# External Modulator Linearization Techniques for High Performance Radio over Fiber Transmission Systems

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**ABSTRACT**
Some of the most promising transmitter linearization techniques for high performance radio over fiber systems are reviewed and compared through simulation tests. Comparison is focused on Mach-Zehnder modulator (MZM) operated at low bias; MZM conventionally biased at quadrature, driven with low modulation depth and cascaded with a notch optical filter; optical single sideband and double sideband plus carrier (SSB / DSB + C); and carrier suppressed plus carrier (CS+C) methods. These transmitters are evaluated through carrier to interference ratio, optical insertion losses, and RF power penalty. The robustness to deviation from ideal transmitter settings is also assessed.
**Keywords**: Mach-Zehnder modulator (MZM), radio over fiber (RoF), sub-carrier multiplexing (SCM), transmitter linearization.

## 1. INTRODUCTION

The consumer demand for broadband wireless services is leading to the necessity for seamless interconnection of wireless and optical systems. Radio over fiber (RoF) technique, associated to subcarrier multiplexing (SCM), offers ultra-high capacity by transmission of different radio channels in each optical carrier. High performance SCM RoF systems are enabled by external modulation, due to reduced relative intensity noise and chirp, and high modulation bandwidth [1]. Nevertheless, such systems are still penalized by the non-linear transmittance response inherent to most modulation schemes. The transmitter non-linearity generates spurious spectral components, leading to intermodulation distortion (IMD) in the detected signals. In most RoF systems, third order IMD (IMD3) is the most determining cause of distortion, since second order IMD can be mitigated by sub-octave spectral occupation or frequency mapping of the channels to transmit [2].

To overcome the limitations caused by modulation non-linearities, several linearization techniques for RoF transmitters have been proposed. Biasing a Mach-Zehnder modulator (MZM) towards minimum transmission – low bias – has been proposed in [3], to enable the use of a low modulation depth while retrieving a low carrier suppression ratio (CSR). The CSR measures the ratio between the optical carrier power and the RoF spectral components: a high CSR penalizes the receiver sensitivity in systems employing direct detection. In [4], the use of low modulation depth together with filtering of the optical carrier was proposed to reduce the transmitter nonlinear response without penalizing the CSR. Complete removal of the optical carrier and non-linear terms lying in its vicinity has been proposed in [5] to improve the IMD3 results; an optical carrier is then added through an interferometric structure. Recently, we have proposed a highly linear transmitter[2][6], which employs a commercially available integrated dual MZM (dMZM) to generate an optical carrier suppressed signal without even order sidebands and couple an optical carrier, leading to reduced IMD3 after direct detection.

In this paper, we present a comparison of the several linearization techniques referred above under similar circumstances. The transmitters are compared in terms of complexity, optical and radio frequency (RF) power losses, and their linearity is accessed by means of electrical carrier interference ratio (CIR). The transmitters' robustness to bias drifts, caused by aging or temperature, for example, is also assessed.

## 2. RADIO-OVER-FIBER TRANSMITTERS

Fig. 1 schematically depicts the transmitters under study. The simplest scheme (Fig. 1a), known as *low biased MZM* [3], a MZM operated with low modulation depth is biased towards minimum transmission. Biasing the MZM close to minimum generates an optical signal with improved linearity, when compared to conventional quadrature biased MZM, while retrieving a low CSR [2]. Such technique is only appropriate for generation of optical double sideband signals (DSB).

Fig. 1b illustrates a technique that employs low modulation depth to enhance the transmitter linearity in combination with attenuation of the optical carrier to reduce the CSR [4]. The carrier attenuation is achieved by a notch optical filter with controlled transmittance; therefore, this requires tuning of the optical filter and the optical CW source. Driving the lower arm of the MZM with the inverse of the SCM signal -$m(t)$ or its Hilbert transform $m_H(t)$, results in DSB or single sideband (SSB) optical signal spectra; thus, this scheme is denominated *DSB + filter* or *SSB + filter* hereafter, accordingly.

In Fig. 1c an interferometric scheme is employed to improve the MZM linearity. In the upper arm a notch optical filter ideally with zero transmittance suppresses the optical carrier of an optical DSB or SSB signal and non-linear terms lying in its vicinity. At the output, the resultant signal is coupled to an undistorted optical carrier, which was attenuated in the lower arm. This scheme is more complex than others, since the interferometer is not commercially available and is commonly assembled with discrete components [5] and the filter must be tuned with the optical carrier. Hereafter, this transmitter is denominated *DSB + C* or *SSB + C*.

Finally, in Fig. 1d the SCM signal drives the minimum biased upper MZM of an integrated x-cut dMZM [7], to generate a carrier suppressed signal. Minimum bias of the MZM eliminates even order optical distortion components, leading to reduced IMD3 [2]. The in-phase optical carrier coupled by the lower dMZM arm enables direct detection; the lower MZM bias allows the control of the added optical carrier power. This method, suitable only for DSB optical signals, is known as *CS + C*.

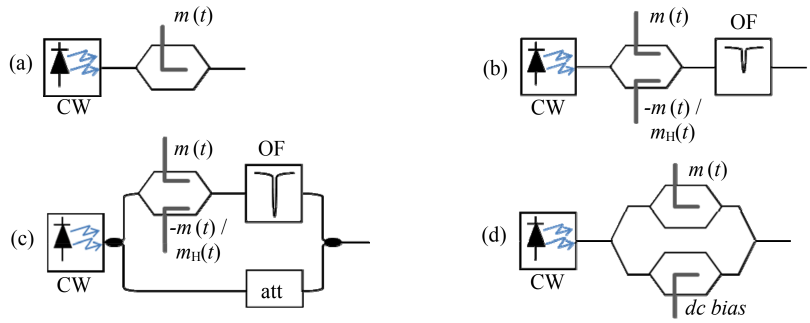


*Fig. 1. Investigated radio-over-fiber transmitters. m(t): SCM signal; CW: continuous wave. (a) low biased MZM; (b) DSB / SSB + filter; (c) DSB / SSB + C; (d) CS + C.*

The setup of Fig. 2 is employed to assess the performance of the transmitters under study. The optical modulators are driven by a SCM signal composed of two electrical tones at $f_1$ and $f_2$. The transmitters are compared in terms of modulation losses, measured as the attenuation suffered by the optical carrier ($P_{CW} - P_{mod}$) in absence of RF modulation, relatively to a common MZM biased at maximum; received RF power at the fundamental tones for constant 0 dBm optical power at the photo-detector input; and electrical CIR, measured as the power ratio between the fundamental tones and the IMD3 components at $2{\cdot}f_1 - f_2$ and $2{\cdot}f_2 - f_1$.

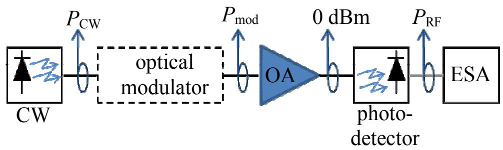


*Fig. 2. Simulation scheme. OA – optical amplifier; ESA – electrical spectrum analyser.*

The linearity of the transmitters can be adjusted at the expenses of higher modulation insertion losses; such dependence is characterized in Fig. 3a, by CIR plotted as a function of the additional modulation insertion losses relative to the reference. For this test, the modulation insertion losses are varied by adjustment of the optical filter attenuation, for *DSB / SSB + filter*, or of the transmitters' bias, for the remaining schemes. For each insertion loss value, the modulation depth is adjusted to maintain a constant RF power after the photo-detector of -55 dBm, for each fundamental tone. Note that other authors usually characterize linearity as a function of the modulation losses while keeping constant CSR; however, this overview includes SSB and DSB formats, which do not present similar detected RF power for the same CSR. Therefore, it is more appropriate to consider constant receiver sensitivity.

The *low biased MZM* with 3 dB of modulation losses is a common MZM biased at quadrature. From Fig. 3a, as the modulator bias approaches transmission minimum, the insertion losses increase and so does the linearity. Linearity improvement is due to reduction of the required modulation depth for constant RF power after detection, as the transmittance characteristic of the MZM becomes more linear when biased close to minimum.

The modulation losses for the *DSB + filter* and *SSB + filter* techniques are controlled by the notch optical filter attenuation at the optical carrier wavelength. A 1 dB insertion loss is considered for the optical filter; therefore the minimum losses of these transmitters are 4 dB, when compared to the reference, as observable in Fig. 3a. For increasing attenuation of the optical carrier, improved CIR is retrieved; however, for the DSB format the results are inferior to those obtained by *low biased MZM* since the former recurs only to reduction of modulation depth, while the later also benefits from biasing the MZM towards minimum. Regarding the SSB format, an optimum insertion loss value is observed, since for this format there is a modulation depth for which the IMD3 contributions approximately cancel; this effect is conceptually similar to that described in [5] for *SSB + C*.

The insertion losses of the *DSB + C* and *SSB + C* transmitters are controlled by the attenuation of the optical carrier at the lower arm. The minimum insertion loss for these techniques is 10 dB, when compared to the reference, as illustrated in Fig. 3a; such value includes the interferometer contribution of 6 dB, 3 dB from the MZM quadrature bias, and 1 dB of optical filter insertion loss. For the DSB format, CIR increases approximately linearly with modulation loss; however, the results are inferior to any other technique. On the other hand, SSB format presents an optimum insertion loss value, similarly to *SSB + filter* [5]. *SSB + C* requires an inferior modulation loss for optimum operation compared to *SSB + filter*; however, the tolerance to deviations from optimum modulation loss is higher for the *SSB + filter*.

In the case of *CS + C*, the minimum additional losses of the transmitter are 6 dB, when compared to the reference. These are controlled by the attenuation of the optical carrier in the lower dMZM arm [2]. Fig. 3a illustrates the similar dependence of the *CS + C* transmitter linearity with losses and that of the low biased MZM.

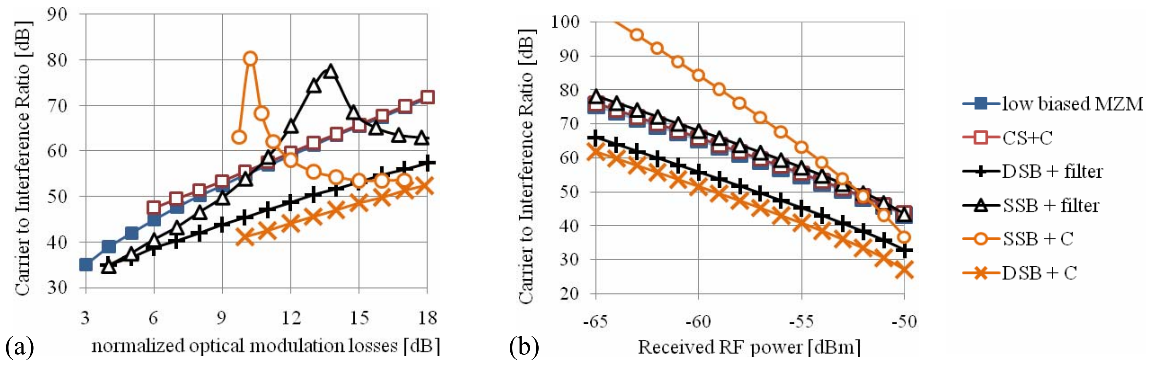


*Fig. 3. Characterization of modulators linearity as a function of: (a) optical modulation losses for fixed -55 dBm RF power after detection and (b) received RF power for constant normalized modulation losses of 10 dB.*

The transmitters' linearity is also determined by the modulation depth, which is controlled through the power of the RF signal driving each modulator. To test the several transmitters under similar conditions, the modulation insertion losses are adjusted to 10 dB when compared to the reference, since this is the minimum modulation loss allowed by all transmitters, and has been previously considered in other works [2][3]. Given that different biases are considered for the several transmitters, the absolute modulation depth does not reflect the relation between the detected RF power and the optical power at photo-detector input. Therefore, Fig. 3b illustrates the CIR as a function of the received RF power. For such purpose, the transmitters' modulation depths are adjusted for variable received RF power, when the optical power at the photo-detector is kept constant at 0 dBm.

From Fig. 3b, all the transmitters present improved linearity for low received RF power (i.e. low modulation depths) and similar dependence with the increase of the modulation depth, with the exception of the *SSB + C* transmitter, whose curve presents a higher slope than others. In terms of absolute results, *DSB + C* presents the worse CIR, followed by *DSB + filter*. On the other side, *SSB + C* presents the highest linearity for low received power; for high received power values, it is surpassed by *CS + C* and *low biased MZM*.

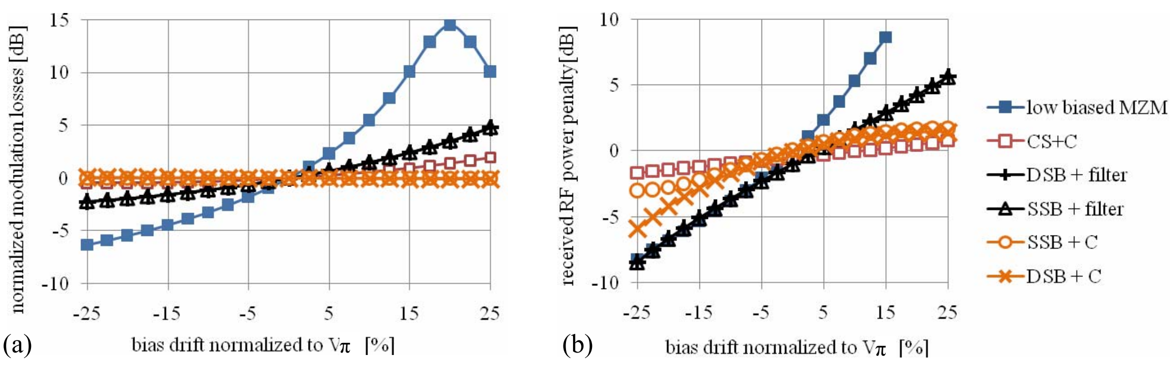


*Fig. 4. Transmitters robustness to bias drifts characterized through (a) normalized modulation losses and (b) received RF power.*

The robustness of the transmitters to bias drifts caused by temperature or aging, for example, is an important asset. If a transmitter presents a high dependence with bias drifts, severe RF power penalties may occur, unless active bias control is used [8]. Fig. 4 characterizes (a) the dependence of the modulation insertion losses and (b) the received RF power penalty of the several transmitters, on the bias voltage drifts normalized to the MZM switching voltages ($V_\pi$). In absence of bias drift, the losses of the modulators were adjusted to 10 dB relatively to the reference; and the modulation depth was adjusted to retrieve -55 dBm after direct detection, when the optical power at the photo-detector input is 0 dBm. For the *CS + C* transmitter, it was considered that the two embedded MZM are affected simultaneously by the bias drift and the optimum bias configuration of [2] is employed.

The *low biased MZM* presents the highest dependence of the modulation losses and detected RF power on the bias drift. This dependence arises from biasing the MZM close to minimum and has been previously reported [8]. The *DSB + filter* and *SSB + filter* transmitters also present non-negligible variations of the modulator losses and RF detected power. *SSB + C* and *DSB + C* verify insignificant dependence of the modulation losses with the bias drift, since the optical carrier travels in the lower arm of the interferometer, which is not affected by the drifts in the MZM. Nevertheless, the power of optical RF tones is affected by the bias drift; therefore, the detected RF signal power suffers penalties due to drift. *CS + C* transmitter presents the most promising results regarding robustness to bias drifts, as already demonstrated in [2], since the two internal MZM are biased to mutually compensate bias drifts.

## 3. CONCLUSIONS

Several techniques for linearization of externally modulated RoF transmitters have been reviewed and compared through simulation tests. *Low biased MZM* is a simple and wavelength independent technique with the ability to reach very high linearity; however, is only appropriate for DSB format, and may require active bias control due to its dependence on bias drifts. Using low modulation depths and simultaneously attenuating the optical carrier at the MZM (*DSB / SSB + filter*) is moderately dependent on the bias drift; however it is wavelength dependent and high linearity can only be achieved for the SSB format. *SSB / DSB + C* techniques require the most complex transmitter, which is wavelength dependent and requires an interferometric structure built with discrete components; for the DSB format this transmitter is not advised, since the linearity is the lowest of all transmitters; for the SSB format this technique may be preferred to *SSB + filter* due to its lower dependence on the modulator bias drift. *CS + C* modulator is wavelength independent and presents non-linearity improvements very similar to *low biased MZM* for DSB format, but surpasses it due to its outstanding independence on bias drifts.

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