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Performance Investigation of OFDM-Based Software-Defined Optical Network

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Abstract This paper investigates the performance of the Software-Defined Optical Network (SDON) based on the Bandwidth Variable Transceiver (BVT). The proposed SDON controlling algorithm offers multiple data rates and different modulation formats, optical launch powers, and reaches. The operation of the BVT is based on two Optical Orthogonal Frequency-Division Multiplexing (O-OFDM) techniques based on direct detection and coherent configurations. The SDON Centralized Controller (SCC) algorithm controls both the modulation format (BPSK, QPSK, or 16-QAM) and the transmitter optical launch power according to the requested bit rate and distance. Simulation results based on Optisystem 14.1 software reveals that the optimum system performance with highest bit rate and longest distance for the three modulation formats are reached by using optimum transmitter launch power. For Direct Detection (DD) O-OFDM system, an optical launch power of 12, 15, and 0 dBm is required for transmitting 20 Gbps BPSK, 50 Gbps QPSK, and 100 Gbps 16QAM over 31, 28, and 15 km, respectively. Whereas for Coherent (C) O-OFDM, an optical launch power of -8, 4, and 2 dBm is required for transmitting 40 Gbps BPSK, 80 Gbps QPSK, and 160 Gbps 16QAM over 275, 170, and 36 km, respectively.

Keywords Software-Defined Optical Network (SDON), Bandwidth Variable Transceivers (BVT), Optical Orthogonal Frequency-Division Multiplexing (O–OFDM), Direct Detection O-OFDM (DDO-OFDM), Coherent O-OFDM (CO-OFDM)

1. Introduction

Communication networks is an important part in modern society. These networks grow continuously nowadays [1-4]; additional devices added to the network will lead to increases the complexity of network [5-8]. Thus when a network service provider wants to add, remove, or reconfigure any device in such network, the reconfiguration of all the distributed devices in the network should be done manually. Furthermore, each device has many parameters needed to be reconfigured [9]. Such operation causes a waste in time, cost, effort, and resources. These issues shed the lights toward thinking about controlling the network automatically by software offers all the requirements needed for the network when necessary and depending on the user request. That leads to emerging of so called Software-Defined Optical Network (SDON) that controls all the distributed devices inside the optical network automatically [10] and reconfigure their parameters quickly [11-16]. On the other hand, the light is shed on a very important optical device known as a bandwidth variable transceiver [17-21]. It's a programmable optical transceiver that provides multiple bit rates by changing the type of modulation format through SDON controller. Basically, when the order of modulation format increases, the number bits per symbol increases too, which means increasing the bit rate, and vice versa.

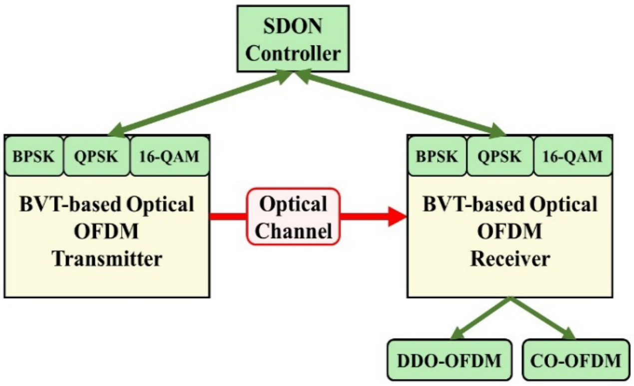

Figure 1. BVT with multiple modulation formats operating under SDON controller. The system incorporates both direct and coherent optical OFDM detection techniques

The programmable optical transceiver saves cost since the user does not need to purchase many transceivers, each with a specific bit rate. Recently there is increasing interest in advanced optical modulation formats and techniques to enhance the performance and spectral efficiency (SE) of

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optical networks. Among these techniques is Optical Orthogonal Frequency-Division Multiplexing (O−OFDM) [22-25]. OFDM increases the SE by the orthogonality between transmitted subcarriers. Technically, O-OFDM transmits multiple parallel small band subcarriers rather than a single wideband carrier to transport data. This leads to two major categories which are used to detect the O-OFDM signals [26, 27], (see Figure 1)

(i) Direct Detection O-OFDM (DDO-OFDM) which has a simple receiver architecture that depends on a single photodiode to detect the received signals. Mostly, it is used in short range transmission [28-32].

(ii) Coherent O-OFDM (CO-OFDM) which has a very sensitive receiver based on coherent detection. Usually, it used in a long range transmission [32-36].

The above discussion motivates the work in this paper to propose a SDON based on BVT incorporating O-OFDM techniques. Choosing direct detection (DD) or Coherent Detection (C) depends on the SDON controller strategy.

2. Related Works

In 2015, Fabrega et al. [37] proposed Discrete Multitone (DMT) transmission combined with coherent detection due to its simplicity and cost effectiveness for evolutional flexible metropolitan regional network. A successfully 10 Gbps connection over 150 km was experimentally assessed on a network testbed between multi-tenant units and the sliceable BVT at a virtual broadband remote access server farm. 4-Quadrature Amplitude Modulation (4-QAM) modulation formats was considered in the implementation, the required optical signal-to-noise ratio at Bit Error Rate (BER) 10^{-13} was 18.3, 19, and 19.9 dB for Back-to-Back (B2B), 50 km, and 150 km paths, respectively.

In 2015, Moreolo et al. [38] numerically and experimentally assessed the behavior of BVT based on DDO-OFDM through metropolitan regional network and inter- data center communication. The use of bit loading and power loading was discussed in Fthe transmitter and receiver Digital Signal Processing (DSP) block.

In 2016, Moreolo et al. [39] presented the architecture and building blocks of a sliceable BVT based on Multicarrier Modulation (MCM) technologies (OFDM and DMT), which controlled by Software-Defined Network (SDN) through optical network based Standard Single-Mode Fiber (SSMF). The multiple adaptive optical transceivers, sliceable BVT, were capable of generating multiple bands and multiple flows. The performance for two slices was evaluated (20, and 10 GHz bandwidth for slice 1 and 2, respectively) at a target BER $= 3 \times 10^{-3}$. The maximum slice capacity was nearly 50 Gbps, and 30 Gbps with B2B, and after 185 km transmission distance, respectively.

In 2016, Moreolo et al. [40] proposed a high capacity sliceable BVT based on MCM technology and DD which was suitable for metropolitan regional elastic optical network. The sliceable BVT was controlled and adapted by SDN controller to efficiently resource usage. The sliceable BVT adaptation, programmability, and configurability were confirmed through the DSP operations by adjusting the bandwidth, rate/distance, modulation type, and other key functionalities. The transceiver advanced functionalities were experimentally demonstrated in a four node optical mish network, with the combination of SDN controlling.

In 2017, Fabrega et al. [41] proposed and experimentally demonstrated an adaptive SDN orchestrator which controls multiple domain optical networks (optical packet switching, optical circuit switching), each domain controlled by its own SDN. Multiple technologies were demonstrated using an adaptive programmable reconfigurable sliceable BVT at each transmission over the optical network. sliceable BVT was designed based on MCM.

3. Modeling of SDON Based on BVT Incorporating OFDM Techniques

The purpose of this section is to present a modeling framework to investigate the performance of SDON based on BVT incorporating direct detection and coherent O-OFDM techniques. Different modulation formats are used with maximum transmission symbol rate of 25 and 40 GSps for the two O-OFDM systems, respectively, to verify the required bit rate. Consequently, different optical launch powers are used to achieve the required reach. The simulation results of both BVT types are obtained using Optisystem 14.1.

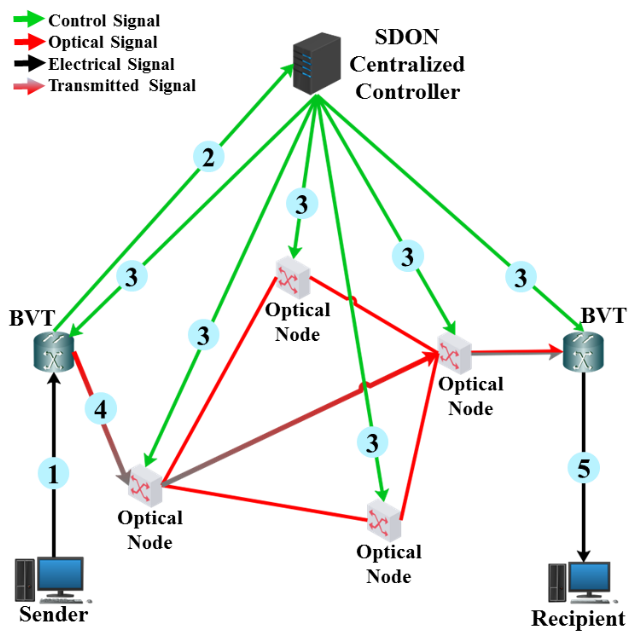


Figure 2. SDON scenario sequence. The link number refers to the corresponding step sequence

The performance behavior of SDON centralized controller (SCC) depends on the end user request including the required bit rate and reach. Thus, this controller selects the appropriate operating parameters values for the BVT to achieve this request in a software-defined optical transmission. The software-defined optical transmission is achieved through the following sequences (the sequence number is labeled in Figure 2)

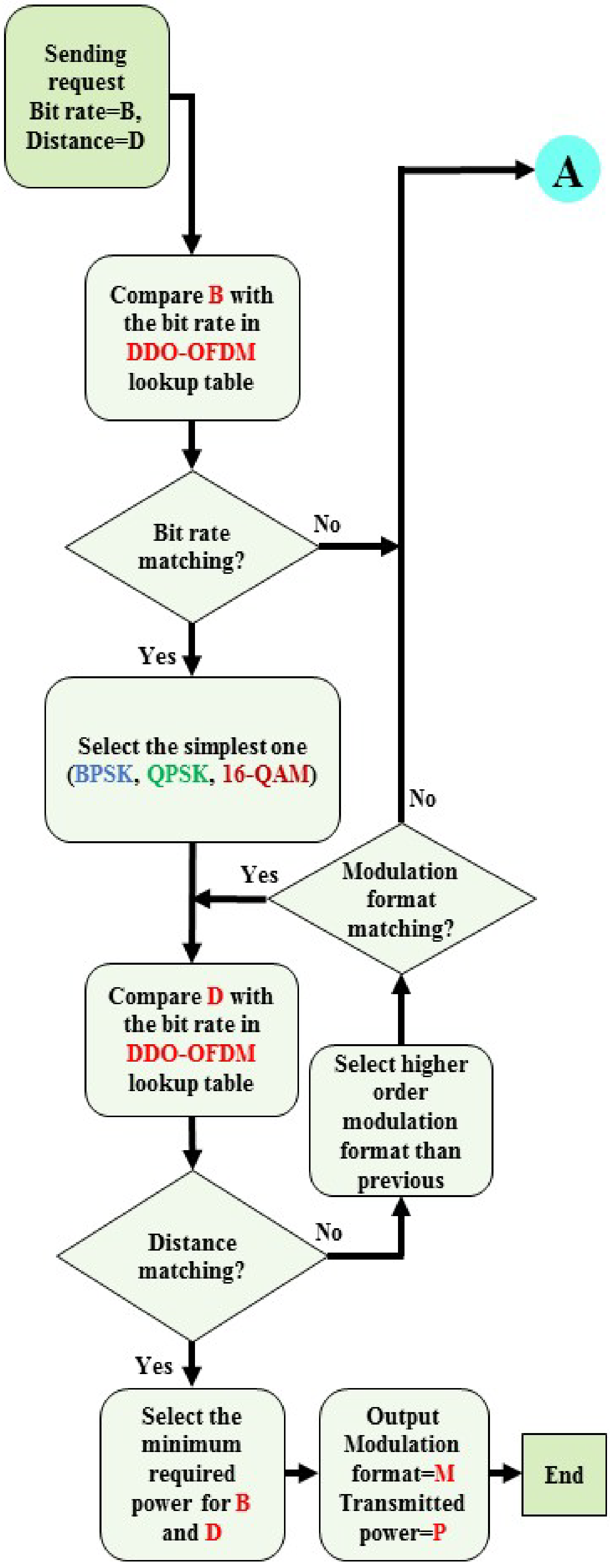
1. The end user sends his request that will be received by the BVT.
2. The BVT forwards the request to the SCC.
3. The SCC compares the request information (bit rate, and reach) with the precalculated information tables (results). If there is matching, a suitable modulation format and optical launch power are assigned to the requested data rate and reach. In the case of no matching between the request information and the information tables, the SCC will drop the request.
4. After that, the BVT starts transmitting the data according to the SCC instruction.
5. When the data arrives at the BVT, it will be forwarded to the destination by the BVT according to the SCC instruction that previously sent in step 3.

The selection of the appropriate values of the BVT parameters by the SCC depends on the algorithm scenario shown in Figure 3 and accomplished by comparing both bit rate and distance that requested by the end user with the precalculated results that stored as tables in the SCC. This will provide the appropriate modulation format and optical launch power. The selection of modulation format and optical launch power is achieved by choosing the simplest format (lowest order) and minimum power which serve the end user request. The SDON algorithm scenario is stated as follow

(i) After the request information forwarded to the SCC by the BVT, it will be compared with DDO-OFDM information tables (the results that precalculated for BVT based on DDO-OFDM technique with multiple data rate, modulation formats (BPSK, QPSK,16-QAM), and range of powers) by the SCC. First choice is given here for the DDO-OFDM since it is simpler and more robust than the second system, CO-OFDM.

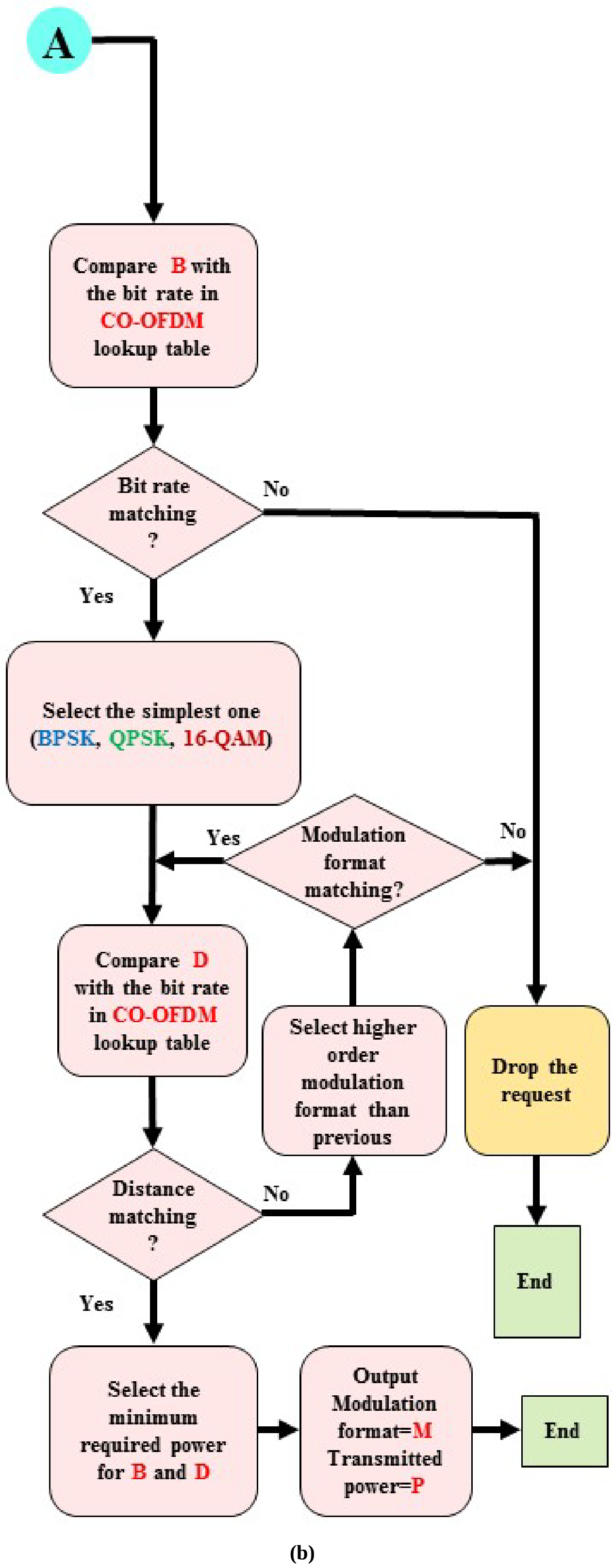
(ii) At first, the requested data rate is compared with the information tables. In case of matching, the corresponding (simplest, i.e. lower order) modulation format will be selected. The case of no matching means all the available modulation formats do not provide the required data rate. Thus, the SCC will go to the CO-OFDM-based BVT because it provides higher data rate than BVT based on DDO-OFDM technique.

(iii) After assigning suitable modulation format for the required data rate, the required reach is compared with the information tables. In case of matching, the corresponding (minimum) optical launch power will be selected. In case of no matching, that's means all the available distances does not provide the required reach, the SCC will depend on the BVT based on CO-OFDM technique because it provides longer distances than the DDO-OFDM counterpart.



(a)

Figure 3. SDON centralized controller algorithm



(b)

Figure 3. (Continued)

In case of both the required data rate and reach are matching with the information tables obtained by BVT based on DDO-OFDM technique, the SCC will enable it. Otherwise, the BVT based on CO-OFDM is enabled by the SCC. In case there is no matching for both the required data rate and reach with the information tables that obtained based on both types of BVT, the SCC will drop the request.

Table 1. Components parameters of DDO-OFDM system used in the simulation

Component	Parameter	Value
RF OFDM Modulator and Demodulator	Maximum possible subcarriers	1024
	Subcarriers/port	512
	Subcarrier locations	257
Modulation Format	BPSK	
	QPSK	
	16-QAM	
Quadrature Modulator and Demodulator	Frequency	7.5 GHz
CW Laser	Frequency	193.1 THz
	Linewidth	0.1 MHz
SMF	Attenuation	0.2 dB/km
	Dispersion	16.75 ps/nm/km
	PMD	0.05 ps/sqrt(km)
EDFA Optical Amplifier	Gain	Fiber length (km) x 0.2 dB
Photodetector	Center Frequency	193.1 THz

Table 2. CO-OFDM system parameters values

Component	Parameter	Value
RF OFDM Transmitter and Receiver	Number of subcarriers	128
	Number of subcarriers/port	80
	Subcarrier locations	25-104
LO Laser	Frequency	193.1 THz
X-coupler	Coupling coefficient	0.5
Phase Shifter	Phase Shift	90 deg.
PD	Center frequency	193.1 THz

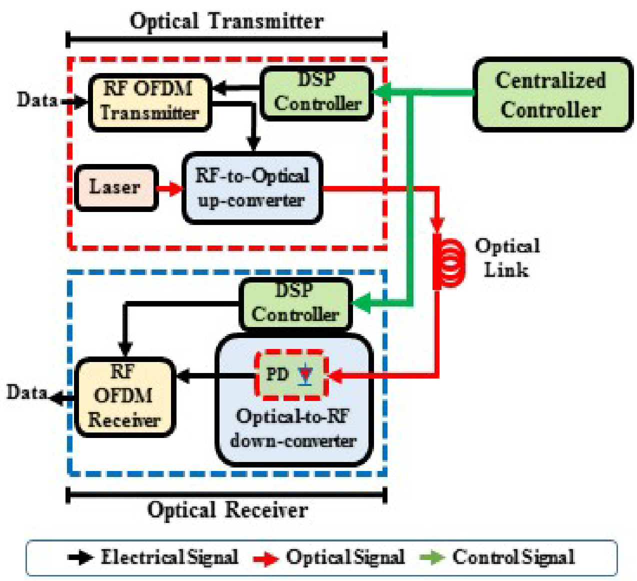


Figure 4. Block diagram of the adaptive DDO-OFDM system used in the simulation

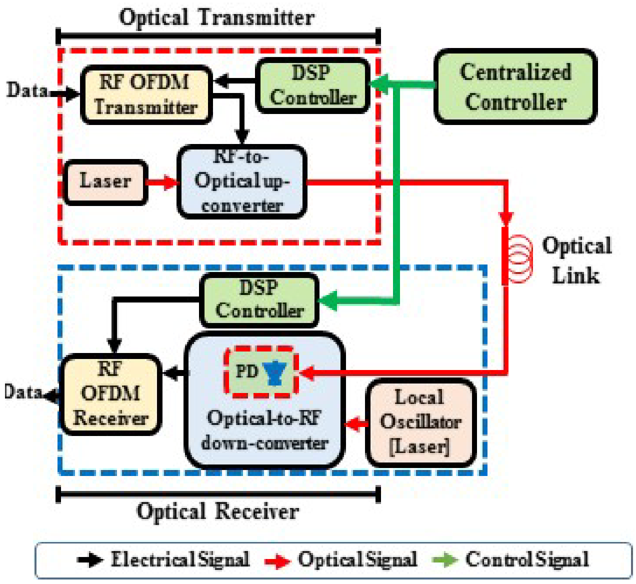


Figure 5. Block diagram of the adaptive CO-OFDM system used in the simulation

The direct detection and coherent O-OFDM systems investigated in this work are presented in Figures 4 and 5. The parameters values used in the simulation are given in Tables 1 and 2.

4. Results and Discussion

The performance of BVT incorporating both DDO-OFDM and CO-OFDM techniques is simulated in Optisystem environment. Each technique has a specific maximum symbol rate of 25 and 40 GSps, respectively. Different modulation formats, different bit rates, and different optical launch powers are used with both techniques. The testing results are obtained depending on the Hard Decision-Forward Error Correction (HD-FEC) with the consideration of the maximum acceptable BER ratio is 10^{-3}.

4.1. Results of DDO-OFDM System

The results of DDO-OFDM system are obtained using the following parameters

(i) The maximum symbol rate for the system is 25 GSps.
(ii) Three different modulation formats (BPSK, QPSK, and 16-QAM).
(iii) Different bit rates with each modulation format which are limited by the maximum symbol rate. Bit rate of (10 and 20 Gbps) with BPSK, (20, 40, and 50 Gbps) with QPSK, and (20, 40, 60, 80, and 100 Gbps) with 16-QAM.
(iv) Different optical launch powers ranging from -10 to 14 dBm with a step of 2 dBm.
(v) Different reaches which are limited by the optimum launch powers and bit rates.

Figure 6 shows the best performance of the BVT incorporating DDO-OFDM based on BPSK modulation format with 10 and 20Gbps bit rates. The optimum launch power and longest reach at 10 Gbps BPSK are 12 dBm and 79 km, respectively, with $\text{BER} = 7.65 \times 10^{-4}$ which is lower than the maximum acceptable BER. The optimum launch power and longest reach at 20 Gbps are 12 dBm and 31 km, respectively, with $\text{BER} = 7.3 \times 10^{-4}$ which is again lower than the maximum acceptable BER.

Note that the existence of optimum power level comes from the effect of fiber optics nonlinearity which prevents increasing the transmission distance with increasing the transmitter power beyond the optimum level. The main source of this nonlinearity is self-phase modulation since the system under investigation is a single-channel system. The effect of Raman scattering is negligible because the used values of launched power is below Raman threshold value (around 500mW in SMF).

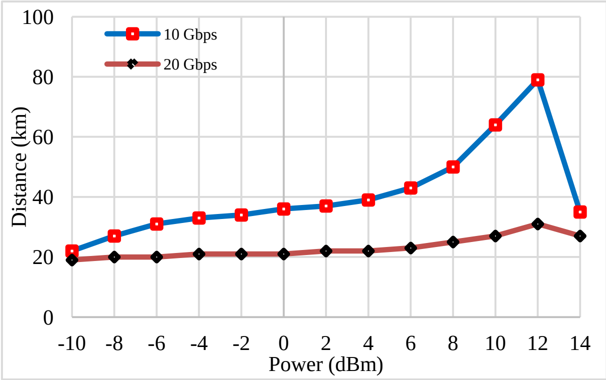


Figure 6. Performance of BVT based on DDO-OFDM with BPSK modulation format

The performance of the BVT incorporating DDO-OFDM technique is tested for three different bit rates 20, 40, and 50 Gbps assuming QPSK signaling format and the results are displayed in Figure 7. Investigating the results in this figure reveals that a maximum transmission of 81, 34, and 28 km are achieved with 20, 40, and 50 Gbps, respectively. The corresponding optimum power is 12, 13, and 15 dBm, respectively.

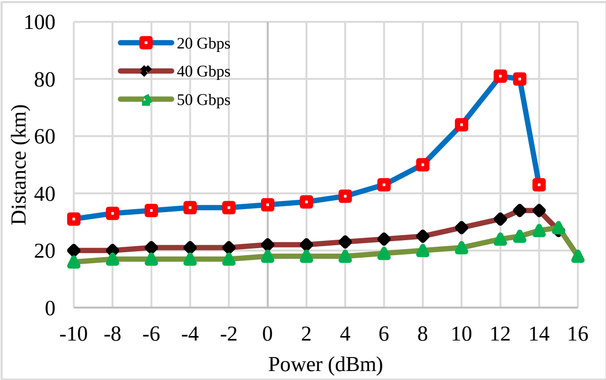


Figure 7. Performance of BVT based on DDO-OFDM with QPSK modulation format

The effect of using 16-QAM modulation format on the system performance is tested for five different bit rates (20, 40, 60, 80, and 100 Gbps), each with different optical launch powers. The results are presented in Figure 8. The optimum launch power and maximum reach for each bit rate can be deduced from this figure and the calculated results are listed in Table 3.

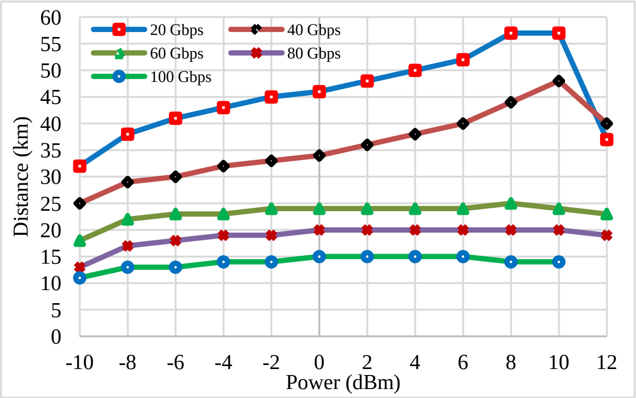


Figure 8. Performance of BVT based on DDO-OFDM with 16-QAM modulation format

Table 3. Summary of the optimum results corresponding to 16-QAM BVT using DDO-OFDM technique

Bit rate (Gbps)	Optimum power (dBm)	Maximum reach (km)	BER
20	8	57	9.70×10^{-4}
40	10	48	5.82×10^{-4}
60	8	25	9.70×10^{-4}
80	0	20	9.70×10^{-4}
100	0	15	7.76×10^{-4}

Investigating the results in Table 3 reveals the following findings

(i) Operating at higher bit rate reduces the maximum reach and hence (in general) a lower launch power is required. The normalized maximum reach (relative to that operating at 20 Gbps rate) is 0.84, 0.43, 0.35, and 0.26 for 40, 60, 80, and 100 Gbps rate, respectively.

(ii) The Bit Rate-Distance Product (BDP) is estimated to be 1140, 1920, 1500, 1600, and 1500 Gbps.km for system operating with 20, 40, 60, 80, and 100 Gbps, respectively. Note that BDP becomes around 1500 Gbps.km at higher bit rate.

Table 4. Performance comparison of DDO-OFDM-based BVT operating with 20 Gbps and for different modulation formats. BDP = bit rate distance product

Mod. format	Optimum launch power (dBm)	Max. reach	BDP (Gbps.km)	BER
BPSK	12	31	620	7.30×10^{-4}
QPSK	12	81	1620	5.69×10^{-4}
16-QAM	8	57	1140	9.70×10^{-4}

It is clear that at fixed symbol rate, going to higher-order modulation format enables the system to carry higher bit rate. Therefore, using 16-QAM becomes essential when the required bit rate cannot be carried by BPSK and QPSK signaling. It is worth also to compare the system performance under the three used modulation formats. For comparison purpose, a 20 Gbps bit rate is chosen which can be carried by the three formats. Table 4 illustrates the performance comparison. It is clear that the QPSK offers the highest reach among the three modulation formats.

4.2. Results of CO-OFDM System

The results here are obtained using the following parameters

(i) The maximum symbol rate for the system is 40 GSps.
(ii) Three different modulation formats (BPSK, QPSK, 16-QAM).
(iii) Different bit rates with each modulation format which are limited by the maximum symbol rate. Bit rates of (20 and 40 Gbps) with BPSK, (20, 40, 60, and 80 Gbps) with QPSK, and (20, 40, 60, 80, 100, 120, 140, and 160 Gbps) with 16-QAM.
(iv) Different optical launch powers ranging from -10 to 10 dBm with a step of 2 dBm.
(v) Different reaches which are limited by the optimum launch powers and bit rates.

The BPSK modulation format is used to test the performance of BVT incorporating CO-OFDM technique with two different bit rates 20 and 40 Gbps. Figure 9 shows the best performance of this BVT at both bit rates. The optimum launch power and longest reach are -6 dBm and 1150 km at 20 Gbps, and -8 dBm and 275 km at 40 Gbps, respectively, with BER $= 9.39 \times 10^{-4}$ and BER $= 9.39 \times 10^{-4}$, respectively. The QPSK modulation format is tested at four different bit rates (20, 40, 60, and 80 Gbps) and the results are displayed in Figure 10. Investigating the results in this figure reveals that a maximum transmission of 2000, 525, 300, and 170 km are achieved with 20, 40, 60, and 80Gbps, respectively. The corresponding optimum power is -4, 2, 0, and 4dBm, respectively. The corresponding BER are listed in Table 5. The main conclusions drawn from Table 5 are

(i) Lower maximum reach is obtained of higher bit rate. At 40, 60, and 80 Gbps bit rates, the maximum reach is about 0.26, 0.15, and 0.09 of that the 20 Gbps bit rate, respectively.
(ii) The BDP is 40, 21, 18, and 13.6 Tbps.km at bit rate of 20, 40, 60, and 80 Gbps, respectively.

Table 5. Summary of the optimum results corresponding to QPSK BVT using CO-OFDM technique

Bit rate (Gbps)	Optimum power (dBm)	Max. reach (km)	BER
20	-4	2000	8.22×10^{-4}
40	2	525	9.25×10^{-4}
60	0	300	9.04×10^{-4}
80	4	170	7.58×10^{-4}

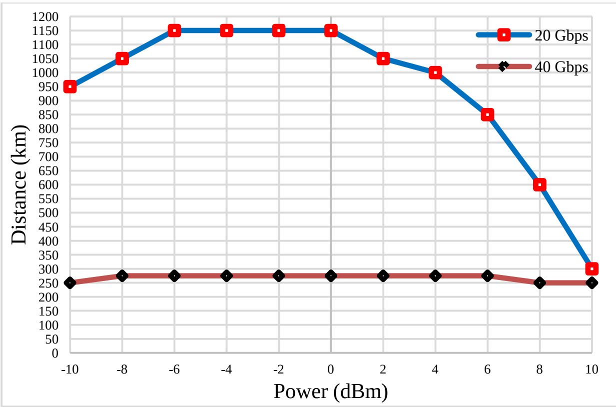


Figure 9. Performance of BVT based on CO-OFDM with BPSK modulation format

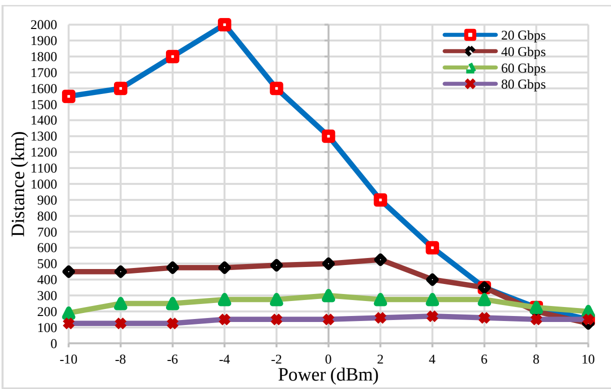
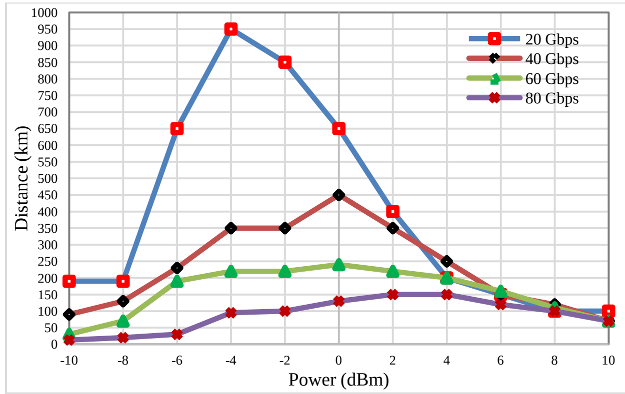


Figure 10. Performance of BVT based on CO-OFDM with QPSK modulation format

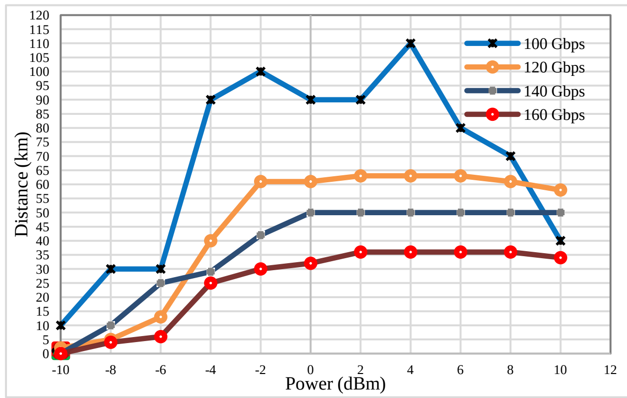
The performance of 16-QAM BVT are also tested here for eight different bit rates (20, 40, 60, 80, 100, 120, 140, and 160 Gbps), each with different optical launch power. The results are presented in Figures 11 (a) and (b). Table 6 lists the main conclusions drawn from these results related to the optimum power and maximum reach. Note that operating at bit rates above 20 Gbps (i.e., 40, 60, 80, 100, 120, 140, and 160 Gbps) reduces the relative maximum reach to 0.47, 0.25, 0.16, 0.12, 0.06, 0.05, and 0.04, of that of 20 Gbps, respectively. The BDP is 19, 18, 14.4, 12, 11, 7.56, 7, and 5.76 Tbps.km, for the bit rates (20, 40, 60, 80, 100, 120, 140, and 160 Gbps), respectively.

Table 6. Summary of the optimum results corresponding to 16-QAM BVT using CO-OFDM technique

Bit rate (Gbps)	Max. reach (km)	Power (dBm)	BER
20	950	-4	6.89×10^{-4}
40	450	0	9.64×10^{-4}
60	240	0	9.65×10^{-4}
80	150	2	6.89×10^{-4}
100	110	4	9.41×10^{-4}
120	63	2	7.57×10^{-4}
140	50	0	8.95×10^{-4}
160	36	2	8.26×10^{-4}



(a)



(b)

Figure 11. Performance of BVT based on CO-OFDM with 16-QAM modulation format

Table 7. Performance comparison of CO-OFDM-based BVT operating with (a) 20 and (b) 40Gbps and for different modulation formats. BDP = bit rate distance product

(a)

Mod. format	Optimum launch power (dBm)	Max. reach (km)	BDP (Tbps.km)	BER
BPSK	-6	1150	23	9.39×10^{-4}
QPSK	-4	2000	40	8.22×10^{-4}
16-QAM	-4	950	19	6.89×10^{-4}

(b)

Mod. format	Optimum launch power (dBm)	Max. reach (km)	BDP (Tbps.km)	BER
BPSK	-8	275	11	9.39×10^{-4}
QPSK	2	525	21	9.25×10^{-4}
16-QAM	0	450	18	9.64×10^{-4}

It is worth to compare the performance of the CO-OFDM system when operating with BPSK, QPSK, and 16-QAM formats. Bit rates of 20 and 40 Gbps are taken for the comparison purpose. Both these bit rates are the supported by three formats. Tables 7 (a) and (b) illustrate the comparison for 20 and 40 Gbps, respectively. The main conclusion drawn from these tables is that the QPSK offers the highest reach.

4.3. Summary of the Results

The proposed algorithm is tested for different transmission link lengths and different required bit rates. Example of the results are given in Table 8 where the algorithm chooses the type of the optical OFDM technique, the modulation format, and the transmitter launch power to satisfy the transmission of the required bit rate according to the link length. The table contains three parts associated with the decision taken by the SCC about the type of the optical OFDM to be used in short-, medium-, and long-reach transmission, respectively. Investigating the results in this table reveals the following findings

(i) The SCC chooses DDO-OFDM to support transmission for short reach (<100km). Note that 16-QAM is used for the transmission of bit rates of 60, 80, and 100 Gbps but only for short distances of 25, 20, and 15 km, respectively.

(ii) For medium and long reaches, the SCC chooses CO-OFDM technique for transmission using BPSK or QPSK modulation formats. Note that the 16-QAM is not used for long-reach transmission scenario here.

Table 8. Summary of the decisions taken by the SDON controller for different bit rates and transmission distances. The numerical values under the modulation format refer to the transmitter launch power in dBm. The QAM formats denotes 16-QAM signaling

(a) Short reach: (The SDON controller adopts DDO-OFDM technique).

Bit Rate (Gbps)	Transmission Distance (km)															
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -8	BPSK -6	BPSK 0	BPSK 6	BPSK 8	BPSK 8	BPSK 10	BPSK 10	BPSK 12	BPSK 12	BPSK 12	
20	BPSK -10	BPSK -10	BPSK -10	BPSK -8	BPSK 8	BPSK 12	QPSK -4	QPSK 6	QPSK 8	QPSK 8	QPSK 10	QPSK 10	QPSK 12	QPSK 12	QPSK 12	QPSK 12
40	QPSK -10	QPSK -10	QPSK -10	QPSK -10	QPSK 8	QPSK 12	QAM 2	QAM 6	QAM 10							
50	QPSK -10	QPSK -10	QPSK -10	QPSK 8	QPSK 14											
60	QAM -10	QAM -10	QAM -10	QAM -8	QAM 8											
80	QAM -10	QAM -10	QAM -8	QAM 0												
100	QAM -10	QAM -10	QAM 0													

Table 8. (Continued)

(b) Medium reach: (The SDON controller adopts CO-OFDM technique).

Bit Rate (Gbps)	Transmission Distance (km)									
	50	100	150	200	250	300	350	400	450	500
20	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10
40	BPSK -10	BPSK -10	BPSK -10	BPSK -10	BPSK -10	QPSK -10	QPSK -10	QPSK -10	QPSK -10	QPSK 0
60	QPSK -10	QPSK -10	QPSK -10	QPSK -8	QPSK -8	QPSK 0				
80	QPSK -10	QPSK -10	QPSK -4							
100	QAM -4	QAM -2								
120	QAM -2									
140	QAM 0									

(c) Long reach: (The SDON controller adopts CO-OFDM technique).

Bit Rate (Gbps)	Transmission Distance (km)								
	550-950	1000	1050	1100	1150	1200-1550	1600	1650-1800	1850-2000
20	BPSK -10	BPSK -8	BPSK -8	BPSK -6	BPSK -6	QPSK -10	QPSK -8	QPSK -6	QPSK -4

5. Conclusions

In this paper, the performance of BVT-based SDON has been investigated with two type of O-OFDM detection techniques, direct and coherent detection. An algorithm of the SCC has been proposed for controlling the two systems. According to the proposed algorithm, the controlling signals which specify the modulation format and optical launch power have been considered as a function of the required data rate and transmission distance. The main conclusions of this work can be stated as follow

(i) The automatic controlling of optical network devices can be accomplished by the SDON controlling technology, and therefore the optical network management can be made more easy.

(ii) The cost, time, efforts, and resources can be saved with the SDON automatic controlling depending on the proposed algorithm.

(iii) For supporting multiple transmission conditions to increase the system flexibility, different modulation formats, multiple data rates, different distances, and different optical launch powers have been used to access the performance of BVT-based SDON with both DDO-OFDM and CO-OFDM techniques.

(iv) The maximum reach of the system incorporating DDO-OFDM technique with 20Gbps BPSK, 50 Gbps QPSK, and 100Gbps 16-QAM is 31, 28, and 15 km, at transmission power of 12, 15, and 0 dBm, respectively.

(v) The maximum reach of the system incorporating CO-OFDM technique with 40 Gbps BPSK, 80 Gbps QPSK, and 160 Gbps 16-QAM is 275, 170, and 36 km, at power of -8, 4, and 2 dBm, respectively.

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