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ELECTRONICS

EVALUATION OF SIGNAL REGENERATION IMPACT ON THE POWER EFFICIENCY OF LONG-HAUL DWDM SYSTEMS

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Due to potential economic benefits and expected environmental impact, the power consumption issue in wired networks has become a major challenge. Furthermore, continuously increasing global Internet traffic demands high spectral efficiency values. As a result, the relationship between spectral efficiency and energy consumption of telecommunication networks has become a popular topic of academic research over the past years, where a critical parameter is power efficiency.

The present research contains calculation results that can be used by optical network designers and operators as guidance for developing more power efficient communication networks if the planned system falls within the scope of this paper. The research results are presented as average aggregated traffic curves that provide more flexible data for the systems with different spectrum availability. Further investigations could be needed in order to evaluate the parameters under consideration taking into account particular spectral parameters, e.g., the entire C-band.

Keywords: *differential phase shift keying, DWDM, energy efficiency, optical fibre networks, phase shift keying, power consumption, power efficiency, single-line rate, spectral efficiency, sub-band spacing, WDM networks*

1. INTRODUCTION

The Information and Communication Technology (ICT) sector is experiencing continuously increasing global Internet traffic due to emergence and establishment of bandwidth-intensive applications (e.g., IPTV, YouTube, and cloud computing) [1]. Recent Cisco study has shown that the total IP traffic increases annually by an average of 23 % for 2014–2019. The increased traffic raised the necessity of updating the existing transmission techniques and developing new ones in order to enchase spectral efficiency of systems.

In terms of wavelength division multiplexing (WDM) systems, the system capacity can be increased by either 1) channel-spacing reduction (increase of the transmitted channel number), or by 2) enhancing of channel capacities. The mentioned relation can be expressed by equation (1) [2]:

$$C = \sum_{i}^{M} C_{ik} \,, \tag{1}$$

where i – the index number of channel; M – the number of transmission channels; C_{ik} – the speed of channel [bit/s].

However, higher spectral efficiency can result in the reduction of a transmission reach [3], [4]. Therefore in order to guarantee the required quality of transmission (QoT), an optical signal might require 3R (Re-amplification, Re-shaping, Re-timing) regeneration procedure by means of optical-to-electrical-to-optical (OEO) conversion process, which in its turn requires the additional equipment in system nodes. As a result, the overall power consumption increases [5]. Thereby, it can be inferred that there is a trade-off among spectral efficiency, power consumption and transmission reach [1], [3], [4].

In the paper, the authors evaluate the impact of signal regeneration on power efficiency of a long-haul dense wavelength division multiplexing (DWDM) system by means of different channel spacing values, which is the most decisive factor for transmission reach of the system. This study aims at the single-line rate (SLR) solutions operating with 10 Gbps, 40 Gbps and 100 Gbps transmission signals with the most frequently used modulation formats in modern high capacity networks – non-return-to-zero on-off-keying (NRZ-OOK), non-return-to-zero differential phase-shift keying (NRZ-DPSK) and dual polarisation quadrature PSK (DP-QPSK), respectively. The calculations of power consumption have been performed for 2960 km transmission distance in order to achieve more pronounced regeneration influence. The present research focuses on the WDM systems with forward error correction (FEC), which by virtue of an error controlling technique, allows successfully demodulating transmitted signals when the bit error rate (BER) does not exceed 10^{-3} threshold. This setup allows taking into account power consumption contributed by the redundant data required for FEC technology, which is commonly used in modern transmission systems [6].

2. METHODOLOGY

For this study, the evaluation of system power consumption was performed in two steps. At first, the relation between BER level and channel spacing was defined on the fixed fibre length using OptSim™ simulation software in order to define transmission reach and its relation with the channel spacing for each considered system setup [7], [8]. The assignment of central channel wavelength was based on the ITU-T recommendation G.694.1. The recommendation also provides the nominal central frequency granularity, which is equal to 6.25 GHz. Therefore, the cross-channel interval was increased by 6.25 GHz at every simulation step with the purpose to find a frequency plan, whereby the BER level became lower than 10^{-3}. Further, based on the obtained data from the above-mentioned simulations the power consumption evaluation model was developed using MATLAB features. In the calculation code, the amount of transmitted data was defined as a variable, which was used to calculate the required number of WDM components, which in conjunction with calculated transmission reach and chosen transmission distance determined the overall system power consumption. In this scenario, power consumption became a function of the transmitted data; therefore, calculation setup allowed evaluating power efficiency by dividing power consumption by the amount of transmitted data. The methodology was described in more detail in the previous papers [3] and [4].

For calculation purposes, the transmission distance was set for 2960 km, which is comparable with the longest node of National Science Foundation Network (NSFNET) – the US network used in many studies, i.e., [9] and [10].

It was assumed that the total power consumption of WDM system could be calculated using equation (2):

$$P_{WDM} = P_{ROADM} + P_{TRANS} + P_{WDMTERM} + P_{OLA} + P_{3R}, \quad (2)$$

where P_{WDM} – total power consumption of WDM system [W]; P_{ROADM} – power consumption of optical reconfigurable add/drop multiplexer [W]; P_{TRANS} – power consumption of transponder [W]; $P_{WDMTERM}$ – power consumption of WDM terminal [W]; P_{OLA} – power consumption of optical line amplifier [W]; P_{3R} – 3R (Re-amplification, Re-shaping, Re-timing) regenerator consumption [W].

Based on the provided datasheets and relevant studies [1], [4], [9], power consumption values of transponders and 3R regenerators are summarised in Table 1.

Table 1

Power Consumption [W] of Transponders and 3Rs

Bit Rate (Gbps)	Modulation format	Consumer	Power (W)
10	NRZ-OOK	TP/3R	34.0 (Typ.)
40	NRZ-DPSK	TP/3R	85 (Max)
100	DP-QPSK	TP/3R	139 (Typ.)

It should be noted that the equipment under normal operational conditions does not consume the declared maximal power. Therefore, for calculations the nominal power consumption accounted for 75 % of the specified maximal value.

Power consumption of ROADM multiplexers and WDM terminals, which are used for calculations, is demonstrated in Table 2 [1], [3], [9]. Power units of the optical line amplifier require 110W [3], [4], [9].

Table 2

ROADM and WDM Terminal Power Consumption [W]

Device	Power Consumption	
	40 ch. realisation	80 ch. realisation
WDM terminal	230	240
ROAD multiplexer	450	600

3. RESULTS AND DISCUSSION

In this section, the authors present the simulation results that show the relation between the consumed power by means of power efficiency and 3Rs' power ratio and the amount of transmitted information, with the view of providing more flexible data for different system realisations, i.e., a different number of transponders due to distinctions in the available spectrum.

With the aim to evaluate power efficiency and regeneration impact at different spectral efficiency states, different channel spacing values were set, based on the recommendation ITU-T G.694.1. In this study, the power consumption values for each considered system realisation were evaluated using different cross-channel intervals on the ground that cross-channel interference is unique for each signal type, operating at the same frequency plan. Therefore it is not reasonable to analyse different systems using equal channel distribution if the purpose is to evaluate regeneration impact on the power efficiency and total power consumption. Lower frequency slot limit intended for analysis was chosen based on the highest spectral efficiency, which could be achieved guaranteeing the fulfilment of BER requirement. The upper limit was derived from conditions when the transmission reach attained its maximum, which meant that further increment of frequency slot would lead only to the minimisation of spectral efficiency without profitable impact on power consumption.

Since the present research considers different spectral efficiencies at different frequency slots, the transmission reach became a function of channel spacing. Relation between frequency slots, spectral efficiency (SE) and transmission reach is summarised in Table 3.

Table 3

Spectral Efficiency and System Reach at Different Channel Spacing Values

Channel Spacing (GHz)	SE (bit/Hz)	Reach (km)
10 Gbps NRZ-OOK		
12.50	0.80	160
18.75	0.53	1680
25.00	0.40	5700
31.25	0.32	8720
40 Gbps NRZ-DPSK		
50.00	0.80	160
56.25	0.71	240
62.50	0.64	560
75.00	0.53	960
87.50	0.46	1440
100.00	0.40	2080
112.50	0.36	2080
100 Gbps DP-QPSK		
31.25	3.20	160
37.50	2.67	400
43.75	2.29	1040
50.00	2.00	1360

By defining transmission reach of the system and power consumption of WDM elements, the power efficiency and power ratio of 3R regenerators were evaluated. The results are shown in Figs. 1–6.

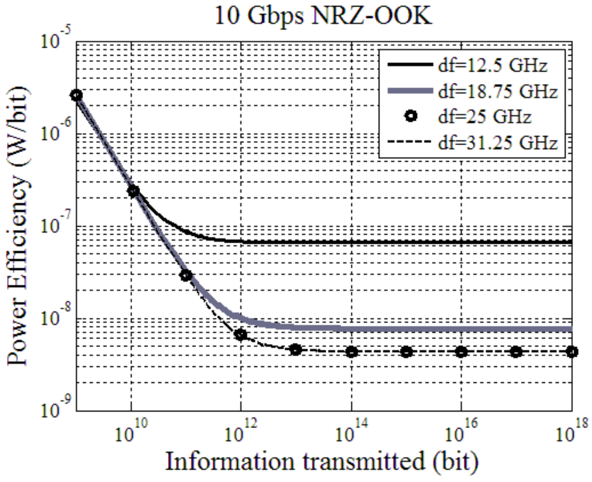

Fig.1. 10 Gbps NRZ-OOK power efficiency curve.

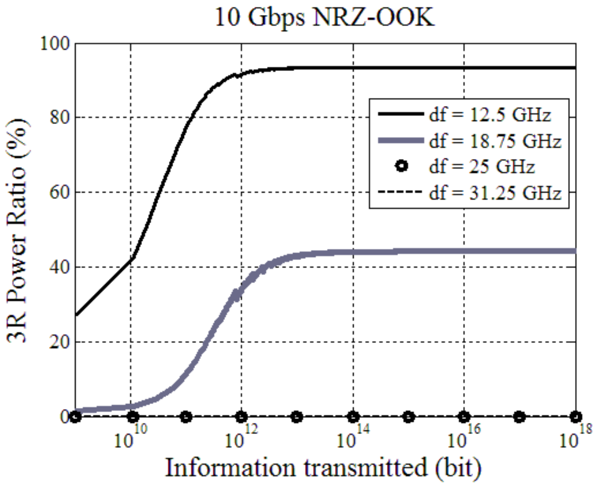

Fig.2. Power ratio curve of 10 Gbps NRZ-OOK 3R regenerators.

Figures 1–2 show the curves of the considered parameters for 10 Gbps NRZ-OOK system configuration from which it can be observed that when the total transmitted traffic reaches $\approx 10^{13}$ bits, power efficiency and 3Rs consumed power ratio stabilise, which allows making an assumption that parameters will not significantly change during system functioning and the obtained values can be used for system assessment and comparison. In spite of equal power efficiency, operation on the channel spacing values greater than 25 GHz in the considered system is impractical in terms of spectral efficiency. Signal reach in those cases become greater than transmission span and signal regeneration is not required, thus power efficiency reaches minimal value in this instance – 4.30 nW/bit. In the case of 12.5 GHz and 18.75 GHz frequency slots, PE values are 7.7 and 65.5 nW/bit, respectively, which is a relatively abrupt leap of power consumption because for the transmission of a single bit the energy required is more than 15 times greater than using 25 GHz frequency span. Thus, it can be concluded that if spectral efficiency should be increased, other signal types should be considered possibly better solutions from the power consumption point of view, because as it can be seen from Fig. 2, using 12.5 GHz and 18.75 GHz frequency slots between channels, 10 Gbps signal regeneration requires 93.43 % and 44.15 % of total power consumed, respectively.

The second transmission signal type under consideration was 40 Gbps NRZ-DPSK. Figures 3–4 and Table 3 show spacing values of the considered channel. Since in this case transmission speed was 40 Gbps, signal spectrum was considerably wider in comparison with 10 Gbps NRZ-OOK spectra. This led to wider frequency slot requirement with the purpose to achieve the same quality of transmission (QoT) and thus the systems were evaluated using 50.0–100.0 GHz channel spacing. Six cross-channel intervals were analysed. The obtained results are provided in Table 4.

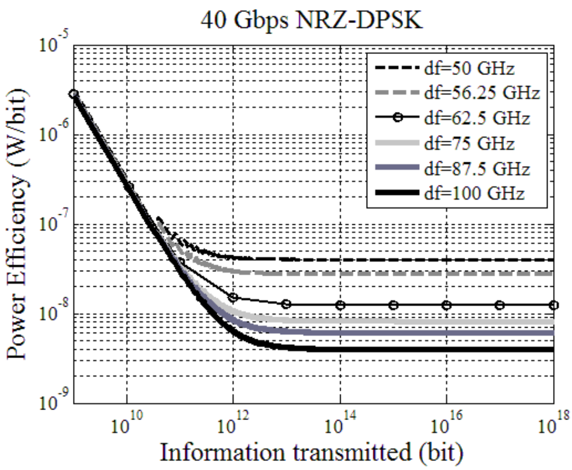

Fig.3. 40 Gbps NRZ-DPSK power efficiency curve.

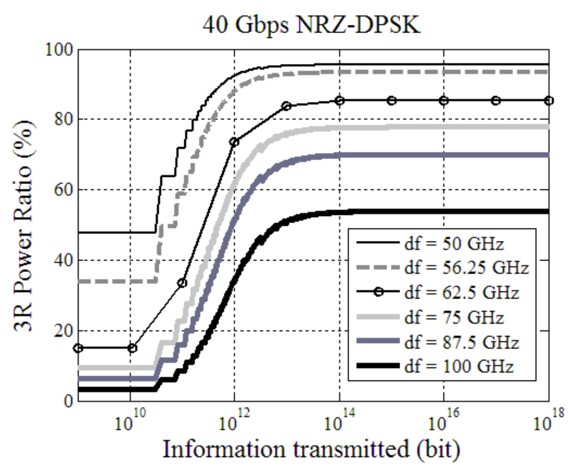

Fig. 4. Power ratio curve of 40 Gbps NRZ-DPSK 3R regenerators.

Table 4

Power Ratio Values of PE and 3Rs Operating at Different Frequency Slots

Channel spacing (GHz)	Power efficiency (nW/bit)	Power ratio of 3Rs (%)
50.00	40.07	95.46
56.25	27.32	93.34
62.50	12.44	85.38
75.00	8.19	77.80
87.50	6.07	70.03
100.00	3.94	53.88

On the ground of wider signal spectrum, by increment of frequency slot the power efficiency changed smoother than in the case of 10 Gbps. Therefore, increment of channel spacing for the amount of 12.5 GHz had no such significant impact on the power efficiency of the system. In this case, the power ratio of 3Rs had more significant impact on total power consumption (more than 50 % for each considered configuration) in comparison with NRZ-OOK because the transmission reach for this signal type was shorter. However, if 40 Gbps NRZ-DPSK operates with 100.0 GHz channel spacing, its power efficiency value is 3.94 nW/bit, when the best scenario for 10 Gbps NRZ-OOK is 4.3 nW/bit operating with 25.0 GHz frequency slot. This means that for the transmission of a single bit NRZ-OOK consumes by ≈ 8.37 % more power than NRZ-DPSK having the same spectral efficiency.

A similar situation occurs in scenarios when cross-channel interference is most pronounced, operating with 12.5 and 50.0 GHz channel spacing, respectively. In spite of the fact that power ratio of 3Rs for OOK and DPSK is 93.43 % and 95.46 % respectively, power efficiency at 40 Gbps system realisation is 40.07 nW/bit against 65.5 nW/bit in the case of 10 Gbps, which provides ≈ 63 % difference in the required power for the transmission of a single bit.

The results of 100 Gbps DP-QPSK are summarised in Figs. 5–6.

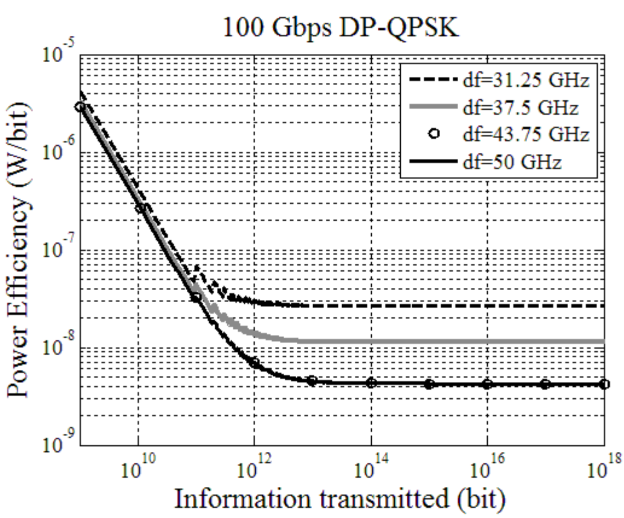

Fig. 5. 100 Gbps DP-QPSK power efficiency curve.

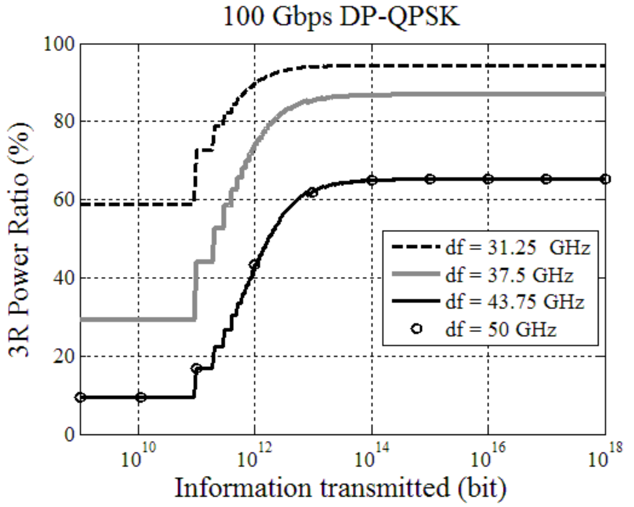

Fig. 6. 100 Gbps DP-QPSK 3R power ratio curve.

The obtained results show that minimal channel spacing to guarantee the required BER level is 31.25 GHz, which provides the power efficiency level equal to 26.50 nW/bit. In virtue of a very efficient modulation format, spectral efficiency in this case is four times greater in comparison with both 10 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK and, furthermore, the considered transmission system is power efficient by 147 % and 51 % in comparison with NRZ-DPSK and NRZ-OOK, respectively. Other issues are practical and financial realisations of such signal transmittance, but this is out of scope of the present research.

Likewise in the previous instances, signal regeneration requires great amount of energy, even when cross-channel interference becomes minimal and only one regeneration action is required. In this case, 3Rs ratios are 65.26 %, 86.80% and 94.42% operating at 43.75, 37.5 and 31.25 GHz cross-channel intervals, respectively. Investigation has shown that using channel spacing values greater than 43.75 GHz for the considered system is unreasonable and does not have impact on the power consumption of the system. Using 43.75 GHz cross-channel intervals, the power efficiency parameter of the system is 4.26 nW/bit, which means that 40 Gbps NRZ-DPSK transmission system, which uses 100 GHz frequency spans, can be by ≈ 8.1 % more power efficient than 100 Gbps DP-QPSK in the best scenario.

4. CONCLUSIONS

In the present research, the power efficiency of the three most popular signal modulation formats in the long-haul DWDM systems has been studied. The analytic model has been designed with the purpose that the error probability ratio for signal detection should be maintained lower than 10^{-3} at the receiving node at 2960 km P2P transmission distance. For this purpose by means of simulation using OptSim software, the transmission reach for each setup has been defined and using the obtained results the power consumption and efficiency of the system have been calculated. In addition, the impact of signal regeneration procedure has been examined on the total power consumption of the system for each simulation setup. The evaluation results have been presented as the functions of transmitted data volume operating at different channel spacing values, which allows adapting the results for WDM realisations with different available spectral bands.

The present research provides power efficiency values and the comparison for the DWDM setups, which operate with 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK or 100 Gbps DP-QPSK transmission signals, and gives an insight into the required power ratio intended for the considered signal regeneration. The results obtained within the framework of the research for the mentioned setups can provide useful guidance on designing a power-efficient DWDM long-haul system.

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SIGNĀLA REĢENERĀCIJAS IETEKMES NOVĒRTĒŠANA UZ GARĀS DWDM SISTĒMAS ENERGOEFEKTIVITĀTI

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K o p s a v i l k u m s

Šajā rakstā ir izpētīta DWDM sistēmu energoefektivitātes lieluma atkarība no izvēlēta pārraides frekvences plāna, kurš izveidots saskaņā ar ITU-T rekomendāciju G.694.1. Ir aprēķināti reģenerācijas iecirkņa garumi un spektrālās efektivitātes lielumi, izmantojot dažādus starpkanālu intervālus. Atsevišķi rakstā ir analizēta signālu reģenerācijas procedūrai nepieciešamā jauda, kura ir grafiski attēlota kā attiecība pret sistēmas kopējo patērēto jaudu. Visi aprēķini tika izpildīti trim populārākajiem signālu modulācijas formātiem - NRZ-OOK, NRZ-DPSK un DP-QPSK, ar 10 Gbps, 40 Gbps un 100 Gbps pārraides ātrumiem attiecīgi, kuri bieži tiek izmantoti mūsdienīgās DWDM sistēmās. Rezultāti ir attēloti kā funkcijas no pārraidītās informācijas apjoma, kas padara tos piemērotām sistēmām ar atšķirīgu pieejamu spektra platumu.

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