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Demonstration of 8-level subcarrier modulation sensitivity improvement in an IM/DD system

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Abstract: We experimentally demonstrate up to 2 dB sensitivity improvement for 8-level subcarrier modulation compared to conventional 8-level subcarrier modulation.

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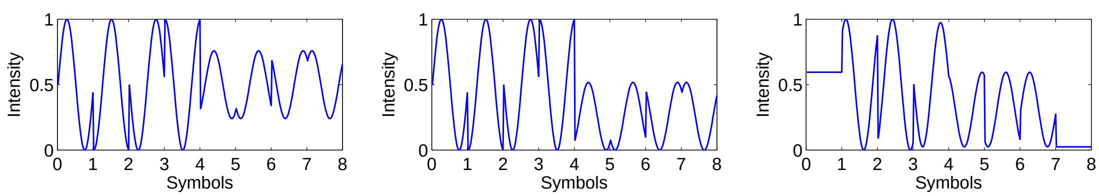
1. Introduction

In the recent years subcarrier modulation (SCM) has attracted significant research attention in the area of optical links with intensity modulation and direct detection (IM/DD), because it enables using more advanced modulation formats, e.g. quadrature amplitude modulation (QAM) in non-coherent systems. Various numbers of subcarriers are used, from one in the single-cycle subcarrier modulation [1–3], to over a thousand subcarriers [4] in discrete multitone modulation (DMT). DMT allows for adaptive bit loading and can provide some benefits in systems with multimode fibers, including polymer fibers [4]. In IM/DD links SCM has a disadvantage since, the sensitivity of this type of modulation is degraded because a DC bias must be added to make the signal non-negative [1]. Sensitivity is a very important consideration in IM/DD links, especially those operating at wavelength of 850 nm where optical amplification is not available. There might be other constraints on the optical power, e.g. operation at eye safe power level in polymer fiber links for consumer applications [5]. A theoretical study of modulation formats for IM/DD links is presented in [2], along with theoretical considerations of the available three dimensional signal space.

In this paper we demonstrate experimentally sensitivity improvement for 8-level subcarrier modulation in an IM/DD link. We show 1 dB improvement bye use of adaptive biasing [6] and 2 dB improvement by use of modulation optimized for the available signal space [7].

2. Improving the sensitivity of subcarrier modulation

In IM/DD systems with directly modulated lasers, any signal modulating the laser must be non-negative to avoid clipping, and the electrical subcarrier has be up-shifted to make it non-negative. The optical intensity, which is modulated, is obviously non-negative. In the simplest case, the subcarrier signal is shifted by the same amount for all symbols, even when for some symbols a lower up-shift would suffice. Consequently, some of the optical power does not carry information, because the modulation depth is lower. An example for star shaped 8-QAM, with constant bias added is illustrated in Fig. 1a, the modulation depth for the symbols 4 to 8 is clearly smaller. Sensitivity can be improved by reduction of the unnecessary optical power, by varying the shift of subcarrier signal



(a) Subcarrier 8-QAM (b) "Adaptively biased" subcarrier 8-QAM (c) Optimized 8-level modulation

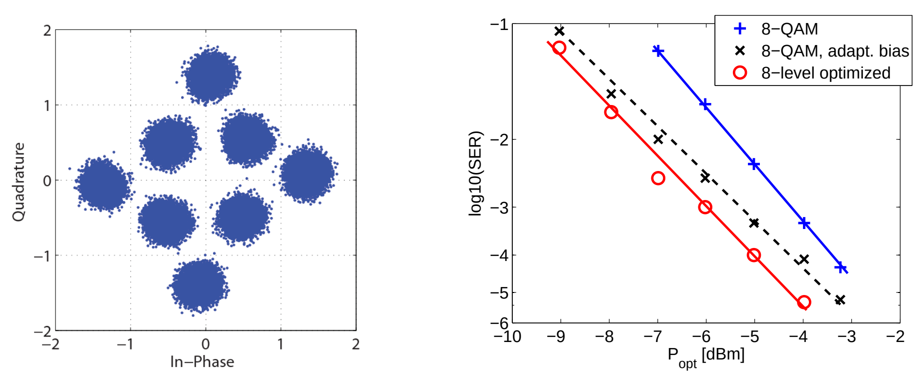
Fig. 1: Examples of different subcarrier modulations.

in each symbol, as shown in the Fig. 1b. This technique is called "adaptive biasing" in [2]. It must not be confused with the laser bias current. It is done by varying the symbol amplitude offset in such a way that after adding the laser bias current in the bias-T, the unmodulated optical power is reduced. Applying this technique to star 8-QAM gives theoretically 1 dB sensitivity improvement [7], compared to regular star 8-QAM. The so-called adaptive bias constitutes an additional degree of freedom in IM/DD systems [2], in addition to the two usual in-phase and quadrature dimensions. The three-dimensional signal space can be defined using the ϕ_1, ϕ_2, and ϕ_3 basis functions in [2]. The first basis function represents the adaptive bias and the remaining two represent the respective cosine and sine components of the subcarrier. The symbols of the adaptively biased 8-level format are defined in terms of (ϕ_1, ϕ_2, ϕ_3), normalized to unit minimum distance, as $\{(1, \pm 1/2, \pm 1/2)$, $((1+\sqrt{3})/\sqrt{2},\ 0, \pm(1+\sqrt{3})/2)$, $((1+\sqrt{3})/\sqrt{2}, \pm(1+\sqrt{3})/2, 0)\}$. The traditional star-shaped 8-QAM can be also defined in this signal space as $\{(1+\sqrt{3})/\sqrt{2}, \pm 1/2, \pm 1/2), ((1+\sqrt{3})/\sqrt{2}, 0, \pm(1+\sqrt{3})/2), ((1+\sqrt{3})/\sqrt{2}, \pm(1+\sqrt{3})/2, 0)\}$. It is identical with the adaptively biased format, with the exception of the first coordinate, which is constant due to the added constant bias.

The nonnegativity requirement puts a constraint on the admissible signal space region, which is defined in [2, Eq. (10)]. Modulation formats with better sensitivity can be designed by optimization of the symbol packing in the admissible signal space. Numerically optimized 8-level subcarrier modulations are introduced in [7]. In the experiments, we use an 8-level modulation format optimized for electrical power, because it performs as well as the one optimized for optical power, but has a simpler and symmetrical structure. The format is defined as $\{(0,0,0)$, $(\sqrt{2/3}, 0, 1/\sqrt{3})$, $(\sqrt{2/3}, \pm 1/2, -\sqrt{3}/6)$, $((5/3)\sqrt{2/3}, 0, -5/(3\sqrt{3}))$, $((5/3)\sqrt{2/3}, \pm 5/6, 5/(6\sqrt{3}))$, $(2\sqrt{2/3}, 0, 0)\}$ and is illustrated in Fig. 1c. This modulation has 2 dB better sensitivity than the traditional star-shaped 8-QAM.

3. Experimental results

The three modulation formats are compared experimentally at symbol rate of 2.5 Gbaud, which gives bitrate of 7.5 Gbps. One carrier period per symbol is used, like in [3], the carrier frequency is 2.5 GHz. A vertical cavity surface emitting laser (VCSEL) operating at 850nm, reported in [8], is used. The receiver is a simple photodetector (PD), without an amplifier. Back-to-back (B2B) configuration is tested only, using a multimode fibre patchcord and a variable optical attenuator. The subcarrier signal is generated in an arbitrary waveform generator. At the receiver, the signal is captured with a real-time sampling oscilloscope and processed off-line for measurement of the symbol error rate (SER).

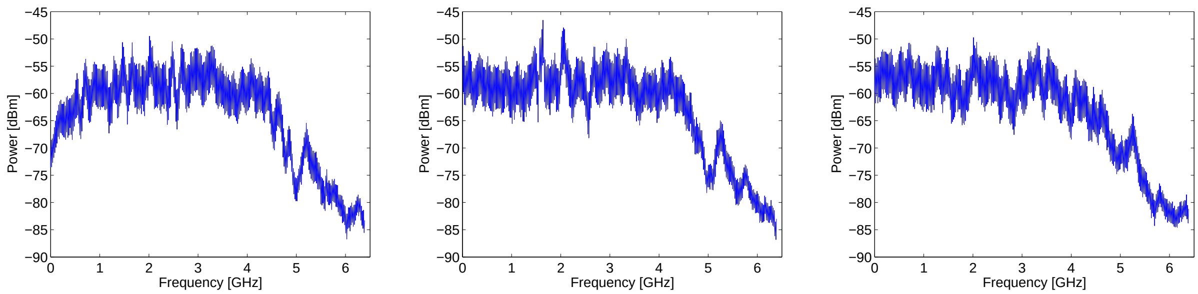


(a) Received star 8-QAM constellation

(b) Back-to-back symbol error rate.

Fig. 2: Star 8-QAM constellation at -3 dBm received optical power and back-to-back SER.

A constellation diagram illustrating the received conventional subcarrier star-shaped 8-QAM, plotted in two dimensions, is illustrated in Fig. 2a. The SER are measured down to 10^{-6}, which is common for experiments with off-line processing. The SER results illustrated in Fig. 2b are in agreement with theoretical expectations [7]. The adaptively biased 8-QAM has about 1 dB better sensitivity, at an SER of 10^{-4}, compared to conventional subcarrier 8-QAM. The optimized modulation gives additional an 1 dB improvement at the same SER, yielding a 2 dB total improvement over traditional star-shaped subcarrier 8-QAM. The receiver for the adaptively biased and optimized formats utilizes the adaptive bias a a third dimension.



(a) Subcarrier 8-QAM

(b) "Adaptively biased" subcarrier 8-QAM

(c) Optimized 8-level modulation

Fig. 3: Electrical spectra of the investigated modulation formats.

For practical transmission, forward error correction (FEC) would have to be used and standard FEC overhead of 7% would yield a total usable bitrate of 6.97 Gbps, though the goal of this work is to demonstrate improvement of the sensitivity of subcarrier modulation as a proof of concept. A cascaded FEC unit in the receiver is expected to influence all formats similarly, so an improved uncoded bit error rate (BER) means better BER with the FEC as well.

In Fig. 3, the electrical spectra of the signal driving the VCSEL, measured with an electrical spectrum analyzer, are illustrated. The spectrum of ordinary star 8-QAM has the center of the main lobe at the carrier frequency 2.5 GHz, and nulls at 0 and 5 GHz. The adaptively biased and optimized modulation spectra do not have nulls at 0 GHz, because of the superimposed adaptive bias, which corresponds to baseband modulation.

4. Conclusions

We have experimentally demonstrated improved sensitivities of subcarrier modulation. The sensitivity for 8-level subcarrier modulation can be improved by 2 dB, compared to ordinary star 8-QAM, by using the extra degree of freedom given by the amplitude offset of the subcarrier symbols. Using just simple adaptive offset of the star 8-QAM gives 1 dB benefit.

5. Acknowledgements

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