Geometric Constellation Shaping in Elastic Optical Networks: Performance Analysis on Resource Allocation

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***Abstract*—The benefits from geometrical constellation shaping (GCS) are explored in a dynamic elastic optical network context. Using simulations, we evaluate the blocking performance of different forward error correction schemes and modulation formats over the NSFTNET and EUROCORE network topologies. Results show that GCS leads to a selection of denser modulation formats when solving the resource allocation problem in the network, which in turn reduces the network blocking performance compared to conventional QAM modulation formats. Traffic load increases between 5 and 13% for a blocking probability of 10^{-3} are reported.**

***Index Terms*—Elastic optical network, optical fiber, geometric constellation shaping.**

I. INTRODUCTION

The capacity limits arising from optical fibers nonlinearities in point-to-point links are also extended to optical networks [1]. These nonlinear effects limit the amount of traffic and/or the number of users that can be served in an optical network. To date, several approaches have been proposed to maximize the information transmitted over point-to-point fiber links (e.g., increasing the amount of multiplexed channels, forward error correction (FEC) and digital signal processing, among others [1]). In a networking environment, however, this task is not a simple one, as it depends on the connected users and how the optical resources are assigned to them.

Forward error correction (FEC) is a key element in modern optical fiber transmission systems and networks. FEC enables high data rate transfers across long distances. Many optical systems are based on hard-decision (HD) codes with relatively low overhead (OH) [2], [3]. Modern systems are more flexible in terms of coding rates, often allowing higher FEC OHs. More importantly, such systems also use soft-decision FEC (SD-FEC) (or SD-like) schemes [4] with the goal of approaching Shannon's channel capacity. With the introduction of SD-FEC and the capabilities of digital coherent receivers, *constellation shaping* was introduced to optical fiber systems [5], [6] to reduce the penalty of conventional rectangular modulation formats. Geometric constellation shaping (GCS) is one of such solutions, wherein the position of the constellation points (i.e., the geometry of the constellation) is optimized. GCS has been shown to increase the transmission reach in multi-span transmission systems (see, e.g., [7] and references therein).

Elastic optical networks (EONs) are an efficient solution to manage spectral resources in an optical network [8]. Compared to fixed grid wavelength division multiplexed networks, EONs employ frequency slot units of 12.5 GHz that can be grouped according to the users requirements. One of the main tasks operators of EON must solve is to assign a path, a modulation format, and a portion of the spectrum to each connection. This problem is known as the "routing, modulation format and spectrum assignment" (RMSA) problem [9]. To solve the RMSA problem heuristic approaches that divide the allocation problem into different steps are used [8], [9]. For example, route, modulation format and spectrum can be assigned in succession, and different algorithms can be used for each step. Recently, deep reinforcement learning has been proposed as alternative to heuristic methods [10]. The selection of modulation format plays an important role in the RMSA problem, as it determines the required spectrum for each connection. The modulation format is chosen from a list with available formats associated to a given maximum reach. From said list, the format with the highest spectral efficiency and reach longer than the selected route is chosen.

Given the growing interest in the use of GCS to increase transmission rates or reach, it is of interest to study its applicability to EONs. To the best of our knowledge, this problem has received little attention, with only [11] having analyzed the impact of using different FEC OH in an EON context. In this paper we study the gains achieved using a combination of SD-FEC and GCS in an dynamic EON. We use the gains offered by GCS in SNR for a given information-theoretic threshold, and study how these gains affect the modulation format selection of the RSMLA problem in a dynamic EON. Our results show that GCS leads to an increase between 5 and 13% in the network traffic load for a fixed blocking performance compared to conventional QAM modulation formats.

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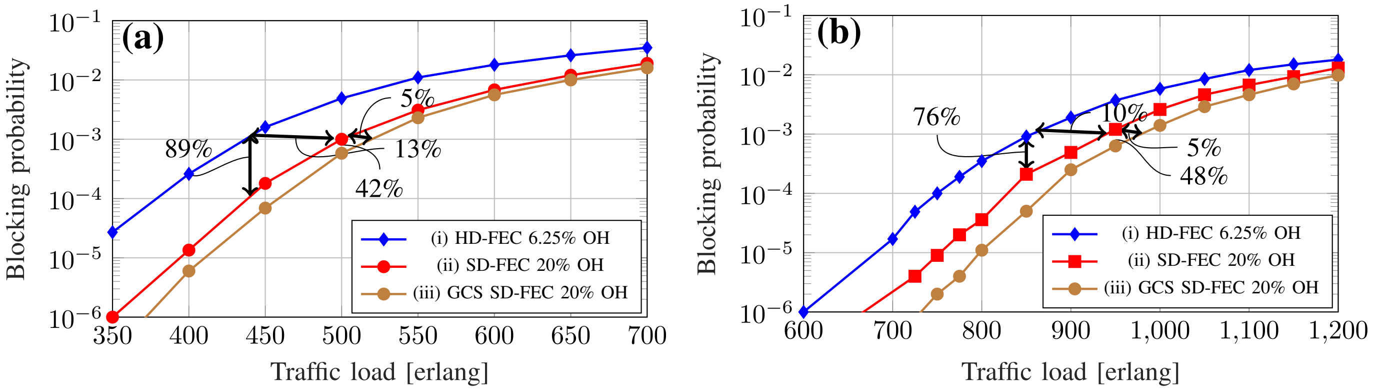

Fig. 1: Blocking probability as a function of traffic load for: **(a)** NSFNET topology and **(b)** EUROCORE topology.

II. METHODOLOGY

The study was performed over two network topologies, namely NSFNET and EUROCORE. The transceiver configuration analyzed used are the following: (i) HD-FEC with 6.25% OH [3] using conventional square QAM constellations; (ii) SD-FEC with 20% OH using conventional square QAM constellations [7]: (iii) geometrically shaped constellations optimized for SD-FEC with 20% OH [7]. The main benefit of switching from transceiver configuration (i) to (ii) and switching from (ii) to (iii) is an enhancement in the maximum transmission reach that can be attained for a given cardinality in the modulation format. We used constellations with $\{2, 3, 4, 5, 6, 7, 8, 9, 10\}$ bit/2D-symbol. In particular for configurations (i) and (ii) we used {QPSK, 8PSK, 16QAM, 32CROSS, 64QAM, 128DSQ, 256QAM, 512CROSS, 1024QAM}, for configuration (iii) we used {QPSK, 2DSQ 8, 2D-GS-16, 2D-GS-32, 2D-GS-64, b2-128, 2D-GS-256, GS-AWGN-2D-512, 2D-GS-1024}. Note that for configurations (i) and (ii) conventional modulation formats from commercial standards were used, while for configuration (iii) the formats with the minimum signal-to-noise ratio (SNR) for a normalized generalized mutual information (GMI) of 0.8 were used (see [14] for further details).

To calculate the maximum reach, the Gaussian noise model [12] was used to estimate SNR assuming a fully loaded C-band, with channels modulated at a rate of 12.5 GBd and standard single mode fiber parameters. For configuration (i), SNR thresholds (SNR_{th}) from [13] were used, while for (ii) and (iii) SNR_{th} reported in [14] were used. Maximum transmission reach and SNR_{th} for each configuration are shown in Table I. Note that the reach increase between configurations (ii)-(i) is significantly larger than the gain observed between (iii)-(ii) due to the difference in SNR_{th}.

A C++ simulator was used to evaluate the blocking probability for the different transceiver configurations in a dynamic EON [15]. The blocking probability is defined as the ratio between the unsuccessful connection requests and the total connections requests. To perform resource allocation, the route, modulation format and spectrum assignment problem (RMSA) was solved using a heuristic approach. The k-shortest paths for route selection was used for route selection, the modulation format with highest spectral efficiency and a reach greater than the route length was selected, and first-fit was used for spectrum allocation [13]. For the simulations, a connection request is defined by the triplet (src, dst, b), where src and dst are the source and destination nodes, respectively and b the bitrate. Connection request arrivals and departures are modeled as a Poisson process of parameter λ. The holding time of each connection is exponentially distributed, with mean value $1/\mu$. The network traffic load is given by λ/μ. The source and destination nodes of a connection request are randomly selected following a uniform distribution, whilst the bitrate is uniformly selected from the set {10, 40, 100, 400, 1000} Gbps. The number of connection requests simulated was 10^7.

TABLE I: Transmission reach and SNR requirements

bit / 2D sym	**Config. (i)**		**Config. (ii)**		**Config. (iii)**	
	Reach	SNR_{th}	Reach	SNR_{th}	Reach	SNR_{th}
2	20800	8.3	25000	4.0	25000	4.0
3	10400	10.9	20300	8.1	22000	7.6
4	5200	14.0	12700	10.2	12800	10.1
5	2500	16.9	6400	13.1	7300	12.6
6	1300	19.8	3700	15.4	4100	15.0
7	800	22.5	1300	19.8	1500	19.4
8	300	25.5	1100	20.48	1300	19.9
9	100	31.1	300	26.4	300	26.4
10	–	–	300	25.5	400	24.5

III. RESULTS

Figure 1 presents the blocking probabilities as a function of the traffic load for the NSFNET **(a)** and EUROCORE **(b)** topologies. In general, for both topologies, the highest blocking is observed for the transceiver configuration (i), and a large reduction is observed when changing from configuration (i) to configuration (ii). The change from configuration (ii) to configuration (iii) results in a further, but smaller reduction in the blocking probability. We focus on the benefits observed at a blocking probability of 10^{-3}. In particular, in NSFNET topol-

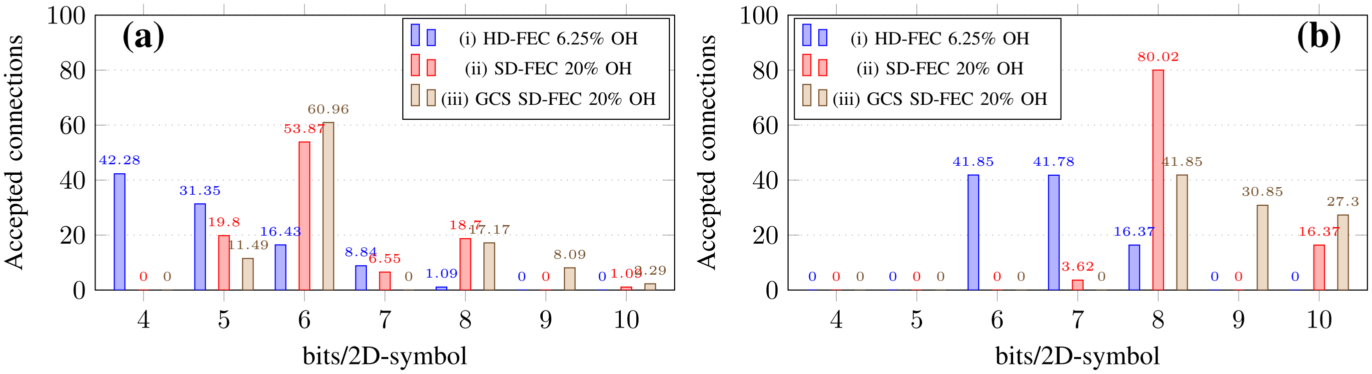

Fig. 2: Percentage of accepted connections for each used modulation format cardinality for: **(a)** NSFNET topology and **(b)** EUROCORE topology.

ogy, a blocking probability reduction of 89% and 42% was found between configurations (i)-(ii) and (ii)-(iii), respectively. Additionally, in EUROCORE topology, a reductions of 76% and 48% was observed between configurations (i)-(ii) and (ii)-(iii), respectively. This reduction of the blocking probability can be exploited to serve a higher traffic load through the network for a given blocking threshold. For a blocking value of 10^{-3}, traffic load increases of 13% and 5% were observed for the NSFNET network, while increases of 10% and 5% were observed EUROCORE.

To understand the the reasons behind the reduction in blocking probability, we study the selection of modulation formats in each network and transceiver configuration, with the results presented in Fig. 2. It is observed that the use of HD-FEC wit 6.25% OH utilizes less efficient formats compared to the other 2 configurations. For the NSFNET, 42.28% and 31.35% of the connections are established using 16-QAM and cross-32-QAM (4 and 5 bits/2D symbol, respectively). SD-FEC with 20% OH, on the other hand, established 19.8%, 53.87% and 18.7% of connections using cross-32-QAM, 64-QAM and 256-QAM (5, 6 and 8 bits/2D symbol, respectively). Finally, the use of GCS with SD-FEC with 20% OH leads to an increase in the connections established using modulation formats with 6, 8 and 9 bits/2D symbol. In the EUROCORE topology the same trend is observed, but due to the shorter distance between nodes, all configurations used denser modulation formats. HD-FEC wit 6.25%OH uses mainly 64-QAM and cross-128-QAM, while the other configurations use mainly modulation formats with 8, 9 and 10 bits/2D symbol. In general, the use of higher cardinality reduces the spectral requirements for each user, thus simplifying the spectral assignment problem and allowing more connections to be established.

IV. CONCLUSIONS

We have studied the gains achieved using a combination of SD-FEC and GCS in a dynamic EON. The SNR gains offered by SD-FEC and GCS lead to a greater utilization of high efficiency modulation formats when solving the RSMLA problem. Reduction of the blocking probability in the studied networks was observed when SD-FEC was used, with even further reductions using GCS.

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