# Coherent OCDMA System Using DPSK Data Format With Balanced Detection

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***Abstract*—In this letter, the application of differential phase-shift keying data format in coherent optical code-division multiple-access (DPSK-OCDMA) has been proposed and investigated theoretically and experimentally to combat noise in the OCDMA system. The DPSK-OCDMA can also ease the receiver's threshold level setting and enhance the system confidentiality.**

***Index Terms*—Balance detection, beat noise, differential phase-shift keying (DPSK), multiple access interference (MAI), optical code-division multiple-access (OCDMA).**

## I. Introduction

RECENTLY, coherent time spreading OCDMA (either direct time spreading by superstructured fiber Bragg grating (SSFBG) [1]–[3] and arrayed waveguide grating (AWG) [4], or spectrally phase coding time spreading by spatial lightwave modulator [5], [6]) has drawn a lot of attention because of the overall superior performance over incoherent schemes. Ten-user truly asynchronous OCDMA has been successfully demonstrated at 1.25 Gb/s [3]. Most recently, the total throughput has been improved to $12 \times 10.71$ Gb/s [4].

However, so far, the modulation format used most for payload data in OCDMA is on–off keying (OOK) with power detection. In a coherent OOK-OCDMA system, the most severe issues are the coherent signal interference (SI) beat noise as well as the incoherent multiple access interferences (MAIs) [1], [3]–[5]. Second, with the changing of the active users' number, a dynamic threshold level setting is required to maintain a wider power margin in the decoder/receiver setup [1], [7]. Third, the OOK-OCDMA is vulnerable in terms of the security that could be easily broken by simple power detection without any knowledge of the code [8], [9].

In this letter, we for the first time propose and investigate the feasibility of using DPSK data format and balanced detection in coherent OCDMA to combat the beat noise as well as MAI, and overcome OOK-OCDMA with respect to the above issues.

## II. Theoretical Model of DPSK-OCDMA

DPSK with balanced detection is an attractive modulation format for long-haul lightwave transmission systems due to its ~3-dB higher receiver sensitivity [10], larger fiber nonlinearity tolerance [11], and better coherent crosstalk tolerance [12] as compared to OOK modulation.

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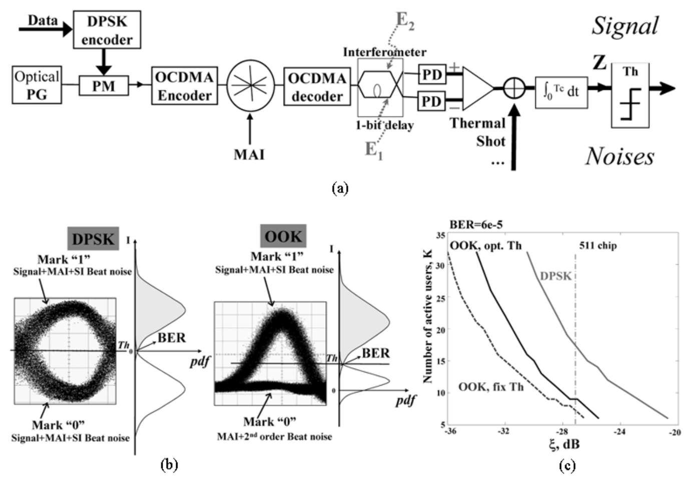


Fig. 1. OCDMA network with DPSK modulation format. (a) Model. (b) Comparison of DPSK- and OOK-OCDMA. (c) Theoretical calculations of $K$ versus $\xi$.

Unlike in the incoherent OCDMA, DPSK could be easily realized in coherent OCDMA since the coding operations are based on the phase of optical field as well. Fig. 1(a) shows a simplified model of the OCDMA networks using DPSK as data format (DPSK-OCDMA). Compared to the model of OOK-OCDMA [1], here the data are encoded by the DPSK encoder, the intensity modulator is replaced by a phase modulator (PM), and the photodetector (PD) is replaced by a 1-bit delay interferometer as the DPSK decoder followed by a balance-detector. The electrical fields $E_1$ and $E_2$ in the interferometer could be expressed as follow:

$$\begin{aligned} E_1(t) &= \sqrt{P_d}\exp j\left(\omega_d \cdot t + \phi_d(t) + D(t)\pi\right) \\ &\quad + \sum_{i=1}^{m} \sqrt{P_i}\exp j\left(\omega_i \cdot (t-\tau_i) + \phi_i(t-\tau_i)\right) \\ E_2(t) &= \sqrt{P_d}\exp j\left(\omega_d (t-\tau_0) + \phi_d(t-\tau_0) + D(t-\tau_0)\pi\right) \\ &\quad + \sum_{i=1}^{m} \sqrt{P_i}\exp j\left(\omega_i \cdot (t-\tau_i-\tau_0) + \phi_i(t-\tau_i-\tau_0)\right). \quad (1) \end{aligned}$$

Therefore, the received electrical signal could be expressed by

$$Z = \int_0^{Tc} \Re \cdot \left[(E_1+E_2)\cdot(E_1+E_2)^* - (E_1-E_2)\cdot(E_1-E_2)^*\right] dt + \int_0^{Tc} n_0(t)dt$$

$$
\begin{aligned}
&\propto T_c P_d \cos\left[(\Delta D(t,\tau_0)\pi\right] + T_c \sum_{i}^{m} P_i \\
&\quad + 2\sum_{i}^{m} \sqrt{P_d P_i} \int_{0}^{Tc} \cos\left(\Delta\omega_{i,d} t - \Delta(\omega\tau)_{i,d}\right. \\
&\qquad\qquad\qquad \left. + \Delta\phi_{i,d}(t,\tau,\tau_0)\right) \\
&\quad + 2 \sum_{i \neq j}^{\frac{m(m-1)}{2}} \sqrt{P_i P_j} \int_{0}^{Tc} \cos\left(\Delta\omega_{i,j} t - \Delta(\omega\tau)_{i,j}\right. \\
&\qquad\qquad\qquad \left. + \Delta\phi_{i,j}(t,\tau,\tau_0)\right) \\
&\quad + \int_{0}^{Tc} n_0(t)\,dt. \qquad (2)
\end{aligned}
$$

Here, $D(t) \in \{0,1\}$ is the encoded binary data, $\Delta D(t,\tau_0) \in \{0,1\}$ is the decoded binary data, $\tau_0$ is equal to the 1-bit duration of data, and other notations are the same as those in [1]. The five terms in (2) represent data, MAI, primary SI-beat noise, secondary interference–interference beat noise, and receiver noise, respectively. Compared to those of coherent OOK-OCDMA [1, eq. (2)], the noise terms have the same distributions, while the term of data changes from "0" to "$-T_c P_d$" for marks "0", due to which, the threshold level is also changed to zero in the DPSK-OCDMA accordingly. Fig. 1(b) shows a schematic comparison of the eye diagrams and noise probability density function (pdf) of the received DPSK- and OOK-OCDMA signals. The bit-error rate (BER) could be easily derived from the pdf [1].

An intuitive model has shown that DPSK has ~6-dB higher crosstalk tolerance than OOK assuming OOK with fixed threshold and symmetric noise distributions for marks "1" and "0" [12]. In our proposed model, marks "1" and "0" have symmetric noise distributions in DPSK-OCDMA, while they are asymmetric in OOK-OCDMA. The pdf and the threshold level determine the BER performance. Below, we will compare the calculated $K$ against $\xi$ using this model. Here, $K$ is the maximum number of active users that could be supported in a network with BER equal to $6 \times 10^{-5}$, and $\xi$ is the interference level that is approximately equal to the inverse of the code length. The data rate is assumed to be 10 Gb/s. For OOK-OCDMA, we calculated the results with optimal thresholder (Opt Th) and fixed Th (1/2 of the received "1"), respectively. Fig. 1(c) shows the result. For a given value of $K$, the DPSK-OCDMA can tolerate about 4-dB higher $\xi$ compared to OOK-DPSK with Opt Th and $5 \sim 6$ dB higher compared to OOK-DPSK with fixed Th. This is a significant improvement for OCDMA because more active users could be accommodated with a shorter optical code length. For example, by using a 511-chip optical code ($\xi \cong 27.1$ dB), about six active users ($K = 6$) could be supported at this BER for OOK-OCDMA with fixed Th, $K = 9$ for OOK-OCDMA with Opt Th, and $K = 17$ for DPSK-OCDMA. Therefore, DPSK-OCDMA could tolerate a higher level MAI and beat noise compared to OOK-OCDMA, which allows it to accommodate more active users.

Second, an Opt Th level has to be found out in OOK-OCDMA in order to obtain the lowest BER [1], while in DPSK-OCDMA, the lowest BER could be easily obtained with a fixed Th $= 0$ without any knowledge of $K$. Therefore, there is no need for dynamic threshold level setting in DPSK-OCDMA, which will simplify the OCDMA receiver.

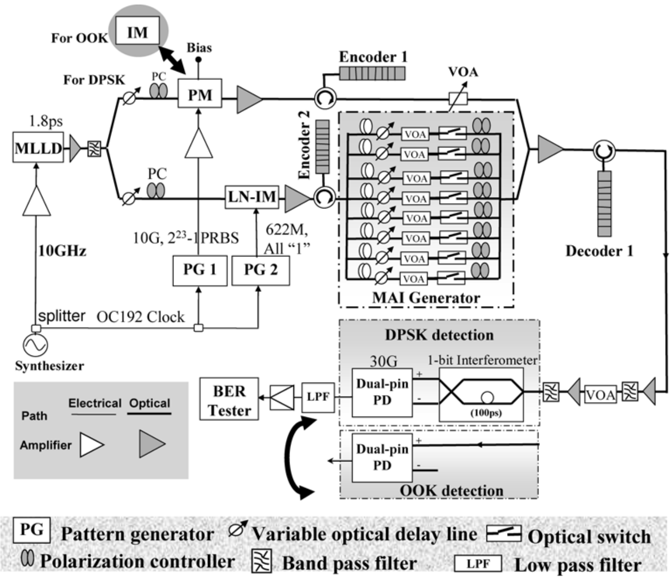


Fig. 2. Experimental setup.

Third, since the modulation is done with the phase of optical signal instead of amplitude in DPSK-OCDMA, both mark "1" and mark "0" have the same energy during transmission, therefore, the above-mentioned security vulnerability of OOK-OCDMA could be completely resolved.

## III. Experiments and Discussion

We have experimentally demonstrated the DPSK-OCDMA using SSFBG E/D for the first time. Fig. 2 shows the experimental setup for the demonstration and comparative investigation of DPSK-OCDMA with OOK-OCDMA. The mode-locked laser diode (MLLD) generated ~1.8-ps optical pulses at a repetition rate of 10 GHz with a central wavelength of 1550 nm. This signal was then split into two paths: The upper path is for a target OCDMA user with 10-Gb/s DPSK or OOK modulation using PMs or intensity modulators, respectively, while the lower one is used to generate different number and level interferences. In the interference path, the "MAI generator" can generate interferences with different $\xi_1$ by tuning the variable optical attenuators (VOAs) and different $K$ by adjusting the optical switches. Here, $\xi_1$ is defined as the power contrast ratio between single interference and the target signal, and $K$ $(0 \leq K \leq 8)$ is the number of interferences. The signal and interferences are mixed and decoded by the decoder. At the receiver, a fiber-based interferometer followed by a balanced detector and a single PD was used for DPSK and OOK detection, respectively.

In the experiment, both the E/D are 511-chip 640-Gchip/s SSFBGs [3]. The durations of the encoded signal and the decoded signal are about 800 ps and 1.6 ns, respectively. Therefore, in the interference path, the data rate is intentionally converted to 622 Mb/s to avoid the intersymbol interference (ISI). However, as in the signal path, the data are transmitted at 10-Gb/s data rate, the ISI will result in the performance degradation [13]. But if we focus on the performance comparison, the ISI could be considered as a fixed level interference to the received signal and be neglected by taking all the measurement

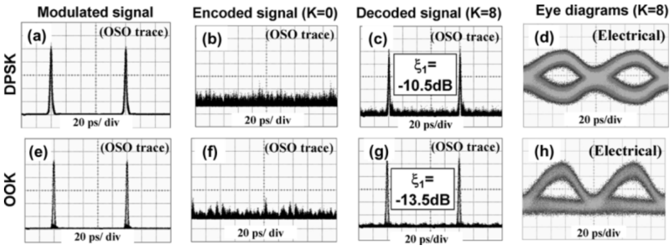


Fig. 3. Measured eye diagrams of the DPSK- and OOK-OCDMA (OSO: optical sampling oscilloscope).

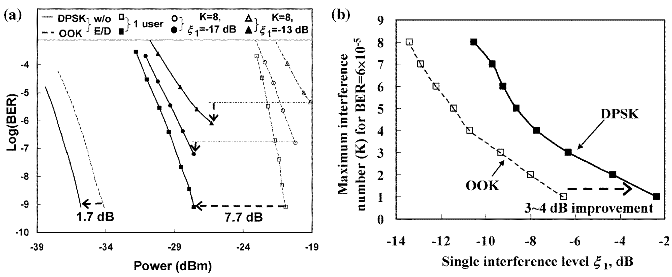


Fig. 4. (a) BER performances with different $K$ and $\xi_1$; (b) $K$ versus $\xi_1$ at $\mathrm{BER} = 6e-5$ for DPSK- and OOK-OCDMA.

against the relative interference level $\xi_1$, which is proportional to the absolute interference level $\xi$ [1] ($\xi_1 \propto \xi$).

Fig. 3 shows the comparison of measured eye diagrams. Figs. 3(a)–(d) and (e)–(h) belong to DPSK and OOK signals, respectively. Figs. 3(a) and (e) are the modulated signals. Figs. 3(b) and (f) are encoded signals without interferences. The blurred waveforms in the encoded signals are due to the ISI [13]. Figs. 3(c) and (d) are decoded OCDMA signals with interferences. Figs. 3(d) and (h) are the electrical eye diagrams of received DPSK- and OOK-OCDMA, respectively. The clear eye opening in the figures verify the feasibility of the proposed DPSK-OCDMA scheme in the presence of ISI, MAI, and beat noises. The signals are measured at the same BER of about $6 \times 10^{-5}$. However, the interference levels are about $-10.5$ and $-13.5$ dB for DPSK- and OOK-OCDMA, respectively. The $\sim$3-dB interference level difference verifies that the DPSK can tolerate higher beat noise and MAI than OOK-OCDMA with the same BER. Also, in the measurement, the threshold level was almost fixed at zero for DPSK while it was varied depending on $K$ and $\xi_1$ in OOK-OCDMA. So, DPSK-OCDMA eases the receiver threshold setting. Fig. 4(a) shows the BER performances of them with different $K$ and $\xi_1$. The improvements for DPSK- over OOK-OCDMA are indicated by the dashed arrows. In the case without OCDMA E/D, the sensitivity improvement in DPSK is about 1.7 dB at $\mathrm{BER} = 10^{-9}$. This is about 1.3 dB less than in previous reports [10]–[12], mainly due to the timing jitter of the MLLD. A low jitter pulse source is a key to overcoming this degradation. In the single OCDMA user's case, the improvement becomes 7.7 dB, the addition 6-dB improvement means that DPSK-OCDMA has larger $Q$-factor than OOK-OCDMA in the presence of ISI. In the $K = 8$ cases, the improvement in both the sensitivity and error floor also shows that the DPSK-OCDMA has better noise tolerance than OOK-OCDMA. Fig. 4(b) shows the measured result of maximum $K$ versus $\xi_1$ for $\mathrm{BER} = 6 \times 10^{-5}$. The improvement of DPSK-OCDMA is $3 \sim 4$ dB. This value is less than the above theoretical prediction, also due to the timing jitter of the MLLD. Since $\xi_1 \propto \xi$, and $\xi \propto (\text{code length})^{-1}$ [1], the DPSK-OCDMA could accommodate more active users with a given code length.

## IV. Conclusion

We have proposed and experimentally demonstrated the DPSK-OCDMA scheme with DPSK data format and balanced detection for the first time. The theoretical modeling shows that the proposed DPSK-OCDMA could be superior over the coherent OOK-OCDMA with advantages of: 1) improved receiver sensitivity; 2) better tolerance to beat noise and MAI noise; 3) no need for optical thresholding; 4) no need for dynamic threshold level setting; and 5) enhanced security. The comparative experimental investigation shows that the DPSK-OCDMA is a more practical approach compared to OOK-OCDMA. The concept could be further extended to other advanced modulation formats in OCDMA systems.

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## References

[1] X. Wang and K. Kitayama, "Analysis of beat noise in coherent and incoherent time-spreading OCDMA," *J. Lightw. Technol.*, vol. 22, no. 10, pp. 2226–2235, Oct. 2004.

[2] P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson, "A comparative study of the performance of seven- and 63-chip optical code-division multiple-access encoders and decoders based on superstructured fiber Bragg gratings," *J. Lightw. Technol.*, vol. 19, no. 9, pp. 1352–1365, Sep. 2001.

[3] X. Wang, N. Wada, T. Hamanaka, A. Nishiki, and K. Kitayama, "10-user, truly-asynchronous OCDMA experiment with 511-chip SSFBG en/decoder and SC-based optical thresholder," in *OFC 2005*, Anaheim, CA, 2005, Postdeadline paper PDP33.

[4] X. Wang, N. Wada, G. Cincotti, T. Miyazaki, and K. Kitayama, "Demonstration of 12-user, 10.71 Gbps truly asynchronous OCDMA using FEC and a pair of multi-port optical-encoder/encoders," in *ECOC 2005*, Glasgow, U.K., 2005, Postdeadline paper Thu 4.5.3.

[5] Z. Jiang, D. S. Seo, S. D. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, A. M. Fejer, and A. M. Weiner, "Four-User, 2.5-Gb/s, spectrally coded OCDMA system demonstration using low-power nonlinear processing," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 143–158, Jan. 2005.

[6] R. P. Scott, W. Cong, K. Li, V. J. Hernandez, B. H. Kolner, J. P. Heritage, and S. J. Ben Yoo, "Demonstration of an error-free $4 \times 10$ Gb/s multiuser SPECTS O-CDMA network testbed," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2186–2188, Sep. 2004.

[7] P. Saghari, R. Gholizadeh, H. Abrishami, E. Pakbaznia, J. E. McGeehan, R. Motaghian, and A. E. Willner, "Experimental evaluation of the optimum decision threshold for varying numbers of active users in a 2-D $t-\lambda$ asynchronous O-CDMA system," in *CLEO 2005*, Baltimore, MA, May 2005, Paper CTuFF4.

[8] T. H. Shake, "Confidentiality performance of spectral-phase-encoded optical CDMA," *J. Lightw. Technol.*, vol. 23, no. 4, pp. 1652–1663, Apr. 2005.

[9] D. E. Leaird, Z. Jiang, and A. M. Weiner, "Experimental investigation of security issues in OCDMA: A code switching scheme," *Electron. Lett.*, vol. 41, pp. 817–819, Jul. 2005.

[10] A. H. Gnauck, "40-Gb/s RZ-differential phase shift keyed transmission," in *Proc. OFC 2003*, Atlanta, GA, 2003, Paper ThE1.

[11] C. Xu, X. Liu, and X. Wei, "Differential phase-shift keying for high spectral efficiency optical transmissions," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 2, pp. 281–293, Mar./Apr. 2004.

[12] X. Liu, Y. H. Kao, M. Movassaghi, and R. C. Giles, "Tolerance to in-band coherent crosstalk of differential phase-shift-keyed signal with balanced detection and FEC," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1209–1211, Apr. 2004.

[13] X. Wang, N. Wada, and K. Kitayama, "Impairments and limitation of inter-symbol-interference and beat noise in data-rate flexible OCDMA with SSFBG en/decoder," *Opt. Express*, vol. 13, pp. 10 469–10 474, Dec. 2005.