Dynamic Optical Arbitrary Waveform Generation and Measurement for Elastic Optical Networks

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Abstract We discuss dynamic OAWG and OAWM technologies as EON transceivers to generate and detect arbitrary waveforms in any modulation format across their operating bandwidth. Compared to other technologies, OAWG/OAWM provides EON with most versatility, flexibility, and optical performance monitoring capability.

Introduction
While the recent deployment of the dense wavelength division multiplexing (DWDM) technology successfully met the exponential traffic growth in the Internet so far, continuing traffic increases fueled by cloud computing and data center services are demanding new networking technologies that can more efficiently and effectively accommodate various services. In order to achieve this in the limited spectral bandwidth, the recent trend in optical communications has been to adopt advanced coherent modulation formats that achieve high spectral efficiency together with DWDM [1]. In addition to the high spectral efficiency, reconfigurable dynamic allocation of the bandwidth and modulation format is important for future networks.

EON Overview
Elastic Optical Networking (EON) has recently been proposed as a spectrally efficient networking technology that effectively supports dynamically varying traffic demands [2]. Instead of using DWDM wavelength channels on a standard wavelength grid (e.g. ITU-T G.694.1) through a specific wavelength assignment process (e.g. RWA), the EON can utilize flexible and elastic wavebands (or SLICEs) for a spectrum assignment process (called RSA for routing and spectrum assignment). Fig. 1 illustrates EON across wide-area and metro-area networks.

The EON benefits from transceiver technologies supporting the following requirements:
1. Independent and flexible allocation of bandwidths and modulation formats.
2. Scalability to superchannels and accommodating of subchannels.
3. Elastic transceivers and flexible bandwidth wavelength selective switches.
4. Supervisory channel and Optical Performance Monitoring across the elastic bandwidth.
5. Dynamic RSA with hitless defragmentation
6. QoS-Aware & Impairment-Aware Networking
7. Automatic & adaptive Networking Control & Management

As illustrated in Fig. 2, multicarrier solutions such as coherent wavelength division multiplexing (CoWDM) [4], Coherent optical orthogonal frequency division multiplexing (CO-OFDM) [5], Nyquist-WDM, as well as dynamic optical arbitrary waveform generation (OAWG) [6] have been proposed as possible transponder
implementations for EON. Ref [3] discusses the comparison of these technologies, and this paper addresses OAWG based EON.

**OAWG for EON Transmitter**

As Fig 3 illustrates, in Dynamic OAWG, the coherent combination of many spectral slices generated in parallel enables the creation of a continuous output spectrum [6]. In this case, arbitrary bandwidth, single- and multi-carrier channels can be generated, in which each channel can be in a different modulation format (Fig.2c). The versatility of this signal generation technique enables customization of generated waveforms over the total operational bandwidth of the transmitter. This enables avoiding large peak-to-average power ratios, and incorporating pre-compensation for impairments such as chromatic dispersion. Unlike OFDM, OAWG also removes the restriction that the modulator bandwidth must be a multiple or sub-multiple of any generated channel or subcarrier bandwidth [6].

Dynamic OAWG begins with a coherent optical frequency comb (OFC), which is spectrally demultiplexed with narrow passbands placing each comb line at a separate spatial location. A set of in-phase and quadrature-phase modulators (I/Q modulators) each with a bandwidth of $\Delta f_G$ apply temporal I/Q modulations to broaden the comb lines to create the spectral slices. Coherently combining the spectral slices using a gapless spectral multiplexer with broad overlapping passbands ensures a continuous bandwidth output waveform.

### Photonic Integration

Photonic integration is extremely important for practical and realistic implementations of flexible bandwidth networking systems. Fig. 3 shows monolithic integration of InP based 100 GHz bandwidth (10 x 10 GHz) OAWG transmitter chip including spectral demux, spectral mux, and arrays of 10 amplitude modulators and 10 phase modulators driven by 10 GHz electronic drivers, realizing the architecture of Fig. 2. For higher capacity chip, it is important to manage I/O of the signal for modulation. Therefore, the second generation 100-channel devices [7-9] incorporate optically driven phase modulators which are controlled by the intensity of remote, fiber-pigtailed lasers. This all-optical cross modulation of optical phase takes place in the waveguide, with or without multiple quantum wells, within the short (< 50 µm) absorption length of the propagating 1310-nm control laser wavelengths. Each of the 100 AWG outputs has a Michelson interferometer consisting of a 2x1 MMI splitter/combiner. The device includes 1200 independently addressable active devices, and is one of the largest-scale integrated photonic devices in the world.

**OAWM technology for EON Receiver**

As Fig. 4 illustrates, the working principle of optical arbitrary waveform measurement (OAWM) is quite analogous to that of OAWG except for the fact that it will do coherent detection instead of coherent generation at each
spectral slice. The optical comb and arbitrary optical waveform will propagate in an opposite direction in OAWM compared to OAWG. For the receiver, a reference OFC with $M$-lines spaced at $\Delta f_M$ provides a reference tone for the detection of each spectral slice [10]. The reference comb lines are isolated using a spectral demultiplexer with narrow and discrete passbands, and the signal is divided into spectral slices using a separate gapless spectral demultiplexer that has strongly overlapping passbands. Each reference comb line is then used to detect the corresponding spectral slice using a standard digital coherent receiver [11]. At this point, Digital Signal Processing (DSP) enables recombination of the spectral slices after electronic detection. In this transmission system, $\Delta f_G$ can be different from $\Delta f_M$ as long as the total measurement bandwidth ($M \times \Delta f_M$) is greater than the generated waveform’s bandwidth ($N \times \Delta f_G$).

Conclusions
Dynamic OAWG and OAWM can generate and detect arbitrary waveforms in any modulation format across their operating bandwidth. EON can greatly benefit from this versatility of OAWG and OAWM to enable EON trancievers scalable to THz and beyond.

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