Modulation Format Aggregation of Nyquist channels by Spectral Superposition with Electro-Optic Modulators

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Abstract: We propose and experimentally demonstrate a new scheme for all-optical coherent modulation format conversion based on vector summation facilitated by coherent spectral superposition with an electro-optic modulator without using any optical nonlinearity. © 2022 The Author(s)

1. Introduction

The continuous growth in capacity demand due to the commercialization of 5G, virtual reality, cloud computing, and telemedicine motivates agile resource management in optical networks along with the use of orthogonal multiplexing techniques. It is practical to choose the suitable modulation format depending on the economic prospects, reach and capacity of a network. Advanced modulation formats like QAM provide high spectral efficiency transmission and are preferred in long-haul networks, whereas conventional lower-order modulation formats like on-off-keying will continue to be used in metro area networks due to their simplicity and cost-effectiveness [1]. In traditional networks, the conversion from lower-order to higher-order modulation formats is carried out through optical-electrical-optical conversion, which is energy inefficient and limited by the resolution and bandwidth of the digital to analog converters [2]. Therefore, an all-optical method to aggregate several lower-order modulation format channels to a higher-order modulation format channel is lucrative owing to the bandwidth advantages, energy efficiency, and the fact that the signals are already in the optical domain. Various photonic aggregation techniques based on nonlinear optical wave mixing involving expensive and complex system design, polarization sensitivity, power consumption, and non-agile operation have been adopted for such conversion [3–5]. These methods are not only complicated but also beyond the possibility of realizing on an integrated photonic platform.

Here we have proposed a simple all-optical approach based on linear signal processing facilitated by electro-optic modulators suitable for integrated photonics. The efficacy of the scheme is shown via experimental demonstration of aggregation of standard as well as Nyquist BPSK signals to QPSK and 4-PAM signals and QPSK to 16-QAM signals. The aggregation happens in the optical domain, and the output signal is readily available for further transmission and processing.

2. Concept

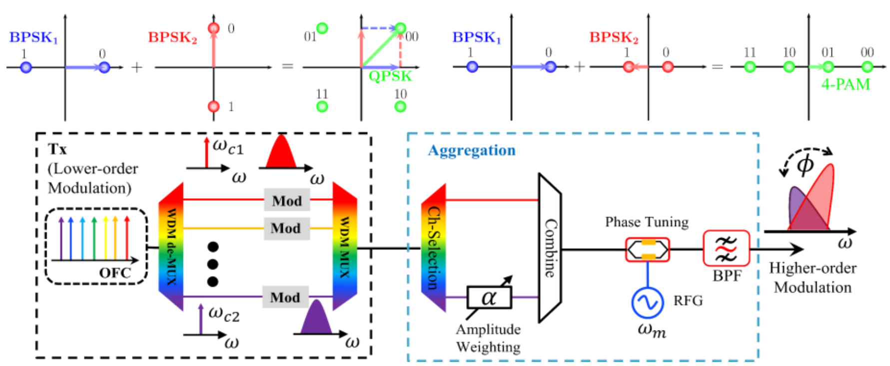

Fig. 1. Principle of vector summation of symbols and the concept of the all-optical aggregation method using electro-optic modulators. OFC: Optical frequency comb, Mod: modulator, BPF: bandpass filter, RFG:

Fig. 1 shows the schematic illustration of the operating principle of the all-optical aggregation method using electro-optic modulators. In principle, several input channels with lower spectral efficiency can be aggregated to fewer output channels with higher spectral efficiency. Here the process is illustrated for two independent lower bit rate optical data channels around ω_{c1} and ω_{c2} generated by modulation of a phase-coherent optical frequency comb

(OFC). These two channels are aggregated to build an output channel with twice the spectral efficiency by vector summation achieved by coherently superposing two signal spectra with suitable amplitude and phase difference in the carriers [3,6]. The symbols in the I-Q plane can be seen as vectors. For aggregation these vectors can be added in the I-Q plane, as shown with the blue and red BPSK arrows in Fig.1 (top left) for the two zero symbols, building the 00 symbol in the aggregated QPSK diagram. The suitable angle between the vectors is defined by the phase difference and a weight factor (α) assigns different magnitudes to the vectors to be summed. If a Mach-Zehnder modulator (MZM) is driven with a phase tunable sinusoidal radio frequency (RF) signal of frequency $\omega_m = (\omega_{c2} - \omega_{c1})/2$, the lower sideband (LSB) from the higher frequency channel (ω_{c2}) overlaps with the higher sideband (HSB) from the lower frequency channel (ω_{c1}) after modulation. The phase difference required for the vector summation is achieved by varying the input RF phase - to the modulator. A bandpass filter (BPF) then allows the separation of the required superimposed band to be transmitted after aggregation. The aggregation of two BPSK signals to a QPSK and a 4-PAM signal is graphically shown in Fig. 1, for instance. For QPSK signal generation, the weight factor $\alpha = 1$, i.e., the vectors are of same amplitude, but the phase offset is $\phi = \pi/2$, for 4-PAM the phases are equal but $\alpha = 1/2$. To validate the concept of phase tuning between the LSB and HSB with the input RF phase to the modulator, a brief mathematical insight into the process is presented below.

If we express an optical signal as $s(t) = \tilde{A}(t)\cos(\omega_c t + \theta)$ then after modulation in an MZM by an RF signal $a_m \sin(\omega_m t + \varphi)$, the modulated signal can be written as [7],

$$s'(t) = (\tilde{A}(t)/\sqrt{2}) \cdot \cos(\omega_c t + \theta) + (\tilde{A}(t)/\sqrt{2}) \cdot \left[J_0(a_m\omega_c) \cdot \cos(\omega_c t + \theta') + J_{-1}(a_m\omega_c) \cdot \cos\big((\omega_c - \omega_m)t - \varphi + \theta'\big) + J_{+1}(a_m\omega_c) \cdot \cos\big((\omega_c + \omega_m)t + \varphi + \theta'\big)\right]. \quad (1)$$

We have denoted all the constant optical phase terms by θ', φ is the phase of the RF and we have used the Jacobi-Anger equations. Moreover, higher order sidebands are neglected.

Considering two channels originating from a phase locked source like a frequency comb, then the relative optical phase between the overlapping spectra is $\phi = (\theta_1' - \theta_2') + 2\varphi$, with $(\theta_1' - \theta_2') = \text{const.}$ due to the phase locking. Therefore, if we have two signal channels with a frequency separation $2\omega_m$, the HSB from the lower frequency channel will spectrally overlap with the LSB from the higher frequency channel and the optical phase ϕ can be arbitrarily tuned by the electrical RF signal phase (φ). Thus, the angle between the symbol vectors is arbitrarily adjustable to achieve the required vector summation.

3. Proof-of-Concept Experiment and Results

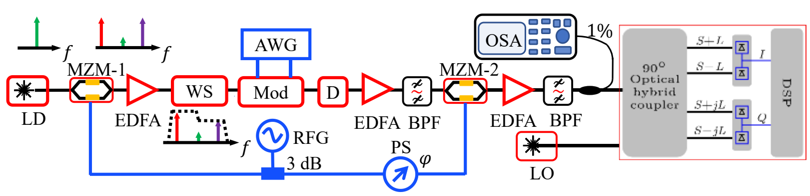

Fig. 2. Proof-of-concept experimental set up for all-optical aggregation. LD: laser diode, MZM: Mach-Zehnder modulator, D: dispersion unit, WS: waveshaper, OSA: optical spectrum analyzer.

To demonstrate the concept, a setup as shown in Fig. 2 was adopted. In the absence of a comb source in the lab, the output from a laser diode (LD) emitting at 193.4 THz was modulated by MZM-1 in carrier suppression to generate two phase-locked sidebands 36 GHz apart. The carrier was suppressed by 20 dB by adjusting the MZM-1 bias to the minimum transmission point. A waveshaper (WS) was used as a programmable filter to have different weights ($\boldsymbol{\alpha}$) for the vector addition. It is noteworthy that the WS independently adjusted only the power in the two ancillary carriers without any phase adjustment. A dual parallel MZM modulated the carriers with desired lower spectral efficiency modulation formats. As the same data was modulated over both the carriers, relative symbol delays were applied between the two channels using a dispersion-compensating fiber module (D) to decorrelate them. The aggregation of the two lower modulation format channels or their coherent superposition was carried out by MZM-2, which is driven with the same 18 GHz RF as MZM-1. As the two superposing spectra are from two different sidebands, they have a relative phase relationship that is tunable by the RF phase shifter (PS). It is worth mentioning that the dispersion module changes the relative phase between the two channels as well. However, since the relative phase for the aggregation is adjusted with the RF signal driving MZM-2, this did not affect the experiment. Finally, we used a coherent detection system to visualize the symbol constellation and measure the signal metrics like Q-factor and error-vector magnitudes (EVM). We did not use the bandpass filter as included in the concept diagram. Instead, post-detection digital signal processing (DSP) served the purpose. The bandpass filters (BPFs) in Fig. 2 were used to suppress the amplified spontaneous emission noise of the Er-doped fiber amplifiers (EDFAs) used to amplify the optical signal whenever necessary.

If at the transmitter, the carriers are modulated with standard 10 GBd QPSK signals (where the symbols are shaped by raised cosine filters of 10 GHz bandwidth and 1.0 roll-off-factor) and $\alpha = 0.5$, by tuning the RF phase to $\phi = \pi/2$ a 16-QAM signal of 10 GBd symbol rate could be generated as shown in Fig. 3(a). Similarly, Fig. 3(b) presents the aggregation of two 8 GBd Nyquist QPSK signals to an 8 GBd Nyquist 16-QAM signal. The experimental conditions were identical except that the symbols were modulated on optical sinc-shaped Nyquist pulses in the parent data [8].

In Fig. 3(c) and 3(d), the results for the aggregation of two Nyquist-BPSK signals to a Nyquist 4-PAM and a Nyquist-QPSK signal are presented, respectively. The measured signal metrics are also given for the input and

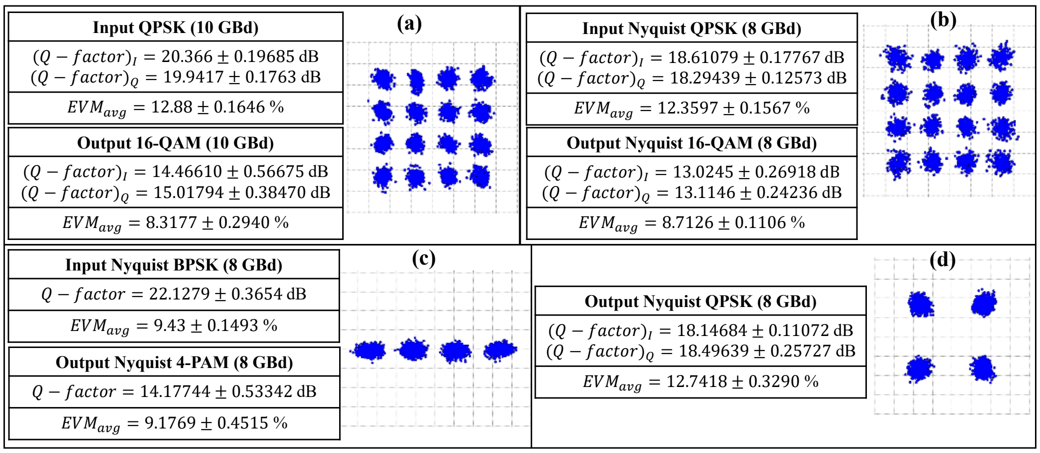

Fig. 3. Measured constellation maps of the aggregated signals along with the Q-factors and average error vector magnitudes of input and aggregated channels.

output signals. It is evident that there is no notable performance degradation due to the aggregation process. The transmitted patterns are of a PRBS of length $2^9 - 1$, and no bit error was measurable for 300,000 bits. However, bit error estimations from the Q-factor yield values few orders of magnitudes lower than the forward error correction limits.

4. Conclusions

We propose a novel scheme on all-optical signal format aggregation using modulators. The method might help to make the optical network more flexible. In the experimental demonstration, Nyquist and conventional BPSK and QPSK signals are aggregated to form QPSK, 4-PAM, and 16-QAM signals. The aggregation might be incorporated in-line between two nodes in the optical network, which exhibit different modulation formats. The method only requires an MZM, which is easy to integrate into photonic integrated circuits based on any material platform. Moreover, the linear signal processing approach eliminates the need for additional sources or complicated system design and provides agile all-optical aggregation.

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