Abstract-This paper examines the four-wave mixing (FWM) effect on optical code-division multiple-access (OCDMA) performance systems in the presence of Multi-Diagonal code (MD). System performance improvement is accomplished by means of fibre length tuning and stratified different modulation shapes, which are Non-return-to-Zero (NRZ), Gaussian, and Sine wave, all examined with 500 and 1Gb/s data rate values. The tests show that the NRZ modulation offers better system performance compared with other modulations for all data rate values used. Moreover, the second channel of each user offered better system performance than the other channels used. For instance, for 1Gb/s, at the second channel, the NRZ modulation offered the best performance with a quality factor (Q-factor) of 5.1 at 100 km fibre length, whereas the first channel introduced a worse Q-factor of 3.1 at the same fibre length value.

Keywords: Nonlinear crosstalk, Multi-Diagonal (MD) code, FWM, OCDMA, NRZ

1. Introduction

The Optical Code Division Multiple access techniques offer optimum safeness in communication and permit different users to pass through an optical network by means of a bandwidth sharing strategy. However, OCDMA systems’ efficiency is restricted by a Multi-Access Interference effect (MAI) [1]. MAI is the main source of deviation in any OCDMA system, and thus attention to design for the code sequences and detection scheme is important to reduce the effects of MAI [1-2]. The design of the sender in OCDMA systems is influenced by the detection technique type, whether coherent or incoherent detection. Coherent detection indicates the detection of signals based on knowledge of the carrier's phase information, while incoherent detection indicates a case without such knowledge. Utilising coherent processing by means of bipolar orthogonal codes is allowed by several schemes, such as gold sequences [3], with close-to-zero cross correlation functions, which minimises MAI. In contrast, the signature code in incoherent optical signal processing is a family of unipolar (0, 1) sequences. For MAI reduction, the signature code must be sparse in binary ones with low side lobes of autocorrelation and functions of cross correlation. Prime codes and optical orthogonal codes (OOCs) are two well-known families of unipolar codes designed for incoherent OCDMA [4]. Both coherent and incoherent OCDMA have been studied and can provide synchronous user access, but in this paper, incoherent OCDMA systems, where less complexity is required than in coherent ones, are examined. In these systems, the phase induced intensity noise (PIIN) imposes the major limit on system performance; the overlapping spectra coming from different users mean that PIIN is related to MAI in OCDMA systems [5-6], but it is important to realise that while electrical subtraction can solve MAI, PIIN cannot be changed. Consequently, in OCDMA systems, whole system performance can be severely affected.
by inherent PIIN issues [7]. A zero cross correlation code design is thus required in OCDMA systems to eliminate the influence of MAI and suppress the PIIN effect. The effect of PIIN can then be ignored where the cross correlation is near to zero when considering the effects of thermal noise and shot noise.

The main factor that may cause interference in transmission systems in which the channels are arranged to be separated by the same spacing is called four-wave mixing (FWM). For optical communication systems, the efficiency of suppressing FWM is a major concern, and to mitigate the defects in FWM efficiency, several techniques have been developed, including modifying the signal output [8–20]. In previous works on OCDMA systems, performance analysis has been done without assuming the FWM effect, which happens due to the mixing of three frequencies to produce a fourth frequency, despite the fact that FWM crosstalk degrades system execution. In this work, the representation of optical code division across multiple access systems assumes the FWM effect has been addressed. A mathematical analysis is thus offered to evaluate the Q-factor of OCDMA systems with SMF under different data rates and pulse shapes. The results suggest that NRZ modulation offers better performance than other modulation types investigated.

2. Related work

In an optical code-division multiple-access network, FWM is the major limitation source of system performance. Several different techniques have thus been used to suppress the effects of FWM crosstalk to improve the signal output [21–24]. Fabrizio et al. [21] suggested a channel spacing design to suppress FWM crosstalk defects, and for a 10-channel system, choosing a suitable space between channels minimised FWM crosstalk and increased the received power to 9 dBm. However, this technique could not decrease the FWM crosstalk outside the receiver bandwidth. Singh et al. [12] generated a numerical analysis for both the single and combined effects of dispersion parameters of the second-, third-, fourth-, and fifth-order on FWM power at varied input power values and cross effective areas. FWM power was suppressed by mixing the second- to fifth-order dispersion term effects; however, the weakness of this analysis lay in the absence of consideration of dispersion compensation. Kaler et al. [13] performed a comparison of FWM using low unequal channel spacing. Increasing channel spacing was seen to prevent interference between spaced channels and to mitigate the FWM effect. However, decreasing the FWM crosstalk levels by using unequal channel frequency spacing is not practical. A previous study also attempted to reduce FWM crosstalk by setting the polarisation state [24]. This paper, on the other hand, investigates the FWM effect on OCDMA performance by assuming Multi-Diagonal code (MD).

3. Multi-Diagonal (MD)

A) Multi-Diagonal (MD) code properties

The parameters (N, W, λc) represent the MD code: N is the code length, W is the code weight (chips with the value of 1), and λc the in-phase cross-correlation [25]. An N-by-N square matrix with elements on the essential diagonal and zeros elsewhere represents the identity matrix. This is referred to as I_N, or I if the size is immaterial or can be trivially determined by context.
The abbreviated diagonal matrices can then be written
\[ I_N = diag(1, 1, ..., 1). \] (1)
A square matrix has real entries where columns and rows are orthogonal unit vectors representing orthogonal matrices. Equivalently, a matrix (matrix A for example) is defined as orthogonal if its inverse is the same value as its transpose:
\[ A^T A = A A^T = I. \] (2)
Alternatively,
\[ A^T = A^{-1}. \] (3)
As an example, if A is a square matrix (NxN), A is orthogonal if and only if
\[ A^T A = I_{N \times N}. \]
If \( x_{ij} \) is an entry element from X and \( y_{ij} \) is an entry element from Y, then the entry from the product \( C = XY \) is given by \( C_{ij} = \sum_{k=1}^{n} X_{ik} Y_{kj} \). For the code sequences \( X = (x_1, x_2, x_3, ..., x_n) \) and \( Y = (y_1, y_2, y_3, ..., y_n) \), the cross-correlation function is thus given by
\[ \lambda_c = \sum_{i=1}^{n} x_i y_i \] (4)
The code has zero cross-correlation properties when the value of \( \lambda_c = 0 \). The matrix of the MD code is thus functionally a \( K \times N \) matrix based on the number of users (K) and the code weight (W). To generate MD code, the adopted weight must thus be greater than 1.

**B) Creation of MD Code**
The points below explain the steps for determining the MD code:

**Point 1:**
In the beginning, a diagonal matrices sequence is constructed using (W) and (K), which represent the weight and number of subscribers, respectively. As a result, the values \( i, j \), and \( j_w \) are taken where \( K \) and \( W \) are positive integer numbers, \( (n = 1, 2, 3, 4, ..., n = K) \) that are recognised by the number of rows in every matrix, and \( (j_w = 1, 2, 3, 4, ..., W) \) offers the number of diagonal matrices required.

**Point 2:**
The MD sequences are estimated for every diagonal matrix such that
\[ S_{k,jw} = \begin{cases} (n + 1 - i), & \text{for } j_w = \text{even number,} \\ i, & \text{for } j_w = \text{odd number,} \end{cases} \] (5)
Thus, based on the previous steps. From equation (10), the rows equal the total user number (K). It is worth noting that the relationship between code weight (W), matrices elements show the diagonal matrix MD code sequence can then be presented as

\[
S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ \vdots \\ K \end{bmatrix}, \quad S_{i,2} = \begin{bmatrix} 3 \\ 3 \\ \vdots \\ 2 \end{bmatrix}, \quad S_{i,3} = \begin{bmatrix} 3 \\ 2 \\ \vdots \\ K \end{bmatrix}, \quad S_{i,4} = \begin{bmatrix} 1 \\ 2 \\ \vdots \\ K \end{bmatrix}
\]

\[S_{i,w} = \begin{bmatrix} w_{i1} \\ \vdots \\ w_{ik} \end{bmatrix}, \quad w_{ij} \in \{0, 1\}
\]

The \(S_{i,w}\) matrices elements show their position in \(T_{i,w}\) matrices that have KxK dimensions where

\[
T_{i,1} = S_{i,1} S_{i,1}^{T}, \quad T_{i,2} = S_{i,2} S_{i,2}^{T}, \quad \ldots, \quad T_{i,w} = S_{i,w} S_{i,w}^{T}
\]

Thus,

\[
T_{i,1} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{K \times K}, \quad T_{i,2} = \begin{bmatrix} 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \cdots & 0 \end{bmatrix}_{K \times K}, \quad T_{i,w} = \begin{bmatrix} 0 & 0 & \cdots & 1 \end{bmatrix}_{K \times K}
\]

**Point 3:**

The total set of diagonal matrices (8) creates an MD code in the form of a matrix of power KxN.

\[
MD = \begin{bmatrix} T_{i,1}; T_{i,2}; \ldots; T_{i,w} \end{bmatrix}_{K \times N}
\]

From equation (10), the rows equal the total user number (K). It is worth noting that the relationship between code weight (W), code length (N) and user number can be expressed as

\[N = K \times W\]

Based on the previous steps in the MD code sequence, i.e. K= 4 and W= 4, the values of \(i = 1, 2, 3, 4\), \(n + 1 = 5\) and \(j_w = 1, 2, 3\) are obtained. The diagonal matrices can thus be depicted as

\[
S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix}, \quad S_{i,2} = \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix}, \quad S_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix}, \quad S_{i,4} = \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix}
\]

The diagonal matrix MD code sequence can then be presented as
\[
\begin{align*}
T_{i,1} &= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}_{4 \times 4}, \\
T_{i,2} &= \begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}_{4 \times 4}, \\
T_{i,3} &= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}_{4 \times 4}, \\
T_{i,4} &= \begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}_{4 \times 4}
\end{align*}
\]

and the final sequence of the MD code should be:

\[
MD = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1
\end{bmatrix}_{16 \times 16}
\]

where \( K = 4, N = 16 \). The code word of every user in the example will thus be

\[
\begin{align*}
\text{user 1} &\Rightarrow \lambda_1, \lambda_2, \lambda_3, \lambda_4 \\
\text{user 2} &\Rightarrow \lambda_5, \lambda_6, \lambda_7, \lambda_8 \\
\text{user 3} &\Rightarrow \lambda_9, \lambda_{10}, \lambda_{11}, \lambda_{12} \\
\text{user 4} &\Rightarrow \lambda_{13}, \lambda_{14}, \lambda_{15}, \lambda_{16}
\end{align*}
\]

C) OCDMA performance analysis

To study the performance of the suggested MD code employing a direct detection method, a Gaussian approximation was utilised to assess system performance of the noise in the detector. The SNR of an electrical signal can be described as the ratio of average signal power \(I^2\) to noise power \(SNR = I^2/\sigma^2\). The MD code words have zero cross-correlation; thus, there is no overlapping in the spectra of various users, so the impact of incoherent intensity noise was ignored. The total noise power of the photo-detector expression is thus

\[
\sigma^2 = 2eBI + \frac{4KT_B}{R_k}
\]

In Equation (15), the first term results from the noise sent and the second term represents influence of thermal noise. Let \(C_K(i)\) refer to the \(i\)th element of the \(K\)th MD code sequences; then, based on the characteristics of MD code, the expression of direct detection technique is

\[
\sum_{i=1}^{N} C_K(i)C_K(i) = \begin{cases} 
W, & \text{For } K = l \\
0, & \text{Else}
\end{cases}
\]

The power spectral density at the photodetector of the receiver during a one period integration can be depicted as

\[
\int_{0}^{\infty} G(v)dv = \int_{0}^{\infty} \left[ \frac{p}{2\pi} \sum_{K=1}^{K} d_K \sum_{i=1}^{N} C_K(i)C_K(i) \left( u[v - v_0 - \frac{N}{2\pi} (-N + 2i - 2)] - u[v - v_0 - \frac{N}{2\pi} (-N + 2i)] \right) \right] dv
\]

As a consequence,
\[
\int_0^\infty G(v)dv = \frac{P_v W}{N}.
\] (18)

The photocurrent, I, can be calculated using
\[
I = \Re \int_0^\infty G(v)dv
\] (19)

Equation (19) can then be expressed as
\[
I = \Re \int_0^\infty G(v)dv = \frac{\Re P_v W}{N}
\] (20)

Substituting Equation (20) into Equation (15) gives
\[
\sigma^2 = \frac{2eB P_v W}{N} + \frac{4K_T B}{R_L}
\] (21)

To assess system performance under the impact of FWM crosstalk and other noise types, however, FWM crosstalk expressions should be added, as in equation (22):
\[
C_{IM}^{(m)} = \frac{1}{8} \sum_j P_{i j k} + \frac{1}{4} \sum_l P_{i l k}
\] (22)

where \( C_{IM}^{(m)} \) is the FWM crosstalk effective in intensity modulation-direct detection (IM-DD) transmission. Note that the probability of transmitting a bit ‘1’ at any time for every user is 1/2; therefore, equation (21) becomes
\[
\sigma^2 = \frac{eB P_v W}{N} + \frac{4K_T B}{R_L}
\] (23)

Finally, from equations (25-27), the average SNR can be calculated as:
\[
\text{SNR} = \left\lfloor \frac{\Re P_v W}{N} \right\rfloor
\] (24)

\[
\text{BER} = P_\text{e} = \frac{1}{2} \text{erf}\left(\sqrt{\frac{\text{SNR}}{8}}\right).
\] (25)

4. Optical system design description

The proposed systems were modelled using commercial software, OptiSystem™ version 14 from Optiwave, as seen in Figure (1). The noise sources, the effect of the input power, fibre length, and data rate were evaluated for the MD code. Figure (1) also describes the transmitter and receiver design for the model. The transmitter part starts with a DC. source (Bias Generator) which is connected to the light emitting diode (LED); the LED parameters are shown in Table (1). The total bandwidth of the LED was set to 40 nm and divided into four main groups. Each group consisted of four users; the wavelength spacing between each user
and the others is around 0.2 nm; thus, the first user wavelength is set to 1550 nm while the last user is adjusted to 1553 nm. The output of each group was then conducted to an external modulator consisting of a Pseudo–Random Bit Sequence (PRBS) linked to a pulse generator to allow optical signal modulation using various pulse shapes. Thereafter, this was connected to a Mach-Zehnder modulator (MZM), which represents an intensity modulator. The transmitted optical signals were collected and fed into one optical combiner. The optical link used a single mode fibre to represent the transmission system.

At the receiver, a power splitter was utilised to split the optical input signal into a number of output signals. Each output signal was then passed to a Bessel optical filter set to a specific bandwidth to select the desired user. The desired users were chosen as 1550 nm, 1550.8 nm, 1551.6 nm, and 1552.4 nm. The signals were detected using a PIN photodiode with a responsivity (K) of 0.8 A/W and a dark current of 10 nA. Subsequently, the signals are passed over the low-pass Bessel filter and linked to the BER analyser, which produces a graph. Table 1 explains the system parameters in the transmitter, optical channel, and receiver.

![Figure (1): Proposed system simulation.](image)

| Table 1: LED parameters |  |  |
|--------------------------|--|--|
| **Name**                 | **Value** | **Unit** |
| Wavelength               | 1550      | nm       |
| Electron lifetime        | $1 \times 10^{-9}$ | s |
| RC constant              | $1 \times 10^{-9}$ | s |
| Quantum efficiency       | 0.05      | -        |
| Bandwidth                | 40        | nm       |

| Table 2: Optical system parameters |  |  |
|------------------------------------|--|--|


5. Simulation results and analysis

In this section, all the simulated results and analyses are discussed to support the objective of this paper.

5.1. Results of proposed system design for NRZ pulse

A. System performance estimation

Figure (2) illustrates fibre length versus Q factor under the impact of nonlinearity, the FWM for the NRZ pulse. The results were obtained after tuning the fibre length from 10 to 100 km and applying a 500 Mb/s data rate. The findings show that increasing fibre length will decrease the Q factor for all given channels. The trend of Q factor differed from one channel to another, however, seemingly based on the durability of channel in response to the nonlinear effects. In the second channel case, the system performance was best, with a Q-factor value of 6 at 100 km fibre length. However, the first channel (Ch1) produced the minimum Q factor of around 2.4 at the same fibre length value. On increasing the data rate to 1Gb/s, the system performance was decreased. However, the trend of channel performance was similar to that of the 500 Mb/s data rate, with the second channel offering better performance and a Q-factor of 5.1 at 100km fibre length, while the first channel introduced a worse Q-factor of 3.1 at the same fibre length, as seen in Figure (3).

| Name               | Values          | Unit       |
|--------------------|-----------------|------------|
| Fibre length       | 10 - 100        | km         |
| Input power        | 5               | dBm        |
| Input wave length  | 1550:0.2:1553   | nm         |
| Dispersion         | 17              | ps/nm.km   |
| Dispersion slope   | 0.075           | ps/nm².km  |
| Cross effective area | 80             | µm²        |
| Refractive index   | 1.48            |            |
| Speed of light     | 3×10⁸           | m/s        |
| Attenuation factor | 0.2             | dB/km      |
| Number of users    | 16              |            |
| Detector responsively | 0.8         | A/W        |
| Data rate          | 0.5, 1         | Gb/s       |
| Modulation type    | NRZ, Sin wave and Gaussian |       |
B. Eye Diagram Performance

The eye diagram of the proposed system design using NRZ in the second channel was clearer than the eye diagram of performance measured at the first channel for the 500 Mb/s data rate, as seen in figure (4).
C. Electrical Signal analysis

The electrical signals output on the electrical filter for 100 km fibre length with NRZ pulse and 500 Mb/s were investigated using scope visualisation. From Figure (5), it can be seen that for optical transmission systems using NRZ, the second channel has a higher power amplitude than the first channel, which means that the signal power dominates the noise power, improving the electrical signal in the receiver.

5.2. Results of proposed system design for sine wave pulse

A. System performance evaluation

To perform further investigation, the proposed design was activated using a sine wave pulse with the same assumptions and parameters used in the simulation of the NRZ pulse. The suggested optical system was thus implemented with a data rate of 500 Mb/s. Figure (6) shows the relationship between the fibre length and Q factor under system nonlinearity. The system
performance attitude of NRZ was repeated with the sine wave pulse. System performance was improved in the second channel, which provided the best value for Q at 5.8 at the 100 km fibre length; the first channel it provided a minimum value of Q factor of 2.5 at the same parameters. The Q-factor is better for the NRZ pulse generator than the sine wave. This means that the NRZ offers higher resistance to nonlinear effects compared with other types. After increasing the data rate to 1Gb/s, the system performance in term of Q-factor was degraded due to the higher data rate. However, the same behaviours were observed in terms of channel utility, with the second channel offering better performance and a Q-factor of 5 at 100 km fibre length, while ch1 introduced a worse Q-factor of 3 at the same fibre length, as shown in Figure (7).

Figure (6): Q-Factor versus fibre length for sine wave pulse at 500 Mb/s data rate

Figure (7): Q-Factor versus fibre length for sine wave pulse at 1Gb/s data rate
B. Eye Diagram Performance:

The eye diagram of the proposed design using a sine wave at the second channel shows greater efficiency and a higher amplitude than the eye diagram of the performance measured at the first channel. For ch1, the eye diagram displays a wider opening than the other channels, as shown in Figure (8).

![Eye Diagram Performance](image)

Figure (8): Eye Diagram performance of 100 km length for sine wave at (a) ch2, and (b) ch1

C. Electrical signal analysis

The electrical signals output for the 100 km fibre length with a sine wave pulse at 500 Mb/s was analysed using an electrical scope. Figure (9) shows that the amplitude of the optical transmission system using the sine wave and applying ch2 has a high power than that using ch1. This means that the signal power is higher than the noise power, and thus the output signal power is increased. Figure (10) offers a comparison of different pulse shapes for four wave mixing crosstalk types. The results show the improvement under NRZ conditions compared to other options using the same input conditions. Table (3) further illustrates the comparison between MD and other codes for same number of users [24-27].
Figure (9): Electrical signal output with oscilloscope set to 100 km for Sine wave (a) ch2, and (b) ch1

Figure (10): Q-Factor versus fibre length for different pulse shape at a data rate of 1Gb/s

Table 3: Comparison between MD and other codes

| No | Codes | No. of Users (K) | Weight (W) | Code Length (N) | Cross-correlation ($\lambda_c$) |
|----|-------|------------------|------------|----------------|-------------------------------|
| 1  | OOC   | 30               | 4          | 359            | $\leq 1$                      |
| 2  | Prime | 30               | 31         | 961            | $\leq 1$                      |
| 3  | MFH   | 30               | 7          | 42             | 1                             |
| 4  | EDW   | 30               | 3          | 60             | $\leq 1$                      |
6. Conclusion

In this paper, the FWM effects on system performance of OCDMA with Multi-Diagonal code (MD) were analysed. In addition, the system performance was evaluated for the effects of fibre length tuning and the application of different modulation shapes. The results showed that the NRZ modulation offered better system performance than other modulation types for all data rate values. In addition, the second channel offered better system performance than other channels at the same input parameters; for example, for 1Gb/s, the NRZ modulation offered better performance where the Q-factor was 5.1, at the 100 km fibre length at the second channel, while the first channel introduced a worse Q-factor of 3.1 at the same fibre length value.

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