Transponder Impact on Power and Spectral Efficiencies in WDM Links Based on 10–40–100 Gbps Mixed-line Rates

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Abstract— It has been proved that Mixed-Line Rate (MLR) could in a cost-efficient manner scope with heterogeneity of constantly increasing traffic demands in core networks. In the same time, the energy efficiency of a Wavelength Division Multiplexing (WDM) transmission system of a MLR solution depends on the number factors (such as energy efficiency of transponders and regenerators, spectral efficiency, length of transmission distance etc.) and number of wavelengths operating with the particular bitrate and modulation format is one of them. Hence, this papers aims at exploring the power efficient 10 Gbps, 40 Gbps and 100 Gbps wavelength assignment strategy as well as the minimum optical bandwidth required to allocate all wavelengths.

1. INTRODUCTION

During the planning of wavelength division multiplexing (WDM) transport network as well as on its operation pace one of the major constraints is the overall power consumption and power costs per transmitted bps, i.e., energy efficiency [1]. The Mixed-Line Rate (MLR) solutions have proved themselves as a cost efficient solution to deal with the heterogeneity of traffic demands [1, 2]. However, the energy efficiency of such WDM solution depends on the number of parameters such as (i) number of wavelengths operating with the particular bitrate and modulation format; *(ii)* energy efficiency of transponder; *(iii)* spectral efficiency which will define the transparent optical reach and, hence, the number of 3R (re-timing, re-shaping, re-amplification) regenerations; *(iv)* distance between two network nodes between whom an end-to-end connection should be provisioned; and (v) signal quality need to be guaranteed at the receiving node. In this paper, we focus on MLR solution which employs three different bitrates — 10 Gbps using the non-return-to-zero (NRZ) on-off keying (OOK), 40 Gbps using the NRZ differential phase-shift keying (NRZ-DPSK) and 100 Gbps realized with the dual polarization quadrature phase-shift keying (DP-QPSK). Furthermore, about MLR with such modulation format and bitrate selection have been reported in [3].

In [4–6] authors explores the trade-off between power costs per each transmitted bps, spectral efficiency and the point-to-point transmission distance for the number of Single-Line Rate (SLR) and MLR solutions but none of these papers do not explore the wavelength assignment scheme that must be used to guarantee the lowest overall transponder power consumption regardless to the capacity that need to be transmitted with defined signal quality. Hence, this papers aims at exploring the power efficient 10 Gbps, 40 Gbps and 100 Gbps wavelength assignment approach as well as the minimum optical bandwidth required to allocate these wavelengths in an end-to-end WDM link where the signal quality ($Q \geq 6$) is mainly limited by a linear crosstalk. In addition, in this paper we: (i) report about power consumption values for different transponder and 3R types; *(ii)* reveal the minimum allowable frequency intervals between collocated wavelengths; *(iii)* compare the power efficiency of proposed MLR solution with the SLR ones; and *(iv)* analyze the gained transponder load as a function of average aggregated traffic.

2. BACKGROUND AND INITIAL PARAMETERS

In previous research papers, e.g., [4, 5, 7] it has been revealed (i) the minimum acceptable frequency intervals (see Table 1) between collocated wavelengths that allows detect signals with $Q \geq 6$ after the transmission over one span of transmission fiber and dispersion compensation module (DCM); *(ii)* transponders and 3Rs power consumption values for the considered modulation formats and bitrates (see Table 2). These parameters will be used further in this research papers.

Comparing these values must be reported that for the transmission capacity higher than 80 Gbps, it is more energy efficiently to use the 100 Gbps DP-QPSK transponders. As for the 3Rs, the situation changes and 40 Gbps NRZ-DPSK ensures lower costs per each transmitted bps.

3. RESULTS AND DISCUSSION

In this section, the impact of transponder power consumption on the width of required frequency band is evaluated. For this reason, firstly we describe an approach that must be used to choose

Table 1: The minimum tolerable channel spacing and Q-factor in the worst system channel.

Wavelengths	**∆ Fmin, [GHz]**	**Q-factor, [dB]**
10 Gbps–10 Gbps	18.75	16.09
40 Gbps–40 Gbps	112.50	15.56
100 Gbps–100 Gbps	37.50	15.75
10 Gbps–40 Gbps	62.50	23.88
10 Gbps–100 Gbps	31.25	17.08
40 Gbps–100 Gbps	75.00	16.90

Table 2: Power consumption [W] of transponders and 3Rs.

Bitrate and modulation format	**Equipment**	**Power, [W]**
10 Gbps NRZ-OOK	TSP/3R	22.4/20.8
40 Gbps NRZ-DPSK	TSP/3R	69.8/43.6
100 Gbps DP-QPSK	TSP/3R	132.1/158.5

which wavelength to use for data transmission to ensure the lowest possible overall transponder power consumption. Secondly, the overall power consumption of transponder for the SLR scenarios is compared with energy efficient MLR scenario, where number of each wavelength is chosen based on the proposed scheme. The width of frequency band required for transmission as a function of average aggregated traffic also is given. And, finally, transponder load is calculated and compared with the SLR scenarios.

3.1. Energy Efficient Approach to Choose a Number and Type of Required Transponders

As it is mentioned above, the power costs per transmitted bps (i.e., W/bps) or energy efficiency (in J/bit) in MLR transmission systems strongly depends on the number of particular wavelengths used to transmit the particular amount of accumulated traffic. Clear that in the MLR case, the same capacity could be transmitted with different numbers of 10, 40 and 100 Gbps wavelengths. Hence, the overall power consumption of required number of transponders could vary in wide range. But since the transponder power consumption will mainly define the energy efficiency of transmission system (power consumption of inline optical amplifiers is a constant value is inherent to the type modulation format used for data transmission), it is important to choose the combination of 10, 40 and 100 Gbps wavelengths that ensure the lowest overall transponder power consumption for each amount of aggregated traffic. Such algorithm is described in Fig. 1. It is based on the fact that 100 Gbps DP-QPSK transponder has the highest energy efficiency comparing to the 10 Gbps NRZ-OOK and 40 Gbps NRZ-DPSK.

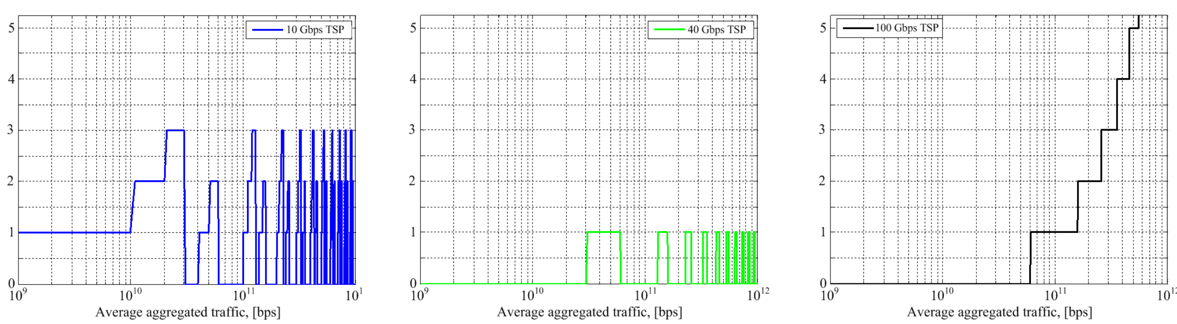
Figure 2 shows that the lowest possible overall power consumption of transponders is secured when not more than three 10 Gbps NRZ-OOK and not more than one 40 Gbps NRZ-DPSK transponders are used for the transmission. In the same time, the number of 100 Gbps DP-QPSK transponders must be increased together with the transmitting capacity (see Fig. 2(c)). This is explained with the highest energy efficiency of 100 Gbps transponders.

If the number of 10, 40 and 100 Gbps wavelengths is chosen based on this proposed algorithm, the overall power consumption required to ensure data transmission over one span of fiber-optical link is: (*i*) the same as it would be in case on 10 Gbps SLR solution, if the transmitting capacity is lower than 30 Gbps; *(ii)* lower than it would be in case of any other number of 10, 40 and 100 Gbps wavelength, if 30 Gbps $< C <$ 60 Gbps; *(iii)* not higher than it would be in pure 100 Gbps SLR solution (see Fig. 3). In addition, it should be noted that curves in Figs. 2–4 have a stepwise form due to the number of transponders which is a discrete and not a continuous variable. For example, 140 Gbps capacity between two nodes should be transmitted by utilizing (*i*) fourteen 10 Gbps, *(ii)* four 40 Gbps or even *(iii)* two 100 Gbps transponders.

The number of particular wavelengths has a strong impact not only on the energy efficiency of transmission but also on the average utilization of WDM system equipment, transponders particularly. From the telecom operator point of view, the installed equipment should be utilized as much as it is possible. Therefore, we also calculated the average utilization of transponders in energy efficient scenario of MLR transmission system, i.e., MLR system where number of 10, 40 and

for each amount of aggregated traffic C
  required number of 100G transponders: $N_{100G} = floor(C/100G)$
  traffic amount transmitted only with 100G TSP: $C_{100G} = N_{100G} \cdot 100G$
  traffic amount that should be transmitted with 40G and/or 10G TSPs: $C_{40G/10G} = C - C_{100G}$
  required number of 40G TSP: $N_{40G} = floor(C_{40G/10G}/40G)$
  traffic transmitted only with 40G TSP: $C_{40G} = N_{40G} \cdot 40G$
  traffic amount left only for 10G TSP: $C_{10G} = C_{40G/10G} - C_{40G}$
  number of 10G TSP: $N_{10G} = ceil(C_{10G}/10G)$
    if power consumption of 100G TSP P_{100G} < (power consumption of 40G TSP $P_{40G}) \cdot N_{40G}$ + (power consumption of 10G TSP $P_{10G}) \cdot N_{10G}$ **then**
      use 40G and/or 10G TSPs
    else
      use 100G TSP
      if $P_{40G} < P_{10G} \cdot N_{10G}$ **then**
        use 40G TSP
      else
        use 10G TSPs
      end
    end
end

Figure 1: Structure of algorithm used to identify the required number of each type of transponders.



(a) (b) (c)

Figure 2: Number of a different type of transponders: (a) 10 Gbps, (b) 40 Gbps and (c) 100 Gbps required to accumulate traffic in considered scenario of a power efficient MLR-based WDM network.

100 Gbps wavelengths is chosen based on the proposed algorithm. Fig. 4 shows that the average transponder load in case of proposed MLR solution is sufficiently higher comparing to the 100 Gbps SLR. Of course, the use of lower bitrate (e.g., 10 Gbps) ensures very high transponder utilization but in the same time, 10 Gbps transponders cannot secure the lowest overall power consumption of transponder. Hence, we will gain something in terms of transponder load but will definitely lose a lot in terms of power consumption, if 10 Gbps wavelength will be selected for the transmission of large amount of traffic between two network nodes.

3.2. Width of the Frequency Band Required for Transmission

Using the values of frequency intervals summarized in Table 1, the width of optical frequency band that must be used to place 10 Gbps, 40 Gbps and 100 Gbps wavelengths in appropriate sub-bands can be calculated for the considered power efficient solution of MLR transmission system. Fig. 5 shows how changes the width of required frequency band with the average aggregated traffic, if proposed algorithm for the estimation of 10 Gbps, 40 Gbps and 100 Gbps wavelengths is used. The width of total required band is marked with broken red line, while the widths of 10, 40 and 100 Gbps sub-bands are colored in blue, green and black, respectively.

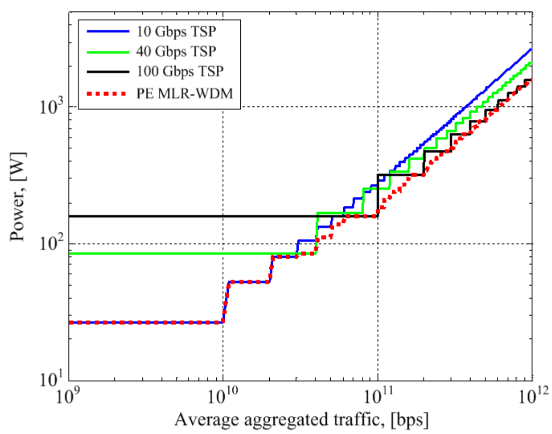


Figure 3: Total power consumption of different TSPs as a function of average aggregated traffic.

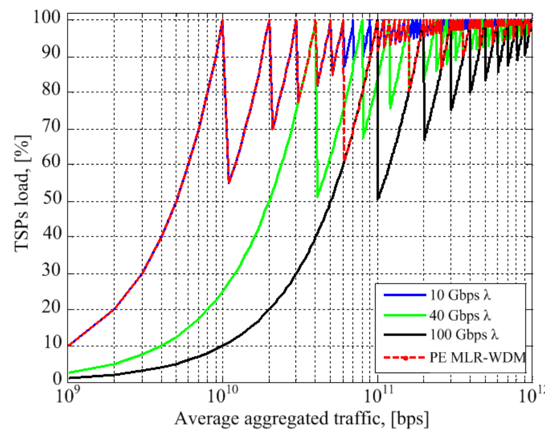


Figure 4: TSPs load in a considered scenario of power efficient MLR-based WDM network as a function of average aggregated traffic.

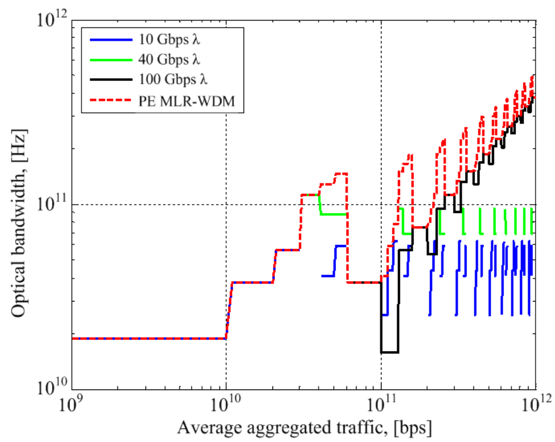


Figure 5: Optical bandwidth required to allocate 10 Gbps, 40 Gbps and 100 Gbps wavelengths as a function of aggregated traffic.

Width of 10 Gbps and 40 Gbps sub-bands is a discrete variable because for some capacities, it is more efficiently from power consumption point of view not to use 10 Gbps and/or 40 Gbps wavelengths at all (see Fig. 2). It also should be noted that for the $C \leq 30$ Gbps, lines colored in red (i.e., total width of required band) and blue (i.e., width of 10 Gbps sub-band) overlap. For the 30 Gbps $\leq C \leq$ 40 Gbps, lines colored in red and green (i.e., width of 40 Gbps sub-band) also overlap. Therefore, it must be concluded that data transmission in power efficient solution of 10–40–100 Gbps MLR system mainly is based on 100 Gbps wavelengths. Such configuration of WDM transmission system secures the lowest transponder power consumption per transmitted bps and gives a flexibility to operate with lower bitrate if necessary.

4. CONCLUSIONS

This paper focuses on a 10 Gbps, 40 Gbps and 100 Gbps wavelength assignment approach that ensures the lowest overall transponder power consumption per 1 bps transmitted over one span of fiber-optical link that consists from 40 km of standard single mode fiber and chromatic dispersion post-compensation module. Wavelengths are placed in optical spectrum using obtained frequency intervals that secure signal detection on the receiver side with Q-factor not lower than 6.

It is revealed that the lowest overall transponder power consumption is secured when not more than there 10 Gbps wavelengths are used to transmit the data and not more than one 40 Gbps wavelength is used regardless to the total capacity need to be transmitted, while the number of 100 Gbps wavelength should be increased as average aggregated traffic grows. This is explained with the highest energy efficiency of 100 Gbps transponders comparing to the 10 Gbps and 40 Gbps. If the number of each wavelength is selected using this proposed algorithm then the total power consumption required to ensure data transmission over one section of transmission line is: (*i*) the same as it would be for the 10 Gbps SLR solution and the capacity less than 30 Gbps; *(ii)* the lowest one for the traffic between 30 and 60 Gbps; *(iii)* not higher as it would be for 100 Gbps SLR solution.

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