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Nonlinear compensation in W-band MM-wave communication system with heterodyne coherent detection

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ABSTRACT

In this paper, we experimentally demonstrate the transmission of 45 Gb/s/λ 16QAM OFDM signal in the W-band MM-wave and fiber converged system. To the best of our knowledge, it is reported for the first time that parallel Volterra nonlinear compensation (VNC) method is applied in the W-band heterodyne detection millimeter wave (MMW) and fiber converged system. By using this method, BER of 3.4 × 10^{-3} is achieved after 25 km standard single mode fiber (SSMF) and 4 m wireless transmission.

1. Introduction

Recently, the capacity demand in access network have grown explosively due to the emerging services such as cloud network, 5G mobile fronthaul and 4 K/8K large video application. However, the current 4G data rate of wireless communication is limited by insufficient frequency resources and can only support up to hundreds of Mbps. Therefore, the W-band millimeter wave (75–110 GHz) is a promising solution to provide multi-Gbps resources for enhanced mobile broadband (eMBB) [1–9]. However, the bandwidth of the electronic devices is limited to provide higher data rate. Photonics-assisted mm-wave generation technology can overcome the bandwidth bottleneck and produce multi-Gbps signals [1–8,10]. Moreover, in order to further improve spectral capacity and efficiency, multi-carrier such as orthogonal frequency division multiplexing (OFDM) is attractive for multi-user access network due to higher spectral efficiency and independent subcarrier optimization.

One of the challenges in W-band OFDM system is their vulnerability to nonlinear effects due to non-ideal electro-optical components in transmitter and receiver side and the high peak-to average power ratio of OFDM. In order to alleviate the nonlinear effects, a parallel VNC algorithm based on OFDM W-band communication systems has been used in this paper. About the application of nonlinear compensation algorithm has been demonstrated in homodyne and heterodyne coherent detection fiber transmission systems [11,12]. Some research papers have reported the VNC method in W-band MMW direct detection systems with the application of envelop and power detector at the receiver [8,9]. In [8], with a 16-ary quadrature amplitude modulation (QAM) Discrete Fourier Transform-Spread (DFT-S) OFDM signal, 2 Gbaud data rate with bit error rate (BER) under the forward error correction (FEC), a threshold (3.8 × 10^{-3}) can be achieved over over 4 m wireless transmission. In [9], a 10 Gbaud 16 QAM OFDM signal is delivered over 25 km fiber and 2 m wireless link under the bit error ratio of 3.8 × 10^{-3}. Coherent detection can realize the modulation of intensity and phase at the same time with enhanced sensitivity [1–7,11–13]. The power of the received signal can be increased by increasing the power of the local oscillation signal. Therefore, the system can realize the long-distance transmission and guarantee the high receiving sensitivity of the receiver. Moreover, heterodyne coherent detection can simplify the coherent receiver with only half of the photodiodes (PDs) and analog digital conversions (ADCs) compared with homodyne.

In this paper, we experimentally demonstrated the 16-QAM OFDM signals in photonic-aided heterodyne coherent detection W-band MM-wave and fiber converged system. And this is the first demonstration of applying parallel VNC for I and Q signal in W-band MMW fronthaul system. By employing parallel VNC, the BER of 12 Gbaud 16-QAM OFDM signals can improve from 4.25 × 10^{-2} to 3.4 × 10^{-3} when they are delivered over 25 km SSMF and 4 m wireless.

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2. Principle

To mitigate the nonlinearity due to non-ideal electro-optical component in the transmitter and receiver side and the high peak-to average power ration of OFDM, a parallel VNC method referred to [8] has been applied. Basically, VNC is used to deal with real number signal. In [8], due to the transmitted signal is discrete-multi-tone (DMT) signal, which is real number. So it can be dealt with directly. However, the transmitted signal is OFDM signal in this paper, which is imaginary number. So it cannot be processed directly by VNC. Consider this, OFDM signal is separated into I/Q part to process it by VNC at receiver, respectively. The equalizer can be described as:

$$y_{i(I,Q)} = \sum_{j=-N}^{N} v_j x_{i-j} + \sum_{k=-N}^{N} \sum_{j=-N}^{k-1} v_{k,j} (x_{(i-k)(I,Q)} - x_{(i-j)(I,Q)})^2 \tag{1}$$

where x and y represent the input and output, respectively. N is the taps number of the digital equalizer.v_j and $v_{k,j}$ denotes the weight of linear and nonlinear filters, respectively. The weights are obtained by adaptively updating based on least mean squares (LMS). The use of LMS can be referred to [8]. I and Q in the equation represent the I/Q part of the signals. At the receiver, the received IF signals are down converted to baseband signals in digital signal process (DSP). Then, the baseband signals are normalized by Schmidt [14]. After that, I/Q signals of the transmitter and receiver will be applied VNC method, respectively.

3. Experimental setup

Fig. 1(a) shows the experimental setup of W-band system with heterodyne coherent detection. Fig. 1(b) and (c) show the offline DSP for OFDM generation and recovery. In MATLAB, 2^{15}-1 pseudo-random binary sequence (PBRS) is produced, and then coded into 16-QAM signal. The FFT length is 1024, of which 1010 subcarriers are occupied for data transmission. Followed with IFFT, a 32-point cyclic prefix is added before parallel to series (P/S) conversion. A frame of data consists of a training sequence (TS) and 49 OFDM symbols. A TS is added in front of OFDM symbols, which is used for synchronization and channel estimation. Offline produced OFDM signals will be loaded into arbitrary waveform generator (AWG). The peak to peak voltage (Vpp) of the AWG output will be optimized. The analog signals from AWG are amplified by two parallel linear amplifiers and then used to drive the I/Q modulator. The I/Q modulator with 32 GHz 3-dB bandwidth is used for signal modulation with an external cavity laser (ECL1). The insertion loss of the modulator is 6 dB. The signal is combined with ECL2 by an optical coupler, which will be controlled by polarization controller. Then the coupled signal will be transmitted through a 25-km SSMF. A variable optical attenuator is used to adjust signal power amplified by an electrical amplifier into PD. An 85-GHz electrical mm-wave signals will be produced in the PD, which is then transmitted in free space through horn antenna. The wireless signals will be received by a symmetric antenna followed by down-conversion to an IF signal through a mixer and a 75-GHz electrical local oscillator. Then the IF signals will be captured by a 30-GHz 80 GSa/s digital storage oscilloscope (DSO) for offline DSP. At the receiver side, offline processing including down-conversion, re-sampling, frame synchronization, volterra nonlinear compensation, FFT, channel estimation, 16QAM demodulation and decoding, followed by BER calculation as shown in Fig. 1(c). The spectrum for back to back transmission is shown in Fig. 2.

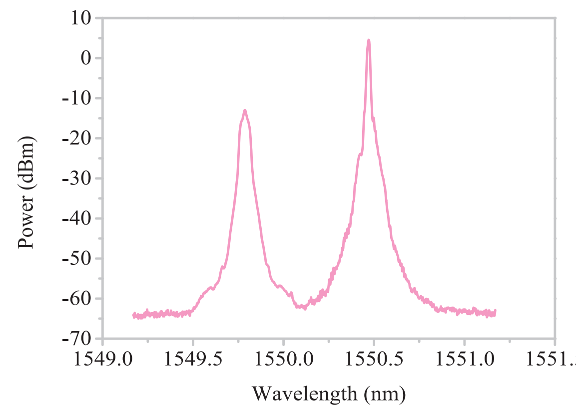

Fig. 2. The spectrum for back to back transmission.

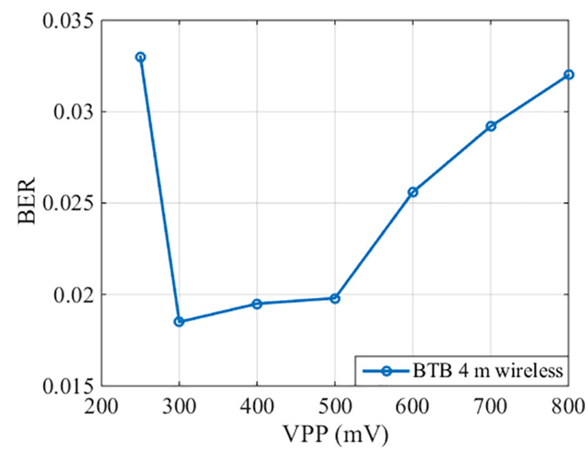

Fig. 3. The curve of BER versus VPP.

4. Experimental results

Fig. 3 shows the BER as function of Vpp of analog signals from AWG

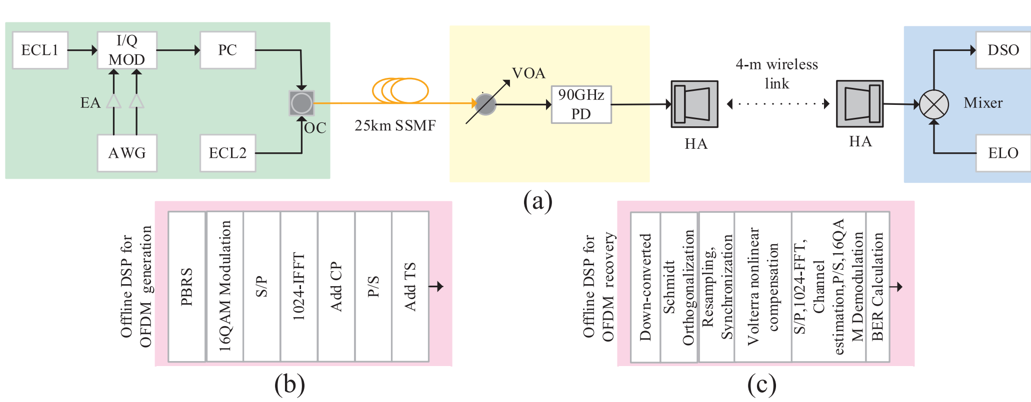

Fig. 1. (a) The experiment set up for heterodyne coherent detection in W-band. (b) Offline DSP for OFDM generation. (c) Offline DSP for OFDM recovery. EA: electrical amplifier, PC: polarization controller, OC: optical coupler, VOA: variable optical attenuator, HA: horn antenna, ELO: electrical local oscillator.

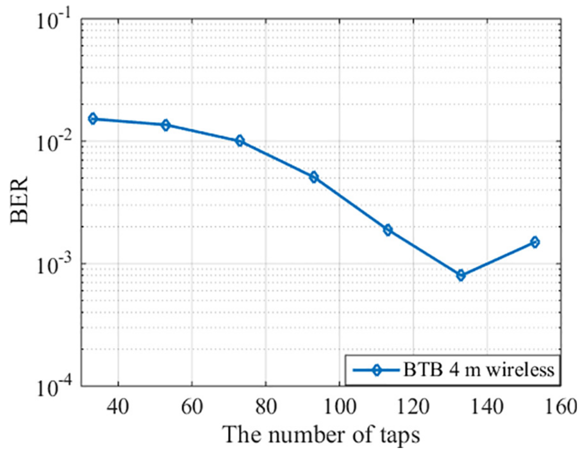

Fig. 4. The curve of BER versus the number of tap.

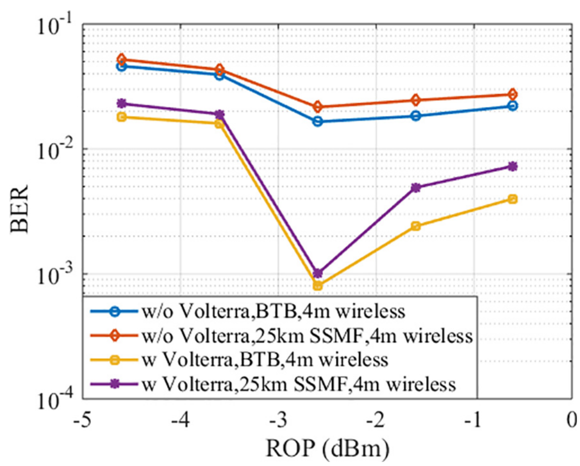

Fig. 5. The curve of BER versus ROP.

at the received optical power (ROP) of −2.6 dBm. As shown in Fig. 3, when Vpp is small, the BER is not good due to low SNR. With the increasing of Vpp, the BER will be getting better due to higher SNR. However, when Vpp continues to increase, the high-power signal will be in the saturated region of I/Q modulator, which gives a degraded BER performance. Therefore, the optimal point of 300-mV will be adopted at the following experiment.

We can observe in Fig. 3 that, BER just achieves the threshold of 2×10^{-2} due to the above-mentioned nonlinearity. In order to improve BER performance, the parallel VNC algorithm is applied. As shown in Fig. 4, the BER performance is optimized under different tap length. The optimal tap of VNC algorithm is found to be 133 taps. 133 taps will be applied at the following experiment.

Fig. 5 depicted the curves of ROP versus BER when the baud rate is 8 Gbaud. It can be seen from Fig. 5, with the increase of ROP, BER performance has significant improvement. We can get the optimal BER at the point of −2.6 dBm. But when ROP continues to increase, the high input power to PD leads to PD working in saturation region. And we can see that due to loss from 25-km SSMF, the curves without fiber transmission has good BER performance than the curves with fiber transmission. When ROP is −2.6 dBm, the square and ⋇ curve have BER of 8×10^{-4} and 1×10^{-3}, respectively.

As shown in Fig. 6(a), when ROP is −2.6 dBm, with a 25-km SSMF transmission and a 4-m wireless delivery, the BER as function of baud rate has been swept. From Fig. 6(a), with the increase of baud rate, the BER performance will become worse as shown in Fig. 6(a). With the help of parallel VNC, the BER of 8-Gbaud and 12-Gbaud 16-QAM OFDM signals can improve from 2.16×10^{-2} and 4.25×10^{-2} to 1×10^{-3} and 3.4×10^{-3}, respectively, the corresponding improved constellations are shown in Fig. 6(b) and (c). The net bit rate of 12-Gbaud is 45-Gb/s (12*4*(49/50)/(1010/1056))).

5. Conclusions

In this paper, to best of our knowledge, this is the first time to experimentally demonstrate a parallel Volterra nonlinear compensation aided 16QAM OFDM signal in W-band wireless delivery with heterodyne coherent detection. The nonlinear issues in this system have been alleviated, and we can achieve BER of 3.4×10^{-3} ($< 3.8 \times 10^{-3}$ threshold) when 45-Gb/s OFDM signals is transmitted in a 25 km SSMF and 4 m wireless.

Author Contribution

Li Zhao: experiment, idea, writing, Run-Kai Shiu: experiment, Wen Zhou: reviewing, Rui Zhang: reviewing, Shuyi Shen: editing, Yitong Li: editing, Jianjun Yu: supervision, G. K. Chang: supervision.

Conflict of Competing Interests

The authors declare that they have no known competing financial

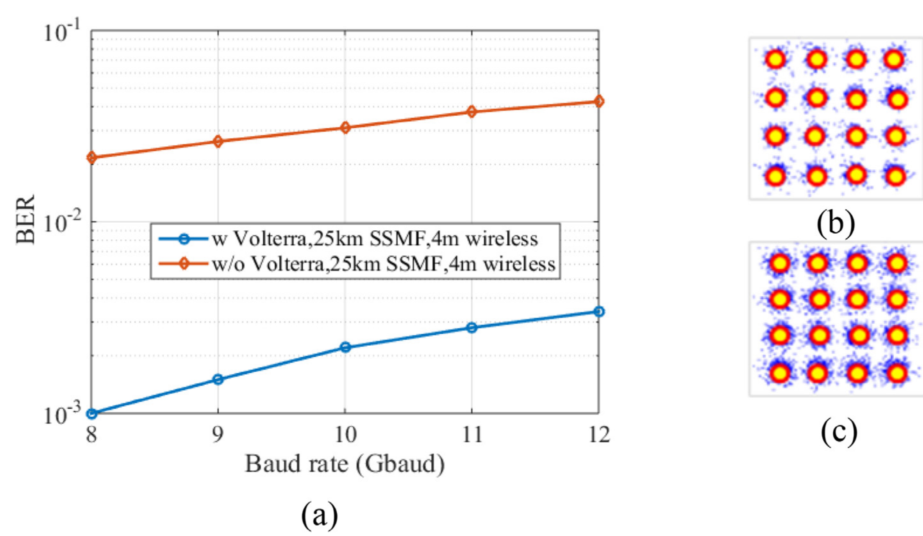

Fig. 6. (a) The curve of BER versus Baud rate. (b) The constellation of 8-Gbaud with Volterra. (c) The constellation of 12-Gbaud with Volterra.

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yofte.2019.102099.

References

[1] L. Zhao, Y. Zhang, W. Zhou, Probabilistically shaped 64QAM OFDM signal transmission in a heterodyne coherent detection system, Opt. Commun. 434 (2019) 175–179.
[2] L. Deng, M. Beltran, X. Pang, X. Zhang, V. Arlunno, Y. Zhao, A. Caballero, A. Dogadaev, X. Yu, R.M. Llorente, D. Liu, I. Tafur, Fiber wireless transmission of 8.3-Gb/s/ch QPSK-OFDM signals in 75–110-GHz Band, IEEE Photonics Technol. Lett. 24 (5) (2012) 383–385.
[3] X. Li, J. Xiao, J. Yu, Long-distance wireless mm-wave signal delivery at W-band, J. Lightwave Technol. 34 (2) (2016) 661–668.
[4] X. Li, J. Yu, J. Xiao, Demonstration of ultra-capacity wireless signal delivery at W-band, J. Lightwave Technol. 34 (1) (2016) 180–187.
[5] X. Li, J. Yu, J. Xiao, Y. Xu, Fiber-wireless-fiber link for 128-Gb/s PDM-16QAM signal transmission at W-band, IEEE Photon. Technol. Lett. 26 (19) (2014) 1948–1951.
[6] X. Li, J. Yu, J. Zhang, F. Li, Y. Xu, Z. Zhang, J. Xiao, Fiber-wireless-fiber link for 100-Gb/s PDM-QPSK signal transmission at W-band, IEEE Photon. Technol. Lett. 26 (18) (2014) 1825–1828.
[7] F. Li, X. Li, J. Zhang, J. Yu, Z. Cao, Fiber-wireless-fiber link for DFT-spread OFDM signal transmission at W-band, IEEE Photonics Technol. Lett. 27 (14) (2015) 1273–1276.
[8] IEEE Photonics J. 9 (1) (2017) 1–7, https://doi.org/10.1109/JPHOT.2016.2645400.
[9] C. Lin, M. Wu, C. Ho, C. Li, C. Lin, H. Huang, W-band OFDM radio-over-fiber system with power detector for vector signal down-conversion, Opt. Lett. 40 (2015) 2477–2480.
[10] IEEE J. Quantum Electron. 53 (6) (2017) 1–17, https://doi.org/10.1109/JQE.2017.2765742.
[11] J. Pan, C.H. Cheng, Nonlinear electrical compensation for the coherent optical OFDM system[J], J. Lightwave Technol. 29 (2) (2011) 215–221.
[12] Junwen Zhang, Yu. Jianjun, Nan Chi, Ze Dong, Xinying Li, Nonlinear compensation and crosstalk suppression for 4 × 160.8Gb/s WDM PDM-QPSK signal with heterodyne detection, Opt. Express 21 (2013) 9230–9237.
[13] X. Li, J. Xiao, J. Yu, Heterodyne detection and transmission of 60-Gbaud PDM-QPSK signal with SE of 4b/s/Hz, Opt. Express 22 (8) (2014) 9307–9313.
[14] I. Fatadin, S.J. Savory, D. Ives, Compensation of quadrature imbalance in an optical QPSK coherent receiver, IEEE Photonics Technol. Letter. 20 (20) (2008) 1733–1735.