Fibre Optic Nonlinear Technologies [FONTE] - A European Industrial Doctorate [GA766115]

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Executive Summary

The exponential increase in the internet traffic is driving the need for higher transmission capacity in the fibre-optic communication systems. The capacity of the current fibre-optic communication systems is mainly limited by the nonlinear effects of fibre and transceiver hardware. Industries and researchers are looking for solutions which are cost-effective and flexible. In this regard, neural networks are drawing much of attention in several fields of fibre-optic communication systems recently. Neural networks are being used for example to model and simplify the digital signal processing (DSP) in transceivers.

In this report, neural networks-based techniques were studied to pre-compensate or post-equalize the undesired linear and nonlinear effects in the fibre-optic systems. In detail, a neural network-based digital pre-distortion (DPD) was designed and tested on a high-baud rate experimental system. The proposed DPD provides a significant improvement in the received signal to noise ratio. Moreover, a recurrent neural network equalizer was also demonstrated for short-reach communication. The technique mitigates the chromatic dispersion in a direct-detected system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

AiPT	Aston Institute Of Photonic Technologies
EC	European Commission
EID	European Industrial Doctorates
ESR	Early Stage Researcher
FONTE	Fibre Optic Nonlinear Technologies
DPD	Digital Pre-Distortion
NN	Neural Network
DAC	Digital to Analog Converter
ECL	External Cavity Laser
DA	Driver Amplifier
BPD	Balanced Photo-Diodes
PME	Polarization Multiplexing Emulator
DSP	Digital Signal Processing
LO	Local Oscillator
EDFA	Erbium-Doped Fiber Amplifier
QAM	Quadrature Amplitude Modulation
RC	Reservoir Computing
RNN	Recurrent Neural Network
RTO	Real Time Oscilloscope
SNR	Signal to Noise power Ratio
DWDM	Dense Wavelength Division Multiplexing
OOK	On-Off Keying
SMF	Single Mode Fiber
IM/DD	Intensity Modulated Direct Detection
FFE	Feed Forward Equalizer
MZM	Mach-Zehnder Modulator
BER	Bit Error Rate

1 INTRODUCTION

Fibre-optic communication systems are the infrastructure backbone of the digital information around the world. It can include short-distance communication in data-centres to under oceanic transmissions. The exponential growth of transmission capacities in optical communication networks was achieved thanks to faster single channel bit rates, denser optical multiplexing (dense wavelength division multiplexing – DWDM), and the use of the extended-spectrum around the C-band and the L-band. The same growth rate is expected in the future which shows the necessity to exploit the resources efficiently. The limiting factors for achieving high data rates in fibre-optic communication systems are nonlinearity, dispersion, and attenuation. Mitigation of these factors becomes more critical for higher transmission rates.

The nonlinearity in a fibre-optic communication system comes from the fibre itself as well as from the transmitter and receiver hardware. At higher data rates with symbol rates beyond 100 GBaud and modulation formats of a large size, e.g. 64-QAM, the compensation of hardware nonlinearity becomes crucial. Typically, in the state-of-the-art optical coherent transmitter, a linear digital pre-distortion (DPD) is used that compensates for the memory effects of the transmitter. In such a scenario, the uncompensated nonlinearity forces the device to operate in the linear regime or with lower-power reducing the amount of information transmitted in the system. As the transmitter usually contains a chain of devices contributing linear and nonlinear effects, a neural network (NN)-based DPD was studied in this report. NNs are shown to be good at modelling nonlinear systems that are difficult to model using classical approaches. Further, the performance of a NN-based DPD is evaluated by varying transmitter nonlinearity on high-baud rate experimental setup.

The short transmission regime is mainly driven by the transmission cost. In this low-cost regime, often coherent detection is prohibitively complex, and direct detection and low-complexity DSP are employed. This means that a single photodiode (PD) converts the amplitude of the optical field into a photocurrent that is sampled and processed. This makes the full-recovery of the information complex. Moreover, the interplay of chromatic dispersion from the fibre and the PD detection causes nonlinear effects which must be mitigated by some low-cost nonlinear signal processing. To address this problem, we experimentally demonstrated an optoelectronic technique with machine learning to transmit 32 GBd on-off keyings (OOK) signal over 80 Km of single-mode fibre (SMF). The technique was recently proposed and is called reservoir computing (RC). It is a recurrent neural network in which only the weights in the last layer are trained with linear regression.

2 TRANSMITTER DIGITAL PRE-DISTORTION

In this study, we investigate neural network-based DPD to pre-compensate the transmitter impairements. We also implemented and trained linear DPD for comparison.

We consider a high baud rate optical coherent transmission setup for our study. A schematic of the experimental setup is shown in Figure 1. A photo of the actual transmitter is also shown in Figure 2. A sequence of 2^{15} symbols of uniform 64-(quadrature amplitude modulation) QAM signal was fed into the transmitter (Tx) digital signal processing unit. We chose to operate the transmitter at maximum symbol rate, hence, pulse shaping was not used. In the Tx-DSP, DPD was applied on the sequence along with clipping and quantization operation. This processed sequence was, then, loaded to the digital to analog converters (DACs). The DACs have 24 GHz 3-dB bandwidth and a nominal resolution of 8 bits respectively. It operate at 128 G sample/second and produces analog electrical signals. Two driver amplifiers (DAs) which have 3-dB bandwidth of about 60 GHz amplify the DAC output signal. The amplified signals were used to drive the lithium-niobate ($LiNbO_3$) IQ modulator which have 41 GHz 3dB-bandwidth. An optical carrier was generated by an external cavity laser (ECL) at 193.5 GHz with <100 kHz linewidth on to which signal will be modulated. The optical carrier was fed into the IQ modulator where it was modulated by the signal coming from DAs. A polarization multiplexing emulator (PME) was used to generate a dual polarization optical signal. The power of optical signal was boosted up by an Erbium doped fiber amplifier (EDFA). The bandwidth of the IQ modulator is significantly smaller than Nyquist rate (64 GHz), hence, it has a strong low-response. A Finisar Waveshaper was used to compensate for this low-pass response by flattening the optical spectrum of the signal. The setup was configure in back-to-back scenario. At receiver, the signal was filtered by an optical band-pass filter with 128 GHz 3-dB bandwidth. The filtered signal was then amplified by an EDFA and mixed with the local oscillator (LO) in an optical 90° hybrid. Four balanced photo-diodes (BPDs) were used to convert the optical signal into electrical signals which were sampled at 256 GSa/s by a Keysight real-time oscilloscope (RTO) with a nomial resolution of 10 bits. The state-of-the-art DSP, detailed in [1], was applied offline to retrieve the sent data.

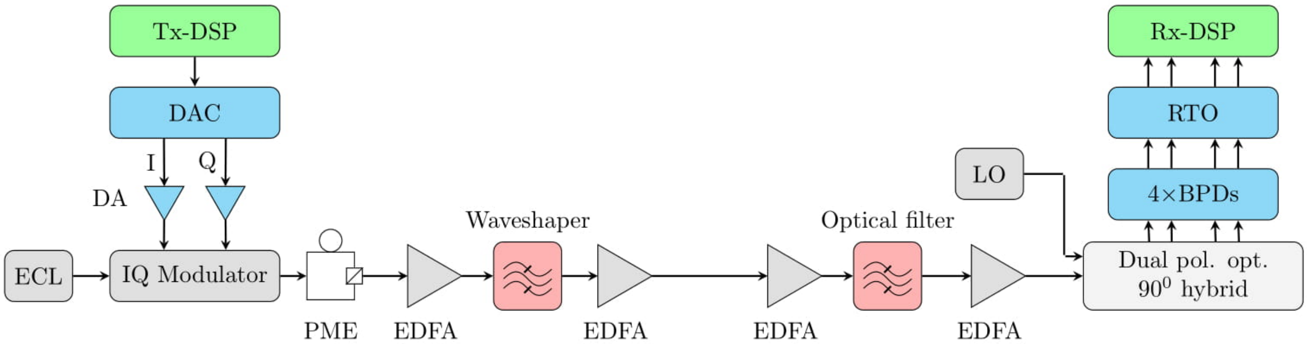

Figure 1- A schematic of the high-baud rate transmission experimental setup.

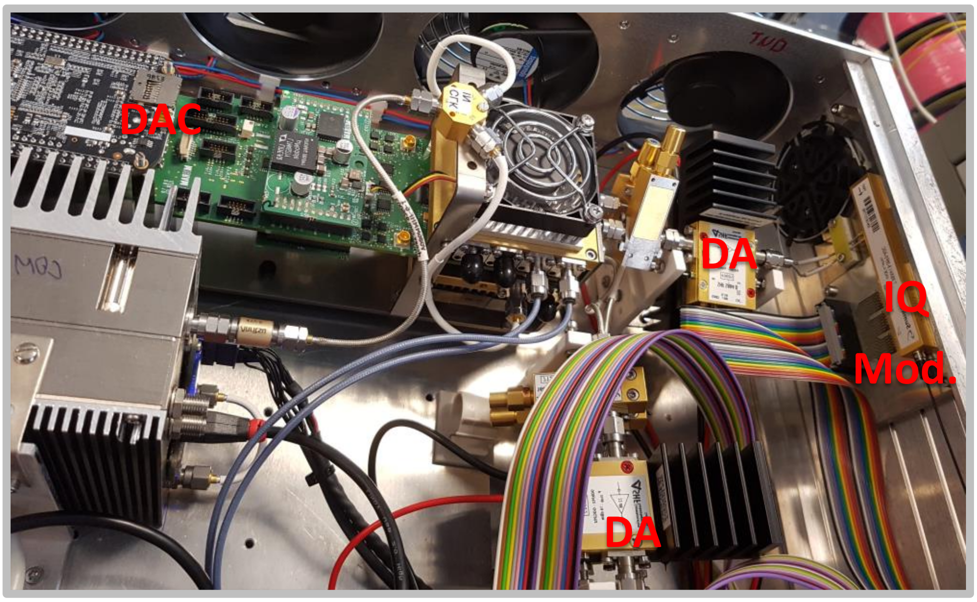

Figure 2- A photo of the transmitter showing key components: DAC, DA and IQ Modulator.

In experiments, we evaluate our NN-based DPD by measuring the signal to noise power ratio (SNR) of the received signal. We also check the performance of a linear DPD to benchmark the results. In the first step, we train a linear DPD by varying the length of the linear DPD filter and evaluate the performance. We observed that the performance stops improving when about 440 taps were used. We set the total number of taps of CNNs in the NN-based DPD to around 440.

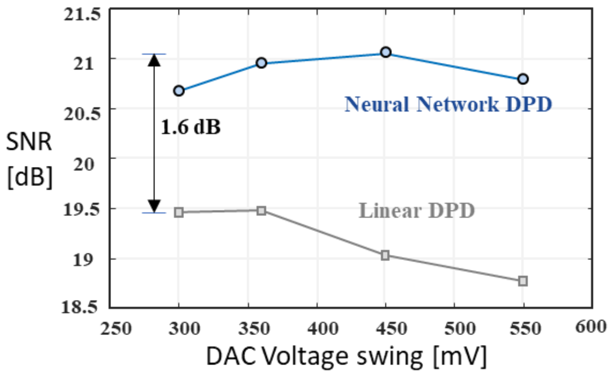

Figure 3- The SNR performance of NN-based DPD and linear DPD at different DAC voltages.

Both DPDs are evaluated by varying the DAC output voltage as shown in Figure 3. An increase in DAC voltage increases the transmitter nonlinearity. Thus, the SNR values for the case of linear DPD decreases as it does not compensate for the nonlinearity. In contrast, NN-based DPD which compensates for the transmitter nonlinearity initially provides an improvement in the SNR with increase in DAC voltage. This is because NN-based DPD allows increase in the DAC voltage without adding severe nonliearity, hence, increases the signal power over the transmitter noise. At very high DAC voltage, the SNR of NN-based DPD decreases because of very strong nonlinearity. It is also interesting that even at lower DAC voltage the transmitter has significant nonlinearity, and NN-based DPD provides more than a dB gain in SNR. Overall, we found that NN-based DPD gave us around 1.6 dB gain in the SNR. This SNR gain can be used as increase in transmission distance or additional margin in the system design.

3 OPTOELECTRONIC RECEIVER FOR SHORT-REACH COMMUNICATION

Intre data-centre communication will be a key technology in the upcoming 5G network scenario. To reduce latency, the data-centres are moving closer to the end-user and the number and connections among these data-centres will increase. For a scalable and low-complexity transceiver, we have proposed the use of IM/DD system with an optoelectronic receiver and machine learning algorithms [2,3].

Figure 4 shows the experimental setup for optoelectronic equalization. At the transmitter, a random binary sequence at 32 GBd with OOK is generated and shaped by a root-raised-cosine (RRC) filter (roll-off equal to 0.1) at 2 samples per symbol (sps). The resulted signal is resampled to the digital-to-analogue converter (DAC) sampling frequency (88 Gsa/s). A Mach-Zehnder modulator (MZM) is then used to modulate the signal with the bias set at the quadrature point. The resulting optical signal is propagated through a length of single-mode fibre (SMF - from 0 to 80 km) and amplified by an erbium-doped fibre amplifier (EDFA).

At the receiver, the signal is filtered by a wavelength selective switch (WSS). The filters are designed as 4 second-order Gaussian filter with a 3-dB bandwidth of 16 GHz with 8 GHz distance of each other. In other words, an overlap of 8 GHz for each filter. The filter's bandwidth choice was based on our numerical analyses in [3]. The signal is then detected by a 4 PDs with a 3-dB electrical bandwidth of ≈ 40 GHz and then digitally sampled by a real-time scope with 80 Gsa/s and 33 GHz of electrical bandwidth. The received signal is then processed offline, with an anti-aliasing filter, the reservoir computing (RC), and a hard decision (DEC). Finally, the bit errors are counted, from that BER is evaluated.

Reservoir computing is a recurrent neural network where only the weights of the output layer are trained. We have used 500 neurons in the reservoir and applied the linear regression algorithm for training the output weights with 5% of the total data used as training, which is 79232 samples. After training, the weights are kept constant. The RC's inputs come from the received sliced signal in which the time samples from different PDs are acquired in parallel. In other words, we have used a single input (plus bias) per signal received by a PD - this is to highlight the intrinsic characteristic of tracking time-variant impairments of the RC. A pseudo-code of the algorithm used is described in [3].

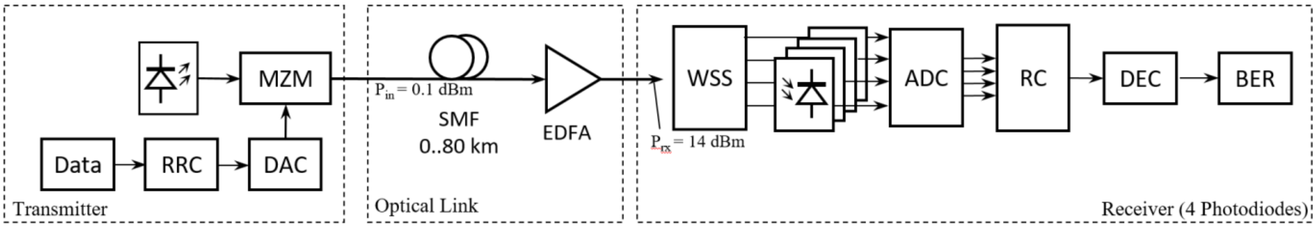

Figure 4- Experimental setup of the optoelectronic system. RRC: root-raised cosine; DAC: digital-to-analogue converter; MZM: Mach-Zehnder modulator; WSS: wavelength selective switch (WSS); ADC: analogue-to-digital converter; RC: reservoir computing; DEC: Decision.

Figure 5 shows the experimental results. The BER equal to zero (no errors) was replaced to a floor value of 10^{-5}. This region is called "error-free", and it is chosen to highlight all the fibre distances analyzed in the experiment and numerical setup. The result shows an optical transmission reach of 80 km of SMF.

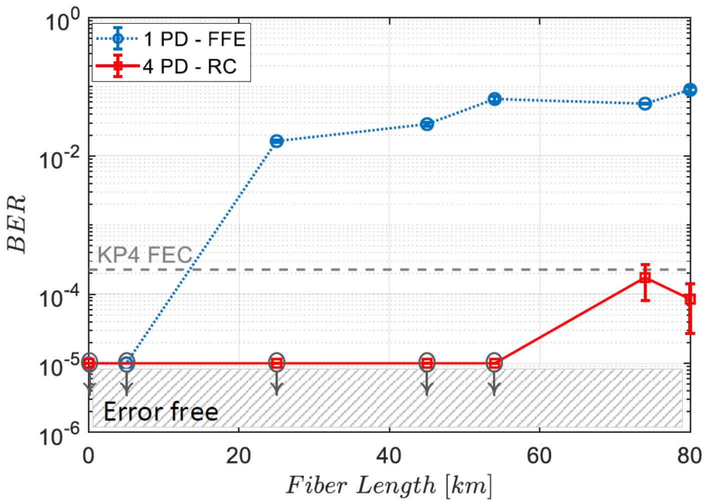

Figure 5– Experimental results.

As a reference, the blue curve (circles) show the performance of using only 1 PD in the reception with the classical feedforward equalizer (FFE) updated with a least-mean square algorithm. The reference system only reaches ~10 km, while the proposed optoelectronic system with reservoir computing reaches at least 80 km. These few kilometres reach from the reference is expected due to the power fading (spectral notches) in the electrical signal from the interaction between chromatic dispersion and square-law detection, which makes the equalization process challenging for IM/DD and high symbol rate system. The optoelectronic system, on the other hand, slices out the spectrum avoiding the power fading effect and the reservoir computing regroups the signal from the slices and mitigate the residual chromatic dispersion.

4 CONCLUSION

In this report, we study neural network-based techniques for high baud rate optical coherent system and short reach transmission system. In experiments, we observed that the NN-based is able to cope with the increase in the transmitter nonlinearity. We achieved significant gains in the received signal SNR by applying NN-based DPD on a high baud rate system. Further, a recurrent NN-based equalizer was evaluated on short reach transmission system in experiment. The equalizer was able to compensate chromatic dispersion in IM/DD system and increase the transmission reach from 10 km to around 80 km.

5 REFERENCES

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