

Spectral and Energy Efficiency Considerations in Mixed-Line Rate WDM Networks with Signal Quality Guarantee

Aleksejs Udalcovs*, *Student Member, IEEE*, Paolo Monti**, *Member, IEEE*, Vjaceslavs Bobrovs*, *Member, IEEE*, Richard Schatz**, *Member, IEEE*, Lena Wosinska**, *Senior Member, IEEE*, and Girts Ivanovs*

* *Institute of Telecommunications, Riga Technical University, Azenes str. 12, LV-1048, Riga, Latvia*

** *KTH Royal Institute of Technology, Isaffordsgatan 22, SE-164 40, Kista, Sweden*

* *Tel: (+371) 28293227, e-mail: Aleksejs.Udalcovs@rtu.lv*

ABSTRACT

Mixed-Line Rate (MLR) is a cost efficient solution to cope with the rapidly increasing and heterogeneous Internet traffic. In a MLR-based scenario wavelength channels are organized in groups (*i.e.*, sub-bands), each of which consisting of channels operating at the same rate, *e.g.*, it is possible to have on the same fiber link sub-bands operating at 10 Gbps, 40 Gbps, and 100 Gbps. In order to increase spectral efficiency one can reduce not only the channel spacing within a sub-band but also the frequency spacing between sub-bands operating at different rates, *i.e.*, the sub-band spacing. On the other hand smaller sub-band spacing may: (i) negatively impact the transparent optical reach of wavelength channels due to the higher inter-channel crosstalk levels, and consequently (ii) increase the network power consumption because of the need of more signal regeneration.

This paper aims at assessing the trade-off between spectral efficiency and the power consumption in a WDM transport network, when a certain quality of transmission needs to be guaranteed at the receiving node. This is accomplished by evaluating a number of spectral efficient MLR solutions, where the number of wavelength channels allocated to each sub-band is varied while keeping the required Bit Error Rate (BER) level at the receiving node fixed. Results show that the width of each sub-band plays a central role in determining the power consumption of an end-to-end connection.

Keywords: energy efficiency, mixed-line rate, spectral efficiency, frequency sub-band, sub-band spacing, channel spacing, optical reach.

1. INTRODUCTION

Network operators are currently facing a challenge that is twofold [1, 2]. On the one hand, the power consumption of the network infrastructure amounts to approximately 12% of the total power necessary to accommodate the Internet traffic. This value is expected to reach 20% by 2020 [3]. On the other hand, the Internet traffic is constantly growing (*i.e.*, 38% annually, at least for the IP backbone [4]) and becoming more and more heterogeneous with respect to the application supported, *e.g.*, a mix of low-bit-rate and high-bit-rate services [1]. This scenario translates into the need for a capacity upgrade of the network infrastructure, while limiting as much as possible the increase in the total power consumption [2].

The Mixed-Line Rate (MLR) concept can be helpful in this regard [5-7]. MLR provides operators with a cost efficient solution to increase the network capacity (*i.e.*, it makes it possible to allocate additional high speed wavelength channels (40 Gbps and/or 100 Gbps) next to the legacy ones (10 Gbps)), while at the same time allowing for a contained power consumption increase thanks to the deployment of transponders using highly efficient modulation formats (*i.e.*, with a high number of bits per symbol) [8]. In a MLR scenario wavelength channels are organized in several groups (here referred to as *sub-bands*), each of which consisting of wavelength channels operating on the same bit rate, *i.e.*, there can be groups of channels transmitted at 10 Gbps, at 40 Gbps, and at 100 Gbps [2].

The design of MLR optical networks can be optimized with respect to a number of performance parameters. One aspect that is important to consider to further increase the network capacity is spectral efficiency (SE), *i.e.*, the amount of bits per seconds transmitted over a given frequency band [8]. There is a number of ways in which spectral efficiency can be improved. One is to increase the percentage of wavelength channels supporting high rates (*e.g.*, operating at 100 Gbps) on a single fiber link. Another possibility (not mutually exclusive with the first one) is to reduce the frequency spacing (*i.e.*, the *sub-band spacing*) between the various sub-bands, where usually 200 GHz intervals are used between 10G/40G and 40G/100G sub-bands [2].

On the other hand, an improved spectral efficiency (achieved via either an increased number of wavelength channels working at high transmission rates or by reducing the spacing between sub-bands) may in turn exacerbate the effect of the optical transmission impairments. As a result the maximum distance that an optical signal can travel without regeneration, *i.e.*, the *transparent reach*, can be reduced [7]. This means that when a specific signal quality has to be guaranteed at the receiving node the optical signal might need regeneration along the way. Regeneration operations, also known as 3Rs (*i.e.*, re-amplification, re-timing, re-shaping) usually involve optical-to-electrical-to-optical (OEO) conversion, which translates into: (i) the need for extra equipment (*i.e.*, 3Rs) at selected nodes in the network, and (ii) an increased overall power consumption [8]. In other words

there is a clear trade-off between spectral efficiency, transparent reach, and power consumption in the network. All these three aspects are closely interrelated and an optimized MLR design process needs to carefully consider how these three parameters influence each other's.

In the literature this trade-off is only partially addressed. The authors in [9] investigate the relationship between energy and cost minimization while designing MLR optical networks. In [7] the authors investigate the trade-off between the bit rate, the modulation format and the cost of a transponder with respect to its transparent optical reach. However, in these papers, no investigation is made on how the relative width of a certain sub-band in a MLR system influences the network power efficiency. Additionally, authors do not address the more general relationship between achievable spectral efficiency, transmission capacity, optical reach, and power consumption when different transponders working at different bit rates co-exist in the same fiber link. This aspect is only partially addressed in [10], where, on the other hand, only a single line rate scenario is considered (*i.e.*, 100 Gbps).

This paper aims at assessing the trade-off between spectral efficiency, power consumption, and optical reach in a MLR-based wavelength division multiplexing (WDM) transport network. More specifically, the objective of this work is to evaluate the power consumption per transmitted bit (W/bps) required to establish end-to-end connections while guaranteeing a specific quality of transmission (QoT) level. This is accomplished by evaluating a number of spectral efficient MLR solutions, where the number of wavelength channels allocated to each sub-band used for transmitting over one or more unamplified fiber spans is varied, while keeping the required Bit Error Rate (BER) level at the receiving node fixed. The line rates considered on each fiber link are: the legacy 10 Gbps Non-Return-to-Zero (NRZ) On-Off Keying (OOK), 40 Gbps NRZ encoded Differential Phase-Shift Keying (NRZ-DPSK) because of its energy efficiency over long haul transmission distances (*i.e.*, when compared to 10G NRZ-OOK), and 100 Gbps DP-QPSK, the 100 Gbps solution that is most used in commercially deployed networks. Spectral efficiency (bps/Hertz) is dependent on the number of bits per symbol used by a specific modulation format; on the number of wavelength channels within the same sub-band and their minimum allowable channel spacing; and on the minimum frequency spacing between sub-bands working at different rates. The values for the channel spacing (*i.e.*, within the same sub-band) and the sub-band spacing (*i.e.*, between sub-bands) are chosen to avoid excessive signal degradation due to crosstalk from adjacent channels and sub-bands, respectively. The power efficiency (W/bps) for each modulation format is calculated using the total power consumption of the corresponding transponders and (when required) the energy cost for additional 3Rs used at intermediate nodes.

Simulation results confirm the earlier intuition that focusing exclusively on spectral efficient solutions may result in extra power consumption. This is especially true over long distances (*i.e.*, multiple fiber spans) where, in order to ensure stringent quality of transmission levels together with high spectral efficiency, the optical signal needs to be regenerated quite often.

2. SYSTEM ARCHITECTURE AND SIMULATION SET UP

This section describes the assumptions for the MLR WDM link used for investigating the relationship between the minimum value of the sub-band spacing and the signal quality at the receiver (section 3). The section is then concluded by presenting the set up used for the RSoft OptSim simulation software.

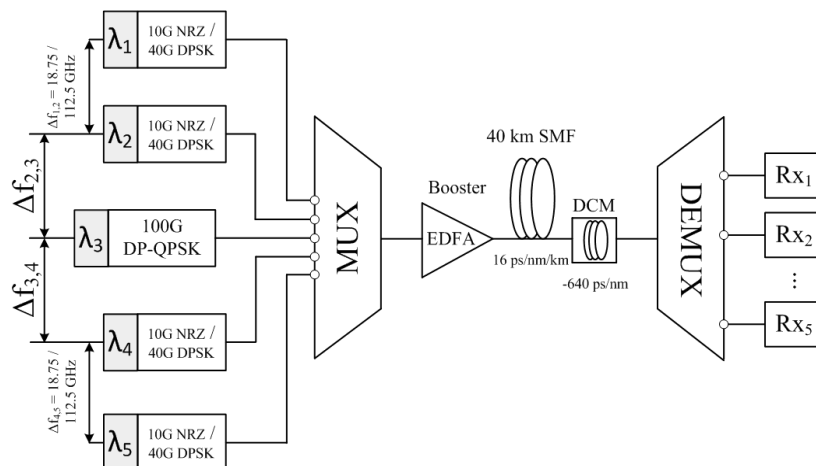


Figure 1. Layout of a Multi-Line Rate WDM fiber-optical link.

The MLR WDM link under exams is shown in Fig. 1. The transmission distance is limited to one fiber span. The WDM system consists of: five transmitters that may be different depending on the rates considered in a specific experiment (*i.e.*, 10G/10G/100G/10G/10G, 40G/40G/100G/40G/40G, or 10G/10G/100G/40G/40G, respectively); a wavelength multiplexer (MUX); a booster amplifier; a single mode transmission fiber (SMF);

a chromatic dispersion compensation module (DCM); a wavelength demultiplexer (DEMUX); and five receivers (Rx_i) that exactly match the sequence and the order of the transmitters. In a realistic long-reach WDM system there would be also a number of fixed-gain inline optical amplifiers (to compensate for the attenuation in the SSMF and the DCM), and a pre-amplifier before the demultiplexer. However, since this study is focused on the maximum tolerable spectral efficiency (SE) for a signal transmitted over a single span, these amplifiers are not considered. When evaluating the signal quality at the receiver it is assumed that the following effects are predominant: (i) linear crosstalk of the second channel (λ_2) as a result of the traffic on the first (λ_1) and the third (λ_3) channel (in a completely symmetric way the third (λ_3) and fifth (λ_5) channels affect the crosstalk levels of the fourth channel (λ_4)); and (ii) linear crosstalk of the third channel (λ_3) as a consequence of the traffic on the second (λ_2) and the fourth (λ_4) channel.

Table 1. Optical and electrical filter parameters.

Bitrate and modulation format	10 Gbps NRZ-OOK	40 Gbps NRZ-DPSK	100 Gbps DP-QPSK
Bessel electrical filters			
▪ Number of poles	5	5	5
▪ -3 dB bandwidth, [GHz]	10	65	20
Super-Gaussian optical filters			
▪ Order	1	2	2
▪ -3dB two-sided bandwidth, [GHz]	14	70	40

The Synopsys' RSoft OptSim 5.3 software was used to perform the required simulations. The software solves the nonlinear Schrödinger equation using a time domain split-step algorithm. The Q-value of the received signal is used to measure the optical signal quality. The accuracy of the obtained Q-factor values strongly depends on the total number of simulated bits. In our simulations, we used at least 2500 bits that yields a Q-factor uncertainty range below 0.5 dB.

The transmitter and the receiver are selected depending on the modulation format and the bitrate considered during each specific experiment. The OptSim block diagrams for the transmitter and receiver of NRZ-OOK and NRZ-DPSK transmitting and receiving units can be found in [11], while the transmitter and receiver description for the DP-QPSK is provided in [12]. The transmitters are driven by rectangular shape NRZ signals filtered through an electrical low pass Bessel filter. For DP-QPSK a Super-Gaussian optical filter is used after the transmitter. A similar optical filter is applied before detection at the receiver side for all modulation formats. The number of poles and the bandwidth of the optical and electrical filters are shown in Table 1. These filter parameters were chosen to provide the maximum Q-value for the WDM system under exam when the channels are arranged using 25 GHz channel spacing for the 10 Gbps NRZ-OOK; 50 GHz for the 100 Gbps DP-QPSK; and 200 GHz for the 40 Gbps NRZ-DPSK. In this scenario the noise level is low and the obtained values of Q factor are assumed to be mainly limited by interchannel crosstalk. Such frequency intervals are common for the modulation formats and for the per-channel bitrates considered. As a booster, we used an Erbium Doped Fiber Amplifier (EDFA) with a fixed output power level (*i.e.*, 10 dBm) chosen to compensate the signal attenuation in the transmission fiber and in the DCM. As a transmission fiber, we used a standard single mode fiber (SSMF) while for chromatic dispersion (CD) compensation we considered a dispersion compensating fiber (DCF). The SSMF and DCF lengths are 40 km and 8 km, respectively. The fibers' parameters used in this work are the same as the ones in [13]. On the receiver side, OOK signals were detected using a single PIN photodetector and DPSK signals with two balanced photodetectors, respectively. The PIN photodiodes were assumed to have 80% of quantum efficiency. A coherent receiver was used to decode DP-QPSK signals.

3. RESULTS AND DISCUSSION

In this section the trade-off between achievable spectral efficiency, power consumption, and transparent reach is evaluated. The focus of the study is on a system without Forward Error Correction (FEC) and with a required Bit Error Rate (BER) level less than 10^{-9} . First, the power consumption of transponders and 3Rs is presented. Then, the minimum sub-band spacing value is determined by studying the degradation of the Q-factor of the received signal due to interchannel crosstalk over a single fiber span of 40 km. Finally, the power efficiency (W/bps) as a function of the distance is studied for a point-to-point MLR-based WDM transmission system (possibly covering multiple fiber spans) configured for maximum spectral efficiency.

3.1 Power consumption of transponders and regenerators

The power consumption values of transponders (TSPs) and regenerators (3Rs) for each of the line rates considered (*i.e.*, 10 Gbps, 40 Gbps, and 100 Gbps) are summarized in Table 2. They are calculated based on the data presented in [14] with the exception of the FEC capabilities, that are omitted in this study. Table 2 also presents the power efficiency values (W/bps) computed for transmitting/regenerating 1 Tbps of aggregated capacity. These data show that for transmission capacities larger than 80 Gbps, it is more efficient to use 100

Gbps transponders. However, the situation is slightly different for 3Rs where, for transmission capacities larger than 200 Gbps, 40 Gbps 3Rs have lower power consumption than the 100 Gbps ones.

Table 2. TSPs and 3Rs power consumption and power efficiency.

Bitrate and modulation format		Power consumption, [W]	Power efficiency, [nW/bps] @ 1 Tb transmitted
10 Gbps	TSP	22.4	2.7
NRZ-OOK	3R	20.8	2.6
40 Gbps	TSP	69.8	2.1
NRZ-DPSK	3R	43.6	1.3
100 Gbps	TSP	132.1	1.6
DP-QPSK	3R	158.5	1.8

3.2 Signal Quality as a function of the sub-band spacing

In order to mitigate the effects that the 10 Gbps channels have on the 100 Gbps channels, in MLR networks one or more 40 Gbps channels are usually placed between them [5]. All these sub-bands are then separated by the sub-band spacing. The smaller spacing the higher is the spectral efficiency of the system. Figure 2 shows the degradation of the Q-factor value of the received signal as a function of the value of sub-band spacing. The values are obtained by simulating the system presented in Fig. 1. The different sub-band spacing values are obtained by gradually reducing the frequency intervals separating λ_3 from λ_2 , and λ_3 from λ_4 . For the 10 Gbps - 100 Gbps curve, λ_1 , λ_2 , λ_4 , and λ_5 are all assumed to operate at 10 Gbps, while $\Delta f_{1,2}$ and $\Delta f_{3,4}$ are both set to 18.75 GHz [8]. For the 40 Gbps - 100 Gbps curve, λ_1 , λ_2 , λ_4 , and λ_5 operate at 40 Gbps, while $\Delta f_{1,2}$ and $\Delta f_{3,4}$ are both set to 112.5 GHz [8]. The values for the 10 Gbps - 40 Gbps curve were computed in an earlier work [11] and reported here.

From the results presented in Fig. 2 it can be deduced that if the BER level is required to be below 10^{-9} the minimum sub-band spacing values are: 31.25 GHz between the 10 Gbps and the 100 Gbps sub-band; 75 GHz between the 40 Gbps and the 100 Gbps sub-band; and 62.5 GHz the 10 Gbps and the 40 Gbps sub-band.

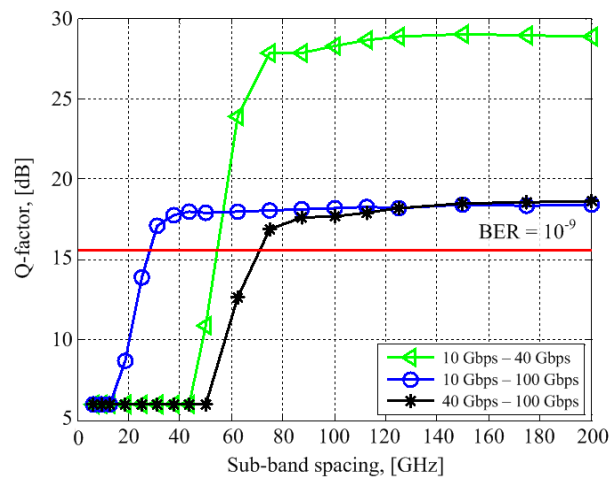


Figure 2. Q-factor for the most affected channel as a function of sub-band spacing.

3.3 Power efficiency vs. end-to-end distance for the different 10G/40G/100G channel allocation schemes

In section 3.2, the minimum sub-band spacing for a number of line rate combinations is calculated assuming a link span of 40 km. If the same sub-band spacing values are used over distances longer than 40 km, signal regeneration will be required to keep the BER at the receiving node below 10^{-9} . The purpose of this section is to assess the relationship between power efficiency (W/bps) and the end-to-end connection distance of a number of MLR solutions where the number of wavelength channels in each sub-band is varied.

In this particular set of experiments the entire C-band ($\Delta F = 4.4$ THz) is divided into three sub-bands, one for each line rate (*i.e.*, ΔF_{10G} for 10 Gbps, ΔF_{40G} for 40 Gbps, and ΔF_{100G} for 100 Gbps) (Fig. 3). The number of channels allocated varies according to the width of each sub-band and depends on the value of the channel spacing used within each sub-band (*i.e.*, 18.75 GHz for the 10 Gbps sub-band, 112.5 GHz for the 40 Gbps sub-band, and 37.5 GHz for the 100 Gbps sub-band). The width of the 10 Gbps sub-band can have any value (*i.e.*, point B in Fig. 3 can move freely along A-D). Once the width of ΔF_{10G} is fixed, the amount of frequency resources allocated to ΔF_{40G} and ΔF_{100G} may vary depending on the values of the X and Y parameters (Fig. 3), *e.g.*, if $X = 1$ and $Y = 7$ then ΔF_{100G} is allocated seven times more frequency resources than ΔF_{40G} .

Available Frequency Band (ΔF)

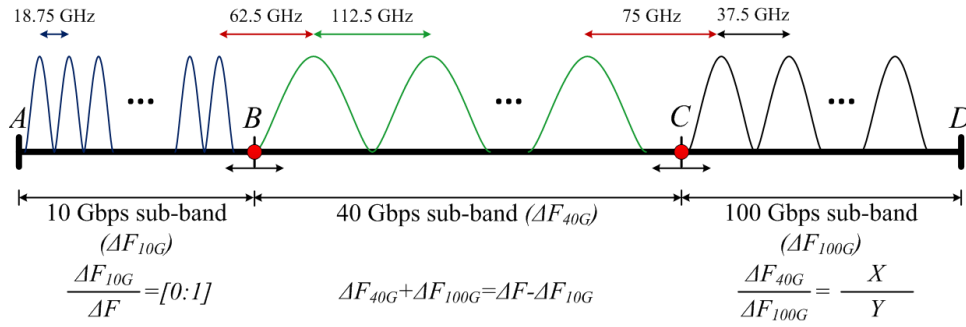


Figure 3. Sub-band and channel allocations in 10-40-100 Gbps MLR WDM system.

Figure 4 presents spectral and power efficiency results as a function of the width of each sub-band and also for different end-to-end connection length values (*i.e.*, L). Figure 4 (a) shows the utilization of the C-band (*i.e.*, spectral efficiency) as a function of ΔF_{10G} , ΔF_{40G} , and ΔF_{100G} . In terms of spectral efficiency, using a lot of channels working at high rate modulation formats (*i.e.*, $X = 1, Y = 7$) has a clear advantage over solutions where the number of 100 Gbps channels is reduced (*i.e.*, $X = 7$ and $Y = 1$). On the other hand, the use of 100 Gbps channels might present some drawback in terms of power efficiency when the end-to-end connection distance increases, as explained next.

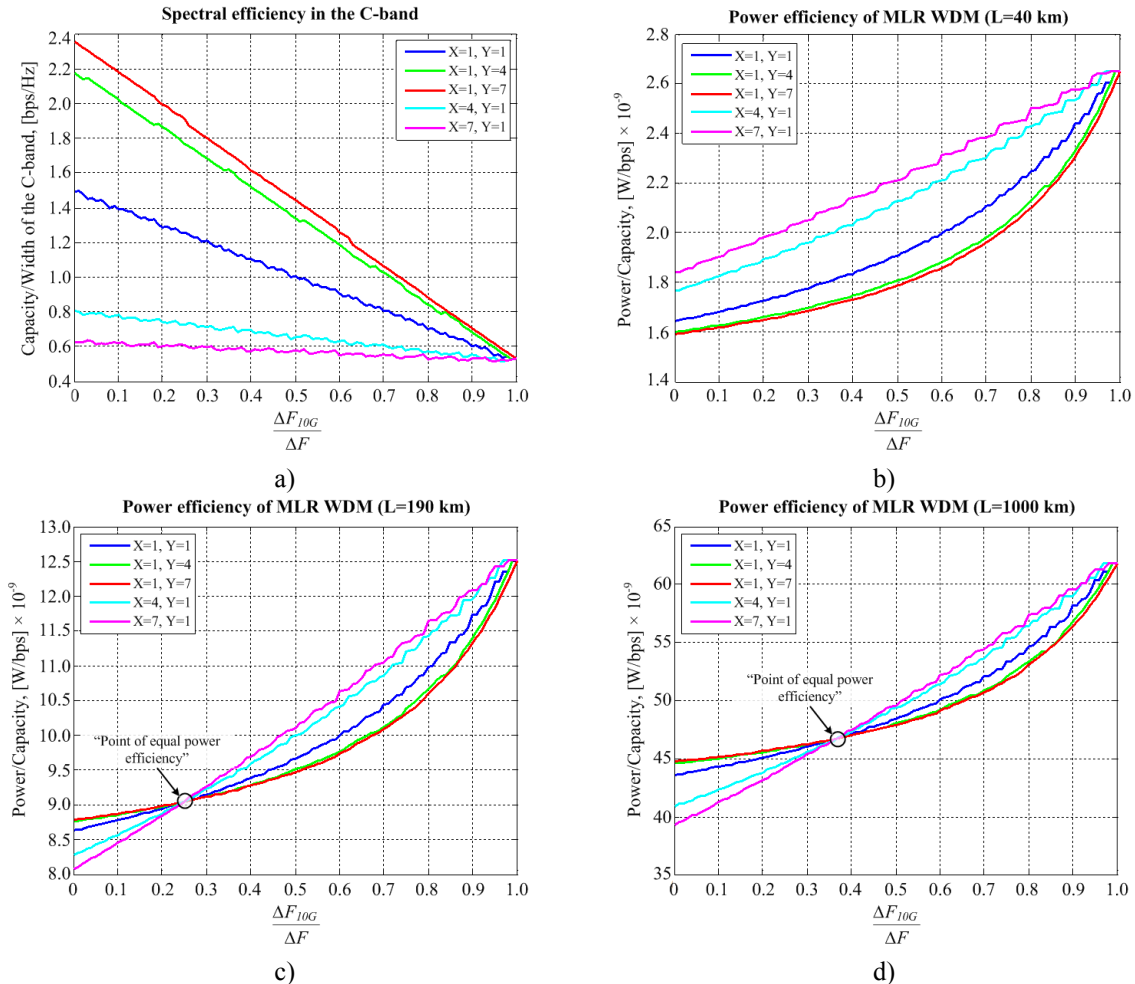


Figure 4. Spectral efficiency over the C-band (a), and power efficiency as a function of the width of each sub-band and of the end-to-end connection lengths: $L=40$ km (b), $L=190$ km (c), and $L=1000$ km (d).

If the end-to-end distance is limited to one fiber span the most power efficient solution is the one taking advantage as much as possible of the 100 Gbps transponders (*i.e.*, $X = 1, Y = 7$). This can be expected from the results presented in Fig. 4(a). However, the situation changes with longer end-to-end-distances. Figures 4(c) and

4(d) present power efficiency results in the case of $L = 190$ km and $L = 1000$ km (*i.e.*, the shortest and the longest link length in the COST 239 network topology [15]), respectively. In both figures when $\Delta F_{10G} = 0$ using many 100 Gbps transponders translates into the worst power efficiency performance. This is mainly due to the fact that 100 Gbps transponders are less energy efficient in regenerating the optical signal than the 40 Gbps. It can also be seen that in both cases the use of 100 Gbps transponders becomes advantageous again only after a certain values of ΔF_{10G} is crossed (*i.e.*, the *point of equal power efficiency*). In such a point the system power efficiency is almost independent of the values of the X and Y parameters.

Figure 5 presents the ratio of the power efficiency performance of two specific sub-band allocations options for ΔF_{40G} and for ΔF_{100G} , *i.e.*, $R = (\text{Power efficiency}_{[X=7, Y=1]} / \text{Power efficiency}_{[X=1, Y=7]})$. With $X=7$ and $Y=1$, $\Delta F_{40G} \gg \Delta F_{100G}$, while with $X=1$ and $Y=7$, $\Delta F_{100G} \gg \Delta F_{40G}$. The value of R varies as function of the 10 Gbps sub-band width, and as a function of the end-to-end length. Figure 5 is divided into three areas. The area marked as " R_1 " refers to values of $R < 1$. The area marked as " R_2 " refers to values of $1 < R < 1.1$. The area marked as " R_3 " refers to $R > 1.1$. The results in the figure confirm the earlier findings by which using 100 Gbps transponders is beneficial only if data are transmitted over a relatively short distance (not longer than 240 km). This choice for the sub-band allocation could potentially reduce the power consumption per each transmitted bps up to 25%.

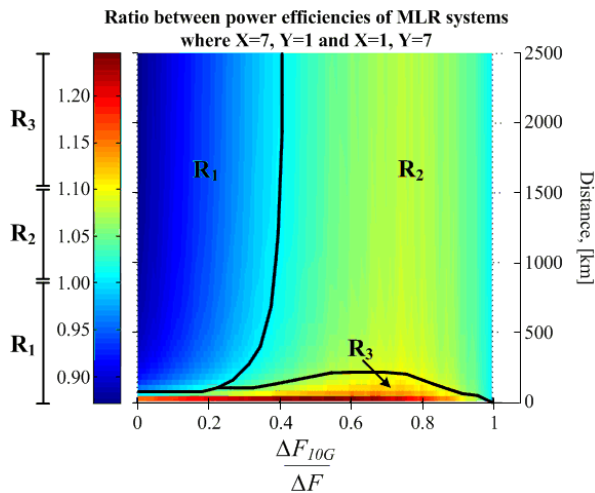


Figure 5. Ratio between power efficiencies of ($\Delta F_{40G} \gg \Delta F_{100G}$) over ($\Delta F_{100G} \gg \Delta F_{40G}$).

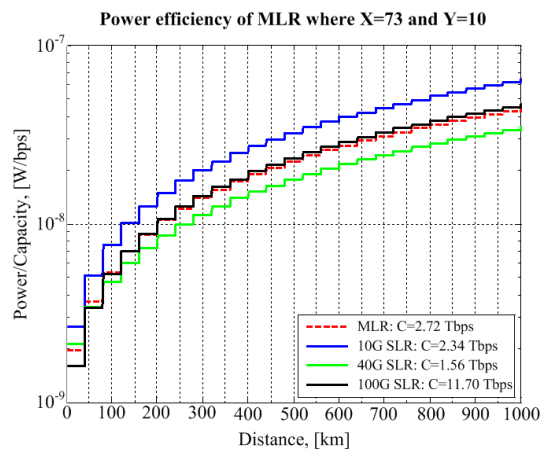


Figure 6. Power efficiency as a function of end-to-end connection length in SLR networks and MLR network where $X=73$ and $Y=10$.

In currently deployed backbone optical networks, a realistic demand distribution over the 10 Gbps, 40 Gbps and 100 Gbps sub-bands is 50:35:15 [5]. Using the channel and the sub-band spacing values appropriate to obtained the results presented in Fig. 4, a 50:35:15 demand distribution translates into $\Delta F_{10G} = 10\%$, $\Delta F_{40G} = 73\%$ and $\Delta F_{100G} = 15\%$ of the entire C-band (assuming that each demand requires an entire wavelength channel). Figure 6 compares the power efficiency results of this specific MLR design with the ones of a number of Single Line Rate (SLR) solutions, *i.e.*, 10 Gbps, 40 Gbps, and 100 Gbps, as a function of the end-to-end connection length. From the figure it can be noticed that this specific MLR design presents a worse power efficiency compared to 10G SLR and 100G SLR networks for transmission distances longer than 200 km. Even worse, when compared to a 40G SLR design, this specific MLR solution is always outperformed when the end-to-end connection length is longer than 40 km. However, with a MLR design the transmitted traffic would be twice as high: 2.72 Tbps vs. 1.56 Tbps (see Fig. 6).

4. CONCLUSION

In this paper, the power consumption and the spectral efficiency of a number of Mixed Line Rate (MLR) design solutions have been compared for point-to-point connections while guaranteeing a given signal quality (*i.e.*, corresponding to $\text{BER} = 10^{-9}$) at the receiving node. It is found that 100 Gbps DP-QPSK channels guarantee good power efficiency performance (W/bps) as long as the needed capacity is larger than 80Gbps and the end-to-end transmission distance does not exceed a few fiber spans. For longer transmission distances the cost for regenerating the optical signal becomes too high and MLR design solutions using mainly 40 Gbps NRZ-DPSK channels become more appealing.

ACKNOWLEDGEMENTS

The work presented in this paper was partly supported by the FP7/2007-2013 program under grant agreement no 318137 (ICT-DISCUS). The conference travel and the registration costs for Aleksejs Udalcovs were supported by the European Regional Development Fund project "Development of international cooperation projects and capacity in science and technology Riga Technical University", Nr. 2DP/2.1.1.2.0/10/APIA/VIAA/003."

REFERENCES

- [1] A. Nag, M. Tornatore: Transparent optical network design with mixed line rates, in *Proc. 2nd Int. Symp. on ANTS*, pp. 1-3, 2008.
- [2] J. L. Vizcaino *et al.*: Energy efficiency analysis for flexible-grid OFDM-based optical networks, *The Int. J. of Comp and Telecomm Netw*, vol. 56, no. 10, pp. 2400-2419, Jul. 2012.
- [3] "SMART 2020: Enabling the low carbon economy in the information age," GESI'08 2008 [Online]. Available: http://www.theclimategroup.org/assets/resources/publications/Smart2020Report_lo_res.pdf
- [4] S. K. Korotky: Traffic trends: Drivers and measures of cost-effective and energy-efficient technologies and architectures for backbone optical networks, in *Proc. OFC 2012*, Los Angeles, CA, USA, paper OM2G1.
- [5] O. Rival, A. Morea: Resource requirements in mixed-line rate and elastic dynamic optical networks, in *Proc. OFC/NFOEC*, pp. 1-3, 2012.
- [6] K. Christodouloupoulos *et al.*: Planning mixed-line-rate WDM transport networks, in *Proc. ICTON 2011*, pp. 1-4.
- [7] A. Nag *et al.*: Optical network design with mixed line rates and multiple modulation formats, *J. of Lightwave Technol.*, vol. 28, no. 4, pp. 466-475, Feb. 2010.
- [8] A. Udalcovs *et al.*: Power efficiency vs. transparent reach in spectral efficient WDM networks with signal quality guarantee, pp. 1-4, 2013, submitted.
- [9] P. Chowdhury, M. Tornatore, A. Nag, E. Ip, T. Wang, and B. Mukherjee: On the design of energy-efficient mixed-line-rate (MLR) optical networks, *J. of Lightwave Technol.*, vol. 30, no. 1, pp. 130-139, Jan. 2012.
- [10] G. Rizzelli, A. Morea, M. Tornatore, A. Pattavina: Reach-related energy consumption in IP-over-WDM 100G translucent networks, *J. of Lightwave Technol.*, vol. 31, no. 11, pp. 1828-1834, Jun. 2013
- [11] A. Udalcovs, V. Bobrovs: Investigation of spectrally efficient transmission for unequally channel spaced WDM systems with mixed data rates and signal formats, in *Proc. 8th IEEE, IET Int. Sym. on CSNDSP*, pp. 1-4, 2012.
- [12] RSoft Design Group Inc: Coherent PM-QPSK versus RZ-DQPSK and DPSK for high bitrate systems. Available: <http://www.rsoftdesign.com/products.php?sub=System+and+Network&itm=OptSim&det=Application+Gallery&id=50>
- [13] A. Udalcovs *et al.*: Evaluation of SMP-induced optical signals distortions in ultra-dense mixed-WDM system, in *Proc. Int. Conf. on FGCT*, pp. 180-184, 2012.
- [14] A. Morea *et al.*: Power management of optoelectronic interfaces for dynamic optical networks, in *Proc. ECOC'11*, paper We.8.K.3, 2011.
- [15] P. Batchelor *et al.*: Study on the implementation of optical transparent transport networks in the European environment – results of the research project COST 239, *Photonic Network Communications 2* (1) (2000) 15-32.