Modeling and Optimization of Experimental S+C+L WDM Coherent Transmission System

Salma Escobar-Landero, Xiaohui Zhao, Abel Lorences-Riesgo, Dylan Le Gac, Yann Frignac, Gabriel Charlet
Optical Communication Technology Lab, Paris Research Center, Huawei Technologies France
20 Quai du Point du Jour, 92100 Boulogne-Billancourt, France
salma.escobar.landero@huawei.com

Abstract: Using accurate ISRS GN modeling and the fast-converging ASE-NL optimization algorithm, we demonstrate 6.2 Tbit/s throughput improvement in a 2-span ultra-wide-band system thanks to the use of the predicted total and per channel power.

1. Introduction

In recent years, ultra-wideband (UWB) transmission systems have attracted much attention as a possible solution to continue coping with the ever increasing bandwidth demand. Several transmission demonstrations have achieved data rates above 200 Tb/s in single span [1-2] and few fiber spans S+C+L systems [3]. Whereas these impressive demonstrations make the most of transmitting in bandwidths larger than 100 nm, modeling and optimizing UWB systems are still challenging mainly due to the signal power transfer caused by inter-channel stimulated Raman scattering (ISRS) effect. The benefits of including power control strategies have been demonstrated, but these have been based on demanding experimental approaches [4-5]. On the other hand, the development of accurate and fast ISRS Gaussian noise (ISRS GN) closed-form models to estimate the amplified spontaneous emission (ASE) noise and nonlinear interference (NL) generation in UWB scenarios [6] has enabled launch power optimization techniques based on the maximization of quality of transmission (QoT) [7-9]. However, these modeling-based techniques have not been validated experimentally yet.

In this work, we first validate the accuracy of our implemented ISRS GN closed-form model to predict end-to-end UWB system performance, by comparing estimated and measured average data rate with regard to the launch power when having a uniform input power distribution, finding a reliable prediction of the optimal total power. Then, we use our recently proposed ASE-NL algorithm [10] which balances ASE and NL noises to obtain the optimized pre-emphasis based on the mean power (P_μ) and tilt (P_T), observing a total throughput improvement of 6.2 Tbit/s, proving the benefits of propagation models for fast and effective UWB system design optimization.

2. Experimental setup and simulation parameters

Figure 1(a) shows the experimental setup of S+C+L transmission system. An ASE source for each band is separately shaped by the corresponding S-band waveshaper (WS), C- and L-band wavelength selective switches (WSSs) to respectively emulate 80 wavelength division multiplexing (WDM) channels using a frequency grid of $\Delta\nu$ = 75 GHz within 6 THz bandwidth per band.

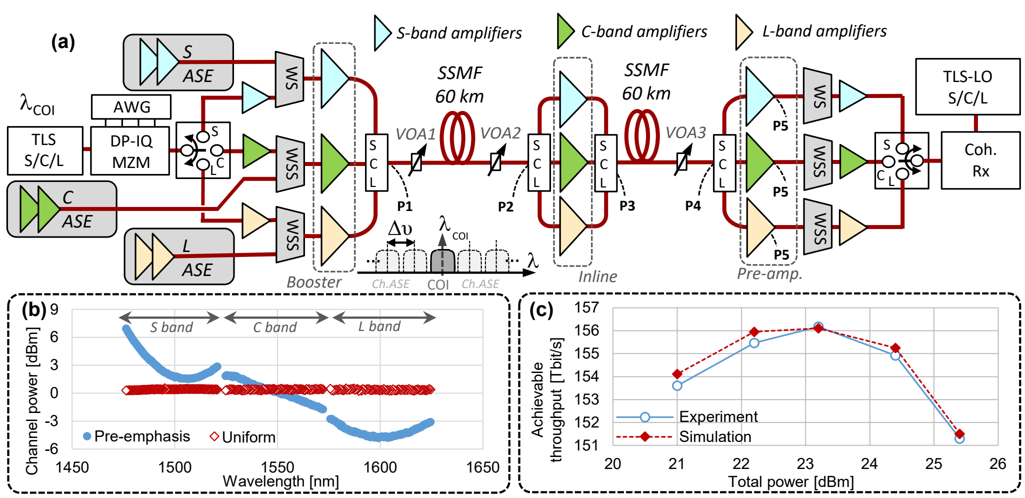

Figure 1. (a) S+C+L transmission system setup, (b) optimized pre-emphasis and uniform launch power profile, (c) estimated and measured achievable throughput vs. launch power for uniform input.

For the channel of interest (COI), we use a 60 Gbaud PCS-256QAM signal, which passes through a single channel amplifier. Each band is amplified by its corresponding booster amplifier to later being multiplexed by an SCL multiplexer. The total output power and output power profile at the input of the fiber is adjusted by a variable optical attenuator (VOA), referred as VOA_1, and WSSs respectively. To show the validity of the ASE-NL heuristic not only by optimizing the booster per channel launch power, but also the mean gains (g_μ) of the inline amplifiers, our transmission link consists of two 60 km single-mode fibers (SMF) whose attenuation coefficient is shown in the inset table of Figure 2(a). After demultiplexing, individual per band amplifiers are employed to compensate for span loss and to adjust launched power into the fiber. Fiber-based amplifiers are used for S and C bands, while semiconductor optical amplifiers (SOAs) operate in L band. The averaged measured noise figure (NF) per band is also presented in Figure 2(a). A last stage of amplification, referred as pre-amp., is located at the end of the line, before the filtering of the WS or WSSs. Finally, the COI is pre-amplified before the receiver. Digital signal processing is described in [3]. The signal-to-noise ratio (SNR) of 15 total channels, 5 per band, is estimated. We use generalized mutual information (GMI) to estimate achievable data rates, multiplying it by using 60 (symbol rate), 2 (dual polarization) and by 63/64 to take into account pilot ratio.

An initial digital twin of this experiment is performed after propagating uniform power spectra at different launch powers, aiming to characterize the transmission system elements, such as the NF of the amplifiers, estimated from the optical signal-to-noise ratio (OSNR) measurements at P2 and P3. These parameters, and the power spectrum measurements obtained with the optical spectrum analyzer (OSA) at P1 and P3 are inputs to the ISRS GN model, to calculate the SNR of the 240 transmitted channels. Figure 1(c) presents the accurate estimations of our modelling, having a simulation error lower than 0.4% for 5 measured total powers. Both, simulation and experiment converge to ~23.2 dBm optimum power.

(a)	S band	C band	L band
Bandwidth (THz)	6	6	6
λ (nm)	1498.4	1548.3	1600.3
α (dB/km)	0.212	0.195	0.200
D (ps/nm/km)	15.2	18	20.6
Raman tilt (dB)	2.9	4	1.3
Average NF (dB)	5.8	4.9	5.9

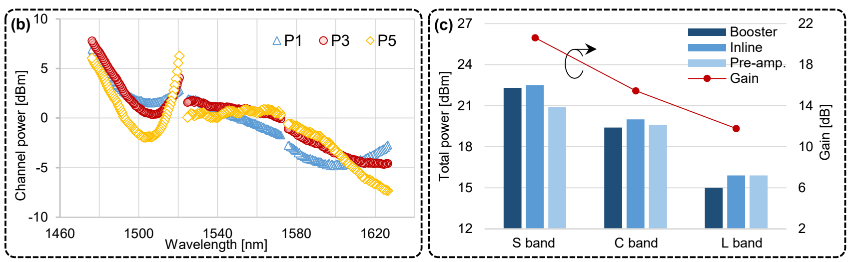

Figure 2. (a) System parameters, (b) channel power spectra at P1, P3 and P5, (c) optimum amplifier total output power per band along the transmission system (left axis) as well as the mean gain per band of the inline amplifiers (right axis).

3. Power optimization simulation and experimental results

Once the simulation parameters have been aligned to the physical transmission elements, we perform a per channel power optimization based on the ASE-NL heuristic. Figure 2(c) shows the optimized booster output power (P_μ) and inline amplifiers gains (g_μ) predicted by the algorithm. There is a clear imbalance between the required amplifier output powers and gains of the three bands. The booster power tilts (P_T) are set to 4 dB and 3 dB in S- and C band respectively, finding an optimum total launch power of 24.5 dBm. Next, per channel equalization is calculated to mainly account for power ripple accumulation due to non-ideal gain profiles. Since the ASE-NL heuristic relies on a python-based implementation of the fast ISRS GN closed-form model, it only takes around 4 minutes to optimize using a single core standard desktop computer. The resulting optimized pre-emphasis is presented in Figure 1(b). As expected, higher power is allocated in the S band to compensate for the ISRS effect and larger fiber losses, while both C and L bands require lower launch power.

Finally, we configure the booster and inline amplifiers to perform with the predicted powers and gains for each band. The measured power spectrum after each stage of amplification is shown in Figure 2(b). It can be observed that the total power per band is closely maintained along the transmission line. One of the main design limitations, is the S band amplification without gain flattening filter (GFF), which translates to almost 8 dB ripple observed at power spectrum measured at P5. Again, the performance of 15 channels is measured and compared with the optimized SNR predicted by our ASE-NL heuristic. Figure 3(a) shows the SNR measured (markers) and predicted (lines) for the two input power profiles. Thanks to the digital twin, we achieve a very good agreement, having a maximum simulation error of 0.5 dB. To validate the optimized total power and the benefits of optimized pre-emphasis, Figure 3(b) plots the measured average data rates for uniform (dotted line) and optimized pre-emphasis (solid line) power profiles with respect to the total launch power. It can be observed that the optimum power varies for both cases.

Although, for flat input spectrum we achieve a maximum capacity of 156.1 Tb/s at 23.2 dBm, as previously stated, the ASE-NL heuristic predicted a larger optimum launch power of 24.5 dBm. At this power and thanks to the pre-emphasis, the measured SNR improves for all the channels, leading to a capacity increase from 154.9 Tb/s to 161.1 Tb/s, plotted along the dashed line of Figure 3(b). Therefore, the ASE-NL algorithm proves to be an accurate strategy to predict total and per channel optimum power.

Besides the potential to develop power optimization schemes, QoT estimations based on the ISRS GN model provide a clearer view to better understand the impact of the physical impairments that affect any WDM transmission system. Figure 3(c) shows the participation of the different noise contributions that impact the total SNR performance. The SNR_{ASE} and SNR_{NL} correspond to the independent contributions of ASE and NL noises at each span inside the optical multiplexing section (OMS), while the $SNR_{PRE\text{-}AMP}$ represents the ASE contributions of the single-channel amplifiers at both transmitter and receiver sides. The SNR_{TRX} is the experimentally measured transponder back-to-back SNR. The average per band contributions affect individually the total SNR. It can be observed that the transmission is mainly limited by the transponder penalties, representing around half of the noise contributions for all the bands. S band is more affected by ASE noise because of the higher amplifier gain required to recover the larger losses. Also, since this band has a relatively higher output power, the NL contributions will be higher than other bands. Most importantly, the target of setting the ASE noise power as twice the NL noise power (P_{ASE}/P_{NL}= 2) is achieved for all the bands.

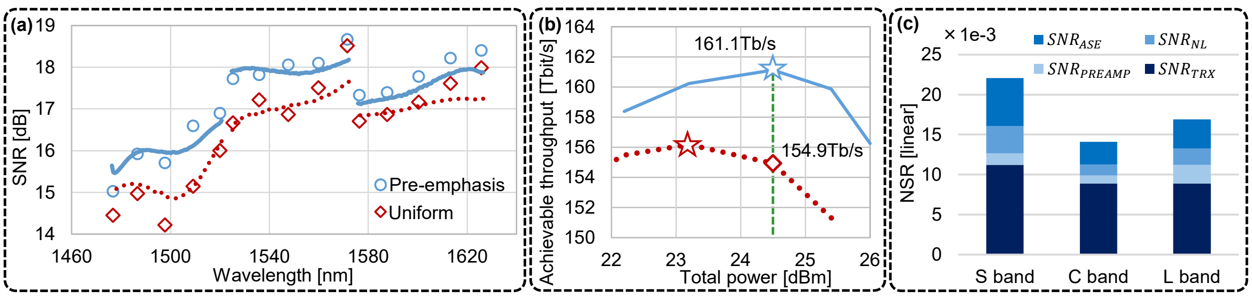

Figure 3. (a) Measured (markers) and estimated (solid lines) SNR for uniform (red) and ASE-NL optimized (blue) pre-emphasis, (b) measured achievable throughput vs. launch power (c) Noise-to-signal ratio (NSR) contributions per band.

5. Conclusions

In our previous work, we showed that the simple and fast ASE-NL heuristic, based on the balance of linear and nonlinear noises, converges to similar value than more complex and time-consuming power optimization techniques. Here, we experimentally demonstrate the improved performance achieved by setting the launch power profile and amplifier gain predicted by this algorithm. Moreover, we prove that effective modeling results in accurate predictions for S+C+L system performance, providing a useful insight to identify the impact of physical impairments and improve the design of UWB transmission systems.

6. Acknowledgements

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7. References

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