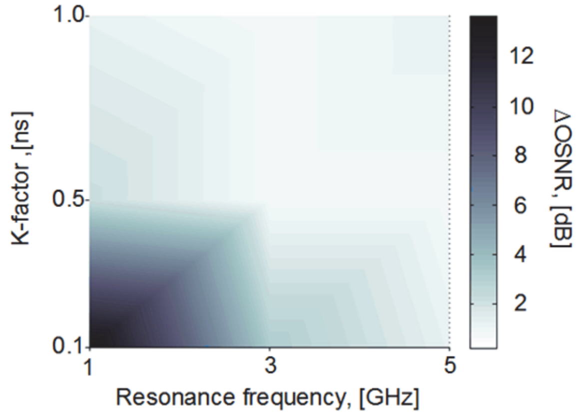
Determining the frequency noise PSD for the used ECL and LO lasers, their summary linewidth has also been defined (see Fig. 14). In this case, it is not greater than 200 kHz, which implies that this method allows for fast enough and precise determination of the radiation linewidth. If in the receiver a "worse" laser were used, the frequency noise PSD and the linewidth obtained by this method would characterize just transmitter laser but not the LO one. In this case, the LO lasers are also ECL, with the linewidth being <100 kHz. As a result, in order to determine exactly the influence of frequency noise on the signal quality it has been decided to "put" the generated frequency noise on the ECL radiation (see equation (10)) using an arbitrary waveform generator (AWG), see Fig. 15.

$$S_\vartheta(f) = \frac{10^9 \cdot \Delta_{\vartheta(1/f)}}{\pi \cdot f} + \frac{\Delta_{\vartheta int}}{\pi \cdot (1+\alpha^2)}\left(1 + \alpha^2 \frac{f_R^4}{\left(f_R^2 - f^2\right)^2 + \left(\frac{K \cdot f_R^2}{2 \cdot \pi}\right)^2}\right) \tag{10}$$

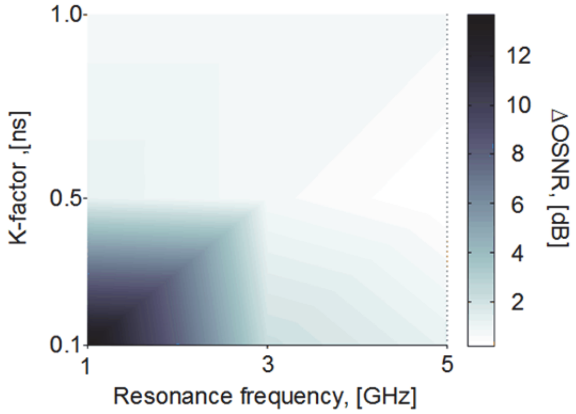
The parameters included in the model of the single-sided power spectral density function of frequency noise described in (10) are as follows.

1) $\Delta_{\vartheta(1/f)}$ describes the level of $1/f$ noise at 1 GHz;
2) $\Delta_{\vartheta int}$ describes the level of the intrinsic frequency noise at low frequency; in the literature this parameter is sometimes referred to as high frequency linewidth (HFLW);
3) f_R is the resonance frequency and the K-factor describes how the damping rate increases with the relaxation frequency. The K-factor of the semiconductor lasers is approximately bias independent and in the range of $0.1 - 1 \cdot 10^{-9}$ $[s]$.
4) α parameter determines the carrier induced frequency noise that gives rise of the noise peak around the resonance frequency.

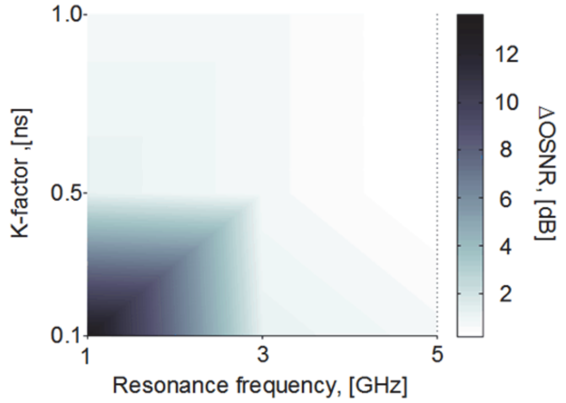
For the generation of frequency noise, its single-sided spectrum has been used, which has been changed by varying the HFLW, K-factor, and resonance frequency values. These values have been chosen in such a way that they would characterize the most probable frequency noises in the tunable semiconductor telecommunication lasers. The resulting values are the following: *(i)* f_R — resonance frequency of 1, 3 and 5 GHz; *(ii)* K-factor of 0.1 ns, 0.5 ns and 1 ns; *(iii)* HFLW of 1 MHz, 10 MHz and 20 MHz.



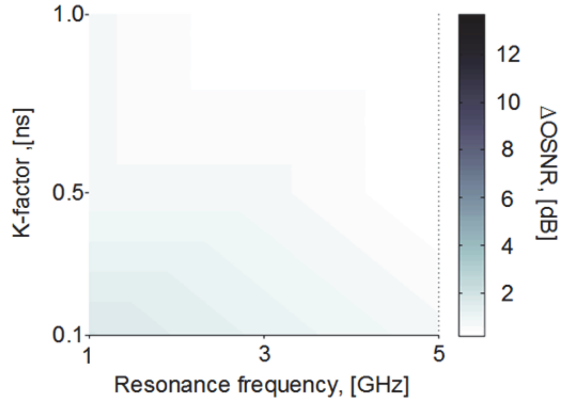
a)112 Gbps DP-QPSK, $\Delta_{\vartheta int} = 20\ MHz$



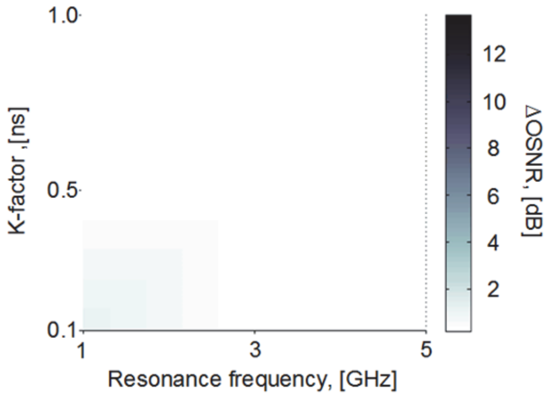
b) 224 Gbps DP-QPSK, $\Delta_{\vartheta int} = 20\ MHz$



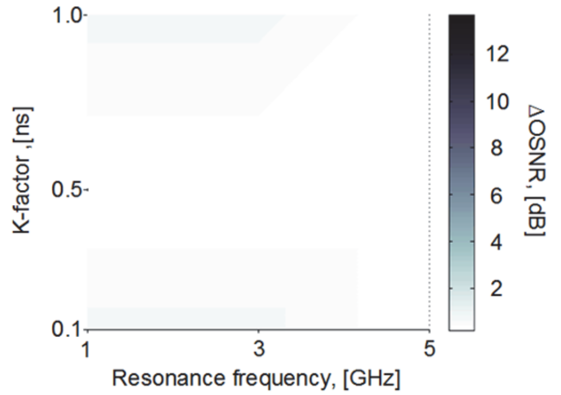
c) 112 Gbps DP-QPSK, $\Delta_{\vartheta int} = 10\ MHz$



d) 224 Gbps DP-QPSK, $\Delta_{\vartheta int} = 10\ MHz$



e) 112 Gbps DP-QPSK, $\Delta_{\vartheta int} = 1\ MHz$



f) 224 Gbps DP-QPSK, $\Delta_{\vartheta int} = 1\ MHz$

Fig. 16. OSNR penalty [dB] for reaching $2 \cdot 10^{-3}$ BER threshold in 112 Gbps and 224 Gbps DP-QPSK coherent transmission cases at different parameters of frequency noise

In total, a run of 27 measurements has been taken for each transmission rate (28 Gbaud/s and 56 Gbaud/s, which in case of DP-QPSK modulation corresponds to 112 Gbps and 224 Gbps). In case when the phase noise is not put on the ECL radiation, the OSNR level is to be 8.8 dB and 11.3 dB in order to achieve BER threshold of $2 \cdot 10^{-3}$ in 112 Gbps and 224 Gbps DP-QPSK cases. When this threshold is reached, it is assumed that the transmitted information can be renewed using FEC (see [22]). The measurement results are shown in Fig. 16. Note that the OSNR level in both cases (28 Gbaud/s and 56 Gbaud/s) has been determined at a distance of 0.2 nm from the signal peak.

Having analyzed the obtained measurement results, we can conclude that the worst case is a = [1 GHz, 0.1 ns, 20 MHz]. At such frequency noise parameters we will have $\Delta OSNR > 13\,dB$ (see Fig. 16 (a) and (b)). As the best parameter combination we can consider c = [5 GHz, 1 ns, 1 MHz]. In this case, $\Delta OSNR$ does not exceed 0.2 dB (see Fig. 16 (e) and (f)). In most cases considered, the OSNR difference is not greater than 0.7 dB. The intermediate case is b = [3 GHz, 0.5 ns, 10 MHz]. The corresponding frequency noise PSD diagrams are shown in Fig. 17.

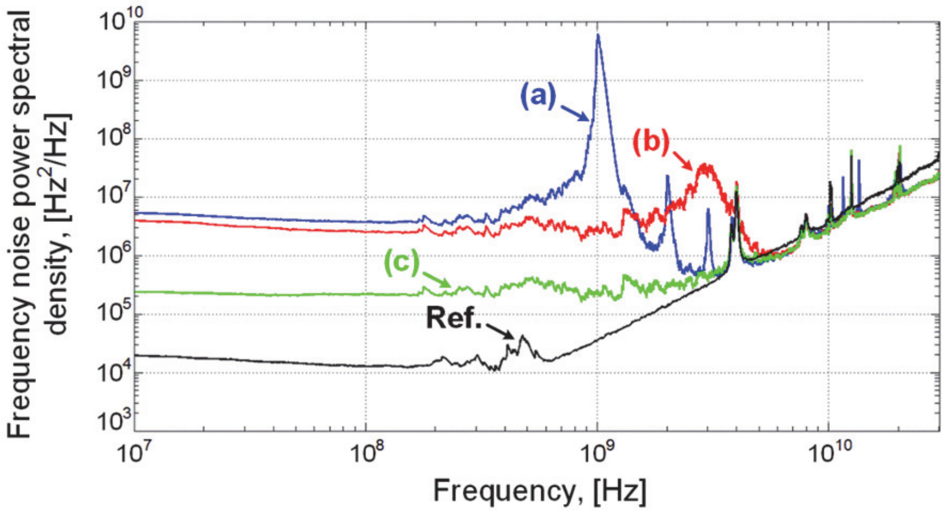


Fig. 17. PSD diagrams of frequency noise at a = [1 GHz, 0.1 ns, 20 MHz], b = [3 GHz, 0.5 ns, 10 MHz] and c = [5 GHz, 1 ns, 1 MHz]

As a result, it has been determined that for 100 G and even 200 G DP-QPSK transmission as a transmitter laser the semiconductor lasers can be used, whose linewidth at high frequencies is up to 20 MHz provided the K-factor and the resonance frequency are greater than 0.5 ns and 3 GHz, respectively.

Chapter 5

This chapter is devoted to the relationship between the spectral and the energy efficiencies of data transmission. The chapter can be divided into two sections. In the first section, this relationship is studied for WDM-based FOTS in SLR design, where a single modulation format and bitrate a re used in all system channels. The primary task of this section is to identify the spectral efficiency values and SSMF span lengths (40 km, 80 km or 120 km) at which the systems without FEC provide lower energy per bit than similar solutions with FEC. In the second section, the energy efficiency is evaluated for the SLR- and MLR-based WDM systems, where aggregated traffic is transmitted using the maximum acceptable spectral efficiency. First, the optical signal modulation format is determined which allows achieving the lowest energy per bit in SLR systems. Then, the schemes used for allocation of 10 Gbps, 40 Gbps and 100 Gbps wavelengths to frequency band are studied along with their impact on the energy efficiency in MLR systems. Finally, the energy efficiencies of the spectral-efficient SLR and MLR solutions are compared.

For the analysis of energy efficiency in SLR systems, the curves have been obtained showing changes of the energy consumption required for 1 bit transmission of a definite signal quality depending on the spectral efficiency. In this study we have used three optical signal modulation formats — *(i)* 10 Gbps NRZ-OOOK, *(ii)* 40 Gbps NRZ-DPSK and *(iii)* 100 Gbps DP-QPSK as well as three SSMF spans lengths — *(i)* 40 km, *(ii)* 80 km, *(iii)* 120 km. It should be noted that 120 km long SSMF spans have been taken only in case of 100 Gbps DP-QPSK. This is explained by the received signal post-processing by digital signal processors (DSP). Evaluating the energy efficiency curves obtained for different link lengths and aggregated traffic, it can be concluded that the use of the 100 Gbps DP-QPSK ensures the best spectral efficiency in combination with the lowest energy per bit required for data transmission over a fiber-optical link (see Fig. 18). In addition, the use of longer SSMF spans allows for reduction in the energy consumption. In turn, for the 10 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK the SSMF span lengths should be chosen in respect of the spectral efficiency, the aggregated traffic to be transmitted, and the length of fiber-optical link.

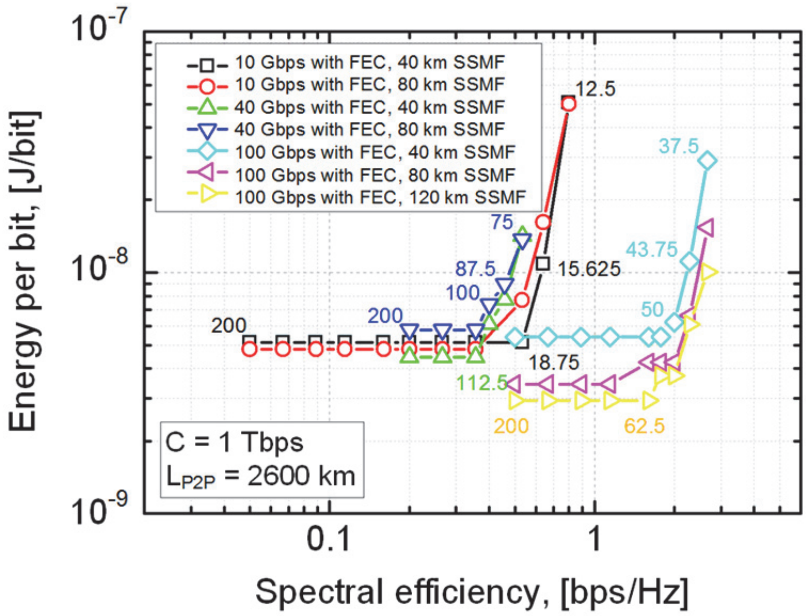


Fig. 18. Energy per bit as a function of spectral efficiency at 1 Tbps of aggregated traffic transmitted over 2600 km of point-to-point fiber-optical link. Numbers next to markers specify the channel spacing in [GHz] used to reach such spectral efficiency

In case when the aggregated traffic is hundreds of Gbps and the link length is few hundreds of kilometers, there is insignificant difference in the energy efficiency performance for different SSMF span lengths. Otherwise, the spectral efficiency should be considered an additional parameter when choosing the length of SSMF spans. If the channel spacing above 28.125 GHz is used in WDM systems with FEC and 10 Gbps wavelengths, the use of the 80 km long SSMF spans ensures a 7 % lower energy consumption as compared with that at other span lengths. For smaller channel spacing values, e. g., 18.75 GHz or even 15.625 GHz, the energy consumption required could be reduced by more than 30 % if instead of 80 km long SSMF spans 40 km spans are used in the fiber-optical link. In 40 Gbps NRZ-DPSK systems with FEC, a lower energy per bit is ensured at 40 km long SSMF spans, in this case the energy savings reach more than 20 % as compared with the case of 80 km spans used if the channel spacing exceeds 112.5 GHz. On the other hand, for a smaller channel spacing the difference in energy efficiency decreases in cases of SSMF spans between 40 km and 80 km. At the minimum acceptable channel spacing (75 GHz) this difference disappears.

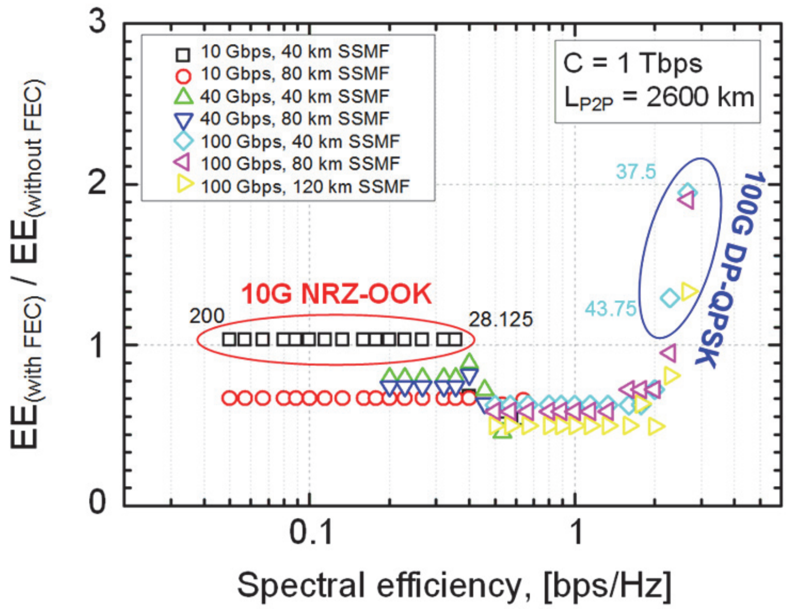


Fig. 19. The energy efficiencies of WDM systems with and without FEC for aggregated traffic set to 1 Tbps and the fiber-optical link length of 2600 km

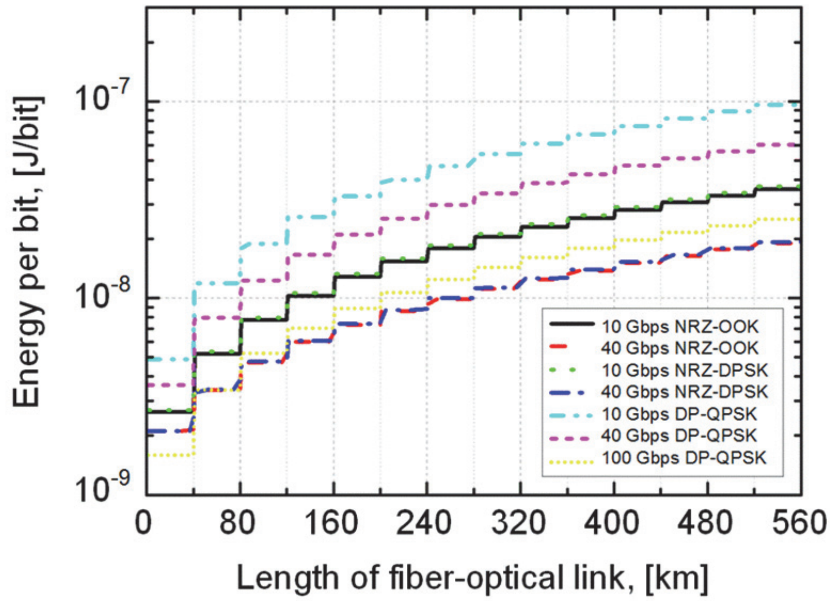


Fig. 20. Energy per bit in spectral-efficient SLR-based WDM systems ($L_{max} = L_{SSMF}$) as a function of fiber-optical link length

The FEC-free WDM transmission systems in terms of energy efficiency outperform those with FEC only in case of 100 Gbps DP-QPSK when the spectral efficiency is set close or equal to the maximum acceptable. Energy savings increase with the number of 3R operations. For example, these savings are more than 50 % if C = 1 Tbps while L_{P2P} = 2600 km (see Fig. 19). For some combinations of SE, C and L_{P2P} parameters, the 10 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK systems without FEC are more energy efficient than those without FEC, but the difference is not greater than 3–7 %. This could be considered negligibly small.

Having assessed the energy efficiency in spectral-efficient SLR systems, it must be concluded that the least energy consumption per bit of aggregated traffic can be provided using the non-coherent 40 Gbps solutions. In this research, two non-coherent solutions have been considered — 40 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK. In terms of energy efficiency, the difference between these two solutions is insignificant. In WDM systems with a high spectral efficiency, the optical signals must be regenerated quite often (e. g., at each node if the maximum acceptable SE is used) to fulfill the QoT requirements. Therefore, the energy consumption required for 1 bit transmission is mainly defined by the power consumption of 3R regenerators. The least energy for 1 bit regeneration is consumed both by 40 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK 3R regenerators, while the most energy-efficient transponder is for 100 Gbps DP-QPSK format. As a result, the use of 40 Gbps NRZ-DPSK instead of 100 Gbps DP-QPSK allows saving 25 % of energy consumption, which would be required for 1 bit transmission over a 527 km long link in spectral-efficient SLR system (see Fig. 20). The energy savings increase with the length of fiber-optical link, e. g., it reaches 33 % for transmission over the L_{P2P} = 1000 km.

In the mixed line rate (MLR) WDM systems, the energy efficiency of transmission will depend on the scheme used for allocating 10 Gbps, 40 Gbps and 100 Gbps wavelength channels to a frequency band. In this research, these wavelengths are placed in specially designated sub-bands (see Fig. 21). The width of each sub-band can vary depending on the taken distribution among 10 Gbps, 40 Gbps and 100 Gbps wavelengths. The sub-bands are separated using the previously detected sub-band spacing, while wavelengths within one sub-band are separated using the previously determined minimum acceptable channel spacing. Therefore, the width of each sub-band, the channel spacing within one sub-band and the sub-band spacing will predefine the number of particular wavelengths that could be compacted in a frequency band available for data transmission, which would mean increase in the overall energy efficiency itself.

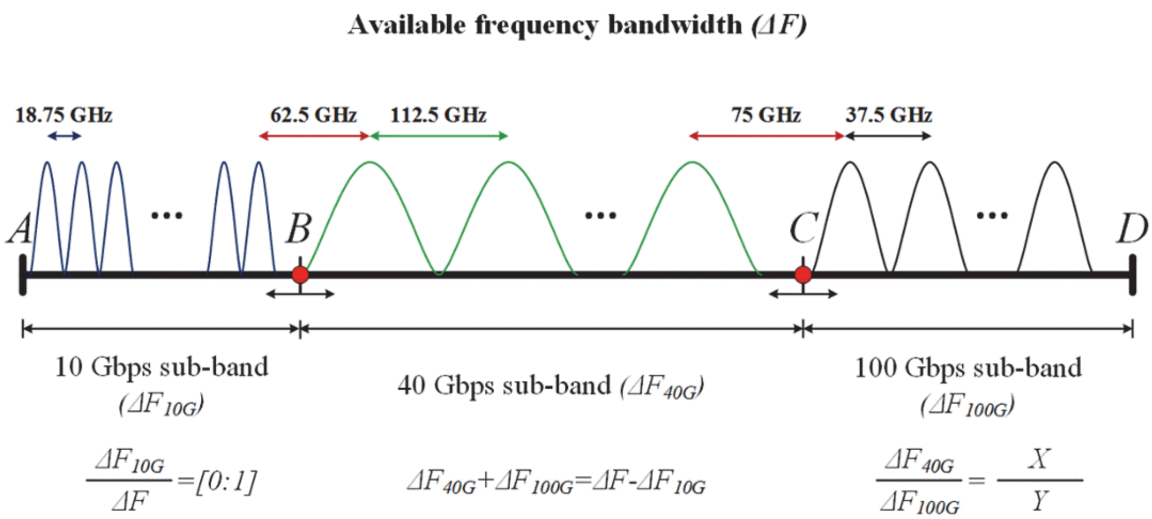


Fig. 21. Sub-band and channel allocation to 10-40-100 Gbps WDM system frequency band available for transmission

Having analyzed the schemes used for placing 10 Gbps, 40 Gbps, and 100 Gbps wavelengths in a transmission band, it should be concluded that there is the so-called “point of equal energy efficiency” (see Fig. 22). At this point, the energy consumption required for 1 bit transmission is equal for all MLR solutions considered, i. e., independent of the frequency band distribution among 10 Gbps, 40 Gbps, and 100 Gbps wavelengths. Its location depends on the length of fiber-optical link and the ratio between the power consumption values of transponders and 3R regenerators. In cases of considered distributions, this point is achieved when 10 Gbps NRZ-OOK channels occupy no more than 40 % of the entire frequency band. It should be highlighted that both the spectral efficiency and the energy efficiency could be improved in MLR systems with relatively short links ($L_{P2P} \leq 200\ km$) if a higher bandwidth is assigned to 100 Gbps DP-QPSK wavelengths. In turn, for longer links the higher bandwidth should be assigned to 40 Gbps NRZ-DPSK wavelengths if the goal is the improvement of energy efficiency.

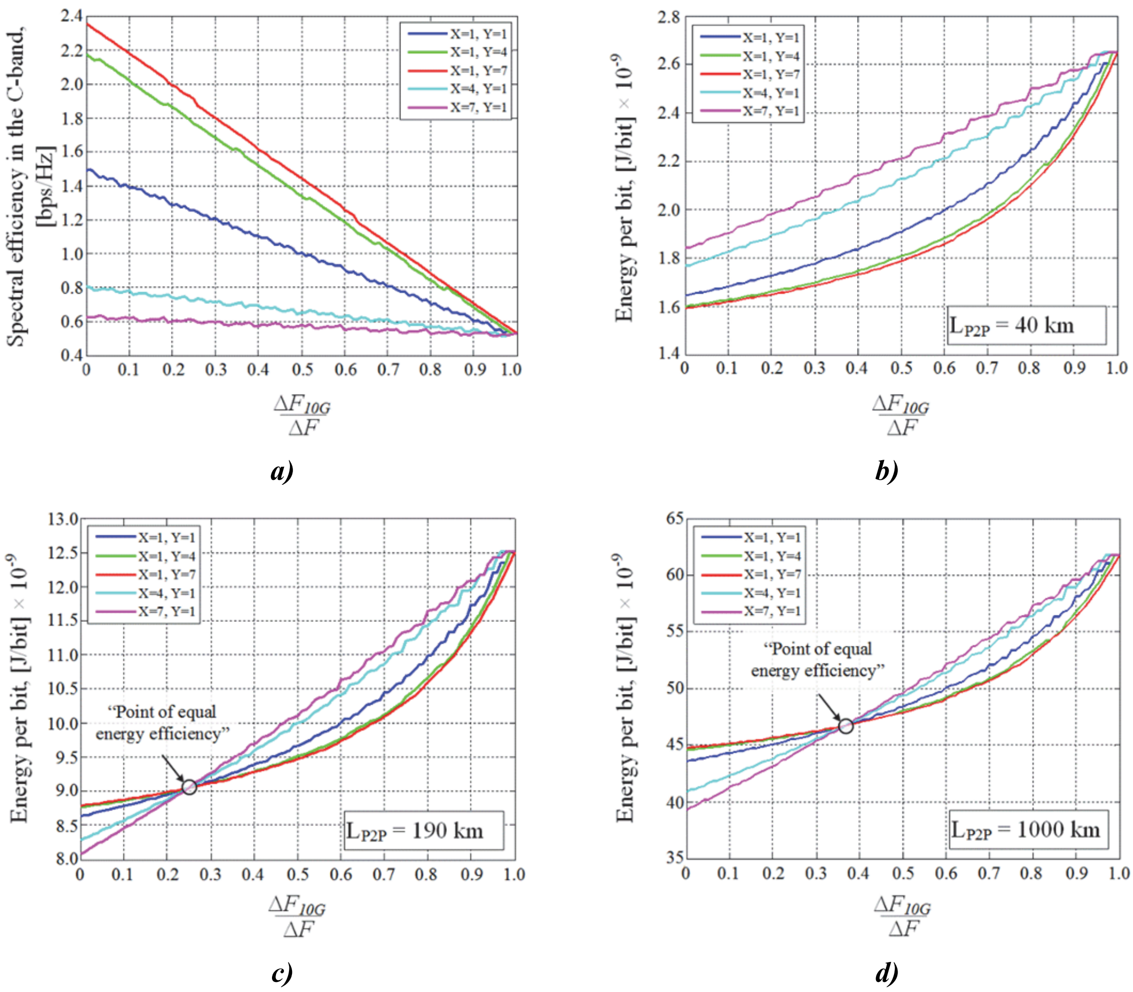


Fig. 22. Spectral efficiency over the C-band (a) and energy per bit as a function of the width of each sub-band and of the fiber optical link length: (b) L_{P2P} = 40 km, (c) L_{P2P} = 190 km, and (d) L_{P2P} = 1000 km

If for determination of the width of each sub-band the ratio among 10 Gbps, 40 Gbps and 100 Gbps requests is used, the energy efficiency of such MLR FOTS is: *(i)* higher than it would be according to 10 Gbps SLR solution at the transmission distance above 200 km ($L_{P2P} > 200\ km$); *(ii)* the same as for 100 Gbps SLR if $120 \leq L_{P2P} \leq 200\ km$; *(iii)* lower than for 100 Gbps SLR solution at $L_{P2P} < 120\ km$. In turn, 40 Gbps NRZ-DPSK SLR solution ensures a lower energy consumption per bit of aggregated traffic transmitted as compared with the MLR solution with the link length not limited by one SSMF span (see Fig. 23).

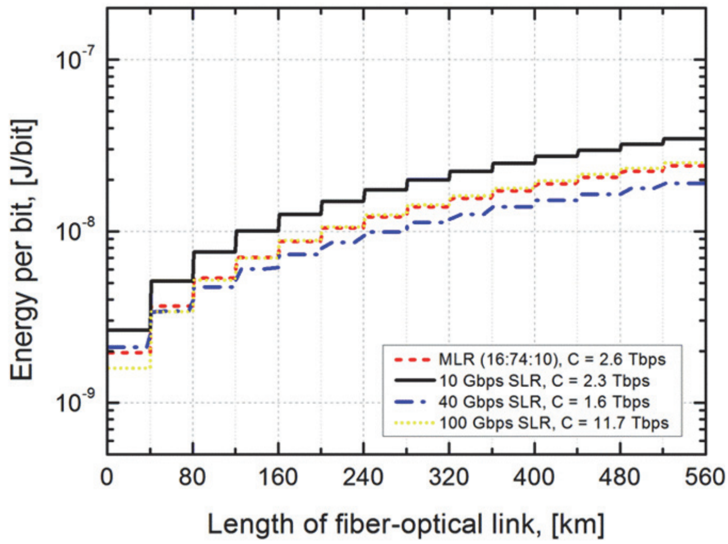


Fig. 23. Energy per bit as a function of fiber-optical link lengths in spectral efficient SLR and MLR ($\Delta F_{10G} = 16$ %, $\Delta F_{40G} = 74$ % and $\Delta F_{100G} = 10$ %) WDM networks

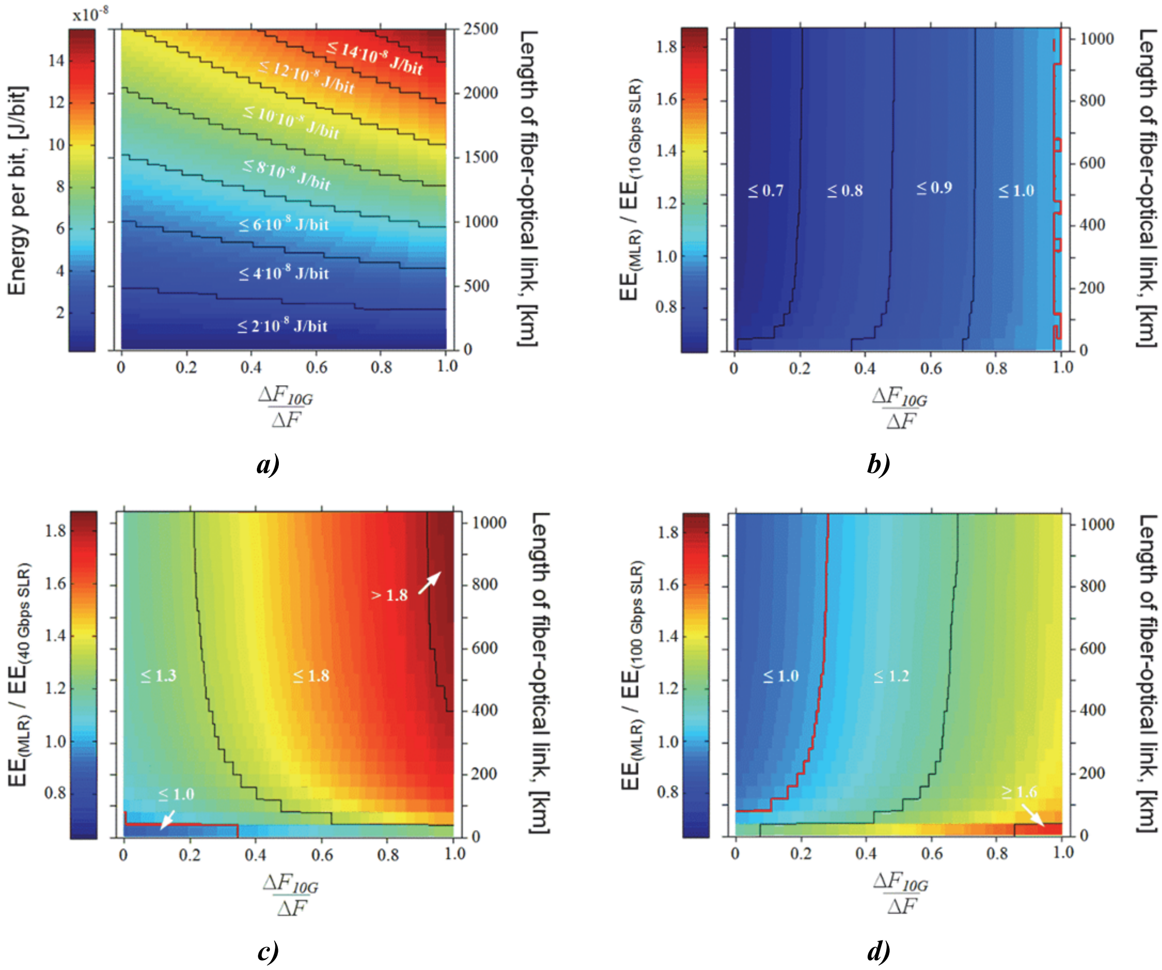


Fig. 24. Energy per bit in the spectral-efficient 10-40-100 Gbps MLR-based WDM system (X = 7, Y = 1): (a), the ratio between the energy per bit of such MLR solution over (b) 10 Gbps, (c) 40 Gbps, and (d) 100 Gbps SLR-based WDM solutions as a function of the fiber-optical link length and of the sub-band width for 10 Gbps NRZ-OOK wavelengths

In addition, the energy efficiency of the MLR system has been compared with that of the considered 10 Gbps, 40 Gbps, and 100 Gbps SLR solutions. This comparison has been made at various sub-band widths that are assigned to 10 Gbps NRZ-OOK wavelengths in a 10-40-100 Gbps MLR system where $\Delta F_{40G} = 7 \cdot \Delta F_{100G}$ (see Fig. 24). Analysis of these results shows that *(i)* lower energy per bit could not be secured by 10 Gbps SLR system solutions as compared with those according to the explored MLR solution, where 10 Gbps NRZ-OOK wavelengths occupy no more than 80 % of the overall frequency band; *(ii)* the explored 40 Gbps SLR solution ensures lower energy per bit than in such MLR solution unless the length of fiber-optical link is limited by one SSMF span and 10 Gbps NRZ-OOK wavelengths occupy more than 35 % of frequency band available for data transmission using the studied configuration of the MLR system; *(iii)* such MLR configuration ensures lower energy per bit as compared with 100 Gbps SLR solution unless the link length is limited by a few spans of SSMF and 10 Gbps NRZ-OOK wavelengths occupy more than 25 % of the frequency band. Otherwise, the use of the 100 Gbps SLR solution reduces the energy consumption for 1 bit transmission to 70 % as compared with the studied MLR case.

Therefore, the energy efficiency in a mixed line rate WDM-based FOTS depends on the aggregated traffic to be transmitted over a particular length of fiber-optical link and on the number of 10 Gbps, 40 Gbps and 100 Gbps wavelengths that must be used for this purpose. This number of channels, the length of fiber-optical link, and the number of 3R regenerator nodes will dictate either this MLR system outperforms in terms of energy efficiency a particular SLR solution or not.

THE MAIN RESULTS OF THE DOCTORAL THESIS

The main **results and conclusions** of the Doctoral Thesis achieved during fulfilment of the tasks defined in Chapter 1 are as follows.

1. The improved DWDM grid designed in this Thesis can be used for spectral efficiency improvement in FOTS while keeping the previously implemented optical wavelength filters. It is experimentally determined that AWG optical filters with 58 GHz bandwidth at a level of −3 dB and 130 GHz bandwidth at a level of −20 dB can be used for separation of 10 Gbps NRZ-OOK modulated wavelengths in case of 50 GHz channel spacing even if a manufacturer specified how to use such a filter for 100 GHz channel spacing. In this case, the received signal quality does not meet the $BER \leq 1 \cdot 10^{9}$ requirement only if wavelength channels are compacted using the channel spacing not higher than 37.5 GHz. It should be noted that the signal quality at the receiving node is defined mainly by the linear crosstalk from adjacent channels (wavelengths).
2. The maximum acceptable spectral efficiency for the defined signal quality ($BER \leq 2 \cdot 10^{-3}$) at the receiving node can be obtained in a WDM-based FOTS with FEC, where 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK wavelengths are collocated using 12.5 GHz, 75 GHz and 37.5 GHz channel spacing, respectively. In FOTS without FEC, these intervals are 15.625 GHz, 87.5 GHz and 37.5 GHz, respectively.
3. The spectral efficiency of the frequency band can be increased up to two times if for channel separation in mixed line rate WDM FOTS instead of the fixed DWDM grating described in the ITU-T recommendation the improved grating with unequal frequency intervals is used. The increase in spectral efficiency depends on the initial system configuration that determines the data transmission rate and modulation formats in different channels (at different wavelengths).
4. Using the derived transmission models for 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK formats, it is determined that in cases of the non-coherent modulation formats the largest system reach is secured in the WDM FOTS configuration

with FEC and 40 km SSMF spans. In turn, 80 km or even 120 km SSMF spans should be used in case of 100 Gbps coherent DP-QPSK. This improves system reach by more than 30 %.

5. The quality of transmission in case of coherent modulation formats depends not only on the linewidth of transmitter laser but also on the shape of its frequency noise spectrum, which is determined by such parameters as carrier resonance frequency, K-factor and high-frequency linewidth (HFLW). The coherent FOTS using DP-QPSK for optical signal modulation with a higher baudrate is more resistant against frequency noise from transmitter's laser source than in the solution with a lower baudrate.
6. The use of non-coherent modulation format (e. g. NRZ-OOK and NRZ-DPSK) in cases of 40 Gbps bitrate allows for saving up to 30 % from the energy that would be needed for transmitting 1 bit in the 100 Gbps DP-QPSK case if the optical fiber link length is 1000 km, while the distance between two consecutive 3R regenerators due to the spectral efficiency is one 40 km span of SSMF. In turn, if the distance between two 3R regenerators is significantly greater than the length of a standard single-mode fiber span (L_{SSMF} = 40 km), then 100 Gbps DP-QPSK format provides the best spectral efficiency ($\gg$1 bit/s/Hz) in combination with the least energy consumption required for 1 bit transmission through a fiber-optical link.
7. Independently of the used configuration of the mixed 10-40-100 GbpsWDM FOTS there is also "the point of equal energy efficiency" determined by the number of 10 Gbps NRZ-OOK channels, by the energy efficiency of 40 Gbps and 100 Gbips transponders and 3R regenerators, and by the length of fiber-optical link after which a definite quality of the received signal must be guaranteed (e. g., $BER \leq 1 \cdot 10^{-9}$).

It should be emphasized that results obtained while working on this Doctoral Thesis can be applied for improvement of spectral and energy efficiency of transmission in wavelength division multiplexing fiber optical networks at the stages of their designing and commercial use.

During the research, several Latvian patents have been obtained and submitted. In particular, a measurement scheme that allows evaluating the efficient bandwidth of optical wavelength filters has been patented (Latvian patent No. 14557). Also, the prototype of spectral-efficient wavelength division multiplexing communication systems with polarization shift keying in the system third channel has been patented (Latvian patent No. 14565). The channel spacing used in this prototype is 75 GHz (or 0.6 nm) and it increases spectral efficiency to 0.40 bps/Hz. Another application for the Latvian patent (application No. P-12-15) is pending, which is related to the design of the wavelength division multiplexing communication systems of energy-efficient mixed line rate at data rates of 10 Gbps, 40 Gbps and 100 Gbps.

Finally, it should be highlighted that in collaboration with the Optical Networks Laboratory (ONLab) of the Royal Institute of Technology (KTH), a Visby programme grant has been given by the Swedish Institute (SI) for the R&D project "Green 3R Placement Strategies for WDM Networks with Mixed-Line-Rate".

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