Integrated Photonic Neuromorphic Processor Enabled Intelligent, Energy-Efficient Signal Processing for the Next-Generation Communication Systems

The Internet is vital in the modern society and global economy. In handling today's optical communication systems, digital signal processing (DSP) chips have adopted advanced CMOS technology nodes and approached the limits of semiconductor technologies in terms of power dissipation and density. Even so, DSP chips still must avoid using powerful but computationally expensive algorithms, in order to maintain their power dissipation below the thermal dissipation limit. In the coming decade, DSP needs to handle 10x more data traffic, and correspondingly, their energy per bit must be reduced by 10 times. However, as semiconductor technologies evolve at the end of Moore's law, DSP will find it increasingly difficult to satisfy future demand.

Therefore, to support continued internet traffic growth, it needs a paradigm shift in signal processing technology that can improve both energy efficiency and processing capability. This project proposes to develop such solutions by investigating a novel integrated photonic neuromorphic processor, which leverages the strengths of intrinsic properties of photonics, deep learning architectures, and integrated photonic technologies. Our approach promises to bring 10x higher energy efficiency and 1000x less processing latency. Meanwhile, the processor offers the capability of compensating for various transmission impairments, which DSP fails to achieve due to its limited bandwidth.

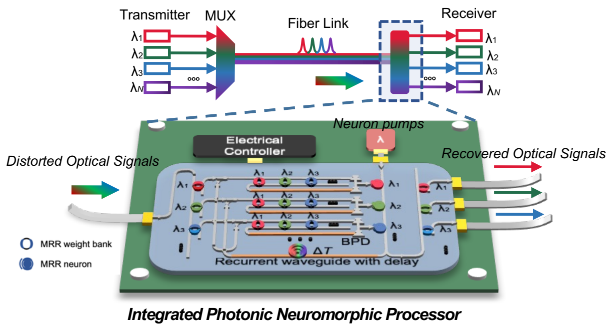

Figure: Proposed fiber communication link with photonic neuromorphic processor.

The proposed photonic neuromorphic processor is a system-on-chip that emulates the recurrent neural network (RNN) model using integrated photonic devices and waveguides. However, our neuromorphic processor is **NOT** simply a faster substitute of software RNN for the same operations (in contrast to some research on photonic AI accelerators). Instead, **our solution builds on our discovery of the strong analogies between the physics models of the proposed photonic neuromorphic processor and that of the fiber transmission systems.** By exploiting such analogies, our photonic neuromorphic processor, with only a small neural network, can advance signal processing beyond what is presently feasible by DSP. **The improvement lies in three aspects. First**, our photonic neuromorphic processor, with only N photonic neurons, can simultaneously process N channels, resolving dispersion, intra-, and inter-channel fiber nonlinearities in the transmission system. These capabilities are uniquely enabled by the wide bandwidth of photonics and, therefore, promise to break the nonlinear Shannon limit. **Second**, our photonic neuromorphic processor can process optical signals in their native form and photonic domain. This avoids prohibitive energy consumption and speed overhead in analog to digital converters (ADCs) and substantially reduces power consumption. **Third**, our photonic neuromorphic processor leverages photonic devices designed for optical communications and, thus, can always offer a processing speed matching the fiber communication line rate in the future.

This project will develop a practical and scalable photonic neuromorphic signal processor, built on our proposed architecture and prior research on integrated neuromorphic photonics. Three major tasks will be completed. (1) We will design a novel photonic system-on-chip that allows processing multi-dimensional communication signals in their native form and in the photonic domain. (2) We will explore the optimized photonic platform and photonic-electronic integration methods to realize practical and scalable photonic neuromorphic processors. This will be done by leveraging our prior research and cross-stack collaborations. (3) We will address a common concern in the optical signal processor: the reduced signal-to-noise ratio (SNR) caused by the device loss. To do that, we will conduct a novel joint design of the communication system and photonic neuromorphic processor at the system level. (4) We will experimentally demonstrate the optimized processor and communication link, showing that the photonic processor can address distortions across wide channels while offering energy advantages over DSP approaches. The success of our project will provide a fundamental solution for meeting the future communication demand by delivering faster, more energy-efficient, and more powerful signal processing technologies.