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Review and analysis of elastic optical network and sliceable bandwidth variable transponder architecture

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Abstract. Traditional dense wavelength division multiplexing (DWDM) technology is no longer enough to meet the extensive growth in the demand of bandwidth in an efficient and effective manner under the fixed grid environment. Thus, a technology is needed to overcome the challenges raised by the ever-increasing demand of bandwidth in an effective manner with efficient utilization of spectral resources. To solve this problem, an elastic optical network (EON) paradigm comes into existence. It uses a flexible grid technology that removes the limitations of fixed grid DWDM technology and increases the channel capacity to meet current bandwidth demand with proper utilization of optical spectrum. We present the evolution of EON from the DWDM network. We have discussed the main components and characteristics of EON that includes superchannel and sliceable bandwidth variable transponder (SBVT). Thereafter, we discuss the different modulation and transmission techniques used in EON. Next, we present the recently proposed architectures of SBVT followed by its applications. Lastly, we have discussed various subcarrier generation techniques in brief. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.57.11.110802](https://doi.org/10.1117/1.OE.57.11.110802)]

Keywords: sliceable bandwidth variable transponder; photonic integration; elastic optical network; optical transport network.

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1 Introduction

The demand for bandwidth increases tremendously due to the explosive growth in Internet services such as video conferencing, net-fix, cloud computing, and mobile access with video clients. This requires an extension in the carrying capacity of optical fiber and evolution of next-generation high-speed optical networks. Currently, deployed dense wavelength-division multiplexing (DWDM) network has a fixed grid (channel) of 50 GHz, which causes wastage of spectrum at the low bit rate. Hence it becomes impossible to manage the traffic at a high bit rate (such as 500 Gb/s and 1 Tb/s) at a standard modulation format without superimposing the 50-GHz boundary. It can support 0.8 Tb/s at a 50-GHz channel spacing, and it can be increased twice if channel spacing is reduced to 25 GHz.^{1,2} But it is inadequate to handle the bandwidth requirement of the current scenario due to its limited resources. Hence, for scalable transport solution, three factors are to be considered overtime, namely increasing the carrying capacity of the fiber channel, reducing the transport cost per Gb/s, and capability of responding the dynamic traffic and network constraint.

Transport capacity of an optical fiber can be enhanced using either of the two methods, such as increasing the number of channel count in the fibers or increasing the carrying capacity per channel. But an increment in the channel count is not possible in the ITU-T C-band as it is already exhausted. But in the L-band, it is possible by the employment of special amplifiers.^{3,4} Hence most of the vendors are focusing on increasing the carrying capacity of a channel. Thus, to meet the dual objectives of increasing capacity per DWDM channel at minimum cost, some technologies are to be implemented in addition with coherent technologies, such as flexible grid technology, multiflow transponder,

and terabit-scale superchannel.⁵ For proper addressing of challenges in bandwidth scarcity and to support all above-discussed techniques, it is necessary to migrate from a fixed grid DWDM network to flexible grid elastic optical network (EON), which has the flexible bandwidth and adaptive channel spacing where channel width dynamically changes according to the bandwidth requirement of the transmitted signal.^{6,7} It helps in improving the spectral efficiency, reduction in the spectrum wastage, and better spectral resource utilization. To realize this flexible grid EON, two modules are necessary, namely superchannel and multiflow transponder. Both flexible and gridless are considered to be the same in the literature.^{8,9} Figure 1 shows the spectrum saving in the flexible grid and gridless optical networks with respect to the fixed ITU-T grid. Gridless defines an ideal case, where “just enough” bandwidth is allocated to the request, whereas flexible grid provides a practical spectrum management, in which spectrum slots are assigned with much finer spectrum granularity than fixed ITU-T grid.¹⁰

In this paper, we discuss the journey of migration from the fixed grid DWDM network to flexible grid EON network along with the comparison of the efficiency of both DWDM and EON network for different bit rates and modulation format. Next, we describe the concept of EON and their essential components such as superchannel and sliceable bandwidth variable transponder (SBVT) architectures followed by their applications. We have also discussed the different modulation and transmission techniques based on different bit rates and optical reach. Lastly, we discuss the subcarrier generation (SCG) techniques as an overview. The rest of the paper is organized as follows: EON with its components are explained in Sec. 2 followed by the modulation and transmission techniques in Sec. 3. We have presented SBVT and its architecture in Sec. 4 and

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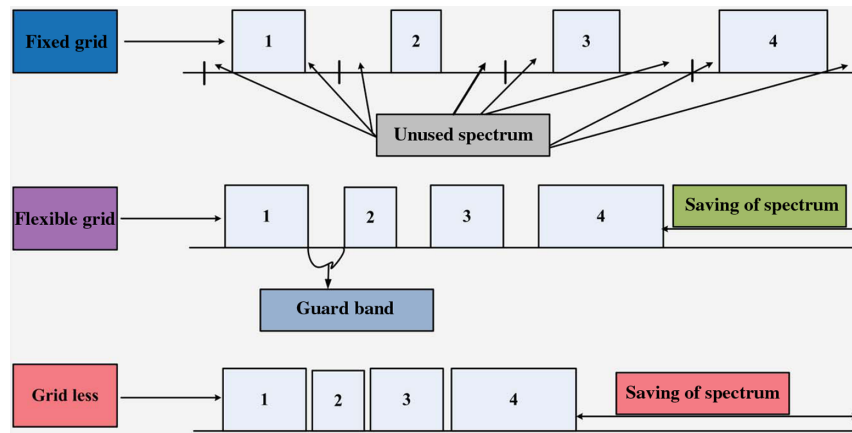


Fig. 1 Fixed grid, flexible grid, and grid less.

explained the subcarrier generation techniques in Sec. 5. Finally, it is concluded in Sec. 6.

2 Elastic Optical Network

EON is the advanced version or next-generation DWDM technology. The challenges in the DWDM technology are the spectrum wastage due to its fixed grid of 50 or 25 GHz, which is specified by International Telecommunication Union (ITU-T) standards. This fixed grid is no longer able to work for high traffic demand such as 400 Gb/s or above.¹¹ This also requires a large number of the single-line-rate transponder, which causes an increment in the network cost and hardware complexity. Even after allocation of a sufficiently broad spectrum, it is difficult to transmit high data rate signals over a long distance with good spectral efficiency. To solve this problem, an adaptive network with the flexible grid is needed, which consists of adaptive transceivers and network elements that can be tuned according to the demand. This combined solution of all the above-discussed issues is EON, which is a flexible grid network that can further divide a 50-GHz channel into narrow width slots.^{12,13} A set of contiguous slots are considered as a channel, which is allocated to any request according to the demand.

This results in improving the channel capacity and optical reach of the fiber. Moreover, it works on the concept of superchannel. Here we employ multiframe transponders instead of the single-line-rate optical transponder, thereby improving the spectrum utilization efficiency and making it an appropriate replacement for a fixed grid DWDM network.^{10,14} Table 1 shows the efficiency of DWDM and EON at different modulation formats and bit rates for 300-km point-to-point link. EON provides good spectral efficiency over a fixed grid DWDM. For example, in fixed grid DWDM, 1000 Gb/s (DP-QPSK) could be transmitted using 10x 100 Gb/s subsignals that require 500 GHz of optical spectrum, whereas in EON it could be transmitted using 200 GHz of optical spectrum. Hence, EON provides up to 150% improvement in the spectral efficiency over a fixed grid DWDM.^{17,18}

2.1 Characteristics of Elastic Optical Network

- i. It supports higher data rates
It uses advanced polarized modulating formats (PM-16QAM, PM-QPSK, and PM-BPSK), super-channel technique, advanced analog-to-digital

Table 1 Comparison of efficiency of DWDM and EON for different modulation formats and bit rate.^{15,16}

Demand bit rate (Gb/s)	Modulation format	Channel bandwidth = spectral bandwidth + guard bandwidth (GHz)	Fixed grid solution	Efficiency enhancement for EON (%)
40	DP-QPSK	25 + 10	One 50-GHz Channel is required for transmission	35 GHz versus 50 = 43%
100	DP-QPSK	37.5 + 10	One 50-GHz Channel is required for transmission	47.5 GHz versus 50 = 5%
100	DP-16QAM	25 + 10	One 50-GHz Channel is required for transmission	35 GHz versus 50 = 43%
400	DP-QPSK	75 + 10	Four 50-GHz channels are required for transmitting data at a bit rate of 100 Gb/s per channel	85 GHz versus 200 = 135%
400	DP-16QAM	75 + 10	Two 50-GHz channels are required for transmitting data at a bit rate of 200 Gb/s per channel	85 GHz versus 100 = 17%
1000	DP-QPSK	190 + 10	Ten 50-GHz channels are required for transmitting data at a bit rate of 100 Gb/s per channel	200 GHz versus 500 = 150%
1000	DP-16QAM	190 + 10	Five 50-GHz channels are required for transmitting data at a bit rate of 200 Gb/s per channel	200 GHz versus 250 = 25%

converter (ADC), coherent detection, and photonic integration technology to support higher data rates.¹⁶

ii. Closer channel spacing

It is having closer and small channel spacing, and sometimes it is gridless channels for effective utilization of spectrum.¹⁶

iii. Spectrally efficient modulation schemes according to the optical reach

It allocates modulation schemes according to the optical reach such as PM-16QAM for small, PM-QPSK for medium, and PM-BPSK for large optical reach.¹⁶

iv. Bandwidth squeezed restoration

It is a different type of recovery service as compared with the conventional recovery like protection path. In BSR, bandwidth of the backup path is reduced according to the client requirement. It is a cost-effective restoration technique.

Example: As shown in Fig. 2, there are two paths, one from A to D and the other from B to C, each has a bandwidth of 300 Gb/s. Here the capacity of fiber is 400 Gb/s, so the path from B to C has 100 Gb/s bandwidth available. In case of failure of the link between A and E, the optical path (A to D) is shifted to the recovery path nodes A, B, C, and D. Therefore, SBVT reduces the bandwidth of the path (A to D) from 300 to the 100 Gb/s so that it can accommodate in the available bandwidth in the paths B to C.¹⁹

v. Sliceable bandwidth variable transponder

The main key aspect of EON is SBVT, which is a BVT of the next-generation network. In conventional BVT, whole transmitter capacity is assigned to a single connection request (source and destination pair). But SBVT is a flexible multiflow transponder, which is capable of routing the data in different destinations simultaneously without increment in the cost and complexity as shown in Fig. 3. Moreover, it also has the ability to tune dynamically according to the optical

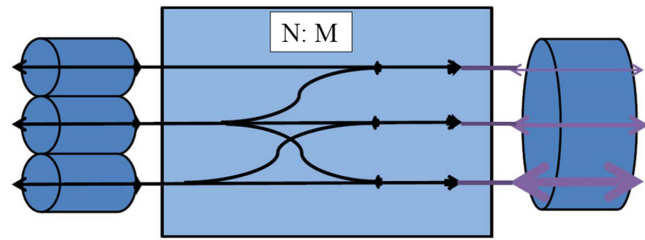


Fig. 3 Multiflow transponder.

reach, optical bandwidth by proper adjustment in the parameters such as modulation format, forward error corrections (FEC) coding, gross bit rate, and optical spectrum shaping. These transponders are responsible for reducing the cost and complexity of EON.²⁰

2.2 Superchannel

Superchannel is a set of DWDM wavelengths that are generated from same optical line card and comes into operation in one operation cycle. It passes through the routing devices such as wavelength selective switches and optical add-drop multiplexers (OADMs) as a single entity providing high data rate and capacity. Coherent superchannel forms the foundation of next-generation intelligent optical transport network (OTN) by increasing the capacity of a channel from 100 Gb/s to 1 Tb/s without any compromise in the optical reach. An increment in the spectral efficiency due to coherent detection and higher order modulation helps in the implementation of coherent superchannel. Tera-bit scale superchannel provides the main difference between DWDM and EON.²¹

Problems addressed by the superchannel:

1. It scales the bandwidth without scaling the operational procedures.
2. It enhances the DWDM network capacity and optical reach.

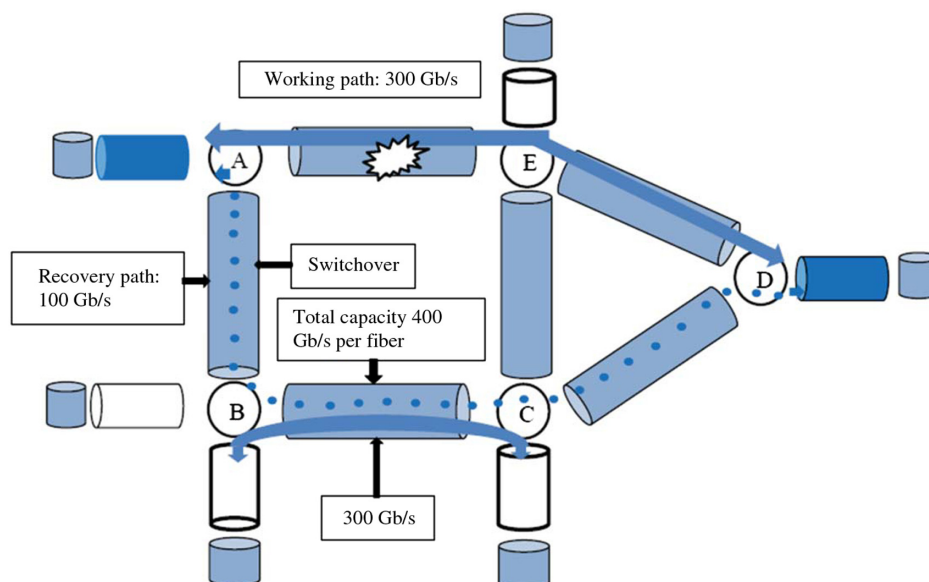


Fig. 2 Bandwidth squeezed restoration.

3. It provides the next-generation high-speed data services.²²

2.2.1 Concept of superchannel

As mentioned earlier, superchannel brought into operation in a single operational cycle. The main concept of superchannel and the difference between superchannel and the normal channel is described below.²²

In DWDM channel, a guard band is present on the lower and upper edges of the channel. This guard band is necessary for optical switching, multiplexing, and demultiplexing of optical channels. But it consumes a huge amount of spectrum that is not useful for the actual payload transport and causing a reduction in the fiber transport capacity. Therefore, to provide the solution of this problem optical industry has moved toward a technology called superchannel, which is much wider than a conventional DWDM channel and it operates in a single operational cycle.²³

As shown in the example in Fig. 4(a), we consider one DWDM conventional channel of capacity 1.2 Tb/s, which is allocated 12×100 Gb/s waves using ITU-T grid, and it is equivalent to a superchannel of 1.2 Tb/s. The DWDM channel requires 600 GHz of optical spectrum to carry 1.2 Tb/s, whereas the superchannel requires 462.5-GHz optical spectrum for transport as shown in Fig. 4(b). Here, a guard band is needed only at the lower and upper edges and not between each subchannel. Therefore, it is considered to be a single unit replacing 12 individual 50-GHz channels to a single 462.5-GHz channel, which is provisioned in a single operation cycle. But it requires a network that supports a flexible grid channel plan. Fortunately, a flexible grid channel plan is recently standardized by ITU-T under ITU-T G.694.1. Thus, the superchannel saves the optical spectrum by 23% as compared with the conventional DWDM channel.⁴

2.2.2 Superchannel can only be possible by photonic integrated circuits technology

As mentioned earlier, superchannel brought into operation in a single photonic integrated circuits (PIC) technology is

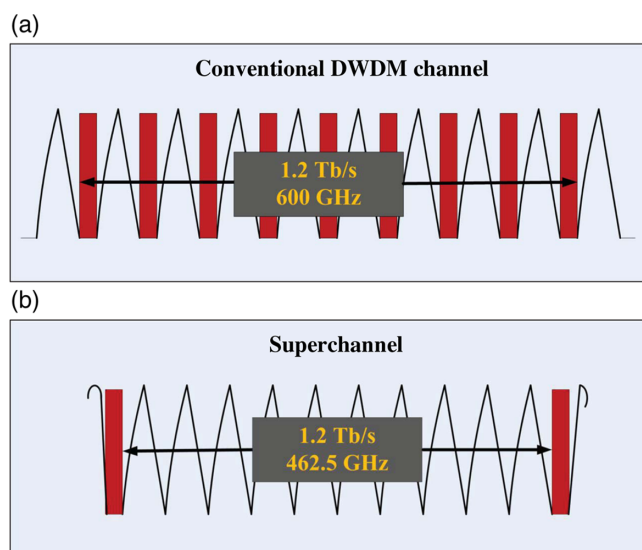


Fig. 4 (a) Conventional channel and (b) superchannel.

mandatory for the superchannel implementation and is shown in Fig. 5. Consider a superchannel consisting of 12 subcarriers (subchannel). In this case, the implementation of superchannel using discrete optical components is highly complex. To implement this, we need 12 sets of optical components per line card, which is unrealistic. The solution to this problem can be obtained from the PIC technology. In this case, we require two PICs, one for transmission and the other for reception. In PIC, all 12 carriers are fused into a single line card forming a superchannel that operates in one operational cycle reducing power and hardware complexity by 12 times in comparison with 12 discrete components.²² It is a compact, efficient, and reliable technique. Beyond 100 Gb/s PIC technology is mandatory, without it the implementation of superchannel is not possible.²⁴

2.3 Limitations of the Flexible Grid/Gridless Optical Networks

The challenges or limitations of the flexible grid/gridless optical networks are the cost and complexity of hardware and software network control systems. To provide the flexible (elastic) bandwidth at high speed, advance control planes are required, which support the flexible transceivers and network elements. On the other hand, flexible grid optical network increases the hardware complexity due to the deployment of flexible grid equipment, such as SBVT, superchannels, and flexible grid reconfigurable optical add-drop multiplexer (FlexROADM). In a flexible grid optical network, conventional channels have been replaced with superchannels. The managing of the flexible-grid superchannels is a big challenge as they occupy variable spectrum on the ITU-T grid based on the modulation format used (PM-BPSK, PM-QPSK, PM-16QAM, etc.). This leads to the evolution of FlexROADM, which can flexibly switch variable optical spectrum.⁴ However, the cost and complexity of FlexROADM equipment including spectrum selective switches, tunable laser, tunable filter, etc increase while reaching to much finer spectrum granularity due to the switching flexibility issues. Furthermore, flexible grid network affects the cost of the power amplifiers due to an increment in the number of channels in the fiber. More numbers of channels inject more power on the link, thereby exceeding the power handling capacity of the amplifier that degrades the link performance unless it is replaced by the high-power amplifiers. Therefore, the requirement of advance control planes and deployment of FlexROADMs, SBVT, superchannels, and high-power amplifiers make flexible grid optical network a quite expensive approach, despite being of providing large capacity.²⁵

3 Modulation and Transmission Techniques

3.1 Modulation

Modulation is the process of imposing a digital signal onto a carrier signal in the analog domain, whereas it is imposed on the beam of light in the optical domain. The simplest and effective form of modulation that has been utilized in the past decades by DWDM network is intensity modulation direction detection (IMDD)—which is also called on/off keying (OOK). In IMDD modulation technique, the signal encodes a single bit (a 1 or 0) in each symbol and each

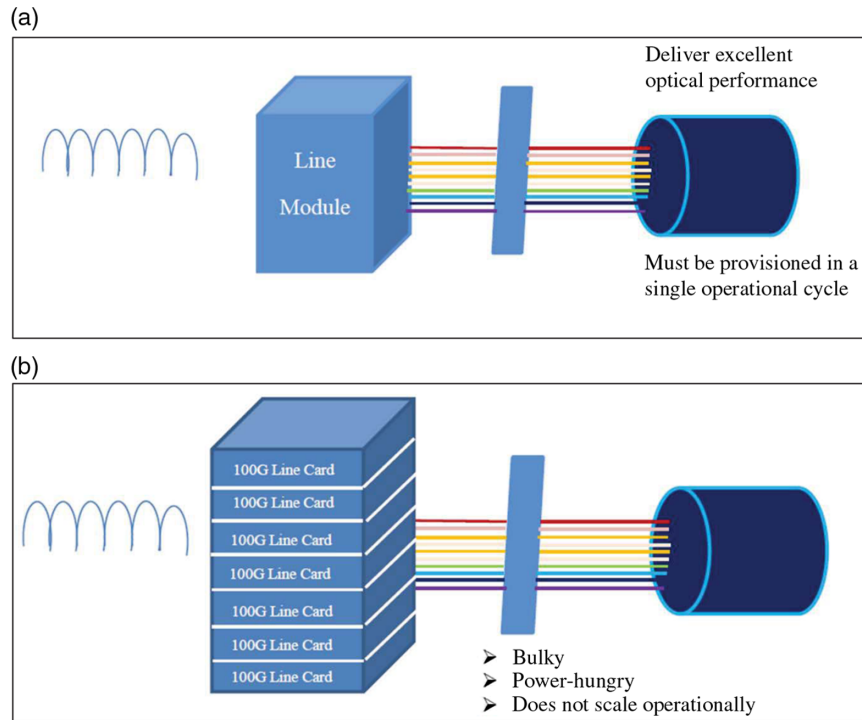


Fig. 5 (a) Superchannel with PIC technology and (b) superchannel with discrete component.

symbol is representing one cycle of a clock. Its implementation is simple and cost-effective with less hardware complexity. But the spectral efficiency is poor along with the limitation for 10 over 2.5 Gb/s. It provides a wider transport spectrum for 10 over 2.5 Gb/s, but the period of the bit rate is small leading to chromatic dispersion. Therefore, to overcome the effect of chromatic dispersion, dispersion compensation is deployed. It is also found that during an increase in the channel capacity or channel data rate (100 Gb/s), the effect of some more factors arises to affect the performance that includes polarization mode dispersion. Hence, it is necessary to consider all such factors while designing a DWDM or EON.²²

Now it is found that IMDD or OOK technique is not suitable for higher channel capacity such as beyond 10 Gb/s. For higher channel capacity, the optical industry prefers to go for higher order modulation techniques (M -ary modulation techniques) that can carry more bits in each symbol. In this M symbols are transmitted where each symbol is comprised with at least $N(N = \log 2M)$ bits. This technique also supports a higher number of bits per symbol supporting high data rate thereby reducing the symbol rate. The effect of dispersion is also reduced in this technique. Therefore, it is seen that higher order modulation techniques have good spectral efficiency with improved information capacity of the fiber.¹ Many higher modulation techniques are available, which supports higher data rate. Bits per symbol of different modulation techniques is shown in Table 2.

Further, symbol rate reduction and spectrally efficiency are improved using polarizing multiplexing (PM). The spectral efficiency and the bits-carrying capacity of the symbol are increased twice in this technique. Bits per symbol in polarized modulation multiplexing techniques is shown in Table 3.

Table 2 Bits per symbol in different modulation techniques.

Modulation	Bits/symbol
BPSK	1
QPSK	2
8-QAM	3
16-QAM	4

Table 3 Bits per symbol in polarized multiplexed modulation techniques.

Modulation	Bits/symbol
PM-BPSK	2
PM-QPSK	4
PM-8-QAM	6
PM-16-QAM	8

Optimum spectrum and resource utilization are achieved in higher modulation technique. It is also noted that an increase in the order of the modulation technique decreases the optical reach. So, we find that all modulation techniques are not suitable for all optical reach. Every modulation technique has its own spectral efficiency for the corresponding optical reach as shown in Table 4.²⁶

Table 4 Normalized reach versus total capacity of different modulation techniques.²²

Modulation	Normalized optical reach (km)	C-band capacity (Tb/s)
PM-BPSK	5000	4
PM-QPSK	3000	8
PM-8QAM	1500	12
PM-16QAM	700	16
PM-32QAM	350	24

3.2 Transmission Techniques

Currently, deployed conventional optical network is using wavelength-division multiplexing (WDM) with incoherent technologies. It can support a maximum data rate of 40 Gb/s. Hence to fulfill the increasing demand for data transmission capacity, it is required to have the better exploration of existing optical network in the C-band along with good transmission techniques that can provide high spectral efficiency.

SBVT supports transmission techniques that include Nyquist wavelength-division multiplexing (NWDM), orthogonal frequency division multiplexing (O-OFDM), and time-frequency packing (TFP). Each transmission technique is spectrally efficient for a particular scenario.²⁷

3.2.1 Nyquist wavelength-division multiplexing

The main idea of Nyquist WDM transmission technique is to employ a digital pulse-shaping filter at the transmitter section that limits the bandwidth of the signal within the Nyquist frequency (i.e., half of the symbol rate) or in the other words, it limits the channel spacing equal to the baud rate. This technique improves the spectral efficiency by placing Nyquist filtered WDM channels closer to each other as shown in Fig. 6.²⁷ Here, a root raised cosine acts as a matched filter to limit the bandwidth. Due to lesser channel spacing, this technique has intersymbol interference (ISI) free transmission, minimum interchannel crosstalk along with good tolerance against the distortion effects such as dispersion and fiber nonlinearity.²⁸ NWDM-based superchannel provides negligible changes in the current single channel receiver by enabling signal demodulation DSP. It provides high spectral efficiency, and it is suitable for long-distance transmission. Nowadays, the NWDM technique provides an integrated solution and it also provides commercial products that are available on the market.²⁹

3.2.2 Orthogonal frequency division multiplexing

OFDM is a multicarrier modulation technique, which provides the transmission of a single data stream over a number of parallel lower rate subcarriers. Due to its parallel transmission, an OFDM symbol is longer as compared with a serial transmission system with the same data rate. In OFDM, subcarriers (subchannels) are overlapped and due to their orthogonality property, their detection takes place without crosstalk. Due to the low rate (e.g., Mbaud) orthogonal subchannels, its optical spectrum becomes narrower thereby

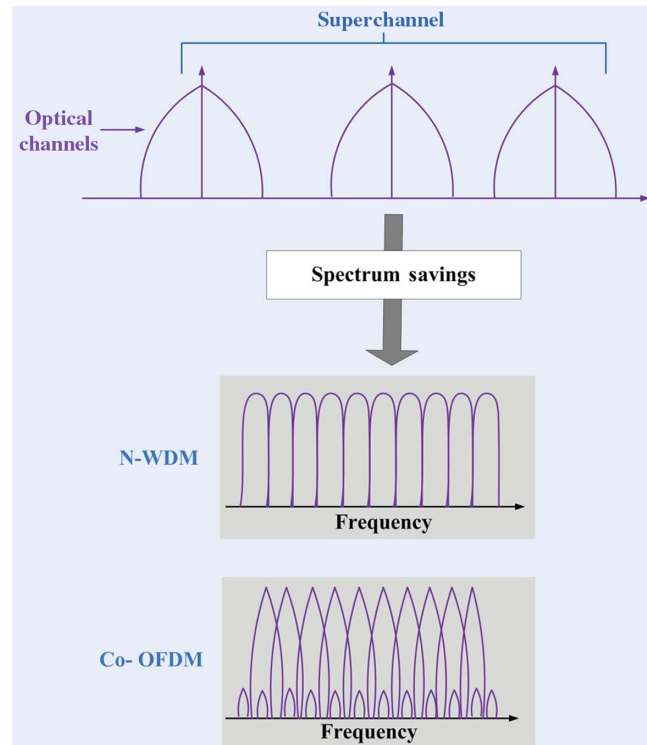


Fig. 6 Spectrum saving in OFDM and NWDM transmission technique.

avoiding the intercarrier interference (ICI). OFDM became more popular in communication because of its high performance against multipath distortion in comparison with other transmission techniques. It is used in mobile communication, wireless LAN, and digital audio broadcast system.^{30,31}

In OFDM, orthogonality has to be maintained between the modulated and demodulated subcarriers. It is very sensitive to the ISI, synchronization error, and frequency offset in the channel, which can affect the orthogonality thereby degrading the BER.³²

3.2.3 Time-frequency packing

TFP generates the pulses that are strongly overlapped in both the time or frequency domains to achieve high-spectral efficiency. But it introduces ICI and ISI. Hence to avoid such interferences, proper coding techniques and compensation in the digital signal processing (DSP) receiver are used. A low-density parity-check code is helpful in achieving maximum information rate at a given modulation format in the presence of ICI, ISI, and noise. These codes are introduced in the transmission system.³³ The hardware system that is required for the implementation of optical fiber system based on TFP is similar to the traditional WDM system. Moreover, transmitter architecture of TFP is simpler than NWDM because it does not require DSP, digital-to-analog converter, and pulse shaping circuit. However, TFP technique needs improvement in the performance and complexity as it is not yet completely matured technique.³⁴

- Table 5 shows the above-discussed transmission techniques in terms of maximum spectral efficiency, optical

Table 5 Summarized all the three transmission techniques.³⁵

	Maximum spectral efficiency	Optical reach	Inter-ISI	Cost and complexity		Uses
				T_x	R_x	
Nyquist WDM	Depends on the modulation scheme; channel spacing \geq the symbol rate or baud rate: e.g., 8 b/s/Hz for PM-16QAM and 4 b/s/Hz for PM-QPSK	Depends on the modulation format (PM-QPSK and PM-16QAM for several thousands of kilometer and lesser for higher formats)	Not present	Operated by DAC (e.g., electronic bandwidth $\geq 0.5 \times$ symbol rate or baud rate)	Operated by ADC and DSP (e.g., electronic bandwidth $\geq 0.5 \times$ symbol rate). Sampling rate \geq symbol Rate	Core/long-haul metro/regional
Time frequency packing (with PM-QPSK)	Channel spacing can be smaller than the symbol rate or baud rate: e.g., 8 b/s/Hz	Supports thousands of km with variable spectrum efficiency: e.g., 3000 km (with 5.16b/s/Hz) 5500 km (with 4.2 bit/s/Hz)	Present	DAC is not needed, Digital preemphasis or predistortion is avoided	Operated by ADC and DSP (e.g., electronic bandwidth $< 0.5 \times$ symbol rate or baud rate)	Core/long-haul metro/regional
O-OFDM	Depends on the modulation format (for >64 subcarriers); channel spacing \geq symbol rate or baud rate: e.g., 4 b/s/Hz in case of PM-4QAM and 8 b/s/Hz in the case of PM-16QAM	Depends on the modulation format and detection scheme (PM-4QAM and PM-16QAM and CO-OFDM for several thousands of km, less for higher formats)	Not present	Operated by DAC and DSP (e.g., inverse Fourier transform processing, oversampling sampling rate $>$ symbol rate or baud rate)	Operated by ADC and DSP (e.g., electronic bandwidth = $0.5 \times$ symbol rate baud rate).	Core/long-haul metro/regional

reach, ISI, and cost and complexity of transmitter and receiver. Spectral efficiency is defined as the information rate transmitted over a given bandwidth.

- The maximum spectral efficiency of any transmission technique depends on various factors, such as modulation formats, code rates, and filtering action. In case of NWDM, channel spacing should be greater than or equal to the symbol rate, e.g., 4 b/s/Hz for PM-QPSK and 8 b/s/Hz for PM-16-QAM and in case of OFDM channel spacing, it should be greater than or equal to the symbol rate, e.g., 4 b/s/Hz for PM-4-QAM and 8 b/s/Hz for PM-16-QAM, whereas, in TFP, channel spacing can be lesser than the symbol rate, e.g., 8 b/s/Hz for PM-QPSK.
- The optical reach of each transmission technique depends on different factors. The optical reach of NWDM and OFDM depends on the modulation formats (PM-QPSK and PM-16-QAM for several thousands of kilometer and less for higher formats), whereas TFP can support the thousands of km with variable spectrum efficiency.
- ISI is a signal distortion, where a symbol provides interference with subsequent symbols, which could result in noise and unreliable communication. NWDM and OFDM do not introduce ISI, whereas TFP introduces ISI and ICI.
- The cost and complexity of the transmitter and receiver mainly depend on the DAC, ADC, and DSP modules. In the transmitter section, NWDM is mainly driven by DAC, OFDM is driven by DAC and DSP, whereas TFP does not require DAC. However, in the receiving section, all three transmission techniques are mainly driven by ADC and DSP.³⁵

4 Sliceable Bandwidth Variable Transponder

The main component of EON that makes it flexible and efficient is SBVT. SBVT is a collection of “virtual” lower capacity BVTs as shown in Fig. 7. It is a multiflow transponder that supports multiple optical flows with different data rates ranging from 10 Gb/s to 1 Tb/s, which are directed into multiple directions simultaneously. It supports adaptive and dynamically changeable distance adaptive modulation format. A group of subchannels is generated at the output of SBVT, which are fed into media channels to get directed into different directions.³⁶

4.1 General Requirements of Sliceable Bandwidth Variable Transponder

- It should be sliceable
This transponder should be capable of supporting the generation of multiple subcarriers that can be sliced and directed toward multiple directions simultaneously.³⁷
- Multiple subcarries with flexible channel spacing
This transponder should be capable of generating subcarrier with flexible channel spacing. This helps to allocate spectral spacing according to the requirement, which can be automatically altered according to the data rate and modulation technique.³⁷
- Support of variable data rates
The transponder should be capable of handling different and variable data rates, by altering the number of subcarriers along with the data rates.³⁷
- It supports dynamically changeable multiple modulation formats

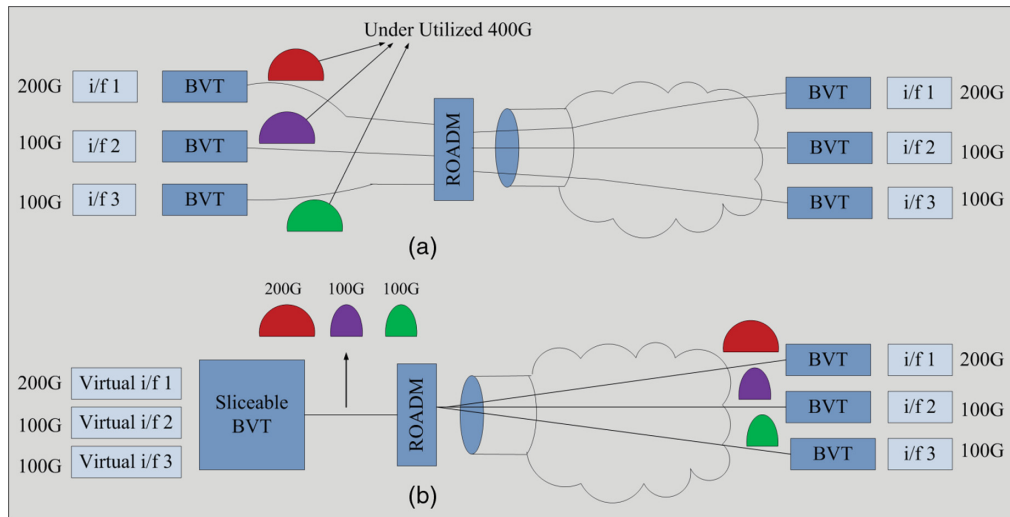


Fig. 7 (a) Bandwidth variable transponder and (b) sliceable bandwidth variable transponder.

The transponder should be capable of supporting different modulation formats (such as PM-BPSK, PM-QPSK, and PM-16QAM) according to the optical reach.³⁷

v. Adaptive code rate

The transponder should support adaptive code rate. The amount of redundancy required by each subcarrier should be adapted according to the physical characteristics of the path.³⁷

4.2 Architectures of Sliceable Bandwidth Variable Transponder

In this section, three architectures have been proposed in Refs. 35–38, as follows.

First architecture of SBVT is as follows.

The above-mentioned architecture shown in Fig. 8 consists of the electronic processing block, the PIC, and mux/coupler. Initially, data are passed through an electronic

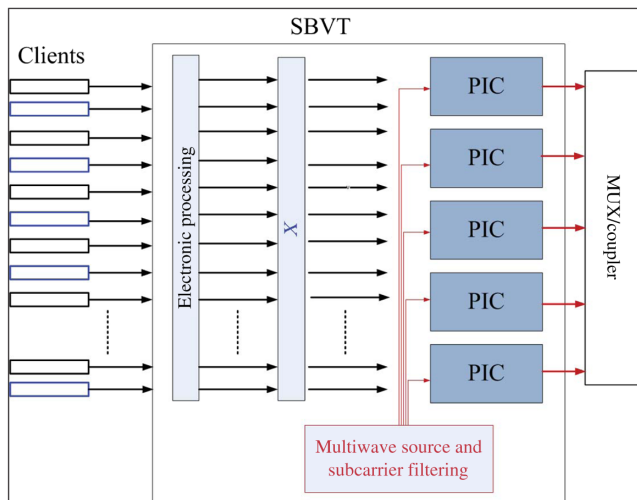


Fig. 8 SBVT architecture.

processing unit (which performs filtering, encoding, and pulse shaping) and then fed into PIC for modulating the signal. PIC is capable of generating two modulation techniques (PM-QPSK and PM-16QAM). The modulated subcarriers are multiplexed by mux/coupler to form a superchannel then directed into the specific media channel.

The architecture section shown in Fig. 9 describes the information rate of 400 Gb/s or we can say modulation and transmission of 400 Gb/s data.³⁷

Here, we have chosen 400 Gb/s PM-QPSK typically, and we realize it as four 100 Gb/s interfaces are considered instead of one 400 Gb/s interface. One 400 Gb/s interface requires a baud rate of around 100 Gbaud, which is practically impossible in the current scenario. Hence, we have used four 100 Gb/s interfaces with a baud rate of 25 Gbaud, which are handled by four PICs. Each PIC will modulate 100 Gb/s. In Fig. 9(a), traffic from clients initially enters into the OTN, which is an interface between client and SBVT or it can also be defined as an electrical layer between IP layer and the optical layer. Later it enters into electronic processing module, where processing is done such as encoding, pulse shaping, filtering, and lastly it is directed to proper PIC for modulation.

Figure 9(b) shows the internal functioning of a dotted block of Fig. 9(a). Here, we consider two cases for the modulation of 200 Gb/s using PIC: initially by PM-16QAM, which is followed by PM-QPSK.

i. 200 Gb/s PM-16QAM modulation:

In this case, two 100 Gb/s interfaces are replaced with a 200 Gb/s interface. In this case, only one PIC A is needed, and the electronic switch is set to the output port 1. Hence, 200 Gb/s is modulated by PM-16QAM.

ii. 200 Gb/s PM-QPSK modulation:

In this case, we need two 100 Gb/s interfaces. Here we need two PIC one for each 100 Gb/s interface. In this, the electronic switch is set in such a way to switch the clients toward port 2, by this way all the clients from one 100 Gb/s modulated by PIC A and other by PIC B.³⁷

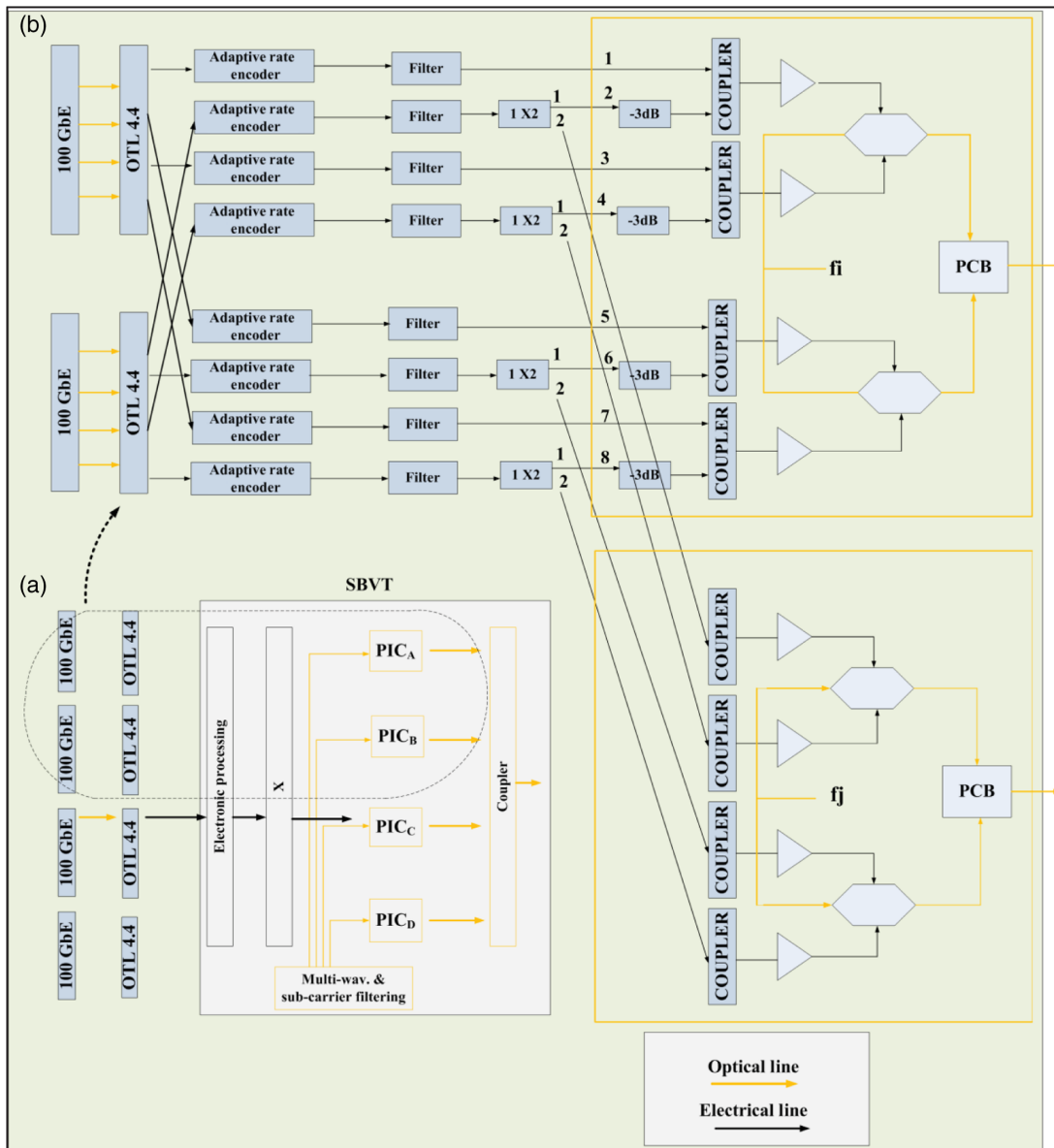


Fig. 9 (a) SBVT architecture enables information rate of 400Gb/s and (b) internal functioning of the dotted block.

4.3 Photonic Integrated Circuit

PIC is essential for the superchannel generation. In this architecture, PIC is modulated the subcarriers by two techniques PM-16QAM and PM-QPSK as shown in Fig. 10.

In this, PM-16QAM signal is generated if clients are applied as an input to all the eight ports, the first four inputs generate a 16-QAM signal then polarizer beam combiner generates a polarization multiplexed signal (PM-16QAM). Next PM-QPSK is generated by applying input to ports 1, 3, 5, and 7 keeping the ports 2, 4, 6, and 8 in a switched OFF condition.³⁷ But in the third SBVT architecture, PM-BPSK is also generated by applying clients as input to ports 1 and 5.³⁸

The second architecture of SBVT is as follows:

The above Fig. 11 shows outlook of the second SBVT architecture. The functioning of SBVT architecture can be explained by three sections. First is OTN interface, next is

a multiflow optical module and lastly optical cross-connects (OXC) as shown in Fig. 11.

OTN interface:

OTN is an electrical layer interface between the IP layer and client's layer. It is an efficient and cost-effective technique for the operators to form a systematic and well-organized optical network. The International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) organization develops and designs the standards and recommendations for this. These recommendations provide the information to meet the future network needs supporting higher data clients. These standards and recommendations change according to the needs and trends in the industry. It performs various functions such as monitoring, client mapping, grooming, and multiplexing making a network able to support all types of present and future client protocols.³⁹

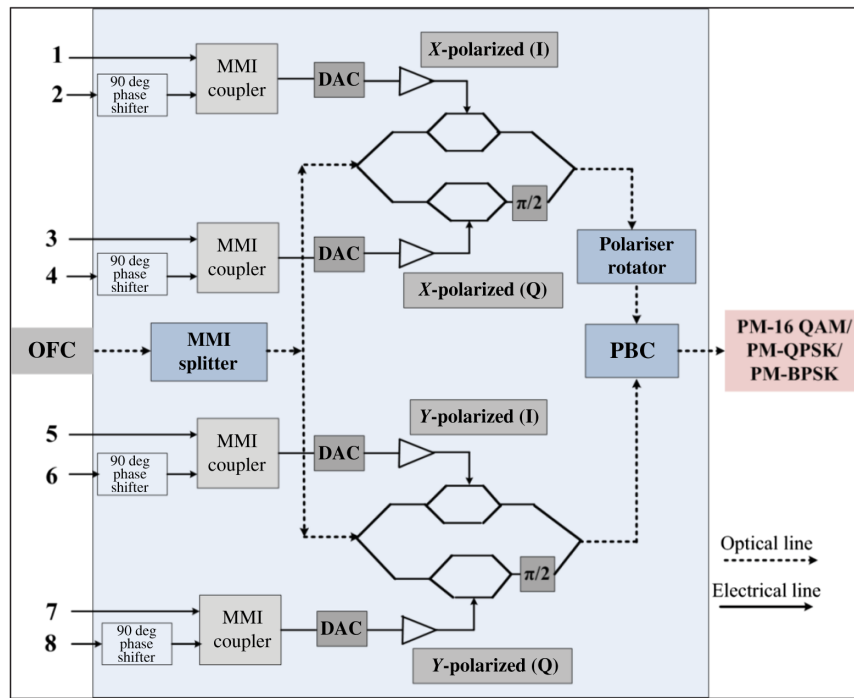


Fig. 10 Photonic integrated circuit.

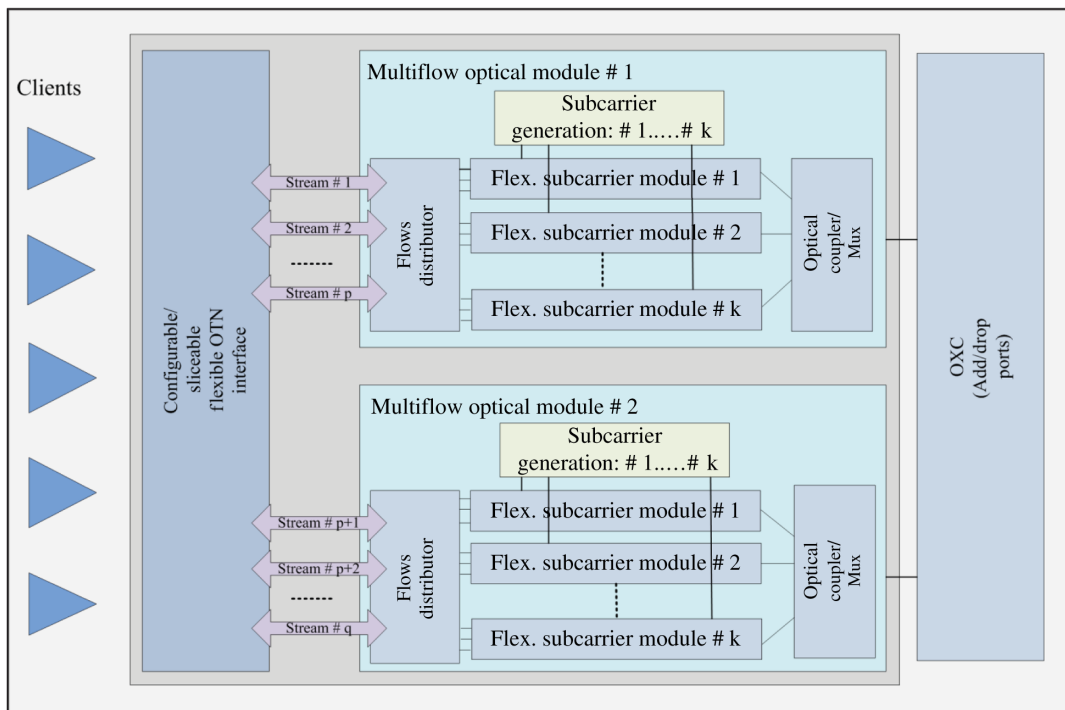


Fig. 11 SBVT architecture.

Another important characteristic of OTN is FEC, which is added in the transmitter and decoded in the receiver. A decoder that is employed at the receiver performs many functions, such as decoding, detecting, and correcting the corrupted. It allows the transmission of the data up to thousands of kilometers with high performance.^{40,41} Multiplexing capability of OTN helps to supports all types of traffic, such as Ethernet, SONET/SDH. Apart from this, it improves

network efficiency by managing the network functions and performances. It mainly contains two units, an optical channel data unit (ODU) followed by an optical transport unit (OTU). ITU-T recommends the OTU4 and ODU4 for 100 Gb/s and for the data formats beyond 100 Gb/s ITU-T G.709 version 3 recommends ODUC_n/OTUC_n, where C is 100 Gb/s granularity and n is an integer number handled by optical network.^{42,43}

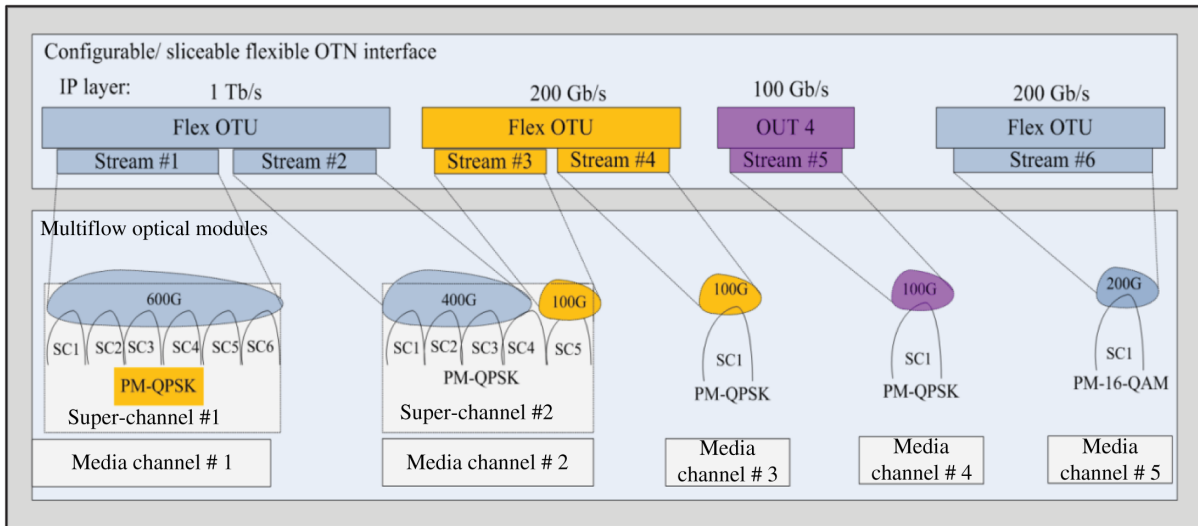


Fig. 12 OTN frames and flexible association with media channel.

The OTN layer also divides higher data streams into the lower data stream, in case it is unable to accommodate the entire data stream into a superchannel due to unavailability of the contiguous spectrum as shown in Fig. 12. Here, 1 Tb/s stream is split into two streams of 600 and 400 Gb/s, respectively. Next, the streams enter into the multiflow optical module.³⁵

Multiflow optical module:

The main parts of a multiflow optical module are flow distributor, subcarrier generator, and flex subcarrier module.

In multiflow module, modulation, transmission, and reception are performed. Flow distributor helps in directing the data stream from OTN to the flex subcarrier module as shown in Fig. 13. The flex subcarrier module contains two sections, such as transmitting section and receiving section.³⁵

Transmission section:

In this section, the input data are first encoded in the encoder followed by the pulse shaping using the pulse shaping circuit and finally fed into the predistortion module.

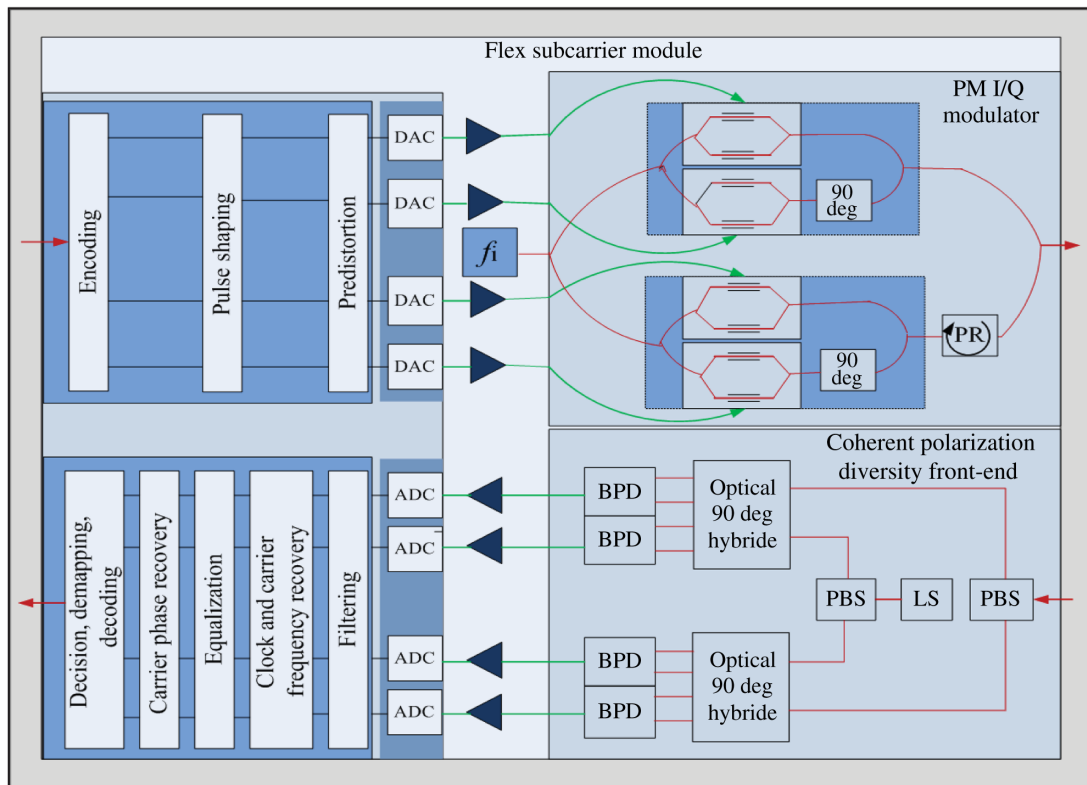


Fig. 13 Flex subcarrier module.

Later, it is fed into the PM I/Q polarized multiplexed modulator for modulation. The modulation format is dependent on bit rate and the optical reach. Now, all the modulated sub-carriers are combined together to form a superchannel, which is guided into a proper media channel for transmission. Later media channels are coupled into the OADM/OXC through a mux/coupler.

Receiving section:

Receiving section consists of two units, namely coherent detection and advanced DSP. In coherent detection unit, a polarized beam splitter divides the signal into two orthogonal polarized components. They are combined with the local oscillator (LS) output in a 90-degree optical hybrid mixer providing in-phase and quadrature-phase components. They are then fed into balanced photodiodes for detection. The detected components are amplified by radio frequency amplifier (RFA), followed by a high-speed coherent ADC. Lastly, data enter into an advanced DSP unit consisting of modules such as filtering, clock, and carrier frequency recovering, equalization, carrier phase recovery, and lastly decision, demapping and decoding module, where finally we get the decoded data.³⁵

The third architecture of SBVT as follows:

Here, we describe the third SBVT architecture consisting of transmitter and receiver section shown in Fig. 14.

Transmitter section consists of various units, such as distance module (DM), which is followed by modulation and transmission module (M&TM). The receiver section consists of demodulator supporting (PM-16QAM/PM-QPSK/PM-BPSK) and DSP unit.³⁸

Transmission section:

Distance module:

Distance module is a programmable module, which dynamically allocates the modulation technique to a data-stream/main-stream according to the optical reach. Data-stream confines the direction and route, where one or more data-stream can have the same direction and route with different dropping points along the route. These data-streams are combined together into a main-stream. Main stream/data stream is carried by a superchannel. While the data stream exceeds the capacity of a superchannel, it gets split forming a new main-stream, which is controlled by a new superchannel. A superchannel is made of multiple sub-channels. A data stream/main stream consists of one and more substreams, which depend on the dropping points along the path. Distance module assigns any one modulation technique to its substreams depending on dropping distance. Every distance module consists of a demux, which demultiplexes the main stream/data-stream into individual sub-streams according to the dropping points in the path and amount of data dropped at each dropping point. A

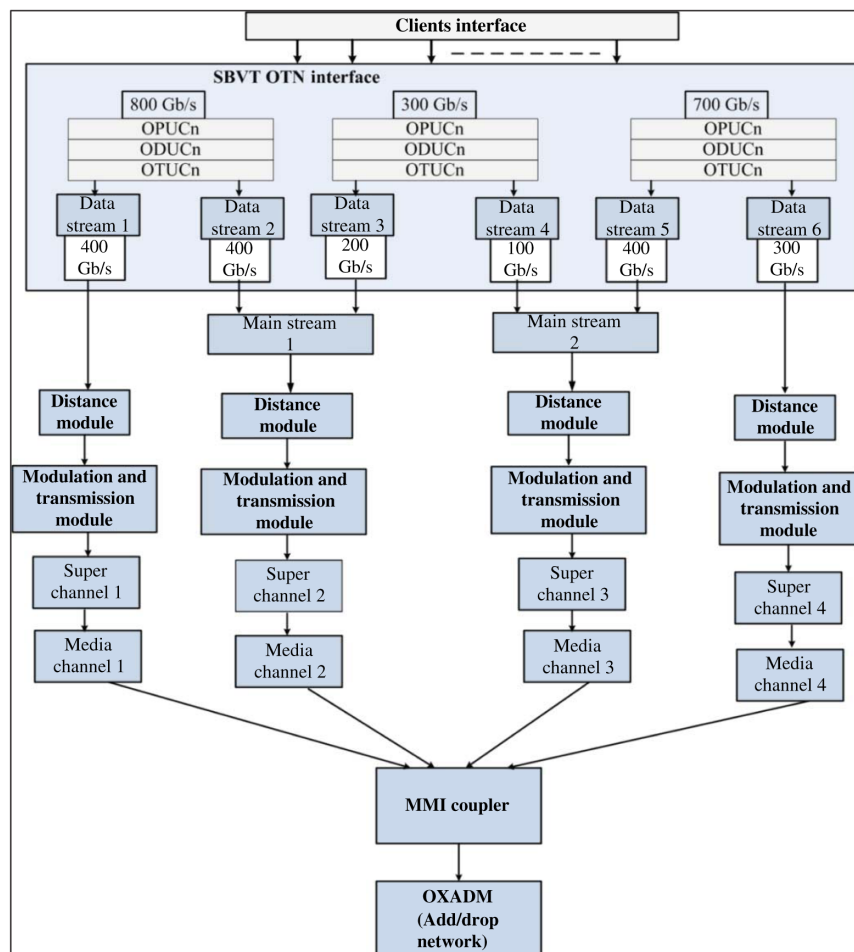


Fig. 14 SBVT transmission section.

modulation scheme is assigned to the demultiplexed output depending on the optical reach of each substream as shown in Fig. 15. Here, three main modulation techniques are used, namely PM-QPSK, PM-16QAM, and PM-BPSK. Each technique is best suited for the given capacity and reach. For short haul distance, PM-16QAM is preferred and PM-QPSK is preferred for the long haul. For extra-long haul and submarines, PM-BPSK is preferred for efficient utilization of spectrum. Each data stream/main stream is carried by a superchannel, whereas substreams are carried by one or more subchannels (subcarriers).³⁸

Modulation and transmission section:

In each of the distance modules, modulation techniques are assigned to data streams. However, in this section, both modulation and transmission are performed. In modulation and transmission section, data-stream/main-stream initially enters into the data processing unit where encoding, pulse shaping, and filtering of data stream/main-stream are performed. Later, it is passed into the demux and switching matrix, where the data stream/main-stream gets split into multiple substreams. They are then directed into suitable planar light wave circuit (PLC) for modulation of the subcarrier according to the distance module. Lastly, modulated subcarriers are coupled by multimode interference (MMI) coupler for the superchannel generation as shown in Fig. 16.

Receiving section:

This section consists of two subsections, namely a decision-making block, which is followed by demodulator block.

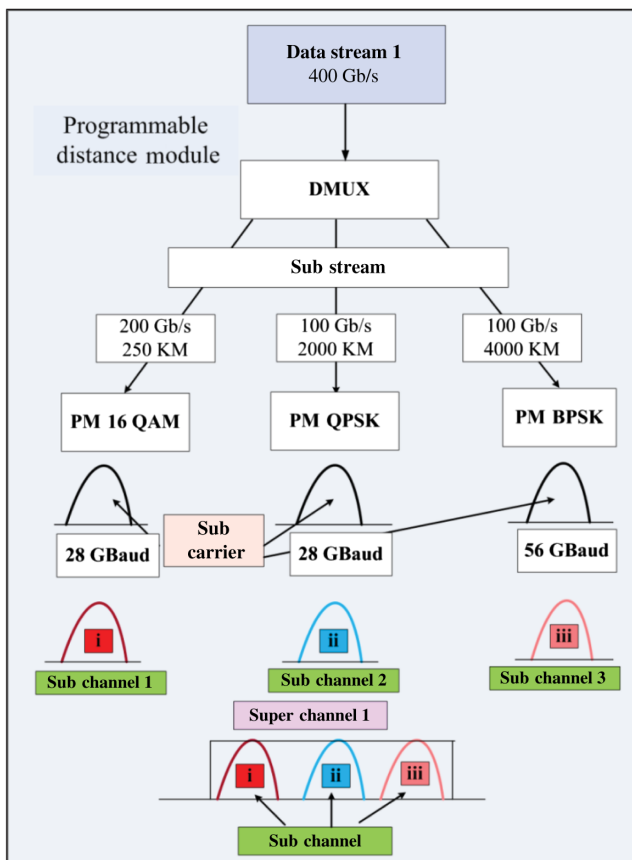


Fig. 15 Distance module.

Decision-making block: This block is used to determine the modulation technique of the receiving signal and directed into a suitable demodulator circuit for demodulation as shown in Fig. 17.

Demodulator block: This block consists of two different demodulator circuits, namely PM-16QAM/PM-QPSK and PM-BPSK demodulation circuits.³⁸

Table 6 shows the comparison of the first, second, and third architectures of SBVT by considering some of their characteristics such as programmable distance module, the concept of subchannel, modulation format, add and drop network, the flexibility of receiving section design, and capability of PLC.

- Programmable distance module is a new module introduced in the third architecture; it works on the distance adaptive modulation, which improves the functionality and spectral efficiency of the architecture.
- The concept of subchannel is not used in first and second architectures, whereas the third architecture uses the concept of subchannel followed by the adding and dropping of the subchannel out of superchannel.
- In the first and second architectures, a complete superchannel is modulated by a single modulation technique, but in the third architecture, subchannels are modulated by different modulation techniques based on their optical reach for efficient utilization of spectral resources.
- In the first and second architectures, OXC is used as an add and drop module, which provides low security, whereas in third architecture, it is replaced by OXADM, which provides high security.
- In the first architecture, demodulators of the receiving section are not mentioned, whereas the demodulators in the receiving section of second architecture support two modulations formats (viz., PM-QPSK and PM-16QAM). The demodulators in third architecture support three modulation formats (viz., PM-QPSK, PM-16QAM, and PM-BPSK).
- PLC is a very essential technique for the implementation of SBVT. In the first architecture, it can modulate the signal in any of the two modulation formats (PM-16QAM and QPSK), whereas the third architecture can modulate the signal in any of the three modulations formats (PM-16QAM, PM-QPSK, and PM-BPSK).

Applications of SBVT:

Dynamically changeable bandwidth:

The sliceable property of SBVT makes it to effectively manage the bandwidths that are dynamically changeable. It serves different destinations with different data rates on demand as shown in Fig. 17. As shown in Fig. 18(a), 400 Gb/s can send the data to four different destinations with each of 100-Gb/s bitrate and 37.5-GHz spacing. Similarly, it can send the data to two different destinations with 200-Gb/s bitrate with 50-GHz spacing each as shown in Fig. 18(b). Finally, it is also seen that it can send data with 400 Gb/s to a single destination with

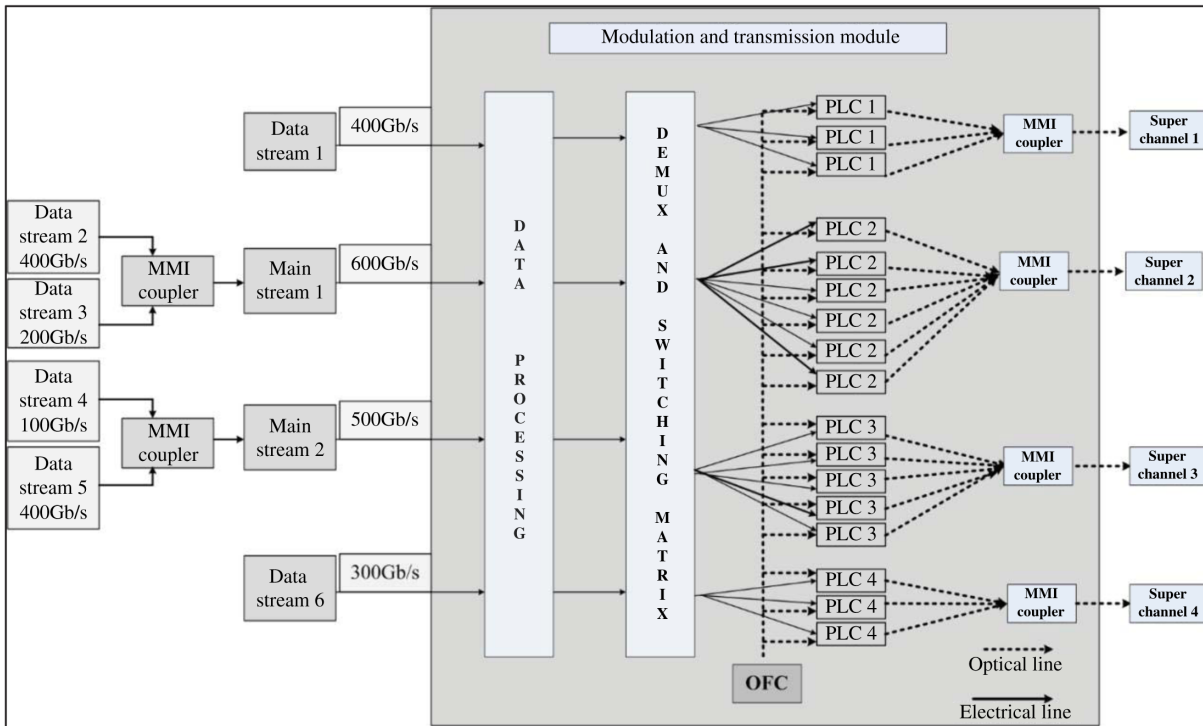


Fig. 16 Modulation and transmission module.

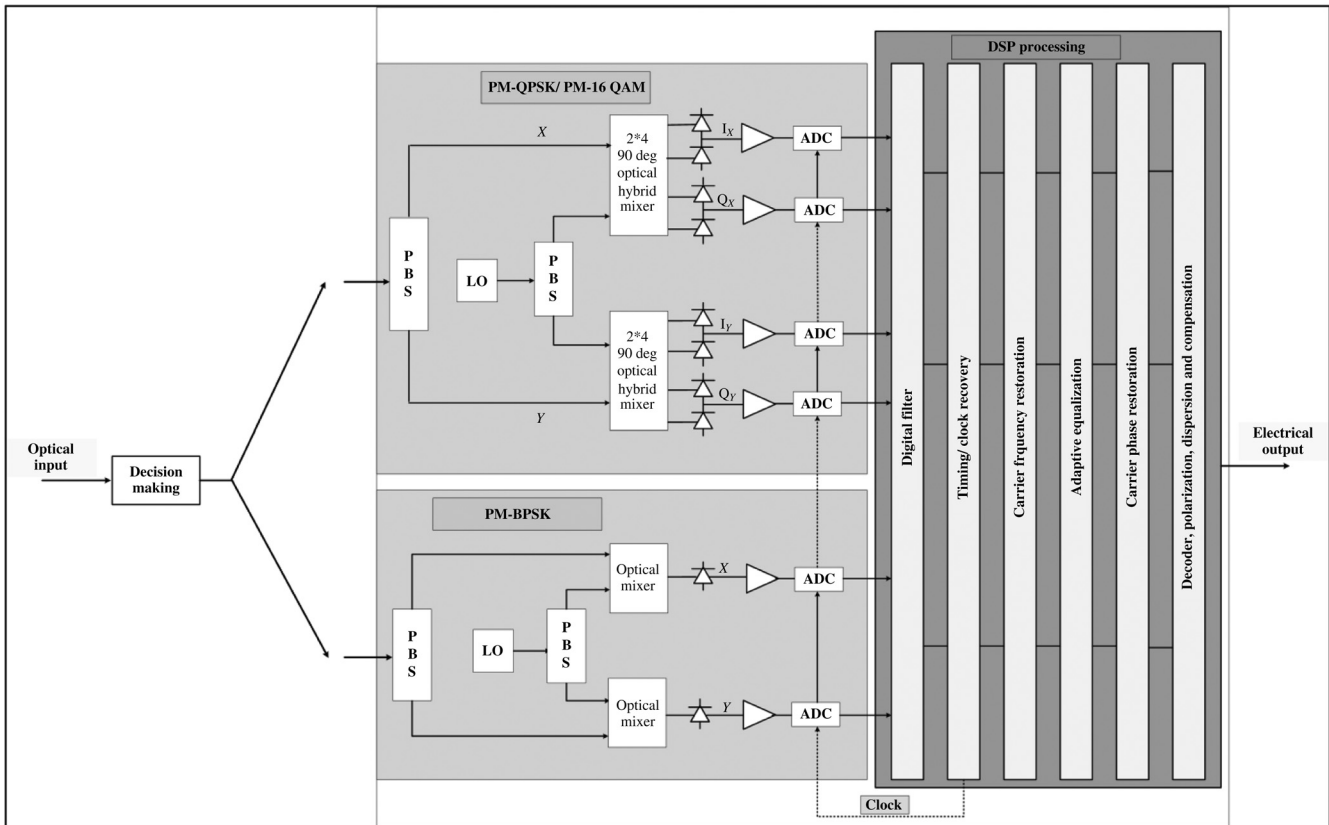


Fig. 17 Receiving section.

Table 6 Comparison between the first,³⁷ the second,³⁵ and third architecture of SBVT.³⁸

Characteristics	First SBVT architecture	Second SBVT architecture	Third SBVT architecture
Complexity	High	Moderate	Low
Programmable distance module	Not present	Not present	Present
Concept of subchannel	Not present	Not present	Present
Adding and dropping of subchannel out of superchannel	Not present	Not present	Present
Modulation format	Single modulation format is used for superchannel	Single modulation format is used for superchannel	Different modulation format is assigned to subchannels according to their optical reach for efficient utilization of spectral resources
Add and drop network	OXC (security is poor)	OXC (security is poor)	OXADM (security is high)
Flexibility receiving section	Not discussed	Demodulator supports (PM-16QAM and PM-QPSK)	Different demodulator circuits for (PM-16QAM, PM-QPSK, and PM-BPSK)
MMI (MMI coupler and MMI splitter)	Not present	Not present	Present MMI devices are used due to their photonic integration ability, low loss, minimum power imbalance, which is essential for SBVT implementation
PLC	Enabling of two modulation techniques: PM-16QAM and PM-QPSK	Not discussed	Enabling of three modulation techniques: PM-16QAM, PM-QPSK, and PM-BPSK

75-GHz spacing and is shown in Fig. 18(c). This shows the flexible grid spacing and sliceability property of SBVT, which helps in dynamically changeable multiple direction optical flow.³⁵

Migrating toward high data rates:

SBVT provides a solution to the optical industry for getting migrated toward higher data rates.³⁵

Restoration of failure of link or fiber:

SBVT helps in the restoration of link or fiber failure without the need for additional transponder due to its sliceability property.

SBVT helps in the restoration of link or fiber failure without any additional transponder due to its sliceable property. For example, consider a super channel of 400 Gbs with a bandwidth of 75 GHz and a link is failed in a path as shown in Fig. 19. The alternate paths are available with 50 Hz, which is less than the bandwidth of the failed link. Now in this situation, the SBVT divides the super channel into two media channels of 50-GHz bandwidth to restore the failure situation. Now, it is seen that under this failure condition, the data are streamlined in two different channels with lower bandwidth thereby delivering the data without loss.³⁵

5 Subcarrier Generation Techniques

The SCG module is an important module consisting of subcarrier modules for optical carrier generation and modulation in case of the transmitter. In the case of a receiver, it has subcarrier modules for coherent detection using the local

oscillators. There are two methods for the generation of optical subcarriers. One method is by using an array of lasers and the other method is using an optical frequency comb (OFC). Each of the methods has its own advantages and limitations.

5.1 Array of Lasers

In this method, an array of lasers is used for the generation of multiple subcarriers.

Advantages:

- i. It provides the independent tunability for each of the subcarrier.
- ii. If C-band tunable lasers are used, the spectrum allocation becomes easier thereby, any part of the spectrum can be used.

Limitations:

- i. It is expensive as more lasers are used.
- ii. Stability is poor due to the degradation of subcarrier overlapping.
- iii. Poor spectral efficiency.⁴⁴

5.2 Optical Frequency Comb

OFC is a multicarrier optical source that simplifies the structure of DWDM and EON involving many individual lasers. In this subcarrier generation technique, a single laser source is capable of generating multiple subcarriers. It is also called a multiwavelength source. OFC refers to an optical spectrum

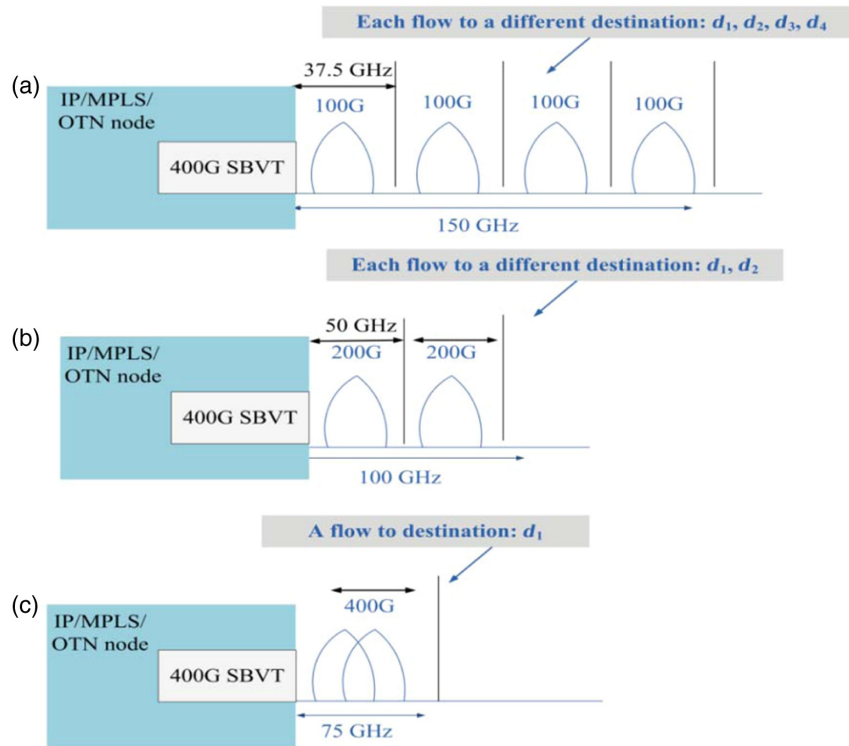


Fig. 18 (a) Data flow directed in four different destinations, (b) data flow directed in two different destinations, and (c) data flow directed in a single destination.

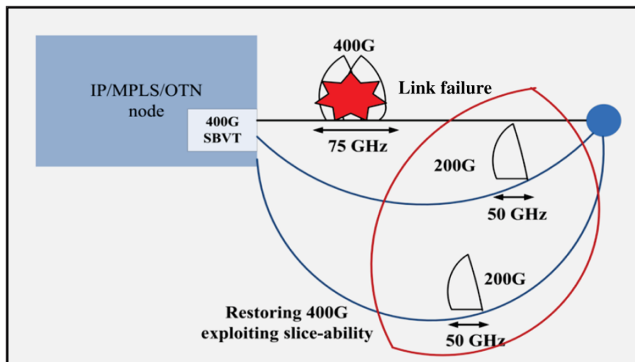


Fig. 19 Restoration of failure.

with evenly spaced optical frequency components with substantial variation in the intensity of comb lines. Usually, this kind of optical spectrum has a regular train of optical pulses associated with it. It has a fixed rate of pulse repetition, which is used for determining the inverse line spacing in the spectrum.⁴⁵

OFC can be represented in the frequency domain by S_n :

$$S_n = S_o + n * S_{rep},$$

where S_n represents the optical frequencies of comb lines, S_o represents the comb offset frequency, n is a large integer, and S_{rep} represents the comb line spacing or repetition rate.

OFC provides a large number of uniform optical lines from a single device, which is required for broadband and high-speed detection. In recent days, OFCs are most preferred for measuring frequency due to its higher accuracy, spectral purity, and broad spectral coverage.⁴⁶ OFCs, which were initially developed to establish a connection between the optical and radio frequency domain, are now being used in many fields of research that includes optical code division multiple access, arbitrary waveform generation, WDM, elastically optical network attosecond science, remote sensing, microwave synthesis, optical communications, laser cooling, optical frequency metrology, astronomical spectrograph calibration, synthesis of ultrapurity optical and RF frequencies, time-frequency transfer based on optical clocks, exoplanet searches, medical diagnostics, molecular fingerprinting, and astrophysics. Now OFC systems are well established in the visible and near-infrared (IR) spectral regions. It is further extending into the mid-IR, along with the terahertz, and extreme-ultraviolet region.⁴⁷

The cost, simplicity, and capability of reducing the effects of Kerr-nonlinearity present in the optical fibers are important factors that determine the appropriateness of this technology, especially in SBVT.⁴⁸

Advantages:

- i. It is cost effective with low-power consumption.
- ii. High stability avoiding the problem of subcarrier interference.
- iii. High spectral efficiency in superchannel generation.

Limitations:

- i. It can tune the overall comb whereas tuning of each subcarrier independently is not available.
- ii. Poor spectrum allocation in the subcarrier.⁴⁹

6 Conclusion

EON is the promising solution for the bandwidth scarcity and for the spectral wastage problem faced by the researchers in the current optical industry. This provides the solution for high bandwidth requirement. This review paper gives the comprehensive survey of EON. In this paper, basic concepts of DWDM and EON are presented followed by the characteristics of EON. Thereafter, we discussed the concept of superchannel and role of PIC technology in the formation of superchannel. Later, the modulation and transmission techniques are discussed. The concept of superchannel implementation was discussed through SBVT transponder along with the general requirements, three architectures, and applications of SBVT. In addition, SCG techniques are explained.

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