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A NEW CLASS OF TWO-DIMENSIONAL (2-D) MODIFIED-FCC (M-FCC) OCDMA FOR CARDINALITY ENRICHMENT TOWARDS 6G NETWORK ACCESSIBILITY

H. DAYANG[1], C.B.M RASHIDI[2], S.A ALJUNID[3]

[1,2,3] Advanced Communication Engineering, Centre of Excellence
Faculty of Electronic Engineering Technology
Universiti Malaysia Perlis, Malaysia

E-mail: [1]h_dayang@unimap.edu.my, [2]rashidibeson@unimap.edu.my, [3]syedalwee@unimap.edu.my

ABSTRACT

In this paper, we introduce a new two-dimensional (2-D) wavelength/time optical code division multiple access (OCDMA) known as 2D Modified-Flexible Cross Correlation (M-FCC) code. The 2-D M-FCC code is developed from the one-dimensional flexible cross correlation code families with flexibility in-phase cross-correlation at any given number of users and weights. The main goal is to reduce noise as well as multiple-access interference (MAI) at the same time to accommodate higher cardinality with minimum noise. The increment of cardinality is to be engaged towards 6G network accessibility. From the numerical results, it indicated good performance whereas the 2-D M-FCC code at bit rate 622 Mbps with at BER of 3.49×10^{-28}, can accommodate 200 number of cardinalities enrichment. Moreover, the 2-D M-FCC code shows good SNR curves as gradually decreases as the number of users increases at different bit rate 155 Mbps, 622 Mbps, 1.1 Gbps and 2.5 Gbps, respectively.

Keywords: *2D CODE, OCDMA, MAI, SNR, BER*

1 INTRODUCTION

Optical Code Division Multiple Access (OCDMA) technology has gained significant attention in research due to its potential for providing flexible and efficient multiple access solutions in optical access networks. The increasing demand for multiple access arises from the changing consumer behavior and the need for on-demand services. Based on these demands, providers take action to improve their quality of services in terms of network performance. One of the techniques is to improve by doing research on the address code. There are various types of one-dimensional code that has been developed over a year's [1][2][3] [4]. To address the limitations of 1-dimensional (1D) codes, a 2-dimensional OCDMA code has been developed to overcome issues such as Multiple Access Interference (MAI) and limitations in cardinality associated with longer code lengths in one-dimensional codes. One of the shortcomings of 1D codes is the increase in MAI with longer code lengths. MAI occurs when multiple users transmit their signals simultaneously, resulting in interference at the receiver. As the code length increases, the possibility of MAI also increases, which can degrade the system performance. Another limitation of 1D codes is the limitation in cardinality, which refers to the number of unique codes that can be generated within a code family. With 1-D codes, the cardinality is limited, which can restrict the number of users that can be accommodated in the system.

Two-dimensional codes are a type of coding technique that has been developed to overcome some of the limitations of traditional OCDMA codes. OCDMA is a technique used in optical communication systems to allow multiple users to share the same optical channel simultaneously. The use of 2-dimensional codes in OCDMA provides additional flexibility in managing Multiple Access Interference (MAI) and cardinality. MAI is a phenomenon that occurs when multiple users transmit their signals simultaneously, and their signals interfere with each other, resulting in degraded performance. By using 2-dimensional codes, the allocation of codes to users can be more efficient, which helps reduce the impact of MAI and improves the overall system performance [5][6][7][8][9][10]17]. Furthermore, 2-dimensional OCDMA codes also allow for accommodating a larger number of users in the system. This is particularly useful in optical access networks, where

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the demand for high-speed data services is increasing rapidly due to modern consumption patterns. The ability to accommodate more users in the system without compromising performance makes 2-dimensional OCDMA codes suitable for modern optical access networks that require efficient allocation of resources to provide full services on demand such as for future in 6G applications. The aim is to increase the capacity of cardinality at a high data rate. The 6G is expected to introduce new capabilities far beyond the limits of 5G. The 6G network application can be viewed as in Figure 1 for encoder and decoder design.

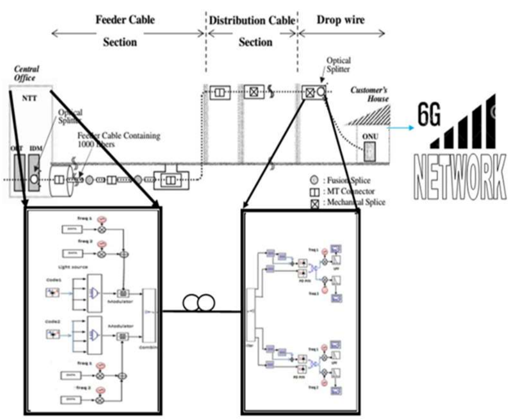

Figure 1: The proposed 2-D M-FCC Encoder /Decoder design for 6 G network access

In addition, the development of 2-dimensional OCDMA codes is a promising solution to address the shortcomings of 1D codes in optical access networks. These codes offer increased flexibility in terms of managing MAI and cardinality, making them well-suited for modern multiple access requirements. Further research and development in this area can potentially lead to advancements in OCDMA technology and its widespread adoption in optical communication systems. Overall, the growth of OCDMA technology is expected to continue as it offers promising solutions for efficient and flexible multiple access in optical networks. As technology advances, these advancements are expected to contribute to the development of more sophisticated and efficient communication systems in the future. And they can have potential applications in various domains, including telecommunications, data centers, and other optical communication applications. It will be interesting to see how 2-dimensional OCDMA codes and other advancements in the field of optical communication continue to evolve and shape the future of communication systems.

The new 2-dimensional code is developed to meet the challenge and improve the performance of the existing 2-dimensional code. From the study, it is found that 2-dimensional codes that have been developed have higher bit rates, have a property where it can reduce the Phase-induced intensity noise (PIIN) and Multiple Access Interference (MAI). The incoherent OCDMA system using 2-D encoding improved the performance of the network and simplified the network control and management, also reducing the processing time and alleviating the difficulty and reduced hardware implementation cost. To overcome the lack of one dimensional OCDMA system, some researchers introduced and investigated the best approaches by combining time, wavelength, space, and polarization. The most popular and best schemes are spectral /time and spectral spatial technique, and these approaches have been implemented and studied in various research works referenced a in [11][12][13]. The findings generally suggest that the performance of the OCDMA system is improved when multiple dimensions are combined, compared to traditional one-dimensional systems. However, the specific results and conclusions may vary depending on the implementation, system parameters, and experimental conditions.

In the next sub-chapter, a new development of 2D code will be presented and analyse. The code is developed by using mathematical derivation to obtain noises equation such as Phase Intensity Induce Noise (PIIN) Shot Noise and Thermal Noise. To verify the validity, it is analyse based on the BER performance. It is expected can overcome the challenges that OCDMA system faces such as to improve cardinality, suppress PIIN, hence reduce the MAI.

2 2-D M-FCC CODE DEVELOPMENT

The 2-D Modified-FCC code is developed from the 1- dimensional FCC family. The 2 D code has properties of code wavelength M, code length N, weight W, and correlation function. The 2-dimensional codeword can be expressed as (MxN, W, λ_a, λ_c) where λ_a is the autocorrelation and λ_c is cross-correlation. As a result, the 2-D M-FCC code obtained as depicted in Table 1. From the generated codeword, the next step is to gain the correlation properties. This is important because it determines the performance and reliability of OCDMA systems.

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Table 1: 2 D Modified-FCC Code

	X_0	X_1	X_2
	$\begin{bmatrix}0&0&0&0&1&1&0&1&1\end{bmatrix}$	$\begin{bmatrix}0&1&1&0&0&0&1&1&0\end{bmatrix}$	$\begin{bmatrix}1&1&0&1&1&0&0&0&0\end{bmatrix}$
Y_0^T $\begin{bmatrix}1\\0\\1\\1\\0\\0\end{bmatrix}$	$\begin{bmatrix}0&0&0&0&1&1&0&1&1\\0&0&0&0&0&0&0&0&0\\0&0&0&0&1&1&0&1&1\\0&0&0&0&1&1&0&1&1\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix}$	$\begin{bmatrix}0&1&1&0&0&0&1&1&0\\0&0&0&0&0&0&0&0&0\\0&1&1&0&0&0&1&1&0\\0&1&1&0&0&0&1&1&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix}$	$\begin{bmatrix}1&1&0&1&1&0&0&0&0\\0&0&0&0&0&0&0&0&0\\1&1&0&1&1&0&0&0&0\\1&1&0&1&1&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix}$
Y_1^T $\begin{bmatrix}1\\1\\0\\0\\1\\0\end{bmatrix}$	$\begin{bmatrix}0&0&0&0&1&1&0&1&1\\0&0&0&0&1&1&0&1&1\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&1&1&0&1&1\\0&0&0&0&0&0&0&0&0\end{bmatrix}$	$\begin{bmatrix}0&1&1&0&0&0&1&1&0\\0&1&1&0&0&0&1&1&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&1&1&0&0&0&1&1&0\\0&0&0&0&0&0&0&0&0\end{bmatrix}$	$\begin{bmatrix}1&1&0&1&1&0&0&0&0\\1&1&0&1&1&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\1&1&0&1&1&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{bmatrix}$
Y_2^T $\begin{bmatrix}0\\0\\1\\0\\1\\1\end{bmatrix}$	$\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&1&1&0&1&1\\0&0&0&0&0&0&0&0&0\\0&0&0&0&1&1&0&1&1\\0&0&0&0&1&1&0&1&1\end{bmatrix}$	$\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&1&1&0&0&0&1&1&0\\0&0&0&0&0&0&0&0&0\\0&1&1&0&0&0&1&1&0\\0&1&1&0&0&0&1&1&0\end{bmatrix}$	$\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\1&1&0&1&1&0&0&0&0\\0&0&0&0&0&0&0&0&0\\1&1&0&1&1&0&0&0&0\\1&1&0&1&1&0&0&0&0\end{bmatrix}$

The cross-correlation of 2-D can be derived by introducing the four characteristic matrices of A(d), where d is the subset of 0, 1, 2 or 3 ((d)∈ (0,1,2,3)) as proposed by [14] four decoding matrices and four correlation functions are defined as follows:-

$$A^{(0)} = Y^T X$$
$$A^{(1)} = Y^T \overline{X}$$
$$A^{(2)} = \overline{Y}^T X$$
$$A^{(3)} = \overline{Y}^T \overline{X} \quad (1)$$

Here,$\bar{X}$ and,$\bar{Y}$ are denotes as the complementary of $X = [x_0, x_1, x_2, x_{M-1}]$and $Y = [y_0, y_1, y_2, x_{N-1}]$ as shown in Table 1.0. Then, the cross-correlation of 2-D code $A^{(d)}$ and $A_{g,h}$ can be expressed as:

$$R^{(d)}(g,h) = \sum_{i=0}^{M-1}\sum_{j=0}^{N-1} a_{ij}^{(d)} a_{(i+g)(j+h)} \quad (2)$$

Using the equation, the cross-correlation value can be obtained and simplified as in Table 2.

Table 2: Cross-Correlation for 2-D M-FCC Code

X (g.h)	$R^{(0)}(g,h)$	$R^{(1)}(g,h)$	$R^{(2)}(g,h)$	$R^{(3)}(g,h)$
$g = 0, h = 0$	**K_1K_2**	**0**	**0**	**0**
$g = 0, h = 1$	**K_1**	**0**	**$K_1(K_2-1)$**	**0**
$g = 1, h = 0$	**K_2**	**$K_2(K_1-1)$**	**0**	**0**
$g = 1, h = 1$	**1**	**K_1-1**	**K_2-1**	**$(K_1-1)(K_2-1)$**

From Table 2, R (0) until R (3) have fixed proportional relation, which is refers to MAI cancellation property can be expressed as:

$$R^{(0)}(g,h) - \frac{R^{(1)}(g,h)}{K_1-1} - \frac{R^{(2)}(g,h)}{K_2-1} + \frac{R^{3}(g,h)}{(K_1-1)(K_2-1)} =$$

$$\begin{cases} K_1K_2 & \text{for } g = 0 \cap h = 0 \\ 0 & \text{Otherwise} \end{cases}$$

In summary, achieving low correlation values for 2-D OCDMA codes offers several benefits, including maximum orthogonality, high capacity, enhanced security, improved performance, and simplified decoding. These benefits make such codes desirable for efficient and reliable multi-user communication in optical networks. From parameter stated in Table 2, the next step is to formulate the noises equation.

3. MATHEMATICAL ANALYSIS OF 2-D M-FCC CODE

Deriving the noise equation for a new code development involves analyzing the impact of various types of noises on the system. In this case, the three types of noises to be considered are Phase Induced Intensity Noise (PIIN), shot noise, and thermal noise. These noises can affect the signal-to-noise ratio (SNR) at the receiver part of the system. At the receiver, photodiode is used as detector or light source to detect thermal lights and it will produce a photocurrent noise that can be expressed as proposed by [15][2].

$$\{i^2\} = 2eIB + I^2 B\tau_c + \frac{4K_b T_n B}{R_L} \quad (3)$$

From equation (3), I present as average photocurrent which is produced by the photodiode. The average photocurrent depends on the system that we develop. To calculate, there are four assumptions that has been made such as in [15]: -

i) Each light source is ideally unpolarized and its spectrum is flat over the bandwidth [{V_o- (ΔV)/2}, {V_o+(ΔV)/2} where Vo is the central optical frequency and (ΔV)/2 are the optical source bandwidth in hertz.
ii) Each power spectral component has an identical spectral width.
iii) Each user has equal power to the receiver.
iv) Each bit stream from each user is synchronized.

Another parameter that should be considered is the source incoherent time denoted by τ_c. It occurs during the incoherent light fields are mixed and incident upon a photodetector. The phase noise of the fields can introduce an intensity noise in the photo-detector output [16]. The source of coherence time can be expressed as per reference [15]. It is important to consider τ_c when analyzing and designing systems that involve the mixing of incoherent light fields and photodetection to accurately characterize the performance and behavior of the system. Coherent time can be expressed as in equation (4).

$$\tau_c = \frac{\int_0^\infty [S^2(f)df]}{\left[\int_0^\infty S(f)df\right]^2} \quad (4)$$

Incoherent time involved of single-sideband power spectral density (PSD) of light incidence to the thermal source which is photodiode S(f). To investigate, Gaussian approximation is used because all the noises are obeyed a negative binomial distribution. Thus, PIIN, shot and thermal noise equation can be shown as below, where M is representing the code length of spectra code sequence, N is the code length of spatial code sequence, W number of simultaneous active users and Psr is the effective received power. Another constant parameter can be referred to in Table 3.

i) PIIN Noise

$$\langle I_{PIIN}^2 \rangle = \frac{B_r \Re^2 P_{sr}^2}{2M\Delta f k_2^2 (MN-1)^2}[\int_1 + \int_2 + \int_3] \quad (5)$$

$\int_{1,2,3}$ refer to the equations below: -

$\int_1 = [K_1 K_2 (MN-1)]^2$

$\int_2 = 2(K_1K_2)(MN-1)K_2(W-1)(N-1)$

$\int_3 = [K_2(W-1)(N-1)]^2$

ii) Shot Noise

$$< I_{SHOT}^2 >= 2eB_r \frac{RP_{sr}}{Mk_2(MN-1)}[\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4] \quad (6)$$

$\Delta_{1,2,3,4}$ refer to the equations below: -

$\Delta_1 = K_1K_2(MN-1)$

$\Delta_2 = k_1\left(\frac{1+K_2}{2}\right)(W-1)(M-1)$

$\Delta_3 = 2K_2(W-1)(N-1)$

$\Delta_4 = 4(W-1)(M-1)(N-1)$

iii) Thermal Noise

$$\langle I_{thermal}^2 \rangle = \frac{4K_bT_nB_r}{R_L} \quad (7)$$

Standard value for parameter used in the equation (5), (6) and (7) can be refer in Table 3.0. The performance of the code that has been develop can be analyses based on the Bit Error Rate (BER) of the system. BER is the key in digital transmission, it refers to the number of bit errors is the number of received bits of a data stream over a communication channel that have been altered due to noise, interference, distortion, or bit synchronization errors. BER is a commonly used metric to evaluate the performance of digital communication systems and can be expressed in Equation (10). It is the general equation for bit error rate, the characteristic of the code development can be determined by derived a signal-to-noise ratio (SNR) of the system. There are three noises involved in the SNR calculation as shown in equation (11) such as phase intensity induced noise (PIIN), shot noise and thermal noise, and placed as denominator. The numerator refers to total output of the photocurrent at the receiver.

i) Bit Error Rate

$$\text{BER} = \frac{1}{2}\text{erfc}\left\{\sqrt{\frac{\text{SNR}}{8}}\right\} \quad (8)$$

ii) Signal-to-Noise Ratio

$$SNR = \frac{I_r^2}{I_{PIIN}^2 + I_{SHOT}^2 + I_{THERMAL}^2} \quad (9)$$

Table 3: Mathematical Analysis Parameter

Parameter	Value
PD quantum efficiency	ŋ= 0.75
Spectral width of broadband light source	D*l* = 30nm (D*l* = 3.75 THz)
Operating wavelength	l_o = 1550 nm
Electrical bandwidth	B = 311 MHz
Data transmission rate	R_b = 622 Mbps (Variable)
Receiver noise temperature	T_n = 300 K
Receiver load resistor	R_L = 1030 Ohm
Boltzmann's constant	$K_b = 1.38 \times 10^{-23}$ W/K/Hz
Electron charge	$e = 1.60217646 \times 10^{-19}$ coulombs
Light velocity	$C = 3 \times 10^8$ m/s

4. RESULT AND DISCUSSION

The performance of 2-D M-FCC code was evaluated on number of user or cardinality and compared with the performance of existing codes. Parameters listed in Table 3 are used to obtain the

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numerical results which is from the novelty of the derived formulae in section 3. The photodiodes quantum efficiency of the receivers is $\eta = 0.75$. The spectrum broadband of light source; λ_o, is centered at 1550 nm with spectral width $\Delta\lambda = 3.75$ THz. The data transmission rate is 622 Mbps and the electrical bandwidth of receivers is 311 MHz, while the standard receiver noise temperature and load resistance are $T_n = 300$ K and $R_L = 1030\ \Omega$ respectively.

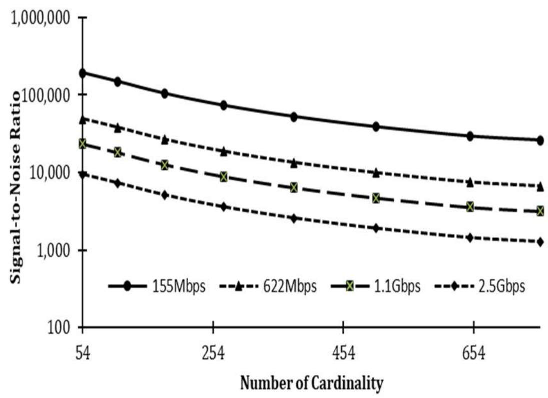

Figure 2: Number of cardinalities versus Signal-to-Noise Ratio at different bit rates.

The numerical result shows as in Figure 2 illustrate the measures conducted by measuring the Signal-to-Noise Ratio (SNR) performance against cardinality at different bit rates. The SNR curves decrease as the number of users increases at different bit rates for 155 Mbps, 622 Mbps, increase to 1.1 Gbps and 2.5 Gbps, respectively. However, the code is still able to accommodate a high number of users with relatively high SNR values, as demonstrated by the curves for different bit rates.

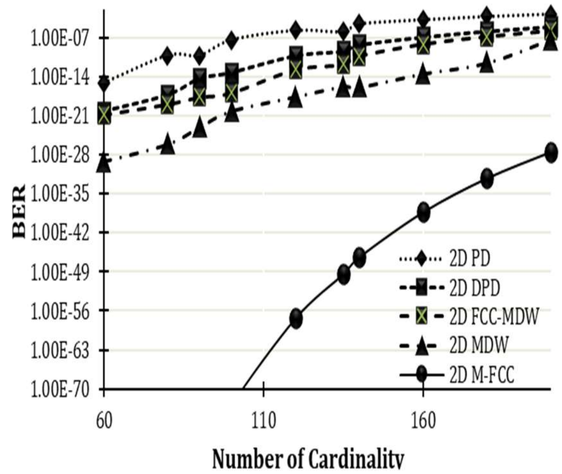

Figure 3: BER versus Number of Cardinality

For further investigation of the 2D M-FCC code, it is important to make a comparison of the performance with existing codes. The trendlines as in Figure 3 show the various OCDMA codes such as 2 D PD code, 2 D DPD code 2 D FCC-MDW code, 2 D MDW code and 2-D M-FCC code runs at bit rate 622 Mbps. Noticed that, at the same number of cardinalities, about 200, the new propose 2-D M-FCC code at BER of $3.49\text{x}10^{-28}$, lower than other 2D codes. Additionally, it seems that the arrangement of the 2D M-FCC code has its own properties that can suppress the effects of noise, potentially leading to an improvement in system cardinality.

The 2D MFCC code was able to overcome the advantages seen in the earlier 2D codes. In terms of cardinality, the 2D MFCC code performs better, and the SNR value decreased as the number cardinalities increased.

5. CONCLUSION

The numerical result shows that the new code 2D M-FCC is achieving the development goals. The use of this code has led to higher cardinality while maintaining a low bit error rate (BER), which is an important value. The derivation of cross correlation property from wavelength and time code sequences provides a measure of how well the code performs in terms of interference and noise. From the correlation property, the SNR is derived thus, from the plot it is provide an overview of the performance of the new code. At the same number of users, 2D M-FCC code can achieved improve 71% of BER from the other code. Thus, it reflects to the increment of cardinality can achieved almost 100% at threshold value of BER at 10^{-9}. To evaluate the code performances can be realized in practical implementation, it needs to have more validation and testing in variety parameters. However, acquired encouraging results are encouraging and present intriguing opportunities for exploring the applications of 2D code development in optical communication towards the 6G technology.

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