Observing and Modeling the Physical Layer in Open and Disaggregated Optical Networks

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Ph.D Thesis Abstract

In this thesis we present our novel contributions in the field of open and disaggregated optical networks. Telecom operators are facing an increasing capacity demand due to the growing IP traffic pushed by the activation of new IP based services, such as intensive media streaming and the upcoming 5G based services, especially in the post COVID-19 pandemic world. These trends will require an overhaul of the optical infrastructure in order to improve the network flexibility and capacity while keeping the infrastructure cost effective.

Thanks to the introduction of DSP-based receiver on coherent transmission, optical networks are becoming more and more *software-defined*, in order to automate the network orchestration. In this context, openness and disaggregation are becoming the keywords of the optical network evolution. With *open*, we refer to the need for open source network devices and software based on standardized data structures, allowing the network operation automation and interoperability between different vendor devices. The interoperability is linked to the concept of *disaggregation*. Traditional optical networks solutions are offered by vendors as monolithic blocks with proprietary orchestration tools. The disaggregation perspective aims to solve the vendor lock-in by treating at least the transceiver side and optical line system (OLS) as separate entities, which are interfaced together by means of open technologies, allowing for seamless and cost effective upgrades of specific network elements.

In this work we first propose a network abstraction based on the generalized signal-to-noise ratio (GSNR) as a general figure for the estimation of a lightpath's quality of transmission (QoT). Such abstraction has the aim to decouple the spectral content from the line system characteristics in order to simplify the optimizaton of the network working point with respect to the physical propagation impairment and to develop effective tools for path computation in lightpath deploying. From this perspective, an effective abstraction of the complex mechanism behind the generation of non-linearities in optical fiber propagation is crucial. In this work, we observe non-linearities generation by means of extensive split-step Fourier method (SSFM)-based simulations, which solve numerically the optical fiber's propagation equation.

We first focus on dispersion-uncompensated (DU) OLSs populated with polarization-multiplexed (PM) coherent channels, considering several symbol rate and spectral grid scenarios, since the market is pushing towards the symbol rate's enlargement to improve capacity. Targeting the SNR as observable figure of performance, we show through a detailed set of SSFM simulations, that the overall non-linear interference (NLI) is composed of the single-channel interference (SCI) and the cross channel interference (XCI) originated by each of the interfering channels, thus allowing for a *spectrally disaggregated* modeling, as opposed to the Four-Wave Mixing (FWM)-like aggregated approach.

Furthermore, a worst-case, *spatially incoherent* estimation of the Cross-Phase Modulation (XPM) can be accomplished, allowing for power and capacity optimizaton on a per fiber-span basis.

We then consider the propagation of legacy intensity modulated-direct detected (IMDD) channels on dispersion managed (DM) networks. In these networks, optical dispersion compensation was performed and optimized for specific trasmission scenarios, thus not allowing for dynamic and reconfigurable networking. We show that modern forward error correction (FEC) algorithms allow simpler modeling of non-linearities and we provide a quality of transmission estimator (QoT-E) enabling easier optimization and performance estimation on these systems.

As a further step, we consider the joint tranmission of coherent and IMDD lightpaths in DM OLS. In such scenario, coherent channels are known to experience severe QoT degradation due to inline dispersion compensation and non-linear crosstalk originated by IMDD channels. We present the results of an extensive SSFM simulation campaign performed to observe the non-linear phase noise (NLPN) originated by IMDD on coherent channels and we carry out Monte-Carlo observation to assess the impact of random birefringence on non-linearity generation. Then, a simple, conservative model for the QoT estimation of such degradations is presented and validated with experimental results.

As a final work, we consider multi-band systems, extending the available transmission bandwidth to the C+L band as a cheaper solution to enlarge the capacity of deployed systems. The extension of the transmission bandwith however triggers intense power transfer from higher frequencies to lower frequencies due to stimulated Raman scattering (SRS). This issue needs to be kept under control by means of power optimization strategies. Exploting SSFM simulations, we show here that disjoint power optimization between existing C-band traffic and newly deployed L-band channels delivers minimal penalties in overall QoT, allowing easier multi-band upgrades of existing, online systems.