Transponder and 3R Regenerator Impact on Energy per Bit and Optical Bandwidth Required for Data Transmission over 10-40-100 Gbps Mixed-line Rate WDM Links

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Abstract— In this paper we aim at exploring the impact of transponders and 3R (re-timing, re-shaping, re-amplification) power consumption on the transmission's power efficiency for the set of link's length and on the optical bandwidth required for the allocation of the wavelength channels which number is chosen in order to minimize the overall energy consumption.

1. INTRODUCTION

Although the mixed-line rate (MLR) design of wavelength division multiplexing (WDM) optical networks has proved itself as a cost-efficient solution for dealing with the heterogeneity of continuously growing traffic demands [1], still some MLR configurations might not be the best in term of energy consumption per bit (or power efficiency in W/bps) required for the accumulation of aggregated traffic [2]. In general, power efficiency of MLR solutions depends on the number of factors, such as power consumption of transponders and 3R (re-timing, re-shaping, re-amplification) regenerators, number of the 10 Gbps, 40 Gbps, and 100 Gbps wavelengths, and the overall transmission distance. Depending on the configuration and the link length the MLR-based WDM system could outperform some of the 10 Gbps, 40 Gbps and 100 Gbps single-line rate (SLR) solutions or not. Therefore, it is important to use the proper criteria (e.g., power consumption of transponder and/or 3R regenerator; spectral efficiency which could be achieved with a particular modulation format; optical bandwidth required for the wavelength allocation in a transmission spectra) for choosing the number of different wavelengths.

Before this research, the power efficiency in WDM fiber-optical links has been studied in number of journal publications and conference papers. In [3], the power efficiency and spectral efficiency have been compared for the number of bitrates, modulation formats and fiber-optical link lengths while securing a given Quality of Transmission (QoT) at the receiving node. In [4], the impact of Mixed-Line Rate (MLR) solutions on the power efficiency and capacity that could be transmitted over the conventional band (C-band) has been compared for the different lengths of the point-to-point links. In [2], the power efficiencies for the number of 10–40–100 Gbps MLR and Single-Line Rate (SLR) solutions have been compared to each other. Such comparison is made for different link lengths in point-to-point WDM system where 3R regeneration of optical signals is made after each section of the link. Each section consists of 40 km long span of standard single mode fiber (SSMF) and inline dispersion compensation module (DCM). Regeneration is required due to the maximum tolerable spectral efficiency for each considered bitrate and modulation format. In this paper we operate with three different bitrates — 10 Gbps realized using the non-return-to-zero on-off keying (NRZ-OOK), 40 Gbps using the NRZ differential phase-shift keying (NRZ-DPSK), and 100 Gbps using the dual polarization quadrature PSK (DP-QPSK). Without 3Rs placed after each section, it would not be possible to fulfill the signal quality requirements at the receiving node. However, none of these publications explore which criterion to use if the optical bandwidth or energy consumption is a constraint when choosing the bitrate and modulation format for the transmission of aggregated traffic. Hence, in this paper we study the effect of transponder and 3R regenerator power consumption on the energy per bit and on the optical bandwidth required for the transmission of aggregated traffic with the $\mathrm{BER} \leq 1 \cdot 10^{-9}$ defined signal quality at the receiving node of the FEC-free WDM system.

2. CONTRIBUTION OF THIS PAPER

Firstly, the comparison is given between the energy consumption in SLR and MLR systems required for data transmission over various fiber-optical link lengths. Its detailed configuration is described in [3], while the power consumption of transponder and 3R regenerator and the minimum tolerable frequency intervals were studied in [2, 4] and summarized in [5]. Then, the contribution of 3R regenerators' on overall power consumption is evaluated. This is done for the spectrally efficient

WDM links where signal quality is limited by linear crosstalk and system reach (without 3R regeneration) is fixed to one span of the transmission fiber. In this case, it is 40 km — the medium span length between two inline optical amplifiers [6]. Later on, criteria are studied that could be used when the decision is made about which bitrate and modulation format to use. In our case, the goal for such decision is to reduce the energy consumption while as criteria we used (i) power consumption of transponders and (ii) power consumption of 3R regenerators. And, finally, it is estimated how changes the optical bandwidth required for the transmission of the aggregated traffic depending on its amount and the criterion used to select one solutions (including the bitrate and modulation format) or another. This helps to explore and understand the trade-off between the spectral efficiency and energy per bit (so-called power efficiency) discovered and studied in previous publications, e.g., [2–5].

3. RESULTS AND DISCUSSIONS

This section consists of two subsections where, firstly, the energy per bit for the MLR and SLR solutions are compared and, secondly, the criteria are studied that could be used for making a decision about the use of one bitrate and modulation format or another. The impact of them on the power efficiency (energy consumption per bit) and on the optical bandwidth required for placing the wavelength in the transmission spectra are explored and compared.

3.1. Energy per Bit in WDM Links Based on the Single Line Rate and Mixed Line Rate

In this sub-section, we will analyze the difference between the energy consumption required for 1 bit transmission over MLR and SLR systems. For the SLR solutions, 10 Gbps NRZ-OOK, 40 Gbps NRZ-DPSK and 100 Gbps DP-QPSK wavelengths will be used. In studied MLR solution, number of the 10 Gbps, 40 Gbps and 100 Gbps wavelengths will be based on the realistic distribution among the 10G, 40G and 100G requests in transport optical networks. This distribution could be described using the 50 : 35 : 15 ratio [7]. If it is assumed that for each request the individual wavelength is assigned, then this ratio could be transformed in to the widths of each sub-band: $\Delta F_{10\mathrm{G}}$, $\Delta F_{40\mathrm{G}}$ and $\Delta F_{100\mathrm{G}}$. Using the previously discovered minimum frequency intervals between collocated wavelengths, the sub-bands widths are: $\Delta F_{10\mathrm{G}} = 16\%$; $\Delta F_{40\mathrm{G}} = 74\%$; $\Delta F_{100\mathrm{G}} = 10\%$ of the entire band.

More than 2.7 Tbps of traffic could be transmitted over the conventional band (C-band) if it is sub-divided using this ratio and the 10 Gbps, 40 Gbps and 100 Gbps wavelengths are placed with the minimum acceptable frequency intervals between them. In comparison, for the 10 Gbps, 40 Gbps and 100 Gbps SLR solutions it would be 2.34 Tbps, 1.56 Tbps, and 11.70 Tbps, respectively. Figure 1 shows how the energy consumption per bit changes with the transmission distance. These values are normalized against the power efficiency in the 10 Gbps NRZ-OOK SLR solution. As it could be seen in Fig. 1, the lowest energy consumption per bit is reached with the 40 Gbps SLR solution employed the NRZ-DPSK modulation format and only for the transmission distances longer than

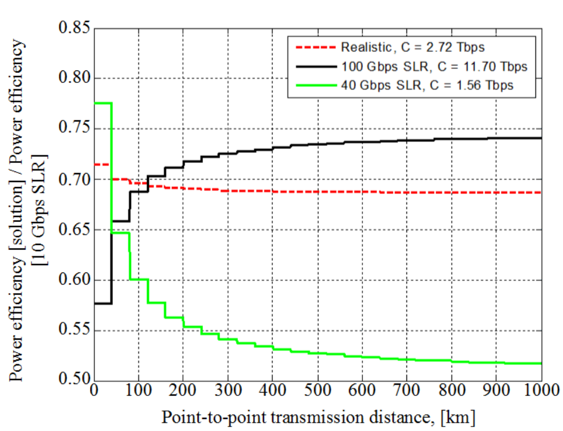

Figure 1: Energy consumption per bit required for the transmission of the aggregated traffic in cases of a spectral efficient SLR and 10–40–100 Gbps MLR solutions.

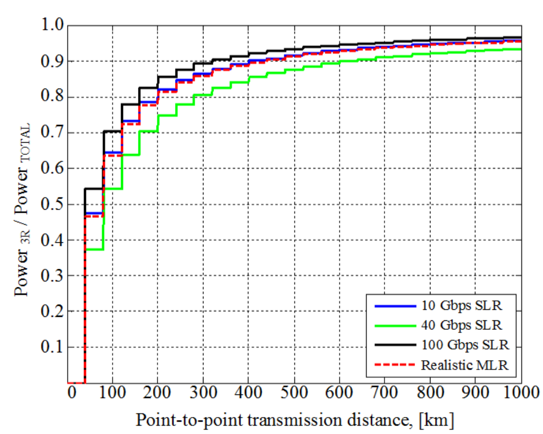

Figure 2: Ration between energy consumption due to 3Rs and the total energy consumption required for the data transmission in a spectrally efficient WDM system.

one span of the transmission fiber. If the transmission distance is more than three SSMF spans (120 km), 100 Gbps SLR solution became worse than the realistic MLR solution. Therefore, if the frequency band is not a constraint, then the MLR solutions provide a good compromise between the power efficiency (energy per bit) and the traffic that could be transmitted over the frequency band. In addition, it should be highlighted that in term of the energy consumption per bit, 10 Gbps NRZ-OOK SLR solution is worse than any other considered (see that the values on the Y-axis are below 1).

Since the optical signals must be regenerated after each link's section due to the maximum tolerable spectral efficiency, then 3R regenerator power consumption will define mainly the power efficiency in the WDM link (see Fig. 2). As one could see, the 40 Gbps curve is located below all others. This evidences about the high energy efficiency of the 40 Gbps NRZ-DPSK regenerators. Therefore, even if the 40 Gbps SLR solution is the worst in term of the traffic that could be transmitted over the frequency band, it could be used in spectrally efficient WDM systems to deal with traffic heterogeneity and to reduce the energy consumption per bit.

3.2. Power Consumption of Transponder and 3R Regenerator as a Criteria for Choosing the Bitrate and Modulation Format

Figure 3 shows the number of 10 Gbps, 40 Gbps and 100 Gbps channels that must be used to accumulate aggregated traffic if the goal is to do it with the lowest energy consumption possible. To make a decision about with bitrate and modulation format to use, two different criteria were used — (i) power consumption value of each considered transponder; (ii) power consumption value of each considered 3R regenerator. This figure shows a significant difference between these two cases. Firstly, if the power consumption of transponders is used as a criterion for choosing the bitrate and

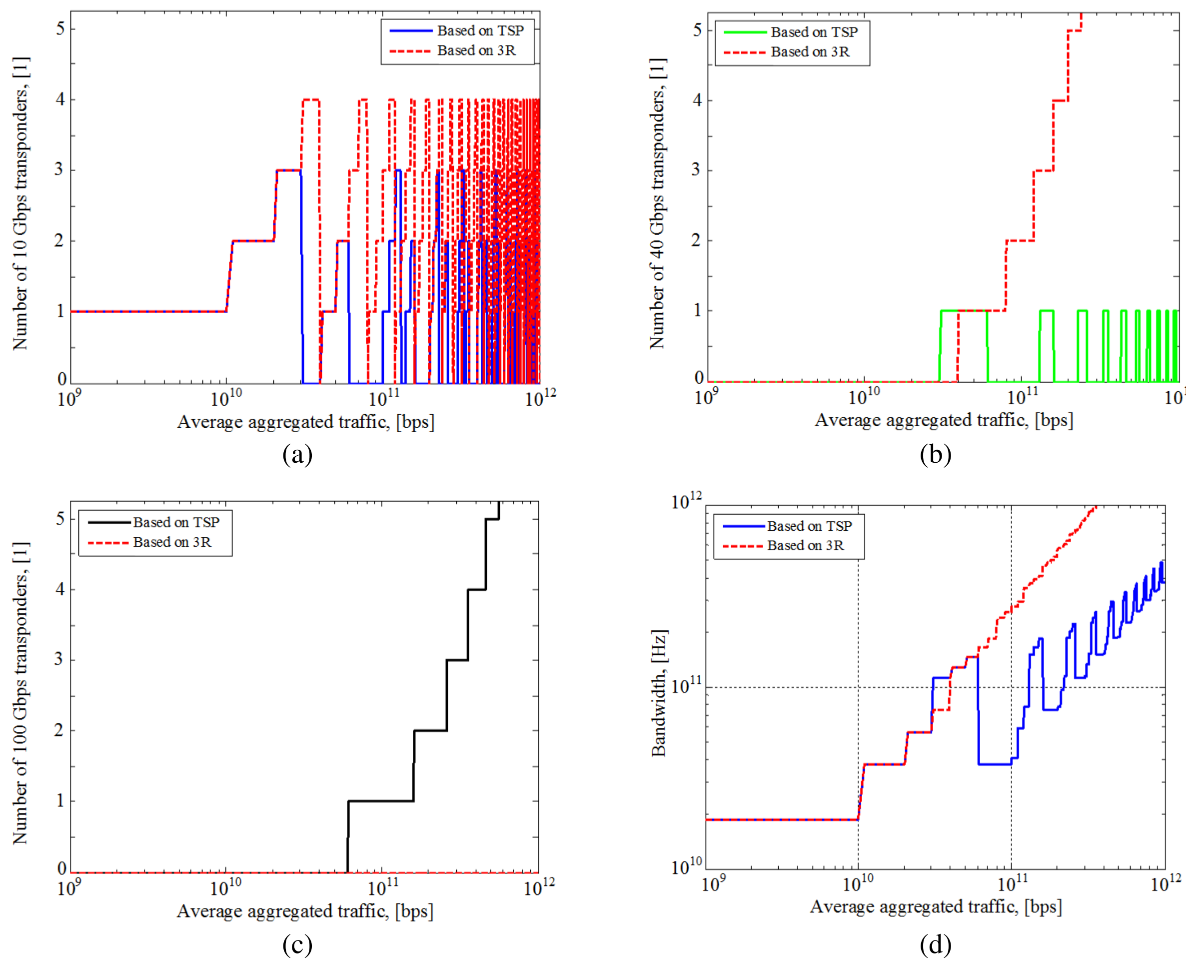

Figure 3: Number of (a) 10 Gbps, (b) 40 Gbps and (c) 100 Gbps wavelengths required for the transmission of the aggregated traffic amounts, and (d) the optical bandwidth required for placing the wavelengths in the transmission spectra if the transponder or 3R regenerator power consumptions are used as a criteria for choosing the bitrate and modulation format.

modulation format, then the lowest energy consumption could be reached if not more than three 10 Gbps NRZ-OOK and not more than one 40 Gbps NRZ-DPSK are used while the number of the 100 Gbps DP-QPSK channels increases with the aggregated traffic amounts. However, situation changes if the power consumption of regenerators is used as a criterion. In this case, the lowest energy consumption could be reached if the number of the 10 Gbps NRZ-OOK channels is not more than four, 100 Gbps DP-QPSK channels are not used at all while the number of the 40 Gbps NRZ-DPSK channels growths with the traffic amount which should be transmitted.

Using the estimated number of channels and discovered previously frequency intervals, we evaluated the frequency bandwidth that must be used to place the required number of wavelengths (see Fig. 3(d)). As one could see, for the traffic amount above 60 Gbps there is a huge difference in the required bandwidths. This difference reaches almost 5 times for the traffic amount more than 300 Gbps. In addition, the decisions made based on power consumption of transponders promote the more efficient use of the frequency band available for transmission. In contrast, for the energy consumption point of view, these decisions must be made based on the power consumption of 3R regenerators.

4. CONCLUSIONS

This paper explores how the criterion used to make a decision about which bitrate and modulation format to use for the transmission of aggregated traffic effects the energy consumption per bit and the required optical bandwidth for placing the wavelength channels. Two different criteria are studied — (i) power consumption of transponders and (ii) power consumption of 3R regenerators. This research performed for the spectrally efficient WDM systems based on the MLR and SLR designs. In such fiber-optical links, system reach is limited by one span of transmission fiber. Therefore, the main power consumer is 3R regenerators in such WDM systems.

After having analyzed the presented results, it should be concluded that aggregated traffic must be transmitted mainly by the 100 Gbps DP-QPSK wavelengths if the optical bandwidth is the constraint. In contrast, the 40 Gbps NRZ-DPSK wavelengths should be used mainly, if the energy consumption is the constraint. In both case, the 10 Gbps NRZ-OOK wavelengths also should be used for both — reduction of energy consumption and accumulation of traffic heterogeneity. Hence, the mixed-line rate approach ensures a good trade-off between the power efficiency and spectral efficiency in the frequency band.

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