Direct-Detection Single-Sideband Systems: Performance Comparison and Practical Implementation Penalties

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ABSTRACT
There is a growing research interest towards high-capacity communication systems for inter data-center (~80 km) communications. While coherent systems are a mature and high-performance technology, their cost is still very high compared to simpler direct-detection solutions. Recently, advanced digital signal processing (DSP) techniques, such as Single Side-Band (SSB) transmission and Kramers-Kronig (KK) receivers have been proposed to increase both spectral efficiency and reach of such direct-detection systems. Apart from the DSP techniques, the main drawback of these solutions is the requirement of a strong (i.e. several decibels higher than the signal) carrier added at the transmitter. This solution inevitably decreases the resulting signal-to-noise ratio (OSNR) and potentially increase the impact of fiber Kerr non-linearities. In this contribution, will provide further insights on the practical implementation penalties which arise from the addition of such carrier in the framework of single-sideband DMT solutions. In particular, we will focus on the modulator biasing technique to add such carrier.
Keywords: direct-detection, single-sideband, Kramers-Kronig, intra-datacenter, optical communications.

1. INTRODUCTION

Current network demand for inter data-center connectivity has been growing at very high rate. Currently, inter data-center links are based on simple intensity-modulation (IM) direct-detection (DD) transceivers. However, to further increase the net data rate these solutions would require unreasonably high symbol rates. Therefore, there is a growing research interest towards solutions with higher spectral efficiencies.

Coherent modulation and detection coupled with polarization-multiplexing (PM) is widely deployed in long-haul links and offers the highest spectral efficiency. Yet, a full coherent transceiver bears a high complexity which may not be feasible to implement for such short-reach systems. Therefore, current research is going towards *hybrid* systems, which try to achieve higher spectral efficiencies than IM/DD systems at a lower cost than coherent transceivers.

There are two main techniques to increase spectral efficiency that have been investigated: non-coherent polarization multiplexing and self-coherent modulation. Polarization multiplexing, which potentially doubles spectral efficiency, can be realized without a coherent transceiver using either a Stokes-vector receiver [1] or an external polarization controller [2]. However, these solutions bear the additional cost of a complex receiver structure and a MIMO DSP to compensate for residual polarization crosstalk. On the other end, self-coherent systems increase spectral efficiency by adding a carrier (which acts like a local oscillator) at the transmitter, which “emulates” coherent reception, while employing a standard single-photodiode receiver. This operation effectively “wastes” transmit power, strongly reducing the optical signal-to-noise ratio (OSNR) sensitivity. However, for short distances, this has a limited impact on system performance.

Another important issue of intra data-center interconnection is chromatic dispersion. While shorter-reach systems operate in the O-band (~1310 nm), where chromatic dispersion of standard single-mode fiber (SSMF) is negligible, at distances above 40 km optical amplification is required, which implies C-band (~1550 nm) transmission. Legacy solutions, such as dispersion-compensating fiber (DCF) or G.653 dispersion-shifted fiber (DS), are not future-proof (especially in terms of coexistence with coherent systems) and must be discarded. A possible solution to this issue is single-sideband (SSB) transmission, which allows receiver-based electrical dispersion compensation with direct-detection, and, at the same time, increase spectral efficiency [3].

2. SELF-COHERENT SINGLE-SIDEBAND TRANSMISSION

2.1 Self-coherent detection

In a self-coherent (or self-homodyne) system, a strong carrier (which acts as local oscillator) is added to the optical signal at the transmitter. At the receiver, composed by a single photodiode, carrier and signal mixes. If we call $s(t)$ the transmit (complex-valued) signal and c the carrier, the signal after photodiode can be written as:

$$i(t) = |s(t)+c|^2 = |s(t)|^2 + |c|^2 + 2\Re\{s(t)c^*\} \tag{1}$$

This operation allows detection of the real part of the transmitted signal, multiplied by the carrier c.

However, it also adds an unwanted term, $|s(t)|^2$, which is called Signal-Signal Beating Interference (SSBI), and it represents the main limitation of the self-coherent scheme. Since this term is (neglecting noise) a deterministic function of the transmitted signal, it can be estimated and removed at the receiver [8]. While this technique is rather simple to implement, its effectiveness is limited. Moreover, it requires a high Carrier-to-Signal Power Ratio (CSPR), defined as the ratio between the power of $s(t)$ and the power of c.

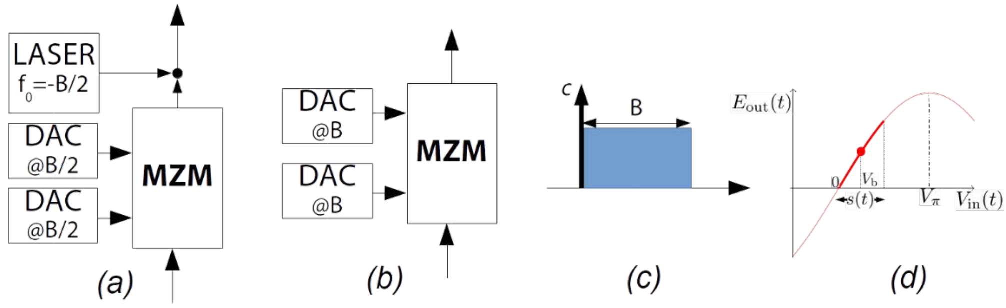


Figure 1. Possible methods to add the carrier for self-coherent single-sideband transmission. In (a) the carrier is added from a second laser, while in (b) the carrier is added by appropriate modulator biasing. In (c) it is shown the spectrum of a SSB signal, while in (d) it is shown the modulator biasing point of solution (b).

2.2 Dual side-band and single-sideband

A self-coherent scheme allows the detection of the real part of the transmit *electric field* (as opposed to intensity for legacy IM/DD schemes). This means that the transmit signal must be real-valued, which corresponds (in the frequency domain) that the negative part of the spectrum is a conjugated copy of the positive part; this is called Dual Side-Band (DSB) spectrum. To perform electronic dispersion compensation (EDC), it is required to detect the *full* electric field (both real and imaginary part). Without it, chromatic dispersion will introduce strong frequency-dependent SNR variations that irreversibly degrade the received signal.

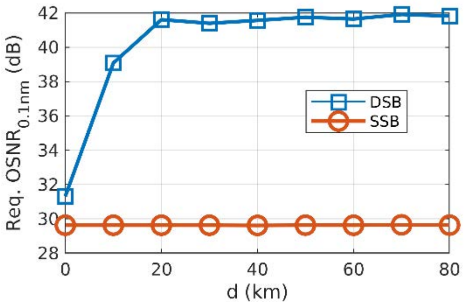


Figure 2. Comparison of SSB and DSB for 100 Gb/s DMT signal [3].

A possible solution would be the use of multi-carrier modulation formats (such as DMT), which allow bit and power loading schemes. However, the effectiveness of these schemes was found to be limited for distances above few kilometers.

The most promising solution to solve this issue is the use of single-sideband (SSB) modulation. This is achieved by adding the carrier c at one edge of the spectrum of $E(t)$. After direct-detection, described by eq. (1), chromatic-dispersion becomes an all-pass (phase-only) filter, which can be electrically compensated without any information loss, similarly to coherent systems.

As an example, Fig. 2 shows a performance comparison of DSB and SSB applied to 100-Gb/s DMT modulation for distances up to 80 km [3]. As seen from the Figure, even at short distances such as 10 km, chromatic dispersion introduces strong penalties which cannot be fully compensated by DMT's adaptive bit-loading.

2.3 Kramers-Kronig receiver scheme

Single-sideband systems are also affected by SSBI. Other than using standard SSBI compensation schemes, the *Kramers-Kronig (KK) receiver* [4], recently proposed in literature, is a novel scheme that offers superior performances. This scheme is based on the Kramers-Kronig relations, which allow exact (without SSBI) detection of an SSB signal, provided that the CSPR is big enough, albeit smaller than standard direct-detection receivers. While this scheme is superior, it requires a received signal that is oversampled at several times the symbol rate, which increase DSP implementation complexity.

The KK receiver has been recently applied to obtain record data-rates with direct detection. In [5], which is one of the first reported experimental results, the authors reported 220-Gb/s single-polarization and single-channel detection and 4 × 240-Gb/s dual-polarization data rates, both after 100 km SSMF. In [6], the authors transmitted an 80-GBd 16-QAM signal over 300 km, achieving a net data rate of 267-Gb/s. In [7], authors transmitted 8 × 200-Gb/s 16-QAM signals over 1200km of SSMF, showing that the KK receiver is also suitable for metro networking scenarios.

3. IMPLEMENTATION OF A SINGLE-SIDEBAND TRANSMITTER

Regardless of the detection scheme, a single-sideband transmitter needs to add the carrier c with a given CSPR. There are several methods to achieve this. The simplest method would be digital addition at the DAC. However, given the limited effective-number-of-bits (ENoB) of high-speed DACs, this method can be used only to achieve small values of CSPR.

The two most common methods to add a carrier with arbitrary CSPRs are shown in Fig. 1(a) and 1(b). In Fig. 1(a), carrier is optically added after modulation from a different laser source. This solution requires two DACs with bandwidth $B/2$ (like a coherent transmitter). However, frequency deviation between two lasers must be carefully controlled, which may not be feasible for short-reach applications. Moreover, it requires a carrier phase estimator (CPE) algorithm at the receiver to track the phase difference between the two lasers.

In Fig. 1(b), the carrier is added by biasing the modulator in a point between the null and the quadrature, as shown in Fig. 1(d). This method does not require an additional laser, but it requires two DACs with twice the electrical bandwidth (B). For this paper, we will focus on this second solution.

3.1 Evaluation of the carrier-to-signal power ratio

To apply this method, it is important to relate the biasing point V_b (with respect to the null) with the CSPR. This relation will then be used by biasing control algorithms [9] to automatically track the correct point. To achieve this, some assumptions needs to be made on the signal and the modulator. First, the signal *s(t)* is assumed a Gaussian random process with zero mean and power (variance) σ^2 (a very realistic assumption when using DMT solutions, as done in this paper). Then the modulator is assumed to have a finite extinction ratio of *ER*, a pi-voltage V_π , and V_b is the biasing point (with respect to the null), applied to the In-Phase arm. The result is:

$$\xi \approx \frac{2e^{-\frac{\pi^2\sigma^2}{V_\pi^2}}\left[\sin^2\left(\frac{\pi Vb}{2V_\pi}\right)-\frac{2\sin\left(\frac{\pi V_b}{2V_\pi}\right)}{ER}+\frac{1+\cos^2\left(\frac{\pi V_b}{2V_\pi}\right)}{ER^2}\right]}{\left[1-e^{-\frac{\pi^2\sigma^2}{2V_\pi^2}}\right]\left[2+\cos\left(\frac{\pi V_b}{V_\pi}\right)e^{-\frac{\pi^2\sigma^2}{2V_\pi^2}}+e^{-\frac{\pi^2\sigma^2}{2V_\pi^2}}\right]} \tag{2}$$

As seen from the equation, the CSPR depends on a combination of extinction ratio, biasing point and power of the signal (which is then related to the peak-to-peak voltage). The actual parameters choice will then depend on the specific system scenario.

Table 1. Simulation parameters.

Parameter	Value
FFT size	1024
Bit-rate	120 Gbit/s
DAC sampling rate	64 Gs/s
BER threshold	10^{-3}
DAC 3-dB bandwidth	13 GHz
DAC resolution	6 bit

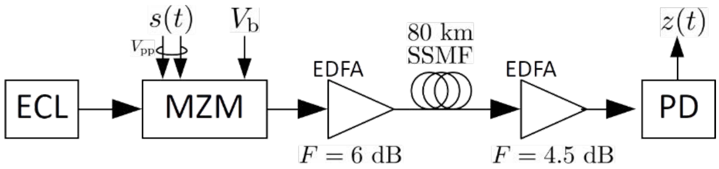
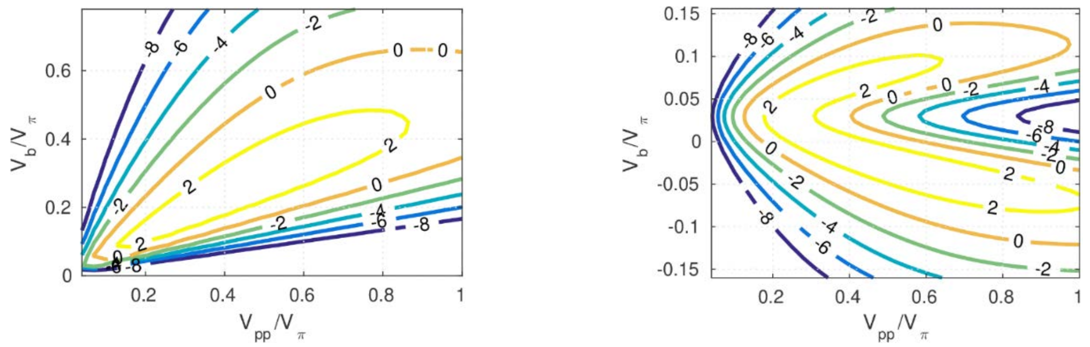


Figure 3. Simulation block diagram.

3.2 Example: optimal parameters choice for SSB-DMT

As an example, we set up a time-domain simulation of a 100-Gb/s SSB-DMT signal, whose parameters (and block scheme) are summarized in Table 1. A block scheme of the simulation is shown in Fig. 3. Light generated from an ECL laser is modulated with an I/Q Mach-Zehnder modulator (MZM). The MZM is fed by the DMT signal *s(t)* and its Hilbert transform to generate an imaginary part. After modulation signal is pre-amplified by an EDFA, transmitted over 80 km of standard single mode fiber (SSMF), amplified and detected with a photodiode. In this scenario, the optimal CSPR was found to be approximately 10 dB [3], which can be obtained with different combinations of signal power and biasing point. However, not all the combinations are optimal, since a small signal power will increase modulator insertion loss, which will reduce the OSNR. Results are shown in Fig. 2. In the Figures, we show the *SNR margin* (in dB) with respect to the BER threshold, set at 10^{-3}. A positive margin means that the system can tolerate a certain amount of extra penalties before reaching the threshold (which corresponds to 0 dB SNR margin). In this example, the system has been designed to have a +3 dB SNR margin with ideal carrier addition, i.e. it can tolerate a maximum penalty of 3 dB due to modulator. In Fig. 2(a) are shown results for an ideal (infinite extinction ratio) modulator. The optimal region corresponds to a linear increase of the biasing point with the increase of the peak-to-peak voltage, as expected. However, to obtain a positive margin, the biasing point needs to be greater than a certain value (around 10% of the pi-voltage). This requires a specific biasing-control algorithm that can track an arbitrary biasing point [9]. Using instead a lower quality modulator, with an extinction ratio of 13 dB, results are rather different, shown in Fig. 2(b). In that case, the optimal CSPR can be obtained by biasing the modulator at the null and tuning the peak-to-peak signal voltage. This is an important result, which allows the use of standard automatic bias controller that can track the null biasing point.



(a) (b)

Figure 4. Contour plot of SNR margin (in dB) as a function of different combinations of DAC peak-to-peak voltage (which is linked to signal power) and modulator biasing point: (a) has been obtained with an ideal modulator with infinite extinction ratio, while (b) has been obtained with a modulator with 13-dB extinction ratio.

4. CONCLUSIONS

In this paper we presented self-coherent single-sideband transmission as an intermediate solution, in terms of cost and spectral efficiency, between legacy intensity-modulation/direct-detection systems and coherent detection. These schemes require a strong carrier added at the transmitter, which can be added by appropriate biasing of a Mach-Zehnder modulator. We presented a formula that can evaluate the carrier-to-signal power ratio as a function of the peak-to-peak voltage of the RF signal and biasing voltage. We showed an example where we optimized parameters for a SSB discrete-multitone transmission.

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