Impact of Symbol Rate Optimization and Laser Frequency Stability on Transmission Reach of Super-Channel Transceiver Configurations for Beyond 1.6 Tb/s

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Abstract: We show that subcarrier symbol rate optimization and better laser frequency stability can maximize transmission reach of super-channels. Configurations with 1.6Tb/s subcarriers achieve longer reach with benefits of smaller size/power and easier management.

1. Introduction

To satisfy the demand for high capacity, transmission of high symbol rate (SR) signals on single wavelength channel is highly preferable due to reduced cost per bit and simplified operation and management. Most recently developed coherent transponders can support SRs up to 135 – 148GBd with total transmission data rate of 1.2Tb/s [1-2]. To enable multi-span transmission of 1.6+Tb/s signals in Metro applications (which would need modulation formats with order 4 or less), ultra-high symbol rates of 250GBd and beyond would be needed, as shown in Fig. 1, where the net data rate is calculated for FEC rate 4/5. However, implementation of > 180GBd [3] is challenging due to limited bandwidth of electro-optical components. The research of ultra-high symbol rates is ongoing with recent reports focusing on symbol rates as high as 256GBd [4]. Moving beyond 260GBd seems difficult with current technologies.

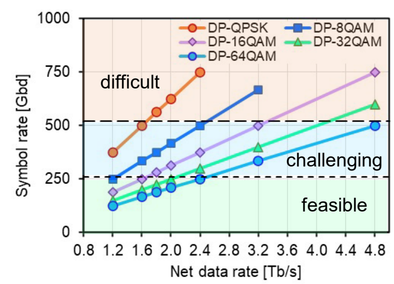

Fig.1 Required symbol rate vs. net data rate.

Therefore, to transmit signals with data rates beyond 1.6Tb/s we need to adopt super-channel (SCH) transceiver configuration with lower symbol rate sub-carriers (SC) and utilizing multi-wavelength tunable laser, TX-, RX- and DSP-arrays. The concept of SCH, where SCs are tightly spaced with each other and seen as a single channel, is not new. It requires a guard-band (GB) at the SCH edges to prevent signal degradation due to optical filtering by reconfigurable optical add-drop multiplexers (ROADMs). When SCH is generated using multiple lasers, subcarrier spacing is needed to minimize linear crosstalk between SCs due to laser frequency stability. SCHs based on digital subcarrier multiplexing (DSCM) with single laser cannot be implemented for ultra-high data rates because they also require wide bandwidth electro-optical components.

Since 800Gb/s and 400Gb/s single carrier solutions are available for Metro applications and 1.6Tb/s will be available soon, we consider SCHs comprised of 1.6Tb/s, 800Gb/s and 400Gb/s SCs. Which SCH transceiver configuration is the best? In SCHs, it is preferable that SCs occupy all available bandwidth. In this work, we investigate the impact of maximizing SR of SCs to fully occupy SCH bandwidth for a given SC spacing and GB. At the same time, we reduce IR to keep the net data rate of SCs the same, which is proven to extend transmission reach [5]. This is possible with modern transceivers, which support finely tunable SR (with granularity of less than 5 GBd) [6] and information rate (IR) enabled by probabilistically shaped (PS) QAM (PS-QAM) signals.

In this paper, we investigate the reach performance of high capacity SCHs, by leveraging SR and IR optimization with consideration to SC spacing and guard-band. We show that transmission reach increases with increase of the net data rate of SCHs up to 4.8 Tb/s. The longest reach is obtained with both 1.6Tb/s and 800Gb/s SCs, while smaller number of 1.6Tb/s SCs is more attractive due to easier management and smaller size/power.

2. Optimization of Super-channel Configuration

Fig. 2 shows an example of SCHs with the net data rate of 3.2-, 4.8- and 6.4Tb/s and carrying 1.6Tb/s subcarriers. The slot width of SCH increases proportionally to the net data rate of SCH. When optimizing SCH configuration, special relationship between 5 key parameters exists (see Fig. 3): SC symbol rate R_S, spectral shaping, characterized by roll-off factor α, SC spacing Δsc, GB Δf and number N of SCs. The interplay between these parameters brings

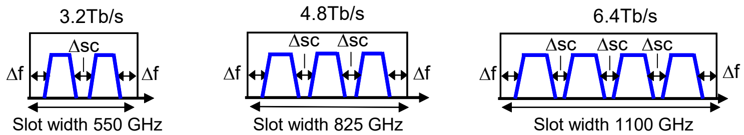

Fig. 2 Super-channel configurations with 1.6Tb/s per subcarrier.

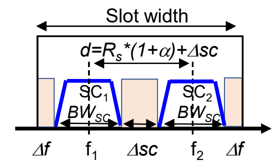

Fig. 3: Subcarrier allocation based on 5 key parameters: R_S, α, Δsc, Δf and N.

interesting new insights, which were never reported before. (1) Impact of spectral shaping: SC 3dB bandwidth (BW) BW_{SC} can be expressed as: $BW_{SC} = R_S*(1+\alpha)$. Thus, SCs with larger SR occupy larger BW_{SC} for the same roll-off factor. For example, 1.6Tb/s SC with R_S = 250GBd and $\alpha = 0.05$, will occupy BW_{SC} =262.5GHz, which is 12.5GHz larger than the SR. In comparison, the BW_{SC} of 800Gb/s and 400Gb/s SCs with 125GBd and 62.5GBd, respectively, is 6.25 and 3.125 GHz larger than the corresponding SR. Thus, we need to allocate a minimum spacing between SCs $d_{min} = R_S*(1+\alpha)$ to avoid linear XT among them. (2) Impact of laser frequency stability: we need to allocate additional subcarrier spacing Δsc to avoid linear XT. (3) Impact of in-line optical filtering: we need to assign spectral guard-band Δf between the edges of the signal and allocated slot (as shown in Fig. 3). This GB should be greater than $\Delta sc/2$ to accommodate for laser frequency stability. These three allocations put a limit on the max R_S that can be assigned to subcarriers in SCH within the slot width (SW):

$$R_S = \frac{SW - 2\cdot\Delta f - (N-1)\cdot\Delta sc}{(1+\alpha)\cdot N} \quad (1)$$

Spectral occupancy (SO) is a spectral usage metric, which is related to the amount by which R_S can be optimized:

$$SO = \frac{R_S\cdot(1+\alpha)\cdot N}{SW} = 1 - \frac{2\cdot\Delta f + (N-1)\cdot\Delta sc}{SW} \quad (2)$$

To maximize SO and reduce the amount of wasted spectrum within SW, it is preferable to have SCHs with R_S as high as possible. Also, SCHs with smaller number N of SCs have more room to maximize SR. SCHs with larger number of SCs have more wasted spectrum due to multiple Δsc and, thus, smaller room to optimize SR.

3. Analysis of Transmission Performance

We estimate transmission reach of SCHs for Metro applications with the net data rate ranging from 1.6 to 8Tb/s and occupying slot width ranging from 275 to 1375GHz, respectively, with the same net spectral efficiency (SE) of 5.8 bit/s/Hz. We transmit WDM signal, which consists of multiple SCHs carrying either N x 1.6Tb/s, M x 800Gb/s or K x 400Gb/s PS-DP-64QAM subcarriers, which are Nyquist pulse shaped with roll-off factor $\alpha = 0.05$. For each SCH configuration, we maximize SR as in Eq. 1 (and reduce IR accordingly to keep the same net data rate) (see Fig. 4 (b), (c)) to maximize SO (shown in Fig. 5 (a)). Thus, we allocate SW = 275GHz to minimally fit single carrier 1.6T signal with SRs around 250GBd. The FEC code rate c = 4/5. The number of SCHs is selected such that the WDM signal occupies about 2.8THz bandwidth. Transmission line consists of multiple spans of 80 km SMF fiber (dispersion coefficient 16 ps/nm/km, attenuation 0.2 dB/km, nonlinear coefficient 1.3 /W/km). We consider Δsc = 3.6GHz and Δf = 10GHz. Transceiver implementation penalty for 1.6Tb/s, 800Gb/s and 400Gb/s SCs is the same 1.4 dB. Maximum reach is calculated using closed-form EGN model. The optimum launch power is 3dBm, 6dBm and 9dBm per SC for 400Gb/s, 800Gb/s and 1.6Tb/s, respectively. The required SNR (RSNR) is calculated at NGMI threshold 0.8 (assuming ideal FEC with no coding gap) for the error free post-FEC operation and transmission reach is estimated at the crossing point between delivered SNR and required SNR.

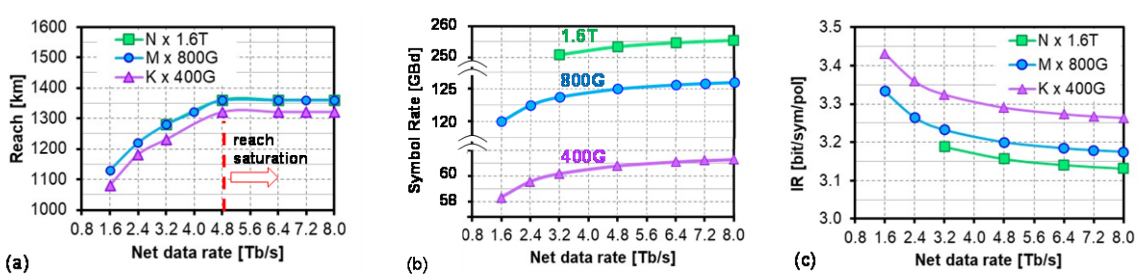

Fig. 4 (a): Transmission reach; (b) Symbol rate and (c) Information rate vs. net data rate of super-channels carrying N x 1.6Tb/s, M x 800Gb/s or K x 400Gb/s PS-DP-64QAM sub-carriers.

Fig. 4 (a) shows transmission reach vs. net data rate for three SCH transceiver configurations: N x 1.6Tb/s, M x 800Gb/s and K x 400Gb/s. We can see that: (1) increasing the net data rate of SCHs for the same SE = 5.8 bit/s/Hz results in increased transmission reach. This reach increase is a direct result of maximizing SR and reducing IR. (2) Increasing the net data rate beyond 4.8Tb/s by having larger number of subcarriers gives diminishing returns. Reach saturation occurs when Δsc becomes the dominant effect and the impact of GB Δf becomes negligible. Beyond this point there is little room for SR and IR optimization, as can be seen in Fig. 4 (b), (c). Fig. 5(a) shows that SO increases when we pack more subcarriers into higher data rate SCH. But the rate of increase is becoming smaller for all SCHs after 4.8Tb/s, because of more spectrum is wasted due to large number of Δsc. (3) Transmission reach of SCHs with 1.6Tb/s and 800Gb/s SCs is almost the same, while SO shown in Fig. 5(a) is slightly different. Further analysis revealed that SCHs with 800Gb/s SCs have slightly larger IR than SCH with 1.6Tb/s SCs (Fig. 4 (c)) and their SRs are smaller, leading to a balance between RSNR gain due to lower IR and RSNR loss due to increased nonlinear phase noise with larger SR, which resulted in similar reach. Transmission reach is the shortest for SCHs with 400Gb/s SCs because they have the largest IR. They also have the smallest SO. This indicates that it is more beneficial to have SCHs with larger SR SCs such as 1.6Tb/s or 800Gb/s. Moreover, larger rate (e.g. 1.6Tb/s) SCs with smaller number of SCs is preferable due to smaller DSP-, TX- and Rx-size and easier management.

The trend in transmission reach of Fig. 4 (a) depends on Δsc and Δf. (1) Impact of SC spacing: When we reduce SC spacing, the SCHs with smaller SR and larger number of SCs, e.g. 400Gb/s, benefit the most from SR and IR optimization. The optimum IR of SR-optimized K x 400Gb/s SCHs reduces significantly, leading to large increase in transmission reach, as shown in Fig. 5(b) for 4.8Tb/s SCHs. When Δsc = 0 GHz (this condition would correspond to SCHs generated using DSCM), SO is maximized. Both SO and IR become the same for all SCH configurations. In this case, the SCHs with 400G subcarriers have slightly longer reach by 80 km compared to 1.6T due to reduced non-linear phase noise of smaller SR signals [7]. This indicates that laser characteristics play important role when designing high data rate SCHs. Improved wavelength stability of next-gen lasers can increase transmission reach and shift the optimum number of SCs from higher data rate-to smaller. (2) Impact of GB: The reach saturation point at 4.8Tb/s in Fig. 4 (a) depends on the Δf value. Smaller GB results in improved SO (see Eq. 2) due to less wasted spectrum, leading to extended reach, but also giving little room for SR and IR optimization. Fig. 5 (c) demonstrates that reach saturation of M x 800Gb/s SCHs occurs at < 4.8Tb/s when Δf < 10GHz and at > 4.8Tb/s when Δf > 10 GHz. This highlights that impact of GB and laser frequency stability can be instrumental in deciding the optimum SCH configuration for beyond 1.6Tb/s.

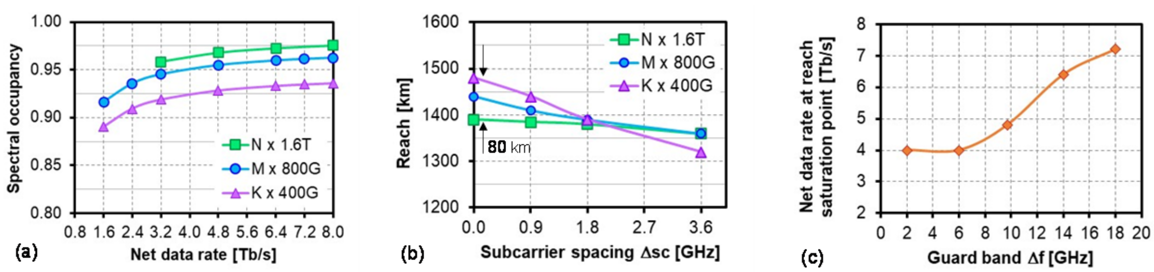

Fig. 5: (a) Spectral occupancy, (b) Reach improvement due to reduced subcarrier spacing for 4.8Tb/s super-channels; (c) Net data rate of M x 800Gb/s super-channels at which reach saturation occurs for various guard band Δf values.

Conclusion

We analyzed the reach performance of high capacity (beyond 1.6Tb/s) super-channel configurations with 1.6Tb/s, 800Gb/s and 400Gb/s subcarriers. We showed that laser frequency stability is instrumental for better spectral occupancy in optimum SCH configuration thereby enabling SR and IR optimization to maximize transmission reach. In general, the optimum number of subcarriers should be selected by considering not only the reach but also transceiver implementation in view of size and power consumption. We showed that SCHs with 1.6Tb/s subcarriers are preferable due to long reach, compact size, and easier management of small number of SCs.

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