International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 3 Issue 12, December-2014, pp: (73-79), Impact Factor: 1.252, Available online at: www.erpublications.com

Performance Improvement of Spectral Amplitude Coding Optical CDMA with Phase Inversion Compensation

Kai-Sheng Chen[1], Chao-Chin Yang[2], Jen-Fa Huang[3]
[1,3]Institute of Computer and Communication Engineering, Department of Electrical and Engineering
[2]Department of Electronic Engineering
[1,3]National Cheng Kung University, Tainan, Taiwan
[2]Kun Shan University, Tainan, Taiwan

Abstract: Researchers of spectral-amplitude coding optical CDMA (SAC-OCDMA) have often suggested that code patterns affect signal-to-noise ratio (SNR) of the system. However, research that as the link between fibre nonlinearity and its impact on SAC pluses evolution is scant. Therefore, the aim of this paper attempts to explore how the deployment of nonlinearity compensation improves the system property. This study comprised of two different parts concerning propagation process of SAC under the appearance of self-phase modulation (SPM) and cross-phase modulation (XPM), and the corresponding compensation scheme. Compensating technique of phase inversion compensation (PIC) participated in the study. The analysis of the system performance was conducted through simulations in order to indicate the relationship between the implementation of PIC and the system bit-error rate (BER). Results of this study showed utilizing PIC in OCDMA system increases the launch power and the number of active users.

Keywords: Optical code-division multiple-access (OCDMA), spectral-amplitude coding (SAC), self-phase modulation (SPM), cross-phase modulation (XPM), fibre nonlinearity compensation.

Introduction

In recent years, there has been an increasing interest in optical code-division multiple access (OCDMA) systems, since they put forth several advantages, for instance, reliability in withstanding eavesdroppers, the state of being free from personal information shared, and good ability to change the number of active users. OCDMA networks permit to make use of channel shared by different users, and the transmission is not governed by specific timing requirements. Thus, users can send data in any order, without waiting for each other. These distinguishing traits make OCDMA different form additional optical multiplexing methods of multi-user communications, such as optical time-division multiple access (OTDMA) or optical wavelength-division multiple access (OWDMA). The applications of OCDMA have been widely investigated. Various approaches are discussed in time-spreading [1], frequency-hopping [2], phase coding [3] and spectral amplitude coding (SAC) [4]. SAC-OCDMA can take out multiple access interference (MAI) during the decoding process.

As the optical components with different wavelengths are transmitted through a fibre channel at the same time, fibre nonlinearity leads to crosstalk result, and the optical signals at distinct wavelengths act on each other. The most common nonlinear phenomenon in fibre is self-phase modulation (SPM), which comes from a variant refractive index determined by the optical intensity. Because the value of the index is lasting steadily only a short period, it makes the phase of optical signals to change in time-variant process. The result of SPM effect causes the spectral amplitude distributing to each chip, at a particular instant, are not the same as original one. Since the intensity of chip varies with time, different portions of the chip, go through different phase action of change. Spectrum is expanded by the demonstration of phase fluctuations that are reliant on the time. Cross-phase modulation (XPM), another nonlinear impairment, which takes place in multiple-wavelength transmission, processes almost the same characteristics of SPM. The results of SPM and XPM make the spectrum boarder and create the optical wave consisting with many peaks.

For a commonly encountered SAC-OCDMA network, a code-word is assigned to a specific user. According to the chip distributions of code-word, the optical encoder converts code information into the spectral patterns of an optical source. The performance of SAC-OCDMA is confined seriously within certain limits of the distorted spectrum, due to the spectral decoding operation in the receiver. Fibre nonlinearities make the code patterns from the normal ones and spoil the spectrum shape completely. The act of getting rid of MAI is not in a complete manner, as signature code fails to keep orthogonal property. Since MAI power cannot be removed without imperfections by balanced detection, interferences from other users make the system performance not as good. Another issue makes SAC-OCDMA network susceptible to nonlinear effects is continually changing waveforms in the frequency domain, which is likely result in random user number and data bit. Thus, SAC-OCDMA is more severely influenced by nonlinear effects than traditional optical communications.

As for linear fibre impairments, such as attenuation and chromatic dispersion (CD), still restricts optical pulse propagation, but compensating CD is without difficulty with a part displaying the opposite effect, for instance, dispersion compensating fibres (DCF). The nonlinear impairments are different in that less compensating schemes than those of linear ones. There are a few materials with such negative coefficient; however, the fact remains that none of them is usable for connecting with real situations. Since nonlinear Schrodinger equation (NLSE) governs the revolutions of the optical field revolves in nonlinear fibre medium, researchers have developed other approaches by deriving NLSE solution precisely for evaluating the degree on pulse changing. For the fibre with zero attenuation and CD, one can derive NLSE solution directly. When both attenuation and CD appear in the channel, advanced algorithms solve NLSE in numerical manners. Split-step Fourier method (SSFM) is often used for getting approximated solutions [5], [6]. Knowledge of fibre nonlinearity compensation has a high importance for improving the performance of fibre network. Compensating fibre nonlinearities in optical domain is an alternative method to mitigate phase noise. Semiconductor optical amplifier (SOA)-based regenerative amplification [7], nonlinear Mach-Zehnder interferometers [8] and nonlinear amplifying loop mirror (NALM) [9] are optical components for building optical compensators. To reduce computational complexity, phase inversion compensation (PIC) has been widely used for mitigating nonlinear fibre effects. Seminal work on compensating SPM effectively in differential phase shift keying (DPSK) modulation was carried out by [10]. Nonlinear fibre was compensated by only one optical modulator, which is used produce an extra phase modulation to cancel the nonlinear phase noise. The papers in [11] provided an extensive discussion of the applications of PIC to delete SPM and XPM partially in coherent optical orthogonal frequency-division multiplexing (CO-OFDM). Utilizing digital signal processing (DSP) in PIC operation, introduced by [12] as a way of compensating both in transmitter and receiver.

A fairly large body of literature exist on the compensating of optical channel effect. However, within that literature, there is a surprising lack of information on the link between fibre nonlinearity and its impact on SAC pluses evolution. No clear direction has emerged to suggest how such considerations of nonlinear fibre impairments influence the orthogonal property of SAC considering the. The study presented in this paper is an attempt to extend the findings of these earlier studies. It is similar the previous studies discussed above, in that the focus is on power-driven phase modulation to fully suppress nonlinear phase shift. It differs from previous studies, however, in the way this phase modulation is carried out in the middle of fibre. This design is closely related to the network structure of SAC-OCDMA. The mid-span compensation is deployed, due to the large number of users in the system. The purpose of this paper is to describe an application of the nonlinearity compensation to enhance the performance of SAC-OCDMA network. More specifically, the study was undertaken in order to understand how the phase deviations induced by SPM and XPM influence the pulse shapes of a spectral-coded optical signal. Also, some theoretical as well as simulating implications of the compensation solution are suggested. If the design of PIC used for this study can be used to compensate other optical transmission schemes, this model can become a much needed method in future research. In view of the preceding research purpose, the first issue of this paper focused on the effect of SPM and XPM on SAC signal transmission. The next question is concerned with the relationship between nonlinear compensation and the performance improvements. This research may provide an alternative to the problem of mitigating nonlinear effects and may lead to a better understanding of the propagation process of SAC-OCDMA signal under the nonlinear optical environment.

Overview of SAC-OCDMA

With a properly written SAC-OCDMA pattern, the light field from the output of the encoder is the coding spectrum according to the address code vector $\mathbf{C}_k$ assigned to the k-th user, $\mathbf{C}_k = [c_k(1), c_k(2),\ldots,c_k(N)]$. Let N be the code length, or the number of wavelength components that can be used for coding, and $c_k(j)$ is the j-th chip value of the k-th code. Each code vector has W nonzero elements, where W is the code weight. The optical encoder spectrally encodes the spectrum of light source into N component chips with centre wavelengths $(\lambda_1, \lambda_2,\ldots, \lambda_N)$. A chip value of “1” or “0” corresponds to an occupied or blank wavelength bin in power spectral density (PSD).If binary codes are used, all amplitudes of wavelength will be exactly like each other to represent the chip value “1”, or low amplitude for the chip value “0”.

The general system setup for the transmitter of SAC-OCDMA is shown in Figure 1. The encoder includes an array of continuous wave (CW) lasers to realize spectral codes according to $\mathbf{C}_k$. Take the example of maximal-length sequence (M-sequence) codes with N=3, W=2 and L=1, where L is the cross-correlation value. The spectral distribution of the M-sequence code vector [1,1,0] is $[\lambda_1,\lambda_2,0]$. To achieve spectral coding, it requires two CW lasers centred at λ_1 and λ_2, respectively. In the case of information format, the bit stream from is modulated by the coded optical signal. A typical form of optical transmission is on-off keying (OOK), where the output of a light source is proportion to the bit value. Table 1 shows the transmitted bit and the corresponding optical spectrum of each user. In the receiver, the combined coded spectrum is divided into two parts, one for the dot-product calculation with the code pattern of the desired user, the other for the calculation with the complementary code. The outputs of two optical fields are taken to a photo-detector, which generates electrical current proportional to the power of optical signals. MAI from other users are taken away by subtraction operation. A balanced detector achieves the above-mentioned processes by performing the following equation, where α is defined as power ratio λ / (ω−λ), ⊙ is the symbol of dot-product, $\mathbf{C}_k$ and $\overline{\mathbf{C}}_k$ are the code vector of the k-th user and its complementary part.

$$\mathbf{C}_l \odot \mathbf{C}_k - \alpha \mathbf{C}_l \odot \overline{\mathbf{C}}_k = \begin{cases} W, l = k \\ 0, l \neq k \end{cases} \tag{1}$$

Figure 2 illustrates the decoders made up by a couple of multiplexers and photo-detectors. The incoming signal from the star coupler is split by an N × 1 de-multiplexer and decoded by two multiplexers. The upper branch filters the spectral component according to $\mathbf{C}_k$, while the lower branch filters the components according to the complementary code $\overline{\mathbf{C}}_k$. After the photo-detector converts the optical signal to photo-current, the power of MAI is deleted by subtraction.

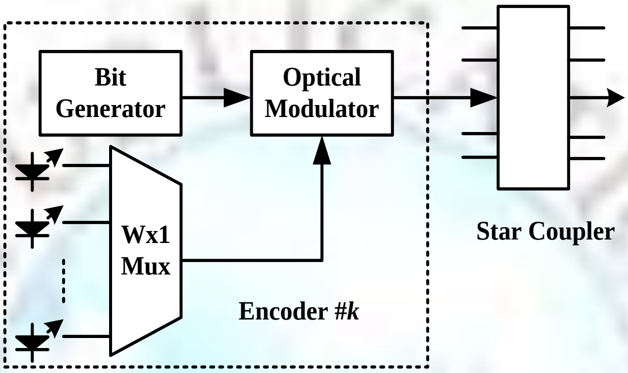

Figure 1. Diagram of transmitter for spectral coded OCDMA network

Table 1: Table Coded-sequence with 3-chip M-sequence code for bit transmission

User Number	Assigned Code Sequence	Data Bit	Transmitted Sequence
#1	1 1 0	1	1 1 0
#2	0 1 1	0	0 0 0
#3	1 0 1	1	1 0 1
Combined Sequence **S**			2 1 1

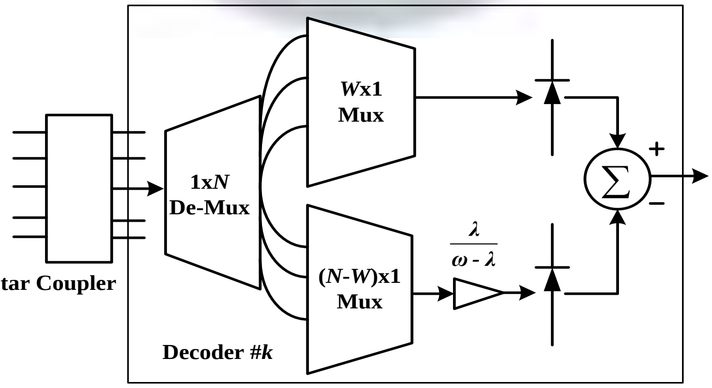

Figure 2. Diagram of receiver for spectral coded OCDMA network

Table 2: Decoding process through balanced detection

User	Correlation		$\mathbf{S}\odot\mathbf{C}_k - \mathbf{S}\odot\overline{\mathbf{C}}_k$	bit
#1	$\mathbf{S}\odot\mathbf{C}_1$	210	3 – 1=2	1
	$\mathbf{S}\odot\overline{\mathbf{C}}_1$	001		
#2	$\mathbf{S}\odot\mathbf{C}_2$	011	2 – 2=0	0
	$\mathbf{S}\odot\overline{\mathbf{C}}_1$	200		
#3	$\mathbf{S}\odot\mathbf{C}_3$	201	3 – 1 = 2	1
	$\mathbf{S}\odot\overline{\mathbf{C}}_1$	010		

Effects of SPM and XPM impairments on SAC-OCDMA

When optical wave is transmitted through a fibre medium with effects of nonlinearity, dispersion and attenuation, it can be put into NLSE to describe the pulses evolution, as shown in (2)

$$\frac{\partial A(z,t)}{\partial z} = -\frac{\alpha}{2}A(z,t) - \frac{i}{2}\beta_2\frac{\partial^2 A(z,t)}{\partial T^2} + i\gamma\left|A(z,t)\right|^2 A(z,t) \qquad (2)$$

where A(z,t) is the signal in complex-value form, z is the transmission distance in km,α is the attenuation coefficient in $\mathrm{dB^1km^{-1}}$, γ is the nonlinearity coefficient in $\mathrm{W^{-1}km^{-1}}$, T is the measured timeframe, and β_2 is the parameter of group velocity dispersion (GVD)in $\mathrm{ps^2nm^{-1}}$. To reduce analysis complexity, the dispersive and attenuated effect are ignored and NLSE is simplified as (3)

$$\frac{\partial A(z,t)}{\partial z} = i\gamma\left|A(z,t)\right|^2 A(z,t) \qquad (3)$$

and $\gamma$is the nonlinear parameter defined as (4)

$$\gamma = \frac{2\pi n_2}{cA_{eff}\lambda} \qquad (4)$$

The value of γ is determined by the nonlinear refractive index n_2, the effective core area of fibre A_{eff}, the optical carrier wavelengthλ and the speed of light in free-space c.

Considering the situation of SAC-OCDMA transmission, a K by 1 passive coupler joins the combined signal spectrum to fibre, where K is the largest number of the active users. The power spectrum density (PSD) of the combination of all users' signal is represented as a(z,ω)

$$a(z,\omega) = \sum_{k=1}^{K} b_k \sum_{j=1}^{N} c_k(j)g(z,\omega_j) \qquad (5)$$

Where $b_k \in \{0,1\}$, for $0 \le k \le K$, is the information bit of the k-th user, g (z,ω_j) is PSD of thej-th chip in the code vector. Let the inverse Fourier transform of a(z,ω) and g(z,ω_j) in (5) be A(z,t) and G(z,t), respectively. A solution of A(z,t) at z = L can be derived analytically by substituting (5) into (3), as shown in (6)

$$A(L,t) = A(0,t)e^{-i\phi(t)} \qquad (6)$$

For the case that the dispersion and attenuation effect are not severe, the time-dependent nonlinear phase is shown in (7)

$$\phi(t) = \gamma LK\left|G(0,t)\right|^2 [\sum_{j=1}^{N} c^2(j) + 2\sum_{k=1,k\neq j}^{N}\sum_{l=1,l\neq j}^{N} c(k)c(l)] \qquad (7)$$

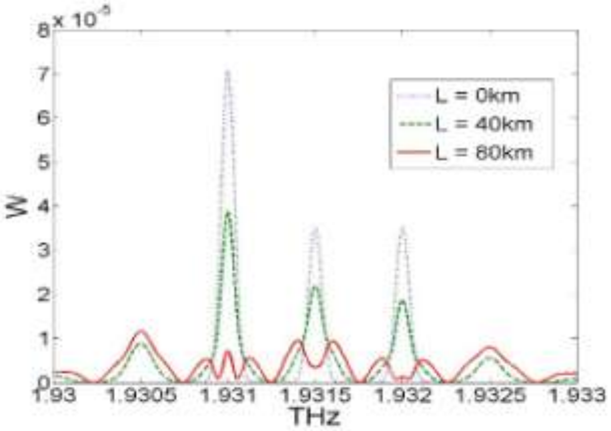

Figure 3. **Pulse distortions of SAC-OCDMA induced by SPM and XPM**

Table 3: Impacts of fibre nonlinearities on losing coding orthogonal property

L(km)	Received Spectrum **S**			Output of Decoder		
				#1	#2	#3
0	2	1	1	2	0	2
40	1.286	1.008	0.756	1.538	0.478	0.962
80	0.485	0.797	0.402	0.880	0.714	0.090

In (7), SPM is expressed in the first term and XPM in the second term. The value of two means the quantity of XPM-induced phase shift is double of that induced by SPM. Figure 3 shows the spectral distortion in SAC-OCDMA caused by fibre nonlinearities. Take the example of Table. 1 for demonstration. The central wavelength of each chip is 50 GHz-spaced, with power of 2 mW. The shape of each chip is modelled as Gaussian distribution. A nonlinear coefficient is 1.3km^{1}W^{-1} in fibre. From Figure 3, the full extent of spectral domain becomes flattened and its intensity varies between alternate extremes. The source of oscillatory spectrum can be observed from (7), which has a time-variant phase chirp.

To evaluate the effects of SPM and XPM on SAC-OCDMA network, the results of the decoding process is shown in Table 3.Accordingly, the summed intensity signal vector (2,1,1) are expected the receiver. A balance detector takes the summed signal to correlation operation for decoding. For active user #1, the ideal threshold is two to judge bit “1” is sent, while zero value to judge bit “0” for non-active case, according to (1). However, during fibre transmission, the code patterns had impairments from fibre nonlinearities that result in spectral broadening. Table 3 shows the difference between levels of bit “1” and “0” are getting close as the transmission distance increases, which results from losing the orthogonal property between address codes. Even a bit “0” sent by user#1, a residual optical component is shown in the receiver, which means MAI is not completely mitigated by balanced detection.

Proposed fibre compensation scheme of SPM and XPM for SAC-OCDMA

In this paper, the nonlinear phase noise is mitigated by the proposed PIC compensator. PIC is employed in the middle of two identical fibre spans to restore the pulse shape. In the receiver end, the optical field is expected to recover completely from fibre nonlinearities. The principle of mid-span PIC for SPM and XPM is verified by using (8). The optical field before PIC is derived by setting the transmission distance z = L/2, where L is the fibre total length. After propagating through the first-half fibre, the optical yields in (8)

$$A(L/2,t) = A(0,t)\exp(-i\gamma L|A(0,t)|^2/2) \tag{8}$$

The phase of optical field A(L/2,t) is inverted by PIC compensator, which is given by a phase-conjugated field A^* in (9)

$$A^*(L/2,t) = A^*(0,t)\exp(+i\gamma L|A(0,t)|^2/2) \tag{9}$$

Then the conjugated optical field A^* is further sent to the second-half fibre. By substituting (9) into (8), the restored signal is found in the receiver

$$A^*(L,t) = A^*(L/2,t)\exp(-i\gamma L|A(0,t)|^2/2) = A^*(0,t) \tag{10}$$

From (10), it suggests that if the phase of optical field is inverted in the middle of the fibre link, SPM and XPM induced in the first-half fibre will be fully cancelled in the section of second-half fibre. It shows that PIC takes fibre nonlinearities away efficiently. Figure 4 shows the proposed scheme of PIC for SPM and XPM in detail. The instant power of SAC optical field is uncovered by a photo-detector. An optical phase modulator modulates the original optical field with the phase modulation proportional to the detected power signal. The phase-inversed process is achieved by a phase modulation with the same amplitude of the nonlinear phase noise induced by the first-half of fibre but with the opposite sign. Then the modified optical field launches into the second-half fibre. As for XPM compensation, because the intensity of optical field in each wavelength is not the same, separate photo-detectors are required to detect the individual power. Low-pass filters (LPFs) remove the electrical noise during the optics-to-electrics conversion. The sum of all filtered signals is used for compensating XPM through an optical modulator. An optical amplifier provides a gain of two, due to the weighted factor for XPM. It is clear that the phase of the original and compensated optical field has the same magnitude but with the opposite sign. Thus, phase inversion is achieved by the proposed scheme. For the system with long code length, multiple photo-detectors and LPFs are needed to identify the power variations.

Simulation results on the compensated SAC-OCDMA systems

In this section, the proposed nonlinearity compensation in SAC-OCDMA system is simulated with the software tool of Optisystem^{TM} 7.0. For the transmitter part, the bit rate is 10 Gb/s, and the data bit is spectrally encoded by M-sequence code with code-length of three. Optical source is modelled as three Gaussian optical pulses centred at 193.10, 193.15 and 193.2 THz, respectively. For system simplicity, this simulation only takes account fibre nonlinear effects. For the receiver parts,

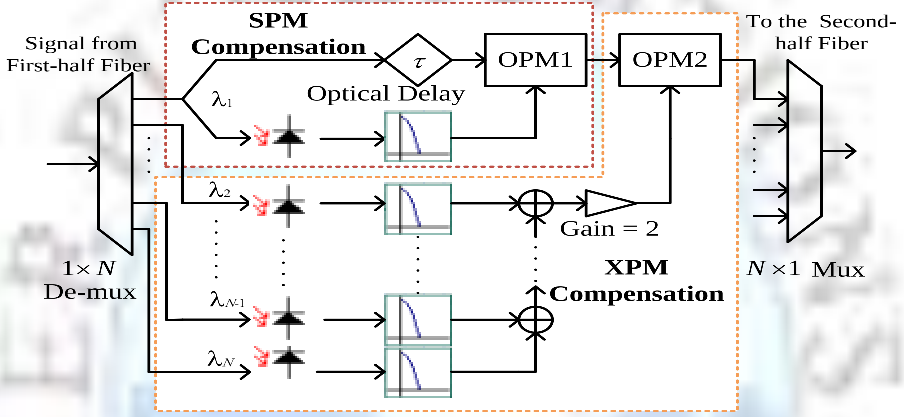

Figure 4. Compensating scheme for SPM and XPM; OPM: optical phase modulator, De-mux: wavelength de-multiplexer thermal noise, which is the most common noise source at photo-detecting process, is assumed to be white Gaussian distributed with PSD of 10^{-22} W/Hz. The responsivity of photo-detector is 1 A/W.

Figure 5 shows the benefit of nonlinear compensation by interpreting the relationship between BER and the power per chip. The transmission distance is 40 km and the chip power ranges from 0.5 mW to 3.5 mW. System performance with PIC is compared with that without PIC. The code pattern used for SQC-OCDMA system is M-sequence code with code length of three. Also, system performance of different numbers of active users is shown in Figure 5. For the chip power is relatively low, optical field with or without PIC has similar performance. At the level of low power, fibre nonlinearities are not severe. The main factor that influence BER is thermal noise in the receiver. When SAC-OCDMA system operates in the low-power region, BER can be simply improved by increasing the chip power. However, once the optical power is greater than the value of nonlinear threshold, SPM and XPM have stronger effects and degrades system performance. Implementing PIC in the system scheme allows higher launch power with lower BER. The compensated with PIC has a 3 dB improvement for k larger than two under BER = 10^{-9}.

Conclusions

In conclusion, a method of fibre nonlinear compensation scheme of phase inversion is proposed to mitigate the effects of SPM and XPM in SAC-OCDMA. A phase modulator is used to inverse the time-dependent phase of the optical field at the beginnings of second-half fibre. The magnitude of this phase modulation is positive related to the power of the optical detected pulse, but its sign is different from the nonlinear phase shift caused by SPM or XPM. Thus the nonlinear phase noise caused by the power variations of SPM and XPM in the first-half fibre is compensated by the second-half fibre. In the proposed compensation schemes, only a single tuning parameter is used in the mid-span compensation, so improvement is achieved without knowing the actual fibre transmission format. The real value of this parameter can be derived by optimization process. Except for M-sequence code, PIC can process for dynamic code variations in the system, so it is transparent to the launch power and code patterns. According the simulations results, SAC-OCDMA at 10 Gb/s with such a PIC plan can provide near 3dB of development in optical transmissions.

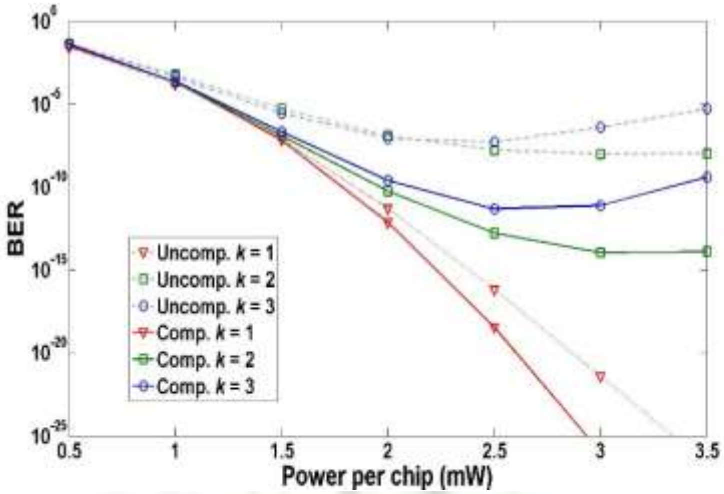

Figure 5. BER performance versus input chip power for 40-km long fibre

Despite the advantages of simplicity in the proposed PIC scheme, it does have some limitations. First, analysis in this paper neglects other linear fibre impairments, such as attenuation and dispersion. These linear effects seriously limits PIC's usefulness in compensating fibre nonlinearities efficiently. Particularly challenging is hard to knowing the real evolutions of optical pulse under the interactions of linear and nonlinear fibre effects. Further research is necessary to explore how linear effects influence the efficiency of PIC. Much more also needs to be known about the performance analysis of other typical parameters in SAC-OCDMA, such as different code lengths and code patterns. There is a continuing need for an adequate theoretical basis for the practical application of implementing PIC into different optical communication systems.

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