Extended reach NRZ-OOK data transmission for 40G/60G/100G SWDM4 systems over multimode OM3/OM4 fibers

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***Abstract*— We propose by system simulation, an extension of transmission distances for shortwave wavelength division multiplexing applications such as 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 links over multimode (MMF) OM3 and OM4 fibers using vertical cavity surface emitting laser (VCSEL) as an optical source. This could be a solution for upgrading optical transmission systems in data centers. Non-return to zero - on off keying (NRZ-OOK) data is transmitted over 420 m of OM3 fiber and 655 m of OM4 fiber for 40G-SWDM4 applications, as well as 220 m of OM3 fiber and 340 m of OM4 fiber for 60G-SWDM4 applications, whereas for 100G-SWDM4 applications, this data is transmitted over 150 m of OM3 fiber and 225 m of OM4 fiber. Bit error rate curves as a function of the received optical power for all the wavelengths 850 nm, 880 nm, 910 nm and 940 nm used made it possible to demonstrate the impact of the modal bandwidth of these fibers on each of these wavelengths.**

Keywords*— *LAN data center, MMF OM3/OM4, NRZ-OOK, SWDM, VCSEL

I. Introduction

Nowadays data centers are the brain that makes possible all cloud and web services widely used around the world. These are large facilities that include an impressive amount of interconnected servers. These servers process and store information available on the Internet, and they promote the development of new cloud applications that we use daily: cloud storage, video streaming, sharing of images and videos on social networks, Internet of Things (IoT), interactive online games, etc [1]. Globally, the total number of Internet users is projected to grow from 3.9 billion in 2018 to 5.3 billion by 2023 at a CAGR of 6 percent. In terms of population, this represents 51 percent of the global population in 2018 and 66 percent of global population penetration by 2023 [2]. Global data center IP traffic is, in fact, constantly increasing according to the forecasts made by Cisco for the period 2016-2021 in its white paper, global index on the cloud [3]. According to forecasts, this traffic will be tripled during this period with 25 percent compound annual growth rate (CAGR). This rate increases to 26 percent for the period 2017-2022 [4]. In addition, it is estimated that the number of data centers will increase from 338 at the end of 2016 to 628 by 2021 [3]. Moreover, by observing the distribution of the total traffic in three (03) groups of which 71.5 percent for within data center traffic, 13.6 percent for data center to data center traffic, 14.9 percent for data center to end users traffic, it is thus proved that within data center traffic is predominant [3]. The largest amount of data is therefore exchanged between different servers and/or storage units installed within data center. In order to cope with this impressive data traffic and to meet the ever-increasing bandwidth needs continually introduced by new applications and services, transmission systems deployed within these data centers must be scalable [5]. As a result, optical interfaces capable of transmitting data rates of 40 Gb/s, 100 Gb/s, 200 Gb/s and beyond [6][7] on multimode fibers are recommended, in order to overcome limitations imposed by copper cables. The 40GBASE-SR4, 100GBASE-SR10, and 100GBASE-SR4 standards provide 4×10G, 10×10G, and 4×25G parallel links using vertical cavity surface emitting laser (VCSEL) sources coupled with optimized multimode OM3/OM4 fibers at 850 nm [8][9]. These fibers have a core diameter equal to 50 µm, a modal bandwidth at 850 nm equal to 2000 MHz.km and 4700 MHz.km respectively, and make it possible to reach distances of less than or equal to 150 m [8][9] according to the specifications of IEEE 802.3ae and 802.3bm standards. In general, most of the links already deployed within data centers are parallel multiple links most often at 10 Gb/s each, and the number of cables increases very rapidly when migrating to higher data rates. In such a configuration, upgrading links to data rates of 40 Gb/s, 100 Gb/s and beyond results not only in large investments [10], but also congestion of the cables at the rack level. This can make the efficient management of space difficult. To facilitate upgrading of these links with a low investment cost, shortwave wavelength division multiplexing (SWDM) was introduced by SWDM Alliance [11], an industrial consortium defining optical specifications of transmitters/receivers required to deploy single links by reusing the existing multimode fibers (MMF) infrastructure. The proposed SWDM solutions increase the capacity without adding additional parallel links as in parallel optical solutions. Thus, standards 40G-SWDM4 and 100G-SWDM4 make it possible to use 4λ×10G and 4λ×25G on optimized MMF fibers OM3, OM4 and more recently OM5 type in the wavelength range of 850 nm to 940 nm with an interchannel spacing of 30-nm [12] [13]. These single links are generally in duplex mode, and allow reaching the distances of 240 m OM3, 350 m OM4 and 440 m OM5 for 40G-SWDM4 and 70 m OM3, 100m OM4 and 150 m OM5 for 100G-SWDM4.

Recently, Finisar Photonics demonstrated reach of 200 m OM3, 300 m OM4 and 400 m OM5 for 100G-SWDM4 links [14]. However, the technical specifications in relation to the proposed transmission systems are proprietary data. Most of the work recently done and reported to us is experimental. In this context, an experimental study carried out on an SWDM4 system allowing transmission of a 100 Gb/s (4λ×25.8 Gb/s) data rate over 300 m of wideband OM4 fiber has been demonstrated. This wideband OM4 fiber, manufactured by Prysmian Group [15], is optimized in 850 nm to 950 nm grid [8]. Work carried out in [16] indicates the transmission of 103.12 Gb/s of data modulated in PAM4 format over a WDM link with 2λ×51.56Gb/s at 850 nm and 880 nm. A distance of 180 m over OM4 fiber was achieved using light injection techniques into the fiber. To our knowledge, the only study carried out by simulation for a 100G WDM link, comes from [17]. The authors showed similar distances on OM3/OM4 fibers as those defined by the standard 100G-SWDM4. In addition to the 850 nm to 940 nm grid, they also proposed a 1030 nm to 1120 nm grid with 30 nm interchannel spacing in order to reach 100 m multimode OM2 distance transmission. OM2 fiber is no longer recommended for very high data rate applications in data centers [17].

In this manuscript, we use a simulation system software named OptiSystem 7.0 to propose a transmission reach extension solution for 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 applications over MMF OM3 and OM4 fibers for optical transmission systems deployed within datacenters, like performed in [17]. Therefore, we provide a detailed description of the technical specifications of the various simulated links. The work reported in this document is organized into two (02) major parts. In the first part, we present the proposed transmission system and its implementation in the simulation environment. The second part shows results obtained in terms of data rate and distance reached for all simulated links. In addition, special attention is paid to the impact of modal dispersion in the MMF OM3 and OM4 fibers based grid wavelength from 850 nm to 940 nm.

II. Simulations Setup

We present in Fig. 1 schematic of the proposed optical transmission system used to simulate our different SWDM links. In this setup, four (04) NRZ-OOK blocks called (Tx1 to Tx4) modulate a SWDM optical channel at the emitter side. In order to estimate the BER performance of the received electrical signal at the SWDM optical channel output, four (04) modules called BER analyzers (Rx1 to Rx4) are used. The optical SWDM channel is composed on respectively : four (04) VCSEL lasers, one 4x1 SWDM multiplexer followed by a MMF fiber and four (04) photodiodes at the output of one 1x4 SWDM demultiplexer. We also used a variable optical attenuator (VOA) in order to vary the photodiodes received optical power. For each NRZ-OOK block, a pseudo-random binary sequence of (2^{12}-1) size is encoded to output an electrical NRZ-OOK signal which is used to directly modulate a VCSEL optical source of the SWDM channel. The four (04) emitted VCSELs optical signals at respectively wavelength values of 850 nm, 880 nm, 910 nm and 940 nm are both multiplexed by the SWDM Mux and later demultiplexed at the output of the optical multimode

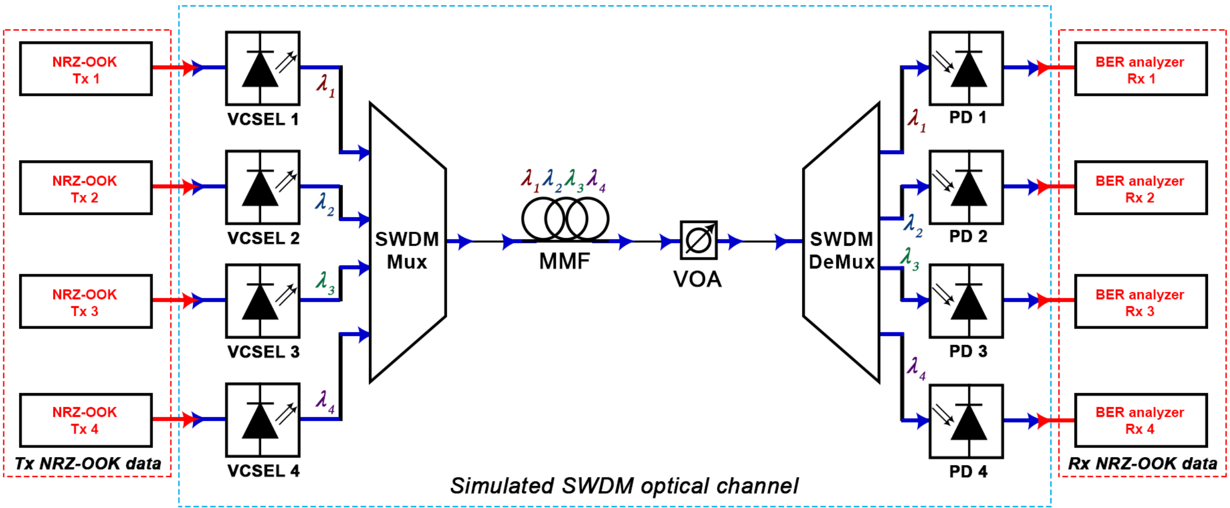

Fig. 1. SWDM-LAN transmission system design.

fiber by the SWDM DeMux [12] [13]. At this step, photodiodes (PD1 to PD4) are used respectively to detect each wavelength of the demultiplexing received signal and convert it back to electrical domain for NRZ-OOK decoding and bit error rate (BER) analyzing. The BER is calculated by comparing the transmitted sequence of bits to the received bits and counting the number of errors. VCSEL sources are low-cost solutions that are widely deployed in optical LANs in data centers because they are easy to couple with multimode fibers [18] [19]. In the simulation, data rates of either 10 Gb/s, 15 Gb/s or 25 Gb/s per wavelength are used in order to simulate 40G-, 60G- or 100G-SWDM4 link. To study performance of the proposed shortwave wavelength division multiplexing system in local area network (SWDM-LAN), simulations were performed for each 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 link using OptiSystem 7.0 software. The simulated photodiode (PD) is modeled by a PIN photodiode with a transimpedance amplifier (TIA) coupled with a low-pass filter.

Table I summarizes the characteristics of the optical sources, as well as those of photodiodes, multiplexer and demultiplexer, which mainly come from datasheets of real components [17]. The emitted optical power by each VCSEL is set to 5 dBm [17] and sensitivity of each PIN photodiode is fixed at -9.1 dBm [20].

Table II gives characteristics used for the MMF fiber OM3/OM4. The system performance is evaluated in terms of BER and eye diagram. According to literature, BER value of 10^{-3} is often chosen considering the use of forward error correction (FEC) codes.

TABLE I. VCSEL, MUX/DEMUX AND PD PARAMETERS [12] [13] [17]

Parameters	Values
VCSEL	
Wavelength [nm]	850, 880, 910, 940
Slope efficiency [W/A]	0.22
Threshold current [mA]	1.2
Bias current [mA]	3.3
Laser transconductance [A/V]	0.02
3dB bandwidth [GHz]	7
Linewidth [MHz]	10
Chirp Alpha	3.7
Adiabatic factor	10000
RIN [dB/Hz]	-128
RIN measured power [W]	1e-05
SWDM Mux / DeMux	
Operating wavelength [nm]	850-940
Spacing channel [nm]	30
Bandwidth [nm]	20
Insertion loss [dB]	0.5
Bandpass filter type	Bessel
Bandpass filter order	4
Photodiode (PIN+TIA+Filter)	
Dark current [nA]	10
Thermal noise [A/Hz^0.5]	1.815e-14
ASE and shot noise	Enabled
TIA impedance [Ω]	1000
Low-pass filter type	Bessel
Low-pass filter order	4
Cutoff frequency [GHz]	9

TABLE II. MMF OM3 AND OM4 FIBERS PARAMETERS [15] [17]

Parameters	Values	
	OM3	***OM4***
Modal bandwidth [MHz.km]	2000 (850nm) 1750 (880nm) 1500 (910nm) 1250 (940nm)	4700 (850nm) 3300 (880nm) 2325 (910nm) 2000 (940nm)
Attenuation [dB/km]	2.3	2.3

III. SIMULATIONS RESULTS

A. *Impact of Modal Bandwidth with the Wavelengths*

Fig. 2 shows BER curves as a function of the received optical power for different wavelengths in back-to-back (B2B) configuration (without fiber) and 240 m OM3 fiber. The results obtained in B2B configuration show similar BER performances for all simulated wavelengths. This can be explained by not only the identical characteristics of the four (04) VCSEL sources generating these wavelengths but also the absence of fiber limitations in B2B configuration. At 240 m OM3 fiber, it can be seen that the BER performance degrades with the optical received power decrease for all simulated wavelength. This is normal due to the noise that becomes significant when the received power becomes low. Moreover, for any considered value of received optical power, it is shown that BER performance is good only for wavelength value of 850 nm and degrades with the wavelength increase. This could be explained by the modal bandwidth of the optical fiber which is maximal (2000 MHz.km) at 850 nm and decreases from 1750 to 1250 MHz.km at wavelength values of 880 to 940 nm.

Fig. 3, which shows BER curves as a function of the received optical power for different wavelengths in Back-to-Back (B2B) configuration and 350 m OM4 fiber. The results obtained show the same results as previously in B2B. This is explained by the fact that in B2B configuration, no optical fiber (OM3 or OM4) propagation effect is taken into account. Since the modal bandwidth values of the OM4 fiber are higher than those of the OM3 respectively, the results found at Fig. 3 for 350 m OM4 can be explained as previously for 240 m OM3 fiber in Fig. 2. The only gap in terms of the BER performances resides in the dispersions penalties. These results are in accordance with studies carried out by [17] and [21] where it is proved that high wavelengths are the worst performers because of the low modal bandwidths that OM3/OM4 fibers exhibit at these wavelengths. Moreover, to

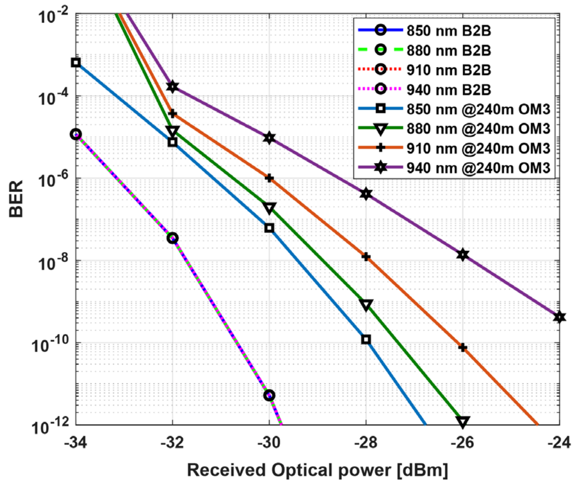

Fig. 2. BER curves of the 40G-SWDM4 system for B2B and over OM3 MMF fiber.

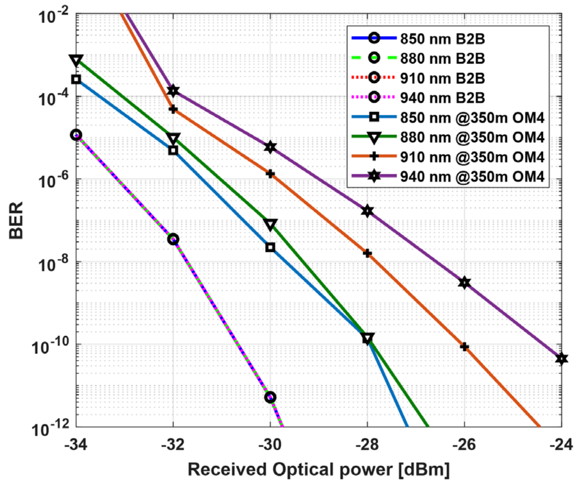

Fig. 3. BER curves of the 40G-SWDM4 system for B2B and over OM4 MMF fiber.

corroborate ours analyzes, we also appreciated the system performance by using eye diagram. From the different diagrams of Fig. 4, we observe that the eye diagram is identical in B2B for all wavelengths, but it closes progressively for 240 m and 350 m of OM3 and OM4 fiber respectively when we move from 850 to 940 nm for example. The eye diagram is more open at 850 nm than at 940 nm, which is the most penalized, and where the modal bandwidth of fibers is the smallest. Hence, in order to appreciate the transmission system performance of all our links, we consider for the rest of our study, performance realized with wavelength value of 940 nm which is the most unfavorable one and for which modal dispersion of the fibers used is the most penalizing.

B. *Transmission Performance of 40G/60G/100G SWDM4 links*

In this section, we present the simulation results in terms of transmission distance and optical budget for the proposed 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 links. Figs.

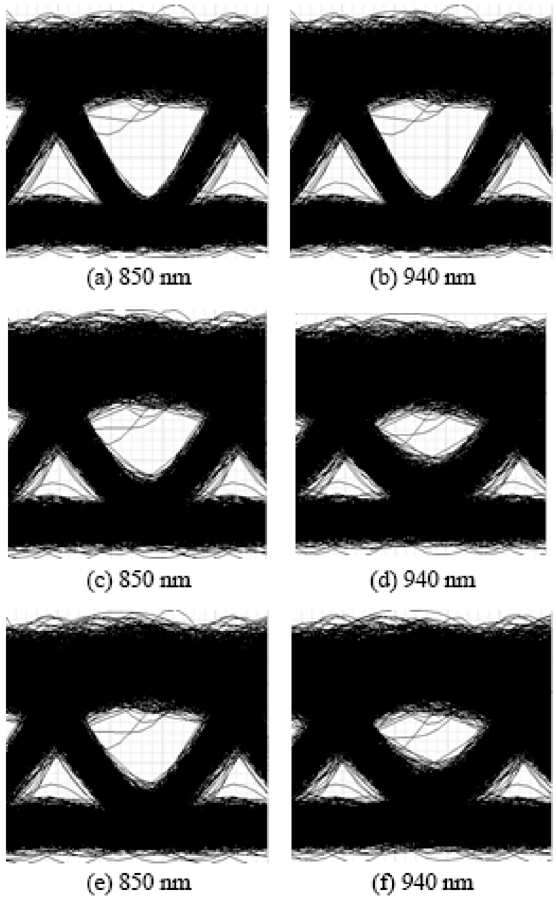

Fig. 4. The eyes diagrams of the 40G-SWDM4 system (a, b) for B2B, (c, d) over 240 m OM3 MMF and (e, f) over 350 m OM4 MMF.

5 and 6 show the BER results as a function of the fiber distance at 940 nm. Please notice that for all results we will present in this section, the data rate per wavelength is considered. This means for example, that 40G-SWDM4 or respectively 100G-SWDM4 link system is simulated if data rate of 10 Gb/s or respectively 25 Gb/s is used.

After setting the optical budget (OB) to 14.1 dB, from results of Fig. 5, we show that in order to guarantee BER value of 10^{-3}, OM3 fiber distances of respectively 420 m, 220 m and 150 m are needed for system links of respectively 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 while based of Fig. 6, OM4 fiber distances of respectively 655 m, 340 m and 225 m are needed for respectively the same configurations. All these results prove the advantage to use OM4 fiber compared to OM3 because of its good and high offered modal bandwidth values. Indeed, it can be seen in both Fig. 5 and Fig. 6 that BER performance degrades with increase of both the distance transmission and data rate. For example, BER degrades faster on 100G-SWDM4 links with an increase of distance. This limitation in terms of distance at very high data rate is induced by the chirp of the VCSELs coupled with the modal dispersion of the multimode fibers. In addition, by migrating the fiber link from OM3 to OM4, it is possible to improve the distance transmission of about respectively 235 m, 120 m and 75 m for system links of respectively 40G-SWDM4, 60G-SWDM4 and

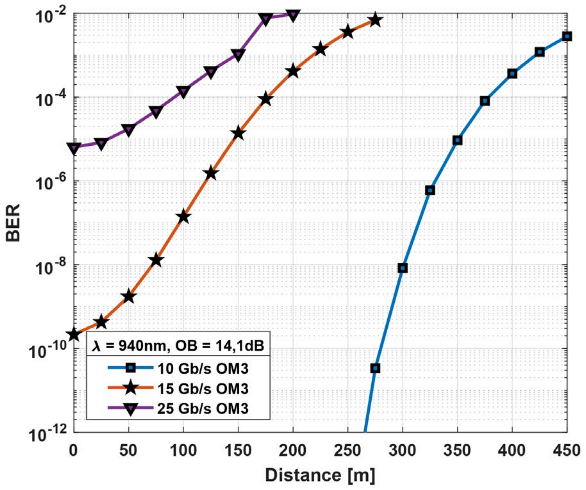

Fig. 5. BER as a function of the OM3 fiber distance for different data rates of the simulated SWDM4 system.

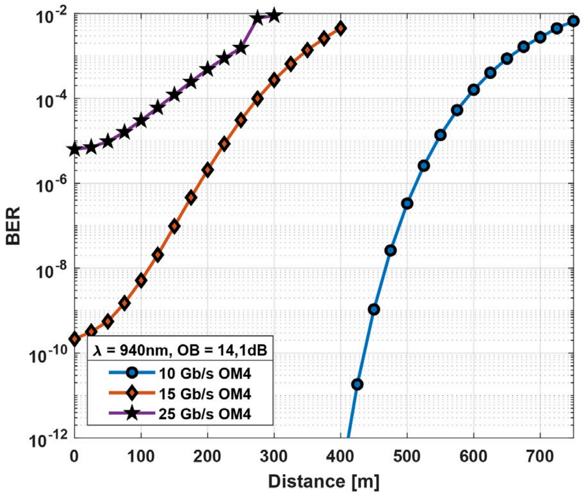

Fig. 6. BER as a function of the OM4 fiber distance for different data rates of the simulated SWDM4 system.

100G-SWDM4. This is justified by the modal bandwidth of OM4 fibers, which is greater than that of OM3 fibers.

Fig. 7 presents the eye diagram obtained at respectively 420 m, 220 m and 150 m OM3/OM4 MMF for the simulated 40G/60G/100G-SWDM4. This allows us to better visualize the impairments induced by each SWDM system links. It can be observe a gradual closing of the eye with increase of the simulated data rate when considering the same multimode fiber category (OM3/OM4). Also, an eye diagram opening can be observed when deciding to change the multimode fiber category from OM3 to OM4 in the same system link.

Table III shows distances transmission obtained with our 40G-SWDM4 and 100G-SWDM4 links compared with results from other authors or recommendations from the SWDM Alliance Standards. According to Table III, we have extended reach of 40G-SWDM4 and 100G-SWDM4 links compared with SWDM Alliance, but also Cisco and Finisar Corporation. Without any knowledge about end-to-end

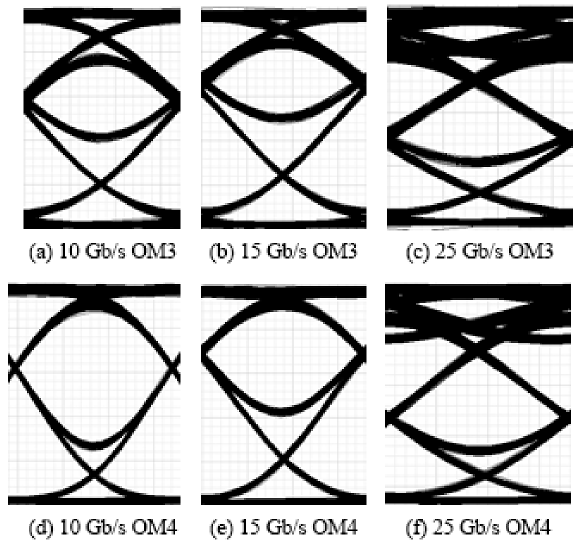

Fig. 7. The eyes diagrams of the 40G/60G/100G-SWDM4 system (a, d) over 420 m OM3/OM4 MMF, (b, e) over 220 m OM3/OM4 MMF and (c, f) over 150 m OM3/OM4 MMF.

experimental values used by these manufacturers to achieve and improve their results, we remain modest and believe that our results could be an approach for upgrading existing and future SWDM transmission systems in data centers. Thus, we demonstrate by our study, an improvement of transmission distance for 40/100G-SWDM4 applications over OM3/OM4 fibers in order to increase data rate on optical systems within data center.

TABLE III. 40 AND 100 GB/S SWDM4 SYSTEMS PROPOSED VERSUS SWDM ALLIANCE, BIDI OF CISCO AND FINISAR SYSTEMS RECOMMANDATIONS

Application	OM3 (m)	OM4 (m)	Ref.
40G-SWDM4	420	655	-
40G-SWDM4 (Alliance)	240	350	[12]
40G-BiDi (Cisco)	100	150	[9]
40G-SWDM4 (Finisar)	300	400	[14]
100G-SWDM4	150	225	-
100G-SWDM4 (Alliance)	75	100	[13]
100G-BiDi (Cisco)	70	100	[9]
100G-SWDM4 (Finisar)	100	150	[14]

IV. CONCLUSION

In this manuscript, we have demonstrated possibility of extending transmission distance of 40G-SWDM4 and 100G-SWDM4 links over OM3 and OM4 fibers for upgrading optical systems within data center. Compared with the recommendations of SWDM applications defined by the standards and some manufacturers, good transmission performance has been proven. The proposed links of 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 allow transmission reach of respectively 420 m / 655 m, 220 m / 340 m and 150 m / 225 m over respectively OM3 / OM4 fibers. The results obtained showed that impact of modal bandwidth of fibers used is more penalizing at 940 nm than at 850 nm. As a result, our system configuration could be adopted as a technical solution for upgrading to 40G-SWDM4, 60G-SWDM4 and 100G-SWDM4 of current and future data center transmission systems with low investment cost. Beyond all these results, an experimental validation is already planned to be carried out for our future work.

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