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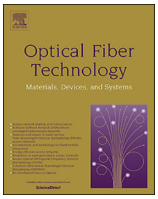

# Blind compensation technique for nonlinear distortions in RoF-based mobile fronthaul network by using EML

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A B S T R A C T

We propose a blind compensation technique to mitigate the waveform distortions caused by the nonlinear transfer function of the electro-absorption modulated laser (EML) in the radio-over-fiber (RoF) system. The proposed technique automatically adjusts its coefficients by using the magnitude of the waveform distortions measured at right outside the signal's bandwidth. By using the proposed technique, we successfully demonstrate the transmission of twelve 198-MHz filtered-orthogonal-frequency-division-multiplexed (f-OFDM) signals modulated in 256 quadrature amplitude modulation (QAM) format in the RoF–based mobile fronthaul network (MFN) implemented by using EML.

## 1. Introduction

Recently, there have been many attempts to realize the mobile fronthaul networks (MFNs) of the 5th generation (5G) wireless system cost-effectively by using the radio-over-fiber (RoF) technology [1–5]. This is because, by using this technology, we can not only reduce the enormous bandwidth required for the transmission of the 5G signals significantly but also minimize the extra latency incurred by the format conversions between the wireless and digital interface signals such as the Common Public Radio Interface (CPRI) [6]. However, this analog transmission technology is inherently more sensitive to the noises and distortions than its digital counterpart. Thus, although we can reduce the bandwidth requirement significantly by using the RoF technology, it is still challenging to transport the wireless signals modulated in a high-level format such as 256-quadrature amplitude modulation (QAM), which is expected to be widely used in the 5G system. For example, the carrier-to-noise-and-distortion-ratio (CNDR) should be higher than 29 dB to transport the orthogonal-frequency-division-multiplexed (OFDM) signals modulated in 256-QAM format in the RoF-based MFN [7]. To achieve such high CNDR, it is desirable to utilize a highly linear optical transmitter such as a directly modulated laser (DML). However, in this case, the CNDR can be seriously limited by the composite second-order (CSO) distortions caused by the interplay between the DML's adiabatic chirp and fiber's chromatic dispersion [3,4]. We can avoid this problem by using an electro-absorption modulated laser (EML), since it has no adiabatic chirp [5]. However, in this case, the CNDR can be degraded by the waveform distortions caused by the nonlinear transfer function of EML. To mitigate this problem, various compensation techniques have been studied for the use in the analog cable television (CATV) systems, including the pre-distortion and post-compensation techniques [8–11]. However, these techniques have utilized the pilot tones or training signals, which could limit the system's dynamic range and/or increase the complexity [8–11].

In this letter, we propose a blind compensation technique for the waveform distortions caused by the nonlinear transfer function of EML. This technique monitors the magnitude of the nonlinear distortions at the frequencies right outside of the signal's bandwidth, and adjusts the compensator coefficients by using this magnitude as a cost function of the steepest descent algorithm. Thus, the proposed technique does not require the use of any pilot tones or training signals. By using the proposed technique, we demonstrate the transmission of the 5G wireless signals modulated in 256 QAM format in the RoF-based MFN implemented by using EMLs.

## 2. Operating principle

When the RoF system is implemented by using an EML transmitter, its performance is typically limited by the 2nd- and 3rd-order nonlinear distortions caused by the nonlinear transfer function of the EML [11,12]. Thus, we can effectively mitigate these distortions by using a compensator having the nonlinear transfer function of the 3rd-order polynomial. For example, we can recover the driving signal, $d(n)$ from the received signal, $r(n)$, as

$$d(n) = r(n) - a_2 r^2(n) - a_3 r^3(n) \tag{1}$$

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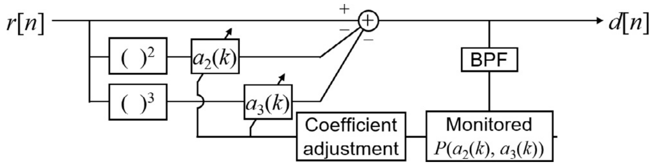

**Fig. 1.** Block diagram of the proposed blind compensation technique (BPF: bandpass filter).

where $a_i$ is the $i$th-order coefficient of the nonlinear transfer function. These coefficients (i.e., $a_2$ and $a_3$) are usually optimized by using the magnitude of the nonlinear distortions generated by the pilot tones or training signals at the output of the optical transmitter [11,12]. However, in the case of using the pilot tones, the performance of the RoF system could be deteriorated by the beat components between the pilot tones and wireless signals. Also, in the case of using the training signals, a complicated processing is required for the demodulation of the training signals. To avoid these problems, we propose to optimize these coefficients by using the magnitude of the nonlinear distortions at the frequencies outside of the signal's bandwidth. Fig. 1 shows the block diagram of the proposed technique. We first generate the 2nd- and 3rd-order nonlinear distortion components by using the received signal, multiply by $a_2(k)$ and $a_3(k)$, and then subtract them from the received signal. Here, $a_i(k)$ represents the estimated optimal value of $a_i$ at the $k$th iteration step. We monitor the magnitude of the nonlinear distortions at right outside of the signal's bandwidth and use it to adjust $a_i(k)$ by using the steepest descent algorithm, as

$$\begin{bmatrix} a_2(k+1) \\ a_3(k+1) \end{bmatrix} = \begin{bmatrix} a_2(k) \\ a_3(k) \end{bmatrix} - \begin{bmatrix} \mu_2 \\ \mu_3 \end{bmatrix} \nabla P(a_2(k), a_3(k)) \tag{2}$$

where the $\mu_i$ is the step size for the $i$th-order coefficient and $\nabla P(a_2(k), a_3(k))$ is the gradient of the magnitude of nonlinear distortions. At each step, we estimate the gradient by calculating the difference between the magnitudes of the nonlinear distortions measured at the $(k-1)$th and $k$th steps. This process leads $(a_2(k), a_3(k))$ to their optimal values of $(a_2, a_3)$. We also note that it is possible to increase the convergence speed of the proposed algorithm by using multiple (or variable) step sizes [13].

## 3. Experiment and results

We evaluated the performance of the proposed technique in the RoF-based MFN of the 5G system implemented by using an EML. Fig. 2 shows the experimental setup. In this evaluation, we assumed that the RoF-based MFN should be capable of transporting twelve 198-MHz filtered OFDM (f-OFDM) signals in 256 QAM format for the use in the 5G system. Thus, we first generated an OFDM signal by taking 4096 inverse fast Fourier transform of 2750 data subcarriers in 256 QAM format and 550 pilot subcarriers in quadrature phase shift keying (QPSK) format. The cyclic prefix and subcarrier spacing of this OFDM signal were set to be 1.17 µs and 60 kHz, respectively. To obtain the f-OFDM signal, we applied an ideal low-pass filter truncated by 2048-tap Hamming window (passband: 199 MHz). We then generated twelve of such 198-MHz f-OFDM signals modulated in 256 QAM format and multiplexed them in the frequency domain. The carrier frequency of these signals was set to be at 200 + 200 × $i$ MHz, where $i$ is channel index in the range of 1–12. We uploaded these signals to the arbitrary waveform generator (AWG). The output signal of this AWG was then fed to the EML. The laser and modulator sections of this EML were biased at 70 mA and −1 V, respectively. Under these conditions, its output power and operating wavelength were measured to be 2 dBm and 1551 nm, respectively. We boosted up the output power of this EML to 7 dBm by using an erbium-doped fiber amplifier (EDFA). This was needed to achieve the required error-vector magnitude (EVM) performances for the signals modulated in 256 QAM format. We transmitted this amplified output signal of the EML through 20 km of the standard single-mode fiber (SSMF) and detected it by using a PIN-FET receiver. The optical power incident on this receiver was set to be −2 dBm. Fig. 3 shows the measured amplitude histograms and RF spectra of the received signal after setting the root-mean-square optical modulation index ($\mathrm{OMI_{rms}}$) to be either (a) 9.1% or (b) 21.5%. When we utilized a large $\mathrm{OMI_{rms}}$, the nonlinear distortion components were clearly observed at outside of the signal's bandwidth. We digitized the received signal by using a digital sampling oscilloscope (DSO) at 40 Gsample/s, and applied the proposed compensation technique. For this purpose, we first obtained the RF spectrum of the received signal (from the DSO) by using the Welch's method and then measured the magnitude of the received signal in the frequency range of 230–270 MHz. (In a practical system, this magnitude could be measured simply by using an RF power meter and a bandpass filter.) We continuously updated the 2nd- and 3rd-order coefficients (i.e., $a_2(k)$ and $a_3(k)$) of the compensator by using this measured magnitude. It should be noted that the proposed technique monitored the magnitude of the received signal in the low-frequency range (thus, there is no need to utilize the high bandwidth to monitor the nonlinear components). Fig. 4 shows the measured trajectory of $(a_2(k), a_3(k))$ in comparison with the EVM values of channel 1 estimated by sweeping $a_2$ and $a_3$ (without using the proposed compensation technique). In this measurement, we set the $\mathrm{OMI_{rms}}$ of the 12 f-OFDM signals to be 21.5% (since the magnitude of the waveform

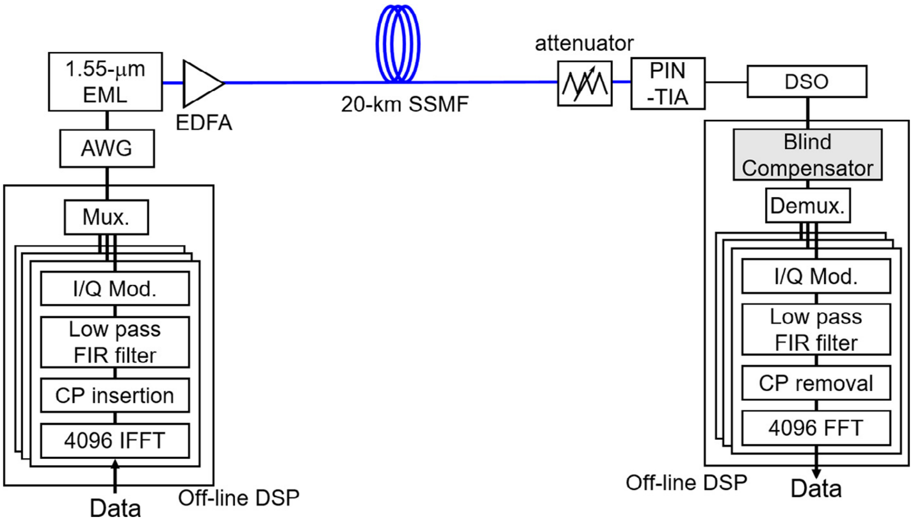

**Fig. 2.** Experimental setup (FIR: finite impulse response).

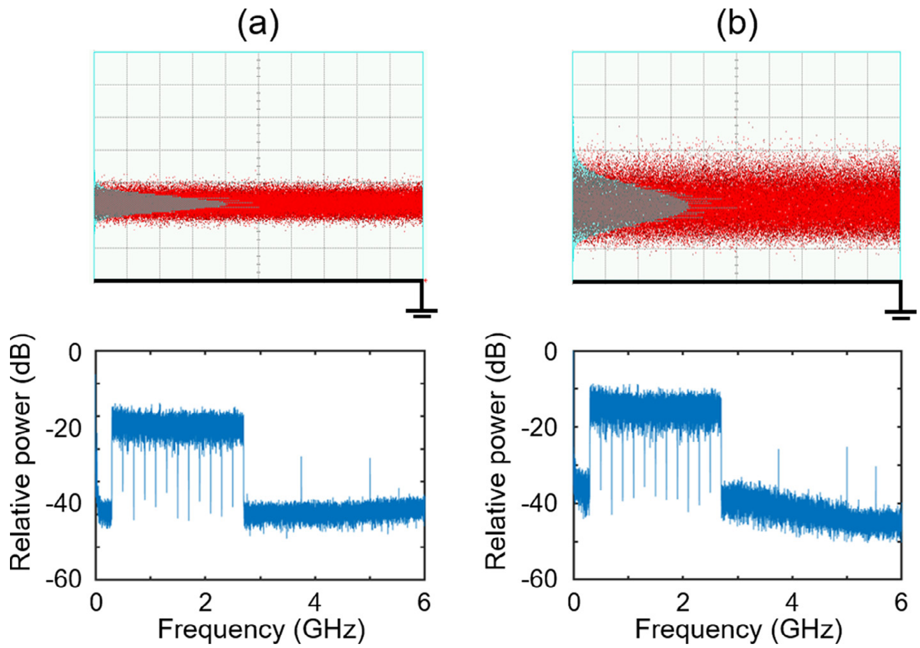

**Fig. 3.** Amplitude histograms and RF spectra of the received signal (a) when the $\mathrm{OMI_{rms}}$ were set to be (a) 9.1% and (b) 21.5%.

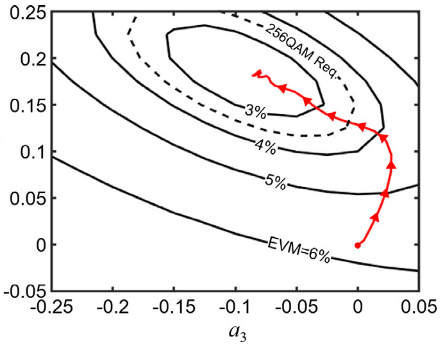

**Fig. 4.** Measured trajectory of ($a_2(k)$, $a_3(k)$) in comparison with the EVM values of channel 1 estimated by sweeping $a_2$ and $a_3$.

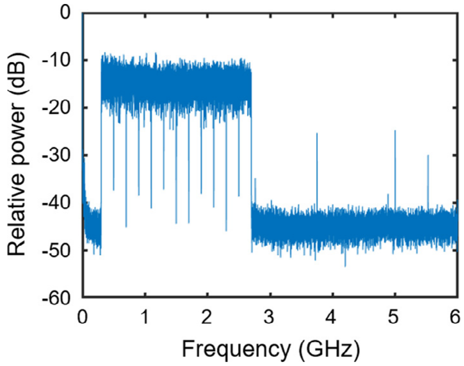

**Fig. 5.** RF spectrum of the received signal with proposed technique when the $\mathrm{OMI_{rms}}$ was set to be 21.5%.

distortions caused by the nonlinear transfer function of EML was measured to be sufficiently large under this condition). The result showed that ($a_2(k)$, $a_3(k)$) could be converged to the optimum values of ($a_2$, $a_3$) within only 18 steps when we set $\mu_2$ and $\mu_3$ to be 0.01 and 0.12, respectively. By using these optimum values, we could suppress the nonlinear distortions completely as shown in Fig. 5. The RF spectrum in Fig. 5 also showed that the frequency response of the RoF system was quite uniform within its bandwidth (~3 GHz). Thus, we assumed that the transfer function of this RoF system could be modeled as the 3rd-order memoryless polynomial.

Fig. 6(a) shows the measured EVM performance of channel 1 as a function of the $\mathrm{OMI_{rms}}$ of the 12 f-OFDM signals after the transmission over 20 km of SSMF. When we utilized the proposed compensation technique, the optimum value of $\mathrm{OMI_{rms}}$ was increased from 9.1% to 21.5% (which was equivalent to the 7.5-dB increase in the power of the driving signal applied to the EML). As a result, the EVM performance of channel 1 was improved from 3.8% to 2.2% (which was equivalent to the CNR improvement of 4.7 dB). We noted that, due to the quantization noises of the AWG and DSO used in this experiment, it was not possible to improve the EVM performances better than 2.2%. Fig. 6(b) shows the EVM performances of all 12 channels measured after the 20-km long SSMF transmission. As shown in this figure, by using the proposed compensation technique, we could satisfy the EVM requirement of 256 QAM format for all 12 channels.

## 4. Summary

We have proposed and demonstrated a blind compensation technique for mitigating the nonlinear distortions caused by the EML transmitter in the RoF-based MFN. In this technique, we monitored the magnitude of the waveform distortions at the frequencies right outside of the signal's bandwidth, and adjusted the coefficients of the proposed compensator by using this magnitude as a cost function of the steepest descent algorithm. Thus, unlike the previously reported compensation techniques for such nonlinear distortions, the proposed technique could operate totally blindly. We evaluated the performances of the proposed compensation technique in the RoF-based MFN implemented by using EMLs. In this evaluation, we assumed that the MFN of the 5G system should be capable of transporting twelve 198-MHz f-OFDM signals modulated in 256 QAM format. These f-OFDM signals were placed at 300–2600 MHz. Thus, we measured the magnitude of the nonlinear distortions in the range of 230–270 MHz at the receiver, and utilized it to update the coefficients of the compensator (i.e., $a_2(k)$ and $a_3(k)$). The proposed compensation technique could adjust these coefficients to minimize the EVM performance of the f-OFDM signals within only 18 iterations. As a result, we could increase the optimum value of $\mathrm{OMI_{rms}}$ by more than a factor of two. The results also showed that, by using the proposed technique, we could satisfy the EVM requirement of the 256-

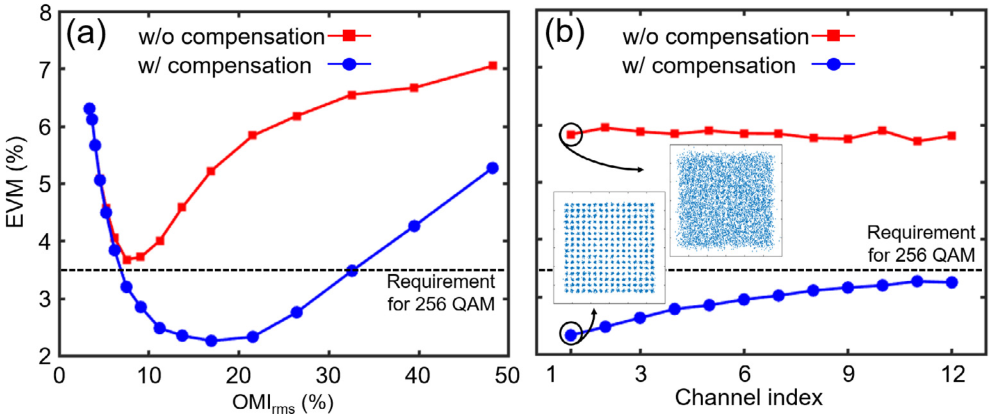

**Fig. 6.** The measured (a) EVM performances of channel 1 as a function of OMI$_{rms}$ and (b) EVM performances of all 12 channels when OMI$_{rms}$ was 21.5%.

QAM format for all 12 channels in the RoF-based MFN implemented by using an EML transmitter. In this experiment, we have demonstrated the effectiveness of the proposed technique by using the f-OFDM signals. However, there should be no problem in applying the proposed technique to other OFDM-based signals such as the OFDM and filter-band multi-carrier (FBMC) signals.

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