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Design and development of a new architecture of sliceable bandwidth variable transponder

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ABSTRACT

In this paper we propose a new sliceable bandwidth variable transponder (SBVT) architecture with the separate analysis on the transmitter and receiver section. In transmission section we propose a distance module (DM) which is a programmable module. It divides a data stream/main stream (which employs a super-channel) into sub-stream and assigned modulation technique to each sub-stream based on their light path distance detailing the concept of sub-channel. In this paper, we have also proposed an algorithm for the distance module. Next we propose a modulation and transmission module (M&TM), where, planar light wave circuit (PLC) is used for enabling three modulation techniques (PM-16QAM, PM-QPSK and PM-BPSK). Finally, we propose the receiving section, which is designed to support three modulation techniques. It consists of two demodulator circuits, one for PM-16QAM/PM-QPSK and the other for PM-BPSK. In this proposed work, we focus on the multi-mode interference (MMI) devices (MMI coupler and MMI splitter) because of their photonic integration technology which is necessary for the implementation of SBVT. Lastly, we propose an elastic optical node architecture which removes the limitations of previously discussed node architecture for long distance communication.

1. Introduction

Bandwidth demand increases continuously around 40% per year due to increase traffic such as video traffic, Netflix, cloud computing and mobile access. This forces the network operators to move toward the optical network which can efficiently transmits at high data rate and at lower cost. Wavelength Division Multiplexing (WDM) technology can provide the solution because of its tremendous growth in the capacity of optical fiber. WDM is used in optical fiber communication for transmission of data in several channels with different wavelength. The ITU-T channel grid provides a fixed optical channel spacing of 25 GHz, 50 GHz and 100 GHz, supporting 160, 80 and 40 channels in the C-band respectively. If each of these channels are allocated with 10 Gb/s optical signal, in C band the capacity of fiber become 1.6, 0.8 and 0.4 Tb/s whereas, WDM has a fixed grid of 25 GHz, 50 GHz and 100 GHz. This becomes the limitation in WDM technology. Therefore, when extra bandwidth is required, it uses more transponders and when smaller bandwidth is required then the unutilized part of the optical spectrum goes waste [1].

To overcome these limitations of fixed grid and to increase the channel capacity beyond 100 Gb/s, techniques such as complex modulation format (PM-QPSK, PM-16QAM, PM-BPSK), polarization multiplexing, advanced digital signal processing, coherent detection and flexible grid is required and thereby proposing the technology known as elastic optical network (EON) [2]. EON increases wavelength data rate from 100 Gb/s to 1 Tb/s and efficiently utilizes the optical spectrum by using flexible grid [3].

The important part of EON to make it flexible is sliceable bandwidth variable transponder (SBVT). It is a multiflow transponder which can transport data in multiple directions simultaneously, along with supporting multiple clients with variable data rates of upto 1 Tb/s. It has a distance adaptive modulation format which can effectively and efficiently utilize the entire optical spectrum [4,5].

The architecture of *SBVT* based on a flexible grid optical networks is presented that provides the advantage of multi-wavelength source over multi-laser source [6]. Based on the analysis, micro-ring resonator (MMR) is used as carrier separator. SBVT architecture consists of photonic integrated circuits for enabling modulation formats. It also supports the connection between the optical transfer network (OTN) stream and media channels [7]. Further, it also describes the application of SBVT architecture for supporting higher traffic dynamics and renewal of link failure along

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with transmission techniques such as optical orthogonal frequency division multiplexing (O-OFDM)/Nyquist wavelength multiplexing (NWDM)/time frequency packing (TFP).

The rest of the paper is organized as follows: in Section 2, we propose a new SBVT architecture that include transmitter section, receiving section and its performance, followed by the elastic optical node architecture in Section 3. Finally Section 4 concludes the paper.

Table 1
Modulation techniques.

Modulation	Normalized reach (KM)	C-band capacity (slit-spectrum)	C-band capacity (grid-less)
PM-BPSK	5000	4 Tbps	5 Tbps
PM-QPSK	3000	12 Tbps	15 Tbps
PM-16QAM	700	16 Tbps	20 Tbps

2. Proposed SBVT architecture

SBVT is a next generation transponder which is a combination of many Bandwidth Variable Transponders (BVT) that supports multiple clients with higher data rates (100 Gb/s to 1 Tb/s). The capacity and optical reach of the SBVT is increased through a distance adaptive complex modulation format (PM-QPSK, PM-16QAM, and PM-BPSK). It uses coherent detection and advanced DSP processing which make it possible to support long haul distance with beyond 100 Gb/s.

SBVT uses the concept of super-channel which makes it sliceable, where multiple optical sub-carriers are combined to form a single unit signal of large capacity with single operating cycle. SBVT uses PLC/PIC technique which can accommodate multiple optical components on a single chip which makes the concept super-channel possible in the proposed architecture. In this proposed SBVT architecture, transmission and receiving sections are separately discussed in the following. Transmitter section consists of OTN, DM and M&TM which are discussed below and receiving section consists of demodulators that supports PM-16QAM/PM-QPSK/PM-BPSK and digital signal processing (DSP) unit that are discussed in latter part.

2.1. Transmission section

2.1.1. Optical transport network (OTN)

OTN provides an interface between the IP layer and optical layer in the electrical domain. It is a combination of standards and recommendations of ITU-T, which utilize the complete advantages of SONET/SDH and Ethernet with variable bandwidth capability. It performs multiple functions such as user mappings, monitoring, multiplexing and management. It is an essential technique for next generation or elastic optical networks which has advanced multiplexing technique to support various traffic types like SONET/SDH, Ethernet, etc. It is designed considering both the present and future bandwidth requirements. Therefore, it is designed to support multiple data rate from 10 Gb/s to 100 Gb/s and beyond for efficient transmission over thousands of kilometer with increase in the flexibility of operators by supporting multiple clients with variable data rates.

It consists of three units namely, optical payload unit (OPU), optical data unit (ODU) and optical transport unit (OTU). The ITU-T Standardization Sector G.872 and G.709 organization has designed and developed the standards and recommendations for this unit considering the future network requirements supporting higher data clients. The standards and recommendations changes according to the needs and trends in the industry.

OTN is an efficient and reliable technique for operators to form a cost effective optical network. Another important feature of OTN is forward error correction (FEC) which is added at the transmitter and at the decoder of the receiver, for detection and correction of error and allowing to transmit data up to thousands of kilo-meters with better performance [8]. For, 100 Gb/s ITU-T recommends the OTU4 and ODU4 but for higher data formats (beyond 100 Gb/s) new steps are carried out by the ITU-T G.709 version 3 [10]. That is ODUCn/OTUCn, where C is the 100 Gb/s granularity and n is an integer number. Apart from this OTN also performs a new function, it divides and slice higher data formats into lower data formats as all the data need not to be sent in one direction or exceed to the capacity of super channel. Example: 800 Gb/s is divided into two streams of 400 Gb/s each [6,9,10].

2.1.2. Distance module (DM)

DM is a programmable module which dynamically assigns modulation technique to data stream based on their optical reach. Each data stream specifies a particular direction and path, if one or more data streams are in same direction and paths, with different dropping points on the path then they can be combined to form a single main stream. Each main stream/data stream has its own super-channel. When the capacity of the super-channel is exceeded, then a new main stream with different super-channel is formed on the same path. Every super-channel consists of several sub-channels (Figs. 1 and 2).

Each data stream/main stream has several sub-streams based on dropping points in the path. Each sub-stream has different dropping and destination points. *DM* provides a competent modulation technique to each of its sub-stream based on their dropping distance instead of using single modulation technique to main stream/data stream. Each *DM* consists of a de-multiplexer which can divide the main stream into several sub-streams depending on the number of dropping points along the path and also the data dropped at each dropping point. Then the dropping distance of each sub-stream and appropriate modulation technique is allocated to each sub-stream based on their optical reach. Three different modulation techniques are used in DM namely, PM-QPSK, PM-16QAM and PM-BPSK. Each technique is best suited for the given capacity and optical reach. For short haul distance PM-16QAM is used whereas, for long haul PM-QPSK is preferred and for extra-long haul and submarines PM-BPSK is used (as shown in Table 1). Modulation techniques should be allocated based on the light path distance for efficient utilization of the optical spectrum. In the example shown in Fig. 4 DM module divides the data stream 1 into three sub-streams (namely 200 Gb/s, 100 Gb/s and 100 Gb/s) and a modulation technique is allocated to each sub-stream based on its optical reach (200 Gb/s-PM-16QAM, 100 Gb/s-PM-QPSK and 100 Gb/s-BPSK).

Each data stream/main stream is carried by a super-channel and sub-stream is carried by a sub-channel(s) (sub-carrier(s)). A sub-stream is carried by one or more sub-channels depending on the number of sub-carriers modulated by the sub-stream. In Fig. 4, data stream 1 consists of three sub-streams and each sub-streams modulate a sub-carrier. Therefore, super-channel 1 has three sub-carrier or three sub-channels and each sub-stream is carried by one sub-channel.

If a sub-stream is of 500 Gbps-PM-QPSK, then it becomes difficult to modulate one sub-carrier because at current scenario sub-carrier with symbol rate 160 GBaud is not achieved. It is expected to be possible after a decade or so. Therefore, it is done by 5 * 100 Gbps and symbol rate reduced to 32 GBaud/carrier. Here five sub-carriers are modulated by the sub-stream so it is carried by five sub-channels.

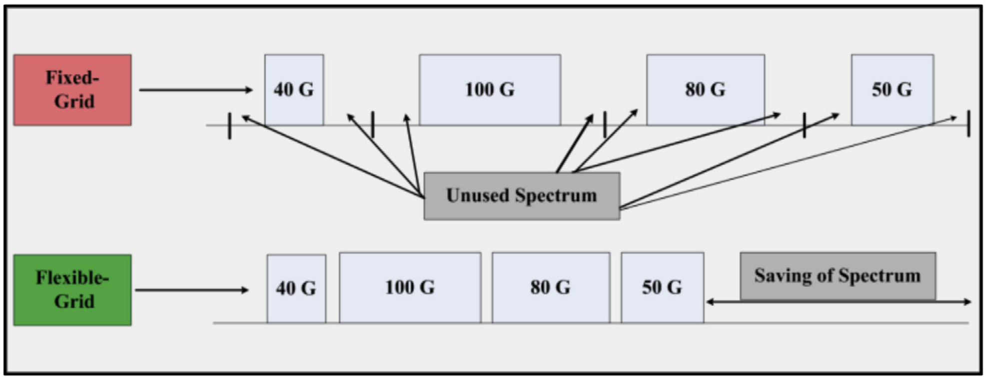


Fig. 1. Fixed and flexible grid.

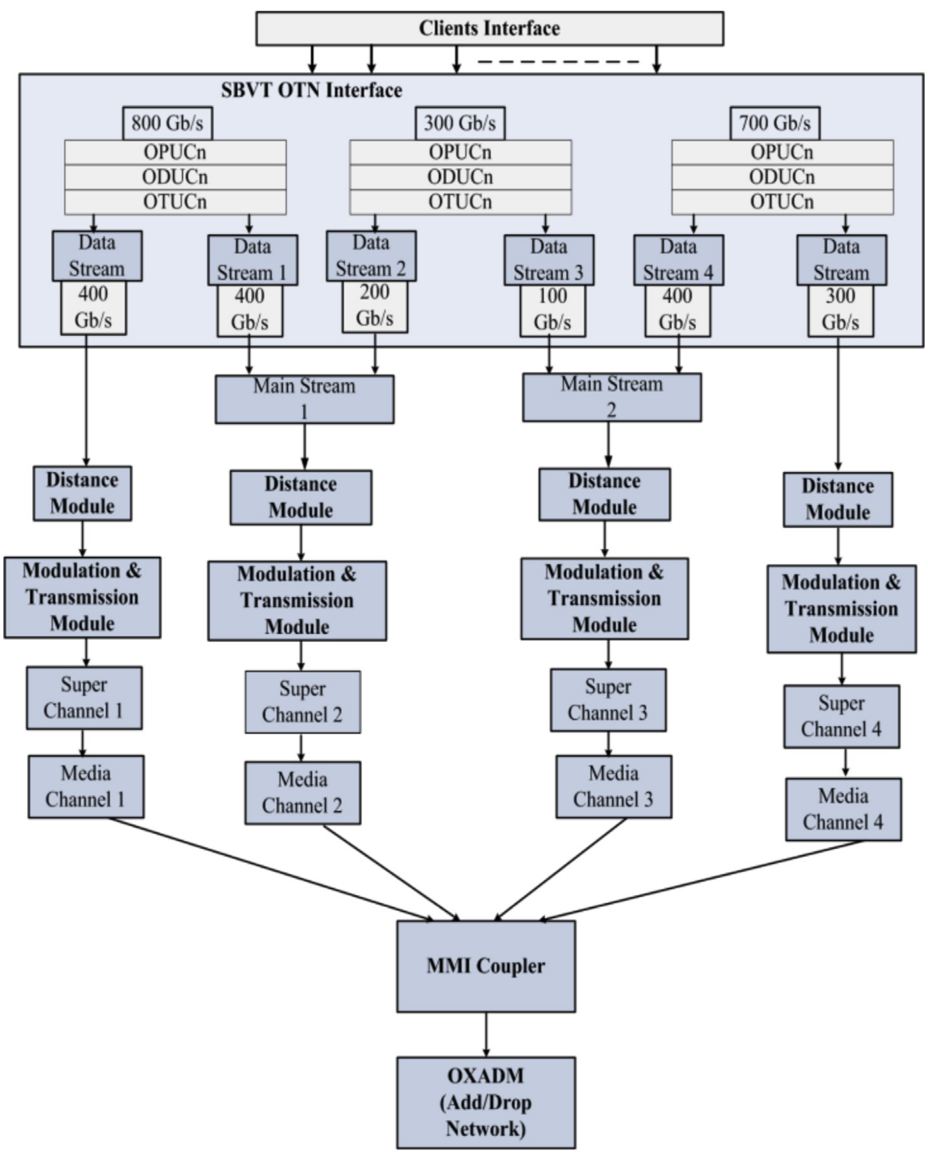


Fig. 2. Sliceable bandwidth variable transponder transmitter section.

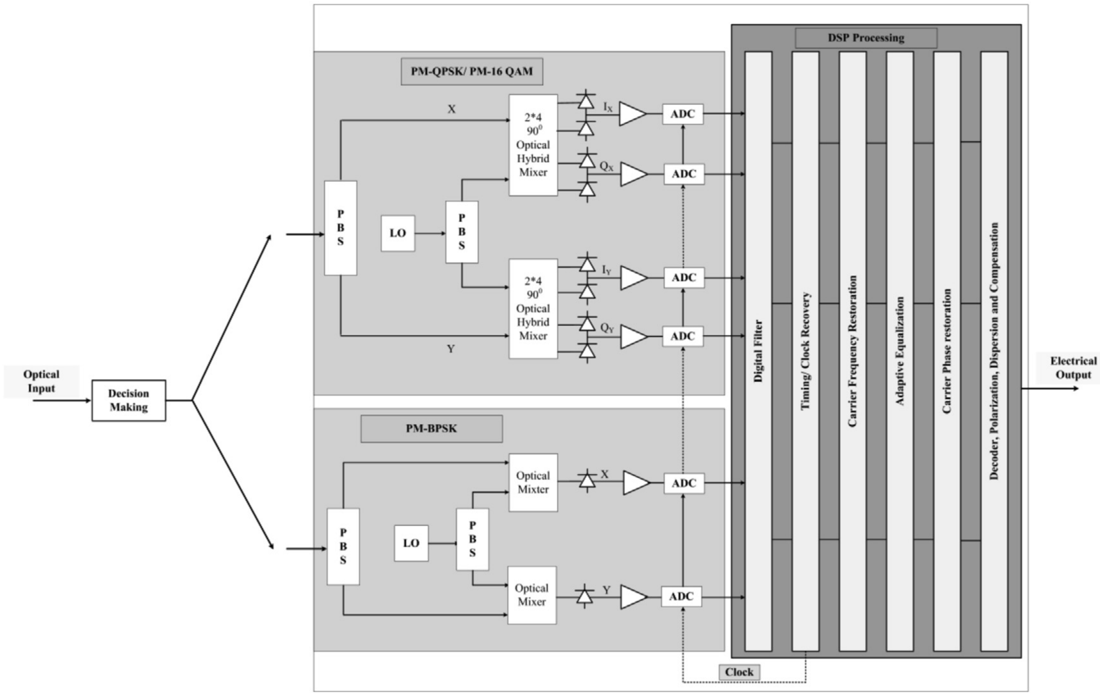


Fig. 3. Sliceable bandwidth variable transponder receiver section.

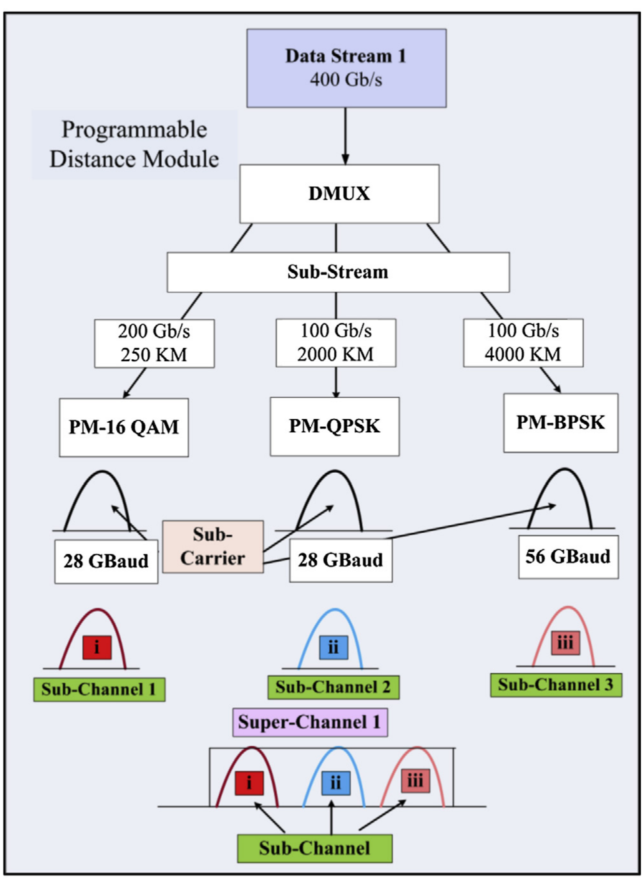


Fig. 4. Distance module block diagram.

The algorithm for the distance module is as follows:

1. Distance_Module_Algorithm (Mainstream MS of size T)
Input: A mainstream named MS of size T, having K destinations and the amount of data to be dropped at each destination in header of MS
Output: The Suitable Modulation Technique for each sub-stream
2. Divide MS into K sub-streams using information in header of MS
3. *FOR* $i = 1$ to k
4. Calculate distance (Dis) in kilometers using Destination (D) and source (S) header attached to each sub-stream
5. *IF* Dist < 500
6. Assign PM-16QAM Modulation Technique to the *i*th stream
7. *ELSE IF* 500 ≤ Dist < 2000
8. Assign PM-QPSK Modulation Technique to the *i*th stream
9. *ELSE*
10. Assign PM-BPSK Modulation Technique to the *i*th stream
11. *END FOR LOOP*
12. *END*

2.2. Implementation of distance module via node architecture

The proposed node architecture for DM is as shown in Fig. 5 which has the port for dropping and adding of sub-channels. Here data stream 1 and super-channel 1 are considered for the design and the data stream 1 has three sub-streams with a dropping distance of 250 km, 2000 km and 4000 km for each sub-stream. The proposed node architecture consists of three dropping nodes (B, C, D) at a distance of 250 km, 2000 km and 4000 km from node A considering super-channel 1 which has 3 sub-channels with first sub-channel (sub-carrier) dropped at node B (250 km), second sub-channel (sub-carrier) dropped at node C (2000 km) and the third sub-channel (sub-carrier) being dropped at node D (4000 km). Here we consider the dropping of sub-channel (sub-carrier) whereas adding and dropping occur simultaneously at a node. Sub-channels (sub-carriers) from the super-channel can be dropped and hence the modulation technique should be allocated to each sub-stream in the main-stream/data stream depending on their dropping distance instead of applying single modulation technique to the main-stream/data stream [11].

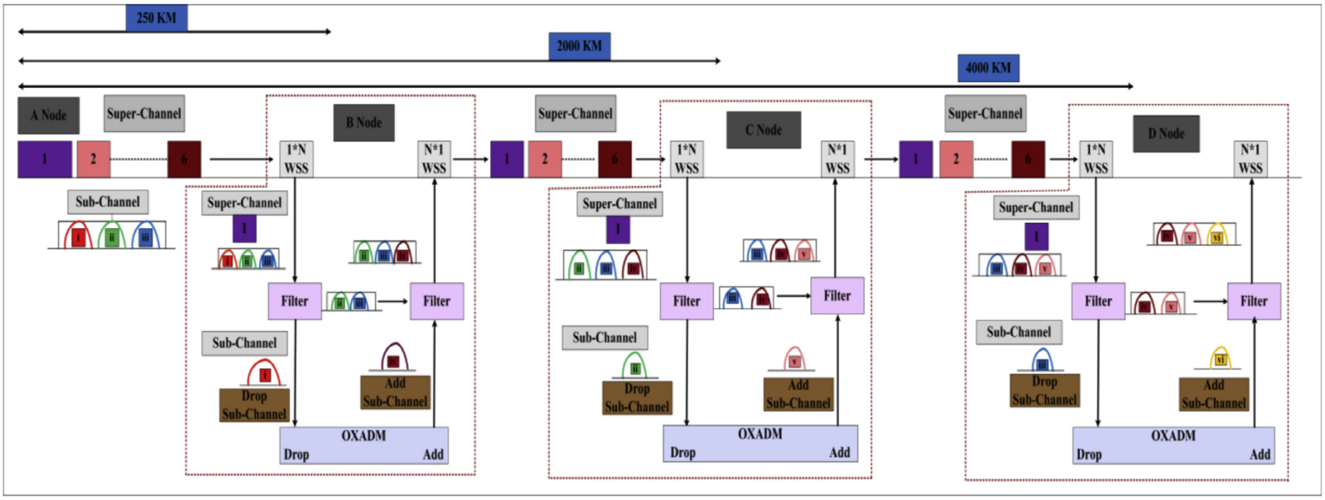


Fig. 5. Sub-channel (sub-stream) dropping from super-channel at each node.

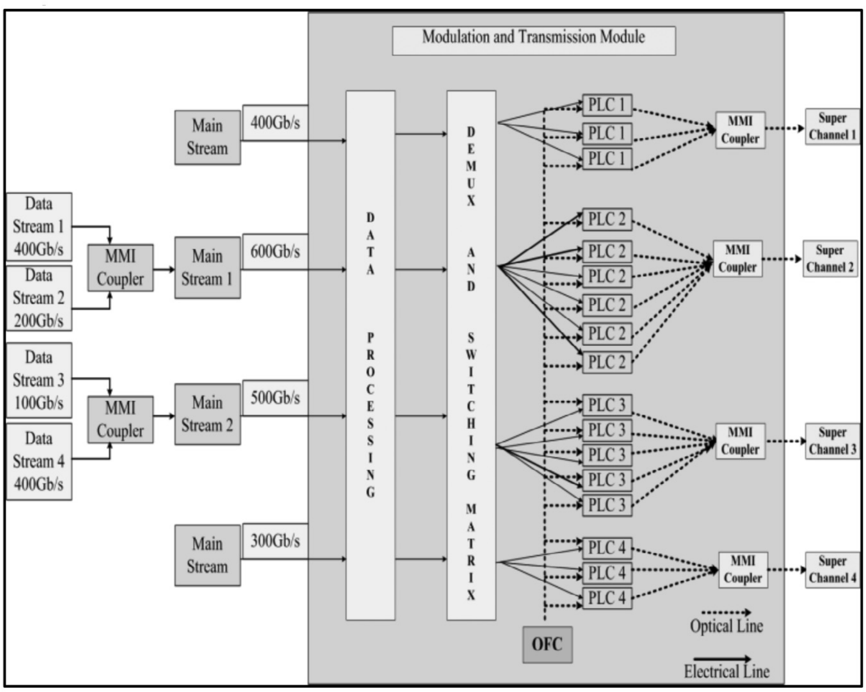


Fig. 6. Modulation and transmission technique diagram.

2.2.1. Modulation and transmission module (M&TM)

As discussed earlier in distance module, a modulation technique is assigned to data streams, whereas in this module, the modulation is performed and transmitted by N-WDM transmission technique. Data stream/main stream from distance module enters the M&TM module and pass through data processing that performs encoding, pulse-shaping, and filtering of data stream and latter it passes through de-multiplexer and switching matrix which de-multiplexes/divide the stream into several sub-streams as mentioned in the earlier section and directed toward proper PLC for modulation according to the technique assigned by DM to each sub-stream. Subcarriers are generated by OFC and directed toward PLC for modulation. Modulated subcarriers are coupled through MMI coupler to form super-channel as shown in Fig. 6. PLC is used for enabling three modulation techniques (PM-BPSK, PM-16QAM, and PM-BPSK) [10].

2.3. PLCs (planar lightwave circuits)

PLC is a photonic integration technology which involves integration of planar light wave components on a single substrate to perform a variety of complex optical functions. It has a wide application in the current generation optical networks which involves number of optical devices without electro-optic (EO) and optic-electro (OE) converters. It is used to integrate or unify large number of optical components on a single chip. It provides large capacity with low power and compact size. This technology is more important for implementation of SBVT transponder which uses the concept of super channel and it is possible only due to this technology. It reduces optical circuit complexity and increases the reliability. For enhancement of channel capacity beyond 100 Gb/s this technology is essential.

Fig. 7 shows the PLC block diagram, which consists of PLC power divider to provide 90° phase shift operated by switches. When the

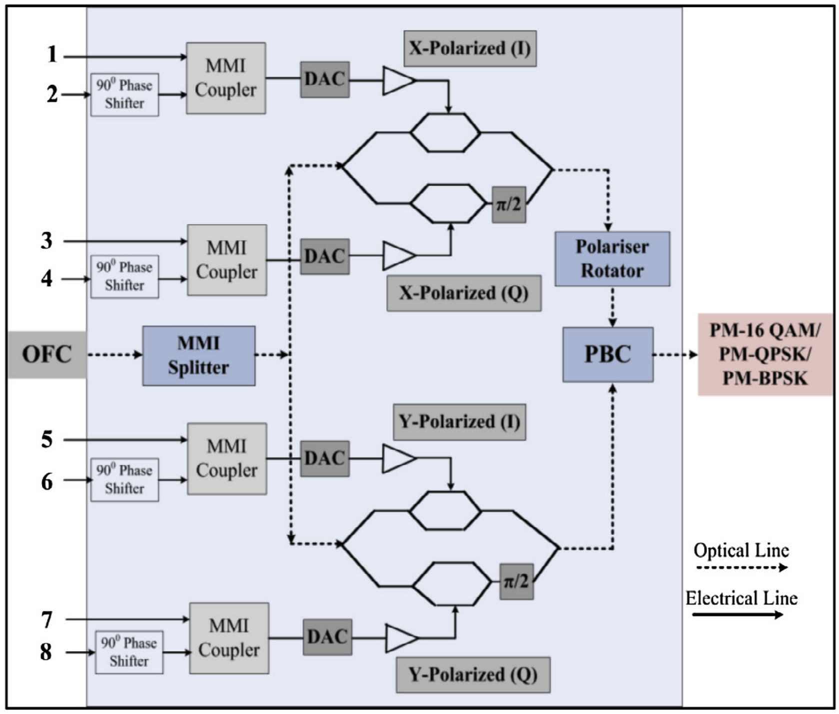


Fig. 7. Planer lightwave circuit diagram.

switch is closed, it provides 90 out of phase input to the MMI coupler or else it provides the direct input [6] which is used for enabling three modulation schemes (PM-16QAM, PM-QPSK and PM-BPSK). When the input is applied to the ports 1–8 it generates PM-16QAM and when the input is applied to ports 1, 3, 5 and 7 it generates PM-QPSK and the input is applied to port 1 and 5 it generates PM-BPSK.

2.3.1. Multimode interference coupler (MMI coupler)

In this proposed architecture multiplexers and couplers are replaced by MMI coupler. As the number of sub-carriers increases, intolerable losses are generated in the coupler. When the couplers are replaced by multiplexer the cost of the device increases. Therefore MMI coupler provides the solution for this issue providing many advantages over other simple coupler and multiplexer such as compact size, low loss, high and steady splitting ratio, high optical bandwidth, better fabrication tolerance with less power imbalance and minimum cross talk. The proposed MMI coupler is fabricated on PLC [14–16].

2.4. Receiving section

Receiving section consists of **decision making block** which decides the modulation scheme of receiving signal and direct toward the appropriate demodulator circuit for demodulation. **Demodulator block** has two demodulator circuits. One for PM-16QAM/PM-QPSK and other for PM-BPSK. In PM-16QAM/PM-QPSK demodulator circuit the receiving signal initially passes through a polarizer beam splitter (PBS) which splits both of the polarized components X and Y. Each polarized component is applied to 90° optical hybrid mixers. The local oscillator is applied to Polarizer Beam Splitter (PBS) which provides two components and each of it is also applied to 90° optical hybrid mixer. Each 90° optical hybrid mixer produces in-phase and quadrature phase component of polarized X and polarized Y component. The in-phase and quadrature phase components are passed through the photodiode for electrical to optical conversion and latter applied to TIA (trans-impedance amplifier). Further, they are converted into digital by analog to digital converter (ADC).

In PM-BPSK demodulator circuit the receiving signal is passed through a polarizer beam splitter (PBS) which splits the signal into two polarized components X and Y. Each polarized component is applied to the optical mixer. The local oscillator is applied to a polarizer beam splitter (PBS) which provides two components and each is applied to optical mixer. Each optical mixer provides the X and Y components of the signal which are passed through photodiodes for optical to electrical conversion and applied to trans-impedance amplifier (TIA). Latter, the output of TIA is converted into digital through ADC. **Digital signal processing block** performs the functions such as digital filtering, timing recovery, carrier frequency restoration, adaptive equalization, carrier phase restoration, decoding and finally the polarization dispersion compensation and is shown in Fig. 3 [19,20].

3. Elastic optical network node architecture

Fig. 8 shows the node architecture [1] which describes the connectivity of SBVT with output side and input side fiber where the node is of degree three, each node consisting of three main devices EDFA, MMI splitter and BV-WSS (1 * *N* filter). Here OXADM is used as add and drop network and each node shares add and drop port of the OXADM. When data arrives to any node, it broadcasts to all other nodes and drop port of the OXADM, which is selected or blocked is decided by the BV-WSS. Example: When data from SBVT passes through the output side fiber 2, then the received data from the add port of OXADM is broadcasted to all three fibers using splitter, but it is blocked by BV-WSS at the output side of fiber 1 and 3, latter filtered by BV-WSS at output side fiber 2.

3.1. Need for EDFA, MMI splitter and OXADM

3.1.1. Erbium doped fiber amplifier (EDFA)

In the proposed node architecture, EDFA is used in prior to MMI splitter because when MMI splitter splits the signal power among

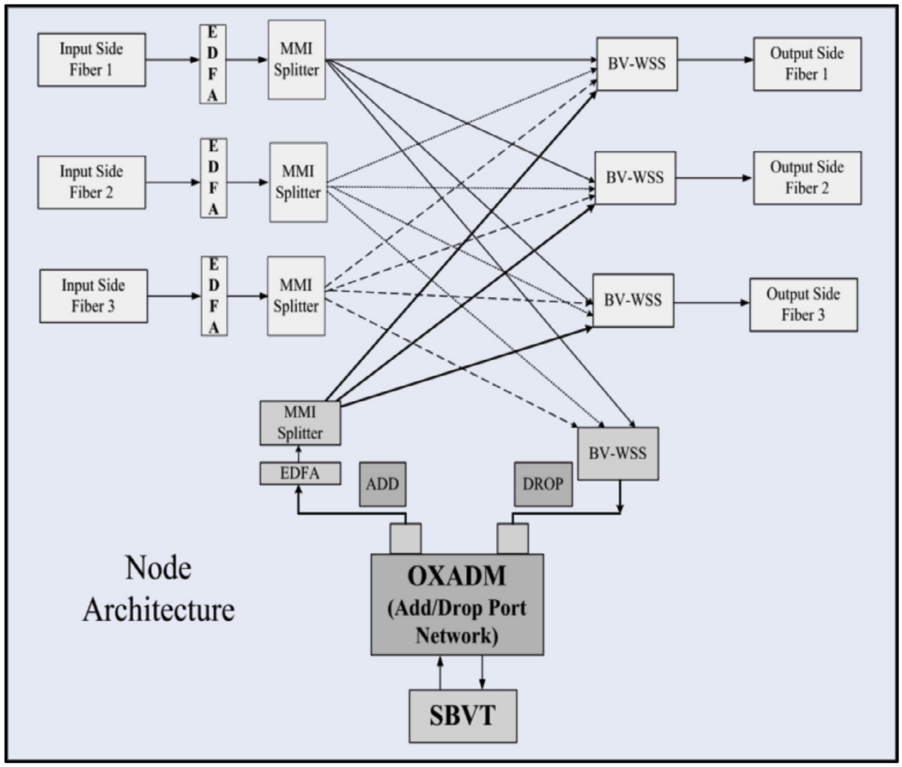


Fig. 8. Node architecture of elastic optical network.

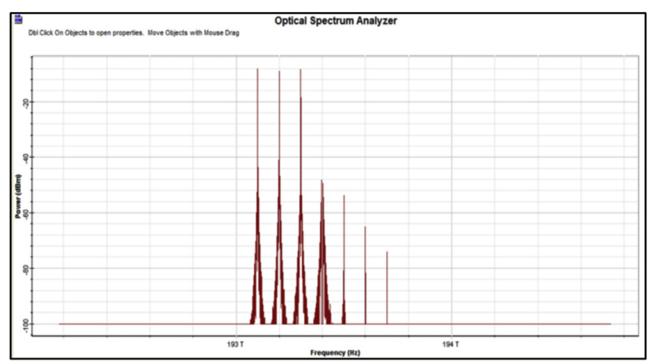
various nodes, the receiving power at the node is not sufficient for long distance communication and to resolve this problem EDFA is used before MMI splitter. EDFA is widely used as preamplifier in long haul communication to maintain the optical power level and used in prior to the MMI splitter to increase the power to sufficient level after splitting [17].

3.1.2. *Multi-mode interference splitter (MMI-S)*

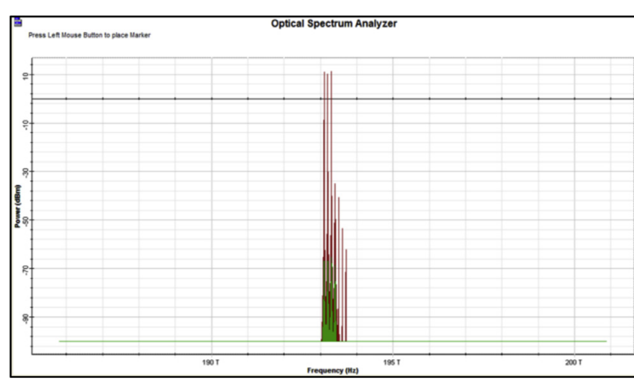
MMI splitter is used as a replacement of simple splitter in node architecture because a simple splitter does not support for higher node inducing un-tolerable losses in case of high degree nodes [3]. As compared to simple splitter MMI devices have several advantages. They provide huge number of power splits supporting large output ports demanding a few device footprint. The 2D-MMI splitter is used for large and compact power splits [18] and can be fabricated on the PLC with compact size.

3.1.3. *Optical cross add and dross multiplexer (OXADM)*

In this node architecture, add and drop network is replaced by OXADM which has the ability to add and drop function, similar to optical add and drop network multiplexer (OADM) and optical cross connects (OXC) but it is better than OADM and OXC providing single input and single output port which has better security along with increased efficiency and reliability of optical network [21]. The result shown in Fig. 9 shows that the power level at the output side fiber is around 20 dB which is more than the previously discussed architectures that is why it enables efficient and long distance transmission. In this we have used MMI splitter in place of simple splitter because of their photonic integration capability and handling higher number of nodes to reduce cost and complexity. The comparison of the proposed SBVT architecture with the existing module is shown in Table 2.



(a) Without EDFA



(b) With EDFA

Fig. 9. Power level at output side fiber (a) without EDFA and (b) with EDFA.

Table 2
Comparison of existing architecture [6,7] with proposed SBVT.

Characteristics	Existing architecture	Proposed SBVT architecture
Implementation complexity	More	Less
Distance module	No	Yes (programmable module)
Sub-channel	There is no concept of sub-channel in super-channel	There is a concept of sub-channel in super-channel
Add and drop sub-channel out of super-channel	No	Yes
Modulation technique	Single modulation technique to a super-channel	Different modulation techniques to sub-channel based on their optical reach for efficient utilization of spectrum
Add and drop network	OXC (low security)	OXADM (high security)
Flexibility in receiving section	Demodulator supporting (PM-16QAM and PM-QPSK)	Demodulator supporting (PM-16QAM, PM-QPSK and PM-BPSK)
MMI devices (MMI coupler and MMI splitter)	No	Yes (MMI is used because of their photonic integration capability, lowloss, minimum power imbalance which is necessary for implementation of SBVT)
PLC	PLC is used to enable PM-16QAM and PM-QPSK modulation scheme	PLC is used to enable PM-16QAM, PM-QPSK and PM-BPSK modulation scheme

4. Conclusion

Here, a new SBVT architecture has been proposed. As compared to other architectures of SBVT, its functionality and efficiency is improved by adding a programmable distance module for assigning different modulation techniques to the sub-streams based on their destination points instead of applying a single modulation technique to a data stream/main stream for efficient utilization of spectrum. It also focus on the concept of sub-channel and dropping of sub-channel from super-channel highlighting the capability of PLC for enabling modulation technique such as PM-BPSK, PM-QPSK and PM-16QAM. Receiver is designed for three modulation techniques. In this MMI device (MMI coupler and MMI splitter) is used because of their photonic integration capability which is necessary for a sliceable bandwidth variable transponder. A node architecture is also proposed to improve the limitations of previously discussed node architectures for long distance communication. In node architecture, the splitter is replaced by an MMI splitter to overcome its limitation of handling higher nodes and EDFA is used before the MMI splitter to avoid the power losses due to splitting of signals among various nodes and make them enable for long distance transmission. OXADM is used as add and drop network to improve the security of data transmission.

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[12,13].

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