Highly linear transmission and EVM improvement of vector modulation signals for radio-over-fiber applications

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The principle of error vector magnitude (EVM) against modulator nonlinearity for vector modulation signal (VMS) transmission in radio-over-fiber (RoF) systems is theoretically and experimentally investigated. A highly linear modulation scheme is proposed and demonstrated using a single-drive dual parallel Mach–Zehnder modulator (MZM). This method improves EVM performance and enlarges the linear input dynamic range of the VMS transmission. An index of maximum allowable input power difference (MAIPD) that reflects the difference of upper input power limits between these two schemes is measured. An EVM limitation of 5% MAIPD has 5 dB. Both 16- and 64-QAM results indicate that the proposed scheme supports VMS transmission better than the MZM one.

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The combination of wireless and fiber access technology makes radio-over-fiber (RoF) application a promising tool in bringing high-speed broadband wireless services into reality[1]. Recent studies have increasingly focused on complex modulation formats, such as quadrature phase shift keying (QPSK), quadrature amplitude modulation (QAM), and even orthogonal frequency-division multiplexing (OFDM), including the transmission quality of these formats. Previous reports have demonstrated the performances of each signal in different RoF systems[2−4]. Moreover, input signal power increase is effective, to some extent, in combating noise[3] and fiber dispersion[4]. Unfortunately, the applicable range is too narrow because nonlinearity, especially modulator nonlinearity, seriously worsens signal-to-noise ratio (SNR) and error vector magnitude (EVM) when more power is added. We have previously reported a highly linear modulation by optically mitigating the third-order inter-modulation distortion (IMD)[5]. The proposed scheme demonstrates better linear transmission capability, with 16-QAM modulation signals compared with the results of a quadrature biased Mach–Zehnder modulator (QB-MZM). Nevertheless, such finding lacks theoretical explanation for EVM improvement, an area that should be studied further for guidance in real applications.

In this letter, experiments are conducted between systems that use a single-drive dual-parallel MZM (SD-DPMZM) and a QB-MZM, respectively. The study is conducted with EVM serving as critical evaluations of vector modulation signal (VMS) transmission in a RoF system. The proposed technique is then extended to incorporate the capability of reducing the EVM of VMS for application in high-power input scenarios. To the best of our knowledge, it is the first time to present the evolution of EVM versus modulator nonlinearity in RoF schemes.

Compared with previous studies, the work presented here focuses on lower RF carrier frequency (5 GHz) and bit-rates (up to 300 Mbps). This work, however, is acceptable in cellular and WLAN applications, where the wireless band rangs from 900 MHz to 5.2 GHz[2]. As previously demonstrated, the proposed configuration works at a higher frequency band such as 40 GHz[6]. The result is also expected to suit 60 GHz millimeter-wave systems[7] with sufficient modulator bandwidth.

Generally, a radial distortion is introduced to the VMS constellation through nonlinearity when the input power increases. The process results in various link coefficients, including gain (or loss) and photodiode (PD) response, which are common divisors divided from the error term and the distortion-free signal term of the EVM calculation. The final expression remains an arithmetic parameter η and a power term of input power. The latter is converted to the expression of the average input power with the help of input equivalent input resistance,$\Re$. In a QB-MZM scheme, the calculated EVM is proportional to the average input power resulting from the third-order IMD (IMD3) of the MZM model.

The EVM of the received VMS in a QB-MZM scheme is given by

$$\mathrm{EVM_M} = \frac{\eta}{2}\Re 10^{\frac{P}{10}}, \tag{1}$$

where P is the average input power in dBm units.

Based on the analysis stated in an earlier work[4], the proposed SD-DPMZM scheme is noted as: $a = \sin\phi_1$ and $b = 4\sin(\phi_1/2)\cos(\phi_2/2)\cos\phi_3$, where the values of $\phi_i (i = 1, 2, 3)$ are the DC phase differences to the sub-MZMs of DPMZM, respectively. As the high linearization condition $8a + b = 0$ suppresses the IMD3, the main IMD becomes the fifth order. Therefore, the EVM in the DPMZM link is proportional to the square of input power. This is mathematically described as

$$\mathrm{EVM_D} = \frac{\eta}{48}\Re^2 10^{\frac{P}{5}}. \tag{2}$$

We define a variable to quantitatively illustrate the difference between the linear input ranges of these two schemes and call it the maximum allowable input power difference (MAIPD). This difference represents the power difference of upper input limits between these two schemes against the same limitation of EVM.

From Eqs. (1) and (2), the MAIPD is deduced as

$$\Delta P = x_{\rm D} - x_{\rm M} = -5\lg(\text{EVM}) + 5\lg(12\eta)\,. \qquad (3)$$

A simple system setup was carried out (Fig. 1). The continuous-wave (CW) laser worked at 1 549.8 nm, while a DPMZM (Mach-10 060, Covega) with half-wave voltage of 4.6 V was driven by VMS at a symbol rate of 50 M samples/s. The signal was generated by a RF vector signal generator (E8267D, Agilent) and centered at a RF frequency of 5 GHz. The optical signal was launched into an erbium-doped fiber amplifier (EDFA) and filtered by a bandpass filter (BPF). The optical signal was detected by a PD (U2T, 3120R) and then measured by a vector signal analyzer (VSA; 89600, Agilent).

The bias control model provides three DC voltages for the sub-MZMs. These voltages, identified as 4.08, 2.2, and 4.46 V, respectively, validated the linearization condition $8a + b = 0$. A comparative experiment was completed by replacing the MOD in Fig. 1 with a MZM (AM-40, Avanex), which was biased at the quadrature point with a half-wave voltage of 4.2 V. Two optical transmitters served the VMS formats 16- and 64-QAMs using SD-DPMZM and QB-MZM, respectively.

The EVM results of the 16-QAM signal against different input powers were measured (Fig. 2). When the RF power input to the modulators increase to a critical level (∼10 and 16 dBm for the MZM and DPMZM schemes, respectively), the systems work in the nonlinear region and the EVMs increase rapidly. In this region, EVMs in the MZM amd DPMZM schemes grow to $10^{x/10}$ and $10^{x/5}$, respectively. This mechanism confirms theoretical analyse in Eqs. (1) and (2),

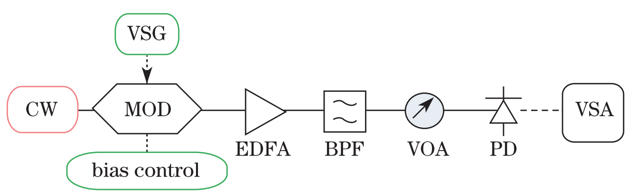

Fig. 1. Experimental setup for RoF link (MOD: modulator; VOA: variable optical attenuator).

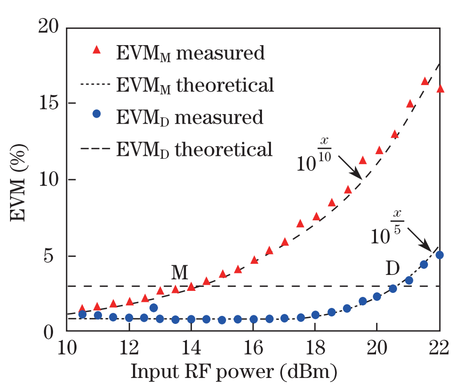

Fig. 2. Measured EVM performances and theoretical curves of the 16-QAM signal transmission.

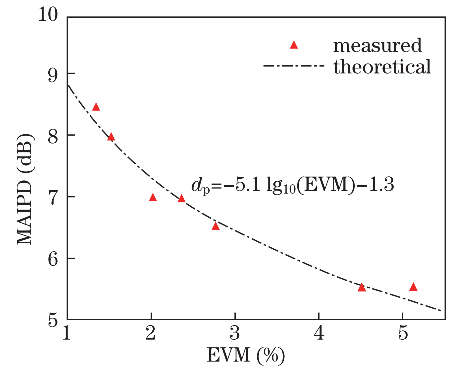

Fig. 3. MAIPD versus EVM for the 16-QAM signal transmission.

respectively. For example, a MAIPD of 6.5 dB is measured between point M and D in Fig. 2, when the EVM is 2.36%.

The experimental MAIPD results for the 16-QAM signal transmission are shown as the triangle points in Fig. 3. Fitting the curve $\Delta P = \alpha \lg(\text{EVM}) + \beta$, where α and β are unknown parameters, results in the dashed line shown in Fig. 3, wherein $\alpha = -5.1$ and $\beta = -1.3$. Therefore, the proposed DPMZM scheme requires less RF power to overcome modulator nonlinearity, especially when low EVM is required. Thus, this letter gives a clear and exact guide on the advantage of our proposed highly linear RoF system for VMS transmission.

Notably, the scan step of the RF power input in our experiment is 0.5 dBm. This setup results in low MAIPD precision and difficulty in finding appropriate pairs of data at the same EVM value. Better experimental results in accordance with the theoretical analysis rely on a dense scan experiment.

Figure 4 shows the EVM results for the higher-order modulation format of 64-QAM. EVM difference increases as the RF power input increases within a critical power level of 17 dBm. The EVMs at this stage are 6.12% (point A for MZM scheme) and 0.98% (point B for DPMZM scheme). After this power level, the EVMs in the MZM scheme become saturated and remain at around 8.5%. However, the situation is much better in the other scheme, probably because the constellations of 64-QAM are not easily distinguishable when meeting such serious distortion in capacity of our VSA. Points C and D corresponding to the EVM values of 8.88% and 2.51%, respectively, are compared at the same RF power input of 20 dBm. The maximum RF power input is measured as 16 dBm at the limited EVM of 5%, whereas, the proposed SD-DPMZM scheme has a larger input range of up to 21.5 dBm. In other words, the SD-DPMZM RoF system provides higher SNR and can support a higher-order VMS transmission format, thereby improving data rate and transmission capacity.

The constellations of marked points (points A to D in Fig. 4) are illustrated in Fig. 5. Figures 5(a) and (b) predict that the constellation in the QB-MZM scheme suffers more from radial distortion, which is physically induced by non-linearity, compared with the constellation in the SD-DPMZM scheme. The constellation bunches up in Fig. 5(c), whereas it is clearly recognizable in Fig. 5(d).

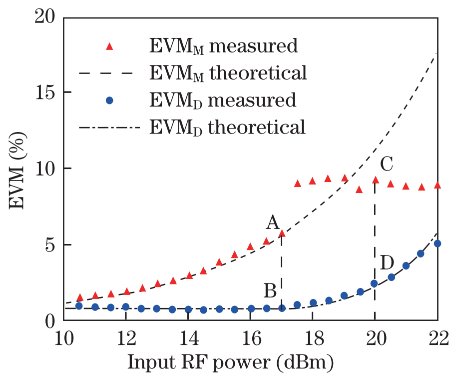

Fig. 4. EVM results versus drive RF power to the modulators for 64-QAM transmission.

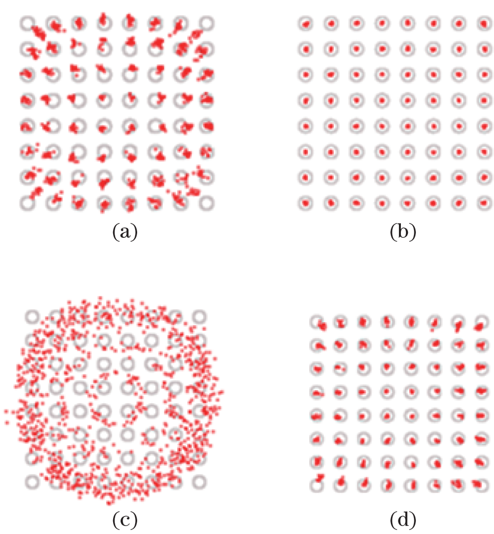

Fig. 5. Received constellations of compared points (a) A, (b) B, (c) C, and (d) D marked in Fig. 4.

Our approach helps improve dynamic range by not only improving system linearity but also restraining the noise. Other linearization technology, such as adopting an off-the-shelf RF amplifier, will amplify noise when linearity is improved. Moreover, due to its single drive input, our technology avoids signal synchronization problems. However, the challenge lies in accurately monitoring and controlling the DC biases as modulator parameter drafting. A bias-tolerant test has also been demonstrated before to illustrate this[4].

In conclusion, a highly linear VMS transmission using a SD-DPMZM is experimentally demonstrated to determine an obviously larger linear dynamic range for real RoF applications. Both 16- and 64-QAM results demonstrated good EVM improvements in high-power input scenarios, compared with QB-MZM. Over 5 dB of MAIPDs between the two schemes have been measured experimentally within an EVM value of 5%. The measured MAIPDs are in accordance with the theoretical prediction. The proposed scheme also provides better resolution to constellation detection as well as improved support for high-order VMS transmission.

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