A Novel Modulation Scheme for Noise Reduction in Analog Fiber Optic Links

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A novel balanced modulation and detection scheme for analog fiber optic links is proposed to overcome the limitations in signal-to-noise ratio (SNR) and dynamic range (DR) . In this scheme, the modulating signal is split into positive and negative halves and applied to a pair of laser diodes. Both arms of the link will convey a half-wave rectified version of the signal. At the receiving end the signal is restored via differential detection. Calculation results show that significant improvement in link SNR together with suppression of second-order distortions are achieved.

Introduction

Analog fiber optic links for antenna remoting applications have stringent requirements in terms of signal-to-noise ratio (SNR) and dynamic range [1]. The dynamic range (DR) is bounded by noise for weak signals and by nonlinear distortion for strong signals. Thus DR will specify the minimum detectable and the maximum transmitted signal [2]. It is intuitive that a link with lower noise level and better linearity will yield higher dynamic range. For this reason, noise reduction and linearization techniques are subject of intensive research. In this paper a novel modulation scheme for noise reduction in such links is proposed.

Classical IMDD : Limitations

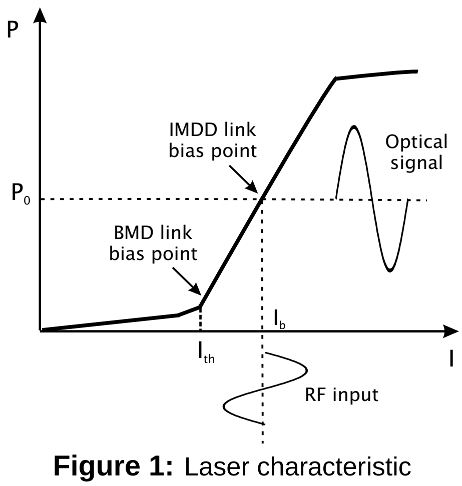


Figure 1: Laser characteristic

Due to its simplicity, intensity modulation followed by direct detection (IMDD) scheme is the universal choice in applications of analog fiber optic links [3]. In such scheme, a laser diode, acting as a light source, is biased at a particular point within the linear part of the laser characteristic (P vs I) curve (Figure 1) in order to avoid clipping of signals with large amplitudes. In case of sinusoidal modulation, the output optical power $P(t)$ is,

$$P(t) = P_0[1 + m\sin(\omega t)], \qquad 0 \leq m \leq 1 \quad (1)$$

where m is the modulation index and ω is the angular frequency of the modulating RF signal. The bias point determines the average output optical power, P_0, and subsequently the average (detected) photocurrent in the receiving end, regardless of the signal strength. As will be clear in the following section, the power of dominant noise sources in analog fiber optic links increases with the average photocurrent. Consequently, weak signals (small modulation index) will suffer from the same noise level as strong signals (large modulation index). This will indeed limit the minimum detectable signal in such links and, accordingly, limit the achievable DR. Thus, it is desirable to modify the classical IMDD scheme in such a way that the noise power scales with the signal strength. In the following section a potential solution to this limitation will be presented.

Balanced modulation and detection (BMD)

A schematic of the novel BMD scheme is presented in Figure 2. The RF signal is applied to a pair of laser diodes (LDs) with common input. When the signal is positive, the lower LD is conducting (and emits light) and a positive half cycle of the sine wave is launched in the lower arm of the optical link. When the signal is negative, the upper LD will conduct and the negative half cycle will be launched in the upper arm but no light is launched in the lower arm. The optical signal in each arm comprises a half-rectified sine wave. At the balanced receiver, the signal will be restored by means of differential detection.

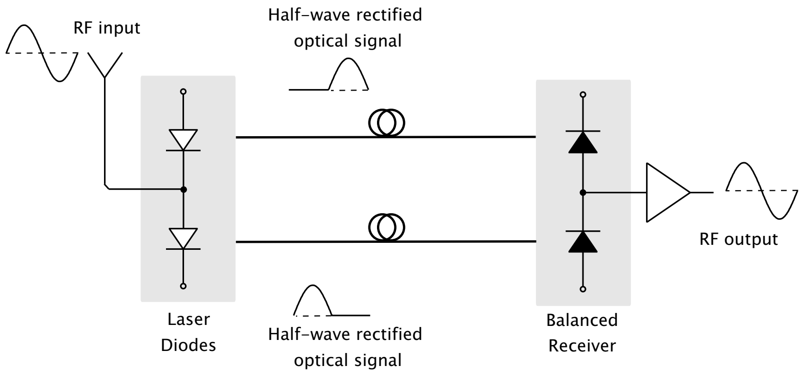
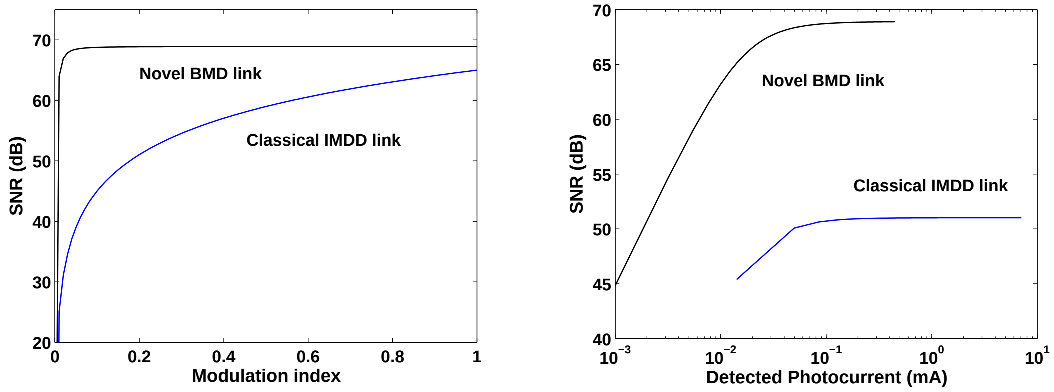


Figure 2: BMD scheme

Splitting the input signal allows both LDs to be biased near the threshold point (I_{th}), which is virtually zero for modern semiconductor lasers. It is easy to show that in this scheme, the average photocurrent in each photodiode is proportional to the average value of the half-rectified signal, $\langle I_{\text{D}} \rangle_{\text{BMD}} = R_{\text{PD}} m P_0 / \pi$, while for the classical IMDD scheme, it is independent of the signal, $\langle I_{\text{D}} \rangle_{\text{IMDD}} = R_{\text{PD}} P_0$, with R_{PD} to be the photodiode responsivity. As mentioned earlier, this average photocurrent is directly related to the noise power in the link. The dominant noise sources in analog optical links are the photodiode shot noise and the laser relative intensity noise (RIN). The current of those noise sources are $\langle {I_{\text{sh}}}^2 \rangle = 2e \langle I_{\text{D}} \rangle B$ and $\langle {I_{\text{RIN}}}^2 \rangle = \frac{1}{2} \langle I_{\text{D}} \rangle^2 10^{\frac{S_{\text{RIN}}}{10}} B$, respectively [3], where e is the electron charge, S_{RIN} is the spectral density of the RIN (in dB/Hz) and B is the single-sided receiver bandwidth. Inserting the expressions of the photocurrent for both schemes into the former equations, one would find that the noise currents for BMD is substantially lower compared to the classical IMDD. Further results regarding the SNR of this scheme will be presented in the following section.

SNR improvement

Various noise sources are taken into account in calculating the SNR for both schemes. Besides shot noise and RIN ($S_{\text{RIN}} = -155$ dB/Hz), thermal noise with spectral density of 8.1×10^{-23} A^2/Hz (corresponds to kT, k is the Boltzmann constant and $T = 290\,\text{K}$) is also included. The bandwidth and photodiode responsivity are taken to be 1 GHz and 0.8 A/W, respectively. The resulting SNR, plotted against the modulation index and the photocurrent, are presented in Figures 3(a) and 3(b), respectively. In the case depicted in Figure 3(a) the modulation index (ie. signal strength) is increased for both schemes, while



(a) (b)

Figure 3: SNR for both modulation schemes, (a) as a function of modulation index (m), with $P_0 = 4$ mW ; (b) as a function of detected photocurrent, with $m = 0.2$

the input optical power, P_0, is kept at 4 mW. Since for BMD the noise power scales with the signal, the SNR saturates much faster than for IMDD. But otherwise, for the whole range of possible modulation indices, BMD is still advantageous over IMDD, with SNR improvement ranging from 3 dB for strong signals up to 40 dB for weak signals. In case of Figure 3(b), P_0 is increased for both schemes, while the m is preserved at the value of 0.2. In this way, the noise power for IMDD increases much faster compared to BMD and results in a difference of about 20 dB in SNR. Hence, from both figures, it can be concluded that BMD significantly improves the link SNR.

Nonlinear distortions

As mentioned earlier, DR is bounded by noise and distortions. Thus, it's of importance to investigate the linearity of BMD to have a careful insight of the dynamic range improvement offered by this scheme. In order to do so, the well-known two tone test [3] is performed. The input current is in a form of

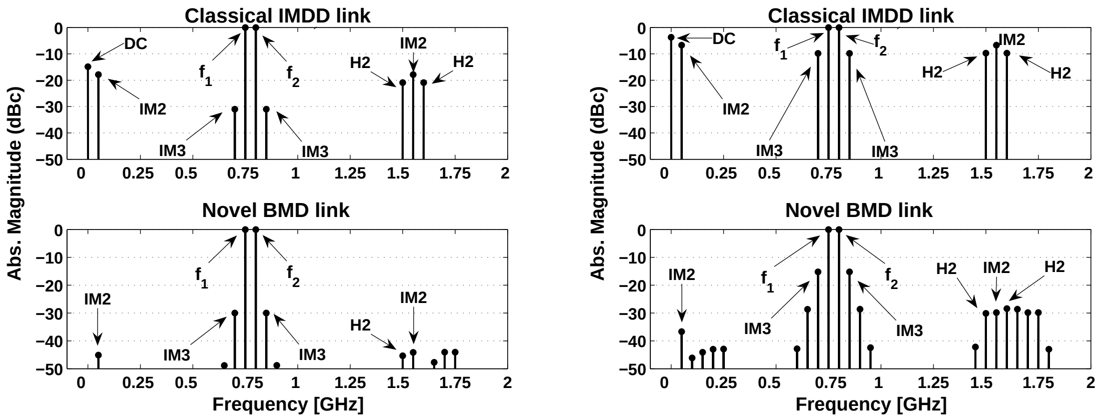
$$I(t) = I_o[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)] \tag{2}$$

with $f_1 = 0.75$ GHz and $f_2 = 0.8$ GHz, respectively. The distortion is assumed to occur due to some nonlinearities in the LD transfer function. A simple third-order nonlinear model has been developed by means of expanding the laser characteristic in Taylor series, $P(t) = c_1(I(t) - I_o) + c_2(I(t) - I_o)^2 + c_3(I(t) - I_o)^3$ [4], with the expansion coefficients c_1, c_2 and c_3 are chosen to be 0.1, 2.5×10^{-4} and -2.5×10^{-6}, respectively. The rectifying process in the BMD scheme is inherently nonlinear where each half-wave rectified signal possesses a broad spectrum. These signals are thus expanded in Fourier series, with only the first six components are included in the calculations. The purpose of doing this is to include the effect of bandwidth limitation in the link processing circuits. The resulting spectrum of the received signal for both schemes are plotted in Figures 4(a) and 4(b), with the modulation index, m, as a parameter. Furthermore, the amplitude of the distortion terms are listed in Table 1. From both figures and the table, it is clear that second-order harmonic (H2) and intermodulation (IM2) in BMD is largely suppressed (up to 25 dB) compared to IMDD. This is of high benefit since often in remote antenna

Distortion Terms	Amplitude (dBc)			
	$m = 0.1$		$m = 1.0$	
	BMD	IMDD	BMD	IMDD
2nd order harmonic (H2)	-42.4	-20.9	-30.2	-9.7
2nd order intermod. (IM2)	-41.7	-17.8	-30.0	-6.7
3rd order intermod. (IM3)	-30.0	-30.9	-15.2	-9.8
Total distortion (0.6 – 1.6 GHz)	-26.66	-14.62	-11.88	-1.95

Table 1: Distortion levels in BMD and IMDD for various modulation index

applications, the frequency range is more than an octave. Hence, second order distortions may fall inside the band, and ultimately limits the spurious-free dynamic range (SFDR). As for the third-order intermodulation (IM3)-limited links, BMD gradually outperformed IMDD as the modulation index increases.



(a) (b)

Figure 4: Distortion levels for various modulation index, (a) $m = 0.1$, (b) $m = 1$

Conclusions

We have shown that analog links employing a novel balanced modulation and detection scheme yield higher SNR and dynamic range compared to the classical IMDD link. Significant noise reduction and suppression of second-order distortion are achieved simultaneously. Further research is ongoing on the effect of imbalance in the BMD scheme.

Acknowledgements

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