Comparative Performance of Single and Combined Neural Networks for Nonlinear Equalization in Optical Fiber Communication

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Abstract

Optical fiber is a widely used network cable for transmitting data over long distances. However, non-linear distortion caused by the mixing of light waves can significantly impact the performance of optical fiber communication systems. Traditional equalizers have limitations in handling complex data signals and delivering optimal performance. To investigate these limitations, this study aims to implement various deep learning algorithms for non-linear optical systems to optimize and enhance optical communication systems. The objectives of the study are to model a dual-polarized coherent detection long-haul optical system using MATLAB, numerically implement single and combined neural network architectures for non-linear equalization, and compare these architectures' performance in reducing the bit error rate while analyzing the tradeoffs in computational complexity. The study reveals that combining different architectures can lead to improved Bit Error Rate (BER) performance compared to using a single architecture alone. CNN+BiLSTM achieves the best BER value of 0.16. This demonstrates that combined neural network architectures have promising results in overcoming the limitations faced by traditional equalizers.

Optical System Architecture

An optical communication system consists of a transmitter, channel, and receiver. A random bit generator generates an input bit-stream at the transmitter, denoted as m. The sequence of symbols is then transformed into a waveform. After receiving and sampling the waveform at the receiver, the corresponding vector x is sent to a Digital Signal Processing (DSP) unit. The objective of the DSP unit is to recover the original sequence of symbols.

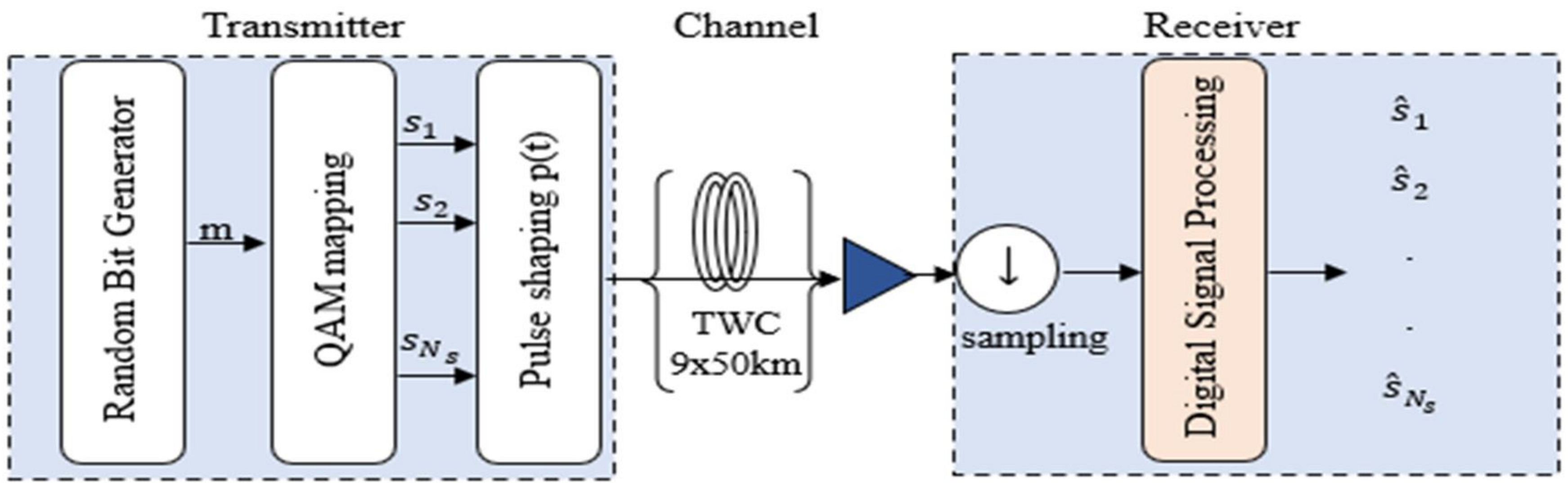

Figure 1: Sematic Diagram of Optical Communication System

Data Modeling using MATLAB

The data signal is modeled in MATLAB using a numerical framework that simulates dual-polarized transmission on a single optical channel. The propagation of dual-polarized signals through the optical fiber channel is governed by a pair of Nonlinear Schrödinger Equations:

$$\frac{\partial E_{(x,y)}}{\partial z} = \frac{\alpha}{2}E_{(x,y)} + \frac{j\beta_2}{2}\frac{\partial^2 E_{(x,y)}}{\partial t^2} + \frac{\beta_3 \partial^3 E_{(x,y)}}{\partial t^3} + j\gamma\left(\left|E_{(x,y)}\right|^2 + \left|E_{(y,x)}\right|^2\right)E_{(x,y)}$$

The specific parameters for the TWC fiber used in this simulation are captured in Table below.

Table 1: Optical Fiber and Noise Parameters

	Value	Parameter
MF	16 QAM	Modulation Format
α	$0.23\ dB/km$	Fiber Loss
β	$2.8\ ps/(nm \cdot km)$	Chromatic Dispersion
γ	$2.5\ (W \cdot km)^{-1}$	Nonlinearity parameter
L_{sp}	$9\ x\ 50km$	Span Length
NF	$4.5dB$	Amplifier Noise Figure
TR	$34.4GBd$	Transmission Rate

Methodology

At the receiver, a Digital Signal Processing recovers the original sequence of symbols. This study focuses on implementing an efficient neural network-based DSP unit to achieve a favorable tradeoff between complexity and performance.

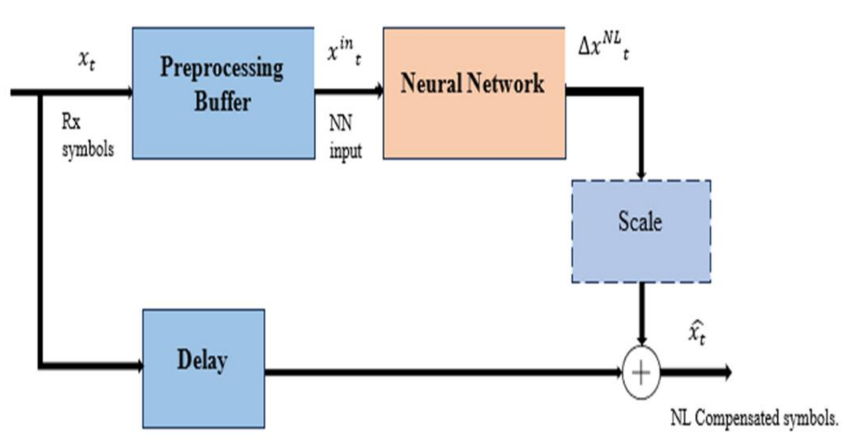

Figure 2: Block diagram for NN nonlinear compensation.

Result

- **Single Neural Network- Convolutional Neural Network (CNN)**

The performance of CNN as shown in the figure below is heavily influenced by the size of the dataset used for training. When assessing the relationship between CNN's BER and the baseline BER without Neural Network (NN), where the baseline BER was 0.2, CNN did not consistently outperform traditional methods. The constellation diagram analysis below reveals shortcomings in capturing the

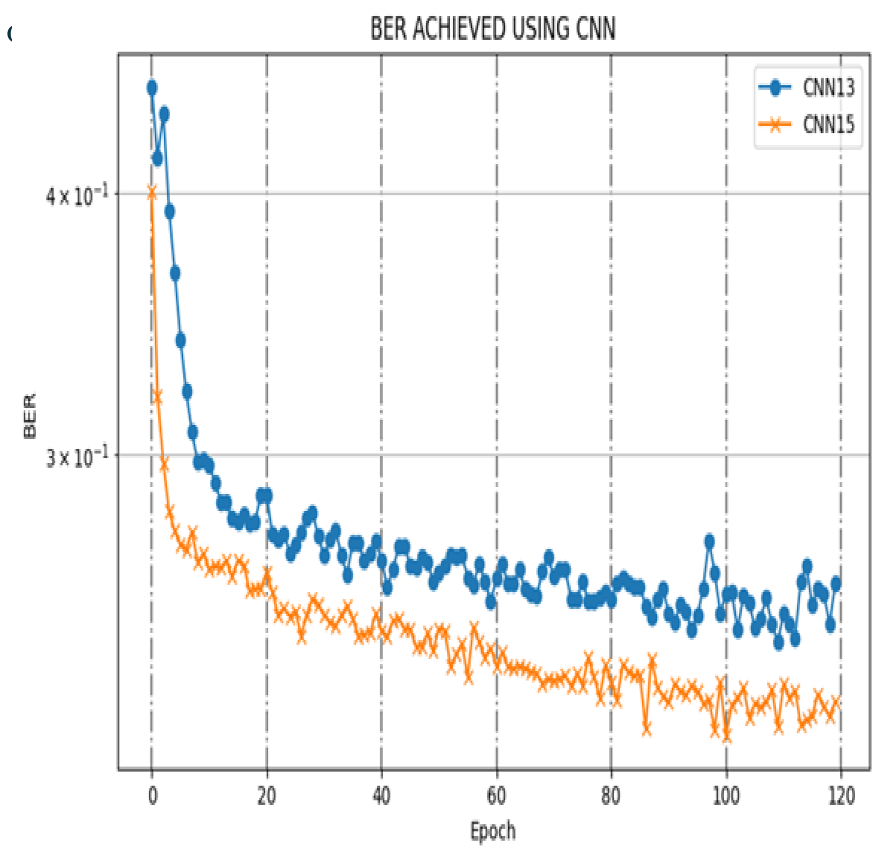

Figure 3: Bit Error Rate (BER) achieved using CNN model.

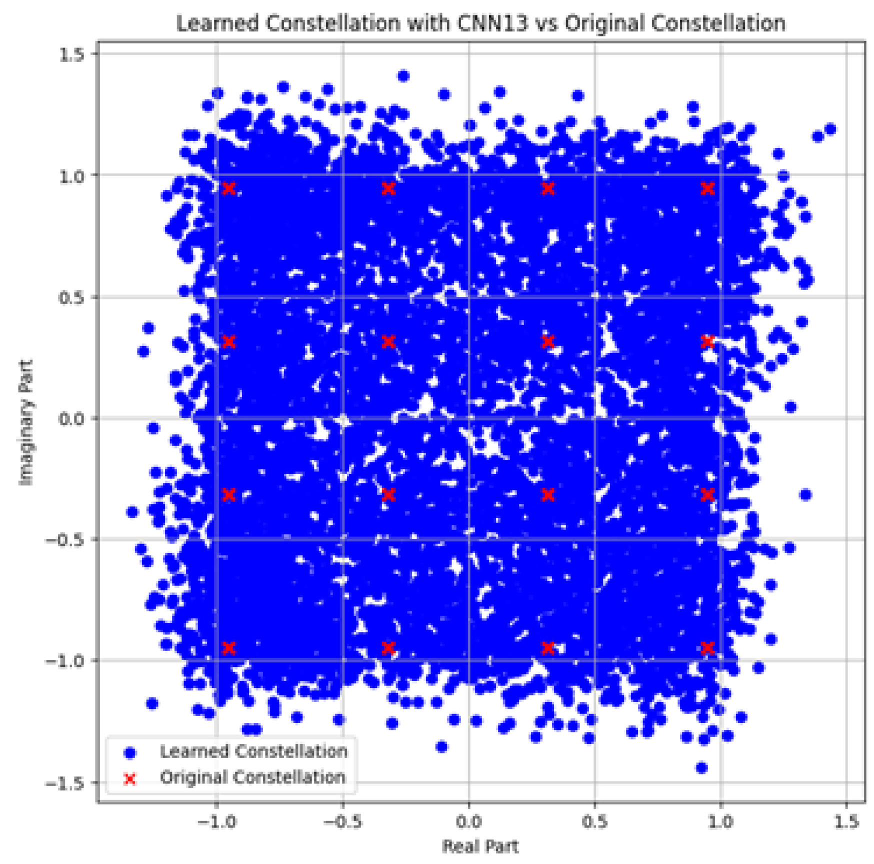

Figure 4: Constellation Diagram using CNN model

- **Combined Neural Network- CNN + BiLSTM (Bidirectional LSTM)**

It is observed that combined BiLSTM outperforms with BER of 0.16 compared with the baseline BER without Neural Network (NN) of 0.2. The model is an efficient solution for receiver detection than traditional signal processing methods because the resource utilization is low, and it can handle complex

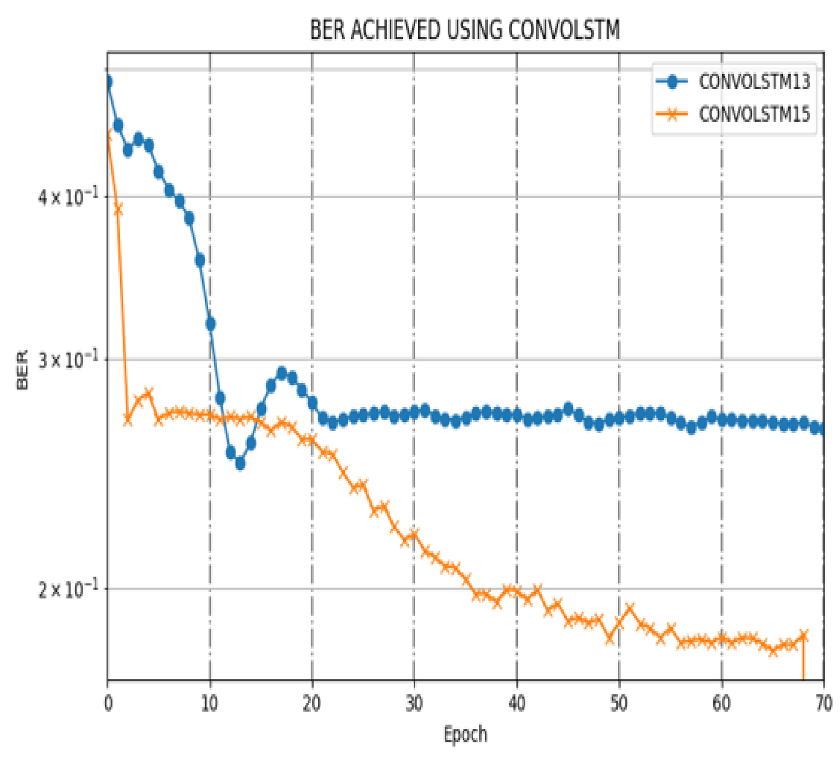

Figure 5: Bit Error Rate (BER) achieved using CNN+BiLSTM model.

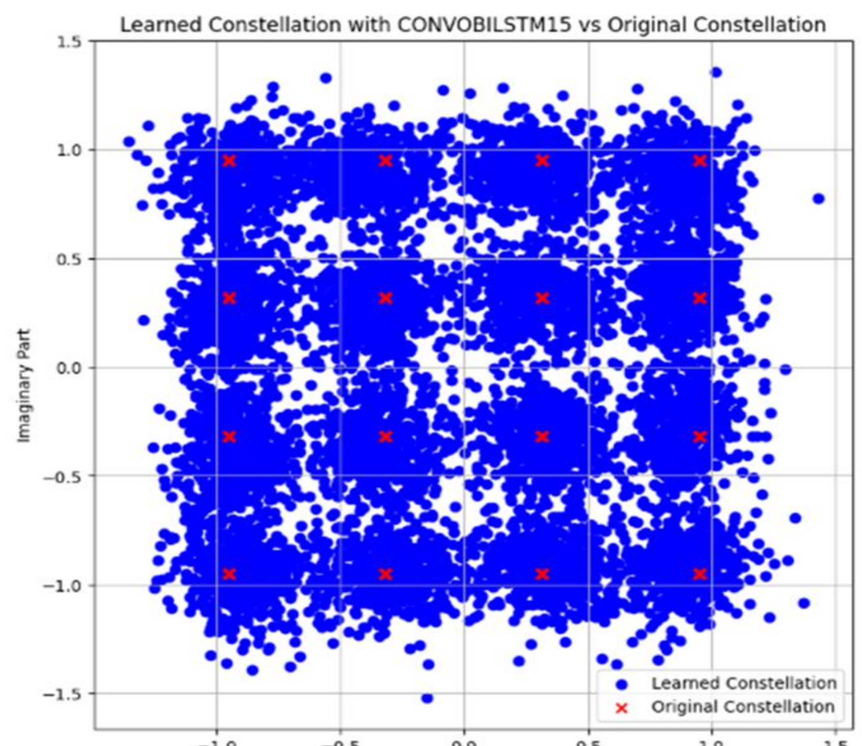

Figure 6: Constellation Diagram using CNN+BiLSTM model

Conclusion

The performance of the CNN model is heavily dependent on the size of the dataset used for training, with larger datasets requiring significantly more computational resources. Due to these constraints, higher levels of training were not pursued. In contrast, CNN+BiLSTM models proved to be more effective and adaptable, particularly in handling complex tasks. The combination of these models offers superior performance, making them highly suitable for improving the design and implementation of neural network-based solutions in long-haul optical systems. This study highlights the potential of advanced deep learning algorithms to enhance the performance and reliability of optical communication systems, suggesting that future research should focus on developing more sophisticated neural network architectures for real-world applications.

Reference

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- [Daniel and Sept(n.d.)] A Daniel and M Sept. ADAPTABLE NEURAL NETWORK-BASED NONLINEAR EQUALIZATION TECHNIQUE FOR COHERENT OPTICAL TRANSMISSION SYSTEM.