Signal Overlap for Efficient 1+1 Protection in Elastic Optical Networks (EONs)

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Abstract: An innovative transmission technique enabling signal overlap is introduced for spectrally-efficient 1+1 protection. Simulation results show that the proposed technique successfully reduces the overall amount of occupied spectrum resources.

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1. Introduction

Elastic Optical Networks (EONs) supporting flexi-grid technology have been successfully introduced together with advanced transmission techniques based on effective coding solutions and complex modulation formats. Polarization multiplexed quadrature phase shift keying (PM-QPSK) and polarization multiplexed 16 quadrature amplitude modulation (PM-16QAM) are examples of the most utilized modulation formats in EONs [1]. Traditionally, in EON an optical signal has to occupy a dedicated frequency range, called frequency slot, with no sharing of spectrum resources with other optical signals. Recently, a novel technique called *signal overlap* has been introduced to overcome this constraint [2, 3]. The technique enables the overlap of two independent optical signals over the same spectrum resources. The technique does not require global time synchronization in the whole network and it does not exploit orthogonal codes as in Optical Code-Division Multiple-Access (O-CDMA) solutions. Instead, it relies on cancellation techniques typically considered for wireless networks [4], now applied in the context of optical networks. The technique is less spectrally efficient and more complex to implement than increasing the constellation size with non overlapping frequency slots, but it targets different use cases for flexible networking, like the considered protection scheme. The feasibility of the technique has been demonstrated both theoretically [2] and experimentally [3].

In this paper, the overlap technique is proposed and exploited in the context of 1+1 optical protection. Differently with respect to traditional protection schemes in EON [5], the larger than necessary Optical Signal to Noise Ratio (OSNR) typically available on the (shortest) working path is not waisted. Instead, such extra quality of transmission (QoT) is here conveniently exploited to support the overlap with a (partially) co-routed working path of a different working connection, successfully improving the overall network utilization.

2. 1+1 Protection in EON

Fig. 1a shows a reference network scenario where the overlap technique is applied. An optical signal S_A is generated at source node A at central frequency f_0 and transmitted along the working path A-B-C-D. A second signal S_B is added at node B at a different central frequency f_1 and transmitted along the working path B-C-D. The two signals coexist along the links B-C and C-D, occupying two different (i.e., non-overlapping) frequency slots on each of these links. Both signals are configured with 1+1 optical protection [5]. In particular, a replica of signal S_A obtained with optical split at node A is transmitted along the protection path passing through node G. Similarly, signal S_B is split at node B and transmitted along the protection path passing through node F. Traditionally, the working path is selected as the shortest one between source and destination, while its protection is selected as the shortest path being disjoint with the working one. The transmission parameters configured for each signal are then imposed by the most impaired path, i.e. the protection one. That is, on the working path the optical signal experiences higher than necessary QoT and typically occupies unnecessary spectrum resources. For example, if S_A and S_B in the working paths could be operated with PM-16QAM modulation format over 37.5 GHz, but their protection path require a more robust format like PM-QPSK over 50 GHz, given the optical protection, both working and protection of each of the two signals have to be operated with PM-QPSK over 50GHz. That is, additional 12.5 GHz spectrum resources per signal have to be occupied along the working path which reaches the destination with higher than necessary QoT. Overall, 100 GHz are occupied on the common links along the working path (e.g., links B-C and C-D).

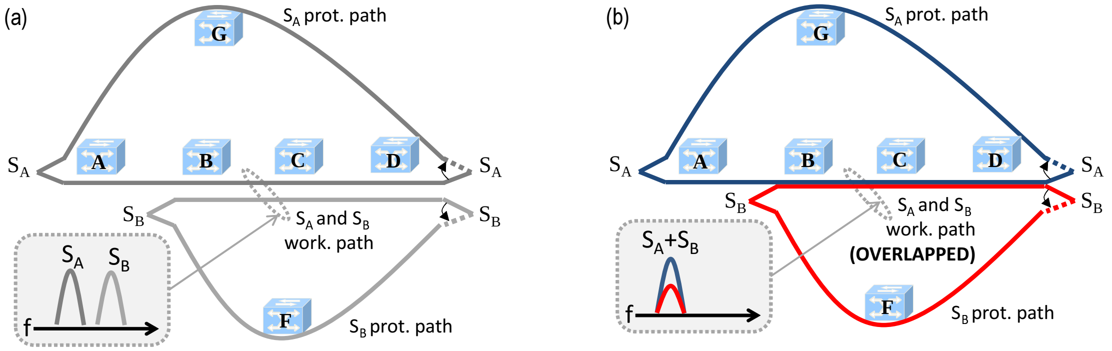


Fig. 1: 1+1 protection: (a) traditional approach with two working signals occupying different spectrum resources; (b) proposed scheme exploiting the overlap technique to share spectrum resources on two different working signals.

3. Proposed 1+1 protection exploiting the overlap technique

Fig. 1b shows the previously considered network scenario when the proposed 1+1 overlap technique is applied. In this case, both signals S_A and S_B are transmitted at the same central frequency f_0. At node B, the two signals overlap. To enable successful detection of either signal, the overlap technique is implemented, taking advantage of the available extra QoT along the working paths. The overlap technique exploits adequate FEC-code rates and proper settings of the signal power levels at the superimposition point (i.e., node B in the example). That is, the PM-QPSK signal S_A is coded at code rate r_A, expressed in the form i/j: i bits of data and $(j$-$i)$ bits of overhead out of the j transmitted. Similarly, the second PM-QPSK signal S_B is coded at rate r_B. For example, when a gross rate of 112 Gb/s is considered, code rate r of 9/10 provides a net bit rate of around 100 Gb/s. The power of S_A is set at the superimposition point to a higher value than the one of signal S_B. The two signals S_A+S_B are then jointly propagated along B-C towards the two coherent receivers in node D (one for S_A and one for S_B). It is important to highlight that node B can be placed anywhere over A-C. Indeed, the two signals can jointly propagate from any distance. Moreover, no synchronization is enforced among nodes A, B and C (and no orthogonal codes are adopted). In order to successfully perform the detection of the proper signal at each receiver at node D, a specifically designed combination of mutual power level and low-density parity-check (LDPC) coding are applied on each of the two signals, in order to provide adequate transmission robustness. At each receiver at node D, after the coherent opto-electronic conversion of the signal S_A+S_B, sampling and digital processing are performed. In particular, a two-step procedure is applied. First, the detection is performed as if just S_A were transmitted, i.e., considering S_B simply as noisy interference. This way, the coded signal S_A is retrieved from the acquired data. Second, the acquired data are re-elaborated to perform the cancellation of signal S_A. Once the cancellation is complete, a second detection stage is performed on the interfering coded channel S_B. In particular, the received signal is processed as to obtain proper estimates, including impairments, that allow the re-modulation of signal S_A, in order to subtract it from the received signal, so that S_B can be detected, ideally without interference. Note that this second step in not needed at the receiver of S_A. The two-step technique is derived from the wireless technology (see [4] and references therein). Two main aspects are taken into account during signal detection: first, the re-modulation of S_A has necessarily a limited accuracy, as some impairments are difficult to be estimated (e.g. non-linear effects); second, the detection of S_B will be also affected by the noise from the S_A lightpath. These two effects impair the performance of the second channel detection. Thus, besides adequate mutual power conditions, as shown later, also adequate QoT is required to successfully detect both signals. We remind to [2] for additional theoretical details on the considered overlap technique.

With reference to the aforementioned example, i.e. the traditional scenario where S_A and S_B have to use PM-QPSK (occupying 100 GHz on common working links while experiencing extra QoT), the proposed 1+1 technique provides significant benefits. Indeed, such extra QoT is exploited to enable the proposed overlap of the two signals, occupying a total amount of just 50 GHz along the working path.

4. Results

The performance of the proposed 1+1 protection scheme enabled by the overlap technique is evaluated considering both transmission and networking performance. To assess the transmission performance, two independent PM-QPSK signals S_A and S_B are first considered at gross bit rate 112 Gb/s. The overlap technique is here applied targeting a net rate of 100 Gb/s for signal S_A (r_A = 9/10). Analog to digital converter (ADC) with analog bandwidth of 20 GHz and a sampling rate of 56 GSample/s is assumed. Both signals are filtered at transmitter and receiver side with 4th-order

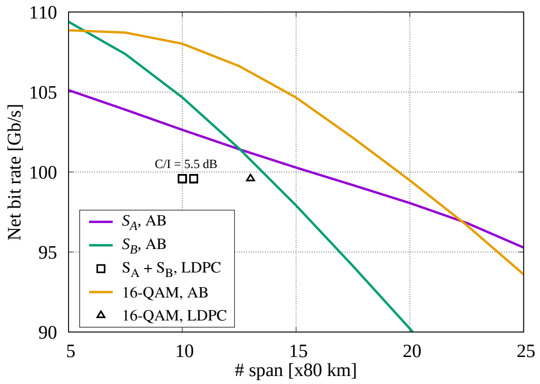
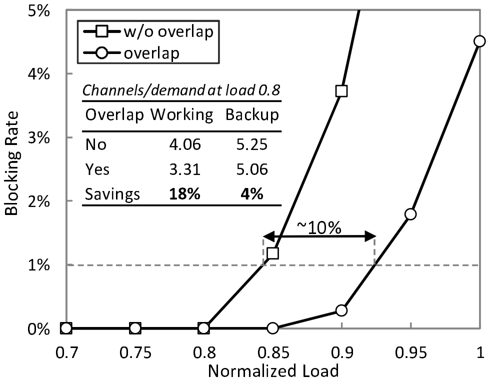


Fig. 2: Transmission performance of the overlap technique.



Channels/demand at load 0.8

Overlap	Working	Backup
No	4.06	5.25
Yes	3.31	5.06
Savings	**18%**	**4%**

Fig. 3: Network resource utilization

Gaussian optical filters with 35-GHz bandpass bandwidth, in-line with the traditional optical network requirements. The performance of the overlap technique has been evaluated by configuring code rates and power levels.

Fig. 2 shows the performance of the theoretical achievable bounds (AB) of the overlap technique. Results show that the limiting optical reach is imposed by S_B (the 100 Gb/s scenario is verified on the left region of the S_B curve). Moreover, the figure highlights the specific case at 100 Gb/s when a 3-dB margin is applied on theoretical bounds [2]. Results show that up to 800 km (on the 3-dB margin) can be successfully traversed by both overlapped signals with practical LDPC codes (r_A = 9/10, r_B = 9/10, S_A / S_B = 5.5dB). For the sake of completeness, also the PM-16QAM performance is reported. The figure also highlights the specific case at 100 Gb/s when 3-dB margin is applied on the PM-16QAM theoretical bounds, showing that up to around 1000 km can be achieved by a PM-16QAM signal. Further details on the models and simulative scenarios and can be found in [2].

To assess the networking performance and the potential benefits of signal overlap in 1+1 protection, we defined an offline provisioning problem based on the Routing, Modulation and Spectrum Allocation (RMSA) problem [6] with the objective of serving as many demands as possible (primary objective) with the minimum spectrum resources usage (secondary objective). We implemented an arc-path RMSA MILP formulation with the necessary extensions to consider 1+1 protection and signal overlap within the feasibility constraints coming from the transmission performance study. For evaluation purposes, we used the 30-node Telefonica national network to generate instances with different number of uniformly distributed 100 Gb/s demands, so to ensure its exact resolution in reasonable time for the largest instance ($\sim$ 10 hours). In the simulations, connections are operated with PM-QPSK over 50 GHz. Overlap is applied on up to two signals, only of type working, subject that their mileage is below the previously computed limit of 800 km (according to Fig. 2). Fig. 3 shows the blocking rate as a function of the normalized network load for both with and without signal overlap cases. The better use of spectrum resources of signal overlap provides a significant increase of the accepted load (around 10% at 1% blocking reference value). Indeed, resource savings are observed not only in working paths (as expected) but also in backup paths. This is illustrated in the embedded table (focus on 0.8 normalized load), where the average amount of channels per demand and path shows remarkable average savings up to 18% for working paths and 4% for backup paths. Therefore, signal overlap promises significant resource savings in 1+1 protection scenarios.

5. Conclusions

Spectrally-efficient 1+1 protection exploiting signal overlap is introduced. Up to 800 km (on 3-dB margin from theoretical bounds) can be covered by overlapped signals. MILP formulation is then applied to show that the proposed 1+1 overlap technique can provide 10% improvement of the accepted load.

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