Evolution of Optical Networking

Exponential increases in data traffic have transformed the landscape of modern networks. In the latter part of the 1990s, the exponential growth in capacity demands were successfully met by the wavelength-division-multiplexing (WDM) technology which had become commercially available by then. This initial phase of optical networking, often referred to as the first generation optical networking deployed in 1997, focused on point-to-point link capacity increases. Beyond the simple capacity increase, the true benefit of optical networking may arise from the reconfigurability of such vast bandwidths directly in the optical layer without involving electronics in the data plane. The second-generation optical networking achieves reconfiguration of optical wavelength circuit paths (lightpaths) by properly configuring the optics within the optical network elements. It also supports format and protocol transparency, and simplifies the hardware requirements in the data plane. With the on-going deployment of reconfigurable optical add drop multiplexers (ROADMs) and optical crossconnects (OXC)s, we anticipate the third-generation optical networking to address dynamic reconfiguration of even higher capacity traffic. The third generation optical networking is expected to appear in two possible configurations. One is a packet-agile optical networking technology and the other is a flow-agile optical networking technology. In both configurations, extremely high data rates must be supported on each strand of fiber. In practical implementations, usable bandwidth of a single mode fiber with amplification is limited by the bandwidth of amplification technologies, which is on the order of 5–10 THz for commonly used erbium-doped fiber amplifiers (EDFAs). In order to achieve high capacity communications in the limited spectral bandwidth, the recent trend in optical communications has been to adopt advanced modulation formats that achieve high spectral efficiency together with dense WDM (DWDM). The historical trend of this evolution appears in Figure 1 and Figure 2 [1].

As Figure 2 [1] indicates, the spectral efficiency gradually increased from 0.1 b/s/Hz to 10 b/s/Hz [2] in a little over one decade. Such high spectral efficiency is achieved by adopting advanced
modulation formats carried on either a single carrier or multiple carriers. Table 1 shows the summary of a) single-carrier modulation with variable bit and symbol rate; b) multicarrier modulation with variable bit and subcarrier for providing data rate $B$. In the orthogonal frequency division multiplexing (OFDM) [3], coherent WDM (CoWDM) [4] and optical arbitrary waveform generation (OAWG) [5-11] methods we will discuss in the next section, multiple carriers are used to substantially reduce the symbol modulation rate necessary for achieving the given data rate. In OFDM, the frequency spacing between the carriers is matched to be exactly $1/T_S$, where $T_S$ is the symbol duration, synchronized across the individual carriers to assure orthogonality.

<table>
<thead>
<tr>
<th>Modulation Level</th>
<th>QPSK</th>
<th>16-QAM</th>
<th>64-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol rate (Hz)</td>
<td>$B/2$</td>
<td>$B/4$</td>
<td>$B/6$</td>
</tr>
<tr>
<td>Number of carriers</td>
<td>1 (const.)</td>
<td>1 (const.)</td>
<td>1 (const.)</td>
</tr>
<tr>
<td>Bits per symbol</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Data rate per polarization (b/s)</td>
<td>$B$ (const.)</td>
<td>$B$ (const.)</td>
<td>$B$ (const.)</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>Modulation Level</th>
<th>OOFDM-QPSK</th>
<th>OFDM-16QAM</th>
<th>OFDM-64QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol rate (Hz)</td>
<td>$B/2n$ (const.)</td>
<td>$B/2n$ (const.)</td>
<td>$B/2n$ (const.)</td>
</tr>
<tr>
<td>Number of carriers</td>
<td>$n$</td>
<td>$n^2$</td>
<td>$n^3$</td>
</tr>
<tr>
<td>Bits per symbol</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Data rate per polarization (b/s)</td>
<td>$B$ (const.)</td>
<td>$B$ (const.)</td>
<td>$B$ (const.)</td>
</tr>
</tbody>
</table>

(b)

Table 1. Parameters in tunable spectral width modulation format: a) single-carrier modulation with variable bit and symbol rate; b) multicarrier modulation with variable bit and subcarrier (adapted from [12]).

Flexible bandwidth networking has recently been proposed as a spectrally efficient networking technology that effectively supports dynamically varying traffic demands [21]. Figure 3 illustrates a flexible bandwidth network in comparison to a conventional DWDM network. Instead of using DWDM wavelength channels on a standard wavelength grid (e.g. ITU-T) through a specific wavelength assignment process (e.g. RWA), a flexible bandwidth network can utilize flexible and elastic wavebands (or SLICEs) for a spectrum assignment process (called RSA for routing and spectrum assignment). Once such a network level RSA becomes possible, a large scale network can be deployed as Figure 4 illustrates.

The advantage of flexible bandwidth networking can be summarized as (a) elimination of stranded spectrum between the wavelength grids, (b) easily accommodating subwavelength granularity traffic, (c) easily accommodating superwavelength traffic, etc. [13]. Key enabling technologies for flexible bandwidth networks are the flexible bandwidth transmitters and receivers (Flex BW Trx) that can scale up to THz bandwidth and beyond, and flexible bandwidth wavelength (spectrum) selective switches (Flex BW WSS) that can switch variable spectral bands.
Multicarrier solutions such as coherent wavelength division multiplexing (CoWDM) [22] and orthogonal frequency division multiplexing (OFDM) [23-26] have been proposed as possible implementations of flexible bandwidth networking. These solutions rely on the generation of many low speed subcarriers to form broadband data waveforms using lower speed modulators. CoWDM maintains orthogonality between closely packed subcarriers by individually modulating each tone from a set of coherent subcarrier tones, and setting the subcarrier symbol rate equal to the subcarrier spacing. OFDM systems utilize an inverse Fourier transform at the transmitter and a Fourier transform at the receiver to ensure orthogonality between subcarriers. Often a guard band is necessary to compensate for chromatic dispersion at the cost of a slight spectral efficiency penalty, but techniques such as no-guard-band OFDM can eliminate the need for guard bands [27]. Both CoWDM and OFDM systems can change the modulation format of individual subcarriers, but lack the ability for arbitrary control over subcarrier symbol rate and spacing with a single physical architecture.

A more general method for broadband waveform generation is based on dynamic OAWG [7, 8]. The generated arbitrary optical waveforms can include data waveforms in both single carrier modulation formats, and multicarrier modulation formats such as CoWDM and OFDM. Here, ‘dynamic’ refers to continuous waveform generation, as opposed to line-by-line pulse shaping [28-32], which has time duration limitations typically on the order of tens of picoseconds. In particular, spectral-slice based dynamic OAWG can create continuous, high-fidelity waveforms that overcome the limitations of rapidly updating the modulations to a line-by-line pulse shaper [33, 34]. Spectral-slice dynamic OAWG utilizes the parallel synthesis and coherent combination of many lower bandwidth spectral slices to create broadband data waveforms [35, 36]. In contrast to multi-carrier systems, the spectral slice bandwidth is not related to the subcarrier bandwidth of generated waveforms. This removes any restrictions on the subcarrier bandwidth and its modulation format, and is only limited by the total operational bandwidth of the OAWG transmitter. The parallel nature of this transmitter structure enables bandwidth scalability without increasing the bandwidth demand on the supporting electronics. The complementary receiver is optical arbitrary waveform measurement (OAWM), in which a broadband, continuous bandwidth waveform is divided into many spectral slices for parallel measurement using independent digital coherent receivers [37].

In the following section, we will discuss OAWG/OAWM based Flex BW Trx and resulting flexible bandwidth networks. Compared to commonly used Co-WDM[22] or CO-OFDM [38] techniques which utilize subcarriers with frequency spacing Bf with a baud rate of exactly Δf, OAWG can generate truly arbitrary waveforms (including Co-WDM, CO-OFDM signals) using optical frequency comb spacings that can differ from that at the receiver. In addition, arbitrary spectral bands of arbitrary modulation formats can be generated and also detected using the OAWG technique [37, 39]. This facilitates multi-vendor interoperability and network evolutions across heterogeneous subnetwork domains.

**OAWG Transmitter Technology**

A flexible bandwidth transmission system based on a dynamic OAWG transmitter and an optical arbitrary waveform measurement (OAWM) receiver can coherently generate and receive data waveforms by dividing the total waveform bandwidth into spectral slices of manageable bandwidth. This enables, using currently available technology in a bandwidth scalable manner, operation over large amounts (>1 THz) of continuous bandwidth. In this fashion, a dynamic OAWG transmitter creates large bandwidth waveforms through the parallel generation and coherent combination of many lower speed spectral slices (e.g., ~10 GHz optical bandwidth) [40]. Similarly, an
OAWM receiver coherently divides the data waveform into spectral slices (e.g., ~40 GHz optical bandwidth) that are individually detected with parallel digital coherent receivers [37]. For example, a 100 GHz transmission system could be implemented using 10 × 10 GHz spectral slices at the transmitter and 4 × 25 GHz spectral slices at the receiver.

Figure 5 shows how dynamic OAWG can generate N spectral slices, each with bandwidth $\Delta f_0$, to form an aggregate output waveform with a total bandwidth of $N \times \Delta f_0$. 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 $\Delta f_0$ 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. Also, incorporating compensation for the multiplexer transmission as a pre-emphasis of the modulation signals ensures high-fidelity waveform generation after the multiplexer [40].

**Integrated Photonic 100 GHz OAWG**

Photonic integration is extremely important for practical and realistic implementations of flexible bandwidth networking systems. As Figure 6 shows, our group has achieved monolithic integration of InP based 100 GHz bandwidth (10 × 10 GHz) an OAWG transmitter chip including spectral demux, spectral mux, and arrays of 10 amplitude modulators and 10 phase modulators driven by 10 GHz electronic drivers shown in Figure 7.

The InP 10 channel × 10 GHz OAWG devices described above proved challenging not only to fabricate, but also to couple RF driver signals to the InP chips. Therefore, the second generation 100-channel devices [42, 43] 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. As shown in the 100-channel, 10-GHz OAWG exploits a reflection-mode
geometry to utilize a compact 50-mm diameter wafer substrate, to allow easy access from the optical control signals to the phase modulators, and to guarantee spectral alignment of the demultiplexer and multiplexer for all 100 channels. Figure 8 shows the fabricated monolithically integrated InP 100-channel × 10-GHz OAWG device with overall dimensions of 30 mm × 35 mm [41]. The device’s 1550-nm input/output on the left cleaved-facet uses a multimode-interference (MMI) 2×1 coupler to separate the input OFC from the output OAWG signals. The AWG contains 200 arrayed waveguides, each with an electro-optic Mach-Zehnder modulator (MZM) for passband shaping. Each of the 100 AWG outputs has a Michelson interferometer consisting of a 2×1 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 Receiver Technology
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 the opposite direction in OAWM compared to OAWG.

Figure 9(b) illustrates how an OAWM receiver characterizes waveforms through the coherent detection of \( M \) spectral slices, each with bandwidth \( \Delta f_M \). 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 [37]. 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 [44]. 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 \((N \times \Delta f_G)\). The use of spectral slices enables independent optimization at the transmitter and receiver for the exact bandwidth of available electronics, and also allows utilization of the transmitters and receivers across heterogeneous network domains.

640 GHz Integrated Photonic OAWM

![Figure 10. Silica planar lightwave integrated circuit (PLC) with 640 GHz spectral bandwidth (16 x 40 GHz) containing two spectral demultiplexers and 16 sets of optical hybrids for coherent detection. Balanced detectors are placed external to the silica PLC.](image)
Figure 10 illustrates silica planar lightwave integrated circuit (PLC) with 640 GHz spectral bandwidth (16 x 40 GHz) containing two spectral demultiplexers and 16 sets of optical hybrids for coherent detection. Commercial balanced receivers are placed external to the silica PLC.

Monolithically integrated OAWM chip development including the balanced receivers are currently in the plans based on recently completed designs.

Flexible Bandwidth Variable Modulation Format Signal Generation and Detection

Figure 11. OOK and DPSK waveforms generated and detected at 360 Gb/s using line-by-line amplitude and phase manipulation of optical frequency comb lines. The agreement between the targeted (dots) vs. measured (solid) data are reasonably good.

Figure 12. (a) 1.2 Tb/s 16 QAM signal with 3 b/s/Hz spectral efficiency. The constellation generated using a limited number of bits (120 bit) showed a reasonably good agreement between (b) the targeted constellation and (c) the measured constellation.

Using the OAWG and OAWM technologies, we generated and detected waveforms of various modulation formats, data rates, and spectral widths. Figure 11 shows OOK and DPSK waveforms generated and detected at 360 Gb/s data rates. The agreement between the targeted (dots) vs. measured (solid) data are reasonably good. Figure 12 shows 1.2 Tb/s 16 QAM signal with 3 b/s/Hz spectral efficiency using a 120 bit sequence.

Flexible Bandwidth Networking Testbed

Figure 13. (a) Flexible bandwidth networking experimental testbed arrangement with (b) experimental system node) with variable modulation formats and bandwidths.

Figure 14. BER curves for BPSK, QPSK, and 8PSK modulation formats in the Flex BW networking testbed.

We have recently established a four-node flexible bandwidth networking testbed using OAWG, OAWM, Flex BW WSS (Nistica) devices. Figure 13 (a) shows the simple topology of the testbed used for the experimental demonstration, and Figure 13 (b) shows a schematic of the network element. One of the experiments recently conducted was to demonstrate impairment-aware networking by experimenting self adaptation of modulation format while the physical layer impairment (OSNR) increases. The network testbed was able to control and to minimize the spectral bandwidth occupied by the adaptive lightpaths (flexpaths) while supporting acceptable bit error rate defined by quality of service (QoS) requirements. Each flexpath utilized one of the variable modulation formats (BPSK, QPSK, 8PSK, 16QAM, etc) As Figure 14 shows the BER curves for various modulation formats at 360 Gb/s BPSK, QPSK, and 8 PSK, which exhibit higher signal-to-noise ratios for modulation schemes for higher spectral efficiency. The testbed experiment successfully showed transition of modulation formats when OSNR degradation caused the supervisory channel BER
to alert the control plane to downgrade the modulation format from QPSK to BPSK while minimizing the stranded spectral bandwidth.

**Conclusion**

Dynamic OAWG and OAWM can generate and detect arbitrary waveforms in any modulation format across their operating bandwidth. Flexible bandwidth networking can greatly benefit from this versatility of OAWG and OAWM to enable Flex BW Trx scalable to THz and beyond.

As a result, in addition to being able to operate using a single carrier modulation format such as binary phase shifted keying (BPSK) and quaternary phase shifted keying (QPSK), it is also possible to utilize multicarrier modulation formats such as CoWDM and OFDM using the same transmitter and receiver structure. Furthermore, multicarrier waveforms can be generated with each carrier having a unique bandwidth and modulation format.

Adaptive network control and management working with OAWG/OAWM based Flexible Bandwidth Network can provide efficient and robust operation under time varying physical layer impairments.

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**References**


