Is unceasing increase of channel symbol rate the panacea for WDM transparent meshed networks?

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Abstract: In the context of transparent meshed WDM networks, we illustrate and explain why very large channel symbol rate (288 GBd) can adversely reduce the achievable total network capacity, whilst still improving global expenditures per Gb/s. © Nokia 2024

1. Introduction

While 130/140 GBd Elastic Optical Transponders (EOT) are now shipped by the industry [1][2] and the first 200 GBd EOTs are expected in 2024, it is important to fully comprehend their benefit versus the previous EOT generations. They are not expected to bring substantial gain of Spectral Efficiency (SE) as the previous generations were already very close to the Shannon limit [3][4]. So, most of the related expectation is about continuing reducing the associated capital and operational expenditures per transmitted Gb/s, especially in terms of power consumption and footprint. Whereas these advantages are without counterpart for the point-to-point WDM systems, this study shows how increasing the channel symbol rate beyond 200 GBd can notably degrade the total capacity in transparent meshed WDM networks without enough traffic grooming. We also suggest possible options to mitigate this negative impact.

2. Models of network and traffic

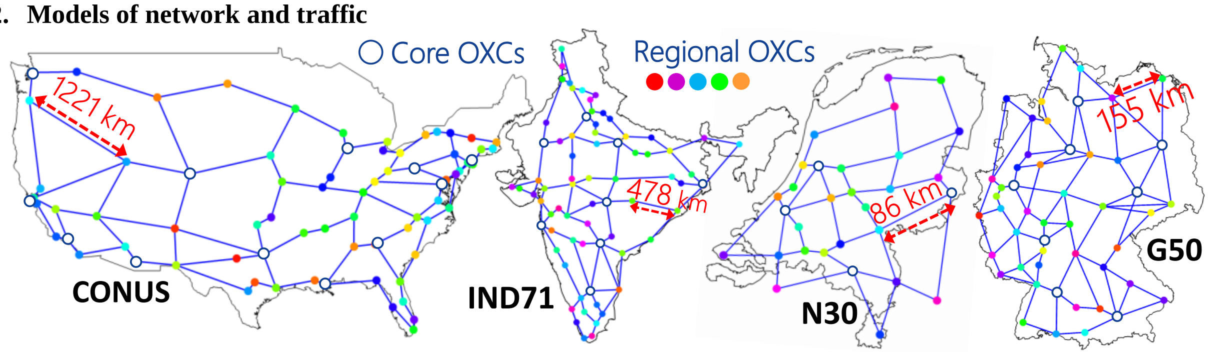

Fig. 1: *4 studied WDM network topologies*

For a comprehensive survey, we consider the 4 WDM topologies depicted in fig. 1 with a diameter gradually growing from N30, G50 [5], IND71 up to CONUS [5]. These topologies reported with more details in [4][6], respectively cover the Netherlands, Germany, India and the U.S.A with 30, 50, 71 and 75 network nodes. The wavelength-routing Optical Cross-Connects (OXC) are modelled with the "Route&Select" layouts [7]. They are interconnected by links simulated as suites of spans of bidirectional pairs of standard single mode fibers. Their optical loss is offset by Erbium doped fiber amplifiers operating with 5.5 dB noise figure over the 4800 GHz-wide C-band transmission window. We benchmark the performance of these networks equipped with the 4 following generations of standalone WDM EOT: 138, 188, 238 and 288 GBd EOTs respectively handling 150, 200, 250 and 300 GHz-spaced channels, leading then respectively to 32, 24, 19 and 16 channels/fiber on the C-band. 138 GBd EOTs are the last generation currently available based on 5 nm Digital Signal Processor (DSP), 188 GBd EOTs correspond to the upcoming ones based on 3 nm DSP, 238 GBd EOTs could be the next generation possibly available within the next 2/3 years [8] and 288 GBd EOTs may emerge thereafter. These EOTs can adjust their channel data rate with steps of 100 Gb/s in between the values reported in Table 1 thanks to QPSK, PCS-16QAM and PCS-64QAM carrier modulations, where PCS stands for Probabilistic Constellation Shaping. Our network study simulates progressive traffic growth in these 4 networks until reaching the moment when 1% of the total demanded capacity cannot be accommodated due to a lack of spectral resources. If the throughput of one connection cannot be fully served, the whole demand is discarded. The total network throughput served until this "1% blocking" moment is called Maximum Network Capacity (MNC). This simu

Table 1: *Flexibilities of WDM channel data rate for the 4 simulated EOT generations featuring PCS modulation*

Baud rate	*138 GBd*	*188 GBd*	*238 GBd*	*288 GBd*
Range of channel data rates (Gb/s)	300 to 1200	400 to 1600	500 to 2000	600 to 2400

-lation is reiterated 100 times with 100 distinct random traffics for each network setup to get a representative MNC value averaged over these 100 draws. We also establish the related mean value of number of EOTs per 100 Gb/s bidirectional services transmitted, tagged as N_{EOT} in the remainder. For each EOT generation, 2 network layouts are envisaged: i) either the network is designed in a fully opaque way, meaning that each connection goes back in the electrical layer at each network node crossed along its light path through the network to benefit from intermediate Traffic Grooming (TG); ii) or the network is implemented transparently only with total or partial end-to-end TG and possible optoelectronic regeneration to circumvent wavelength contention or Quality of Transmission (QoT) too degraded by the optical physical impairments. QoT is calculated specifically for each possible channel modulation by accounting for accumulation along each tested light path of the linear noise and residual spectral gain tilt of the optical amplifiers, of non-linear noise from the WDM transmission [9], of polarization dependent losses, of crosstalks as well as of filtering effects owing to the network elements traversed by the simulated signal. As usual, chromatic and polarization mode dispersions are totally compensated by the coherent detection postprocessing. The final electrical signal to noise ratio is established from these combined degradations along the light path of interest and from the intrinsic EOT bit error rate floor. The corresponding highest channel data rate enabled by the considered EOT technology is then allocated on the available wavelength(s) throughout the allocated light path.

We consider 2 random distributions of traffic called T_{800} and T_{1600} with connections served via inversed multiplexing on several parallel optical carriers if needed. Both distributions comprise 2 parts: a first fixed part ensuring 800 Gb/s bidirectional services exchanged between all the pairs of cores nodes and each regional node with each of its 2 closest core nodes. For T_{800} (resp. T_{1600}) the second part is made of random bidirectional and symmetrical services with throughput uniformly ranging from 400 to 1200 Gb/s with 400 Gb/s steps (resp. from 800 to 2400 Gb/s with 800 Gb/s steps). For this 2nd part, 33% of the random connections are drawn between the pairs of core nodes and 67% between any pair of core and regional nodes, except for CONUS network for which these 67% remain between any regional node and any of its 2 closest core nodes.

3. Simulation results and discussion

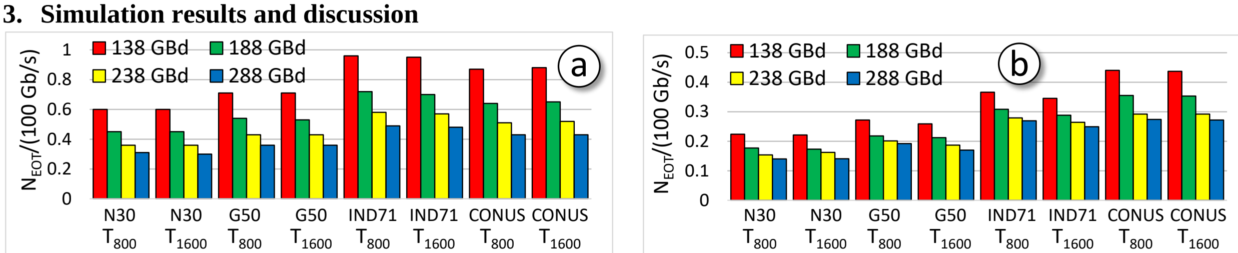

Fig. 2: *N_{EOT} for the 4 studied networks and 4 EOT technologies, with T_{1600} traffic, under opaque (a) or transparent (b) design*

Fig. 2a and 2b illustrate our outcomes in terms of N_{EOT}. As expected, the opaque implementation requires 2 to nearly 3 times more EOTs per Gb/s than the transparent one, depending on the network topology. These 2 figures also confirm the substantial N_{EOT} drop by down to -45% when increasing channel symbol rate from 138 GBd up to 288 GBd. This is now the main motivation for keeping on increasing carrier Baud rate.

Next lines focus on the MNC performance to see how it evolves with respect to the EOT technology, as reported in Fig. 3a and 3b. Fig. 3a shows that under opaque design, MNC is nearly independent from the EOT symbol rate. Because along almost each WDM link of the 4 tested networks, the same ultimate SE can be reached by any of the 4 envisaged EOT technologies. 238 GBd channels 250 GHz apart lead to slightly lower MNC as this spacing does not totally fill the 4800 GHz-wide C band, unlike the 3 other spacings. 138 GBd speed yields a few percents lower MNC only for CONUS topology as compared to what 188 and 288 GBd rates provide. Because the WDM links longer in average in CONUS than in N30, G50 and IND71 imply lower range of SE settings. In that context, the common 100

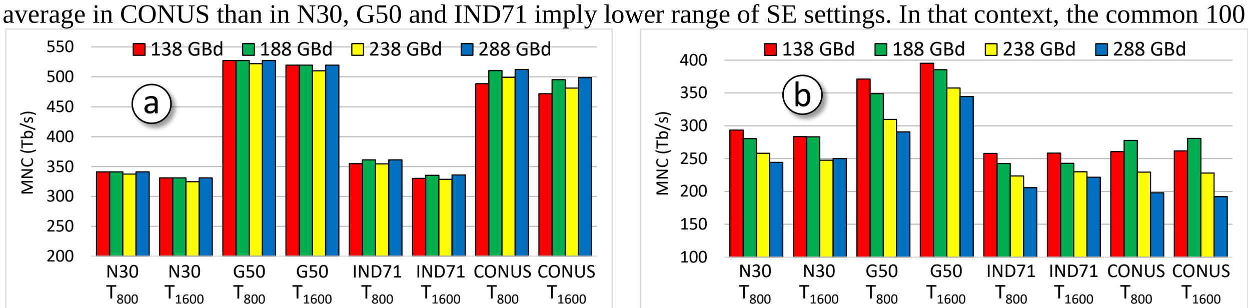

Fig. 3: *MNC for the 4 studied networks and 4 EOT technologies, under opaque (a) or transparent (b) design*

Table 2: *Possible SEs in Gb/s/Hz with 138 GBd 150 GHz-spaced WDM carriers and 188 GBd 200 GHz-spaced ones*

Channel data rate (Gb/s)	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1000*	*1100*	*1200*	*1300*	*1400*	*1500*	*1600*
SE with 138 GBd EOT	**2.00**	**2.67**	**3.33**	**4.00**	**4.67**	**5.33**	**6.00**	**6.67**	**7.33**	**8.00**				
SE with 188 GBd EOT		**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	**7.50**	**8.00**

Gb/s channel data rate granularity induces significantly lower PCS entropies steps for the faster channel modulations at 238 and 288 GBd than at 138 GBd. These finer steps better adapt the channel data rate to the various link lengths with these faster channel modulations, leading eventually to slightly higher MNC in CONUS as shown in fig. 3a.
More surprisingly, it appears in Fig. 3b that MNC culminates with 138 GBd carriers in N30, G50 and IND71. From this 138 GBd baseline, MNC decay remains relatively small for 188 GBd ones, but becomes significant with 238 and 288 GBd carriers. This is because both simulated traffics T_{800} and T_{1600} do not as well fill the larger capacity of these faster WDM carriers. In the context of the simulated transparent mesh WDM network without intermediate TG, this downside worsens when the average channel capacity increases along with its growing Baud rate. Besides, doubling the average throughput of the demanded connections up to 1.6 Tb/s only marginally settles this issue, as the relative bar heights remain similar for T_{800} to T_{1600} traffics in fig. 3b. This problem can also get worse when the number of possible interconnecting network nodes increases, because the end-to-end TG less efficiently aggregates traffics that less often share common source and destination nodes. The second explanation for lower MNC beyond 188 GBd in our simulations stems from the number of channels per fiber. Unchanged total transmission bandwidth while the channel width raises involves much fewer channels per fiber, from 32 channels over the C-band with 138 GBd carriers 150 GHz apart down to only 16 channels with 300 GHz-spaced 288 GBd carriers. This diminishes the quantity of pairs of nodes that can be connected simultaneously and transparently through one given network WDM link, and eventually throughout a suite of WDM links across the network topology.
CONUS is a unique simulated case for which MNC culminates with 188 GBd carriers instead of with 138 GBd ones. Because the 2 previously mentioned drawbacks from the highest carrier symbol rates are more than counterbalanced in CONUS by the smaller SE granularity of the 188 GBd EOTs, especially in between 3 and 6 bit/s/Hz as shown by the boxes with gray background in Table 2. This SE interval is the most used in the CONUS network we emulate.

4. Further discussion and conclusion

The main takeaway of our exhaustive network studies performed for 4 various advanced EOT technologies, over 4 meshed WDM terrestrial core networks and under 2 distinct traffic distributions, is that beyond a given channel symbol rate in between 138 and 188 GBd, the maximum network capacity does not remain at its maximum level when designing the network transparently even with up to 1.2 Tb/s average transmitted services, whatever the topology even with intermediate regeneration avoiding wavelength contention. Keeping on growing the channel symbol rate will still be pertinent to reduce expenditures, as it will still significantly lower the number of EOTs to be deployed per Gb/s (see Fig. 2). However, specific evolutions will also be needed to maximize network capacity whatever the traffic breakdown. For instance, complementing the C-band WDM systems by C+L band ones is a first evident "stop-gap" way to stay with a high enough number of channels per fiber, even with 288 GBd carriers. For the longer terms, strictly transparent implementation of meshed WDM networks could be counterproductive and more traffic grooming will be useful to better fill the larger capacity of the future 288 GBd carriers. This can be inferred from our results depicted in fig. 3a showing no meaningful capacity discrepancy from 138 up to 288 GBd EOTs if applying extensive traffic grooming. This does not imply future WDM networks will have to be opaque. But to some extent, more intermediate traffic aggregation could be beneficial if the mean transmitted throughput does not surpass 1.6 Tb/s.

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