Clip-and-Filter-Based Crest Factor Reduction and Digital Predistortion for WLAN-Over-Fiber Links

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***Abstract*— In this letter, we investigate the combined use of crest factor reduction and digital predistortion (DPD) as an effective method for increasing the performance in radio-over-fiber (RoF)-based downlinks. The experimental results show that combining the two techniques further improves the performance as compared with the case solely using DPD in terms of error vector magnitude (EVM) and adjacent channel power ratio (ACPR) for both directly modulated and externally modulated RoF links. Given a threshold in EVM or ACPR, the RF power transmit efficiency is also further enhanced.**

***Index Terms*— Crest factor reduction, digital predistortion, nonlinearity, radio-over-fiber.**

I. Introduction

RADIO-OVER-FIBER (RoF) has been proposed as a promising fronthaul solution to 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 [1], [2]. Analog RoF-based fronthaul link may outperform its digital counterpart due to its radio-technology transparency, shared front-haul fiber infrastructure, and good scalability [3], [4]. There are two categories of analog RoF links in terms of modulation fashion: directly-modulated and externally-modulated ones. 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. Basically, both RoF links suffer from inherent nonlinearities from either directly-modulated lasers or external optical modulators.

In order to run a RoF-based downlink 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 and RoF links [5]–[8]. CFR is a cost-effective technique to reduce the magnitude of the infrequent peaks of the signal and achieve lower peak-to-average power ratio (PAPR), which allows the systems operate closer to saturation [9]–[11]. CFR is especially crucial for orthogonal frequency division multiplexing (OFDM) signals which feature high peak-to-average power ratio (PAPR). In [12], the combination of DPD and CFR techniques was attempted for improving the power efficiency of RF amplifiers. However, the effectiveness of the combination of DPD and CFR is unclear for RoF links. In addition, the performance was evaluated in terms of adjacent channel power ratio (ACPR) in [12], whereas error vector magnitude (EVM) was not taken into account.

In this letter, we first introduce and experimentally investigate the combination of CFR and DPD in RoF links. It's found that incorporating these two techniques improves the performance in both directly-modulated and externally- modulated RoF links in terms of ACPR and EVM.

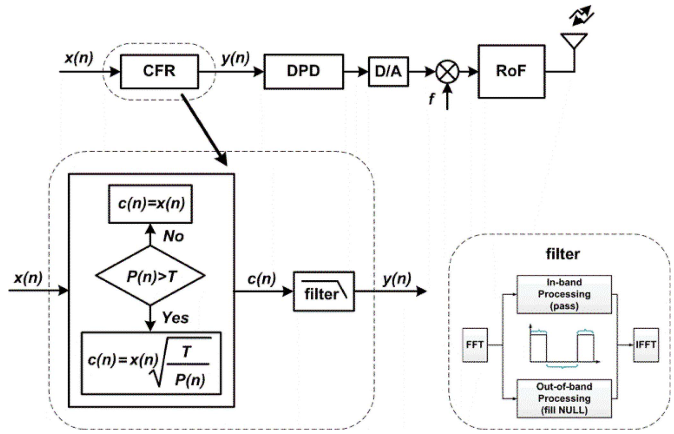

Fig. 1. The architecture of a RoF link with DPD and CFR.

II. Principle of CFR Technique

Several PAPR reduction techniques have been developed among which the clip-and-filter CFR technique is simple while maintaining a good performance [9]. In the clip-and-filter technique, baseband signal is clipped, filtered, and modulated onto a RF carrier. The architecture of a RoF link with DPD and CFR is shown in Fig. 1. $x(n)$ denotes the original baseband

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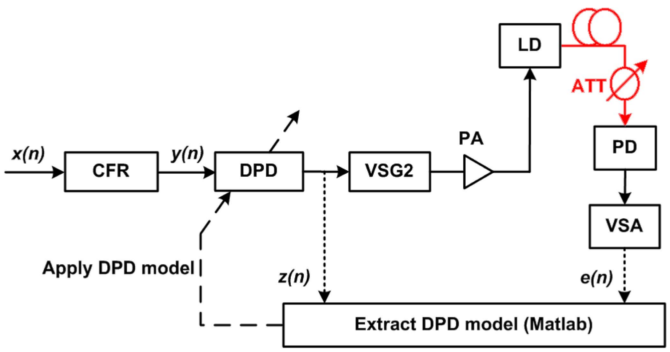

Fig. 2. The experimental setup for a directly-modulated RoF link.

complex signal, the signal's power, i.e. the $P(n)$ is defined by

$$P(n) = |x(n)|^2 \tag{1}$$

The peak detection and peak clipping is applied based on

$$c(n) = \begin{cases} x(n) & (P(n) \le T) \\ x(n)\sqrt{\frac{T}{P(n)}} & (P(n) > T) \end{cases} \tag{2}$$

where T is the peak detection threshold. We define the clipping ratio (CR) as the ratio of the clipping level (i.e. the peak detection threshold T) to the mean power of the unclipped baseband signal. The peak clipping is followed by digital filtering to reduce out-of-band power, which guarantees the required emitting spectral mask. The digital filter consists of two FFT operations. The forward FFT transforms the clipped signal back into the discrete frequency domain. The in-band discrete frequency components of the clipped signal are passed unchanged to the inputs of the second IFFT while the out-of-band components are nulled. For a practical DPD implementation, a sampling rate of 5× signal bandwidth is a typical "rule-of-thumb" [5]–[8]. For instance, the sampling rate is supposed to be 100MHz with respect to a WLAN signal bandwidth of 20MHz. Accordingly, CFR is also suggested to operate at this sampling rate, which enables the clip-and- filter operation.

For DPD, the classic memory polynomial model [6] was used, and the model coefficients was extracted by least-square algorithm. Basically, a digital predistorter has a transfer function inverse to that of RoF link. Hence, the predistorter might again increase the PAPR of a signal after CFR, but the PAPR keeps after the combination of the predistorter and the RoF link.

III. Directly-Modulated RoF Links

A. Experimental Setup

As shown in Fig. 2, one vector signal generators (VSG Agilent E8267D) were used to generate 64-ary quadrature amplitude modulation orthogonal frequency division multiplexing (64QAM-OFDM) RF signals with 20 MHz bandwidth at 2.412 GHz. The RF signals were then applied to a commercial directly-modulated laser diode (LD) module with a pre-amplifier 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 was kept to be 3 dBm. 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.

TABLE I
Comparison in ACPR and EVM for Directly-Modulated RoF Links

Case	ACPR (in dBc) (LSB/USB)	EVM
w/o DPD	-24.87/-24.72	11.87%
w/ DPD	-28.21/-28.26	9.38%
w/ CFR+DPD	-32.98/-31.76	6.57%

B. Experimental Result

First, three scenarios were evaluated: the scenario without DPD, the scenario only using DPD, and the scenario with both CFR (CR = 5.5 dB) and DPD. The RF power applied on the LD module was −2 dBm. Figure 3 shows the measured RF power spectra and constellation diagrams of the output signal from the RoF link. The quantitative results are summarized in Table I. It is obvious that DPD only provides limited performance improvement, whereas more than 7 dB adjacent channel power ratio (ACPR) improvement is observed at both upper sideband (USB) and lower sideband (LSB) for the combination of CFR and DPD. The use of the CFR and DPD reduces the error vector magnitude (EVM) from 11.87% to 6.57%, the bit error rate (BER) is also reduced from 11.22% to 0.16%. The reason is that CFR reduces the PAPR of signals, result in higher precision in DPD process, especially when high RF input power is applied. However, the CR must be carefully selected, little clipping may lead to insufficient peak reduction while over-clipping will degrade signals seriously.

Second, EVMs in terms of different CR were analyzed for different RF input powers (−4 dBm, −3 dBm, −2 dBm, −1 dBm). The results are depicted in Fig. 4. For reference, EVM performance only with DPD is also illustrated (dash line). It is found that for each RF input power, there is a best CR value for optimum performance in EVM, just as we analyzes in the paragraph above. The EVMs at the best CR value are evidently better than the result with only DPD. It is also observed that the best CR value varies for different RF input power (best CR value = 9 dB, 7 dB, 5.5 dB, 4.5 dB for RF input power = −4 dBm, −3 dBm, −2 dBm, −1 dBm respectively), indicating lower best CR value for higher RF input power.

We also investigated the performance for signals with different PAPR, it was found that the signals with higher PAPR have much more distinct EVM improvement, which indicate the technique we studied is more effective for the signals with higher PAPR.

Finally, EVM as a function of RF input power was studied. As illustrated in Fig. 5, applying CFR in combination with DPD further improves the performance as compared with the

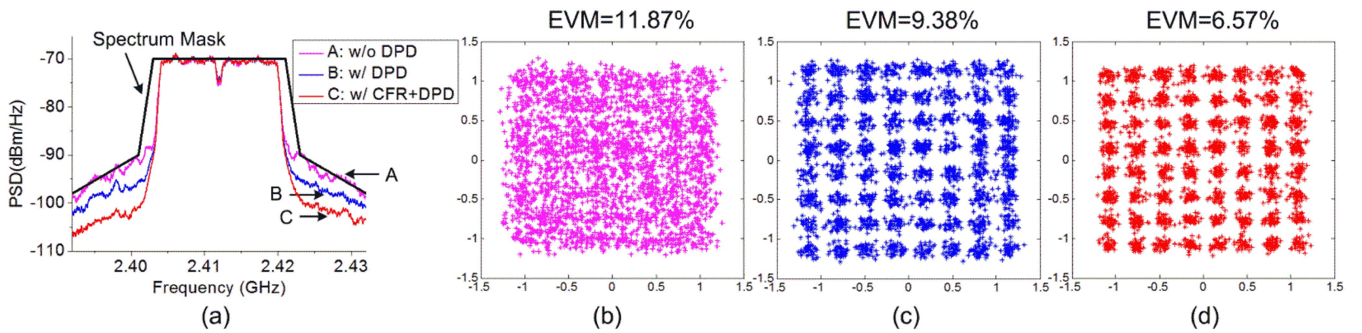

Fig. 3. Power spectra and constellation diagrams after directly-modulated RoF link. (a) Power spectra; (b) constellation diagram without DPD; (c) constellation diagram with DPD; (d) constellation diagram with CFR and DPD.

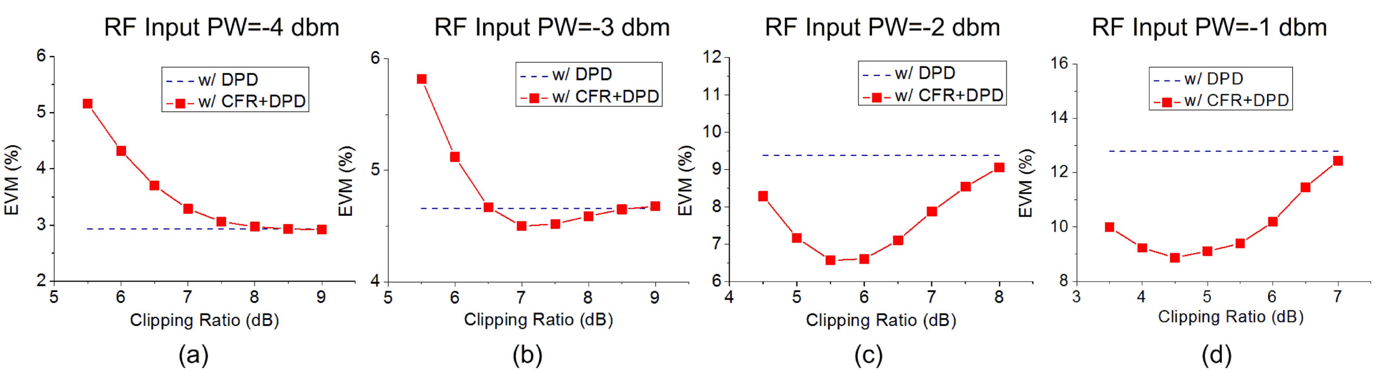

Fig. 4. EVM as a function of CR after directly-modulated RoF link. (a) RF input power = −4 dBm; (b) RF input power = −3 dBm; (c) RF input power = −2 dBm; (d) RF input power = −1 dBm.

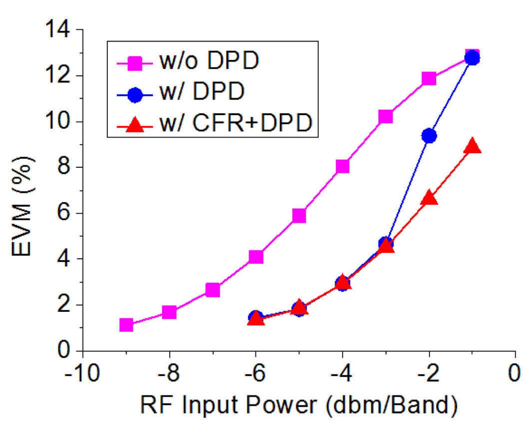

Fig. 5. EVM performance versus RF input power for directly-modulated RoF link.

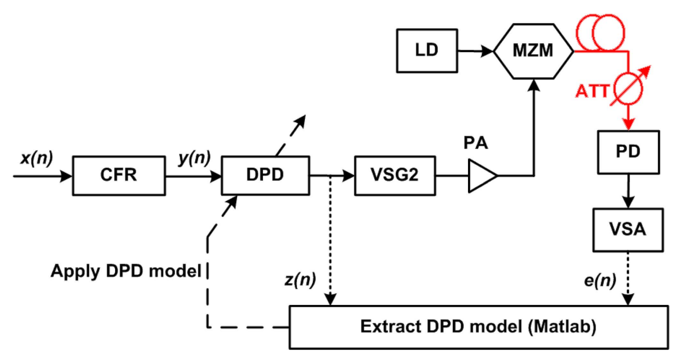

Fig. 6. The experimental setup for an externally-modulated RoF link.

case solely using DPD, especially at high RF input power levels. Given the same EVM threshold, RF input power increases due to the combination of CFR and DPD, indicating enhancement of RF power transmit efficiency.

IV. Externally-Modulated RoF Links

A. Experimental Setup

Similar investigations were done for externally-modulated RoF links. As shown Fig. 6, 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 were 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 was kept to be 3 dBm.

B. Experimental Results

First, three scenarios were evaluated: the scenario without DPD, the scenario only using DPD, and the scenario combining CFR (CR = 5.5 dB) and DPD. The RF power applied on the MZM was 11 dBm. Figure 7 shows the measured RF power spectra and constellation diagrams of the output signal from the RoF link. The quantitative results are summarized in Table II. It is obvious that DPD only provides little EVM improvement, whereas more than 2 dB ACPR improvement

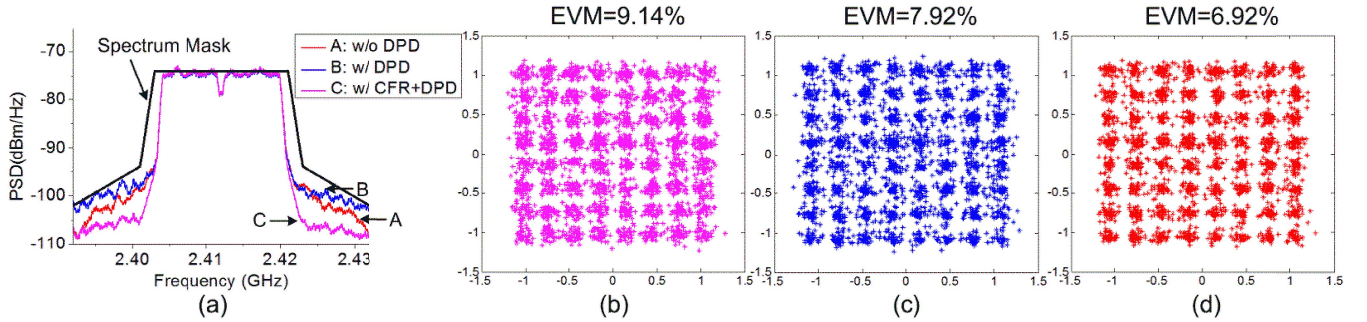

Fig. 7. Power spectra and constellation diagrams after externally-modulated RoF link. (a) Power spectra; (b) constellation diagram without DPD; (c) constellation diagram with DPD; (d) constellation diagram with CFR and DPD.

TABLE II
COMPARISON IN ACPR AND EVM FOR EXTERNALLY-MODULATED ROF LINKS

Case	ACPR (in dBc) (LSB/USB)	EVM
w/o DPD	-28.93/-28.95	9.14%
w/ DPD	-25.28/-26.21	7.92%
w/ CFR+DPD	-31.46/-32.26	6.92%

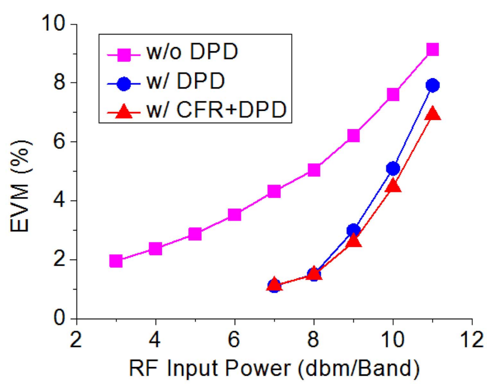

Fig. 8. EVM versus RF input power for externally-modulated RoF link.

is observed at both USB and LSB for the combination of CFR and DPD. The use of the CFR and DPD reduces EVM from 9.14% to 6.92%, the bit error rate (BER) is also reduced from 2.95% to 0.28%.

Second, EVMs as a function of different CR were analyzed for different RF input Power (8 dBm, 9 dBm, 10 dBm, 11 dBm). Similar results to the directly-modulated RoF link were found. For each RF input power, there is a best CR value for optimum performance in EVM. The EVMs at the best CR value are evidently better than the result with only DPD. It is also observed that the best CR value varies for different RF input power (best CR value = 9 dB, 7.5 dB, 6.5 dB, 5.5 dB for RF input power = 8 dBm, 9 dBm, 10 dBm, 11 dBm respectively), indicating lower best CR value for higher RF input power.

Finally, EVM as a function of RF input power was studied. As illustrated in Fig. 8, applying CFR in combination with DPD further improves the performance as compared with the case solely using DPD, especially at high RF input power level. Given the same EVM value, RF input power increases due to the combination of CFR and DPD, indicating an enhancement of RF power transmit efficiency.

V. CONCLUSION

We have investigated the use of CFR in combination with DPD as a method for increasing performance in both directly-modulated and externally-modulated RoF links. With the combination of CFR and DPD, the output EVM and ACPR are improved as compared with the case solely using DPD. RF input power applied to RoF links increases while maintaining the same EVM level, indicating an enhancement of RF power transmit efficiency. In addition, the results also show that the CFR is more effective for directly-modulated RoF links than for externally-modulated RoF links.

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