Impact of Amplifier Noise Figure on Network Throughput

Alex Alvarado, David J. Ives, Seb J. Savory and Polina Bayvel
Optical Networks Group, Dept. of Electronic & Electrical Engineering, UCL, London, WC1E 7JE, UK
alex.alvarado@ieee.org

Abstract: The impact of the amplifier noise figure (NF) on the optical network throughput is quantified from an information viewpoint. For every dB of NF decrease, throughput gains between 4% and 7% are reported.

OCIS codes: (060.4080) Modulation, (060.4256) Networks, network optimization.

1. Introduction

Optical mesh networks utilize wavelength routing to transparently connect source and destination. Noise introduced by the erbium-dopped fiber amplifiers (EDFAs) cause signal degradation, which depends on the distance between transmitter and receiver. The increase in traffic demand, together with the development of software-defined transceivers, has lead to an increased interest in designing networks that adapt the transmission parameters to the physical channel. One promising approach is to vary the modulation format and the forward error correction (FEC) to the signal-to-noise ratio (SNR) of the different routes. Different aspects of this problem have been investigated in, e.g., [1–5].

One of the key components in an optical network are the EDFAs, which are characterized by their noise figure (NF). This NF varies between 3 dB (the theoretical minimum) and $5-7$ dB (for most commercially available amplifiers). The NF of the EDFAs is perceived to be an important parameter to consider when designing a new optical network or when upgrading an existing one.

The theoretically maximum throughput of a network can be obtained from an information theoretic point of view by assuming transceivers operate ideally (i.e., achieving the channel capacity). We studied this problem in [6] for the NSF network and ideal hard-decision FEC (HD-FEC). We recently extended those results to different network topologies and also to soft-decision FEC (SD-FEC) in [7]. In all those results, a NF of 5 dB was considered.

In this paper, we study the effect of the amplifier NF on the maximum network throughput. We analyze different network topologies assuming transceivers that achieve the channel capacity, or that use discrete constellations with ideal HD-FEC and SD-FEC. To the best of our knowledge, such analysis has never been reported in the literature. Somewhat surprisingly, the obtained results show no major impact of the NF on the network throughput.

2. System Model and SNR Results

In this paper we consider 3 network topologies: the Deutsche Telekom Germany (DTG) network (9 nodes; two core nodes per city merged), the 21-link NSF mesh topology (14 nodes), and the Google B4 (GB4) network connecting data centres (12 nodes). These three networks are representative of networks at three different scales: country, continental, and transcontinental, and are shown in [7, Figs. 2–4].

The SNR for a route with N_s spans is calculated as $\mathrm{SNR} = P/(N_\mathrm{s}(P_\mathrm{ASE}+\eta P^3))$, where P is the launch power per channel, P_ASE is the ASE noise added after each span, and η is the nonlinear coefficient. An AWGN channel is assumed and the nonlinear coefficient η is calculated using the incoherent GN model of [8]. This calculation is made for the central channel assuming fully loaded WDM channels. SPM is assumed to be ideally compensated and the ROADM nodes were assumed lossless. The fiber attenuation, dispersion, and nonlinear coefficient are 0.22 dB/km, 16.7 ps/nm/km, and 1.3 1/W/km, resp. We consider 80 WDM channels with Nyquist sinc pulses at 32 Gbaud on a 50 GHz grid, and a span length of 80 km. For the parameters under consideration, we obtain $\eta \approx 742$ 1/W^2.

We consider amplifier NFs from the set 3,4,5,6,7 dB, which lead to different values of ASE noise per span, namely, $P_\mathrm{ASE} \approx 0.47, 0.59, 0.75, 0.94, 1.18$ μW. The optimum launch power for the SNR defined above is given by $P^* = \sqrt[3]{P_\mathrm{ASE}/(2\eta)}$, which gives $P^* \approx -1.66, -1.33, -0.99, -0.66, -0.33$ dBm. This 1/3 dB increase per every dB increase in the amplifier NF follows directly from the expression of P^*.

The routing and wavelength assignment problem was solved numerically as an integer linear programming (ILP) problem as described in [5, Section 4.1]. We maximized the network throughput under a uniform traffic demand and

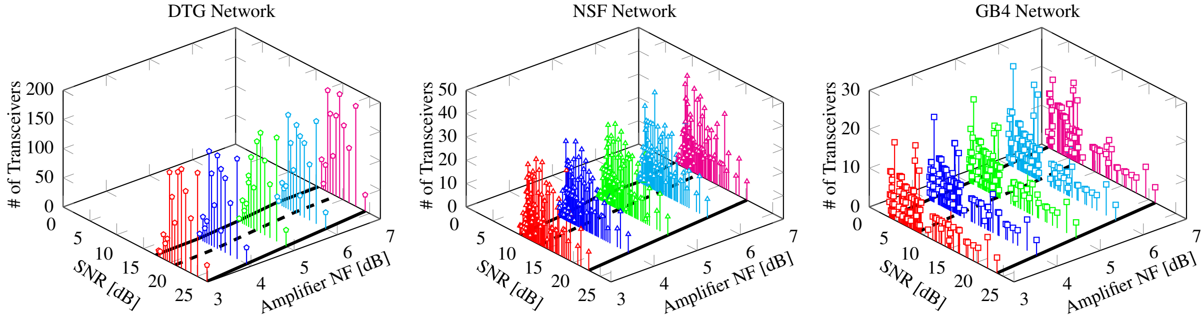

Fig. 1: Number of transceivers for different networks and different amplifier NFs. Mininum and maximum SNR (black lines) as well as mean SNR values (dashed black lines) are also shown.

by assuming all transceivers can achieve the channel capacity $C = 2\log_2(1+\text{SNR})$. The solution of this ILP includes the routes, the SNRs of each route, the number of transceivers, and the overall network throughput.

Fig. 1 shows the obtained SNR “distributions” and how they evolve as a function of the amplifier NF for the three networks under consideration. The results for NF = 5 dB were reported in [7]. In Fig. 1, we also show the minimum, maximum, and mean SNR for each case. The general trend (for each network) is that by increasing the NF of the EDFAs, the SNR distribution shifted to lower SNR values, but its shape is approximately maintained.

As the NF increased, the obtained maximum SNR values were found to increase by $2/3$ dB, for all three networks. This can be be explained as follows. A 1 dB increase in NF causes a 1 dB decrease in noise power, which in turn causes a $1/3$ dB increase in the optimum launch power P^*. The $2/3$ dB increase in maximum SNR follows from the cubic relationship between nonlinear noise and launch power. This result seems to indicate that the route with the highest SNR, which determines the highest order modulation format that can be used in the network, is directly connected to the amplifier NF. Unfortunately, no similar (simple) relationships were found for minimum and mean SNR values.

The obtained SNR results also showed that when the NF increased between 3 dB and 7 dB, the total number of transceivers for the DTG network varied between 1238 and 1228, for the NSF network between 1098 and 1084, and for the GB4 network between 570 and 564. These small variations in the number of transceivers anticipates that the network throughput will not be very sensitive to the amplifier NF. This is investigated in the next section.

3. Throughput Results

In this section we consider the network throughput as a function of the amplifier NF. The receiver structure we consider is a bit-wise receiver combined with Gray-labeled square QAM constellations [9, 10]. In such (pragmatic) approach, the received symbols are first converted into “soft bits” (logarithmic likelihood ratios) or “hard bits”. If soft bits are used, then a SD-FEC decoder is used. If hard bits are computed, then a HD-FEC decoder is used.

For capacity-approaching SD-FEC codes, it is known that the generalized mutual information (GMI) can be used to obtain the optimal modulation size and code rate. Under some assumptions on the soft-bit calculation and bits' statistics, the GMI is given by [10, eq. (13)] $\text{GMI} = \sum_{k=1}^{m} I(B_k;Y)$, where B_k are the bits before the modulator, m is the number of bits per symbol in the modulation format, Y are the received symbols, and $I(X;Y)$ is the mutual information between the random variables X and Y.

For capacity-approaching HD-FEC codes, the metric to describe the optimum modulation size and code rate is the HD-MI, given by [11, eq. (8)] $\text{HD-MI} = m(1 - H_\text{b}(\text{BER}))$, where $H_\text{b}(p) = -p\log_2 p - (1-p)\log_2(1-p)$ is the binary entropy function and BER is the average pre-FEC BER (across m bit positions).

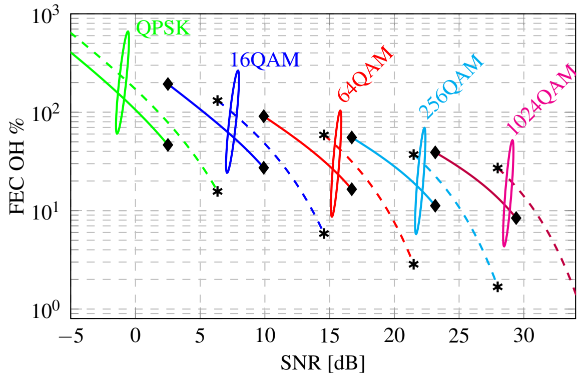

Fig. 2: Optimal OHs from GMI (solid lines) and HD-MI (dashed lines). Markers show switching SNR values.

The GMI curves for square QAM constellations are known to cross at certain SNR values [9, 10, 12]. The same occurs for HD-MI [6]. This leads to the results in Fig. 2, where the optimal FEC overhead (OH) and modulation

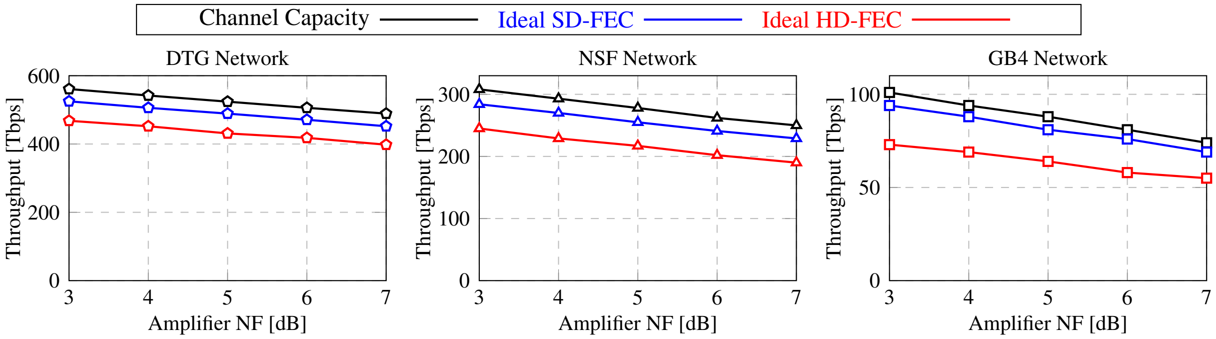

Fig. 3: Network throughput as a function of amplifier NF for different network topologies.

format for both SD-FEC (solid lines) and HD-FEC (dashed lines) are shown. These results indicates the modulation format and code rate should be adapted to the SNR of the channel. For example, for SD-FEC, QPSK should be used when the SNR is below 2.5 dB, 16QAM when the SNR is between 2.5 dB and 9.9 dB, etc. These curves also give the optimum code rate R_c, obtained as $R_c = (1+\mathrm{OH})^{-1}$.

By assuming the transceivers ideally adapt their modulation and coding to the channel, the SNR values in Fig. 1 were used to obtain the network throughput. We call these cases “ideal SD-FEC” and “ideal HD-FEC”. The obtained results are shown in Fig. 3. As an upper bound, we consider the throughput obtained when all transceivers achieve the channel capacity (black lines). As expected, as the NF increases, the network throughput decreases. These results show that the relative losses caused by an increase in amplifier NF increase as the network size increases. For the DTG network, an average loss of 4% per 1 dB increase in NF is obtained. These values become 5.5% and 7% for the NSF and GB4 networks, respectively.

The results in Fig. 1 also show the potential gains offered by SD-FEC over HD-FEC. These result show that the gains offered by SD-FEC are much more important in large networks. For example, the relative throughput gains for the DTG network are, in average, 13%; for the GB4 network these gains increase to 28%. The results in Fig. 1 also show the tradeoff between SD-FEC and amplifier noise figure: for all three networks, a given throughput obtained with HD-FEC can be maintained if SD-FEC is implemented and the NF is increased by 3 dB.

4. Conclusions

The throughput of several multi-scale optical networks was studied as a function of the amplifier noise figure. The highest impact of the noise figure on network throughput was observed for large networks. All observed gains were, however, relatively small. This appears to indicate that the network throughput is not very sensitive to the amplifier noise figure.

Acknowledgments: Financial support from the UK EPSRC (through the project INSIGHT (EP/L026155/1) and the programme grant UNLOC (EP/J017582/1)) is gratefully acknowledged.

References

1. A. Nag, *et al.,* “Optical network design with mixed line rates and multiple modulation formats,” J. Lightw. Technol. **28**, 466–475 (2010).
2. G.-H. Gho, *et al.,* “Rate-adaptive coding for optical fiber transmission systems,” J. Lightw. Technol. **29**, 222–233 (2011).
3. G.-H. Gho and J. M. Kahn, “Rate-adaptive modulation and low-density parity-check coding for optical fiber transmission systems,” J. Opt. Commun. Netw. **4**, 760–768 (2012).
4. D. A. A. Mello, *et al.,* “Optical networking with variable-code-rate transceivers,” J. Lightw. Technol. **32**, 257–266 (2014).
5. D. J. Ives, *et al.,* “Routing, modulation, spectrum and launch power assignment to maximize the traffic throughput of a nonlinear optical mesh network,” Photon. Netw. Commun. **29**, 244–256 (2015).
6. A. Alvarado, *et al.,* “On optimal modulation and FEC overhead for future optical networks,” in Proc. OFC, Th3E.1 2015.
7. A. Alvarado, *et al.,* “On the impact of optimal modulation and FEC overhead on future optical networks,” (2015). Available online at http://arxiv.org/abs/1508.04716.
8. P. Poggiolini, *et al.,* “The GN-model of fiber non-linear propagation and its applications,” J. Lightw. Technol. **32**, 694–721, 2014.
9. L. Szczecinski and A. Alvarado, *Bit-Interleaved Coded Modulation: Fundamentals, Analysis and Design,* John Wiley & Sons, 2015.
10. A. Alvarado and E. Agrell, “Four-dimensional coded modulation with bit-wise decoders for future optical communications,” J. Lightw. Technol. **33**, 1993–2003 (2015).
11. T. Fehenberger, *et al.,* “On achievable rates for long-haul fiber-optic communications,” Opt. Express **23**, 9183–9191 (2015).
12. R. Maher, *et al.,* “Modulation order and code rate optimisation for digital coherent transceivers using generalised mutual information,” in Proc. ECOC, Mo.3.3.4 2015.