All-optical processing with dynamic frequency transformations

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Abstract: We propose an all-optical frequency processor (AFP) for transparent optical networking, based on optical pulse shaping and electro-optic phase modulation. We numerically examine the AFP for frequency channel hopping and broadcasting operations, and show the required number of components scales favorably with the network size.

Photonic technologies are increasingly replacing electronics in interconnects for high-performance computing, due to the potentially low power and high speed of silicon photonics [1–4]. Nevertheless, a silicon-based wavelength-multiplexed network may still struggle to cut down the power cost as the number of users grows. For example, a fully connected N-node system, in which each node can transfer data to any other utilizing a unique light color, requires $\mathscr{O}(N^2)$ frequency-selective ring resonators, and thus increases resource provisioning and total power burden. Optically transparent wavelength conversion, on the other hand, can potentially eliminate some of these resource challenges by actively converting the carrier frequencies of input data streams to match the designated output channels. Recently, motivated by the application of quantum information processing, we introduced a quantum frequency processor (QFP) for all-optical wavelength control, based on cascading electro-optic phase modulators (EOMs) and Fourier-transform pulse shapers (PSs). The QFP can in principle realize any unitary operation on frequency bins in a scalable fashion [5], and several fundamental quantum gates have been demonstrated experimentally [6–8]. In this paper, we propose a novel frequency-multiplexed network building on this technology [Fig. 1(a)]. Here, each node possesses a unique receive and transmit wavelength, while a centralized QFP functions as an all-optical frequency processor (AFP), dynamically reprogrammed to map different frequency channels onto their desired destinations.

The AFP consists of EOMs driven by radio-frequency (RF) waveforms periodic at the channel spacing, separated by PSs that apply arbitrary phase shifts to each channel; the total number of elements is Q (defined as the sum of all EOMs and PSs). Here we focus on two characteristic operations: a cyclic frequency hop and 1-to-N channel broadcast. The nearest-neighbor frequency hops ($\omega_0 \to \omega_1$, $\omega_1 \to \omega_2$,...,$\omega_{N-1} \to \omega_0$) can be modeled as a permutation matrix S_N, with elements $(S_N)_{mn} = \delta[(m-n-1) \bmod N]$ and $m,n \in \{0,1,...,N-1\}$. Other hops can be written as powers: $S_N, S_N^2, ..., S_N^{N-1}$. We consider powers through floor($N/2$), as the remaining are simply transposes which can be obtained physically by reversing element order and conjugating all phases. As for the broadcast transformation, we concentrate on the N-point discrete Fourier transform (DFT), whose elements are $(F_N)_{mn} = \frac{1}{\sqrt{N}} e^{2\pi i \frac{mn}{N}}$. This unitary

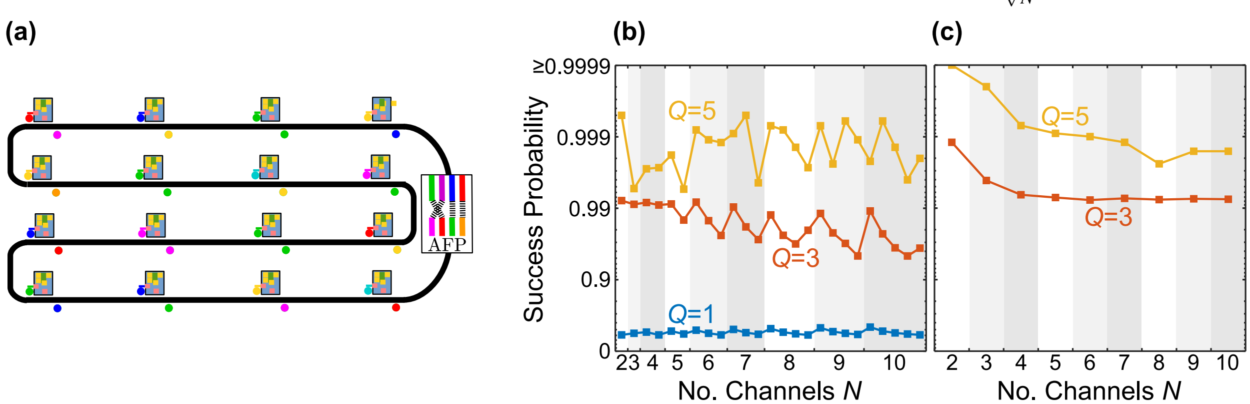

Fig. 1. (a) Proposed network design. Optimal solutions for (b) frequency hopping and (c) broadcast operations using arbitrary temporal modulation patterns, with $\mathscr{F} \geq 0.99$ as constraint.

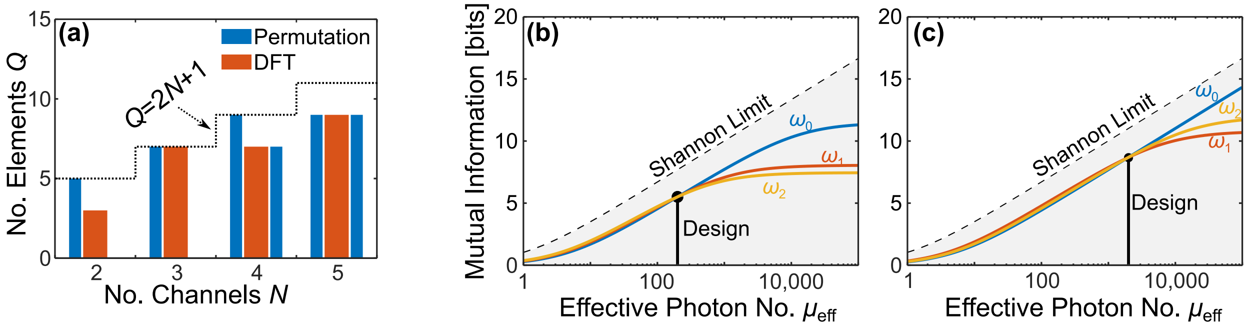

Fig. 2. (a) Number of elements needed to reach $\mathscr{P} \geq 0.99$ for sinewave-only modulation. Gaussian mutual information by output channel for solutions optimized at (b) $\mu_{\text{eff}} = 200$ photons/symbol and (c) $\mu_{\text{eff}} = 200$ photons/symbol.

operation can spread the data stream in one input channel to all N output wavelengths.

To analyze how Q scales with the network size N, we numerically find sets of phase patterns for the AFP which maximize success probability $\mathscr{P}$ constrained to fidelity $\mathscr{F} \geq 0.99$. These two metrics, $\mathscr{F}$ and $\mathscr{P}$, often used in the context of quantum information processing [5, 6], quantify the purity of the operation, and the overall efficiency, respectively. In the first part of the simulations, we consider each EOM as driven by arbitrary modulation patterns. Fig. 1(b) presents our findings for all frequency hops for $N = 2$ to $N = 10$ channels, with the points for each N sorted left-to-right by power S_N^n $[n \in \{1, 2, ..., \text{floor}(N/2)\}]$. The simulation findings for the broadcast operation follow in Fig. 1(c), also for $N = 2$ to $N = 10$. These results indicate favorable scaling of the required number of components with the network size, as $Q = 3$ is able to realize all transformations with $\mathscr{P} > 0.95$, and $Q = 5$ boosts these values closer to unity. If we further limit the phase modulation applied by each EOM to a sinewave for the sake of practicality, the minimum number of components required to achieve a certain success $\mathscr{P}$ does increase with the network size, but only linearly; as shown in Fig. 2(a), $Q = 2N + 1$ components are sufficient to realize both permutations and the DFT at a given number of channels N, up to the dimension $N = 5$ (currently limited by our computational resources).

In classical signal processing, successful data transmission rests on being able to distinguish between symbols, an objective impacted both by total signal amplitude (related to $\mathscr{P}$) and the amount of noise (related to $\mathscr{F}$). Supposing one cannot attain both $\mathscr{F} \to 1$ and $\mathscr{P} \to 1$ due to physical limits, which metric should be the target optimizer? To answer this question, we consider a new metric, mutual information, which incorporates the input signal and noise properties into AFP gate design. We again consider N input frequency channels, but now explicitly set the data format as Gaussian modulation in both quadratures. (See [9] for details on the full model.) Examples of mutual information scaling for two $N = 3$ frequency-hopping solutions are shown in Figs. 2(b) and 2(c), optimized assuming an effective number of photons per symbol of $\mu_{\text{eff}} = 200$ and 2000, respectively. Each curve corresponds to a particular output frequency channel, and at the designed flux values, all channels have equal total mutual information with respect to their corresponding inputs, despite different values of $\mathscr{F}$ and $\mathscr{P}$ across channels. However, moving away from the design flux, the channels separate, depending on whether the dominating noise is power-limited (where $\mathscr{P}$ matters most) or crosstalk-limited (where $\mathscr{F}$ matters most). These simulations highlight how the mutual information approach balances the parallel pulls of low crosstalk and high overall throughput, as well as the importance of the noise model and power level in resource-limited network designs.

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