On High-Power Optical Amplification in Hollow Core Fibers for Energy Efficiency and Network Throughput Maximization

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Abstract *We investigate how to optimally set the EDFA output power in Hollow Core Fiber (HCF) networks. We show that, using high-power amplification, HCF allows 2.4x increase in throughput and 52% decrease in transponders along with a 41% reduction in EDFAs power consumption per Tbps.*

Introduction

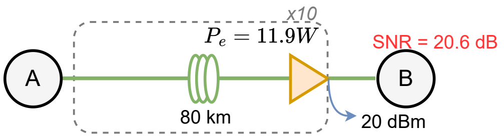
While Standard Single-Mode Fibers (SSMFs) have been the *go-to* solution in optical communication systems for the past 50 years, the technological advancements in Hollow Core Fiber (HCF) production[1] are expected to be the groundbreaking enabler for *6G-and-beyond* systems.

Compared to conventional SSMFs, HCFs have several advantages, such as lower non-linear effects by four orders of magnitude, lower attenuation, lower propagation latency, and a wider usable bandwidth[2], that can lead to significant network performance improvement. Among them, a lower attenuation (less than 0.11 dB/km[1]) implies fewer EDFA amplifiers, lower non-linear effects, and a wider usable bandwidth allows for higher throughput, and a lower propagation latency allows for latency-sensitive applications in the *6G-and-beyond* context[3].

In this paper, we focus on the role of high-power EDFA amplification and how we can achieve gains in network throughput and energy efficiency by deploying high-power EDFAs. In particular, since non-linearities in HCF are very low, we can transmit powers up to two orders of magnitude higher compared to SSMF. This implies deploying EDFAs capable of outputting powers up to 38 dBm[2], compared to 20 dBm output power in SSMF networks. The challenge is to optimize the working point, i.e., optimal output power, of high-power EDFA amplifiers in an HCF network, such as to maximize the benefits of operating at a high power (leading to a network throughput increase) while ensuring an energy-efficient solution. In SSMF networks, deploying high-power EDFA amplifiers is not feasible as the network would operate in a non-linear regime, i.e., not operate at nominal power according to the LOGO strategy[4], leading to lightpath Signal-to-Noise Ratio (SNR) degradation. In HCF networks, even if today several practical challenges regarding the management of high launch powers[2] remain, much higher transmission power can be achieved.

Figure 1 shows a simple illustrative example comparing an SSMF line system vs an HCF line system in terms of EDFA power consumption and lightpath SNR, calculated according to the EDFA power consumption and physical layer models in Section 2. In the case of the SSMF network with EDFA amplifiers outputting 20 dBm optical power, the total power consumption of inline EDFAs equals 119 watts, and lightpath SNR equals 20.6 dB. In the case of the HCF network with EDFA amplifiers outputting 29 dBm optical power, the total power consumption of inline EDFAs equals 128 watts, and lightpath SNR equals 28.1 dB. Despite the higher total EDFA power consumption of HCF, the higher SNR allows the assignment of higher-order modulation formats, resulting in higher throughput, lower number of transponders, and lower power consumption per bit.

A) Traditional SSMF optical communication system



B) Beyond SoTA HCF optical communication system

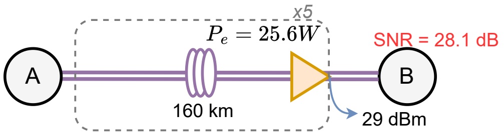


Fig. 1: Illustrative example of an SSMF (10 x 80 km spans) and an HCF (5 x 160 km spans) optical communication system

While investigation on the deployment of HCF has been carried on for almost a decade now, most of the related work refers to the fabrication process[5]–[7]. Only a few prior works[2],[8] show the impact of HCF in increasing the network throughput and span length. Recently, we have investigated the impact of deploying HCF at the network layer[3]. Compared to these works, we investigate how to optimally set the output power of high-power EDFA amplifiers in HCF networks, with the objective of minimizing the EDFA power consumption and maximizing network throughput. We show that an HCF network can achieve an increase of 2.4x in network throughput, while reducing by 41% the EDFA power consumption per bit, compared to an SSMF network.

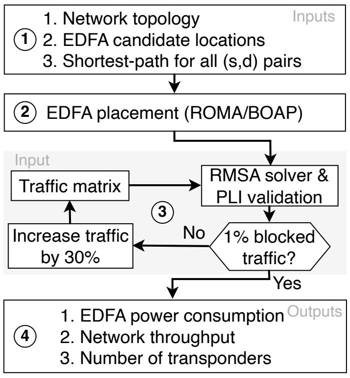


Fig. 2: Framework of the proposed solution

Problem statement, physical layer and power consumption modeling

Problem statement. The problem of minimizing the EDFA power consumption per Tbps and maximizing the network throughput through optimizing the output power in high-power EDFA amplifiers in HCF optical networks can be formulated as follows: **Given** a network topology, an initial set of traffic demands (with source-destination nodes and data rate), an increase rate of traffic, an initial deployment of EDFAs at the nodes, a set of inline candidate locations to deploy EDFA, **decide** the placement of inline EDFAs and Routing, Modulation format, and Spectrum Assignment (RMSA) of all traffic demands, **constrained by** *i)* lightpath SNR, *ii)* spectrum continuity and contiguity, and *iii)* fiber capacity, with the **objective** of minimizing the EDFA power consumption per Tbps and maximizing the minimum lightpath SNR in the network (these two objectives can be weighted to prioritize one main goal).

Physical layer modelling. We assume that all network nodes support (C+L) transmission and that C-band and L-band EDFAs are placed in the same cabinet location. For SSMF, we adopt the physical-layer model in[9], while for HCF, we adopt the model in[2]. We assume SSMF and HCF with average attenuation coefficients of 0.22 dB/km and 0.11 dB/km, respectively. In the case of HCF, we assume an Inter-Modal-Interference (IMI) of -60 dB/km. We consider EDFA amplification and that links operate in ASE loading. A lightpath is feasible when its SNR is above a threshold determined by data rate and modulation format, plus a 2 dB system margin[10]. At each span, we assume a band demultiplexer separates the C-, and L-band, which are amplified independently and then recombined using an optical coupler. The band demultiplexer and coupler insertion losses amount to 2 dB[11].

Power consumption model. The power consumption of an EDFA in Watt [W] (P_e) is computed according to the model in[12]:

$$P_\text{e} = \frac{1}{\eta_\text{epc}} \cdot N_\text{ch} \cdot P_\text{ch} \cdot \left(1 - \frac{1}{G_\text{e}}\right) + P_\text{m} \tag{1}$$

where η_epc is the electrical-to-optical power conversion efficiency, N_ch is the number of channels, P_ch is the channel power at the output of the EDFA, G_e is the EDFA gain in linear units, and P_m is the monitoring and management power consumption.

Energy-efficient high-power EDFA amplification deployment in HCF Networks

In Fig. 2, we show the main building blocks of the proposed solution. **(1) Inputs.** We provide the network topology, a set of EDFA candidate locations (where to place EDFAs), and calculate the shortest path between all node pairs.

(2) EDFA placement. We consider two strategies to deploy amplifiers: 1. eneRgy-efficient Optical aMplifier plAcement (**ROMA**), and 2. **B**aseline **O**ptical **A**mplifier **P**lacement (**BOAP**). 1. ROMA: is a greedy heuristic that minimizes the weighted sum of EDFA power consumption and of the minimal SNR, expressed as $min(\alpha * P_{E\bar{D}FA} - \beta * min\bar{S}NR)$. We consider two scenarios of (α, β), taking values equal to $(0.1, 0.9)$ and $(0.9, 0.1)$, to prioritize of one objective over the other. P_{EDFA} is the EDFA power consumption, normalized to the EDFA power consumption of BOAP baseline. $min\bar{S}NR$ is the minimum SNR in the network, normalized to the minimum SNR in case of the BOAP baseline. Normalization is necessary to ensure consistency between the two terms summed in the objective function. *ROMA* starts placing EDFAs in all the candidate locations, initializing an empty list of non-removable EDFAs. Then, in each iteration, we identify a list of shortest spans. From the list, we choose a span in the link traversed by the highest number of shortest paths. We then remove the EDFA at the beginning of this span and evaluate whether this removal improves the objective function. If not, we revert the action and insert the EDFA into the list of non-removable EDFAs. Conversely, if the removal improves the objective function, we clear the non-removable EDFAs list and proceed to the next iteration. The loop ends when there are no more removable EDFAs. 2. BOAP places EDFAs at the ingress and egress of each node, and inline amplifiers (along the fibers) to ensure uniformly spaced span lengths of 40 km to 100 km in each link, depending on link length.

(3) RMSA solver and PLI validation. Starting from an initial traffic matrix, we consider an incremental traffic scenario with a 30% per-step traffic increase. The traffic is generated considering uniformly distributed source-destination pairs and, in each step, we perform RMSA of traffic demands. We then validate the Physical Layer Impairments (PLI) in terms of SNR, for all lightpaths. The simulation stops when reaching 1% of blocked traffic.

(4) Outputs. We report 1) EDFA power consumption per Tbps, 2) Total network throughput in Tbps, and 3) Total number of transponders (TXPs).

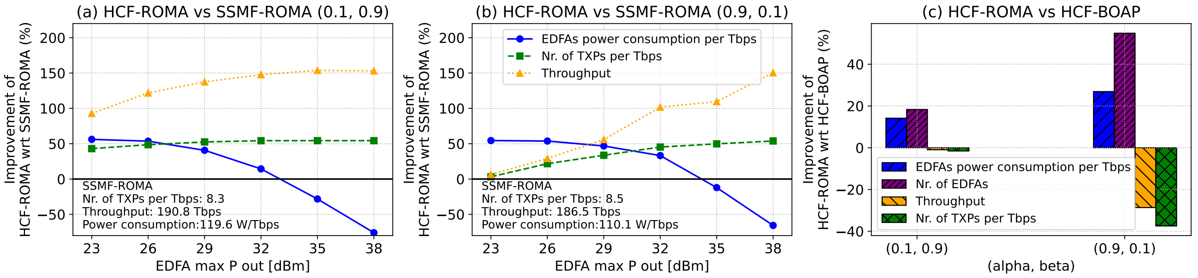


Fig. 3: Percentage improvement of EDFA power consumption per Tbps, number of TXPs per Tbps, and throughput of HCF-ROMA over SSMF-ROMA for (α, β) equal to (a) $(0.1, 0.9)$ and (b) $(0.9, 0.1)$, and (c) average percentage improvement of EDFA power consumption per Tbps, number of TXPs per Tbps, throughput and number of EDFAs of HCF-ROMA over HCF-BOAP for (α, β) equal to $(0.1, 0.9)$ and $(0.9, 0.1)$

Illustrative numerical results

We consider the 19-node European topology (EU19[13]), and a total fiber capacity of 10.1 THz (5.9 THz for C-band and 4.2 THz for L-band) considering frequency slots of 12.5 GHz. We consider three types of TXPs[14] and modulation formats ranging from QPSK to 64-QAM. We consider k-shortest-path routing (k=3) with minimal loss[15] and first-fit spectrum allocation. We compare two scenarios: EU19 with SSMFs and with HCFs. For HCFs, we explore a range of maximum output powers for EDFAs between 23 and 38 dBm. For SSMFs, the EDFAs output power is set according to LOGO[4]. Regarding deploying amplifiers, we compare an optimized placement through *ROMA* and baseline placement through *BOAP*.

Figure 3 shows the percentage improvement of HCF-ROMA with respect to SSMF-ROMA for (α, β) equal to (a) $(0.1, 0.9)$ and (b) $(0.9, 0.1)$, and (c) the percentage improvement on average over all EDFAs output powers of HCF-ROMA with respect to HCF-BOAP for $(\alpha = 0.1, 0.9; \beta = 0.9, 0.1)$. We report the EDFA power consumption per Tbps, the number of TXPs per Tbps, the number of EDFAs, and the network throughput in Tbps, computed as the served traffic at 1% of blocking rate.

HCF-ROMA vs SSMF-ROMA. Increasing the EDFA output power improves the SNR thanks to the ultra-low non-linearities of HCF, leading to higher throughput and fewer TXPs per Tbps. However, the EDFA power consumption per Tbps gradually increases, up to being higher than in SSMF. Let us consider the case in which (α, β) is $(0.1, 0.9)$, which translates into prioritizing the maximization of the minimum SNR. HCFs enable a throughput increase compared to SSMF, ranging from 1.9x at 23 dBm to 2.5x at 38 dBm of EDFA output power, and a decrease in the number of TXPs per Tbps, ranging from 43% at 23 dBm to 54% at 38 dBm of EDFA output power. At 29 dBm we get a throughput increase by 2.4x and 52% fewer TXPs per Tbps, along with a 41% reduction in EDFAs power consumption per Tbps. Increasing the power beyond 29 dBm does not yield significantly greater benefits in terms of throughput or number of TXPs per Tbps, while it worsens energy efficiency. Let us now consider (α, β) equal to $(0.9, 0.1)$, prioritizing the EDFAs power consumption minimization. In this case, to get a 2.5x throughput increase and a 54% reduction in the number of TXPs per Tbps compared to SSMF, we need to increase the EDFA output power up to 38 dBm. However, at this threshold we have a 66% increase in EDFA power consumption per Tbps, indicating a significant reduction of energy efficiency compared to SSMF. Prioritizing the minimum SNR maximization proves to be the best approach for maximizing the throughput while preserving energy efficiency. These results highlight the importance of optimizing the EDFA output power to maximize the benefits brought by HCFs. At 29 dBm of EDFA output power with (α, β) equal to $(0.9, 0.1)$, we achieve a sweet spot, featuring substantial improvement in throughput and number of TXPs per Tbps while enhancing the energy efficiency compared to an SSMF-based network.

HCF-ROMA vs HCF-BOAP. Fig. 3.c shows the impact of optimizing the EDFA placement through ROMA vs BOAP. By exploiting the low propagation loss of HCF, we can reduce the EDFA number and improve energy efficiency. In the case of (α, β) equal to $(0.1, 0.9)$ we achieve a 15% reduction in the EDFA power consumption and an 18% reduction of the number of EDFAs, on average across all EDFA output powers. This improvement comes with a marginal 0.6% decrease in throughput and a 1.5% increase in the number of TXPs per Tbps. For (α, β) equal to $(0.9, 0.1)$, there is an average reduction of 26% in EDFA power consumption and an average decrease of 54% in the number of EDFAs. However, this improvement comes with a significant 30% decrease in throughput and a 37% increase in the number of TXPs per Tbps. Also in this case, prioritizing the maximization of the minimum SNR shows the best tradeoff between energy efficiency and throughput.

In conclusion, we show the benefits of deploying high-power EDFAs in an HCF network compared to an SSMF network, in terms of network throughput and EDFA energy efficiency.

Acknowledgements

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