Multi-dimensional crest factor reduction and digital predistortion for multi-band radio-over-fiber links

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Abstract: A multi-dimensional crest factor reduction (MD-CFR) technique is proposed to improve the performance and efficiency of multi-band radio-over-fiber (RoF) links. Cooperating with multi-dimensional digital predistortion (MD-DPD), MD-CFR increases the performance of both directly-modulated and externally-modulated RoF links, in terms of error vector magnitude (EVM) and adjacent channel power ratio (ACPR). For directly-modulated RoF link, more than 5 dB output ACPR reduction is obtained, output EVMs are reduced from 11.83% and 12.47% to 7.51% and 7.26% for two bands respectively, while only a slight improvement to 11.58% and 10.78% is obtained solely using MD-DPD. Similar results are achieved in externally-modulated RoF link. Given a threshold in EVM or ACPR, the RF power transmit efficiency is also further enhanced.

OCIS codes: (060.5625) Radio frequency photonics; (060.2360) Fiber optics links and subsystems; (060.4230) Multiplexing.

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1. Introduction

Owing to the diversity of modern wireless communication standards working at discrete allocated frequency bands such as wireless local-area networks (WLAN), Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE) [1, 2], multi-standard multi-band integrated technologies are under intensive research for flexibility and potential cost and energy saving. Meanwhile, in the context of distributed antenna systems where the traditional base transceiver station (BTS) processing functions are centralized in a central unit (CU) and thereby the remote antenna units (RAUs) are much simplified, multi-band analog radio-over-fiber (ROF) links can serve as a promising front-haul option due to their well-known benefits such as low-loss transmission, radio-technology transparency, easy multi-band transmission, and good scalability [3–5]. There are two categories of analog RoF systems in terms of modulation techniques: directly-modulated and externally-modulated RoF systems. The former one is suited to low-cost applications, while the latter one offers high performance due to dedicated high-performance laser source and large-bandwidth optical modulator. Basically, both RoF links suffer from inherent nonlinearities from either directly-modulated lasers or external optical modulators.

In order to run a RoF link with as high power transmit efficiency as possible, both crest factor reduction (CFR) and digital predistortion (DPD) are crucial. DPD has been demonstrated to be a powerful linearization technique for nonlinear systems, such as RF amplifier [6, 7] and RoF links [8]. In [9, 10], we have proposed and investigated a low-complexity multi-dimensional DPD (MD-DPD) technique for multi-band RoF links. CFR is a technique to suppress peak-to-average power ratio (PAPR) by cutting off the infrequent peaks of an RF signal. It allows a nonlinear system to operate closer to saturation [11, 12]. However, traditional CFR is only developed for single-band scenario. In multi-band RoF links, running CFR independently on each individual band is no more effective, since peak growth occurs after combining the multiple concurrent bands together. A straightforward solution is to consider multiple concurrent bands as a wideband integral signal. However, the frequency spacing between multiple bands are always much larger than the signal bandwidth of each band. Therefore, applying CFR on the composite signal necessitates high sampling rate and computational complexity.

In this paper, we propose a multi-dimensional CFR (MD-CFR) technique for multi-band RoF links, inspired by the developed multi-dimensional DPD in [9, 10]. In the MD-CFR approach, peak clipping is applied to each band individually, while peak detection is calculated based on the combined signal of multiple bands. It guarantees both the peak reduction benefits and low-complexity hardware. Furthermore, we first experimentally investigate the cooperation of the proposed MD-CFR and MD-DPD. It will be found that incorporating these two techniques improves the performance and efficiency in both directly-modulated and externally-modulated RoF links.

2. Principle of the multi-dimensional CFR

Several PAPR reduction techniques have been developed among which the clip-and-filter CFR algorithm is simple while achieving a good performance [11]. In the clip-and-filter algorithm, the baseband signal is clipped, filtered, and then modulated onto a carrier frequency. Here, we extend the clip-and-filter algorithm for multi-band scenarios.

The architecture of a multi-band RoF link with MD-CFR and MD-DPD is shown in Fig. 1. $x_i(n)$ (i = 1, 2… L) denotes the original baseband complex signal of the i^{th} band. To estimate the combining effect of multiple bands, we define the sum of multiple bands' power (i.e. $P_{sum}(n)$) by (1), where α_i denoted the i^{th} band's power proportion of total power. Then the peak detection and peak clipping are applied based on (2), where T is the peak detection threshold. In this MD-CFR technique, peak clipping is applied to each band individually, while peak detection is calculated based on the combined signal $P_{sum}(n)$. Therefore, the peak of combined signal is properly clipped and the sample rate depends on individual band's bandwidth rather than the bandwidth of the overall signal. From the hardware design point of

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view, the single band architecture is efficiently reused, and the only new block for the MD-CFR is the multi-band peak detection logics. The peak clipping is followed by frequency domain filtering to reduce out-of-band power.

$$P_{sum}(n) = \sum_{i=1}^{L} \alpha_i \, | x_i(n) |^2 \tag{1}$$

$$c_i(n) = \begin{cases} x_i(n) & (P_{sum}(n) \le T) \\ x_i(n)\sqrt{\dfrac{T}{P_{sum}(n)}} & (P_{sum}(n) > T) \end{cases} \tag{2}$$

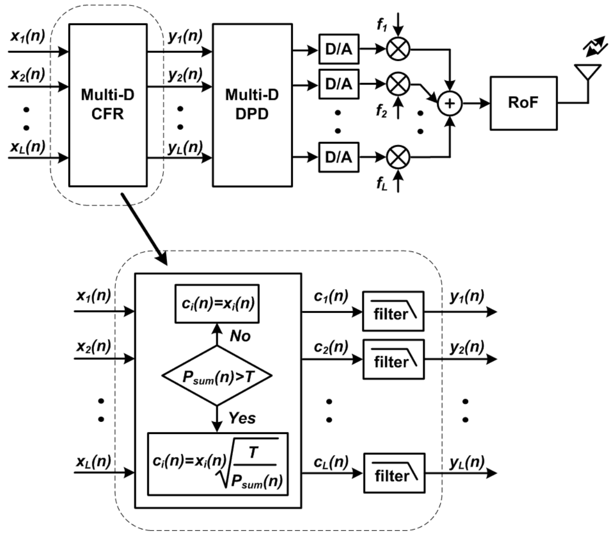

Fig. 1. The architecture of multi-band RoF systems with multi-dimensional CFR (MD-CFR).

Multi-dimensional memory polynomial model is used to characterize a multi-band RoF link and the corresponding MD-DPD. The model coefficients can be adaptively trained with the input and output baseband complex signals of the RoF link [9, 10]. In order to compensate for the nonlinear distortions, a digital predistorter constructs an inverse transfer function with respect to the RoF link which has a characteristic of gain compression. That is, the digital predistorter needs to have a gain expansion which can balance the inherent gain compression in RoF links. A digital predistorter performs well in the presence of weak nonlinearity, but degrades significantly in high-saturation region. This is because the magnitude of inverse transfer function might be infinite, which results in inaccurate or even impractical extraction of the DPD model coefficients for several input samples with high amplitude. Fortunately, CFR helps clipping the peak of signals, although CFR itself introduces certain nonlinearities. With an optimized clipping ratio, the interaction of CFR and DPD can further improve the performance of RoF links in the saturation region.

3. Experiments for directly-modulated RoF systems

3.1 Experimental setup

As shown in Fig. 2, we took a two-band directly-modulated RoF link as an example in the experiments to study the MD-CFR technique. Two vector signal generators (VSG Agilent E8267D and Anritsu MS2690A) were used to generate two 64-ary quadrature amplitude modulation orthogonal frequency division multiplexing (64 QAM-OFDM) RF signals both with 20 MHz bandwidth at 2.412 GHz and 2.6 GHz. The RF carrier frequencies at 2.412 GHz and 2.6 GHz are compliant to WLAN and the time-division LTE (TD-LTE) in China,

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respectively. The two RF signals were combined and then applied to a commercial directly-modulated laser diode (LD) module with a pre-amplifier with ~15 dB gain embedded in it. The wavelength of the LD is around 1550 nm. After transmission over standard single-mode fiber (SMF) and a variable optical attenuator, a photodetector (PD) was used to perform the optical to electrical conversion. The optical input power to the PD kept 3 dBm. The MD-DPD structure based on memory polynomials [9, 10] was implemented in the experiment, A vector signal analyzer (VSA Agilent N9030A) was used to capture the output of PD from which we can extract the DPD model coefficients by Matlab.

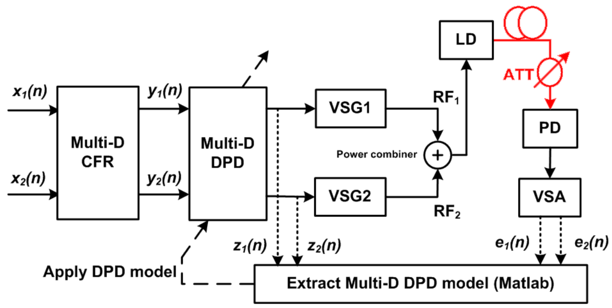

Fig. 2. Experimental setup for a two-band directly-modulated RoF link.

3.2 Experimental results

We define the clipping ratio (CR) as the ratio of the clipping level (i.e. the peak detection threshold *T*) to the average power of the unclipped baseband signal. Figure 3 shows the complimentary cumulative distribution function (CCDF) curves of combined multi-band signal after MD-CFR for different CRs, which indicates a lower CR achieves lower PAPR.

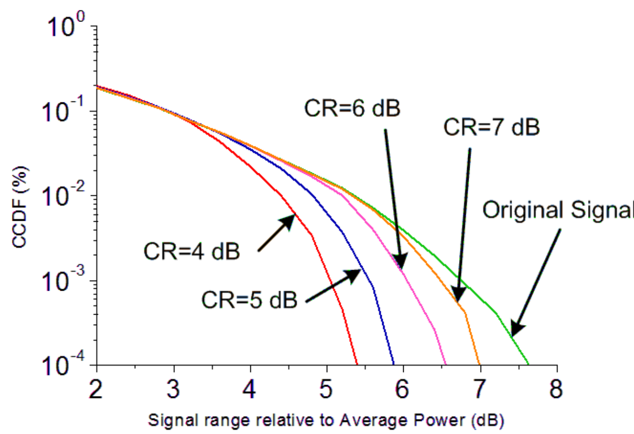

Fig. 3. CCDF curves for different CR.

Table 1. Comparison in ACPR and EVM for Directly-modulated RoF Systems

Case	ACPR (in dBc)		EVM	
	Band 1 (LSB/USB)	Band 2 (LSB/USB)	Band 1	Band 2
w/o DPD	−25.6/-25.5	−24.9/-24.9	11.83%	12.47%
w/ DPD	−25.9/-25.6	−25.8/-27.1	11.58%	10.78%
w/ CFR + DPD	−32.5/-31.1	−30.4/-32.2	7.51%	7.26%

First, three scenarios were evaluated: the scenario without DPD, the scenario with only MD-DPD, and the scenario with both MD-CFR (CR = 3.5 dB) and MD-DPD. The RF power

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applied on the LD module was −3 dBm per band. Figure 4 shows the measured RF power spectra and constellation diagrams of the output signal from the RoF link. The quantitative results are summarized in Table 1. It is obvious that MD-DPD only provides limited performance improvement, whereas more than 5 dB adjacent channel power ratio (ACPR) improvement is observed at both upper sideband (USB) and lower sideband (LSB) for the combination of MD-CFR and MD-DPD. The cooperation of the MD-CFR and MD-DPD reduces the error vector magnitude (EVM) from 11.83% and 12.47% to 7.51% and 7.26% for the two bands respectively. The reason is analyzed as following: MD-DPD is always a powerful linearization technique for RoF links, but when the RF input power goes too high, the compensation performance will degrade [10]. That's because the infrequent peak signals which are seriously compressed by the nonlinear RoF links lead to imprecise MD-DPD model extraction. MD-CFR decreases the peak of signals, resulting in higher precision in MD-DPD process. However, the CR must be carefully selected, little clipping may lead to insufficient peak reduction while over-clipping will degrade signals seriously.

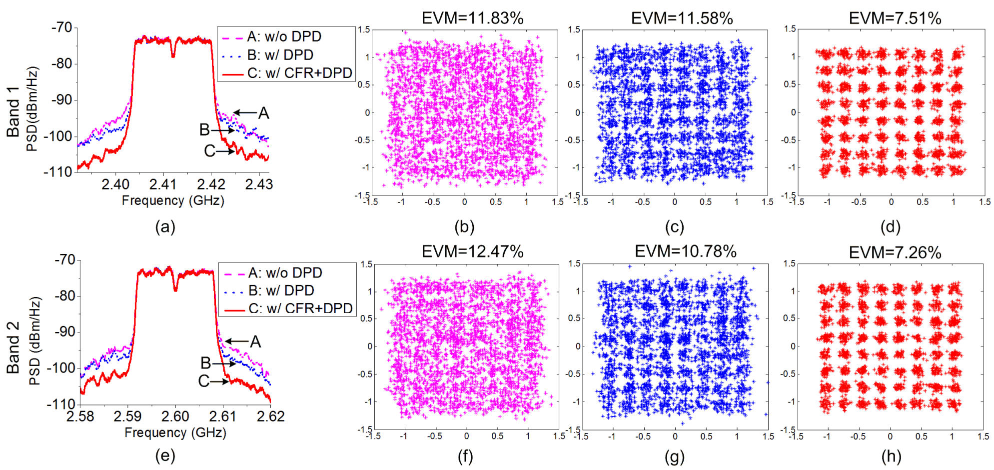

Fig. 4. Power spectra and constellation diagrams after directly-modulated RoF link. (a) power spectra of Band 1 at 2.412 GHz; (b) constellation diagram of Band 1 without DPD; (c) constellation diagram of Band 1 with MD-DPD; (d) constellation diagram of Band 1 with MD-CFR and MD-DPD; (e) power spectra of Band 2 at 2.6 GHz; (f) constellation diagram of Band 2 without DPD; (g) constellation diagram of Band 2 with MD-DPD; (h) constellation diagram of Band 2 with MD-CFR and MD-DPD.

Second, EVMs with respect to different CRs were analyzed for different RF input power (−6 dBm/Band, −5 dBm/Band, −4 dBm/Band, −3 dBm/Band). The results are depicted in Fig. 5. For comparison, EVM performance only with MD-DPD is illustrated simultaneously (dash line). It is found that for each RF input power, there is a best CR value for the most EVM improvement, just as we analyze in the paragraph above. The EVMs at the best CR value are obviously better than the result with only MD-DPD. It is also observed that the best CR value varies for different RF input power (best CR value = 7 dB, 6.5 dB, 4.5 dB, 3.5 dB for RF input power = −6 dBm/Band, −5 dBm/Band, −4 dBm/Band, −3 dBm/Band, respectively), indicating lower best CR value for higher RF input power.

In a practical RoF downlink from a base station to a remote antenna unit, digital predistortion needs a feedback path for adaptive training of model coefficients, as stated in [10]. With this feedback path, the optimized peak detection threshold T or clipping ratio can also be determined by training signals. As the RF input power to the RoF downlink often keeps constant, the training process can be implemented periodically.

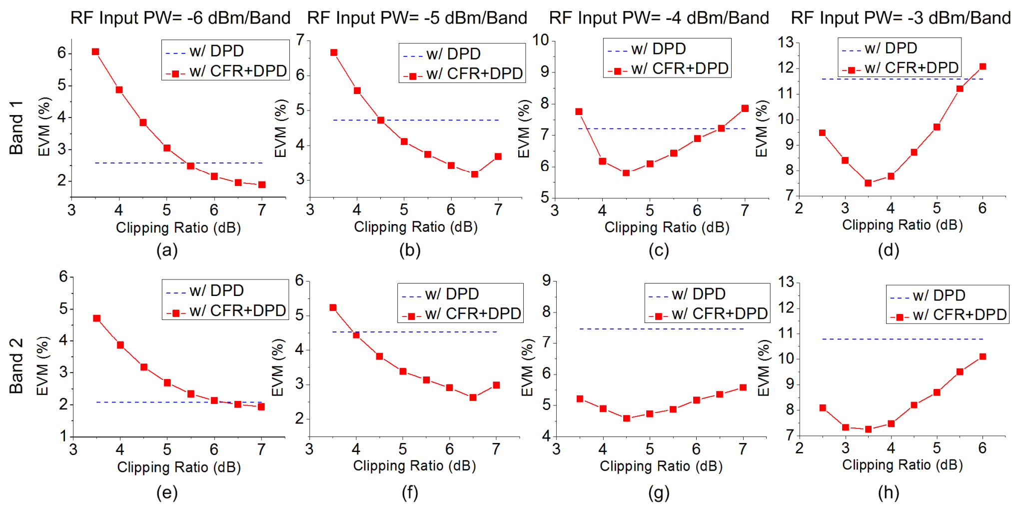

Fig. 5. EVM as a function of CR for different RF input power. (a) Band 1, RF input power = –6 dBm/Band; (b) Band 1, RF input power = –5 dBm/Band; (c) Band 1, RF input power = –4 dBm/Band; (d) Band 1, RF input power = –3 dBm/Band; (e) Band 2, RF input power = –6 dBm/Band; (f) Band 2, RF input power = –5 dBm/Band; (g) Band 2, RF input power = –4 dBm/Band; (h) Band 2, RF input power = –3 dBm/Band.

In the experiments above, we kept the RF input power of both bands identical. Here we further investigated the performance when the two bands have imbalanced RF input powers. Figure 6 and Fig. 7 shows the spectra of the output signal from the RoF link when the two bands have a power difference of 3 dB (–6 dBm/-3 dBm) and 6 dB (–8 dBm/-2 dBm) respectively. It's obvious that the cooperation of MD-CFR and MD-DPD gives more performance improvement than solely with MD-DPD, which verifies the capability of MD-CFR and MD-DPD when multiple bands have different RF input power.

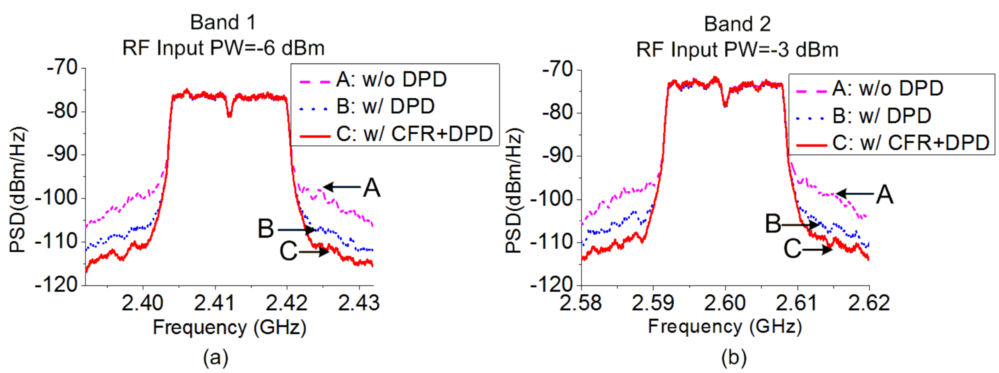

Fig. 6. Power spectra after directly-modulated RoF link. (a) Band 1 at 2.412 GHz, RF input power = –6 dBm; (b) Band 2 at 2.6 GHz, RF input power = –3 dBm.

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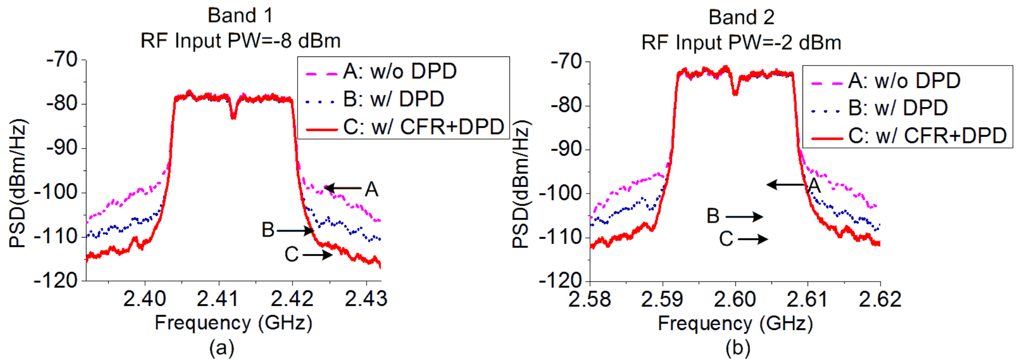

Fig. 7. Power spectra after directly-modulated RoF link. (a) Band 1 at 2.412 GHz, RF input power = −8 dBm; (b) Band 2 at 2.6 GHz, RF input power = −3 dBm.

Fourth, we studied the performance when two bands utilize different digital modulation format (i.e. Band1: QPSK-OFDM, Band 2: 64 QAM-OFDM). Figure 8 depicts the constellation diagrams after RoF link in three scenarios (i.e. without DPD, with MD-DPD, with MD-CFR + MD-DPD). The RF power applied on the LD module was −3 dBm per band. It can be observed that the combination of MD-CFR and MD-DPD provides better EVM performance than only using MD-DPD for both bands, using only MD-DPD even makes EVM worse for QPSK signals. It can also be found that the performance improvement of 64 QAM signals is much more distinct than QPSK signals, which indicate the technique we proposed is more effective for the signals with higher PAPR.

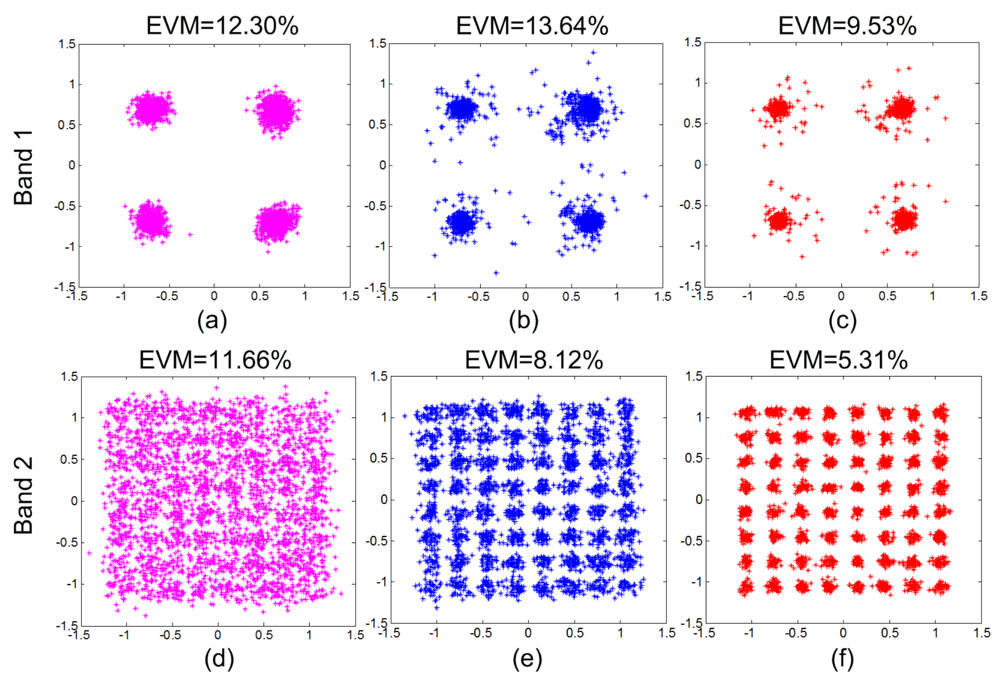

Fig. 8. Constellation diagrams after directly-modulated RoF link. (a) constellation diagram of Band 1 without DPD; (b) constellation diagram of Band 1 with MD-DPD; (c) constellation diagram of Band 1 with MD-CFR and MD-DPD; (d) constellation diagram of Band 2 without DPD; (e) constellation diagram of Band 2 with MD-DPD; (f) constellation diagram of Band 2 with MD-CFR and MD-DPD.

Finally, EVM as the function of RF input power after the directly-modulated RoF link was studied. Note that the input RF power of both bands kept identical. As illustrated in Fig. 9,

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applying MD-CFR in conjunction with MD-DPD further improve the performance compared with solely using MD-DPD, especially at high RF input power level. Given an EVM threshold, RF input power increases due to the combination of MD-CFR and MD-DPD, indicating an enhancement of RF power transmit efficiency.

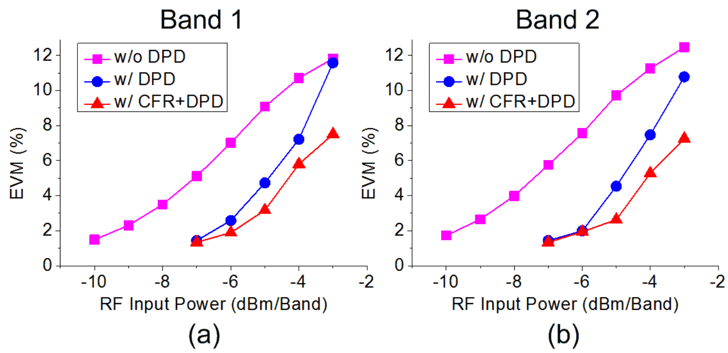

Fig. 9. EVM performance against RF input power after directly-modulated RoF link. (a) Band 1 at 2.412 GHz; (b) Band 2 at 2.6 GHz.

4. Experiments for externally-modulated RoF systems

4.1 Experimental setup

Externally-modulated RoF link is also a nonlinear system, but it has entirely different mechanisms with directly-modulated RoF links, so the investigations on MD-CFR for externally-modulated RoF systems are necessary. In the externally-modulated RoF link shown in Fig. 10, a 10 dBm CW light at 1550 nm was sent to a broadband $LiNbO_3$ Mach-Zehnder modulator (MZM) with a half-wave voltage of about 3.6 V. The RF signals at two bands were combined and then applied to the MZM. After transmission over standard SMF and a variable optical attenuator, a PD was used to convert the optical signal to electrical domain. The optical input power to the PD kept 3 dBm.

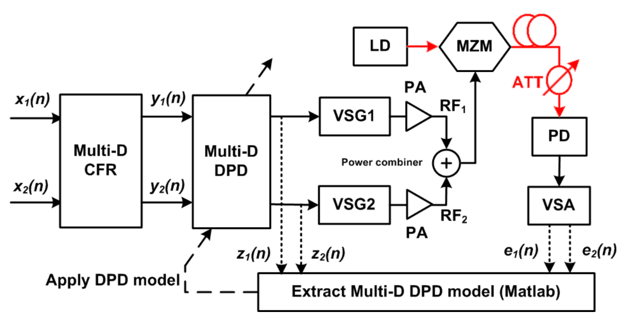

Fig. 10. Experimental setup for a two-band externally-modulated RoF link.

4.2 Experimental results

First, three scenarios were evaluated: the scenario without DPD, the scenario with only MD-DPD, and the scenario with both MD-CFR (CR = 5 dB) and MD-DPD. The RF power applied on the modulator was 7 dBm per band. Figure 11 shows the measured RF power spectra and constellation diagrams of the output signal from the RoF link. The quantitative results are summarized in Table 2. It is obvious that MD-DPD only provides limited performance improvement, whereas more than 2 dB ACPR improvement is observed at both USB and LSB for the combination of MD-CFR and MD-DPD. The cooperation of the MD-CFR and MD-DPD reduces the EVM from 6.45% and 6.61% to 4.77% and 4.18% for the two bands respectively.

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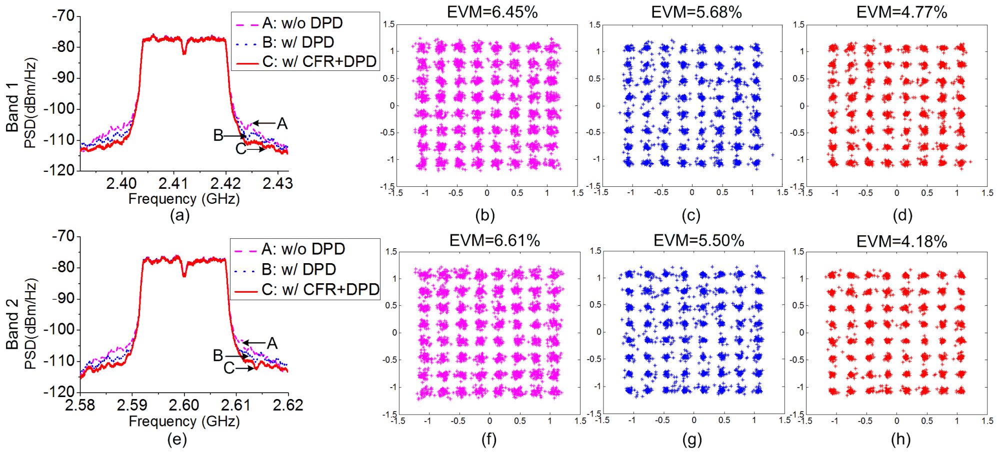

Fig. 11. Power spectra and constellation diagrams after externally-modulated RoF link. (a) power spectra of Band 1 at 2.412 GHz; (b) constellation diagram of Band 1 without DPD; (c) constellation diagram of Band 1 with MD-DPD; (d) constellation diagram of Band 1 with MD-CFR and MD-DPD; (e) power spectra of Band 2 at 2.6 GHz; (f) constellation diagram of Band 2 without DPD; (g) constellation diagram of Band 2 with MD-DPD; (h) constellation diagram of Band 2 with MD-CFR and MD-DPD.

Table 2. Comparison in ACPR and EVM for Externally-modulated RoF Systems

Case	ACPR (in dBc)		EVM	
	Band 1 (LSB/USB)	**Band 2 (LSB/USB)**	**Band 1**	**Band 2**
w/o DPD	−32.2/-32.1	−32.1/-32.0	6.45%	6.61%
w/ DPD	−33.3/-33.2	−33.3/-32.6	5.68%	5.50%
w/ CFR + DPD	−34.9/-34.8	−34.8/-34.1	4.77%	4.18%

Second, EVMs with respect to different CR were analyzed for different RF input power (5 dBm/Band, 6 dBm/Band, 7 dBm/Band, 8 dBm/Band). The results are depicted in Fig. 12. For comparison, EVM performance only with MD-DPD is illustrated simultaneously (dash line). It is found that for each RF input power, there is a best CR value for the most EVM improvement. The EVMs at the best CR value are obviously better than the result with only MD-DPD. It is also observed that the best CR value varies for different RF input power (best CR value = 7 dB, 6 dB, 5 dB, 4.5 dB for RF input power = 5 dBm/Band, 6 dBm/Band, 7 dBm/Band, 8 dBm/Band respectively), indicating lower best CR value for higher RF input power.

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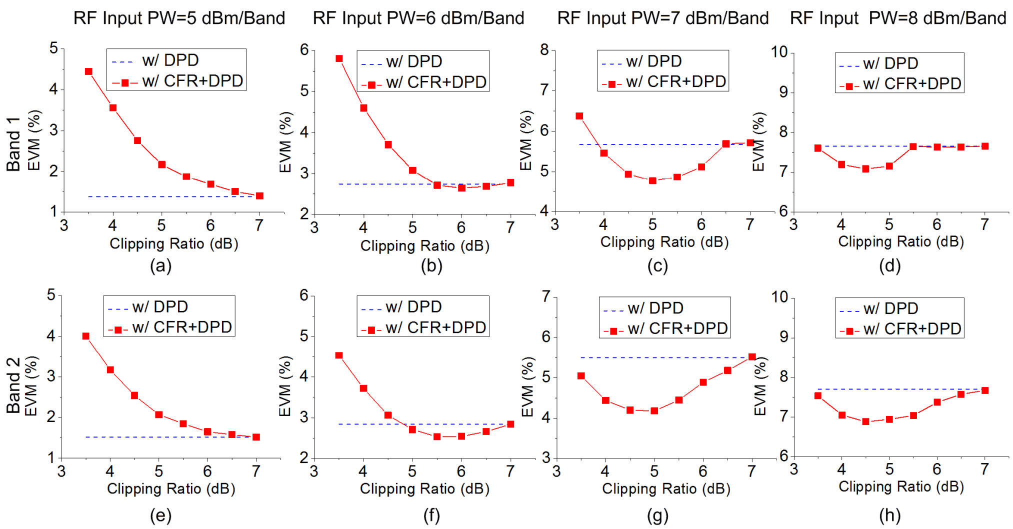

Fig. 12. EVM as a function of CR for different RF input power. (a) Band 1, RF input power = 5 dBm/Band; (b) Band 1, RF input power = 6 dBm/Band; (c) Band 1, RF input power = 7 dBm/Band; (d) Band 1, RF input power = 8 dBm/Band; (e) Band 2, RF input power = 5 dBm/Band; (f) Band 2, RF input power = 6 dBm/Band; (g) Band 2, RF input power = 7 dBm/Band; (h) Band 2, RF input power = 8 dBm/Band.

Third, we further investigated the performance when the two bands have imbalanced RF input power. Figure 13 and Fig. 14 shows the spectra of the output signal from the RoF link when the two bands have a power difference of 3 dB (6 dBm/9 dBm) and 6 dB (3 dBm/9 dBm) respectively. It's obvious that the cooperation of MD-CFR and MD-DPD gives more performance improvement than solely with MD-DPD, which verifies the capability of MD-CFR and MD-DPD when multiple bands have different RF input power.

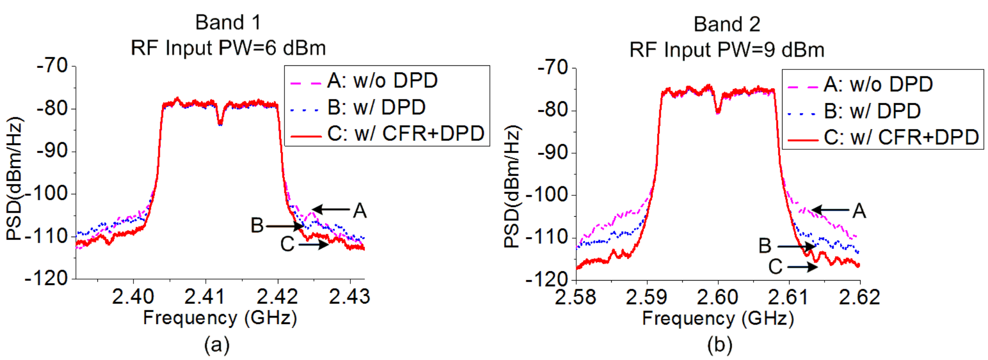

Fig. 13. Power spectra after externally-modulated RoF link. (a) Band 1 at 2.412 GHz, RF input power = 6 dBm; (b) Band 2 at 2.6 GHz, RF input power = 9 dBm.

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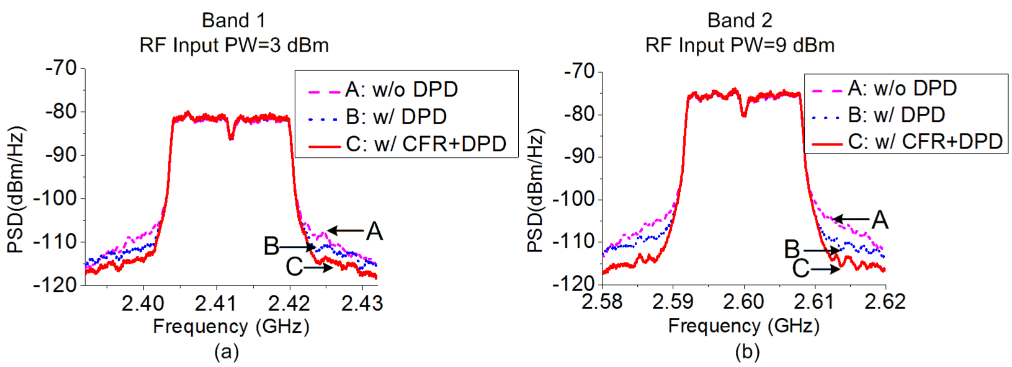

Fig. 14. Power spectra after externally-modulated RoF link. (a) Band 1 at 2.412 GHz, RF input power = 3 dBm; (b) Band 2 at 2.6 GHz, RF input power = 9 dBm.

Fourth, we studied the performance when two bands utilize different digital modulation format (i.e. Band1: QPSK-OFDM, Band 2: 64 QAM-OFDM). Figure 15 depicts the constellation diagrams after RoF link in three scenarios (i.e. without DPD, with MD-DPD, with MD-CFR + MD-DPD). The RF power applied on the modulator was 7 dBm per band. It can be observed that the combination of MD-CFR and MD-DPD provides better EVM performance than only using MD-DPD for both bands, using only MD-DPD even makes EVM worse for QPSK signals. It can also be found that the performance improvement of 64 QAM signals is much more distinct than QPSK signals, which indicate the technique we proposed is more effective for the signals with higher PAPR.

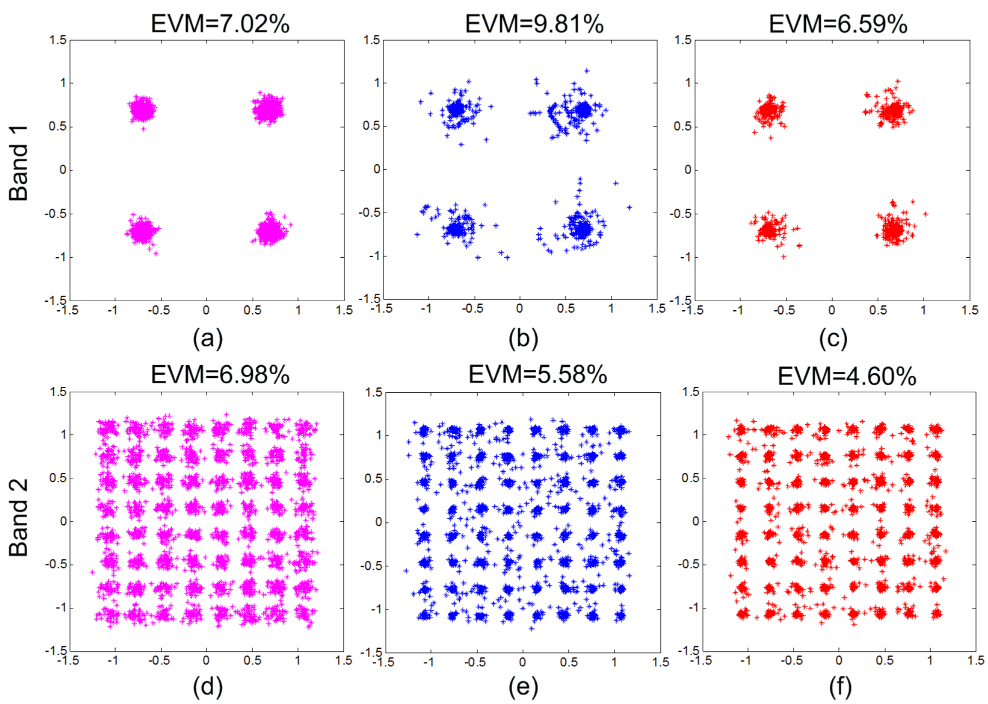

Fig. 15. Constellation diagrams after externally-modulated RoF link. (a) constellation diagram of Band 1 without DPD; (b) constellation diagram of Band 1 with MD-DPD; (c) constellation diagram of Band 1 with MD-CFR and MD-DPD; (d) constellation diagram of Band 2 without DPD; (e) constellation diagram of Band 2 with MD-DPD; (f) constellation diagram of Band 2 with MD-CFR and MD-DPD.

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Finally, EVM as the function of RF input power after the externally-modulated RoF link was studied. Note that the input RF power of both bands kept identical. As illustrated in Fig. 16, applying MD-CFR in conjunction with MD-DPD further improve the performance compared with solely using MD-DPD, especially at high RF input power level. Given an EVM threshold, RF input power increases due to the combination of MD-CFR and MD-DPD, indicating an enhancement of RF power transmit efficiency.

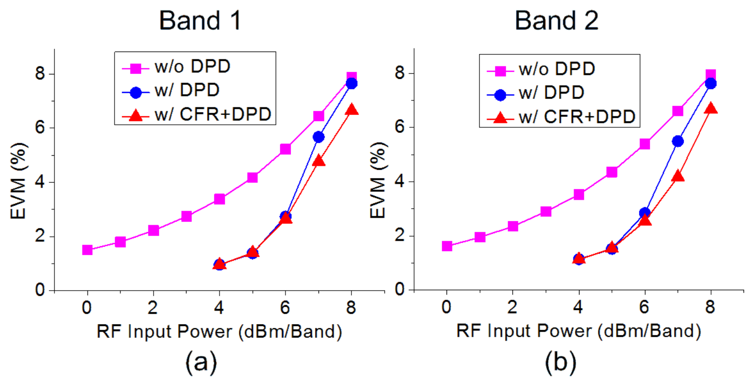

Fig. 16. EVM performance against RF input power after externally-modulated RoF link. (a) Band 1 at 2.412 GHz; (b) Band 2 at 2.6 GHz.

6. Conclusion

We have proposed an MD-CFR technique to improve the power transmit performance and efficiency in both multi-band directly-modulated RoF links and externally-modulated RoF links. With the combination of MD-CFR and MD-DPD, the output EVM and ACPR are improved as compared with the case solely using MD-DPD. The technique we proposed works well when multiple bands have different RF input power and different digital modulation format. RF input power applied to RoF links increases when given an EVM threshold, indicating an enhancement of RF power transmit efficiency. In addition, the results also show that the MD-CFR is more effective for directly-modulated RoF links than for externally-modulated RoF links.

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