

Spectrally efficient direct-detected OFDM transmission employing an iterative estimation and cancellation technique

Wei-Ren Peng^{1,2*}, Xiaoxia Wu², Kai-Ming Feng³, Vahid R. Arbab², Bishara Shamee², Jeng-Yuan Yang², Louis C. Christen², Alan E. Willner², and Sien Chi¹

¹Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R. O. C.

²Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA

³Institute of Communications Engineering, National Tsing Hua University, HsinChu, Taiwan 300, R. O. C.
*pwr.eo92g@nctu.edu.tw

Abstract: We demonstrate a linearly field-modulated, direct-detected virtual SSB-OFDM (VSSB-OFDM) transmission with an RF tone placed at the edge of the signal band. By employing the iterative estimation and cancellation technique for the signal-signal beat interference (SSBI) at the receiver, our approach alleviates the need of the frequency gap, which is typically reserved for isolating the SSBI, and saves half the electrical bandwidth, thus being very spectrally efficient. We derive the theoretical model for the VSSB-OFDM system and detail the signal processing for the iterative approach conducted at the receiver. Possible limitations for this iterative approach are also given and discussed. We successfully transmit a 10 Gbps, 4-quadrature-amplitude-modulation (QAM) VSSB-OFDM signal through 340 km of uncompensated standard single mode fiber (SSMF) with almost no penalty. In addition, the simulated results show that the proposed scheme has an ~2 dB optical-signal-to-noise-ratio (OSNR) gain and has a better chromatic dispersion (CD) tolerance compared with the previous intensity-modulated SSB-OFDM system.

©2009 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communication

References and links

1. B. J. C. Schmidt, A. J. Lowery, and J. Armstrong, "Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM," *IEEE J. Lightwave Technol.* **26**(1), 196–203 (2008).
2. W. Shieh, H. Bao, and Y. Tang, "Coherent optical OFDM: theory and design," *Opt. Express* **16**(2), 841–859 (2008).
3. S. L. Jansen, I. Morita, and H. Tanaka, "10x121.9-Gb/s PDM-OFDM transmission with 2-b/s/Hz spectral efficiency over 1,000km of SSMF," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, OSA Technical Digest (CD) (Optical Society of America, 2008), paper PDP2. <http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2008-PDP2>.
4. W.-R. Peng, X. Wu, V. R. Arbab, K.-M. Feng, B. Shamee, L. C. Christen, J.-Y. Yang, A. E. Willner, and S. Chi, "Theoretical and experimental investigations of direct-detected RF-tone assisted optical OFDM systems," *IEEE J. Lightwave Technol.* **27**(10), 1332–1339 (2009).
5. Z. Zan, M. Premaratne, and A. J. Lowery, "Laser RIN and linewidth requirements for direct detection optical OFDM," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, OSA Technical Digest (CD) (Optical Society of America, 2008), paper CWN2. <http://www.opticsinfobase.org/abstract.cfm?URI=CLEO-2008-CWN2>.
6. W.-R. Peng, K.-M. Feng, and A. E. Willner, "Direct-detected polarization division multiplexed OFDM systems with self-polarization diversity," *LEOS'08*, paper MH 3 (2008).
7. W.-R. Peng, X. Wu, V. R. Arbab, B. Shamee, L. C. Christen, J. Y. Yang, K. M. Feng, A. E. Willner, and S. Chi, "Experimental demonstration of a coherently modulated and directly detected optical OFDM system using an RF-tone insertion," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic*

- Engineers Conference*, OSA Technical Digest (CD) (Optical Society of America, 2008), paper OMU2. <http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2008-OMU2>.
8. D. F. Hewitt, "Orthogonal frequency division multiplexing using baseband optical single sideband for simpler adaptive dispersion compensation," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper OME7. <http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2007-OME7>.
 9. W.-R. Peng and S. Chi, "Improving the transmission performance for an externally modulated baseband single sideband OFDM signal using nonlinear post-compensation and differential encoding schemes," ECOC'07, paper P078 (2007).
 10. M. Schuster, S. Randel, C. A. Bunge, S. C. J. Lee, F. Breyer, B. Spinnler, and K. Petermann, "Spectrally efficient compatible single-sideband modulation for OFDM transmission with direct detection," *IEEE Photon. Technol. Lett.* **20**(9), 670–672 (2008).
 11. W.-R. Peng, X. Wu, V. R. Arbab, B. Shamee, J. Y. Yang, L. C. Christen, K. M. Feng, A. E. Willner, and S. Chi, "Experimental demonstration of 340 km SSMF transmission using a virtual single sideband OFDM signal that employs carrier suppressed and iterative detection techniques," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, OSA Technical Digest (CD) (Optical Society of America, 2008), paper OMU1. <http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2008-OMU1>.
 12. V. Cizek, "Discrete Hilbert transform," *IEEE Trans. Audio Electroacoust.* **18**(4), 340–343 (1970).
 13. R. van Nee, and R. Presad, OFDM for wireless multimedia communications. Norwood, MA: Artech House, 2000.
 14. W.-R. Peng, B. Zhang, X. Wu, K.-M. Feng, A. E. Willner, and S. Chi, "Experimental Demonstration of 1600 km SSMF Transmission of a Generalized Direct Detection Optical Virtual SSB-OFDM System," ECOC'08 paper Mo3E6 (2008).
 15. F. Buchali and F. Supper, "Optimization of an optical OFDM system by peak to average signal ratio reduction," ECOC'07 paper Tu. 5.2.4 (2007).
 16. S. J. Savory, Y. Benlachar, R. I. Killey, P. Bayvel, G. Bosco, P. Poggiolini, J. Prat, and M. Omella, "IMDD transmission over 1,040 km of standard single mode fiber at 10 Gb/s using a one-sample-per-bit reduced complexity MLSE receiver," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper OThK2. <http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2007-OThK2>.
-

1. Introduction

Optical orthogonal-frequency-division-multiplexing (OFDM) is a promising technique for long-haul transmission since it provides a path for electronic equalization of fiber chromatic dispersion (CD) and polarization-mode-dispersion (PMD) [1–4]. The optical OFDM can be mainly categorized as 1. coherent and 2. incoherent (i.e. direct-detected) systems. The coherent optical OFDM (CO-OFDM) has shown to be very robust to fiber CD and PMD when using the polarization diversity receiving [2,3]. The CO-OFDM, when combined with the polarization division multiplexing (PDM-OFDM), can further increase the spectral efficiency and relax the bandwidth requirement of the transmitters and receivers [2,3]. However, these benefits come at a price of higher-cost implementations, which includes the narrow-linewidth lasers, optical local oscillators, 90° optical hybrids, and the signal processing circuitries accounting for phase and frequency offset estimation. On the other hand, the direct-detected OFDM (DD-OFDM) can accommodate a low-cost MHz-linewidth DFB laser [5], requires only one photodiode at the receiver, and need not worry about the phase and frequency offset, therefore making the direct-detected approach very easy to be implemented. In addition, one recent report has demonstrated the first direct-detected PDM-OFDM system with the self-polarization diversity receiving which not only doubles the spectral efficiency but also increases the PMD tolerance [6]. Thus, the direct-detected OFDM tends to be an alternative choice for the long-haul transmission other than the CO-OFDM.

To overcome the inherent CD fading problem, the direct-detected OFDM is transmitted in a single sideband format (SSB-OFDM) [1,4]. Typically, SSB-OFDM requires a frequency guard-band between the optical carrier and the data signal [1] or interleaves the data with blank subcarriers [4,7] to prevent the signal from being interfered by the signal-signal beat interference (SSBI), and therefore the spectral efficiency (SE) is lower than that of a coherent system. A recently proposed intensity-modulated and direct-detected SSB-OFDM that does not need this guard-band has been proposed as a spectrally-efficient format [8–10]. However, that technique has a design trade-off between better sensitivity (i.e., high modulation index)

and robustness to chromatic dispersion (i.e., nonlinear distortion from the optical modulator) [4,9]. Moreover, the required electrical bandwidth in the transmitter for this SSB-OFDM signal is double the bandwidth of the output optical signal because the real-valued OFDM signal is needed for the intensity modulation. Therefore, half the electrical bandwidth has not been effectively used for transmission and is “wasted.” As a result, a laudable goal to generate a SSB-OFDM signal is not only to modulate the signal more spectrally efficiently, but also to preserve a high receiving sensitivity and a good tolerance to fiber CD.

Recently, we have demonstrated a linearly field-modulated and direct-detected virtual SSB-OFDM (VSSB-OFDM) system that employs an RF tone at the edge of signal spectrum with an iterative detection approach [11]. The iterative detection can estimate and cancel the SSBI at the receiver such that the frequency gap, typically reserved for allocating the signal-signal beat interference (SSBI) [1,4,7], can be thrown away and the signal’s spectral efficiency can be doubly improved. In addition, because the optimum optical carrier to signal power ratio (CSPR) for the best sensitivity can be digitally manipulated in the transmitter, there is no trade-off between the receiving sensitivity and the CD tolerance for our proposed scheme. In this paper, we revisit this VSSB format by providing its linear transmission model which analytically shows that the linear impairments throughout the link could be compensated for. We further detail the signal processing relevant to the digital algorithm of the iterative equalizer, which enables the high spectral efficiency of VSSB-OFDM format. To obtain an reliable channel estimation for regular operation of the iterative equalizer, we propose to use the interleaved OFDM [4,7] training symbols combined with the receiver-end interpolation approach. We also give and discuss the current issues and limitations of the iterative equalizer. Later we experimentally transmit a 10-Gbps data with a 4-quadrature amplitude modulation (4-QAM) format using the VSSB-OFDM signal over 340 km uncompensated standard single mode fiber (SSMF). The results show that both the back-to-back sensitivity and the CD tolerance are improved with our proposed VSSB-OFDM system. Based on the numerical results, the back-to-back sensitivity could be further improved by ~2.7 dB by using smaller optical modulation index (OMI), optimized optical bandwidth (OBW), and a better-designed SSBI estimator.

2. Principle of Operation

Figure 1 shows the concepts of the previous intensity-modulated SSB-OFDM [8,9] and the proposed RF-tone assisted VSSB-OFDM systems. For the previous SSB-OFDM, the data, together with their conjugates, are converted to a real-valued signal after the inverse fast Fourier transform (IFFT). This electrical signal and its Hilbert transform [12] are fed into the two arms of a quadrature-biased dual-drive Mach-Zehnder modulator (DD-MZM), thus resulting in a SSB-OFDM. Since half the subcarriers are used as the conjugates of the data subcarriers, the required electrical bandwidth is $\sim 2B$, of which B is the transmission bandwidth (i.e. output optical signal bandwidth). Obviously the required electrical bandwidth is double the transmitted optical bandwidth. Thus, half the electrical bandwidth, including the bandwidth of the DSP processor and the digital to analog converter (DAC) of the OFDM generator, is not used for transmission and is wasted. Another issue of this intensity-modulated approach is the strong dependency of the receiving sensitivity on the optical modulation index (OMI). The definition of the OMI is $OMI = (V_{in})_{RMS}/V_{\pi}$, where $(V_{in})_{RMS}$ is the root-mean-squared (RMS) amplitude of the electrical input to the DD-MZM and V_{π} the switching voltage of the MZM. Note that we define OMI in terms of the RMS amplitude, instead of the peak-to-peak amplitude used in the conventional OMI definition, simply because the amplitude of the OFDM signal in essence is randomly-distributed [13]. Typically, a larger OMI which drives the MZM more deeply would result in a better sensitivity and vice versa. However, a larger OMI would result in a nonlinear distorted signal that could not be well equalized after the accumulated fiber CD [4]. Thus, there exists an optimum OMI value that trades the sensitivity with the transmission CD tolerance.

For our proposed VSSB-OFDM, the data, along with one inserted RF tone at the left-most subcarrier, are transferred to a complex signal by IFFT. The real and imaginary parts of the signal are sent to the two arms of an optical I/Q modulator. With the modulators biased at the null point, the original optical carrier is suppressed and a new optical carrier induced by the inserted RF tone appears at the left edge of the signal spectrum. Because our system does not require the redundant subcarriers for the conjugates of the transmitted data, our system saves half the electrical bandwidth compared with the previous SSB-OFDM. The required electrical bandwidth B is equal to the output optical bandwidth B . Without using the Hilbert transform or any filtering technique, which are conventionally required for a SSB modulation, the output optical spectrum of the VSSB-OFDM signal is virtually like that of the previous SSB-OFDM signal. Thus, we use the surname of virtual single side-band (VSSB) for the proposed OFDM system. Note that the carrier to the signal power ratio (CSPR), defined as $CSPR = |A|^2 / \sum |d(k)|^2$, where A and $d(k)$ are the amplitudes of the RF tone and the data on the k -th subcarrier, respectively, can be optimized by controlling the relative amplitudes of the electrical signal and RF tone.

3. Iterative estimation and cancellation technique

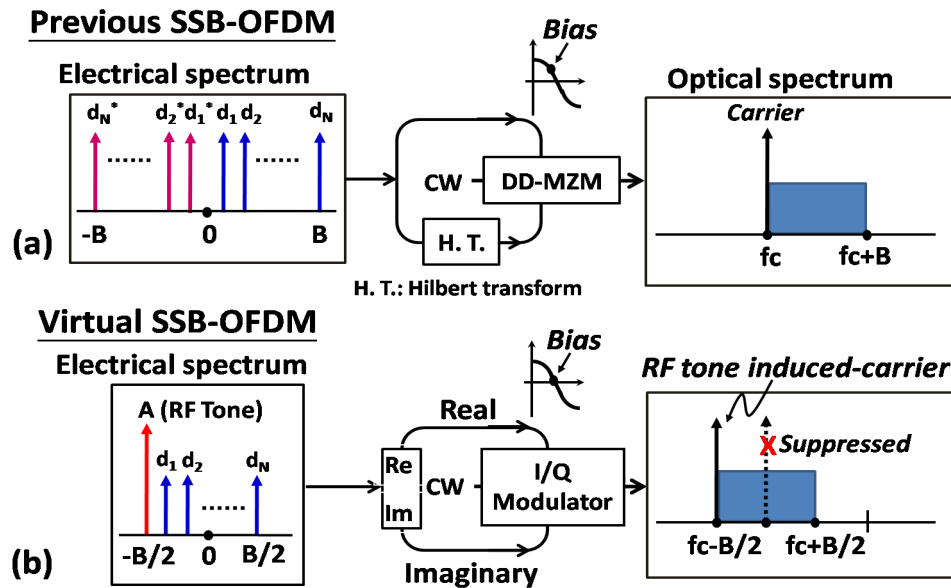


Fig. 1. Operation principles for (a) previous intensity-modulated SSB-OFDM, and (b) proposed virtual SSB-OFDM (VSSB-OFDM).

Since the VSSB-OFDM signal is linearly field-modulated in nature, the beats among all the data subcarriers at the photodiode, SSBI, will yield a non-negligible interference to the signal. To reduce the impacts of SSBI, we introduce an iterative estimation and cancellation technique at the receiver with its operating concept shown in Fig. 2. This technique can be simply described as follows: (i) the converted signal, which consists of the desired data and SSBI, is firstly stored in memory. After the signal is transferred to the frequency domain via FFT and equalized by the channel equalizer, the decisions of the processed signal are made. (ii) The newly-generated decisions are sent into the feedback loop, which contains the de-equalizer, IFFT and the absolute square function. The de-equalizer is to reload the channel effects from the transmitter to the receiver on the decided symbols, IFFT is used to transfer the frequency-domain symbols to the time-domain waveform just prior to the photodiode, and the absolute square performs the beating effect of the photodiode. Thus, SSBI can be approximately rebuilt with such an approach. (iii) Subtract this rebuilt SSBI from the stored

converted signal and get the newly updated signal. Then, replace the original signal in the memory with this updated signal. (iv) Repeat (i)-(iii) N_i times until the constellation of the received symbols converges.

The above working principle of the iterative detection can be more precisely understood by the mathematical models and the DSP algorithms described as follows: the discrete VSSB-OFDM signal can be written as

$$E(n) = Ae^{-j\pi n} + \sum d(k)e^{j2\pi\frac{kn}{N}} \quad (1)$$

where n is the discrete time index, k is the subcarrier index ranging from $(-N/2)$ to $(N/2-1)$, A is the amplitude of the RF-tone at the $(-N/2)$ -th subcarrier, $d(k)$ is the data symbol on the k -th subcarrier, and N is the IFFT size. After transmission, the optical signal prior to the photodiode becomes

$$E_T(n) = \alpha_A Ae^{-j\pi n} + \sum \alpha(k)d(k)e^{j2\pi\frac{kn}{N}} \quad (2)$$

where α_A and $\alpha(k)$ are complex values representing the linear distortions of the RF tone and the k -th data symbol through the fiber link. After the photodiode, the converted photocurrent $I(n)$ can be expressed as:

$$I(n) = |E_T(n)|^2 = |\alpha_A A|^2 + 2\text{Re}[\alpha_A^* A \sum \alpha(k)d(k)e^{j2\pi\frac{(k+N/2)n}{N}}] + \left| \sum \alpha(k)d(k)e^{j2\pi\frac{kn}{N}} \right|^2 \quad (3)$$

where $\text{Re}[x]$ takes the real part of x . In this equation the first term is simply the direct current (DC), and the second and third terms stand for the desired signal and SSBI, respectively.

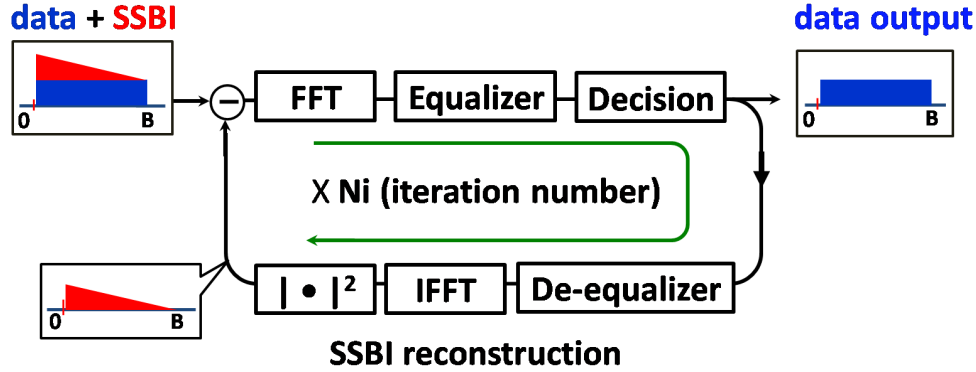


Fig. 2. Iterative estimation and cancellation technique of the VSSB-OFDM. SSBI: signal-signal beat interference, FFT: fast Fourier transform.

For a smaller CSPP, which means $|A|^2 / \sum |d(k)|^2 \ll 1$, the interference SSBI is relatively larger with respect to the desired signal and thus the system suffers more from the interference than the noise. For a larger CSPP, that is $|A|^2 / \sum |d(k)|^2 \gg 1$, the desired signal is relatively larger compared with SSBI and thus the system performance would be mainly limited by the noise. Notably if the signal has not been interfered by the interference SSBI, the optimum CSPP should be located at ~ 0 dB [1,4,7].

Since the equalizer needs the channel information to recover the transmitted signal, a specific designed training sequence, which will not be interfered by SSBI, should be developed and utilized to accurately estimate the channel response. We firstly assume that the

approximated channel response $H(k) = \alpha_A^* \alpha(k) A^*$ is known at the receiver and later we will explain how this can be achieved in a real transmission. With the known channel information of $H(k)$, the initially equalized symbol is denoted as $R_0(k) = \text{FFT}[I(n)] / H(k)$, where $\text{FFT}[x]$ is the fast Fourier transform of x . We denote the initial decisions of $R_0(k)$ as $d_0(k)$ and follow the procedures described before to start the iterative process with the initial iterative index $i = 0$:

(i) Reconstruct the interference SSBI using the decisions, $d_i(k)$:

$$I_i(n) = \frac{1}{|\alpha_A A|^2} \left| \sum H(k) d_i(k) e^{j2\pi \frac{kn}{N}} \right|^2 = \left| \sum \alpha(k) d_i(k) e^{j2\pi \frac{kn}{N}} \right|^2 \quad (4)$$

(ii) Subtract SSBI from the stored signal in the memory and get the new equalized symbols, $R_{i+1}(k)$

$$R_{i+1}(k) = \text{FFT}[I(n) - I_i(n)] / H(k) \quad (5)$$

(iii) Make decisions for $R_{i+1}(k)$ and get the new decisions $d_{i+1}(k)$ for the $(i + 1)$ -th iteration.

(iv) Repeat (i) to (iii) with $i = i + 1$ until the performance converges.

Since the efficiency of mitigating the SSBI critically depends on an accurate estimation for the channel response $H(k)$, the training symbols, for channel response estimation, should be properly designed for an efficient iteration. One simple solution is to allocate the training symbols on only the odd-numbered channels and leave the even-numbered channels unused. Shown in Fig. 3 illustrates a suggested transmitted packet for VSSB-OFDM with the training symbol leading ahead. The training symbols, $t(k)$, are modulated on only the odd-numbered channels and the even-numbered channels are left blank. The following data symbols, $d(k)$, are modulated on all the channels as described in Section 2. As explained in [4,7], the training symbol with such a symbol allocation (i.e. the interleaved OFDM format in [4,7]) will not be interfered by SSBI and can be used to estimate the channel responses of the odd-numbered channels. As for the even-numbered

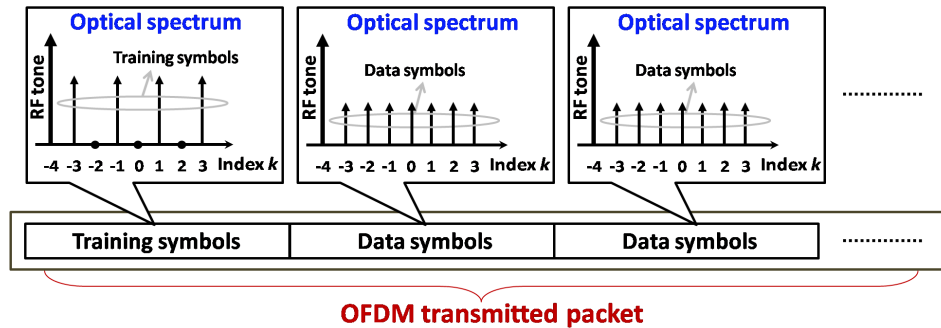


Fig. 3. Optical spectra of the training symbols and the data symbols in a transmitted VSSB-OFDM packet.

channels, which are filled with SSBI after photodiode, their channel responses can be approximated via interpolating the odd-numbered channels' responses. With such an approach, the channel responses of all the channels can be reliably estimated without the interference of SSBI. Note that to maintain an equalized power transmission in an OFDM packet, the power of the training symbol should be controlled with around twice the power of the data symbol, that is $\epsilon[|t(k)|^2] = 2\epsilon[|d(k)|^2]$, where $\epsilon[x]$ means the expectation of x .

In addition to the channel estimation, in the first step of the iteration process, the algorithm needs the information of the resizing coefficient of $|\alpha_A A|^2$ to properly rebuild SSBI. This coefficient can be estimated as follows. Firstly we denote the converted DC component as I_{DC} , which can be represented as

$$I_{DC} = |\alpha_A A|^2 + \sum |\alpha(k)d(k)|^2 \quad (6)$$

Then we assume that the optical filtering has minor effect to the received signal prior to the photodiode, that is, $|\alpha_A| \approx |\alpha(k)|$ for all k . With such an assumption, the DC component becomes

$$I_{DC} \cong |\alpha_A|^2 (|A|^2 + \sum |d(k)|^2) \quad (7)$$

Then the required coefficient, $|\alpha_A A|^2$, can be simplified as

$$|\alpha_A A|^2 \cong I_{DC} \times \text{CSPR} / (1 + \text{CSPR}) \quad (8)$$

where CSPR is a selected system parameter and should be known to the receiver. Thus, for a photodiode without an embedded DC block, the DC current can be obtained directly by taking the mean value of the photocurrent; while for a photodiode with a built-in DC block, the DC current can still be accessed via $I_{DC} \approx \text{Mean}[I(t)] - \text{Min}[I(t)]$, where $\text{Mean}[x]$ and $\text{Min}[x]$ stand for the mean and minimum values of x , and $I(t)$ is the photocurrent. Note that a proper operation for the iterative detection depends on the negligible filtering effect throughout the optical path. Once the signal has been significantly distorted by strong optical filtering effects, the coefficient of $|\alpha_A A|^2$ will be improperly estimated and the efficiency of the iterative detection will be diminished.

Although the iterative equalizer can remove the SSBI and increase the spectral efficiency of a DD-OFDM system, for each iteration it needs one FFT and IFFT processing to assist in rebuilding SSBI, which would limit its practical application in a real-time transmission. Besides, the extra processing for each iteration would consume more electrical power to maintain the iterative equalizer's regular operation. Hence, the number of required iterations and the processing complexity for each iteration should be further reduced and simplified, which could be possibly achieved via: 1) a more powerful DSP algorithm that can estimate SSBI more efficiently, or 2) utilizing a tunable frequency gap between the optical carrier and data sideband to mitigate the SSBI level and reduce the required iterations [14].

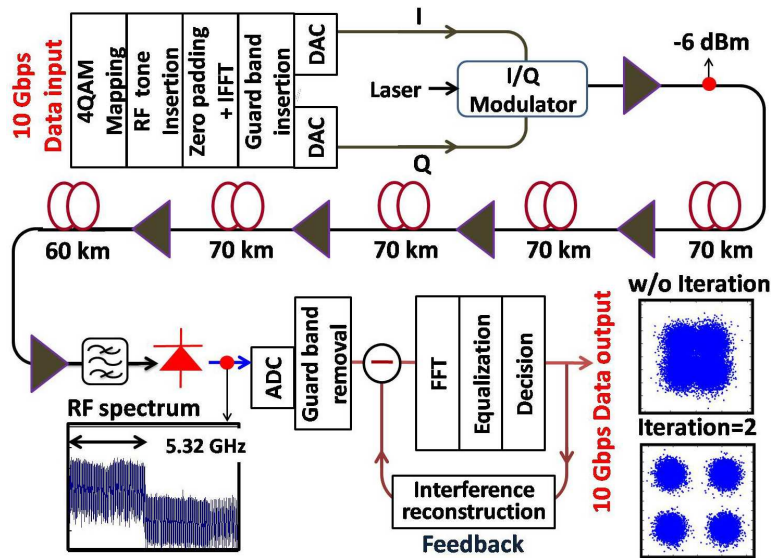


Fig. 4. Experimental setup for the virtual SSB-OFDM.

4. Experimental setup

Figure 4 depicts the experimental setup for the VSSB-OFDM. The OFDM signal is generated by Matlab offline in advance and loaded into a two-channel, 10 GS/sec arbitrary waveform generator (Tektronix, AWG7102) which functions as a digital to analog converter (DAC). The subcarrier number for the RF tone and the transmitted data is 145 and is zero-padded to an IFFT size of 256. A cyclic prefix of $\sim 1/16$ OFDM symbol duration is applied for channel synchronization and for mitigating the inter-symbol interference (ISI) caused by fiber CD or any filtering effect. The data rate is operated at 10 Gbps with a 4 QAM format. An optical I/Q modulator, which are made of two parallel DPSK modulators, is fed with the two outputs of the AWG, which outputs the real and imaginary information of the OFDM signal, respectively. The optical output of the I/Q modulator, with an input power of around -6 dBm, is transmitted through 340-km uncompensated SSMF. An optical preamplifier followed by a 0.3-nm optical bandpass filter is used before a 12-GHz photodiode. The converted photocurrent is sampled and recorded by a real-time scope (Tektronix, TDS6604) with a bandwidth and sampling rate of 6 GHz and 20 GS/sec, respectively. The related signal processings, which consists of synchronization, cyclic prefix removal, FFT, and equalization, are implemented offline in Matlab for performance evaluation. The insets in Fig. 4 depict the received RF spectrum and the constellations of the 4-QAM signals with and without the iterative detection. The RF spectrum shows that the effective bandwidth of the 10-Gbps VSSB-OFDM signal is only ~ 5.32 GHz and is very spectrally efficient, while the constellations indicate the necessity and efficiency of the post iterative detection.

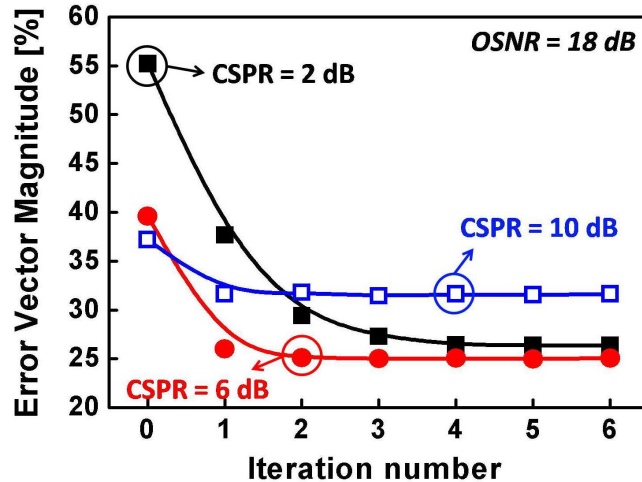


Fig. 5. Measured EVM (OSNR = 18 dB) versus the iteration numbers with different CSPR values of 2, 6 and 10 dB.

5. Results and discussion

Shown in Fig. 5 is the error vector magnitude (EVM) as a function of the iteration number with different CSPR values of 2, 6 and 10 dB. EVM is a measure of the signal quality and a lower EVM means a better performance. Its rigorous definition is given in [7,11]. When the iteration number equals 0 (i.e. there is no iterative detection), we found that the performance is better for a larger CSPR. This can be attributed to the relatively smaller SSBI for a larger CSPR. When the iterative processing starts to assist the signal recovery of the received symbols, the performances move toward to a lower EVM for all the three different CSPR values. With the increase of the iteration number, the improvement of the performance gradually becomes insignificant and virtually disappears when the CSPR is large enough (> 4). Since a high iteration number will increase the complexity of the receiver design, while a few iteration number cannot remove the SSBI thoroughly and will degrade the system performance, a proper iteration number must be chosen with the consideration of this trade-off between complexity and performance. Here we choose 4 as the iteration number for the following measurements according to the results in Fig. 5 because it achieves the least number of iteration that can stabilize the system performance for the CSPR values ranging from 2 ~10 dB.

Figure 6 shows the measured EVM as a function of CSPR with an OSNR of 18 dB within 0.1-nm optical bandwidth. The CSPR of ~ 4 dB is found to be the optimum for the system, which implies that the system is with the best receiving sensitivity. Specifically, this optimum value is different from the previous known results of 0 dB for direct-detected OFDM systems [1,4,7]. This disagreement can be explained as follows. In the previous SSB-OFDM system results, the optimum CSPR of 0 dB is derived under the conditions that after the photodiode the desired signal and the SSBI are intentionally allocated at different frequency bands which can be achieved by reserving a frequency gap or utilizing the interleaved blank subcarriers beforehand [4]. However, the condition has been changed when the desired signal are

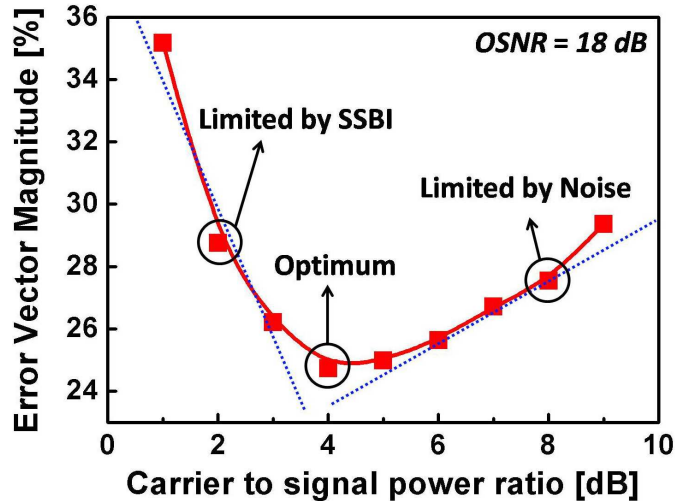


Fig. 6. Measured EVM (OSNR = 18 dB) versus the carrier to signal power ratio (CSPR) with the iteration number of $N_i = 4$.

overlapped with SSBI after photodiode, which is exactly the case of the VSSB-OFDM. For the VSSB-OFDM, when a larger CSPR is used, as has been explained in Section 3, SSBI is relatively smaller with respect to the desired signal and will not play an important role to the system performance; whilst when CSPR is decreasing (< 4 dB), SSBI becomes relatively larger compared with the desired signal, which in turn will increase the number of error bits in the initial iteration, and makes the iterative processing difficult to rebuild an accurate SSBI, thus eventually reducing the iteration efficiency and degrading the system performance. Thus, the optimum CSPR has been shifted to ~ 4 dB due to the introduced interference SSBI.

The bit error rate (BER) performance shown in Fig. 7 is measured for both the previous intensity-modulated SSB-OFDM and the proposed VSSB-OFDM. Due to the higher electrical bandwidth (i.e., the sampling rate of AWG) requirement for the previous SSB-OFDM, the minimum QAM size, limited by the 10 GS/sec AWG, for 10 Gbps data rate is 8 QAM. The OSNR at a BER of 10^{-3} for our system is ~ 5 dB better than the previous system, which has been optimized with an OMI of around 0.12 in back to back. This ~ 5 -dB gain could be attributed to 1) the optimum CSPR [4] which inherently contributes > 2 dB gain in VSSB-OFDM and the details will be discussed later, and 2) the smaller QAM size used in the VSSB-OFDM. Note a smaller QAM size not only has an inherent sensitivity gain but is also more robust to various nonlinearities resulted either from electrical components or optical transmission. Following 340 km uncompensated SSMF, there is negligible penalty observed for our system.

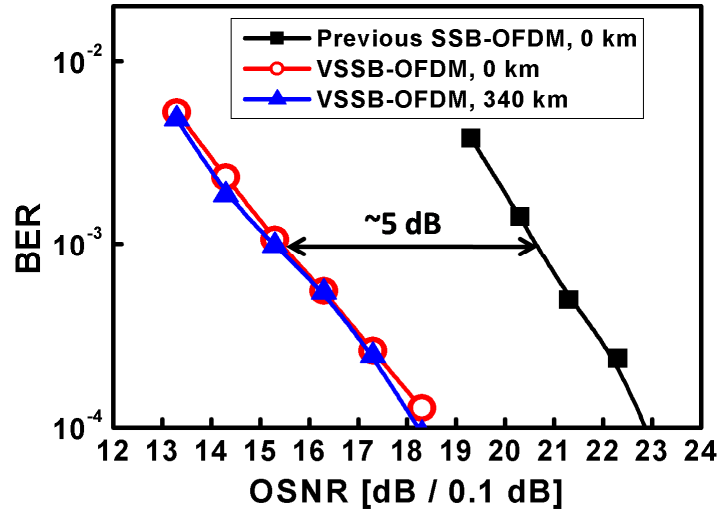


Fig. 7. Measured bit error rate versus the optical signal to noise ratio (0.1 nm) for the previous intensity-modulated SSB-OFDM and the proposed virtual SSB-OFDM with $N_i = 4$.

Figure 8 compares the CD tolerances between the previous intensity-modulated SSB-OFDM and the VSSB-OFDM by numerical simulations. The simulated data rate and format for the two systems are 10 Gbps and 4 QAM, respectively. For the previous SSB-OFDM, clipping the electrical signal in the transmitter which prevents the overshoot has been employed for a better sensitivity [15]. The optimum OMI for the previous SSB-OFDM is found to be ~ 0.125 , which is limited by the nonlinear electrical-to-optical transfer function of the MZM. The trade-off between the sensitivity and the CD tolerance of the previous SSB-OFDM is shown in Fig. 8, which exhibits that a larger OMI has a better receiving sensitivity but a poor transmission performance while a smaller OMI has a poor sensitivity but a better transmission performance. Compared with the previous SSB-OFDM, the proposed VSSB-OFDM shows a > 2 -dB sensitivity improvement and is much tolerable to the fiber CD.

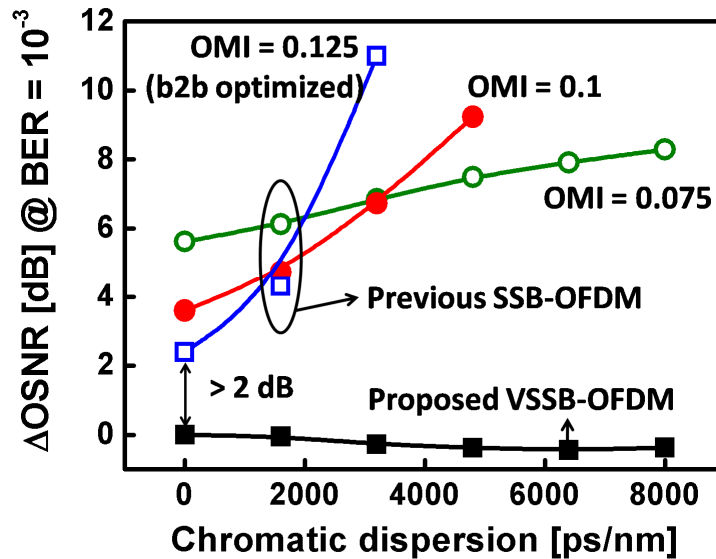


Fig. 8. Simulated results for the previous intensity-modulated SSB-OFDM and the proposed virtual SSB-OFDM.

Although in back-to-back the proposed VSSB-OFDM outperforms the intensity-modulated method by ~ 2.3 dB, it has > 3.5 dB OSNR penalty compared with the conventional on-off keying (OOK) format [16]. In Fig. 9 we demonstrate by numerical results that this ~ 3.5 dB difference could be reduced by utilizing a smaller OMI value or an optical filter with optimized optical bandwidth (OBW). With the experimental conditions of $\text{OMI} = 0.12$ and $\text{OBW} = 38$ GHz, the simulated OSNR for $\text{BER} = 10^{-3}$ is found to be ~ 14.1 dB, which is ~ 1 dB lower than the experimental results shown in Fig. 7. This ~ 1 -dB difference could be attributed to the nonlinear distortions of the electrical components, which are not taken into account for SSBI reconstruction. Then we replace the OMI with a much smaller value of $\text{OMI} = 0.01$ and keep the OBW unchanged as $\text{OBW} = 38$ GHz. Since with such a small OMI value of 0.01 the nonlinear effect of MZM could be almost excluded, the required OSNR is found to be ~ 1 dB lower than that with $\text{OMI} = 0.12$. If we further optimize the OBW ($\text{OBW} = 8$ GHz) with $\text{OMI} = 0.01$, the required OSNR becomes ~ 12 dB and shows an ~ 2 -dB OSNR improvement compared to that with the experimental conditions. Afterwards, the curve labeled “Ideal Estimator” shows that the system performance could be further enhanced by ~ 0.6 dB with an ideal SSBI estimator, which can perfectly rebuild the SSBI so that the SSBI can be completely removed from the received interfered signal. In simulation this ideal estimator is effectively implemented by providing the receiver with correct SSBI information; while in reality this estimator could be achieved with a more powerful and better-designed DSP algorithm. Thus, with a smaller OMI value, optimum OBW, and a better-designed SSBI estimator, the sensitivity in terms of OSNR can be further improved by ~ 2.7 dB based on the numerical analysis.

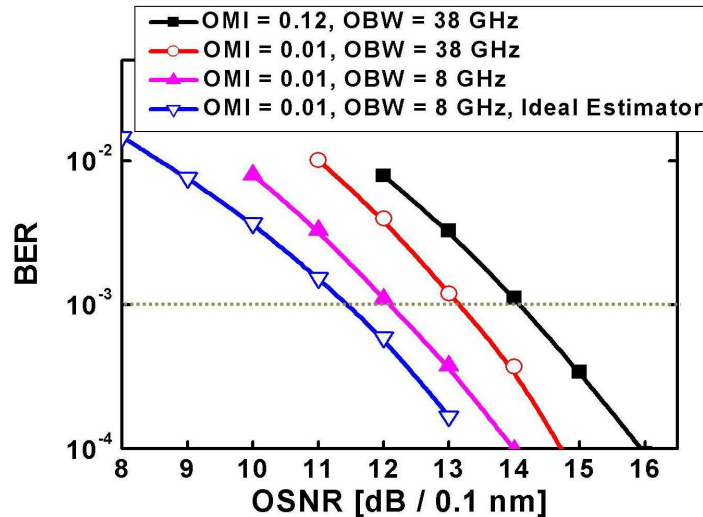


Fig. 9. Simulated sensitivity curves for the proposed VSSB-OFDM with different OMI values and optical bandwidth (OBW). The curve labeled by “Ideal Estimator” uses an ideal SSBI estimator which can help completely remove the SSBI at the receiver.

6. Conclusions

We have demonstrated a linearly field-modulated and direct-detected OFDM system, which is referred to as the virtual SSB-OFDM. Since the beat interference can be iteratively estimated and eliminated via a newly proposed iterative detection, the frequency gap, which typically is reserved for allocating the beat interference, is removed and thus the spectral efficiency is doubly enhanced. We detail explain how the iterative detection technique works via the mathematical models of the transmission system, and some possible limitations of this iterative scheme are also given and discussed. The optimum CSNR is found to be ~ 4 dB and

the required iteration using our suggested algorithm is about 4. Compared with the previous intensity-modulated SSB-OFDM, the VSSB-OFDM has an ~2 dB better OSNR gain and shows a much better tolerance to the fiber CD, by both experimentally and theoretically demonstrations. To sum up, this spectrally efficient format, which uses a simple direct up-converted transmitter, saves half the electrical and optical bandwidth, and exhibits the improved system performance both in back-to-back and after transmission, has a great potential as a future-proof format in the long-haul transmission.

Acknowledgement

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 97-2221-E-007-101-MY3.