Power efficient subcarrier modulation for intensity modulated channels

Johnny Karout,[1,*] **Erik Agrell,**[1] **and Magnus Karlsson**[2]

[1]*Department of Signals and Systems, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

[2]*Department of Microtechnology and Nanocience, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

*[*johnny.karout@chalmers.se](mailto:johnny.karout@chalmers.se)*

Abstract: We compare formats for optical intensity modulation limited by thermal noise with the assumption of having ideal devices. At the same bitrate and bandwidth, a hitherto unknown format turns out to be more power efficient than known formats. This new modulation, which is a hybrid between on-off keying and phase-shift keying, belongs to the subcarrier modulation family. At asymptotically high signal-to-noise ratios, this hybrid scheme has a 1.2 dB average electrical power gain and 0.6 dB average optical power gain compared to OOK, while it has a 3.0 dB average electrical power gain and 2.1 dB average optical power gain compared to subcarrier QPSK.

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

References and links

1. P. J. Winzer and R.-J. Essiambre, "Advanced modulation formats for high-capacity optical transport networks," J. Lightwave Technol. **24**, 4711–4728 (2006).
2. S. Randel, F. Breyer, and S. C. J. Lee, "High-speed transmission over multimode optical fibers," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, (2008), paper OWR2.
3. P. Westbergh, J. S. Gustavsson, Å. Haglund, A. Larsson, F. Hopfer, G. Fiol, D. Bimberg, and A. Joel, "32 Gbit/s multimode fibre transmission using high-speed, low current density 850 nm VCSEL," Electron. Lett. **45**, 366–368 (2009).
4. B. Inan, S. C. J. Lee, S. Randel, I. Neokosmidis, A. M. J. Koonen, and J. W. Walewski, "Impact of LED nonlinearity on discrete multitone modulation," J. Opt. Commun. Netw. **1**, 439–451 (2009).
5. J. E. Cunningham, D. Beckman, X. Zheng, D. Huang, T. Sze, and A. V. Krishnamoorthy, "PAM-4 signaling over VCSELs with 0.13 μm CMOS chip technology," Opt. Express **14**, 12028–12038 (2006).
6. S. Hranilovic and F. R. Kschischang, "Capacity bounds for power-and band-limited optical intensity channels corrupted by Gaussian noise," IEEE Trans. Information Theory **50**, 784–795 (2004).
7. S. Walklin and J. Conradi, "Multilevel signaling for increasing the reach of 10 Gb/s lightwave systems," J. Lightwave Technol. **17**, 2235–2248 (1999).
8. S. Hranilovic, "On the design of bandwidth efficient signalling for indoor wireless optical channels," Int. J. Commun. Systems **18**, 205–228 (2005).
9. J. M. Kahn and J. R. Barry, "Wireless infrared communications," IEEE Proc. **85**, 265–298 (1997). *(Invited Paper)*.
10. J. R. Barry, *Wireless Infrared Communications* (Kluwer Academic Publishers, Norwell, MA, USA, 1994).
11. A. O. J. Wiberg, B.-E. Olsson, and P. A. Andrekson, "Single cycle subcarrier modulation," in *Optical Fiber Communication Conference*, OSA Technical Digest, (2009), paper OTuE1.
12. B.-E. Olsson and A. Alping, "Electro-optical subcarrier modulation transmitter for 100 GbE DWDM transport," in *Asia Optical Fiber Communication and Optoelectronic Exposition and Conference*, OSA Technical Digest, (2008), paper SaF3.
13. B.-E. Olsson and M. Sköld, "QPSK transmitter based on optical amplitude modulation of electrically generated QPSK signal," in *Asia Optical Fiber Communication and Optoelectronic Exposition and Conference*, OSA Technical Digest, (2008), paper SaA3.

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

14. S. Hranilovic and D. A. Johns, "A multilevel modulation scheme for high-speed wireless infrared communications," in *IEEE International Symposium on Circuits and Systems*, (1999), pp. 338–341 .
15. R. You and J. M. Kahn, "Average power reduction techniques for multiple-subcarrier intensity-modulated optical signals," IEEE Trans. Commun. **49**, 2164–2171 (2001).
16. S. C. J. Lee, F. Breyer, S. Randel, and A. M. J. Koonen, "High-speed transmission over multimode using discrete multitone modulation," J. Opt. Netw. **7**, 183–196 (2008). *(Invited Paper)*.
17. B.-E. Olsson, J. Mårtensson, A. Kristiansson, and A. Alping, "RF-assisted optical dual-carrier 112 Gbit/s polarization-multiplexed 16-QAM transmitter," in *Optical Fiber Communication Conference*, OSA Technical Digest, (2010), paper OMK5.
18. H. Yang, S. C. J. Lee, E. Tangdiongga, C. Okonkwo, H. P. A. van den Boom, F. Breyer, S. Randel, and A. M. J. Koonen, "47.4 Gb/s transmission over 100 m graded-index plastic optical fiber based on rate-adaptive discrete multitone modulation," J. Lightwave Technol. **28**, 352–359 (2010).
19. W. Kang and S. Hranilovic, "Optical power reduction for multiple-subcarrier modulated indoor wireless optical channels," in *IEEE International Conference on Communications*, (2006), pp. 2743–2748.
20. X. Liang, W. Li, W. Ma, and K. Wang, "A simple peak-to-average power ratio reduction scheme for all optical orthogonal frequency division multiplexing systems with intensity modulation and direct detection," Opt. Express **17**, 15614–15622 (2009).
21. H. Elgala, R. Mesleh, and H. Haas, "A study of LED nonlinearity effects on optical wireless transmission using OFDM," in *Proceedings of the Sixth international conference on Wireless and Optical Communications Networks*, (2009), pp. 388–392.
22. S. Hranilovic and F. R. Kschischang, "Optical intensity-modulated direct detection channels: signal space and lattice codes," IEEE Trans. Information Theory **49**, 1385–1399 (2003).
23. W. Mao and J. M. Kahn, "Lattice codes for amplified direct-detection optical systems," IEEE Trans. Commun. **56**, 1137–1145 (2008).
24. G. P. Agrawal, *Lightwave Technology* (John Wiley & Sons, Inc., New Jersey, 2005).
25. R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," J. Lightwave Technol. **28**, 662–701 (2010). *(Invited Paper)*.
26. M. C. Gursoy, "Error rate analysis for peaky signaling over fading channels," IEEE Trans. Commun. **57**, 2546–2550 (2009).
27. J. G. Proakis and M. Salehi, *Digital Communications* (McGraw-Hill, New York, 2008), 5th ed.
28. K. L. Kaiser, *Electromagnetic Compatibility Handbook* (CRC Press, 2004).
29. M. K. Simon, S. M. Hinedi, and W. C. Lindsey, *Digital Communication Techniques* (Prentice Hall PTR, USA, 1995).

---

1. Introduction

Multilevel modulation, with information encoded onto the amplitude and phase of the optical carrier, has attracted significant research interest in fiber-optical communication to boost the transmission rates and spectral efficiencies [1]. However, the enabling technology consisting of coherent transmitters and receivers is not feasible for short-haul applications such as local area networks, data centers, and computer interconnects [2], where the overall cost and complexity has to be kept down. Therefore, intensity modulation and direct detection (IM/DD), where the information is modulated onto the intensity of the optical carrier using a laser diode and the receiver detects the instantaneous power of the received signal using a simple photodiode, is more suitable for such types of low cost and complexity applications. For such links, there arises a challenge in selecting a modulation format which offers a good trade-off between spectral and power efficiency as well as having low peak amplitudes in the generated electrical waveform; in the case of high peaks, the laser diode will operate in a highly nonlinear fashion [3, 4].

Since the optical phase in an IM/DD system cannot be used to carry information, multilevel pulse amplitude modulation (M-PAM), which directly modulates the optical carrier, is a simpler way to achieve higher spectral efficiency than the widely spread on-off keying (OOK) modulation format while keeping the hardware complexity low. A link analysis was performed in [5] for a vertical-cavity surface-emitting laser (VCSEL) operating with 4-PAM signaling, and the first sensitivity measurements were presented. Upper and lower bounds on the capacity of 2-, 4-, 8-, and 16-PAM were derived in [6], and the power efficiency of M-PAM was shown to be low in [7] due to the increased number of levels. Further, M-ary pulse-position modulation

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

(M-PPM) has been considered in free-space optics due to its high power efficiency, but it has a poor spectral efficiency [8, 9], making it less suitable for fiber-optical communication.

On the other hand, the subcarrier modulation (SCM) family described in the wireless infrared communications context [10, Ch. 5] allows the adoption of any bandwidth-efficient multilevel modulation for IM/DD systems. The concept is to first modulate the data onto an electrical subcarrier, whose frequency is of the same order as the symbol rate, using the standard I/Q-modulation formats such as multilevel phase-shift keying (M-PSK) or multilevel quadrature amplitude modulation (M-QAM). A direct current (DC) bias is added in order to make the modulated signal nonnegative, before it directly modulates the light source. The DC bias is crucial to avoid signal clipping by the laser diode which deteriorates the system performance. Compared with coherent transmission, the complexity in the transmitter and receiver of SCM is shifted to the electrical domain. An experimental demonstration of the SCM concept can be found in [11], and a novel transmitter design for the subcarrier quadrature phase-shift keying (QPSK) and 16-QAM using fast digital exclusive-OR (XOR) gates is presented in [12] and [13]. However, the drawback in using SCM at the same baud rate as the modulation formats that directly modulate the optical carrier, e.g., the aforementioned OOK and M-PAM, is that it occupies twice the bandwidth of such modulations due to the intermediate step of modulating the information onto an electrical subcarrier before modulating the optical carrier [10, p. 125]. In addition, the DC bias, which carries no information, consumes transmission power without adding any noise resilience since it is independent of the transmitted information. To increase the power efficiency of SCM, [14] minimized the bias for the transmitted signal on a symbol-by-symbol basis, and [15] allowed the bias to vary even within the symbol interval.

An extension of the above subcarrier modulation family is to superimpose several carriers resulting in a multiple-subcarrier modulation (MSM) [10, p. 122], or orthogonal frequency-division multiplexing (OFDM) if the carriers are orthogonal. Further, a subclass of OFDM known as discrete multitone (DMT), where the output of the inverse fast Fourier transform modulator is real instead of complex, is investigated in [16]. A demonstration of a dual carrier system with 16-QAM can be found in [17], and transmission using DMT over a multimode fiber in [18]. The main drawback of the MSM family is the poor optical average power efficiency due to the high peak-to-average power ratio (PAPR) in the MSM electrical signal, which requires an increased DC bias to make the signal nonnegative. [15, 19] investigated power reduction techniques for MSM, [20] investigated PAPR reduction for OFDM, and [4, 21] studied the light emitting diode (LED) nonlinearity effects on OFDM and DMT, respectively.

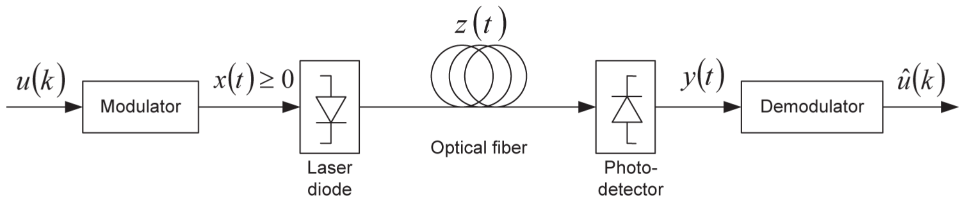
In this work, our contribution is to present a novel quaternary subcarrier modulation scheme called on-off phase-shift keying ($\text{OOPSK}_{\text{SCM}}$), and compare it with OOK and the subcarrier QPSK (QPSK_{SCM}), since they have the same spectral efficiency. According to [10, Ch. 5], [9], OOK is the most power efficient among the known modulation formats having the same spectral efficiency. However, as we will see, $\text{OOPSK}_{\text{SCM}}$ turns out to be the most power efficient among known formats.

2. System model

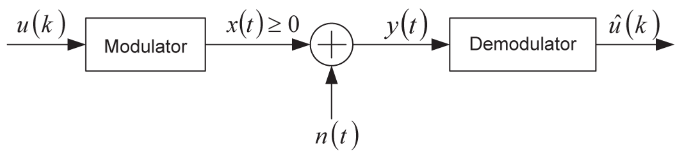
The system under investigation is depicted in Fig. 1(a). The transmitter consists of a modulator which maps the symbol $u(k) \in \{0, 1, \ldots, M-1\}$ at instant k to a waveform belonging to the modulation signal set $S = \{s_0(t), s_1(t), \ldots, s_{M-1}(t)\}$. The resulting electrical waveform $x(t)$ is positive and directly modulates the laser diode. Its output is the optical field

$$z(t) = \sqrt{2cx(t)}\cos(2\pi\nu_0 t + \theta) \tag{1}$$

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010



(a)



(b)

Fig. 1. Passband transceiver (a) and equivalent baseband model (b) of the optical intensity channel.

which propagates in the optical link, where c is the slope efficiency of the laser [3], ν_0 is the optical carrier frequency, and θ is a random phase, uniformly distributed in $[0, 2\pi)$. The photodiode does the optical-to-electrical conversion, which is then followed by a demodulator whose output is $\hat{u}(k)$, an estimate of $u(k)$. The demodulator is a correlator or matched filter receiver, which minimizes the symbol error rate at a given signal-to-noise ratio (SNR) [29, Sect. 4.1]. In the special case of SCM, this demodulator involves mixing the signal with the subcarrier and a 90° phase-shifted subcarrier, and using those and the detected total power as detection variables [22].

Due to the nature of the applications involving short-haul links, the dominant channel impairment is thermal noise in the photodetector [23], [24, p. 155]. Therefore, the system under investigation can be well modeled as a modulator and demodulator with additive white Gaussian noise (AWGN), where the propagating signal satisfies the nonnegativity constraint as shown in Fig. 1(b) [9], [24, p. 153]. The AWGN has a double-sided power spectral density $N_0/2$ and models the thermal noise. The same baseband model can be used to represent the wireless infrared channel [6, 9, 22], [10, Ch. 5].

3. Investigated modulation schemes

We propose the so called $\text{OOPSK}_{\text{SCM}}$ subcarrier modulation, which is a hybrid between OOK and phase-shift keying. Therefore, the DC bias required to make the signals positive is also utilized to carry information. It consists of a signal set with size $M = 4$ defined for $0 \leq t < T_s$ as

$$\begin{aligned}
s_0(t) &= 0 \\
s_1(t) &= A[1+\sin(2\pi f_c t)] \\
s_2(t) &= A\left[1+\sin\left(2\pi f_c t + \frac{2\pi}{3}\right)\right] \\
s_3(t) &= A\left[1+\sin\left(2\pi f_c t - \frac{2\pi}{3}\right)\right],
\end{aligned} \tag{2}$$

where $A = (2/3)\sqrt{2E_s/T_s}$, $E_s = E_b \log_2 M$ is the average symbol energy, E_b is the average bit energy, $T_s = 1/R_s$ is the symbol period, and R_s is the symbol rate. In this case, we con-

Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

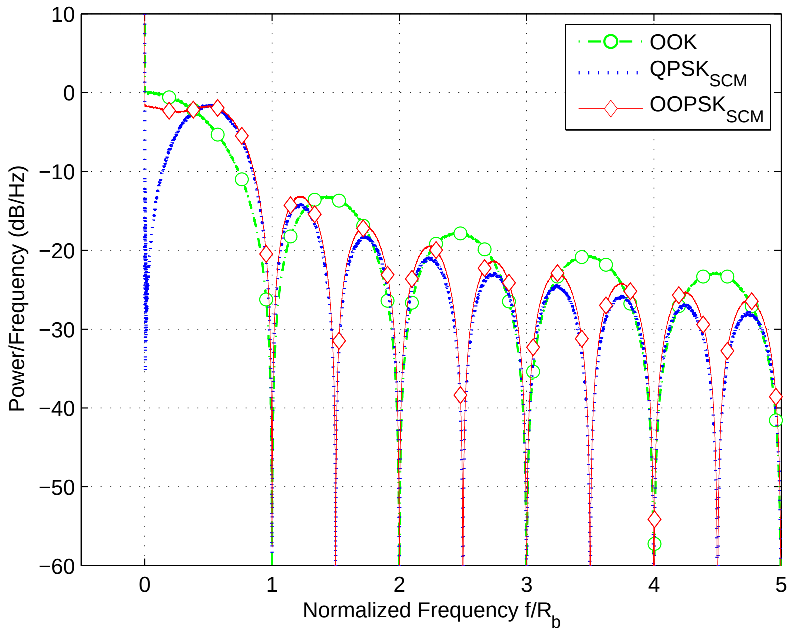


Fig. 2. Electrical baseband spectra for the various modulation formats. (The Dirac impulse is due to the DC bias.)

sider $f_c = 1/T_s$ as the subcarrier frequency. Other hybrids between amplitude-shift keying and phase-shift keying have been studied in [25], where their performances were evaluated for the AWGN channel using coherent detection, and in [26], where analytical expressions for the error probabilities over fading channels have been obtained. However, such modulation formats do not satisfy the nonnegativity constraint; therefore, they do not belong to the SCM family and cannot be used over intensity modulated channels.

Our investigation encompasses modulation formats with spectral efficiency 1 (bits/s)/Hz, where the OOK modulation defined for $0 \le t < T_s$ as

$$\begin{aligned} s_0(t) &= 0 \\ s_1(t) &= \sqrt{\frac{2E_s}{T_s}}, \end{aligned} \tag{3}$$

will be used as a benchmark as in [9], [10, Ch. 5], and compared with QPSK_{SCM}, defined as

$$s_i(t) = \sqrt{\frac{2E_s}{3T_s}} \left[1 + \sin\left(2\pi f_c t + \frac{\pi i}{2} \right) \right] \tag{4}$$

for $0 \le t < T_s$ [10, Ch. 5] and $i \in \{0, \ldots, 3\}$ with Gray mapping, and with the proposed $\text{OOPSK}_{\text{SCM}}$. The above definitions ensure that all three modulation formats have the same average symbol energy.

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

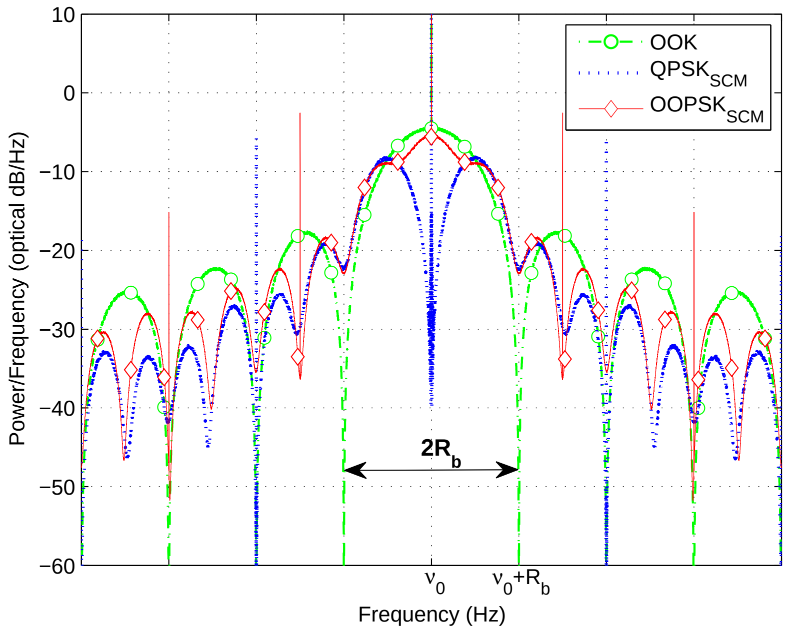


Fig. 3. Optical spectra for the various modulation formats.

4. Performance investigation

Figure 2 shows the electrical spectrum $S_x(f) = F[\overline{R_x(\tau)}]$ of the transmitted signal $x(t)$ [27, p. 70], where F is the Fourier transform and $\overline{R_x(\tau)}$ is the average autocorrelation function of the cyclostationary process $x(t)$, at the same bit rate $R_b = R_s \log_2 M$ using OOK, QPSK_{SCM}, and $\text{OOPSK}_{\text{SCM}}$. For the subcarrier baseband waveforms $x(t)$, the normalized carrier frequency is $f_c/R_b = 1/2$. With the definition of the absolute bandwidth as the width of the spectral main lobe [28, Ch. 12], Fig. 2 shows that all the considered schemes occupy the same absolute electrical bandwidth although OOK has twice the symbol rate. This is because OOK has half the number of levels compared with the other considered modulation formats. An interesting observation is the spectral dependence of $\text{OOPSK}_{\text{SCM}}$, making it a blend between the spectrum of OOK and QPSK_{SCM}.

Figure 3 shows the optical spectrum $S_z(f) = F[\overline{R_z(\tau)}]$ centered at the optical carrier frequency ν_0 of the signal $z(t)$ propagating in the fiber using the different modulation schemes. The modulations still have the same spectral efficiency, although OOK has higher side lobes than the subcarrier modulations. A clear difference compared to the electrical spectra is the existence of spectral spikes for the QPSK_{SCM} and $\text{OOPSK}_{\text{SCM}}$ modulation formats. These spikes are the result of the nonlinear relationship between $x(t)$ and $z(t)$ due to the laser diode, as shown in Eq. (1). This effect is not present in the OOK spectrum due to the fact that rectangular pulse shaping was used in all the simulations, and that the baseband waveform of OOK does not contain a carrier as in the case of the SCM family. The square root of a rectangular pulse is still rectangular, while the square root of a sinusoid is not sinusoidal.

Figure 4 shows the simulated bit error rate (BER) performances of the three modulation schemes using the baseband model depicted in Fig. 1(b), where ideal hardware is assumed, together with their theoretical results. The used model is accurate for links not close to the

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

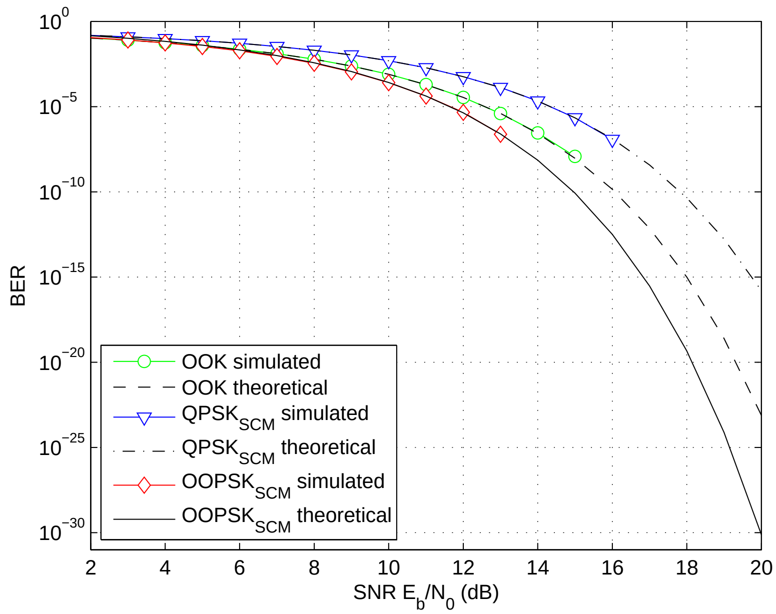


Fig. 4. BER using simulations of the system model in Fig. 1, and theory according to Eqs. (5–9).

bandwidth limits of the channel or the electronic bandwidth limits of the transmitter and receiver. From the above definition of OOK, the BER derivation [27, p. 175] yields

$$P_{b\ (\mathrm{OOK})} = Q\left(\sqrt{\frac{E_b}{N_0}}\right), \tag{5}$$

whereas the theoretical BERs of $\mathrm{QPSK_{SCM}}$ and $\mathrm{OOPSK_{SCM}}$ were approximated using the standard union bound found in [29, Eq. (4.88)]. This bound can be simplified to

$$P_b \approx \frac{2KB}{M \log_2 M}\, Q\left(\sqrt{\frac{d^2}{2N_0}}\right), \tag{6}$$

where d is the minimum signal distance defined by

$$d^2 = \min_{i \neq j} \int_0^{T_s} (s_i(t) - s_j(t))^2 dt, \tag{7}$$

K is the number of distinct signal pairs $(s_i(t), s_j(t))$ with $i < j$ for which $\int (s_i(t) - s_j(t))^2 dt = d^2$, and B is the average number of bits that differ between these K pairs. Evaluating (7) for all pairs of signals is straightforward for the signal sets in (2)–(4). The results for Gray-mapped $\mathrm{QPSK_{SCM}}$ are $M = 4$, $K = 4$, $B = 1$, and $d^2 = 4E_b/3$, which yields

$$P_{b\ (\mathrm{QPSK_{SCM}})} \approx Q\left(\sqrt{\frac{2E_b}{3N_0}}\right), \tag{8}$$

Table 1. Asymptotic performance of intensity modulation formats relative to OOK. The results for the previously known formats, OOK and $QPSK_{SCM}$, can be found in [10, Ch. 5] and [9].

Modulation Scheme	M	Average Electrical Power Gain [dB]	Average Optical Power Gain [dB]	Electrical Peak Power Gain [dB]
OOK	2	0	0	0
$QPSK_{SCM}$	4	–1.8	–1.5	–3.0
$OOPSK_{SCM}$	4	1.2	0.6	–1.2

and for $OOPSK_{SCM}$ $M = 4$, $K = 6$, $B = 8/6$, and $d^2 = 8E_b/3$, which yields

$$P_{b\ (\mathrm{OOPSK_{SCM}})} \approx 2\,Q\left(\sqrt{\frac{4E_b}{3N_0}}\right). \tag{9}$$

For OOK, finally, the parameters are $M = 2$, $K = 1$, $B = 1$, and $d^2 = 2E_b$, in which case the union bound (6) actually yields the exact expression (5).

It should be noted that simulations are accurate at low SNR, and union bounds at high SNR. Furthermore, there will be performance degradation when the physical realization and its influence on the signals are considered. Since different modulation formats are affected differently by a specific implementation choice, making fair performance comparisons becomes challenging. Therefore, it is beyond the scope of this work to study limitations from the system hardware viewpoint.

To achieve a BER of 10^{-6}, $OOPSK_{SCM}$ offers a 1 dB average electrical power gain compared to OOK, the widely used modulation in this field, and 2.8 dB gain compared to $QPSK_{SCM}$. These performance gains do not include the power consumption of the drive and decision circuits.

Table 1 presents the average electrical power gain, the average optical power gain, and the electrical peak power gain, all with respect to OOK at the same BER. The comparison is valid asymptotically at high SNR, where the error performance is determined by d, see (6). Thus the signal amplitudes were normalized to give the same d for all modulation formats.

The average electrical power gain is defined as

$$\bar{P}_{e_{gain}} = 10\log_{10}\frac{\bar{P}_{e_{(OOK)}}}{\bar{P}_e}\ \ [\mathrm{dB}] \tag{10}$$

at asymptotically high SNR E_b/N_0, where $\bar{P}_{e_{(OOK)}}$ is the average electrical power of OOK, and $\bar{P}_e = E_s/T_s$ is the average electrical power of the modulation format under study. As a result, $OOPSK_{SCM}$ is shown to have a 1.2 dB average electrical power gain compared to OOK, while it has a 3.0 dB gain compared to $QPSK_{SCM}$.

Table 1 also presents the average optical power gain of the different modulation formats relative to OOK

$$\bar{P}_{o_{gain}} = 10\log_{10}\frac{\bar{P}_{o_{(OOK)}}}{\bar{P}_o}\ \ [\mathrm{dB}] \tag{11}$$

to achieve the same BER at asymptotically high SNR. The average optical power of a modulation format $\bar{P}_o$ depends solely on the DC bias required to make $x(t) \geq 0$ [6]. $OOPSK_{SCM}$ offers a 0.6 dB average optical power gain relative to OOK and 2.1 dB relative to $QPSK_{SCM}$.

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010

From the expressions of the signal waveforms, we derived the electrical peak power gain of the different considered modulation schemes with respect to OOK. This entity is the ratio of the electrical peak power of OOK to the peak power of the other modulations under study. The electrical peak power of a modulation is

$$P_{e_{peak}} = \max_t x^2(t) = \max_{i,t} s_i^2(t). \tag{12}$$

The electrical peak power gain gives a measure of tolerance against the nonlinearities in the laser diode which limit the link performance [4]. In the SCM family, QPSK_{SCM} is 3.0 dB worse than OOK, whereas $\text{OOPSK}_{\text{SCM}}$ is 1.2 dB worse than OOK, making it 1.8 dB better than QPSK_{SCM}, and thus more robust to the nonlinearity impact by the laser diode and this leads to a better link performance.

5. Conclusion

Among the studied modulation schemes, OOK, QPSK_{SCM}, and $\text{OOPSK}_{\text{SCM}}$ occupy the same electrical and optical bandwidth. If power consumption is the main concern for environmental and cost reasons, $\text{OOPSK}_{\text{SCM}}$ is the best choice, whereas if reducing the impact of laser nonlinearity on the link performance is the main concern, OOK is the best choice.

A promising track for future work is to implement this new modulation scheme experimentally, where the effect of nonlinearities and the other impairments present can be quantified, and theoretical models describing the overall system can be derived. This will be the basis for investigations of transceiver complexity and exploration of even more power-efficient higher level modulation formats.

#127671 - $15.00 USD Received 27 Apr 2010; revised 22 Jul 2010; accepted 27 Jul 2010; published 5 Aug 2010