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Original
Split spectrum: a multi-channel approach to elastic optical networking / Xia, M; Proietti, R; Dahlfort, S; Yoo, Sjb. - In: OPTICS EXPRESS. - ISSN 1094-4087. - ELETTRONICO. - 20:28(2012), pp. 29143-29148. [10.1364/OE.20.029143]

Availability:
This version is available at: 11583/2972460 since: 2022-10-19T14:44:05Z

Publisher:
Optical Society of America

Published
DOI:10.1364/OE.20.029143

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29 November 2022

Split spectrum: a multi-channel approach to elastic optical networking

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Abstract: This paper introduces Split Spectrum, which enhances elastic optical networking by splitting a bulk traffic demand into multiple channels, when a single-channel transmission is prohibited by distance or spectrum availability. We performed transmission simulations to determine the maximum reach as a function of modulation format (dual polarization BPSK, QPSK, 16QAM), baud-rate (from 5 to 28 GBd), and number of ROADMs, for a Nyquist WDM super-channel with subcarrier spacing equal to 1.2 × baud-rate. Performance evaluation on two representative topologies shows that, compared to the previously proposed elastic optical networking, Split Spectrum doubles the zero-blocking load and achieves 100% higher network spectral efficiency at zero-blocking loads as a result of extended transmission distance and efficient utilization of spectrum fragments.

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OCIS codes: (060.4250) Networks; (060.4510) Optical communications.

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1. Introduction

The annual traffic growth rate of optical backbone networks is predicted to be about 40%~60% in the coming years [1], *i.e.* increased by a factor of 29~109 in 10 years. This fast-growing traffic is quickly exhausting the installed fibers, which limits network scalability and constrains new services. As installing new fibers and inline amplifiers can be extremely expensive, it is desired to maximize the efficiency of existing resources. For example, the conventional C band ranging from 195.9 THz to 191.6 THz offers 4.3 THz spectrum. This

#177370 - $15.00 USD Received 3 Oct 2012; revised 16 Nov 2012; accepted 21 Nov 2012; published 17 Dec 2012
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gives a total of 184.9 THz spectrum resources in a 43-link U.S. core network (Fig. 4(a)). Therefore, achieving high network-wide *spectral efficiency* (SE, in bps/Hz) is critical to accommodate more traffic. This is a major driver for elastic optical networking (EON) [2], where transmission can be adapted to rate and distance to squeeze more bits in one Hz.

Typically, high-rate transmission requires high-order modulation formats, which are however susceptible to transmission impairments over a long distance. In addition, elastic transmission allows non-uniform spectrum allocations, and hence results in spectrum fragments (small discontinued spectrum slots) that cannot be efficiently used by bulk demand. In this work we introduce Split Spectrum (SS) to address these two issues. By splitting a bulk traffic demand into multiple channels, the transmission distance can be extended thanks to lower channel rate. Each channel may require fewer spectrum resources, which can be potentially satisfied by the spectrum fragments. To identify the optimal modulation format for each channel, we conduct extensive simulations to determine the maximum transmission distance as function of modulation format (*i.e.* dual polarization (DP) Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and 16 Quadrature Amplitude Modulation (16QAM)) and the baud-rate (*i.e.* from 5 to 28 GBd) for a Nyquist WDM super-channel with 10 subcarriers and channel spacing equal to 1.2 × baud-rate. As an enhancement from our previous work in [3], we take into account the insertion loss of bypassing intermediate nodes and optimize the launch power for each of the baud-rate of interest. We also propose a possible hardware implementation for the optical module of SS. Based on the performance evaluation on two representative core networks, SS is shown to significantly outperform the elastic approach without traffic splitting in terms of zero-blocking network load and network spectral efficiency (NSE). The rest of the paper is organized as follows: Section 2 describes the general idea of SS. Section 3 studies elastic transmission by various modulation formats assuming Nyquist WDM [4] as solution for elastic transponders. Section 4 conducts performance evaluation. Finally, Section 5 summarizes the study.

2. Description of split spectrum

Split Spectrum is built on elastic transmission with the additional capability of splitting a single traffic demand into multiple channels. A channel is defined as concatenated allocation of the same spectrum along an end-to-end path. When a bulk traffic demand is prohibited by either distance or spectrum availability, SS splits the demand into multiple channels, and selects the modulation format with higher spectral efficiency for each channel. The multiple channels of the same original traffic demand are allowed to be routed over different paths; therefore, an analogy of SS would be the scheme of inverse multiplexing applied network wide [5]. Splitting traffic offers two immediate benefits: 1) channel rate is lower than the original demand, which facilitates adoption of lower-order modulation format and baud-rate to address transmission impairments; and 2) spectrum fragments can be reclaimed by the smaller spectrum demands of each channel. SS also has the following potential advantages:

Spectrum defragmentation: Small spectrum slots can be efficiently utilized at channel basis to reduce the overall spectrum fragments. While network-wide spectrum re-shuffling is possible [6], it comes with extra provisioning complexity and cost.

Resilience: The multi-channel nature exploits path diversity over a mesh network, such that it is less likely that all the channels are interrupted by a single link failure. Resource overbuild for multi-path protection is only a fraction of the dedicated protection, and can be further reduced from the generic multipath protection schemes [7].

Optical-layer networking: Because traffic splitting and resembling are performed only at edge nodes, this mechanism provides a network-wide optical-layer transport solution, and reduces complexity at intermediate nodes thanks to protocol and bit-rate transparency.

The above advantages are achieved at additional costs and requirements for the network elements and control plane to enable multipath provisioning. As channels are routed over different paths, it may cause different delays, and require the traffic arriving at an earlier time

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to be buffered at the destination before resembling. Routing schemes with differential delay (typically several to a few tens of ms) awareness [8] can be employed to reduce the needed capacity of high-speed buffers.

Figure 1 shows a possible elastic optical transponder (EOTP) for SS, which makes use of C-band tunable laser arrays and block of modulators to support different modulation formats, *e.g.* BPSK, QPSK, and 16 16QAM [4]. To improve SE, dual polarization (DP) will be employed. For the electrical part, Optical Transport Networking (OTN) framing with Forward Error Correction (FEC), Digital Signal Processing (DSP) and Analogue to Digital/Digital to Analogue conversion (ADC/DAC) are used to allow variable bitrates to drive the modulator blocks. With the current ADC/DAC conversion electrical interfaces at 28 Gbps per In-phase/Quadrature port, the DP-BPSK/QPSK/16QAM maximum line rate per channel would be 56, 112 and 224 Gbps. Assuming 10-array lasers, the module capacity will be as high as 2.24 Tbps, allowing high node capacity with just a few optical modules.

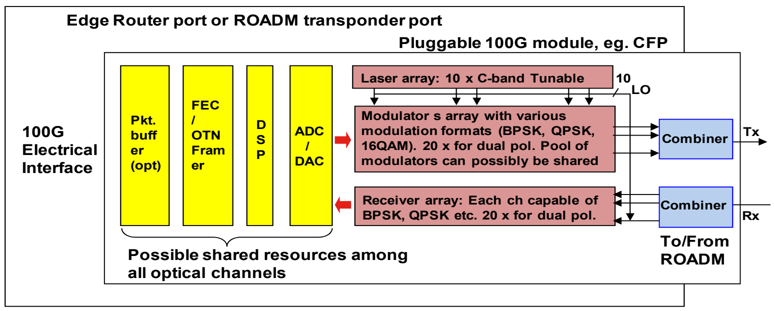

Fig. 1. A sample implementation of Split-Spectrum elastic optical transponder (EOTP).

3. Elastic transmission

This section provides an analysis on elastic transmission by various modulation formats, which can be exploited by both SS and other EON schemes. Table 1 shows the summary result of our transmission simulation based on the SS hardware implementation described above. A dual polarization (DP) Nyquist WDM super-channel with 10 subcarriers is considered here [4]. The subcarrier spacing is assumed constant and equal to 1.2 × baud-rate, which represents a good trade-off between system performance and complexity of the required optical and electrical filtering at the TX and RX, respectively [4]. Note that, for a given modulation format (*i.e.* BPSK, QPSK and 16 QAM), the spectral efficiency is constant as the baud-rate increases. Figure 2 shows the simulation setup. The optical link consists of uncompensated transmission over N spans of standard SMF fiber, each one 80-km long. An EDFA with noise figure NF = 6 dB is used after each span to compensate exactly for fiber attenuation (0.2 dB/km). Differently from what reported in [3], the launch power per channel is optimized for each baud-rate, with benefits in terms of maximum transmission distance. The optimum launch power as function of the baud-rate was determined by running a set of simulations with different launch power per subcarrier (a step of 0.2 mW was used). For each simulation run, we determined the maximum transmission distance for a bit error rate (BER) = 10^{-3}. The optimum launch power corresponds then to the value allowing longer distance. The insertion loss caused by M reconfigurable optical add/drop multiplexers (ROADMs) (M = 2, 4, 7, and 10) in the link was also taken into account. Each ROADM is modelled with a 1:8 power splitter (10.5 dB insertion loss) and a wavelength selective switch (WSS) with 4th-order Gaussian filter profile (6 dB insertion loss). The filtering effect is not considered, since for small channel spacing (*i.e.* 1.2 × baud-rate in this work), the WSSs output ports should be configured in a way that the super-channel is filtered as a single entity (case 2 in Fig. 2).

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Table 1. Spectral efficiency vs. transmission distance

	DP-BPSK (SE = 1.67 bps/Hz)		DP-QPSK (SE = 3.33 bps/Hz)		DP-16 QAM (SE = 6.67 bps/Hz)	
Baudrate [GBd]	Bit rate [Gb/s]	Max Distance [km]	Bit rate [Gb/s]	Max Distance [km]	Bit rate [Gb/s]	Max Distance [km]
5	10	14400	20	6800	40	984
6	12	13587.7	24	6587.1	48	967.9
7	14	13324	28	6334.3	56	949.2
8	16	12672	32	6128	64	960
9	18	12812.9	36	6091.2	72	930.8
10	20	12320	40	5968	80	880
14	28	11628	56	5680	112	853.6
16	32	11393.5	64	5416.4	128	844
18	36	11172.7	72	5310	144	844
20	40	11095.2	80	5200	160	853.6
22	44	10743.9	88	5107.6	176	844
24	48	10976	96	4984	192	840
26	52	10535.7	104	5008.6	208	795
28	56	10080	112	5120	224	757.6

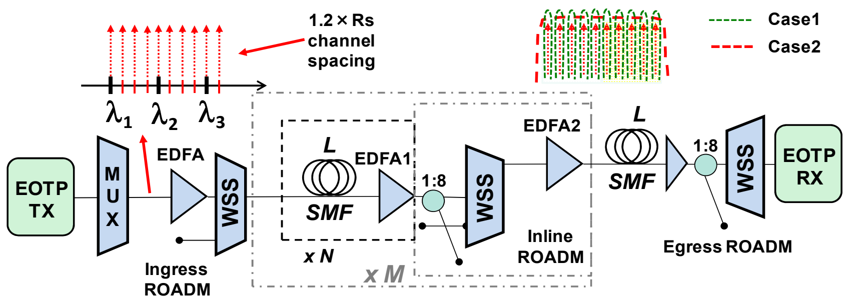

Fig. 2. Simulation setup. EOTP: elastic optical transponder; WSS: wavelength selective switch; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber; *L*: span length; *M*: number of ROADMs.

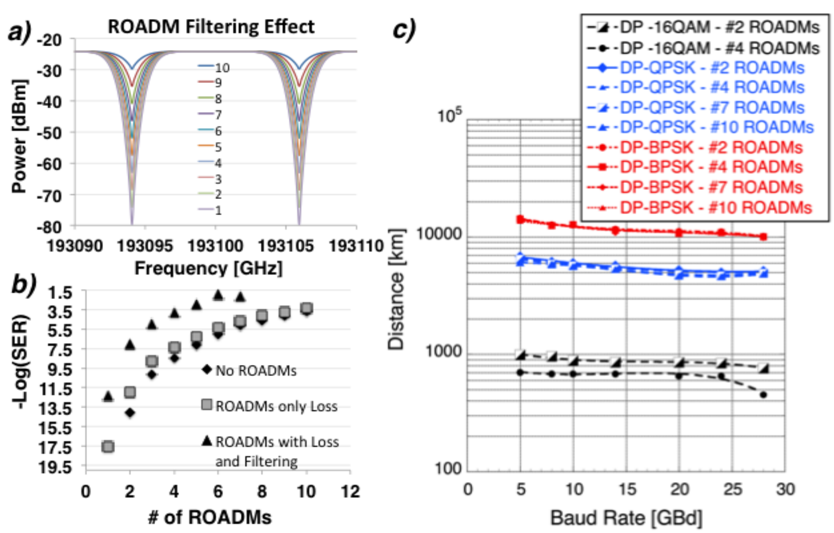

Fig. 3. (a) ROADMs filtering effect. (b) SER as function of the number of ROADMs. (c) Maximum distance as function of the baud-rate for different modulation formats and number of ROADMs.

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In fact, filtering each subcarrier separately would strongly degrade the signal after a few ROADMs, as shown in Fig. 3(b). The simulations in Fig. 3(c) shows that the ROADMs insertion loss effect on the transmission distance for BPSK and QPSK is negligible even for 10 ROADMs, while is notable for 16QAM even for small number of ROADMs (i.e. M = 4). A laser line-width of 100 kHz was assumed for TX lasers and local oscillator (LO) lasers at the RX. Fiber propagation was simulated using a full-band time-domain split-step method to solve dual-polarization Schrödinger equations. A digital coherent RX with ideal chromatic dispersion compensation was used as in [4], while carrier phase estimation was carried out according to [9]. VPI Photonics software was used for all the simulations. Table 1 shows SE values ranging from 1.67 bps/Hz of DP-BPSK to 6.67 bps/Hz of DP-16QAM.

4. Performance and comparison

We use bandwidth blocking ratio (BBR) to evaluate both SS and the EON scheme without traffic splitting. BBR is defined as the ratio of rejected bandwidth over the total requested bandwidth, and is used to characterize the capability of accommodating traffic. The end-to-end transmission spectral efficiency is assumed based on a set of transmission tables for 2 ROADMs (Table 1), 4 ROADMs, 7 ROADMs and 10 ROADMs. SS employs baud-rates only from 5 GBd to 10 GBd to lower the hardware cost, while 5 to 28 GBd is used by the single-channel EON to support high-bit-rate demands. Flexible grid [10] is applied, which allows a spectrum allocation to take multiple integers of channels. For example, a 28 GHz spectrum demand can be assigned with three 12.5-GHz channels. We also study the conventional 40/100Gbps scheme based on 50 GHz spacing specified in ITU-T G.694.1, with a maximum reach of 10,000 km and 3,000 km, respectively. Our simulations are conducted on a 24-node U.S. national network and a 28-node pan-European network (Fig. 4), and each link is assumed with C-band 4.3 THz spectrum. Traffic is generated for each node pair, inversely proportional to nodes distance.

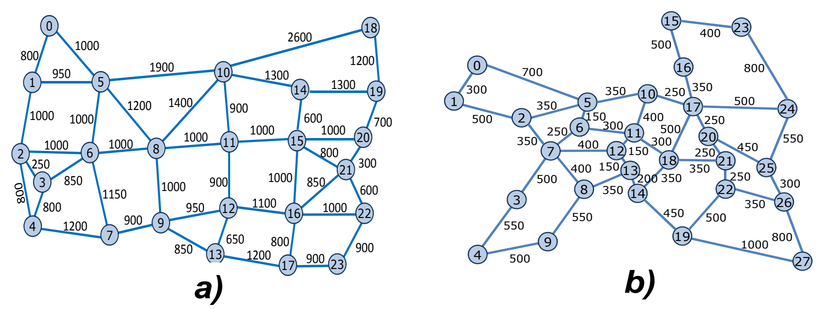

Fig. 4. (a): 24-node U.S. topology. (b): 28-node pan-E.U. topology. Links length is expressed in km.

Figure 5 shows the BBR variation as traffic grows. The results show similar trends for the two topologies, which demonstrates the generality of SS. Among the three schemes, SS achieves the best performance in terms of: 1) the highest zero-blocking load (40 Tbps in the U.S. topology and 60 Tbps in the pan-E.U. topology, vs. 20 Tbps in both the U.S. and the pan-E.U. topologies by the EON without splitting); and 2) the lowest BBR in the load range. The pan E.U. network can load more traffic, mainly thanks to the shorter node-to-node distances that allows higher-order modulation formats. The results also show two main factors that cause BBR: transmission limitation and spectrum insufficiency. SS outperforms the non-splitting EON, as it addresses the transmission limitation by increasing reach for each channel. In addition, SS takes advantage of the spectrum fragments to accommodate the demands of each individual channel. In contrast, the 40/100Gbps scheme performs the worst due to both the wide channel spacing and incapability of handling demands higher than 100 Gbps.

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We then compare the three schemes in terms of NSE (see Fig. 6), which is defined as the total admitted traffic amount over the total network spectrum resources. SS achieves a linear increase of NSE as network load grows thanks to zero traffic blocking. Then, the NSE slightly slows down its increase rate when a small percentage of traffic is blocked by the network. The highest non-blocking NSE is 0.216 bps/Hz for the U.S. topology, and 0.340 bps/Hz for the pan-E.U. topology, which are twice and three times compared to the EON scheme without splitting. It is also noted that the NSE is significantly lower than the transmission spectral efficiency shown in Table 1 (1.67 bps/Hz ~6.67 bps/Hz), due to the spectrum waste by wide spacing, spectrum continuity constraint, and un-utilized spectrum fragments.

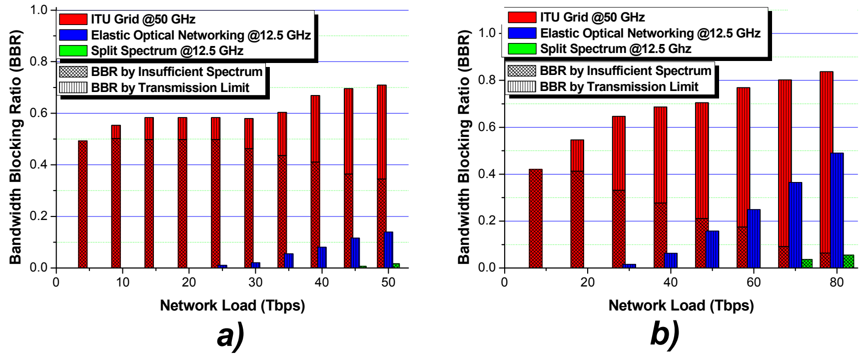

Fig. 5. Network load vs. Bandwidth Blocking Ratio. (a) U.S. topology; (b): pan-E.U. topology.

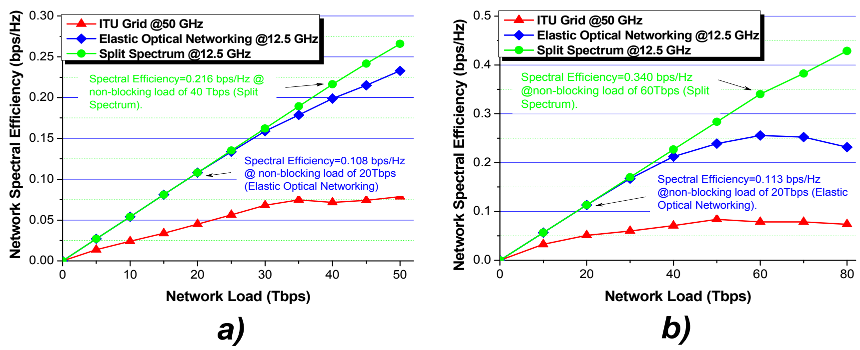

Fig. 6. Network load vs. Network spectral efficiency. (a) U.S. topology; (b) pan-E.U. topology.

5. Conclusion

We proposed Split Spectrum (SS), a variant of elastic optical networking (EON) that can split a traffic demand into multiple channels and transmit them using different spectrum allocations and paths. SS enhances the previously proposed EON schemes by addressing the transmission distance limitation and spectrum fragments. We conducted extensive simulations for Nyquist WDM super-channels, and determined transmission distance as a function of modulation formats, baud-rate, and number of intermediate nodes. A network-level performance evaluation showed that, compared to the EON scheme without splitting, SS can accommodate more traffic by allowing longer-distance transmission and by taking advantage of spectrum fragments. At zero-blocking network loads, higher network spectral efficiency (NSE) can be achieved by SS in the investigated U.S. and pan-E.U. networks.

Acknowledgment

This work was supported in part by Ericsson POPCORN project.

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