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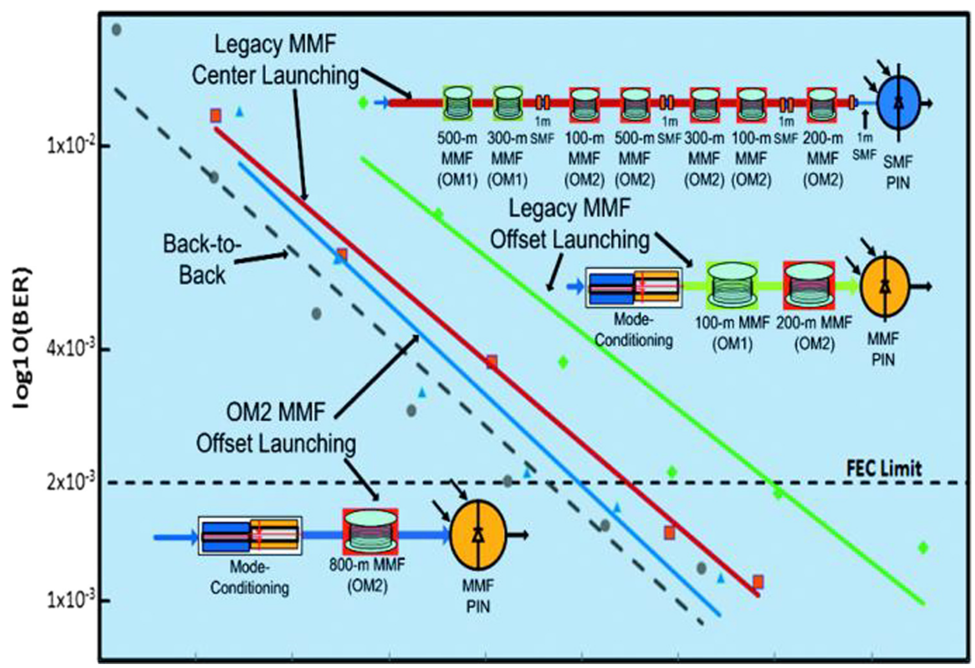

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Directly Modulated VCSEL-Based Real-Time 11.25-Gb/s Optical OFDM Transmission Over 2000-m Legacy MMFs

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Abstract: In directly modulated vertical cavity surface-emitting laser (DM-VCSEL)-based, end-to-end real-time, 11.25-Gb/s optical orthogonal frequency division multiplexing (OOFDM) systems utilizing legacy OM1/OM2 multimode fibers (MMFs), as well as simple intensity-modulation and direct-detection (IMDD) detailed experimental explorations, are undertaken, for the first time, for the effectiveness of various optical launching conditions, including center launching and conventional offset launching in maximizing the transmission distances of the legacy MMF systems. It is shown that, in the aforementioned legacy MMF systems, center launching enables an adaptive power-loaded OOFDM transmission at a raw signal bit rate of 11.25 Gb/s over an unprecedented distance of 2000 m with an optical power penalty as low as 0.8 dB. When center launching is replaced by conventional offset launching, the transmission distance of the legacy MMF system is reduced to 300 m, and the corresponding optical power penalty is increased to 2.3 dB. Comparisons of measured maximum achievable transmission distances of various MMF IMDD system configurations subject to different launching conditions show that DM-VCSEL-based, adaptive power-loaded OOFDM at center launching is a viable and cost-effective solution for use in legacy MMF systems. This work may have great potential for upgrading installed MMF local area networks to 10 Gb/s and beyond.

Index Terms: Directly modulated vertical cavity surface-emitting lasers (DM-VCSELs), fiber optics systems, optical modulation and orthogonal frequency division multiplexing (OFDM).

1. Introduction

Owing to the exponential growth in end-users' bandwidth demand with the advent of multimedia-rich applications such as video/photo sharing, 3-D television, Internet Protocol television, and cloud computing, local area networks (LANs) face great challenges of being upgraded [1]. In existing LANs, multimode fibers (MMFs) are widely implemented as the transport medium for high-speed data transmission. It has been estimated [2] that approximately 19.5 million kilometers of legacy MMFs have been installed in campuses and in-building network backbones. To upgrade these LANs from 1 Gb/s to 10 Gb/s and beyond, enterprise customers prefer to use their installed legacy MMFs rather than lay new fibers, as significant cost-savings can be achieved.

To achieve the customer-preferred technical strategy, 10GBASE-LRM (10GBASE-LX4) technology with a maximum transmission distance of 220 m (300 m) has been standardized. In addition, for the enhancement of 3-dB optical bandwidths of MMFs via restricted optical mode excitation, use can be made of different optical launching techniques including center launching and conventional offset launching [3]–[5]. In center launching, the fundamental optical mode is almost excited exclusively, while in conventional offset launching, a number of higher-order optical modes are excited. Moreover, to improve the 3-dB optical MMF bandwidths and system transmission capacities, spatial light modulation (SLM) [6] and mode group division multiplexing [7] have also been proposed, which excite selected optical modes only. However, these two techniques [6], [7] are strongly system-dependent, implying that considerable technical barriers still remain to be solved before they are viable for future mass deployment.

In addition to the restricted optical mode excitation-enabled enhancement in 3-dB optical MMF bandwidth, the improvement in signal spectral utilization efficiency through employing advanced modulation formats is also greatly advantageous for further increasing the transmission performance of legacy MMF systems. Due to its inherent and unique advantages including adaptive and highly efficient utilization of channel spectral characteristics, excellent resistance to a large amount of differential mode delay (DMD), as well as potential for cost-effective implementation, optical orthogonal frequency division multiplexing (OOFDM) is a promising "future-proof" technique that has demonstrated huge potential to support $>$ 50 Gb/s over 300 m transmission in 99.5% of already-installed legacy MMFs [8], [9].

Given the fact that LANs are extremely cost-sensitive, to significantly reduce the OOFDM transceiver cost, the use of directly modulated vertical cavity surface-emitting lasers (DM-VCSELs) in OOFDM transceivers is of great importance for practical implementation, since, in addition to their low-cost and low power consumption due to small threshold currents applied, VCSELs also have unique properties such as high reliability, long lifetime, easy packaging and testing [10]–[12]. Moreover, the availability of multiwavelength and multidimensional VCSEL arrays may further improve, in a cost-effective manner, the network flexibility and scalability. The significant challenge associated with DM-VCSEL-based legacy MMF systems is low modulation bandwidths of commercially available VCSELs and the very narrow system frequency responses of legacy MMF systems, both of which can, however, be exploited through the spectrally efficient and adaptive OOFDM modulation scheme [10], [12], [13].

The utilization of DM-VCSELs to transmit 28 Gb/s OOFDM signals over 1000 m OM4 MMF systems has been reported [14], where the measurements were, however, undertaken utilizing offline digital signal processing (DSP) approaches that do not consider the limitations imposed by the precision and speed of practical DSP hardware for realizing end-to-end real-time transmission. More importantly, the experiments reported in [14] were performed over OM4 MMF systems, whose 3-dB optical bandwidths are significantly higher than those corresponding to installed legacy MMF systems of interest of the present paper. Very recently, we have experimentally demonstrated end-to-end real-time 11.25-Gb/s OOFDM transmission over DM-VCSEL-based 800-m OM2 MMF systems based on intensity-modulation and direct-detection (IMDD) and conventional offset launching [10].

The thrust of the present paper is to experimentally explore, for the first time, the feasibility of using uncooled, low-cost, low modulation bandwidth DM-VCSEL-based, real-time 11.25-Gb/s OOFDM transceivers with adaptive power loading to upgrade legacy OM1/OM2 MMF systems subject to center launching. In order to highlight the effectiveness of center launching over conventional offset launching in maximizing the transmission distances of the legacy MMF systems, extensive comparisons of the measured maximum transmission distances of the aforementioned systems are made between various system configurations including a) legacy OM1/OM2 MMF systems subject to conventional offset launching, b) conventional offset launching over systems consisting of the same type of MMFs, and c) legacy OM1/OM2 MMF systems subject to center launching. It is shown that center launching enables real-time 11.25 Gb/s adaptive power-loaded OOFDM transmission over 2000-m legacy OM1/OM2 MMFs with an optical power penalty as low as 0.8 dB. While when center launching is replaced by conventional offset launching, the transmission distance of the aforementioned MMF system is reduced to 300 m, and the corresponding optical power penalty is increased to 2.3 dB. Furthermore, even for transmission

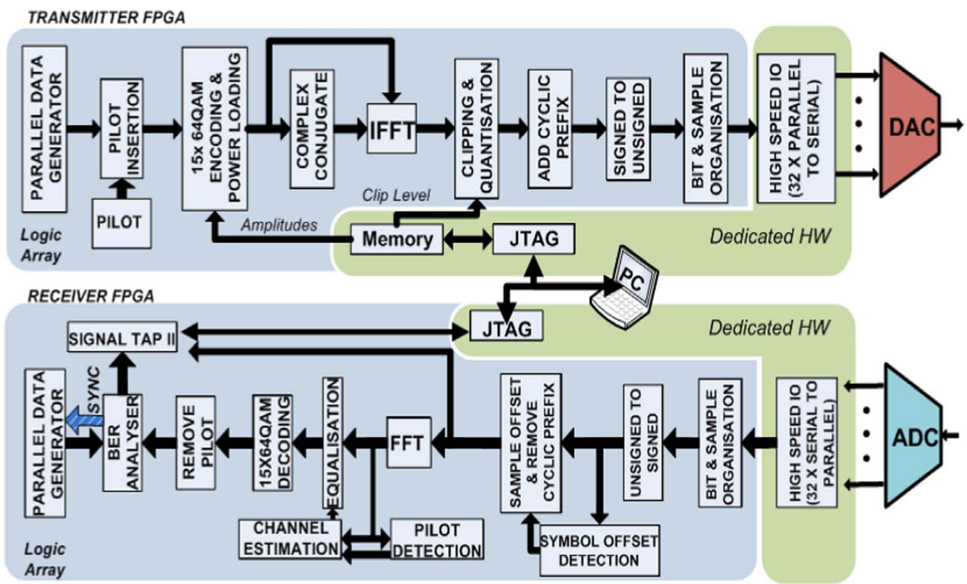

Fig. 1. Real-time FPGA-based OFDM transceiver architectures.

systems with OM2 MMFs only, which have much larger 3-dB optical bandwidths than OM1-MMF-only systems of identical lengths, conventional offset launching is just capable of supporting 11.25 Gb/s over 800 m transmission with an optical power penalty of 0.3 dB. These unprecedented experimental results indicate that adaptive power-loaded OOFDM with center launching is a viable and cost-effective solution for practical use in high-speed legacy OM1/OM2 MMF IMDD systems incorporating DM-VCSELs.

Here, it is worth mentioning the following two facts: 1) In the present real-time OOFDM transceivers with adaptive power loading, online performance monitoring of total channel bit error rate (BER), individual subcarrier BER, and system frequency response are implemented [15]. These online monitoring functions not only provide vital information for live control of total digital signal amplitude, signal clipping level, digital amplitude of individual subcarriers and VCSEL operating conditions, but also enable live maximization of system transmission performance by effectively compensating for the low modulation bandwidths of low-cost optical/electrical components and narrow legacy MMF system frequency responses. 2) Throughout the paper, as stated in Section 2.1, a raw signal bit rate of 11.25 Gb/s is utilized, which includes the cyclic prefix and a 7% forward error correction (FEC) overhead. The raw signal bit rate can be further improved by using digital-to-analog converters (DACs)/analog-to-digital converters (ADCs) with higher sampling speeds and/or relatively short cyclic prefixes [8], [9].

2. Real-Time OOFDM Transceiver Architectures and Experimental Systems

2.1. Real-Time OFDM Transceiver Architectures

Fig. 1 shows the detailed architectures of the real-time electrical OFDM transmitter (top) and receiver (bottom). The real-time OFDM transceiver is implemented with field programmable gate arrays (FPGAs) for high-speed DSP and a 4-GS/s@8-bit DAC/ADC. Full descriptions of the FPGA-based OFDM transceiver architectures, their functionalities including inverse fast Fourier transform (IFFT)/FFT, adaptive power loading, online performance monitoring, live parameter optimization, automatic symbol synchronization and channel estimation/equalization can be found in [12], [13], [15]–[17]. In the transmitter, pseudo random data are generated as a stream of 84-bit parallel words, which are combined with a fixed 6-bit pilot word used for channel estimation/equalization. The combined 90-bit words are mapped onto 15 parallel 64-QAM encoders, and the encoded parallel

TABLE 1

Electrical OFDM Transceiver Parameters

Parameter	*Value*
Total number of IFFT/FFT points	32
DAC & ADC sampling rate	4GS/s
DAC & ADC resolution	8 bits
Data-carrying subcarriers	15
n-th subcarrier frequency	N x 125MHz
Symbol rate	100MHz
Modulation format on all subcarriers	64-QAM
Data bits per symbol	84 bits
Pilot bits per symbol	6 bits
Total bits per symbol	90 bits
Error count period	88,500 symbols
Raw signal bit rate	11.25Gb/s
Net signal bit rate	9Gb/s
Cyclic prefix duration	2ns

complex data are first adaptive power-loaded and subsequently converted into a real-valued time domain signal using the IFFT. Taking into account the OFDM transceiver parameters presented in Table 1, it is easy to work out that the present OFDM transceiver design gives rise to a raw signal bit rate of 11.25 Gb/s, of which 9 Gb/s can be employed to carry user data, as a cyclic prefix length of 2 ns per symbol is adopted in the transceiver design. It should be pointed out that pilot data are only inserted as regular bursts of pilots. This allows all the 15 subcarriers to be used for user data transmission between pilot bursts. The insertion rate of the pilot bursts can be as low as 10 Hz, leading to an overhead occupied by pilot data as low as 0.001% [17].

At the receiver side of the transceiver, the received analog electrical signal is digitized by an 8-bit ADC operating at 4 GS/s. Following symbol synchronization and subsequent DSP procedures detailed in [16], only 15 data-carrying subcarriers in the positive frequency bins are required for channel estimation/equalization and data recovery. In addition, the BER analyzer continuously counts errors every 88 500 symbols, which corresponds to the total test pattern length of 7 965 000 bits.

2.2. DM-VCSEL-Based Real-Time OOFDM Transceivers and MMF IMDD Systems

Fig. 2 illustrates the developed DM-VCSEL-based, end-to-end real-time, 64-QAM-encoded, 11.25 Gb/s OOFDM transceivers and corresponding experimental system setup. Table 2 presents the key parameters adopted in the OOFDM transceivers and the experimental systems. The real-valued, unsigned electrical OFDM signal emerging from the DAC output port is first adjusted by a variable electrical attenuator to produce an optimum driving signal with an amplitude of $\sim$286 mVpp. After combining the driving signal with an optimized DC bias current of 5.13 mA, the combined electrical OFDM signal is then employed to directly modulate a 3.63 GHz modulation bandwidth, single-mode fiber (SMF)-pigtailed, uncooled VCSEL operating at 1547 nm. Having boosted the

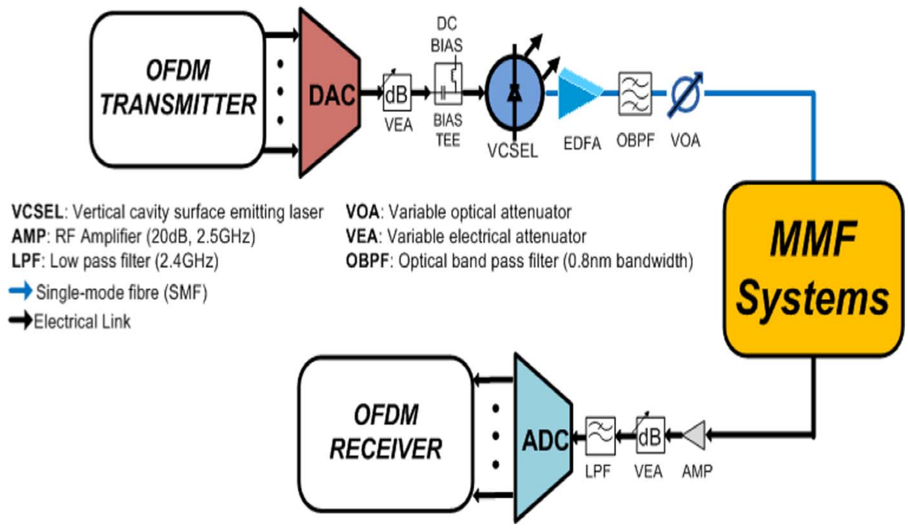

Fig. 2. End-to-end real-time OOFDM transceivers and MMF IMDD systems using DM-VCSELs.

TABLE 2

Optical System Parameters

	Case I	*Case II*	*Case III*
MMF length	300m	800m	2000m
MMF core size	62.5µm x 100m 50µm x 200m	50µm	62.5µm x 800m 50µm x 1200m
MMF fiber type	OM1/OM2	OM2	OM1/OM2
Optical launching power	-1.74dBm	+2.24dBm	+5.55dBm
PIN detector type	MMF-pigtailed		SMF-pigtailed
PIN detector mode diameter	50µm		9µm
Small-signal VCSEL modulation bandwidth		3.63GHz	
Optimum VCSEL bias current		5.13mA	
Optimum VCSEL driving voltage		286mVpp	
VCSEL wavelength		1547nm	
VCSEL threshold current		2mA	
PIN detector sensitivity		-17dBm*	
PIN detector bandwidth		12GHz	

*Corresponding to 10 Gb/s Non-Return-to-Zero data at a BER of 1.0×10^{-9}

optical output signal power, a variable optical attenuator is utilized to adjust the optical signal power coupled into various MMF transmission systems under specific launching conditions listed in Table 2. At the output of the MMF systems, the transmitted optical signal is detected by a PIN detector which

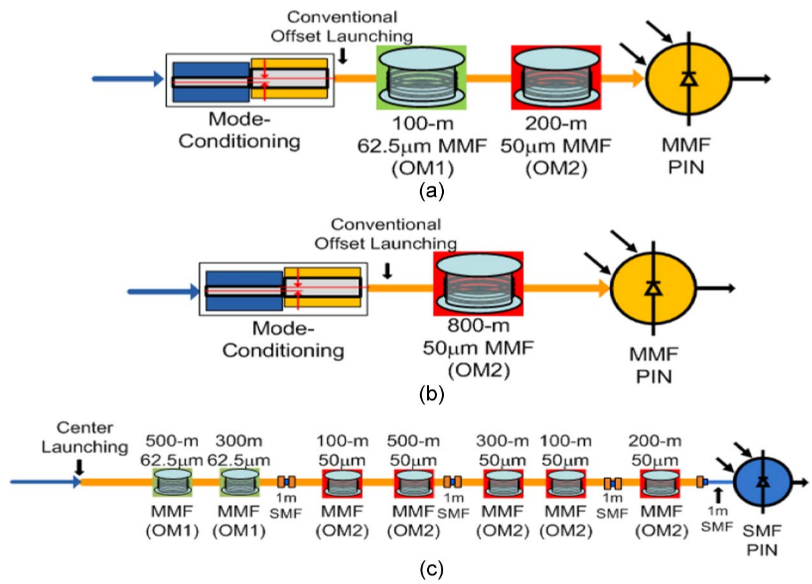

Fig. 3. MMF system configurations. (a) Case I: 300-m legacy OM1/OM2 MMFs subject to conventional offset launching; (b) Case II: 800-m OM2 MMF subject to conventional offset launching; and (c) Case III: 2000-m legacy OM1/OM2 MMFs subject to center launching.

performs the optical-to-electrical conversion. Finally, the received electrical signal from the PIN is amplified to an optimum power level prior to digitization by the ADC.

As already mentioned in Section 1, to extensively compare the maximum achievable transmission distances supported by various optical launching conditions in the aforementioned DM-VCSEL-based, real-time 11.25-Gb/s OOFDM MMF IMDD systems, three different cases are experimentally investigated, which are detailed below:

- Case I. This case is to explore the maximum achievable OOFDM transmission distance supported by conventional offset launching in DM-VCSEL-based 11.25-Gb/s legacy MMF IMDD systems. A 300-m legacy OM1/OM2 MMF system subject to conventional offset launching is considered. A commercially available mode-conditioning patchcord, compliant with the IEEE 802.3z Gigabit Ethernet standard, is employed to perform the radial offset between the incident optical beam from the DM-VCSEL and the center of the legacy MMF system input facet [18]. The legacy MMF system consists of a 100-m OM1 MMF and a 200-m OM2 MMF, which are connected by standard fusion splicing. In addition, a 12-GHz bandwidth MMF-pigtailed PIN is also employed at the output of the legacy MMF system, as shown in Fig. 3(a).
- Case II. This case is to explore the maximum achievable OOFDM transmission distance supported by conventional offset launching in DM-VCSEL-based 11.25-Gb/s MMF IMDD systems incorporating the same type of fibers. Given the fact that OM2 MMFs have much larger 3-dB optical bandwidths than OM1 MMFs, the experimental measurements of OOFDM signal transmission over OM1 MMF systems subject to conventional offset launching is thus unnecessary for demonstrating the effectiveness of center launching, as discussed in Section 3. Here, an 800-m OM2 MMF system subject to conventional offset launching is therefore considered, whose system configuration is identical to that adopted in Case I, except that a single spool of 800-m OM2 MMF is employed, as illustrated in Fig. 3(b).
- Case III. This case is to explore the maximum achievable OOFDM transmission distance supported by center launching in DM-VCSEL-based 11.25-Gb/s legacy MMF IMDD systems. The total length of the legacy MMF system is 2000 m, which includes 800-m OM1 MMFs and 1200-m OM2 MMFs, as shown in Fig. 3(c). Here, center launching is achieved by a widely adopted simple approach of using a standard SMF patchcord at the input of the legacy MMF

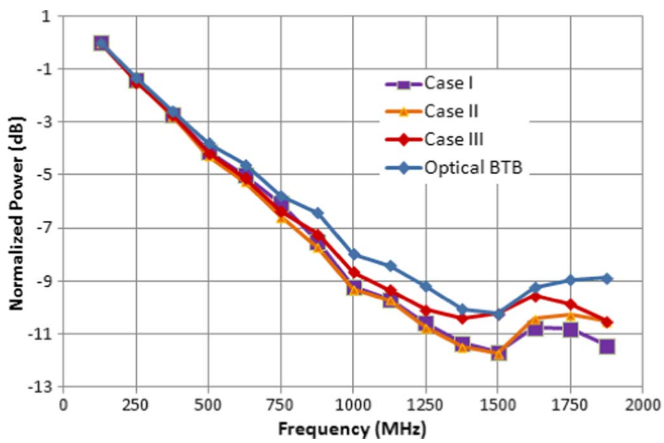

Fig. 4. Measured system frequency responses for different MMF system configurations.

system [5], [19]. Such a center launching technique enables approximately 80% of the optical signal power to be coupled into the desired fundamental mode (LP_{01} mode) at the transmitter end [4]. Considering the fact that the mode propagation constant differences between the LP_{01} mode and higher order modes are relatively large [4], to maintain the excited LP_{01} mode for relatively long transmission distance and simultaneously filter the coupling-induced higher-order modes, further 3×1 m SMF patchcords are also employed within the system, together with a 12-GHz bandwidth SMF-pigtailed PIN detector at the receiver end, as seen in Fig. 3(c). All the remaining MMF spools are directly spliced together. In normal laboratory conditions, acceptable performance robustness of the aforementioned legacy MMF system is experimentally observed, which has also been confirmed independently by experimental measurements in coherent OOFDM MMF systems [19]. Detailed theoretical and experimental explorations of the system performance robustness against practical mechanical perturbations such as lateral offset between fiber connectors, fiber bending and fiber shaking are currently being undertaken, and results will be reported elsewhere in due course.

3. Experimental Results

3.1. Measured System Characteristics

Making use of a pilot tone-assisted system frequency response measurement method detailed in [17], the transceiver parameters listed in Table 1, as well as the MMF system operating conditions presented in Table 2, for the various MMF system configurations described in Section 2.2, the measured system frequency responses are plotted in Fig. 4, where the measurements are performed from the input of the IFFT in the transmitter to the output of the FFT in the receiver, and each measured system frequency response is normalized to its corresponding first subcarrier power. It can be seen in Fig. 4 that, for the optical back-to-back (BTB) system, a large system frequency response roll-off of about 10.3 dB occurs in the high subcarrier frequency region. This agrees with measurements previously published in [12]. The occurrence of the observed system frequency response roll-off effect is mainly due to the coexistence of the following two physical mechanisms: 1) the on-chip output filtering of the DAC and its inherent sin(x)/x response and 2) the DM-VCSEL intensity modulation nonlinearity. As also seen in Fig. 4, the DMD effects associated with Case 1 and Case II give rise to further 1.5-dB reductions in system frequency response roll-off for high frequency subcarriers in comparison with the optical BTB system. On the other hand, compared with Case I and Case II, Case III shows a 1.5-dB improvement in system frequency response roll-off in the high subcarrier frequency region, as shown in Fig. 4. In addition, Case III also has a system frequency response profile very similar to the optical BTB system. These

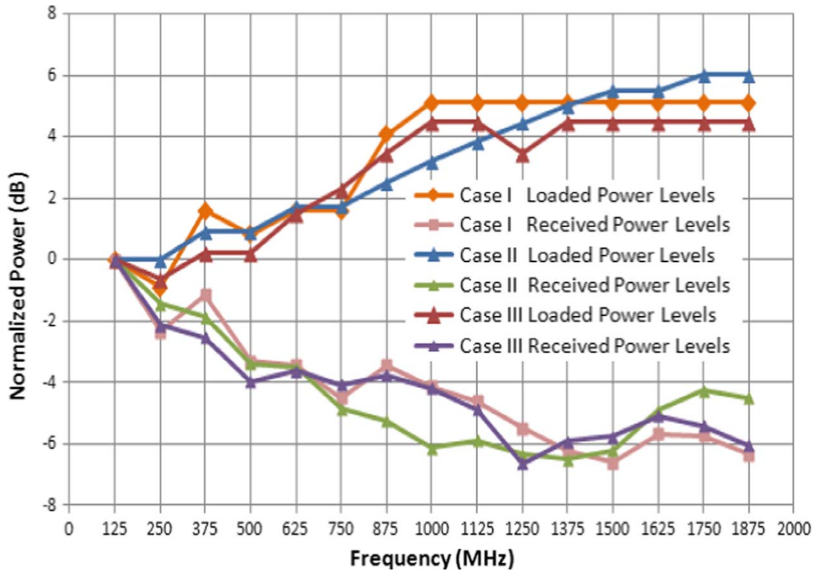

Fig. 5. Loaded/received subcarrier power levels for different cases.

features imply that center launching applied in Case III can mainly excite the fundamental mode, and the transmission system adopted here can maintain the majority of the optical signal power in such an optical mode along the entire legacy MMF system. Clearly, this results in significant reductions in both the number of higher-order modes and the associated DMD effect.

Following the procedure detailed in [15], use is made of adaptive power loading to effectively compensate the system frequency response roll-off effect shown in Fig. 4. For Case I, Case II, and Case III, the loaded subcarrier power distributions prior to the IFFT in the transmitter are presented in Fig. 5, together with the received subcarrier power distributions after the FFT in the receiver, all of which are normalized to the powers of their corresponding first subcarriers. As expected, Fig. 5 shows that for all the cases considered, adaptive power loading can reduce the system frequency response roll-off effect by approximately 5 dB. The residual received subcarrier power variation is determined by quantization noise and the finite dynamic range of the subcarrier amplitude at the IFFT inputs. The reduced subcarrier power variation in the receiver leads to an almost uniform error distribution across all the subcarriers, as shown in Fig. 6. It is clear in Fig. 6 that for Case I, Case II, and Case III, their subcarrier error distributions vary within a range of less than $\pm 7\%$ for all the subcarriers, except that a relatively high error corresponding to the 15th subcarrier occurs for Case I. The occurrence of such a large error on the subcarrier is mainly because of the large system frequency response roll-off experienced by the subcarrier, as shown in Fig. 4.

To further verify the results presented in Fig. 5, with the optimum adaptive power loading profile being applied on all the subcarriers, an OOFDM signal spectrum recorded using a high resolution optical spectrum analyzer at the output of the DM-VCSEL is given in Fig. 7, where for comparison, a corresponding optical spectrum of an unmodulated CW wave from the same VCSEL is also plotted. Fig. 7 shows that there exists an $\sim$2.75-dB decrease in subcarrier power between the first subcarrier and the 15th subcarrier for the DM-VCSEL modulated OOFDM signal. This is in excellent agreement with the electrical-domain measurements shown in Fig. 5. In addition, considering an approach reported in [20], a 3-dB linewidth of the VCSEL operating at the CW mode can be obtained to be $\sim$12 MHz, which is slightly increased to $\sim$13.5 MHz when the VCSEL is modulated by the optimized electrical OFDM signal. This suggests that OOFDM signal modulation has a relatively small impact on the laser linewidth and, more importantly, that the OOFDM IMDD system has an excellent tolerance to the laser linewidth impairments [21].

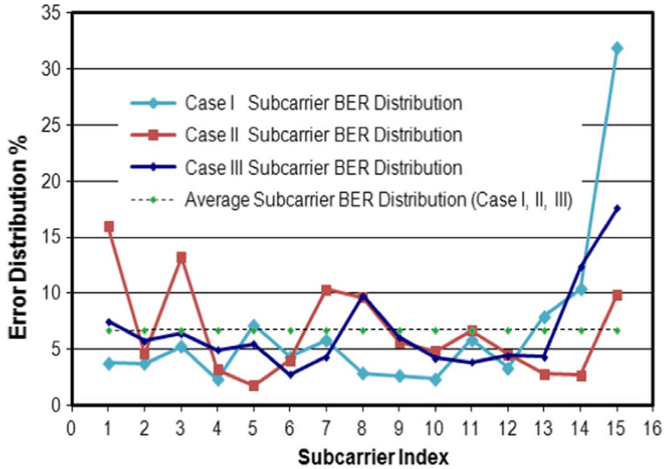

Fig. 6. Typical subcarrier error distribution for Case I, II, and III when adaptive power loading is used.

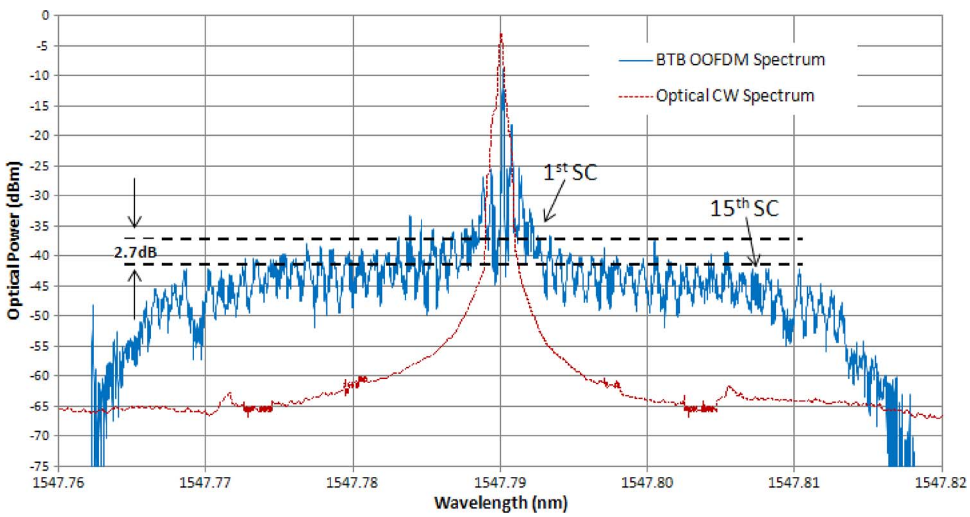

Fig. 7. Continuous-wave (CW) optical spectrum and real-time OOFDM signal spectrum at the output of the DM-VCSEL (measured using Aragon Photonics BOSA, 10.1692-MHz resolution, 80-dB dynamic range).

3.2. BER Performance of DM-VCSEL-Based 11.25-Gb/s OOFDM MMF IMDD Systems

Based on the identified optimum adaptive power loading profiles illustrated in Fig. 5, and the parameter values listed in Tables 1 and 2 for the OOFDM transceivers and the various transmission systems, end-to-end real-time transmissions of 64-QAM-encoded 11.25-Gb/s OOFDM signals are experimentally undertaken for Case I, Case II, and Case III. The measured total channel BER performances as a function of received optical power are shown in Fig. 8, in which the total channel BER performance of the corresponding optical BTB system is also presented.

It is shown in Fig. 8 that, among these three cases considered, at the FEC BER limit of 2×10^{-3}, the 300-m Case I system has the largest optical power penalty of $\sim$2.3 dB, which is, however, reduced to 0.3 dB and 0.8 dB for the 800-m Case II system and the 2000-m Case III systems, respectively. Such reductions in optical power penalty arise due to the combined effects of DMD and modal noise: As demonstrated in Fig. 4, Case I suffers from the strongest DMD effect because of the existence of a relatively large number of higher-order modes excited by conventional offset launching, and the

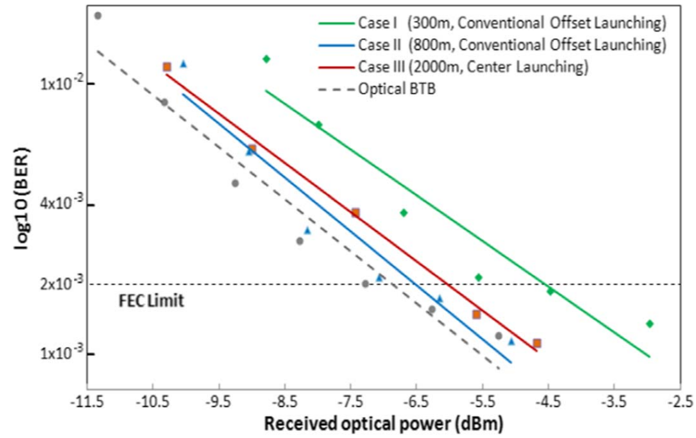

Fig. 8. Measured total channel BER performances as a function of received optical power for different MMF system configurations.

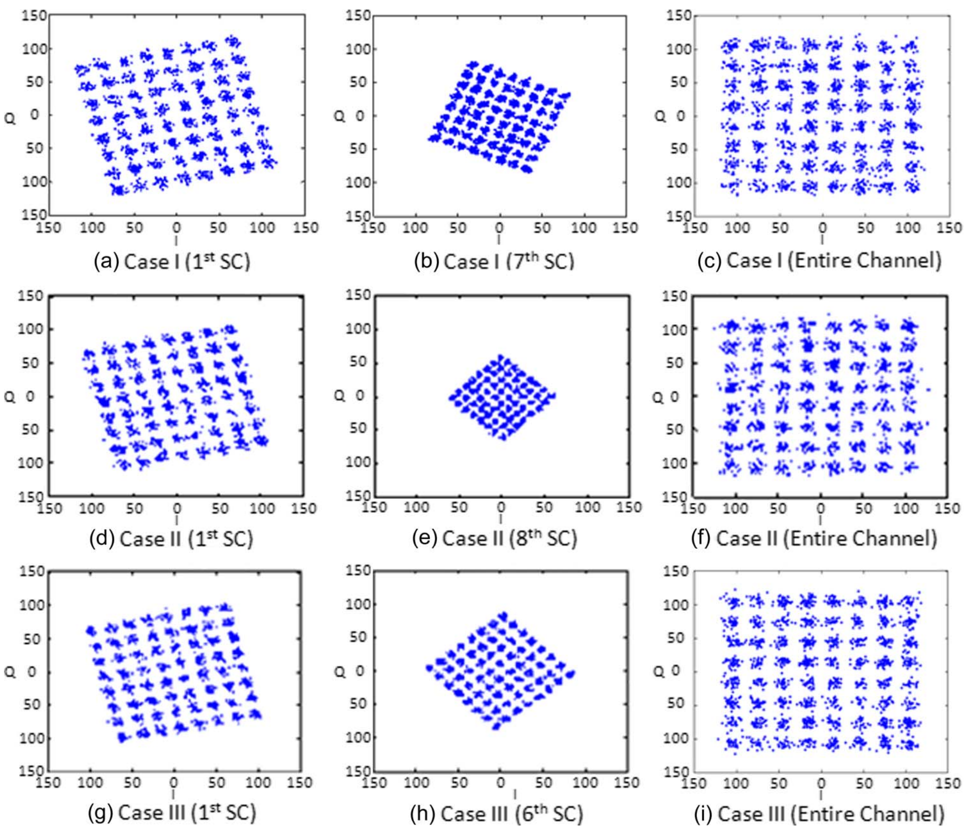

Fig. 9. Received constellations for different cases. SC: subcarrier. The total channel BERs are 1.01×10^{-3} for Case I, 1.16×10^{-3} for Case II, and 1.13×10^{-3} for Case III.

number of higher-order modes is further enhanced by the core diameter mismatch and/or offset between different types of MMFs involved in Case I. In addition, the shortest transmission distance in Case I also causes the strongest modal noise effect [22], this is confirmed in Fig. 8, where large BER deviations with respect to the best-fitting line are observed for Case I. On the other hand, Case III enjoys the weakest effects of DMD and modal noise because of the dominance of the fundamental mode resulting from the limited coupling from the fundamental mode to higher-order modes, as discussed in Section 2.2. Once again, the weakest modal noise effect experienced by Case III can also be observed in Fig. 8, where small BER deviations with respect to the best-fitting line are seen for Case III. In addition, it is also revealed in Fig. 8 that the optical power penalties for Case II and Case III are relatively small, indicating that the cyclic prefix adopted in the experiments are sufficiently long to combat the DMD effect associated with Case II. It should be pointed out that the low extinction ratio of the DM-VCSEL modulated OOFDM signal is the main factor limiting the maximum achievable transmission distance for Case III [12].

For various transmission configurations considered here, the representative constellations of individual subcarriers before channel equalization and the corresponding constellations of the entire transmission channel after channel equalization are shown in Fig. 9, in which the corresponding total channel BERs are 1.01×10^{-3} for Case I, 1.16×10^{-3} for Case II and 1.13×10^{-3} for Case III. In the figure, the subcarrier constellation sizes alter because of the subcarrier power variation shown in Fig. 5.

4. Conclusion

In DM-VCSEL-based, end-to-end real-time, 64-QAM-encoded, 11.25-Gb/s OOFDM IMDD transmission systems based on legacy OM1/OM2 MMFs, detailed experimental explorations have been undertaken, for the first time, of the effectiveness of various optical launching conditions including center launching and conventional offset launching in maximizing the transmission distances of the legacy systems. It has been shown that center launching enables a real-time 11.25-Gb/s, adaptive power-loaded OOFDM transmission over an unprecedented distance of 2000 m in a legacy OM1/OM2 MMF IMDD system with an optical power penalty as low as 0.8 dB. When center launching is replaced by conventional offset launching, the transmission distance of the above legacy MMF system is reduced to 300 m, and the corresponding optical power penalty is increased to 2.3 dB. Through comparisons of measured maximum achievable transmission distances between various MMF system configurations subject to different optical launching conditions, it has been concluded that DM-VCSEL-based, adaptive power-loaded OOFDM at center launching is a viable and cost-effective solution for use in legacy MMF systems. This work may have great potential for upgrading installed MMF LANs to 10 Gb/s and beyond.

References

[1] Hyperconnectivity and the Approaching Zettabyte Era, pp. 1–23, Jun. 2010, Cisco White Paper.

[2] H. Azgomi, *Enabling Enterprise 10 gigabit Ethernet Deployment With Long Reach Multimode Optics*, pp. 1–10, 2007, Cisco White Paper.

[3] R. E. Freund, C. A. Bunge, N. N. Ledentsov, D. Molin, and C. Caspar, "High-speed transmission in multimode fibers," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 569–586, Feb. 2010.

[4] D. H. Sim, Y. Takushima, and Y. C. Chung, "High-speed multimode fiber transmission by using mode-field matched center-launching technique," *J. Lightw. Technol.*, vol. 27, no. 8, pp. 1018–1026, Apr. 2009.

[5] L. Raddatz, I. H. White, D. G. Cunningham, and M. C. Nowell, "An experimental and theoretical study of the offset launch technique for the enhancement of the bandwidth of multimode fiber links," *J. Lightw. Technol.*, vol. 16, no. 3, pp. 324–331, Mar. 1998.

[6] A. Amphawan, "Holographic mode-selective launch for bandwidth enhancement in multimode fiber," *Opt. Exp.*, vol. 19, no. 10, pp. 9056–9065, May 2011.

[7] C. Yu, J. Liou, Y. Chiu, and H. Taga, "Mode multiplexer for multimode transmission in multimode fibers," *Opt. Exp.*, vol. 19, no. 13, pp. 12 673–12 678, Jun. 2011.

[8] X. Q. Jin, J. M. Tang, P. S. Spencer, and K. A. Shore, "Optimization of adaptively modulated optical OFDM modems for multimode fiber-based local area networks," *J. Opt. Netw.*, vol. 7, no. 3, pp. 198–214, Mar. 2008.

[9] X. Q. Jin, J. M. Tang, K. Qiu, and P. S. Spencer, "Statistical investigations of the transmission performance of adaptively modulated optical OFDM signals in multimode fibre links," *J. Lightw. Technol.*, vol. 26, no. 18, pp. 3216–3224, Sep. 2008.

[10] E. Hugues-Salas, X. Q. Jin, R. P. Giddings, J. L. Wei, C. Shu, and J. M. Tang, "First experimental demonstration of VCSEL-based real-time end-to-end 11.25 Gb/s optical OFDM signal transmission over 800 m MMFs," presented at the Eur. Conf. Exhib. Optical Commun., Geneva, Switzerland, Sep. 2011, Paper Tu.3.C.1.

[11] A. Schimpf, D. Bucci, and B. Cabon, "Optimum biasing of VCSEL diodes for all-optical up-conversion of OFDM signals," *J. Lightw. Technol.*, vol. 27, no. 16, pp. 3484–3489, Aug. 2009.

[12] E. Hugues-Salas, R. P. Giddings, X. Q. Jin, J. L. Wei, X. Zheng, Y. Hong, C. Shu, and J. M. Tang, "Real-time experimental demonstration of low-cost VCSEL intensity-modulated 11.25 Gb/s optical OFDM signal transmission over 25 km PON systems," *Opt. Exp.*, vol. 19, no. 4, pp. 2979–2988, Feb. 2011.

[13] X. Q. Jin, J. L. Wei, R. P. Giddings, T. Quinlan, S. Walker, and J. M. Tang, "Experimental demonstrations and extensive comparisons of end-to-end real-time optical OFDM transceivers with adaptive bit and/or power loading," *IEEE Photon. J.*, vol. 3, no. 3, pp. 500–511, Jun. 2011.

[14] S. Lee, F. Breyer, S. Randel, D. Cárdenas, H. van den Boom, and A. Koonen, "Discrete multitone modulation for high-speed data transmission over multimode fibers using 850-nm VCSEL," presented at the Conf. Optical Fiber Commun., San Diego, CA, Mar. 2009, Paper OWM2.

[15] R. P. Giddings, X. Q. Jin, E. Hugues-Salas, E. Giacoumidis, J. L. Wei, and J. M. Tang, "Experimental demonstration of a record high 11.25 Gb/s real-time optical OFDM transceiver supporting 25 km SMF end-to-end transmission in simple IMDD systems," *Opt. Exp.*, vol. 18, no. 6, pp. 5541–5555, Mar. 2010.

[16] X. Q. Jin and J. M. Tang, "Optical OFDM synchronization with symbol timing offset and sampling clock offset compensation in real-time IMDD systems," *IEEE Photon. J.*, vol. 3, no. 2, pp. 187–196, Apr. 2011.

[17] X. Q. Jin, R. P. Giddings, and J. M. Tang, "Real-time transmission of 3 Gb/s 16-QAM encoded optical OFDM signals over 75 km SMFs with negative power penalties," *Opt. Exp.*, vol. 17, no. 17, pp. 14 574–14 585, Aug. 2009.

[18] R. P. Giddings, E. Hugues-Salas, B. Charbonnier, and J. M. Tang, "Experimental demonstration of real-time optical OFDM transmission at 11.25 Gb/s over 500 m MMFs employing directly modulated DFB lasers," *IEEE Photon. Technol. Lett.*, vol. 23, no. 1, pp. 51–53, Jan. 2011.

[19] Y. Ma, Y. Tang, and W. Shieh, "107 Gbit/s transmission over multimode fibre with coherent optical OFDM using centre launching technique," *Electron. Lett.*, vol. 45, no. 16, pp. 848–849, Jul. 2009.

[20] A. Villafranca, J. Lasobras, J. A. Lazaro, and I. Garces, "Characterization of the main semiconductor laser static and dynamic working parameters from CW spectrum measurements," *IEEE J. Quantum Electron.*, vol. 43, no. 2, pp. 116–122, Feb. 2007.

[21] W.-R. Peng, "Analysis of laser phase noise effect in direct detection optical OFDM transmission," *J. Lightw. Technol.*, vol. 28, no. 17, pp. 2526–2536, Sep. 2010.

[22] I. Gasulla and J. Capmany, "Modal noise impact in radio over fibre multimode fibre links," *Opt. Exp.*, vol. 16, no. 1, pp. 121–126, Jan. 2008.