Optics Communications 318 (2014) 31–36

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Power efficiency of WDM networks using various modulation formats with spectral efficiency limited by linear crosstalk

Aleksejs Udalcovs [a,b,*], Paolo Monti [b], Vjaceslavs Bobrovs [a], Richard Schatz [c], Lena Wosinska [b]

[a] Institute of Telecommunications, Riga Technical University, Azenes str. 16/20, LV-1048, Riga, Latvia
[b] Optical Networks Laboratory (ONLab), School of Information and Communication Technology, KTH Royal Institute of Technology, Isafjordsgatan 26, SE-164 40, Kista, Sweden
[c] Laboratory of Photonics, School of Information and Communication Technology, KTH Royal Institute of Technology, Isafjordsgatan 26, SE-164 40, Kista, Sweden

ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form
17 December 2013
Accepted 17 December 2013
Available online 3 January 2014

Keywords:
Energy efficiency
Linear crosstalk
Modulation
Regeneration
Spectral efficiency
Transparent optical reach

ABSTRACT

Small channel spacing in WDM systems offers very good spectral efficiency, but may reduce the transparent optical reach because of interchannel crosstalk. In turn, an increase in the network power consumption can be expected, due to the need for signal regeneration. This paper explores the trade-off between spectral efficiency, transparent optical reach, and power consumption. The results confirm that using the most energy efficient transponder (i.e., in terms of W/bps) does not always guarantee the lowest overall network power consumption. This is especially true over long point-to-point distances (i.e., multiple transmission fiber spans) where, in order to ensure stringent quality of transmission levels together with high spectral efficiency, the optical signal needs to be regenerated many times.

1. Introduction

An important challenge for network operators is to accommodate an always-increasing traffic demand while maintaining the network power consumption at an acceptable level [1]. One possibility to cater for more bandwidth is to make a more efficient use of the existing fiber resources, i.e., increasing the spectral efficiency (SE). On the other hand, a better spectral efficiency gained with higher transmission rates and smaller channel spacing may in turn exacerbate the effect of optical transmission impairments [2], reducing the maximum distance that an optical signal can travel without regeneration, i.e., the transparent reach. This means that, when a specific quality of transmission (QoT) level has to be ensured at the receiving node, the optical signal might need to be regenerated along the way [3]. 3R operations (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. Therefore, spectral efficiency, transparent reach, and power consumption are closely interrelated and an optimization process needs to carefully consider how these three parameters influence each other.

In the literature, this aspect is only partially addressed. In [2], the authors investigate (over a single fiber span) what is the maximum allowable spectral efficiency to keep the QoT above a certain threshold, but they do not look into the relationship between QoT and power consumption. Latter this aspect is addressed in [3] where an efficient optical network design strategy with signal quality guarantee is proposed, but no investigation is made on how various spectral efficient solutions influence the system power consumption. The impact of coherent and non-coherent technologies on the power consumption in translucent networks is studied in [4], but no conclusions are drawn on the maximum achievable transparent reach. Finally, systems and components are usually modeled in terms of their power consumption, but no considerations are made on how efficiently they utilize the limited frequency resources of the transmission band they use [1,5].

In this paper, we explore how spectral efficiency, transparent optical reach, and power consumption influence each other in the same transmission system. More specifically, the objective of this work is to evaluate the power cost per transmitted bit per second (W/bps) required to establish an end-to-end optical connection

* Corresponding author at: Riga Technical University, Institute of Telecommunications, Azenes str. 16/20, Room 500, LV-1048 Riga, Latvia. Tel.: +371 28 293 227.
E-mail address: Aleksejs.Udalcovs@rtu.lv (A. Udalcovs).

0030-4018/$ - see front matter
http://dx.doi.org/10.1016/j.optcom.2013.12.033

over a spectrally efficient WDM network while guaranteeing a specific QoT level at the receiver (without using forward error correction). This objective is achieved by considering the power consumption of the transponders (TSPs) and the 3Rs (for a given bitrate and modulation format) required to transmit over one or more unamplified fiber spans, with maximum spectral efficiency, and while a given QoT level is required and the receiver. The study is done in the limit of maximum spectral efficiency where the signal is regenerated after each fiber span to mitigate the impairment due to linear crosstalk between wavelength channels. Therefore, this study addresses the worst-case scenario in terms of energy efficiency.

The modulation formats under examination are: 10 Gbps and 40 Gbps non-return-to-zero on-off keying (NRZ-OOK); 10 Gbps and 40 Gbps NRZ differential phase-shift keying (NRZ-DPSK); and 10, 40, and 100 Gbps coherent dual polarization quadrature phase-shift keying (DP-QPSK). These modulation formats reflect the technologies that are commercially available today. The intensity modulated NRZ signals were taken with respect to legacy 10 Gbps solutions. The DPSK format represents one of the available alternatives (besides DQPSK or Duobinary) to provide 40 Gbps channel rates, while DP-QPSK is very common for the practical implementation of 100 Gbps channels in core networks due to its capability to support 50 GHz ITU-T fixed grid. Solutions that leverage on even higher modulation levels/baudrates, or that make use of superchannels to achieve channel bitrates of 400 Gbps and 1 Tbps are not considered in this work. The power efficiency and spectral efficiency of all modulation formats are compared assuming the same QoT level at the receiver, before the use of any forward error correction. Spectral efficiency (bps/Hz) is dependent both on the number of bits per symbol used by a specific modulation format, and on the minimum allowable channel spacing, i.e., to avoid excessive signal degradation due to crosstalk from adjacent channels. 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 that high spectral efficiency values may trigger extra power consumption due to 3R operations. This is especially true when an optical connection needs to be provisioned over multiple fiber spans. On the other hand, strategies focused on power efficiency only may not use the spectral resources in the best possible way.

2. Simulation setup

This section describes the assumptions used to simulate a fiber-optic link, and the configuration parameters of the link and the system components.

2.1. Numerical methods and accuracy

Synopsys' RSoft OptSim software is used for simulations. The software solves the nonlinear Schrödinger equation using a time domain split-step algorithm. The *Q*-factor of the received signal is used to measure the optical signal quality and it is defined as [6]:

$$Q_{dB} = 20\log_{10}\left(\frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}\right),$$

where μ_1, μ_0 and σ_1,σ_0 are the mean and the standard deviations of the received signal when "1" or "0" are transmitted. The accuracy of the obtained *Q*-factor values strongly depends on the total number of simulated bits. In our numerical experiments we used at least 8000 bit that yields a *Q*-factor uncertainty of less than 0.28 dB [6].

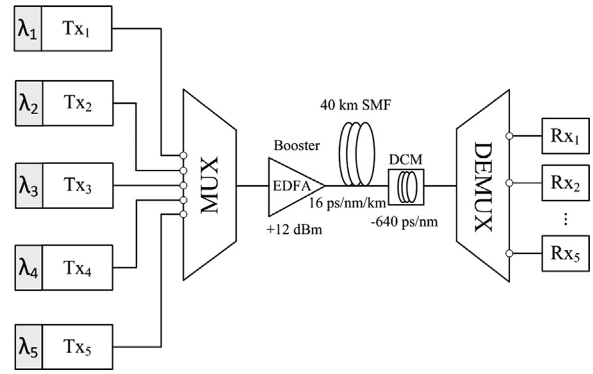

Fig. 1. Description of the optical link under exam.

2.2. System setup in OptSim 5.3

The scenario under exam is based on a five-channel wavelength division multiplexing (WDM) system that consists of five transmitters (Tx_i), a wavelength multiplexer (MUX), a booster amplifier, a standard single mode fiber (SMF) used for transmission, a chromatic dispersion compensation module (DCM) and five receivers (Rx_i). The booster amplifier – an Erbium Doped Fiber Amplifier (EDFA) with a fixed 12 dBm output power – is placed after the multiplexer. Using a five channels WDM link gives us the possibility to compare the *Q*-factor values for the three central channels (λ_2, λ_3, and λ_4) to ensure that the system under exam is indeed limited by linear crosstalk from neighboring channels only, and not by fiber nonlinearities (see Fig. 1).

In a realistic long-reach WDM system there would also be a number of fixed-gain inline optical amplifiers (to compensate for the attenuation in the SMF and the DCM), and a pre-amplifier before the demultiplexer. However, since this study is focused on the maximum tolerable spectral efficiency for signal transmission over a single span, these amplifiers are not considered. The optical dispersion compensation module is based on a dispersion compensating fiber (DCF). The SMF and DCF lengths are 40 km and 8 km, respectively, and their characteristics are the same as the one described in [7]. Optical dispersion compensation is omitted for the DP-QPSK-based modulation formats. Instead, electronic dispersion compensation is used at the receiver side. The characteristics of the transmitter and of the receiver vary 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 [2], while the block diagrams for DP-QPSK unit are shown in [8]. The transmitters are driven by rectangular shape NRZ signals filtered through an electrical low pass Bessel filter. For the 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 numbers of poles for the Bessel electrical filters is set to 5, while optical Super Gaussian filters of second order are used at the receiver side. The filter bandwidth is fixed and equal to 70% of the baudrate for all modulation formats. The OOK signals are detected using a single positive-intrinsic-negative (PIN) photodetector while the DPSK signals using two balanced photodetectors, respectively. The PIN photodiodes are assumed to have 80% quantum efficiency corresponding to 1 [A/W] responsivity. A coherent receiver is used to decode the DP-QPSK signals. The electrical receiver filter is assumed to be similar to the electrical transmitter filter.

Finally, it is assumed that the main optical impairment limiting the system spectral efficiency is linear interchannel crosstalk, even when the number of channels increases beyond five. The fixed

12 dBm output power for the five channel system (3 mW per channel) and the fixed link distance of 40 km were therefore chosen conservatively, so that the influence of nonlinear crosstalk and of the receiver noise would be small, which was also confirmed by our simulations. For example, in a 10 Gbps NRZ-OOK system, the impairments due to linear crosstalk dominates over impairments due to noise and nonlinearities if the total power launched in the fiber is between -21 dBm and $+13$ dBm. For the other considered modulations formats and channel spacing values, there are different limits when this assumption holds. The corresponding values for the 40 Gbps NRZ-OOK are -13 dBm and $+17$ dBm. For lower powers, the system starts to become noise limited and for larger powers it starts to be limited by fiber nonlinearities. The assumption that the system is limited by linear crosstalk simplifies the simulations considerably and makes the results more transparent compared to a fully realistic case where the channel spacing, the output power, and the link distance would have to be optimized for each number of WDM channels. With the current assumptions the total power consumption might be overestimated when only few channels are used, in which case longer, i.e., 80 km, fiber spans can be chosen. On the other hand, with the same assumptions the total power consumption might be underestimated when a large number of channels are used, in which case nonlinear impairments will start to become a limiting factor.

3. Results and discussion

In this section, the trade-off between spectral efficiency, power consumption, and transparent reach is evaluated. The focus of the study is on systems 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 (for the different modulation formats) is calculated, and then compared with the values found in the literature. This allows to compare the value of the power efficiency (W/bps), (i.e., consumption needed to transmit a certain capacity) for each given bitrate and modulation format over a single fiber span. The maximum spectral efficiency (bps/Hz) of the different modulation formats under exam is also determined by studying the degradation of the *Q*-factor of the received signal due to interchannel crosstalk, when the channel spacing is decreased. The total power consumption needed to transmit a certain capacity throughout the 4.4 THz C-band is also calculated. Finally, the power efficiency as a function of the distance is studied for an end-to-end (i.e., over possibly multiple fiber spans) WDM transmission system set to use the maximum spectral efficiency allowed by each modulation format.

3.1. Power consumption of transponders and 3Rs

The functionalities and schematics of transponders and regenerators are the same as the ones presented in [12] with the only exception of FEC capabilities that are not considered in this study. Table 1 lists the main components included in a transponder (TSP) and a regenerator (3R). In general, a regenerator can be considered as the combination of two half-transponders (i.e., "($\times 2$)" in the table), one for receiving and one for retransmitting the regenerated signal, but without their client side (i.e., client cards, framer or de-framer, "N.A." in the table). The number and the type of components may vary depending on the specific bitrate and modulation format. For simplicity reason, the table includes only a subset of all the transponder and regenerator types considered in the study. More specifically only three different bitrate and modulation format (i.e., 10G NRZ-OOK, 40G NRZ-DPSK and 100G DP-QPSK), are described, but the same principle applies to all the other transponders and regenerators.

The values of the power consumption of transponders and 3Rs, computed for all the different rates and modulation formats, are summarized in Table 2. Based on the data presented in [15] it is assumed that the power consumption values of some components (e.g., DSP, ADC, and driver) change linearly with the bitrate.

Table 2 summarizes the power efficiency of each transponder and 3R option. The power consumption values are calculated using the data presented in [12] and then benchmarked using other research papers and datasheets. The value of the power consumption of the100G transponder is derived from [11] where on the other hand FEC was included. In order to be consistent with the power calculation for all the other transponders, the FEC power consumption (in amount of 4.7% of the total power consumption [12]) was subtracted from the value available in [11]. 100G 3R consumes by 18% more power than the TSP. Both these figures could be derived also based on the data presented in the [12]. The power consumption values presented in the table already include the contribution of management power [1,12] that is estimated to amount to about 20% of the total power consumption of a transponder/regenerator.

The table shows that, for transmission distances limited to one SMF span (i.e., no 3Rs needed) and for low capacities (i.e., below 30 Gbps) the 10 Gbps NRZ-OOK and NRZ-DPSK transponders are the most power efficient (i.e., in terms of W/bps). On the other hand, for capacities larger than 80 Gbps the coherent 100G DP-QPSK transponder is more power efficient. It can also be concluded that coherent 10G and 40G DP-QPSK transponders have the worst power efficiency (Fig. 2). Since the number of transponders is a discrete and not a continuous variable, the curves have a stepwise form. For example, 140 Gbps can be transmitted using fourteen 10 Gbps, four 40 Gbps, or two 100 Gbps transponders.

The situation is different for 3Rs (Fig. 3), where the ones utilizing direct detection are more power efficient than the coherent 3Rs. 10G NRZ-OOK or 10G NRZ-DPSK 3Rs have the lowest power consumption at capacities lower than 20 Gbps. At higher capacities, 40G NRZ-OOK or 40G NRZ-DPSK 3Rs are the most power efficient. Note that in Figs. 2, 3 and 6 the line marked with circles (40G NRZ-OOK) and the one with diamonds (40G NRZ-DPSK) overlap each others.

3.2. Detected signal quality versus spectral efficiency

If the capacity of a system is limited by the available optical bandwidth, the spectral efficiency of a modulation format becomes an important parameter. Spectral efficiency depends both on the number of bits each symbol can carry and on the minimum possible channel spacing that can be set without significantly degrading the quality of the optical signal. Fig. 4 presents the degradation of the *Q*-value as a function of the maximum spectral efficiency over a distance of 40 km, the medium span length for inline optical amplifiers in WDM optical networks [5].

The value of the maximum spectral efficiency for each modulation format is determined by finding the minimum tolerable channel spacing in order to guarantee that the most degraded channel (e.g., the central one) has always a $\text{BER} \leq 10^{-9}$. This corresponds to a minimum *Q*-factor value of 6 ($=15.56$ dB on electrical side). Hence, as long as the value of the spectral efficiency is equal or lower than the maximum one, all channels in the system will have BER values better than 10^{-9}.

In the experiment, the channel spacing is restricted to a 3.125 GHz granularity while the central frequency of each channel is set in accordance to ITU-T G.694.1 fixed grid. The maximum

Table 1
Main component included in a transponder and 3R: DSP—digital signal processor, TIA—transimpedance amplifier, ADC—analog-to-digital converter, OTU—optical channel transport unit.

	Component	TSP	Units: 10G NRZ-OOK	Units: 40G NRZ-DPSK	Units: 100G DP-QPSK	3R
Client side	Client card	+	1	4	10	**N.A.**
	Framer	+	1 (OTU2)	1 (OTU3)	1 (OTU4)	**N.A.**
E/O modulation	Drivers	+	1	1	4	**(×2)**
	DSP	+	0	0	0	**(×2)**
	Laser (on-off)	+	1	1	1	**(×2)**
O/E receiver	Local oscillator	+	0	0	1	**(×2)**
	Photodiode+TIA	+	1	2	4	**(×2)**
	ADC	+	0	0	4	**(×2)**
	DSP	+	0	0	1	**(×2)**
Client side	Deframer	+	1 (OTU2)	1 (OTU3)	1 (OTU4)	**N.A.**
	Client card	+	1	4	10	**N.A.**

Table 2
Computed power consumption values [W] of transponders and 3Rs.

Rate and modulation format	Equipment type	Computed power values (no FEC) [W]	Power consumption values from the literature
10G NRZ-OOK	TSP/3R	22.0/21.2	34.0 [1], 35.0 [9]
40G NRZ-OOK	TSP/3R	69.4/42.8	66.0 [13]
10G NRZ-DPSK	TSP/3R	22.4/22.0	20.5 [14]
40G NRZ-DPSK	TSP/3R	69.8/43.6	85.0 [10]
10G DP-QPSK	TSP/3R	40.6/58.4	–
40G DP-QPSK	TSP/3R	120.4/144.8	113.0 [1]
100G DP-QPSK	TSP/3R	132.4/150.8	139.0 [11], 188.0 [1]

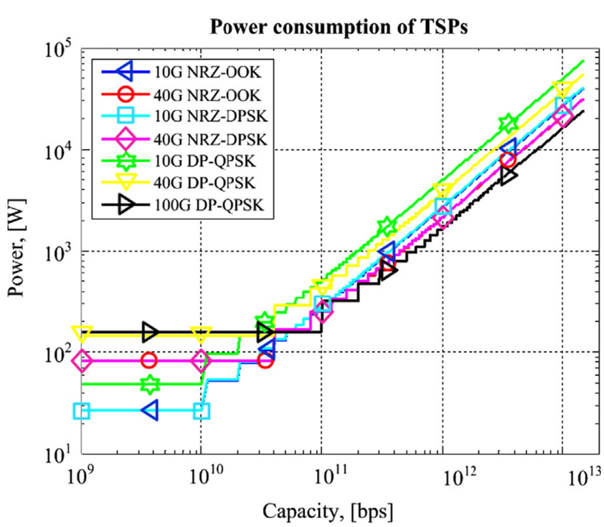

Fig. 2. Power consumption of different transponder types as a function of the transmitted capacity.

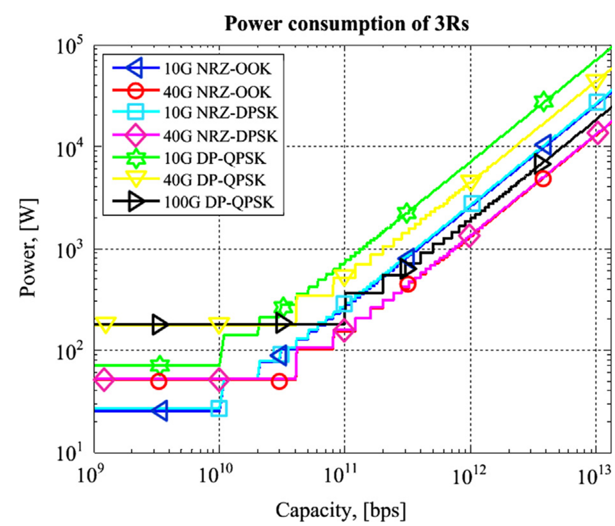

Fig. 3. Power consumption of different 3Rs types as a function of the transmitted capacity.

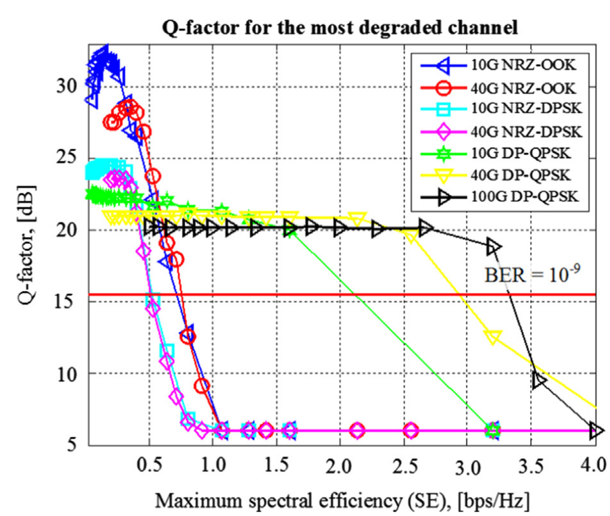

Fig. 4. *Q*-factor values detected for the most degraded channel as a function of the spectral efficiency.

spectral efficiency that is obtained for the different modulation formats is presented in the first column Table 3.

Once the value of the maximum spectral efficiency is fixed (i.e., based on the maximum acceptable BER value) it is interesting to evaluate what is the maximum transmission capacity (and the respective power consumption), that a given modulation format can offer over the entire C-band (4.4 THz). This gives an idea of how efficiently the total available bandwidth of the C-band is used. Fig. 5 shows that for each modulation format the power consumption increases linearly with the capacity provided as more and more wavelength channels are utilized until the maximum spectral efficiency (given in Table 3) is reached. A 100G DP-QPSK transponder gives the lowest overall power consumption in combination with high spectral efficiency. The number of needed transponders and the total (transponder) power for maximum spectral efficiency of each modulation format are also given in Table 3.

3.3. Power efficiency versus transmission distance

In Section 3.2, the maximum spectral efficiency for each modulation format is calculated assuming a link span of 40 km. If the

Table 3
Spectral efficiency, capacity, and power consumption values when BER $\le 10^{-9}$.

Rate and modulation format	Spectral Efficiency [bps/Hz]	Capacity [Tbps]	No. of TSP	TSP power [kW]
10G NRZ-OOK	0.64	2.82	282	7.45
40G NRZ-OOK	0.71	3.16	79	6.58
10G NRZ-DPSK	0.40	1.76	176	4.73
40G NRZ-DPSK	0.46	2.04	51	4.27
10G DP-QPSK	1.60	7.04	704	34.30
40G DP-QPSK	2.56	11.28	282	40.74
100G DP-QPSK	3.20	14.10	141	22.40

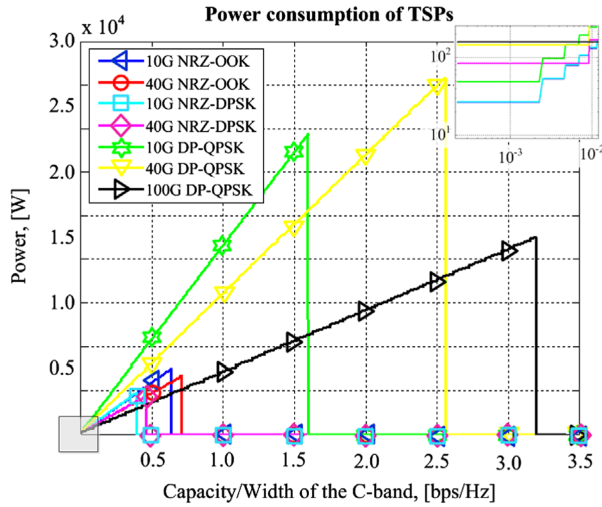

Fig. 5. Power consumption values for the different types of transponders in function of the transmitted capacity over C-band (4.4 THz).

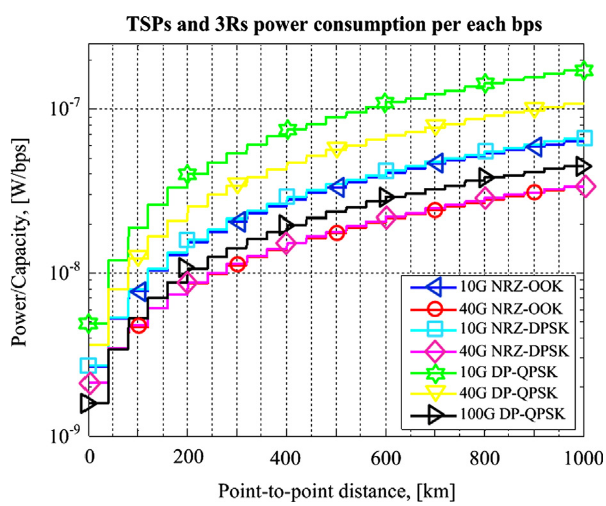

Fig. 6. Power per bps as a function of the point-to-point distance.

same maximum spectral efficiency value is used over several such 40 km SMF spans, signal regeneration will be required to keep the BER at the receiver below 10^{-9}. Hence, the point-to-point distance in Figs. 6 and 7 linearly scales with the SMF span length.

When more than one fiber span is used the total power consumption will then mainly depend on the number and on the power consumption of the 3Rs and not anymore on the transponder power consumption. Fig. 6 presents power efficiency values (i.e., W/bps) over a given distance for all the considered modulation formats. 3Rs are assumed to be deployed at the end of each fiber span (i.e., every 40 km to ensure the required BER value over the entire end-to-end connection). If the transmission distance is longer

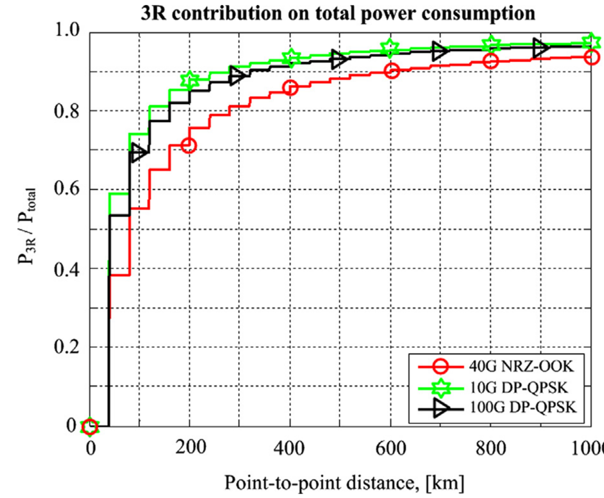

Fig. 7. Ratio between 3Rs power consumption over total power consumption as a function of the point-to-point distance.

than 80 km, the lowest energy per bit is obtained using 40 Gbps NRZ-OOK and with 40 Gbps NRZ-DPSK transmission technologies. For a 1000 km point-to-point connection, using 100 Gbps DP-QPSK instead of 40 Gbps NRZ-OOK transponders increases the power consumption by more than 33% for each transmitted bps.

Fig. 7 shows the impact of 3Rs on the total power consumption over a given transmission distance for three modulation formats: (i) 40 Gbps NRZ-OOK that is the most power efficient after multiple fiber spans; (ii) 10 Gbps DP-QPSK that is the worst in terms of energy efficiency, and (iii) 100 Gbps DP-QPSK that have the most power efficient transponder.

More than 90% of the total power consumption is due to 3Rs if the point-to-point distance is longer than 280 km, 320 km, and 600 km for the 10 Gbps DP-QPSK, 100 Gbps DP-QPSK and 40 Gbps NRZ-OOK, respectively. For the other considered bitrates, the curve of the 3Rs contribution over the total power consumption values would be in between the one marked with hexagrams and with circles.

4. Conclusion

In this paper, the power consumption and spectral efficiency of different modulation formats have been compared for point-to-point connections while securing a given QoT level. It is found that transponders for coherent 100G DP-QPSK have the lowest power consumption if a total link capacity above 80 Gbps is considered. However, the situation for 3Rs is different from transponders. It is shown that 3Rs for 40G NRZ-OOK and NRZ-DPSK are more energy efficient than 100G DP-QPSK 3Rs. Hence, for long point-to-point transmissions where several 3Rs are used, a system utilizing direct detection 40G NRZ-OOK gives better power efficiency (W/bps) than a system utilizing coherent 100G DP-QPSK, i.e., up to 33% less energy consumption for a 1000 km point-to-point link using maximum spectral efficiency when a BER of 10^{-9} is required at the receiver. On the other hand, if the optical bandwidth is a constraint, the 100G DP-QPSK system is superior since it can provide a capacity that is far higher (and with a reduced power) than the other modulation formats.

Acknowledgements

This work has been supported by the Swedish Institute scholarship, European Social Fund within the project Nr. 2013/0012/1DP/1.1.1.2.0/13/APIA/VIAA/051, FP7/2007-2013 program under grant agreement no 318137 (ICT-DISCUS), and FP7-PEOPLE-2012-IAPP project GRIFFON under grant agreement no 324391.

References

[1] J.L. Vizcaino, Y. Ye, I.T. Monroy, Int. J. Comput. Telecommun. Netw. 56 (10) (2012) 2400.
[2] A. Udalcovs, V. Bobrovs, Investigation of spectrally efficient transmission for unequally channel spaced WDM systems with mixed data rates and signal formats, in: Eighth IEEE, IET International Symposium CSNDSP. , pp. 1, 2012.
[3] C. Cavdar, M. Ruiz, P. Monti, L. Velasco, L. Wosinska, Design of Green Optical Networks with Signal Quality Guarantee IEEE ICC, pp. 3025, 2012.
[4] G. Rizzelli, A. Morea, M. Tornatore, O. Rival, J. Comput. Netw. 56 (10) (2012) 2443.
[5] W.V. Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, P. Demeester, J. Photonics Netw. Commun. 24 (2012) 86.
[6] RSoft Design Group Inc, “OptSim User Guide”.—USA, 2008, pp. 404.
[7] A. Udalcovs, V. Bobrovs, J. Porins, Evaluation of SMP-induced optical signals distortions in ultra-dense mixed-WDM system, in: International Conference on FGCT, pp. 180–184, 2012.
[8] Fujitsu, The path to 100G. Available: 〈http://www.fujitsu.com/downloads/TEL/fnc/whitepapers/Pathto100G.pdf〉.
[9] Ciena, F10-T 10G Transponder, Data Sheet, pp. 1–2, 2011. Available: 〈http://www.ciena.com/products/f10-t/tab/features/〉.
[10] MRV, LambdaDriver—DWDM 40 Gbps Transponder (TM-40GT8), 2011. Available: 〈http://www.mrv.com/datasheets/LD/PDF300/MRV-LD-TM-40GT8_HI.pdf〉.
[11] ADVA, FSP 3000 Coherent Transponders, Fact Sheet, 2012. Available: 〈http://www.advaoptical.com/~/media/Innovation/Efficient%20100G%20Transport/100G%20Coherent%20Transponder.ashx〉.
[12] A. Morea, S. Spadaro, O. Rival, J. Perello, F. Agraz, D. Verchere, Power Management of Optoelectronic Interfaces for Dynamic Optical Networks ECOC′11, We.8.K.3.pdf, pp. 1–3, 2011.
[13] E. Palkopoulou, D.A. Schupke, T. Bauschert, Energy Efficiency and CAPEX Minimization for Backbone Network Planning: Is There a Tradeoff?, ANTS 2009, Delhi (India), DOI: 10.1109/ANTS.2009.5409867.
[14] SHF 46211A 10 Gbps Multiformat Optical Transmitter Datasheet, 2013. Available: 〈http://www.shf.de/fileadmin/download/46210/datasheet_shf_46211a_v001.pdf〉.
[15] X. Chen, L.-S. Peh, G.-Y. Wei, Y.-K. Huang, P. Pruchnal, Exploring the Design Space of Power-Aware Opto-Electronic Networked Systems, HPCA-11 2005, pp. 120.