# Demonstration of Multiplexing and Transmission of QPSKto-16QAM Channels over 100 km using Wave Mixing for Aggregation and Noise Mitigation

A. Mohajerin-Ariaei<sup>(1)</sup>, M. Ziyadi<sup>(1)</sup>, A. Almaiman<sup>(1)</sup>, Y. Cao<sup>(1)</sup>, C. Bao<sup>(1)</sup>, P. Liao<sup>(1)</sup>, B. Shamee<sup>(1)</sup>, F. Alishahi<sup>(1)</sup>, A. Fallahpour<sup>(1)</sup>, M. R. Chitgarha<sup>(1)</sup>, A. J. Willner<sup>(1)</sup>, Y. Akasaka<sup>(2)</sup>, T. Ikeuchi<sup>(2)</sup>, S. Wilkinson<sup>(3)</sup>, J. Touch<sup>(4)</sup>, M. Tur<sup>(5)</sup>, C. Langrock<sup>(6)</sup>, M. M. Fejer<sup>(6)</sup>, and A. E. Willner<sup>(1)</sup>

1) Ming Hsieh Department of Electrical Engineering, University of Southern California, 3740 McClintock Ave, Los Angeles, CA 90089, USA 2) Fujitsu Laboratories of America, 2801 Telecom Parkway, Richardson, TX 75082, USA

3) Raytheon Co., San Diego, CA, USA

4) Information Sciences Institute, University of Southern California, 4676 Admiralty Way, Marina del Rey, CA, 90292, USA
5) School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel

6) Edward L. Ginzton Laboratory, 348 via Pueblo Mall, Stanford University, Stanford, CA 94305, USA

<u>mohajera@usc.edu</u>

**Abstract:** We demonstrate an optical multiplexing and transmission of QPSK-to-16QAM channels over 100 km using wave mixing for aggregation and noise mitigation. For the input signals with phase noise of ~50, 35 degree and 300 MHz noise bandwidth, the OSNR penalty of ~1dB is obtained at BER  $10^{-3}$  for aggregated 20 Gbaud 16QAM signal compared to the case of having no phase noise in input signals. **OCIS codes:** (060.2360) Fiber optics links and subsystems; (190.4223) Nonlinear wave mixing

## 1. Introduction

Networks are envisioned to become more dynamic and heterogeneous in the future [1,2]. This becomes ever more important as: (i) optical spectrum becomes scarce at certain points in the network, (ii) certain parts of the network have higher capacity or more available spectrum than other parts [1,3,4]. One possibility of alleviating the scarce spectrum at certain points in the network is to aggregate multiple data channels onto a single higher-spectral-efficiency channel for subsequent transmission. For example, two QPSK data channels can be optically multiplexed into a single 16 QAM channel that has twice the spectral efficiency [5,6]. Importantly, these two data channels might contain phase noise that one would want to mitigate. In the past, there have been reports of techniques to optically aggregate lowerorder modulation format channels into a single higher one [3,5] and other reports to optically mitigate phase noise [7,8]. However, there has been limited reported of any approach that aggregates and mitigates phase noise at the same time. We demonstrate the optical multiplexing and transmission of QPSK-to-16QAM channels over 100 km using wave mixing for aggregation and noise mitigation. The phase noise of the QPSK signals are filtered in a nonlinear element using optical wave mixing and tunable optical delays. Simultaneously, the noise mitigated QPSK signals are coherently multiplexed and generate a 16QAM signal. For aggregated 10 and 20 Gbaud 16QAM signals, the EVM reduction of more than 30% is achieved for phase noise of ~50 degree and 300 MHz bandwidth. For the input signals with phase noise of  $\sim$ 50 and  $\sim$ 35 degree and 300 MHz bandwidth, the OSNR penalty of  $\sim$ 1dB is achieved at BER 10<sup>-3</sup> for 20-Gbaud 16QAM signal compared to the case of aggregation from signals with negligible amount of phase noise. 2. Concept



Fig. 1. The concept of the simultaneous optical aggregation and phase noise mitigation system. The incoming two QPSK signals contaminated with phase noise, e.g. phase noise of lasers with large linewidths, are received. The conjugate copies of signals with one symbol delay are generated using PPLN-1 waveguide and a dispersive medium. In PPLN-2, each signal multiplied with its conjugate copy to filter out the phase noise, and in a simultaneous process, they coherently multiplexed to generate the output 16 QAM signal.

The conceptual block of the system is shown in Fig. 1. The two incoming QPSK signals contaminated with phase noise, e.g. phase noise from lasers with large linewidths, are received. The noisy signals, along with a pump  $P_1$ , are injected into a nonlinear wave mixer to generate the conjugate copies of the signals. All signals are then sent into a dispersive medium to apply one symbol delay. Next, the signals are sent to the programmable optical filter in which appropriate amplitudes and phases are applied. The signals along with a second pump are injected into a second

#### JTh2A.127.pdf

nonlinear element in which two tasks will be done: **1**) Phase noise mitigation by coherently mixing each signal and its corresponding delayed conjugate. We denote the generated noise mitigated signals by  $X_i(t) \propto exp(j\Phi_{s_i}(t) - \Phi_{s_i}(t-T))$ . Since the phase of each incoming signal consists of data and phase noise, then the phase of  $X_i(t)$  becomes  $\Phi_{X_i}(t) = [\Phi_D(t) - \Phi_D(t-T)] + [\varphi_N(t) - \varphi_N(t-T)]$ . The first bracket is a decoding of the data and the second bracket can be viewed as a filter on the phase noise, which is able to filter out the low frequency components of phase noise (e.g., laser phase noise). The second simultaneous nonlinear process leads to **2**) all-optical aggregation by phase-locked multiplexing of the noise mitigated signals  $X_1(t)$  and  $X_2(t)$  with appropriate relative coefficients.

## 3. Experimental Setup

A MZM is used to generate 10-20 Gbaud QPSK data at ~1537.5nm and 1539nm. The signals are phase modulated with an ASE source to emulate phase noise with different powers and bandwidths. The noisy signals are sent to transmission links and the outputs are amplified and coupled with a pump around 1541.6 nm and injected to periodically-poled-lithium-niobate (PPLN-1) waveguide. The signals are then sent to a ~150 m DCF to apply one symbol delay and sent to a SLM filter for adjusting the amplitudes and phases. The signals are coupled with another pump and sent to PPLN-2 to 1) mix each signal with its conjugate, and 2) phase-lock multiplex the noise mitigated signals. The aggregated signal is filtered and sent to a transmission link and finally is detected by a coherent receiver.



Fig. 2. (a) Experimental setup. PM: Phase modulator, PPLN: Periodically poled lithium niobate, DCF: Dispersion compensated fiber, SLM: Spatial light modulator, PD: Photo detector, VOA: Variable optical attenuator. (b) 20 Gbaud optical spectra after nonlinear stages (PPLN-1, 2). **4. Results and Discussion** 

The performance of the system is assessed by implementing the scheme on 10-20 Gbaud QPSK-to-16QAM channels. Fig. 3(a) shows the constellation diagrams of the aggregated 16QAM signal of noisy QPSK signals. The phase noise levels of the two channels are around 50 and 35 degree and the phase noise bandwidth of the channel with higher phase noise varies from 300 MHz to 5000 MHz and the phase noise bandwidth of the other channel is 300 MHz. The phase noise reduction for the phase noise with lower bandwidths ( $\Delta v$ ~300 MHz, 1000 MHz) compared to the cases with higher bandwidths (3300 MHz, 5000 MHz) is significant. Fig. 4 (b) shows the BER performance of the aggregated 20-Gbaud 16QAM signal before and after transmission. The BER are obtained based on QPSK channels with phase noise of around 50 and 35 degree. The noise bandwidth of the channel with higher phase noise is changed to 300 and1000 MHz and the phase noise bandwidth of the other channel is 300 MHz noise bandwidth of the other channel is 300 MHz. For input signals with phase noise of ~50, 35 degree and 300 MHz noise bandwidth the OSNR penalty of ~1dB is achieved at BER 10<sup>-3</sup> for 20-Gbaud 16QAM signal compared to the case of aggregation from signals with negligible amount of phase noise.



Fig. 3. The constellations diagrams for 10-20 Gbaud signals (a) The aggregated 16 QAM signals from QPSK channels with phase noise levels of around 50 and 35 degree. The phase noise bandwidth of the channel with higher phase noise varies from 300 to 5000 MHz and the phase noise bandwidth of the other channel is 300 MHz. (c) The BER performance of the 16QAM aggregated signal for input signals with phase noise of  $\sim$ 50 and  $\sim$ 35 degree and different phase noise bandwidths, before and after transmission.

Acknowledgements The authors would like to thank the support of NSF, CIAN, and Fujitsu.

## 5. References

- [1] J.M. Simmons,"Optical network design and planning," Springer (2014).
- [2] J. Berthold, et al., J. Lightw. Technol., vol. 26, no. 9 (2008).
- [3] A.A.M.Saleh et al., Proceedings of the IEEE vol. 100, no. 5 (2012).
- [4] J. Zhang, et al., J. Lightw. Technol., vol. 33, no. 1 (2015).
- [5] M. I. Anis et al., Tech. Lett. 17, OFC, paper OW3A.3 (2013).
- [6] M. R. Chitgarha, et al., Optics Lett. **38**, 3350-3353 (2013).
- [7] K.R.H. Bottrill et al., ECOC paper ID: 0627 (2015).
- [8] A. Mohajerin-Ariaei et al., Optics Lett. 40, 3328-3331 (2015).