D3.1: Transmission Regime Definition and Plan of Experiments

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Executive summary

This deliverable presents the transmission regime definition and experiment planning activities carried out during the first year of the project. As the first year has been mainly devoted to the selection of the four early-stage researchers (ESRs) and their basic training to become experts in the field of optical communications, the amount of experiments that has been carried out was still low. Mostly, the experiments have been defined and some initial experiments carried out.

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1 Introduction

1.1 Document objectives and structure

The goal of this deliverable is to report the transmission regime definition and plan of experiments of the COIN project during its first year. The transmission regime definitions and ultimately, the experiments to be carried out, should be aligned as optimally as possible with the objectives defined in deliverables D1.1, D2.1, and also D1.2 and D2.2.

The deliverable is structured as follows. Section 2 reports the transmission regime definition that we have identified which Section 3 reports the main experiments that will be carried out during the project. We have 3 experimental setups that will be used that are each described in detail together with the initial experiments planned. As the advanced experiments depend on the outcomes of the preliminary experiments, we only describe the initial plan of experimental work. Section 4 concludes the deliverable.

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2 Transmission Regime Definition

In this section, we provide a report of the transmission regime definition performed in the first year of the project. It is important to note that during the first project year, besides advertising and hiring the ESRs, the research activities were mainly focused on literature review for analysing the state of the art and initial training of the ESRs. In the initial training phase, we have identified two main transmission regimes which are impacted by optical fibre nonlinearity and other nonlinear effects, over which coding plays an essential role.

2.1 Background – Optical Communication Networks

Fibre-optic communication systems carry most of the digital information around the world. This infrastructure provides high data bandwidth. However, the exponential growth of the demand for higher data rates made it essential to exploit the resources efficiently. The limiting factors for achieving high data rates in fibre-optic communication systems are nonlinearity, dispersion, and attenuation. Nonlinearities can mainly arise due to two reasons, the first being the fibre transmission itself. In this case, nonlinear phase noise (NLPN) which is also known as self-phase modulation, is one of the dominant impairments in fibre-optic channels with inline amplifiers. This phase noise is induced by interaction of amplified spontaneous emission noise and the fibre Kerr effect. The nonlinear phase noise can impair the detection of phase-modulated signals such as phase-shift keying (PSK) symbols. As a result, the quest for efficient methods of compensating the effect of NLPN has spurred a great deal of research on various approaches. It has been observed that the received signal power can be used to mitigate the NLPN. Moreover, phase noise can be mitigated by exploiting the correlation between received power and phase. Besides constellation optimization for coherent optical channels with nonlinear phase noise, Maximum-likelihood (ML) detection and optimal decision regions for distributed amplified systems and M-PSK modulation were previously investigated, resulting in approximate phase post-compensation methods.

An additional source of nonlinearities is within the transmitter and receiver hardware itself. Particularly in low-cost optical communication systems, often coherent detection is prohibitively complex and direct detection is employed. This means that a single photodiode converts the amplitude of the optical field into a photocurrent that is sampled and processed. All phase information is lost by doing so and moreover, the interplay of chromatic dispersion on the fibre and the detection causes nonlinear effects that need to be compensated or actively exploited in order to maximize the achievable data rate in such systems.

2.2 Transmission Regimes

2.2.1 Long-haul Optical Communication Impaired by Fibre-Nonlinearities

In general, there are two well-known all optical schemes for signal amplification in long-haul and metro fibre-optic links. The first one is called distributed amplification, which is an optical compensation of the fibre attenuation in a distributed way along the length of the fibre. Distributed amplification is a good model for fibre-optic communication systems that employ Raman amplification. However, such systems are not yet widely deployed in practice. Hence, we consider in our transmission mainly the case where Erbium Doped Fibre Amplifiers (EDFAs) are deployed at

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the end of each span of 50-100km of optical fibre. This second scheme is called lumped amplification, using a finite number of spans and discrete amplifiers, and forms the basis of our long-haul and metro transmission regime.

To study the effects of nonlinearities, we first neglect chromatic dispersion, as it introduces memory which makes the process hard to analyse. Hence, a first regime for consideration is a dispersion-free optical channel model with lumped amplification. This channel has a well-defined per-sample channel model beside the waveform channel model. Such a channel models transmission in the zero-dispersion point of the optical fibre. As this model has some limitations, we will go on to extend it to the more general model including dispersion.

2.2.2 Low-Cost Optical Communications Impaired by Transceiver-Nonlinearities

The second model we consider is a short-reach system with low-cost targeting data-centre intraconnects or data-centre interconnects with distances ranging from a few kilometres to up to 120 km. This system is based on a conventional direct-detection (DD) transmission system. At the transmitter, a Mach-Zehnder Modulator (MZM) biased at the null-point generates the real-valued transmit signal, which is transmitted over a non-zero dispersion fibre (usually a single span), and at the receiver, possibly amplified and then, after photo-detection using a single photodiode, sampled. The interplay between chromatic dispersion and the photodiode introduces nonlinearities, which must be combated either by compensation techniques or using coding techniques investigated in the project.

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3 Plan of Experiments

3.1 General Experimental Setup for Long-Haul Fibre-Optic Communications

3.1.1 Experimental Setup

The transmission testbed that we use is shown in Figure 1. After digital to analogue conversion (DAC) using a high-speed DAC operated at 88 GSa/s, the data is electro-optically converted. This is done using a state-of-the art optical I/Q modulator including driver amplification. We use a recirculating fibre loop for optical transmission, which is equipped with three 80 km length SMF spans and EDFAs for distributed amplification. The loop is composed of a G.654B compliant pure-silica core fiber Corning® Vascade® EX2000 (112 µm² effective area, attenuation of 0.161 dB/km at 1550 nm, span loss≈8.5 dB, chromatic dispersion of 20.5 ps/nm·km at 1550 nm, and polarization mode dispersion (PMD) below 0.04 ps/√km). However, in case where other transmission regimes should be tested, we can easily replace the fibres inside the loop as they are plugged using standard optical fibre connectors.

We transmit the data either as a single channel or in a DWDM configuration using a DWDM setup with a flex grid incorporating 16 load channels. In the receiver, an optical band-pass filter (OBPF) extracts the channel under test and we apply state of the art dual polarization coherent reception using an ECL laser acting as local oscillator (LO) that drives *n* optical coherent frontend (FE) consisting of a 90° optical hybrid with 4 pairs of balanced photodiodes (BPD). Subsequently, we apply analogue-to-digital conversion (ADC) using a digital sampling oscilloscope operating at 80Gsa/s and having a bandwidth of more than 30 GHz. In the receiver DSP we usually apply a fully data aided digital signal processor, where the constellation is recovered. In comparison to a system with blind adaptation we are gaining up to 0.3 dB in required OSNR due to perfect adaptation of all filters. This fully aided DSP will provide an upper bound on the performance of the transmission systems so that differing DSP adaptation routines will not influence the performance of the system.

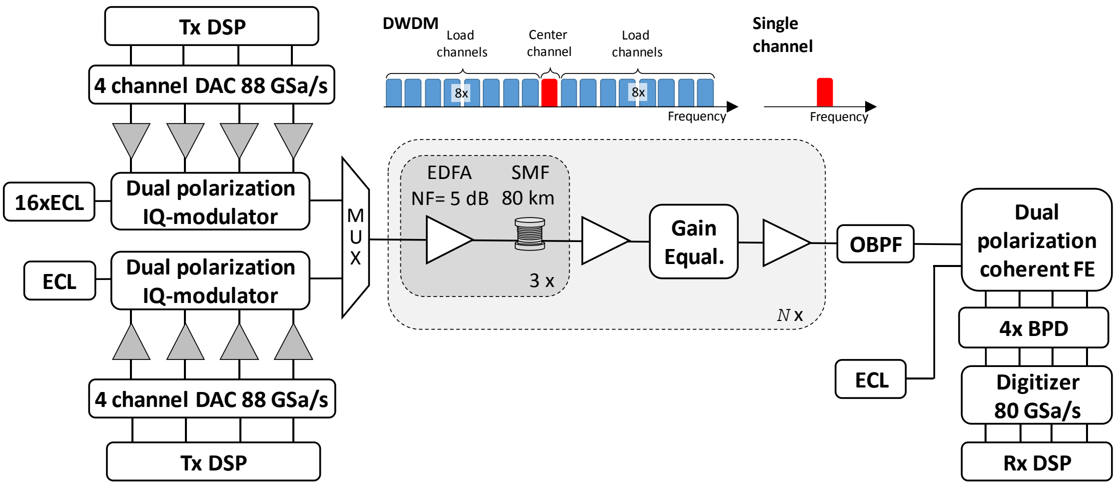

Figure 1: Experimental setup of the loop-based testbed

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3.1.2 Planned Experiments

This transmission testbed, due to the use of versatile DACs, ADCs, and four-dimensional optical modulators, is flexible enough to evaluate the performance of many different modulation formats and nonlinear coding schemes. As the testbed is a permanent set up in the Nokia laboratory facilities, experiments can be carried out on an ad hoc basis (with minimal planning required to avoid overlapping experiments). Further to this versatile, constantly available facility, we do not need to plan ahead the experiments to be carried out but can provide to the ESRs a platform that they can use whenever the need arises. This platform can also be used to assess the performance of Nonlinear Fourier-Transform (NFT) based formats (as initially described in D1.1/D2.1), which is detailed in the next session. Only a few changes are necessary, which can be realized using switches within a few hours. Mostly ESR3 will carry out experiments using this testbed and it is planned that ESR2 will, in a later stage of his research, significantly make use of this platform. The ESRs do not need to be physically present at the Nokia premises, but the Bell Labs supervisor can carry out the experiments on site and exchange the results and raw data with the ESRs using the private web space.

It should be noted that similar experimental resources are available at both UCL and CUT, and so it is expected that preliminary investigations and smaller-scale experimental work can be carried out at the host institutions by each ESR as required. It is expected that each ESR will maintain a regular programme of experimental work throughout this project.

3.2 Experiments for Nonlinear-Fourier Transform-Based Modulation Formats

3.2.1 Description of Experimental Setup and Transmitter DSP

The schematic of the experimental setup for NFDM transmission systems with offline digital signal processing (DSP) is depicted in Figure 2(a). The offline DSPs at the transmitter (Tx) and receiver (Rx) are shown in Figure 2(b-c).

Firstly, at the transmitter, the transmitted signal was designed in the NFT domain by encoding the data onto either the discrete part (discrete eigenvalues, multi-soliton transmission) and/or the continuous part of the signal's nonlinear spectrum. The time domain signal is then generated using the inverse nonlinear Fourier transform (NFT) rather than the conventional transmission systems. For the NFDM transmission systems with the modulated continuous part, the conventional analogue signal can be obtained by using the inverse discrete Fourier (DFT) to generate the time domain signal instead of the INFT. In such case, the block diagram shown in Figure 2(b) can be used to generate both NFDM signal and its analogue conventional signal for a fair comparison of NFDM transmission and its linear counterpart.

For example, when the continuous part is modulated as an OFDM signal the modulated nonlinear spectrum can be written as:

$$q_c(\xi, m) = A \cdot \sum_{k=-N/2}^{N/2} c_{m,k} \frac{\sin(\xi T_0 + k\pi)}{\xi T_0 + k\pi} e^{-2im\xi T_1},$$

where A is the power control parameter, L is the transmission distance, ξ is the nonlinear frequency. The summation describes the synthesized NFDM nonlinear spectrum in which m is the

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burst index, $c_{m,k}$ is the symbol sequence drawn from a QAM constellation, T_0 is the initial burst duration before pre-compensation T_1 is the total burst duration.

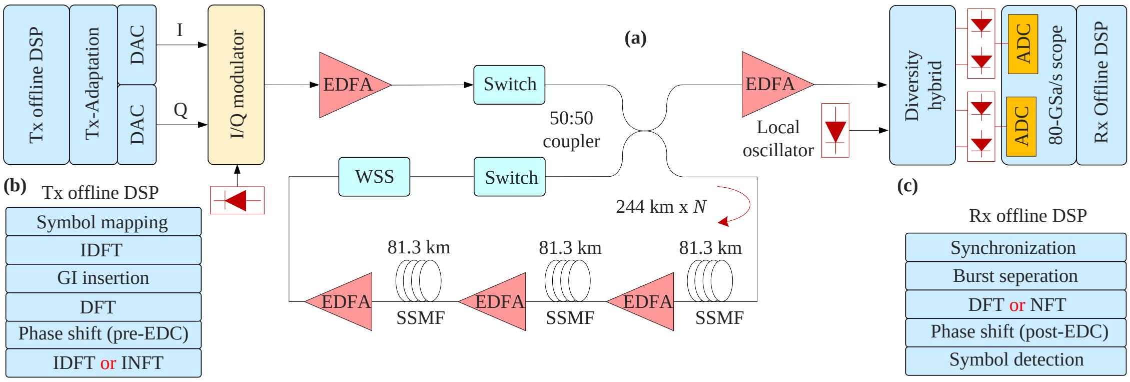

Figure 2: (a) General experimental setup NFDM transmissions over SSMF with EDFA-only amplification; (b - c): Transmitter (Tx) and receiver (Rx) DSPs; DFT (IDFT) – discrete (inverse) discrete Fourier transforms; NFT (INFT) – nonlinear (inverse) nonlinear Fourier transforms; EDC – electrical dispersion compensation; GI – guard interval.

Due to the required vanishing boundary condition, NFDM systems are designed in the burst mode, with a guard interval between neighbouring bursts (or symbols). Depending on the modulation format and coding scheme the required guard interval can be different, given the same signal bandwidth and transmission distance. Excepting the case of multi-soliton transmission with the first order the required guard interval can be estimated through the signal bandwidth and transmission distance as:

$$T_1 - T_0 = T_g \geq \pi B \beta_2 L,$$

where T_g is the required interval, B is the signal bandwidth, β_2 is the chromatic dispersion coefficient and L is the transmission distance.

Next, the time domain signal $E(t)$ will be resampled to 88 GS/s before being normalized according to the lossless path average model for optical links with lumped amplifiers as follows:

$$\overline{E}(t,z) = E(t,z)\sqrt{G(z)},$$

where $\mathrm{G(z)}$ is the total loss defined as

$$G(z) = \exp\left(2\int_0^z g(l)dl\right).$$

To pre-compensate for both linear and nonlinear responses of the transmitter, including drivers, DAC (at 88 GS/s with ~16 GHz electrical bandwidth and ~5.5 bits of effective resolution) and optical modulator, an iterative adaptation routine as shown in Figure 3(a) was applied in the B2B configuration. The Tx adaptation includes a FIR filter for pre-compensating the linear response of the DAC and a data-aided nonlinear adaptive filter for compensating the linear and nonlinear responses of IQ modulator and possible bias offsets by gradually modifies the input vector into the DAC in an iterative loop until the measured waveform at modulator output con-

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verged to the calculated ideal waveform $E(t)$. The effectiveness of Tx adaptation routine is visually illustrated in Figure 3(b) by comparing the ideal signal (black, solid) with the received signal (red, dash) in the B2B setup.

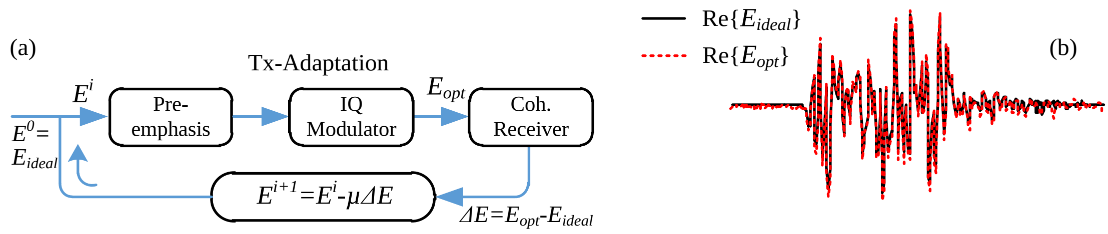

Figure 3: (a): Block diagram of the transmitter (Tx) adaptation routine; b) a comparison of the ideal and the generated signal

3.2.2 Recirculating loop

The transmission experiment uses an AOM-based re-circulating loop consisting of a 3×81.3 km spans of standard single mode fibre (~17 dB insertion loss per span) and a wavelength selective switch (WSS) for removing out-of-band amplified spontaneous emission (ASE) noise. The signals were amplified by EDFAs with a noise figure of 5 dB. At the receiver, the signal was filtered and amplified before being coherently detected using real-time 80 GS/s sampling oscilloscope. Both the transmitter laser and local oscillator were from a single fibre laser source with a low linewidth of ~1 kHz to minimize the impact of laser phase noise.

3.2.3 Receiver DSP

The receiver DSP (shown in Figure 2(c)) firstly uses a training symbol to perform both timing synchronization and frequency offset compensation. The signal was then separated into a number of discrete bursts before being normalised according to the lossless path averaged model. Next, for each data block, forward NFT is performed to recover the continuous nonlinear spectrum. After that, single-tap phase-shift removal operation is performed to remove the interplay of dispersion and nonlinearity. Finally, additional equalization for synchronization error compensation, phase noise estimation and data detection are carried out. The B2B performance is constantly monitored using the bit-error-rate (BER) estimated from the error vector magnitude and the transmission performance is analysed by direct error counting, where more than 100 errors are usually obtained for each BER estimation to provide an acceptable statistical confidence.

3.2.4 Planned Experiments Using the Recirculating Loop

3.2.4.1 Coded Soliton Transmission

Fundamental solitons (purely imaginary discrete eigenvalues or first order soliton) are very resilient to the noise and fibre impairments during propagation due to the balance of dispersion and nonlinearity. As a result, high order modulation formats can be applied for fundamental solitons. In addition, to maximize the achievable data rate, shaped PAM can be considered to

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form a coded fundamental soliton transmission. We would like to design and implement such a system by considering fundamental solitons with imaginary part in the interval [0.7, 1]. The occurrence probability of each level will be optimized to maximizing the data rate. In addition, through this experiment we also would like to investigate the impact of noise and imperfect channel conditions (e.g., EDFA) to the performance of fundamental soliton transmission, including a definition of the noise distribution, thus enabling a derivation of the optimum distribution of the eigenvalues in the imaginary axis.

This testbed is used by ESR4 to gather channel statistics of multi-eigenvalue systems. By transmitting a train of soliton pulses (with different eigenvalues), a channel model can be estimated and compared with the analytical model. Furthermore, it is planned that the shaped soliton-pulses are transmitted over this testbed to show the significant performance advantages that ESR4 has shown already in the initial phase of his research.

3.2.4.2 Dual-Polarization NFDM Transmission

One crucial challenge for achieving a high data rate of NFDM transmission is how to exploit both polarization modes of light for data transmission. So far, most of the reported NFDM transmission experiments use only a single polarization of light for data transmission. Based on the theoretical analysis from ESR1, we plan to experimentally investigate the achievable performance of dual-polarization NFDM transmission. The plan includes several crucial tasks such as:

- Developing efficient numerical NFT transformations (both forward and backward) for dual polarization signals
- Developing efficient methods for channel estimation for dual-polarization NFDM transmission
- Developing a transmitter adaptation routine for dual-polarization NFDM transmission
- Developing a phase noise estimation technique for dual-polarization NFDM transmission
- Developing design rules and modulation formats tailored to dual-polarization NFDM transmission

Once the above tasks are complete, our goal is to achieve the first 200 Gb/s NFDM transmission over 1000 km. This will require a careful choice of constellation size and shape, symbol duration, the number of modulated subcarriers, and the signal bandwidth. In addition, minimizing the algorithm's numerical error and practical implementation penalty will be very important, especially when such impairments can be enhanced through the interaction of polarization mode dispersion and deterministic impairments through NFT processing. This research is mostly carried out by ESR1, who will make use of this testbed (and, subsequently, the parallel testbed at UCL) to verify his approaches.

3.3 Experiments for Nonlinear Short-Reach Channels

3.3.1 Description of the Experimental Setup

We employ a conventional direct-detection (DD) based transmission system, as shown in Figure 4. At the transmitter, a Mach-Zehnder Modulator (MZM) biased at the null-point will modulate an external cavity laser operating in the C-Band with an RF signal coming from a Digital to Analog

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Converter (DAC). The transmit vectors will be real-valued and zero-mean, and thus the MZM serving as an electro-optical transducer will be biased at null to make assure the generated optical field maintains these properties. After propagation in a single-mode fibre (SMF) of various lengths exhibiting chromatic dispersion, the optical signal is detected with a PIN-TIA photo-receiver. A real-time Analog-to-Digital-Converter (ADC) samples the photo-current. This experimental setup realizes perhaps the simplest nonlinear system with only a single nonlinear element: the receiver photo detector. It forms the basis for a class of transmission and coding systems for the nonlinear regime that we intend to study in this project.

3.3.2 Planned Experiments

The first such system will be the application of a neural-network (NN) based transmission system specifically designed for the nonlinear channel, which is currently investigated by ESR2. This experiment will help us evaluate and assess the potential of neural-network based receivers for more general and more complicated nonlinear transmission systems.

3.3.2.1 Neural-Network-Based Transmission over Nonlinear Short-Reach Channels

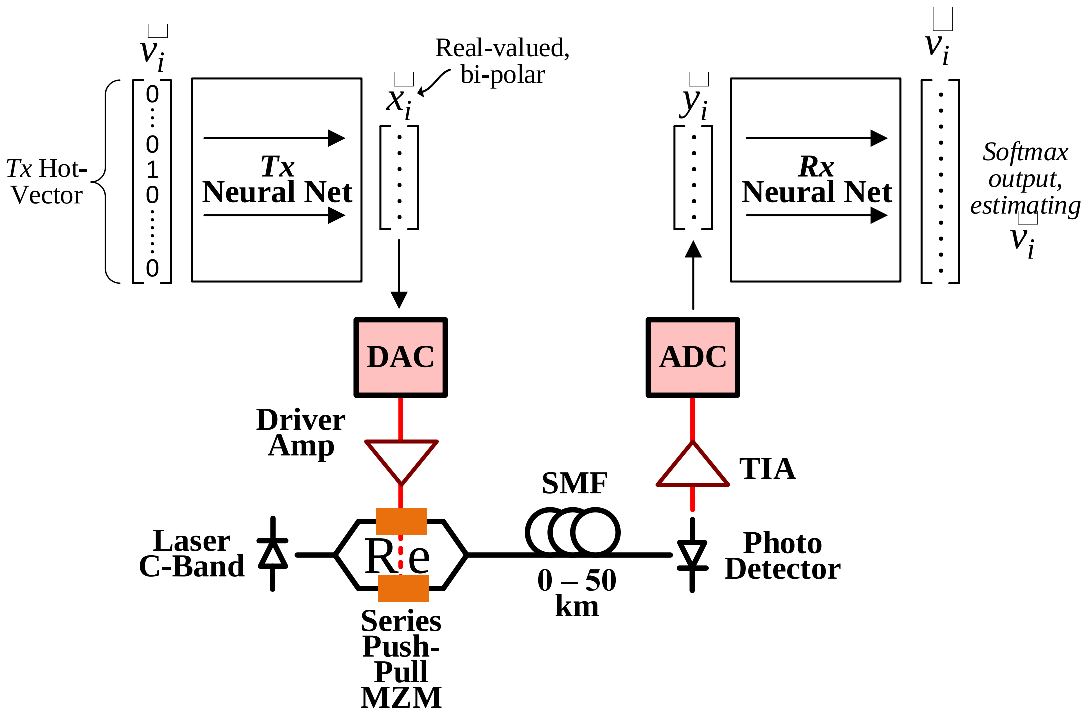

Figure 4: Schematic of the experimental test-bed, and how it interfaces with the dual transmit-receiver (Tx-Rx) Neural Networks.

In this experiment, which is exemplified in Figure 4, we will validate the results obtained in simulations using a machine learning programming framework. The MZM biased at the null-point will modulate an external cavity laser operating in the C-Band with an electrical signal. This signal will be a random temporal concatenation of possible transmit vectors $\vec{x}_i$ generated by our Transmitter (*Tx*) Neural Network (NN), which we will have previously trained off-line. Said vectors $\vec{x}_i$ will be real-valued and zero-mean, and thus the MZM serving as an electro-optical trans-

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ducer will be biased at null to make assure the generated optical field maintains these properties. After propagation in a single-mode fibre (SMF), detection and sampling, the receiver stacks said samples in vectors that are fed to our Receiver (*Rx*) NN, itself also previously trained offline in simulation. We will apply Transfer Learning to the simulation-based *Rx*-NN to better estimated the real transmission channel and to take into account the specific responses of the components employed in the test-bed, which will improve transmission performance. We will use as a performance assessment metric the average number of incorrect estimates of the transmitted 'hot-vector' $\vec{v}_i$ for a large realization set.

3.3.2.2 Other and Further Experiments

As with the long-haul testbed, the short-reach testbed is constantly available in the lab, such that experiments can be carried out on an ad hoc basis and at short notice. It will be mainly ESR2 making use of this platform but it is intended to also use this platform for work carried out by other ESRs, in particular ESR3 and ESR4, whose first results can immediately apply to short-reach communications as well. The ESRs do not need to be physically present at the Nokia premises, but the Bell Labs supervisor can carry out the experiments on site and exchange the results and raw data with the ESRs using the private web space. As previously noted, it is anticipated that both ancillary and follow-on experimental work can be conducted by ESRs at their host institutions, expanding on the work completed on the Nokia testbed.

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4 Conclusions

This deliverable has documented the definition of transmission regimes, of which we have identified the two main regimes (long-haul and short-reach), each with their own problems and challenges, requiring different nonlinear coding solutions. Furthermore, the experimental testbed at Nokia premises has been described over which the experiments can be carried out. The testbeds at UCL and CUT have also been identified as appropriate for follow-on investigatory work for each ESR. A first set of experiments has been discussed and presented that will be carried out by the ESRs in their initial phase of research.

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