Is there a most appropriate channel spacing in WDM networks when individually routing 67 GBaud carriers?

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Abstract: As elastic optical transponders faster than 60 GBaud emerge in meshed terrestrial WDM networks, we investigate whether 75 GHz spectral channel spacing outperforms 87.5 GHz spacing when routing individual optical carriers transparently through optical nodes. © 2020 The Authors
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1. Introduction

The current advent of Elastic Optical Transponders (EOT) faster than 60 GBaud [1] poses the question of the related most appropriate spectral channel space in the WDM terrestrial meshed networks routing channels individually [2]. 50 or 62.5 GHz spacing, already in use today in these networks [3], is not suitable since it would be smaller than or too close to the channel symbol rate. When complying with the 12.5 GHz grid granularity of the ITU-T G.694.1 recommendation [4], the 2 next possible candidate spaces are 75 and 87.5 GHz. At first sight, 75 GHz would be the best spacing, since 87.5 GHz one would exhibit 15.6% fewer channels per fiber. However, this network study applied to 2 WDM topologies, shows why this too simple "rule of thumb" is incorrect in terms of total network capacity and of number of required transponders per Gb/s transmitted. Because the lower number of channels per fiber could be balanced in average by the highest Spectral Efficiency (SE) enabled by 87.5 GHz spacing.

2. Assumptions of the network study

For this network study, we consider the same transmission model as [5], based on WDM network individually routing 62 and 67 GBaud optical carriers, modulated via polarization multiplexing and Probabilistic Constellation Shaping (PCS). By progressively changing the constellation from QPSK to 64QAM, as well as by increasing the entropy of the PCS, the carrier data rate can grow from 100 Gb/s up to 600 Gb/s with 50 Gb/s granularity, using 2 distinct code rates for Forward Error Correction (FEC), and thus 2 different symbol rates. For a given channel data rate, the lowest code rate, or the largest Baud-rate, yields to longer WDM transmission reaches. On the other hand, the smallest Baud-rate remains of interest to better withstand the physical degradation when the detected signal goes through a relatively high number of tight filters in the wavelength routing Optical Cross-Connects (OXC) it traverses.

We envisage 2 network topologies: G50 and CONUS illustrated in figure 1, both relying on spans of Standard Single Mode Fiber (SSMF), with respectively 80 km and 100 km maximum span length and 0.22 dB/km loss, uncompensated in-line chromatic dispersion. Each WDM link is equipped with Erbium Doped Fiber Amplifiers (EDFA) that compensate for optical loss. We assume a 4800-GHz-wide C-Band transmission window where the 75 GHz and 87.5 GHz channel spaces may coexist. The OXCs are based on the "Route & Select" layout [7] leveraging Wavelength Selective Switch (WSS), meaning a channel is filtered twice when crossing an OXC. The EOT imperfections, the fiber nonlinear distortions and the Amplified Spontaneous Emission (ASE) noise are accurately approximated as uncorrelated additive noises. The quality of transmission of each channel is estimated through the calculation of the Signal to Noise Ratio (SNR) [5]. The contribution of the ASE-induced linear Optical SNR (OSNR) accounts for the OSNR penalty induced by the filters inside the OXCs traversed by the signal. This penalty depends on the filter shape, on the detuning between the channel optical frequency and the filter central frequency and on the channel modulation [8]. With the same physical model as [5], we run simulations of WDM transmission and filtering to establish the coefficients for the aforementioned SNR calculation for 62 and 67 GBaud channels modulated with PCS for net data

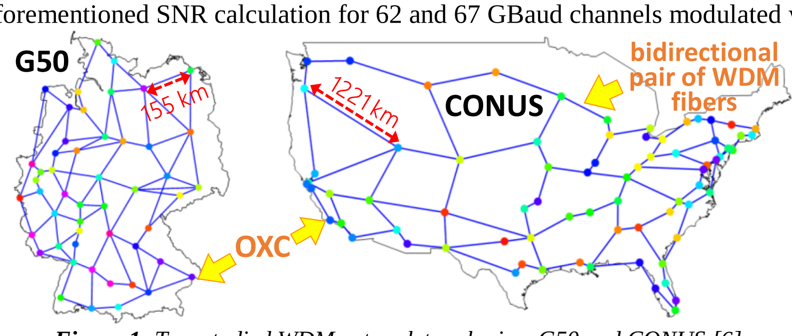

Figure 1: *Two studied WDM network topologies: G50 and CONUS [6]*

Table 1: *WDM transmission reaches for fully loaded C-band WDM system and 1 dB margin versus SNR at FEC*

Carrier modulations at 67 GBaud	**Reaches along 100 km-long spans of SSMF, with 75 / 87.5 GHz channel spacing**
100 Gb/s	5100 km / 5400 km
150 Gb/s	3800 km / 4100 km
200 Gb/s	2600 km / 2800 km
250 Gb/s	1700 km / 1800 km
300 Gb/s	1200 km / 1300 km
350 Gb/s	900 km / 900 km
400 Gb/s	500 km / 600 km
450 Gb/s	300 km / 300 km
500 Gb/s	200 km / 200 km

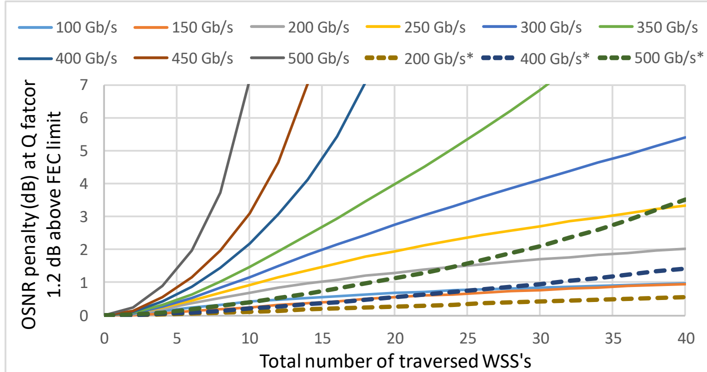

Figure 2: *Simulated OSNR penalties due to spectral narrowing incurred by 67 GBaud carrier modulations (* indicated 62 GBaud modulations) carrier propagating through a series of 75 GHz-wide filtering WSS's*

rates from 100 to 500 Gb/s, and for 75 GHz and 87.5 GHz filter bandwidths. As an illustration, Table 1 shows the calculated ultimate transmission reaches along a series of 100 km-long spans of SSMF with EDFA-based in-line amplification, assuming a 5.5 dB noise figure per EDFA and without considering the filtering impact at the ingress and egress terminals. 87.5 GHz spacing brings up to 8% longer transmission distance than 75 GHz spacing for channel data rates smaller than 350 Gb/s. Figure 2 illustrates the growth of the OSNR penalty through the cascade of 75 GHz-wide filters for each of the 9 possible 67 GBaud channel data rates as well as for a few ones at 62 GBaud. To keep this figure simple, we do not report the same curves for 87.5 GHz filtering bandwidth, since the related OSNR penalties do not exceed 0.1 dB after 40 traversed WSS's for any of the 18 tested channel modulations. Thus, nearly eliminating the impact of optical filtering is one of the primary benefits of 87.5 GHz spacing against 75 GHz one.

We simulate the network performance by incrementally serving optical bidirectional connections the symmetrical capacity of which ranges from 100 Gb/s to 1 Tb/s with 100 Gb/s steps, assuming prior electrical end-to-end grooming. The routing and wavelength assignment of each demand selects the best of its 5 shortest paths, possibly by inverse multiplexing with common light path and modulation for its subcarriers. The placement of optoelectronic Elastic Regenerators (ER) combined with the allocation of the most appropriate subcarrier modulation and spectral slots is driven by the SNR calculated for each tested transparent sub-light path in between two successive envisaged ER sites. It also depends on one of the 3 strategies "***no ER***", "***fewest EOT***" and "***least spectrum***", that the network designer applies to place ERs. "*No ER*" means no regenerator is allowed. "*Fewest EOT*" enables ER deployment only to combat wavelength contention or insufficient SNR to bridge transparently the source end destination OXCs. "*Least spectrum*" indicates further ERs might be installed when serving a connection for higher SE to save spectral resources and so to end up with a larger Maximum Network Capacity (MNC). We refer to 2 metrics to benchmark the network performance. The first one is MNC, defined as the mean total throughput accommodated in the simulated network when 1% total demanded capacity is rejected. The second metric is the mean number of EOTs (N_{EOT}) per 100 Gb/s allocated service, including ERs, to be deployed for reaching MNC.

3. Simulation results and discussion

Table 2 reports MNC and N_{EOT} values from our simulated designs of G50 and CONUS, for various channel grids and averaged on 100 random draws of traffic based on even distribution of connections between all the pairs of OXCs. It shows that uniform 75 GHz-spaced grid nearly always yields higher MNC than 87.5 GHz-spaced one. The "*CONUS, No ER*" case is the sole exception, because 75 GHz-wide filtering is too penalizing for allocating 67 GBaud carriers along the longest CONUS transparent light paths and this cannot be effectively balanced via 62 GBaud carriers due to their limited transmission reach relatively to the set of distances to bridge in CONUS. Therefore, MNC is quickly reached when the traffic grows. By contrast, 87.5 GHz uniform channel spacing has no filtering impact on 62 and 67 GBaud carriers and can be used to cover longer CONUS light paths. For the other cases, 75 GHz-spaced grid brings

Table 2: *Simulation results averaged over 100 distinct random traffic draws.*

Network topology	Spectral inter-carrier spaces	***no ER***		***(with ER) fewest EOTs***		***(with ER) least spectrum***	
		MNC (Tb/s)	N_{EOT}/(100 Gb/s)	MNC (Tb/s)	N_{EOT}/(100 Gb/s)	MNC (Tb/s)	N_{EOT}/(100 Gb/s)
G50	75 GHz	221.4	0.62	267.4	0.68	271.3	0.69
	87.5 GHz	201.7 (**222.8**)	0.58 (**0.6**)	242.5	0.64	243.5	0.65
	75 and 87.5 GHz	220.6	0.58	272.4	0.64	275.7	0.66
CONUS	75 GHz	17.3	1.26	82.8	1.52	123.4	1.8
	87.5 GHz	25.4	1.14	77.3 (**101**)	1.36 (**1.52**)	105.6	1.55
	75 and 87.5 GHz	26.1	1.14	85	1.44	117.5	1.65

about 10% extra MNC, and even up to 17% for the "CONUS, *least spectrum*" case. This MNC growth stays in average smaller than the 15.6% extra number of channels/fiber enabled by 75 GHz channel spacing versus 87.5 GHz one, meaning that higher SEs with 87.5 GHz spacing partially offset the drop of this number of channels/fiber. As an illustration, Figure 3 shows these more frequent higher SEs thanks to 87.5 GHz spacing for the "*fewest EOTs*" option. It also shows 62 GBaud modulation only prevails in G50 network with 75 GHz spacing. Otherwise, 62 GBaud is seldom and even never chosen by our planning tool for 87.5 GHz spacing. So, its utilization is not reported in figure 3 for 87.5 GHz spacing. Another benefit of the larger SE elasticity enabled by 87.5 GHz spacing is N_{EOT} reduction appearing in Table 2 and ranging from -6.5 % (0.62 vs. 0.58, for G50) to -13.9 % (1.8 vs. 1.55, for CONUS). Therefore, there is room for slightly more ERs with 87.5 GHz uniform channel spacing, while keeping N_{EOT} equal to or smaller than with 75 GHz spacing. Table 2 illustrates twice this opportunity by enabling connections to be served if needed with one more ER than the rule indicated in the top line of Table 2. These 2 results, shown in red and under brackets, indicate that if ER deployment is initially limited ("*no ER*" for G50 and "*fewest EOTs*" for CONUS) such an ER relaxing with 87.5 GHz spacing can achieve the same MNC as or even higher MNC than with 75 GHz spacing, while still keeping N_{EOT} not greater than with 75 GHz spacing. If ERs are already abundant like in the "*with ER, least spectrum*" case or if adding further ERs is useless (like along the relatively short distances of G50), this ER relaxing has no benefit. Thus, we have not reported the related results in Table 2 for these other cases.
The most well-balanced network performances are observed when combining the 2 channel spaces (see lines "*75 and 87.5 GHz*" in Table 2). To mitigate the detrimental spectral fragmentation when mixing distinct channel spaces [9], each of them is applied on specific spectral sub-bands of the C-band. These sub-bands are disjoint and dynamically defined along with the advent of new demands of connection. Handling the 2 channel spaces simultaneously in that way brings the best of both. Indeed, it negligibly increases N_{EOT} as compared to 87.5 GHz uniform spacing, whereas MNC gets much closer to, if not higher than, with 75 GHz uniform channel spacing.

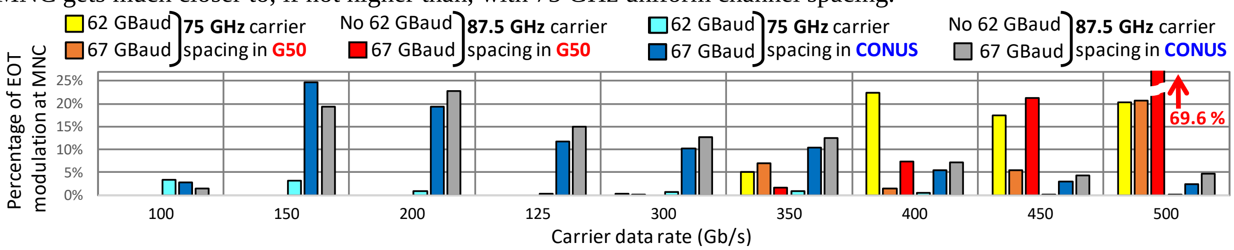

Figure 3: *Percentages of different carrier modulations applied at MNC for G50 and CONUS networks with "fewest EOTs" regeneration policy and with 75 GHz or 87.5 GHz uniform spectral channel spacing*

4. Conclusion and further work

For two very distinct core WDM network topologies, G50 and CONUS, as well as with different rules of regeneration, this study shows 87.5 GHz channel spacing leads to a notably smaller mean quantity of required transponders per Gb/s than 75 GHz spacing. This benefit can be traded off against the maximum achievable network capacity, so that the same (and even sometimes higher) network capacity can be reached with 87.5 GHz spacing as compared to 75 GHz spacing. Hence, as far as greenfield deployment of 62/67 GBaud carriers is concerned in WDM core networks equipped with state-of-the-art WSS's, 87.5 GHz spacing turns out to be slightly better than 75 GHz spacing for ultimate network optimization. Further work could focus on how this conclusion holds for a wider range of breakdowns of exchanged traffic and/or in case of more impacting filtering WSS technology. Moreover, following this result for greenfield deployment, it remains to be seen whether 87.5 GHz channel spacing is still as competitive against 75 GHz one in case of brownfield deployment, when legacy 50 GHz-spaced channels are already in place.

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