Advanced Nonlinear Digital Signal Processing for Short-Reach Applications

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Abstract: In this paper, we discuss different nonlinear impairments in short-reach fibre transmission systems. Recent progress on the nonlinear digital signal processing techniques to mitigate such nonlinear impairments are summarized.

1. Introduction

In recent years, short-reach fibre transmission systems become the fastest growing section of the fibre communication market [1]. According to different application scenarios, the transmission distance of short-reach systems covers from hundred of meters to ~100 km. Therefore, the transmission schemes in short-reach systems can be varied under different application scenarios when the factors such as cost, power consumption and footprint should also be considered.

In short-reach transmission systems, the linear impairments such as chromatic dispersion, polarization mode dispersion and bandwidth limitation have been discussed [1]. In this paper, we mainly focus on the nonlinear impairments in short-reach transmission systems. Recent progress on the nonlinear digital signal processing (DSP) techniques to mitigate such nonlinear impairments are summarized.

2. Nonlinear DSP Techniques in Short-Reach Systems

Theoretically, most nonlinear DSP techniques in long-haul transmission systems can be applied directly in short-reach systems [2]. However, due to different transmitter/receiver schemes and fibre link conditions, the implementations of these DSP techniques can be different. It is noted that the channel model can be described by different nonlinear functions. Below we classify the main nonlinear DSP techniques according to how the nonlinear functions are used to describe the nonlinear impairments.

2.1. Mathematical Model-based Nonlinear DSP

Some nonlinear impairments can be described by explicit nonlinear mathematical functions. We first consider the most popular short-reach transmission scheme, which is based on intensity modulation and direct detection (IMDD) technique. It is known that the electrical-to-optical conversion process is characterized by a sinusoidal transmission function in the Mach-Zehnder modulator (MZM). The linearization process can be simply achieved by the *arcsin* operation when the extinction ratio (ER) of MZM is assumed to be infinity. A more practical *arcsin* iterative algorithm is then proposed by considering the MZM with finite ER [3].

Another popular short-reach transmission scheme is based on single-sideband (SSB) modulation technique when the system is operated on C band with direct detection. This scheme can effectively mitigate the chromatic dispersion induced power fading. However, such scheme suffers from strong signal-to-signal beating noise (SSBN), which can be regarded as a second-order nonlinear noise. Based on the definition and formula of SSBN, an iterative SSBN cancellation scheme has been experimentally demonstrated to efficiently reduce the effect of SSBN [4]. Recently, Kramers-Kronig (KK) receiver for SSB-modulated signal has drawn considerable attention due to its capability to recover the complex-valued electric field of light from the intensity waveforms [5]. Considering the computational complexity of KK receiver, practical issues regarding the nonlinear DSP including square-root, logarithm, and exponential operations becomes a hot research topic nowadays [6].

Finally, we consider the fibre nonlinear effects in short-reach systems. It is generally assumed that fibre nonlinear effects in short-reach links can be ignored due to small launch power and short transmission range. However, in some application scenarios, low-cost semiconductor optical amplifier (SOA) rather than Erbium doped optical fibre amplifier (EDFA) is preferred [7]. In these conditions, the fibre nonlinear noise cannot be ignored since the optimal launch power is increased due to higher noise figure of SOA. Moreover, in the access networks, the largest power budget is always obtained at high launch power [8]. To mitigate fibre nonlinear noise, digital back-propagation (DBP) algorithm based on the complex model of fibre transfer function has been applied both at the transmitter side for pre-compensation [9, 10] and at the receiver side for post-compensation [11].

2.2. *Maximum Likelihood Sequence Estimation*

Maximum likelihood sequence estimation (MLSE) is a classical technique to deal with severe bandwidth limitation issues in fibre transmission systems [12]. The performance of MLSE is generally depended on how accuracy the channel response can be described. In conventional MLSE to combat with linear channel impairments, a linear digital filter is always used to model the channel response [13]. However, in order to mitigate the nonlinear channel impairments, the channel response should be described by nonlinear digital filter [13] or mean values of the probability density functions (PDFs) [14]. The information about the digital filter coefficients or PDFs is then stored in the form of look-up tables, in order to be used in the Viterbi algorithm (VA). A practical problem about the conventional MLSE is that the implementation complexity will be prohibitive when the modulation order is large and the channel memory is long. Therefore, low-complexity implementation of MLSE which is suitable for low-cost short reach systems has attracted more attentions nowadays [15].

2.3. *Volterra Series Transfer Functions*

In most scenarios, the nonlinear impairments cannot be described by explicit nonlinear functions. One universal method to describe both linear and nonlinear effects in short-reach fibre transmission link is based on the time-domain Volterra series transfer functions (VSTF) [16]. However, the number of VSTF kernels increases exponentially with the increase of memory length. In order to reduce the computational complexity, sparse VNLE has been proposed to reduce the less important kernels with negligible performance degradation [17]. The computational complexity can also be reduced by applying the VNLE in a decision feedback equalizer (DFE) scheme [18]. The VSTF can also be applied at the transmitter side to achieve nonlinear digital pre-distortion, and the coefficients can be stored at the transmitter side. Therefore, only low-complexity linear feed-forward equalizer (FFE) is required at the receiver side [19].

2.4. *Machine Learning Techniques*

Over the past ten years, machine learning (ML) techniques have been seen as a powerful tool to make predictions or decisions based on experience, which is also known as ”training data” [20]. In the short-reach transmission systems for signal recovery, we focus on two ML algorithms. The first one is support vector machine (SVM) algorithm, which has been applied to mitigate the modulation nonlinearity distortions in vertical cavity surface emitter laser multi-mode fiber (VCSEL-MMF) link [21].

Another one is neural network (NN) based techniques, which have shown their abilities to approximate complex nonlinear functions and deal with the problems that cannot be easily described analytically [22]. Therefore, NNs can describe and then mitigate the nonlinear impairments in the fibre transmission links. However, the overfitting issue in the training stage of NNs has to be seriously considered when the NNs are used for nonlinear channel equalization. A general rule to avoid overfitting is that independent random statistics should be ensured for the training and evaluation sets [23]. Different types of NNs have been used to compensate the nonlinear impairments in the short-reach fibre links based on IMDD scheme, from the basic artificial neural network (ANN) with only one hidden layer [24] to radial basis function ANN [25], convolutional neural networks (CNNs) [26, 27], long short-term memory (LSTM) networks [28] and multi-layer deep neural networks (DNNs) [29]. An end-to-end DNN-based transceivers for IMDD system is also proposed, which is robust to distance variations with a significant level of flexibility [30].

One problem about NNs is that there is no guidance about how to choose the number of nodes in each layer. A common method is to sweep the number of nodes in each layer and then observe the performance, which is impractical if the channel condition is changed [28]. Several studies have shown that Gaussian Processes (GPs) can approximate both single-layer [31] and multi-layer NNs with infinite width in each layer [32].

3. Conclusion

Nonlinear DSP techniques can continuously improve the transmission performance in short-reach systems. Recent advances in short-reach systems have been reviewed. It is expected that research in nonlinear DSP techniques will continue to be the major drivers for short-reach systems in the next few years.

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