Experimental comparison of modulation formats in IM/DD links

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Abstract: We present an experimental comparison of modulation formats for optical intensity modulated links with direct detection. Specifically, we compare OOK, QPSK on an electrical subcarrier and a new modulation format named OOPSK. The OOPSK modulation format is shown to have better sensitivity than the other modulation formats, in agreement with theoretical predictions. The impact of propagation in multimode fiber is also studied and the results show that all modulation formats have similar sensitivity penalties, with respect to the fibre length.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4080) Modulation; (060.2360) Fiber optics links and subsystems.

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1. Introduction

In the area of short range optical communications, e.g. data center applications, optical interconnects and local area networks, intensity modulation with direct detection (IM/DD) is used, primarily for cost reasons. The cost constraint precludes use of external modulators and coherent systems. The components used for short range links are directly modulated lasers, multimode fiber (MMF) and direct detection receivers. MMF is preferred over single mode fibre, because of larger alignment tolerances and lower connectors cost. The vertical cavity surface emitting lasers (VCSELs) are popular because of their low cost and low power consumption. Recently very fast directly modulated VCSELs were developed and used with on-off keying (OOK) modulation at 32 Gbps [1] and 40 Gbps [2, 3]. The use of OOK at high data rates in links with MMF means that the transmission length is limited by the modal dispersion and there is demand for multilevel modulation formats with higher spectral efficiency. Such modulation formats require higher signal to noise ratios and therefore sensitivity is an important consideration in design of multilevel modulation formats.

There are two common approaches to spectrally efficient modulation formats for short range optical links. The first approach is baseband multilevel pulse amplitude modulation (PAM). Multilevel PAM has been successfully demonstrated in links using VCSELs and conventional MMF [4] as well as polymer fibers [5, 6], up to 10 Gbps. Another approach is subcarrier modulation, where a microwave subcarrier signal is first modulated with quadrature amplitude modulation (QAM) or phase shift keying modulation (PSK) [7, Ch. 5], [8, Ch. 4–5]. The number of subcarriers used can vary. A configuration which uses a single subcarrier, with subcarrier period equal to a symbol period is called a "single-cycle subcarrier modulation" and has been successfully demonstrated, both with external modulators [9] and with directly modulated VCSELs [10]. The microwave subcarrier for this scheme can be generated in real time using high speed logic gates as demonstrated in [10, 11]. The number of subcarriers can be increased,

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without introducing their orthogonality [12, 13]. The subcarriers can be also orthogonal, as in orthogonal frequency division multiplexing (OFDM). A variation of OFDM called discrete multitone modulation (DMT), where the output of the inverse Fourier transform is real rather than complex, has been proposed for use in IM/DD links [14]. The DMT modulation has succesfully been used with MMF [15] and polymer fibers [16]. The drawback of subcarrier modulation is that, at the same symbol rate as baseband modulation, the subcarrier modulation uses twice the bandwidth, due to the intermediate step of modulating the microwave subcarrier [17]. Furthermore, the subcarrier modulation sensitivity is degraded due to the fact, that a DC bias must be added to make the signal non-negative [17]. The added DC component does not carry any information and does not contribute to increased noise resilience. With increasing number of subcarriers the situation gets even worse, and for an N-subcarrier scheme $5\log_{10} N$ more optical power is required, compared to corresponding single subcarrier scheme [17]. Various methods for reduction of average optical power in subcarrier schemes were studied in [18, 19].

Apart from the baseband PAM and various subcarrier schemes some novel modulation schemes were investigated for the IM/DD channel in [20–22]. A particularly interesting modulation format for the IM/DD channel, called on-off phase shift keying (OOPSK), was introduced in [23]. The theoretical analysis of the performance of that modulation format promises 0.6 dB improvement in sensitivity over OOK [23]. In this paper we verify experimentally the theoretical work on the OOPSK modulation format, done in [23], presenting the performance in back to back case (B2B) and also show transmission performance over a link using a VCSEL and OM3+ graded index multimode fiber (GI-MMF) and a simple photodetector. For the first time, a modulation format with sensitivity better than OOK is shown in an IM/DD link.

2. Theoretical background

Conventional modulation formats for IM/DD links are either M-PAM or various kinds of subcarrier modulation. The PAM format has only one degree of freedom, which constitutes one dimension. The degree of freedom is defined by a basis function which in the simplest case is a rectangular pulse, the amplitude of which is modulated. The subcarrier modulation formats use two dimensions per each subcarrier, being the classical in-phase and quadrature components, in addition to the PAM basis function. Subcarrier modulation formats with a single subcarrier can therefore be described using the following orthogonal basis functions, which define a three-dimensional signal space [17, 21] [8, Sec. 4.1-4.2]:

$$\Phi_0(t) = \frac{1}{\sqrt{T}}\mathrm{rect}(t/T), \tag{1}$$

$$\Phi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f t)\mathrm{rect}(t/T), \tag{2}$$

$$\Phi_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f t)\mathrm{rect}(t/T), \tag{3}$$

where

$$\mathrm{rect}(t) = \begin{cases} 1, & \text{if } 0 \le t < 1 \\ 0, & \text{otherwise} \end{cases},$$

T is the symbol period, and f denotes the subcarrier frequency. As in previous works [7, Sec. 5.2.2], [8, Sec. 4.2.1], [9, 10, 20] we use $f = \frac{1}{T}$, meaning that the subcarrier period and symbol period are the same.

There is however a constraint on this signal space. Since the optical intensity is modulated, and it cannot be negative, the electrical signal driving the directly modulated laser cannot be negative, after adding the bias current. This means that only a part of the three-dimensional

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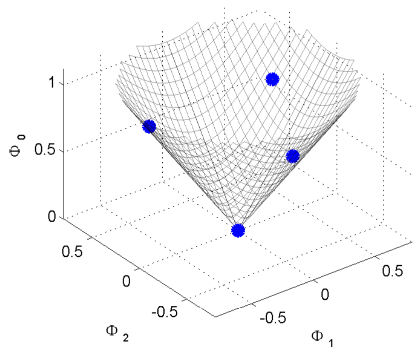
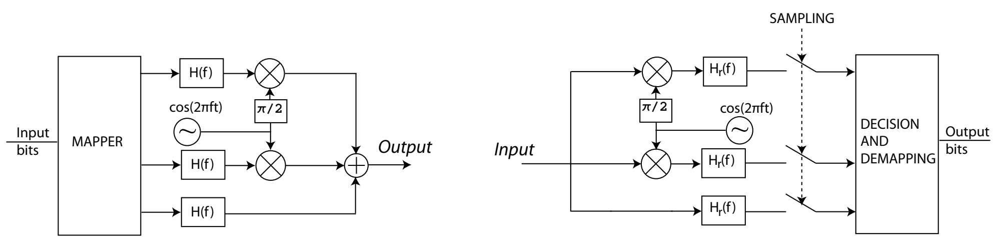


Fig. 1. Three dimensional constellation diagram of the OOPSK modulation format inscribed into the available signal space. The admissible signal space, from [21, Fig. 2], [8, Fig. 4.2], is the interior and the surface of the cone.



(a) transmitter

(b) receiver

Fig. 2. Transmitter and receiver structures for the OOPSK format. The $H(f)$ block denotes a rectangular pulse shaping filter and the $H_r(f)$ is a matched filter. The mapper maps bits pairs to symbols.

signal space is available for modulation. The problem of admissible signal space for IM/DD channels was solved for generalized case in [21]. For the basis functions [Eqs. (1)–(3)], the admissible signal space is a three-dimensional cone, illustrated in [21, Fig. 2], [8, Fig. 4.2]. The signal space of the OOPSK format [23] consists of four equidistant points on the surface of this cone, as shown in Fig. 1.

The structure of the OOPSK transmitter is a synthesis of the transmitter structures for PAM and subcarrier PSK. Since there are three basis functions, the transmitter has three branches forming the corresponding part of the final signal. Two branches are generating the PSK signal, using classical IQ modulation and a third branch generates the bias signal, which is the PAM component. A rectangular pulse shaping filter is used in each of the branches. The receiver structure reflects the transmitter structure, with two branches corresponding to the IQ components and a third branch corresponding to the bias signal. Filters matched to the transmitted pulse shape are used. In Fig. 2, these transmitter and receiver designs are shown. They consist of a conventional IQ transmitter and receiver (see, e.g., [24, Figs. 6.7–6.8]), with the addition of an extra branch to handle the bias. They can also be regarded as a variant of the IM/DD system in [7, Fig. 5.6], generalized so that the bias signal too carries data.

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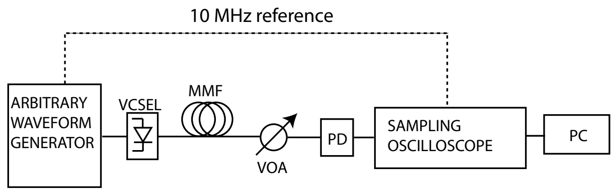

Fig. 3. The experimental setup diagram.

The OOPSK modulation format has lower average electrical and optical power for the same minimum symbol distance as the OOK and QPSK, and the result is increased sensitivity of OOPSK compared with OOK and QPSK. A detailed analysis of performance of OOPSK and comparisons with other modulation formats, such as the OOK or QPSK, were carried out in [23]. Specifically, it was found that the OOPSK format has 0.62 dB better optical sensitivity than OOK and 2.12 dB better sensitivity than subcarrier QPSK.

3. Experimental setup

The three modulation formats were experimentally compared using the same hardware setup. A directly modulated VCSEL was used at the transmitter end and a New Focus 1481-S-50 photodetector was used at the receiver end. The VCSEL was developed in-house and has been reported earlier [1]. The modulation bandwidth of this laser is around 20 GHz, the modulation bandwidth of the photodetector is 25 GHz. This high modulation bandwidth ensured, that the components were not the limiting factor in the experiment. No amplifier was used after the photodetector to avoid potential problem with amplifier nonlinearities. OM3+ MMF was used for transmission. The bandwidth-distance product of this fiber is 4700 MHz·km. The tested fiber lengths were 800 m and 1000 m. A back to back (B2B) configuration with a short MMF patchcord was also tested. The test setup is shown in Fig. 3.

The arbitrary waveform generator (AWG) was programmed with the test waveforms for all tested modulation formats. The modulating signal was fed to the VCSEL via a bias-T, which combined the modulating signal with the bias. The VCSEL was biased to keep the same extinction ratio for every modulation format.

The test waveforms generated with the AWG were prepared offline on a personal computer. The sampling rate of the AWG was 10 GS/s and the analog bandwidth was 7.5 GHz. At the receiver, a real time sampling oscilloscope was used, with a sampling rate of 50 GS/s and an analog bandwidth of 16 GHz. The signal was further processed off-line on a computer in order to obtain the BER results. The oscilloscope and the AWG were synchronized to avoid sampling frequencies drift, to provide fair performance comparison. Including the carrier and symbol timing recovery algorithms would mean, that their performance would affect the results. No equalizers were used, because one of the objectives was to observe the impact of propagation in multimode fiber. For similar reasons, rectangular pulse shaping was used, instead of for example raised root cosine or similar pulse shape. The experimental results presented in this paper are intended to show the intrinsic sensitivity results, but also to serve as a benchmark for further work on synchronization, pulse shaping and equalization algorithms.

The modulation formats were compared at the same bit-rate of 5 Gbps. The main-lobe bandwidth of each modulation was the same, 5 GHz for all modulation formats. The OOPSK and QPSK were operated at symbol rate of 2.5 Gbaud, since those modulation formats use 2 bits per symbol, while OOK was operated at 5 Gbaud. In the QPSK subcarrier modulation a single carrier period per symbol was used, in so called single-cycle subcarrier configuration.

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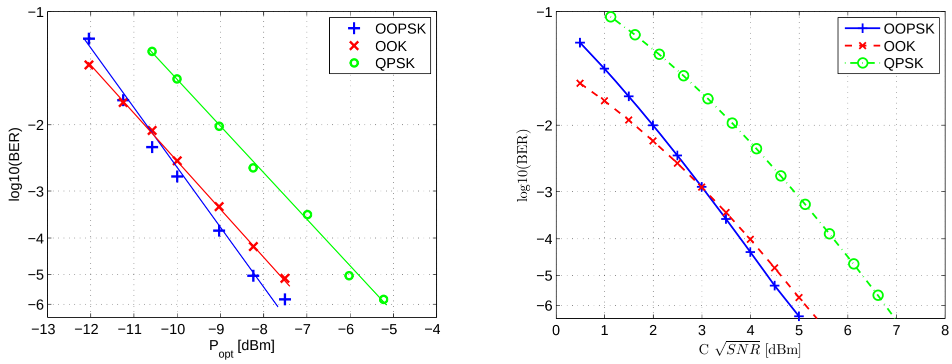
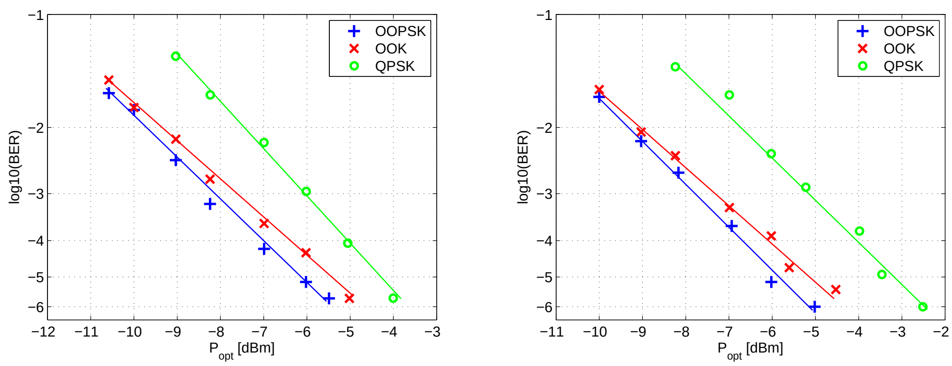


(a) Experimental BER, B2B (b) Theoretical performance

Fig. 4. Experimental BER in the back to back case (a) and theoretical BER (b). At low BER, the OOPSK format has the the best sensitivity of all the compared modulation formats. The bit rate was 5 Gbps.



(a) Experimental BER, 800 m MMF (b) Experimental BER, 1000 m MMF

Fig. 5. Experimental BER after propagation over 800 m (a) and 1000 m (b) of MMF. The OOPSK modulation format is still the best one, the subcarrier QPSK has the worst performance.

4. Experimental results

To compare the sensitivity, the bit error rate (BER) against receiver optical power was measured for each modulation format and for each propagation. The lowest practical measurable BER at this bit rate was around 10^{-6}. Some of the practical limitations were oscilloscope buffer length, the time to transfer the data from the oscilloscope to the computer and the off-line processing time.

It was found, that the main noise contribution is the thermal noise. Theoretically calculated, the shot noise, at the optical power levels used, was around -77 dBm. The measured thermal noise was -50 dBm, this was the main noise contribution in the system.

The BER results for the B2B configuration are presented Fig. 4a, for comparison theoretical performance is in Fig. 4b. Because the signal to noise ratio (SNR) depends on the square of the optical power [17], the theoretical BER is plotted against $C\sqrt{SNR}$, where C is proportionality

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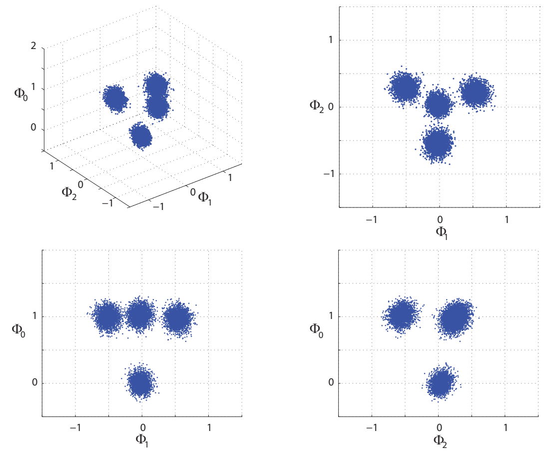

Fig. 6. Experimental constellation diagram of the the OOPSK modulation in the back to back case. The top left diagram is an isometric projection of the three dimensional constellation. The top right diagram is a projection of the constellation on the traditional IQ plane. The two lower diagrams are side projections of the constellation.

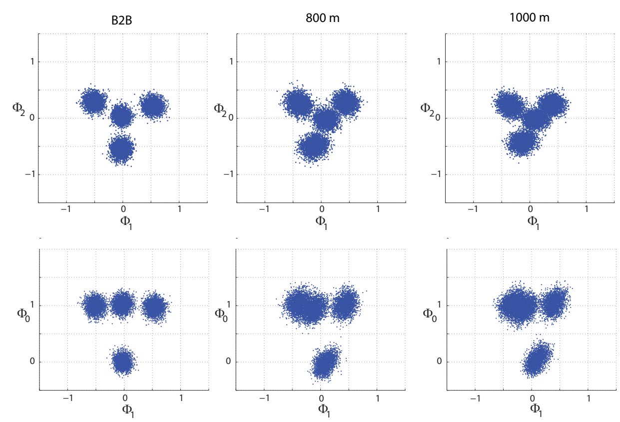

Fig. 7. Comparison of experimental OOPSK constellation diagrams for B2B, transmission over 800 m and 1000 m of MMF. The leftmost column contains projections of the OOPSK constellation diagram for B2B case, the centre one for 800 m and the rightmost one for 1000 m.

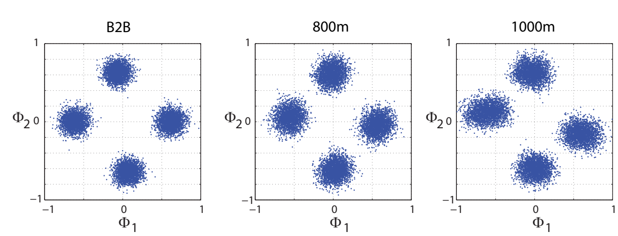

Fig. 8. Experimental constellation diagrams of the the subcarrier QPSK modulation after back to back, to the left, transmission over 800 m of GI-MMF in the centre and after 1000 m of MMF to the right.

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constant depending on the bit rate and photodetector responsivity, analogously to [17, eq. (5)]. Theoretically, the OOPSK modulation format has the best sensitivity at BER lower than 10^{-3}, but in experimental B2B case OOPSK is better already below 10^{-2}. The theoretical BER performance was obtained from the union bound in [23], rescaled against the $C\sqrt{SNR}$. As it is the union bound, it is not accurate at high BER. At BER of 10^{-4} OOPSK has sensitivity better by around 0.5 dB, than OOK. Theoretically, at asymptotically high SNR, OOPSK should be 0.62 dB better than OOK [23]. In an ideal case, when real time transmitter and receiver would be available, it would be interesting to operate in the low BER region to take full advantage of the improved sensitivity of OOPSK. The subcarrier QPSK modulation has the worst sensitivity, being around 2 dB worse than OOPSK. This is in agreement with theoretical predictions in [23].

The BER values for transmission over 800 m and 1000 m of MMF are shown in Fig. 5a and Fig. 5b. The OOPSK format offers the best sensitivity for all tested fiber lengths, even at high BER, followed by the OOK, the subcarrier QPSK shows the worst sensitivity.

The effect of the bandwidth limitation on the transmitted signal is most easily seen on the constellation diagrams. Since the OOPSK modulation format uses three basis functions, three spatial dimensions are needed to plot a constellation diagram. Received constellation diagram after back to back is show in Fig. 6. In the upper left there is an isometric projection of the constellation diagram, the rest of are orthogonal projections.

It is clear, that the constellation diagram obtained experimentally in the back to back case is very close to the ideal constellation, presented in the theory section in Fig. 1. It shows that such three dimensional modulation formats can be easily applied to the IM/DD links and successfully use the three available degrees of freedom to improve the sensitivity.

A constellation diagram of the signal transmitted over 1000 m of MMF is shown in Fig. 7. The constellation diagrams for propagation over 1000 m show the effect of the bandwidth limitation. It is clear that one of the symbols in the constellation is affected more than the others. The reason for this behavior lies in the fact, that firstly, a rectangular pulse shaping was used, and secondly only one carrier period per symbol is used for the PSK symbols. This means that between some symbols there are steep transitions. This is also true of the the QPSK modulation. It can be seen on the constellation diagrams of the QPSK signal, after B2B, after 800 m and after 1000 m of GI-MMF shown in Fig. 8. The effects of limited bandwidth on QPSK and OOPSK are comparable.

5. Conclusions and future work

We have experimentally compared the sensitivities of three modulation formats for IM/DD links, OOK, subcarrier QPSK and OOPSK, introduced in [23]. The OOPSK format has the best sensitivity, which is 0.5 dB better than OOK and 2.1 dB better than subcarrier QPSK at a BER of 10^{-4}. This result is in agreement with theoretical results in [23]. The test of the three modulation formats over the MMF shows that they have similar performance penalty due to modal dispersion. To our knowledge, this is the first time a modulation format with sensitivity better than OOK is demonstrated in an IM/DD link. The gain is however relatively small and comes at the cost of a higher transmitter and receiver complexity.

As a follow-up to this work, we plan to compare the modulation formats regarding their robustness to nonlinearities and imperfections in lasers or electronic amplifiers. Another work direction is to apply pulse shaping to improve the robustness to intersymbol interference induced modal dispersion. We should note that in presence of forward error correction, the relative performances between these formats may be different, but such an investigation is deferred to future publications.

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