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Performance improvement of hybrid SCM SAC-OCDMA networks using multi-diagonal csode

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Hybrid Subcarrier Multiplexing (SCM) incorporating spectral amplitude coding optical code division multiple access (SAC-OCDMA) technology was investigated both mathematically and by simulation. The hybrid SCM/SAC-OCDMA system combined two schemes in such as a way that the resulting hybrid system is robust against the Multi- Access Interference (MAI) and much enhanced the channel data rate. In this paper, we describe the improved performance of the hybrid SCM/SAC-OCDMA system based on the use of spectral amplitude coding to suppress impairments and to improve the overall system improve the overall sensitivity of system performance at a BER of 10^{-9}. As a result, the proposed system based on Multi-Diagonal (MD) code shows better performance in comparison to the conventional code that employs the SAC-OCDMA system. We also evaluate the different design parameters under the maximum number of subcarriers (18 subcarriers in each optical channel) multiplexed for integrating OCDMA technology onto the existing fiber-wireless infrastructure at 155 M bit/s data rate for different fiber lengths. Further, a BER of 4.4×10^{-10} was achieved based on the proposed system for 45 km at 1.21 GHz.

Key words: Subcarrier multiplexing (SCM), spectral amplitude coding optical code division multiple access (SAC-OCDMA), multi diagonal (MD) code.

INTRODUCTION

In Radio-over-Fiber (RoF) networks, radio frequencies (RFs) are carried over optical fiber links between a central station and multiple low-cost remote antennas (RAUs) in support of a variety of wireless applications. It was experimentally demonstrated in (Tang et al., 2004) that RoF networks are well suited to simultaneously transmit wideband code division multiple access (WCDMA), personal handyphone system (PHS), and global system for mobile communications (GSM) signals. In (Bao and Niemegeers, 2005), different types of multimode fiber were experimentally tested to demonstrate the feasibility of indoor RoF-MMF networks for the in-building coverage of second-generation (GSM) and third-generation cellular radio networks [universal mobile telecommunications system (UMTS)] as well as

IEEE 802.11a/b/g WLAN and digital enhanced cordless radio service (Dang et al., 2007).

The aforementioned limitations of WLAN-based RoF network can be avoided in so-called radio-and-fiber (R&F) networks. In R&F networks, access to the optical and wireless media is controlled separately from each other by using (in general) two different MAC protocols in the optical and wireless media. R&F networks are well suited to build WLAN-based WiFi networks of extended optical CDMA systems without imposing stringent limits on the size of the optical backhaul, as opposed to RoF networks that limit the length of deployed fibers to a couple of kilometers. New RoF techniques are proposed which demonstrate the benefits of subcarrier multiplexing over OCDMA networks (Sahbudin et al., 2009), which provides a way for several radio signals to access the OCDMA networks. Subcarrier multiplexing (SCM) demonstrates potential to be a convenient and efficient technique for transmission of analog or digital information

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(Khaleghi and Kavehrad, 1995).

Optical subcarrier multiplexing (SCM) offers a promising system to solve the needs of telecommunication networks. The hybrid system could provide the necessary bandwidth for the transmission of broadband data to end-users (Kaszubowska et al., 2006). The hybrid SCM optical code division multiplexing access (SCM-OCDMA) network employs two efficient multiplexing techniques, namely (1) the technology of subcarrier multiplexing (SCM) and (2) spectral amplitude coding optical code division multiple access (SAC-OCDMA) networks. SCM systems have significant advantages, such as the fact that microwave devices are more mature than optical devices and the frequency selectivity of microwave filters is much better than their optical counterparts. In addition, the low cost of system implementation of SCM is another advantage which makes it a good propositionfor transmission of multi-channel digital optical signals for local area networks (Hui et al., 2002).

In contrast, the SAC-OCDMA system recently received consideration due to its ability to allow many users to share the same transmission medium asynchronously and simultaneously with a high level of transmission security (Sahbudin et al., 2009; Palais, 2005). However, the SAC-OCDMA system suffers from various noises such as shot noise, thermal noise, dark current and multiple access interference (MAI) from other users. Among these noises, MAI is considered as a dominant source of system performance degradation. Therefore, an intelligent design of code sequence is necessary to reduce the effect of MAI (Stok and Sargent, 2000).

To overcome this problem in SAC-OCDMA systems, several codes have been proposed such as Random Diagonal code (RD), Khazani–Syed (KS) code (Ahmad et al., 2009), Enhanced Double Weight (EDW) code (Hasson et al., 2008), Modified Frequency Hopping (MFH) code (Zou et al., 2001), and Modified Quadratic Congruence (MQC) code (Zou et al., 2001).

The former SAC-OCDMA codes suffered from limitations such as: the code length is too long (e.g., KS and EDW codes), the code construction is limited by the code parameter (e.g., MQC and MFH codes), or the cross-correlation is increased with an increase in the weight number (e.g., RD code). In addition, the codes that have been proposed for SAC-OCDMA could not accommodate large number of simultaneous users and could not support the system at a high data rate.

Therefore, to overcome these problems, the authors suggest the use of Multi Diagonal (MD) code which is designed based on a combination of diagonal matrixes. The MD code has several advantages such as, (1) zero cross-correlation code which cancels the MAI (multi access interference); (2) flexibility in choosing W, K parameters over other codes like MQC, MFH and KS codes; (3) simple design; (4) supports a large number of users at a high data rate compared to other codes; (5) no

overlapping of spectra for different users.However, KS code (Ahmad et al., 2009) is proposed for the hybrid SCM /SAC-OCDMA system to reduce the system complexity and reduce the MAI. KS code suffers from various limitations, such as too long code length, the code construction is limited by the code parameter, and the code could not support a high number of simultaneous users.

In this paper, we propose a new technique for improving the performance of the SCM/SAC-OCDMA system. The proposed system is evaluated based on Multi Diagonal (MD) code, in order to mitigate the MAI effects. A direct detection technique is used to detect the optical and RF signals, which reduces the system cost, complexity and improves the overall system performance. Furthermore, we investigate the performance of the hybrid system numerically and by using optical simulator software, "$OptiSim^{TMn}$", taking into the account the effect of inter-modulation distortion noise.

MATERIALS AND METHODS

MD code design

The MD code is characterised by the following parameters (N, W, λ_c) where N is the code length (number of total chips), W is the code weight (chips that have a value of 1), and λ_c is the in-phase cross-correlation. The cross-correlation theorem could be defined as follows: in linear algebra, the identity matrix or unit matrix of size N is the N-by-N square matrix with ones on the main diagonal and zeros elsewhere. It is denoted by I_N, or simply by I if the size is immaterial or can be trivially determined by the context.

$$I_1 = [1], I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, I_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \cdots, I_N = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & 1 \end{bmatrix}. \tag{1}$$

Using the notation that is sometimes used to concisely describe diagonal matrices, we can write:
$I_N = diag(1,1,....,1).$ An orthogonal matrix is a square matrix with real entries whose columns (and rows) are orthogonal unit vectors (i.e., orthogonal). Equivalently, a matrix A is orthogonal if its transpose is equal to its inverse:

$A^T A = AA^T = I.$ Alternatively, $A^T = A^{-1}.$

A square matrix whose transpose is also its inverse is called an orthogonal matrix; that is, A is orthogonal if $A^T A = AA^T = I_N$, the identity matrix, i.e. $A^T = A^{-1}.$

For example, $A(N \times N)$ square matrix, A is said to be orthogonal if $AA^T = A^T A = I_{N \times N}.$

The cross-correlation theorem states that cretin sets of complementary sequences have cross-correlation functions that

sum to zero by using all pairwise permutations. Here, all cross-correlation function permutations are required in order that their sum be identically equal to zero. For example, if the rows and columns of a $(K \times N)$ matrix are orthogonal and all the columns except one sum to zero, then the sum of all cross-correlations between non-identical codewordcodewords is zero.

So if x_{ij} is an entry from X and y_{ij} is an entry from Y, then an entry from the product $C=XY$ is given by

$$C_{ij} = \sum_{K=1}^{N} x_{iK} \, y_{Kj}.$$

For the code sequences $X = (x_1, x_2, x_3, \ldots, x_N)$ and $Y = (y_1, y_2, y_3, \ldots, y_N)$, the cross-correlation function can be represented by:

$$\lambda_c = \sum_{i=1}^{N} x_i \, y_i.$$ When $\lambda_c = 0$, it is considered that the code possesses zero cross-correlation properties.

The matrix of the MD code consists of a $K{\times}N$ matrix functionally depending on the value of the number of users (K), and code weight (W).

For MD code the choice of weight value is free, but should be more than 1 $(W > 1)$.

MD matrix design

The following steps explain how the MD code is constructed.

Step 1:
Firstly, construct a sequence of diagonal matrices using the value of the weight (W) and number of subscribers (K). According to these values, the i, j_W will be set.

Where K and W are positive integer numbers, $(i = 1,2,3,4 \cdots, i_n = K)$ are defined by the number of rows in each matrix, and $(j_W = 1,2,3,4, \cdots, W)$ will represent the number of diagonal matrices.

Step 2:
Based on the next equations the MD sequences will be computed for each diagonal matrix.

$$S_{i,j_W} = \begin{cases} (i_n + 1 - i), & \text{For} \quad j_W = \text{even number} \\ i, & \text{For} \quad j_W = \text{odd number} \end{cases} \tag{2}$$

$$S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, S_{i,2} = \begin{bmatrix} K \\ \vdots \\ 3 \\ 2 \\ 1 \end{bmatrix}, S_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, \ldots, S_{i,W} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix} \tag{3}$$

Any elements of the $S_{i,W}$ matrices represent the position of one in $T_{i,W}$ matrices with $K{\times}K$ dimensions.

where $T_{i,1} = [S_{i,1}]_{KxK}$, $T_{i,2} = [S_{i,2}]_{KxK}$ and $T_{i,W} = [S_{i,W}]_{KxK}$.

Therefore

$$T_{i,1} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{KxK}, \quad T_{i,2} = \begin{bmatrix} 0 & \cdots & 0 & 1 \\ 0 & \cdots & 1 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 1 & \cdots & 0 & 0 \end{bmatrix}_{KxK}, \ldots,$$

$$T_{i,W} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{KxK} \tag{4}$$

Step 3:
So, the total combination of diagonal matrices (3) represents the MD code as a matrix of power $K{\times}N$.

$$\text{MD} = \begin{bmatrix} T_{i,1} \vdots T_{i,2} \vdots \cdots \cdots \vdots T_{i,W} \end{bmatrix}_{KxN} \tag{5}$$

$$MD = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,N} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,N} \\ a_{3,1} & a_{3,2} & \cdots & a_{3,N} \\ \vdots & \vdots & \cdots & \vdots \\ a_{i_n,1} & a_{i_n,2} & \cdots & a_{i_n,N} \end{bmatrix} \tag{6}$$

From the above basic matrix (5), the rows determine the number of users (K). Notice that the association between code weight (W), code length (N) and number of subscribers (K) can be expressed as:

$$N = K{\times}W. \tag{7}$$

For example, to generate a MD code family according to the previous steps, let's say $K= 4$ and $W= 3$.

Therefore, $i = 1,2,3,4$, $i_n + 1 = 5$ and $j_W = 1,2,3.$

The diagonal matrices can be expressed as:

$$S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix}, S_{i,2} = \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix}, S_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix} \tag{8}$$

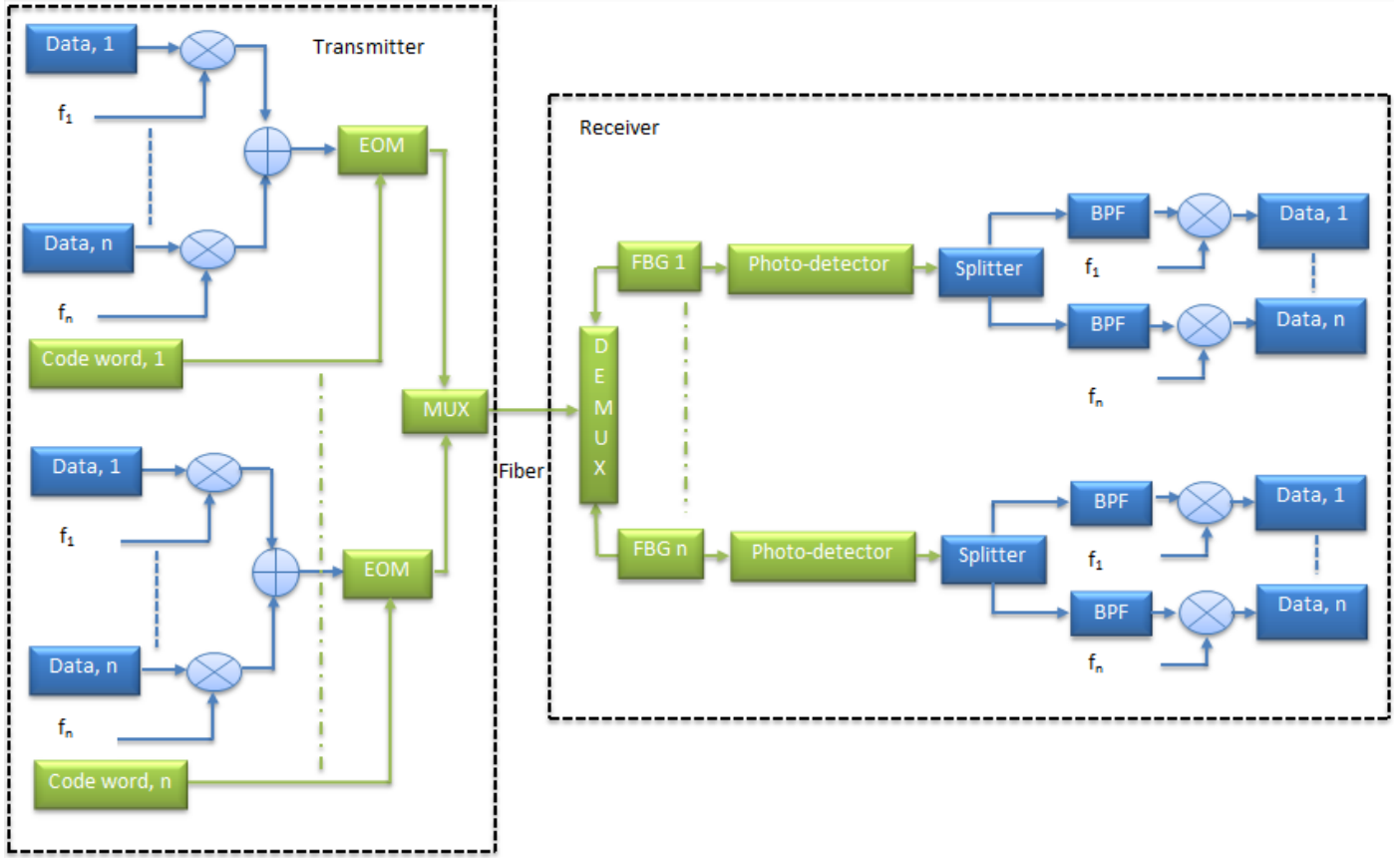The MD code sequence for each diagonal matrix is shown as:

Figure 1. The proposed block diagram of a SCM-SAC-OCDMA system using MD with direct detection technique.

$$T_{i,1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4x4}, \qquad T_{i,2} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}_{4x4},$$

$$T_{i,3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4x4} \tag{9}$$

$$codeword = \begin{cases} user1 \Rightarrow \lambda_1, \lambda_8, \lambda_9 \\ user2 \Rightarrow \lambda_2, \lambda_7, \lambda_{10} \\ user3 \Rightarrow \lambda_3, \lambda_6, \lambda_{11} \\ user4 \Rightarrow \lambda_4, \lambda_5, \lambda_{12} \end{cases}$$

The MD code design depicts that changing elements in the matrices in the same diagonal part will result in a constant property of zero cross-correlation, and it is constructed with zero cross-correlation properties, which cancels the MAI. The MD code presents more flexibility in choosing the W, K parameters and with a simple design can supply a large number of users compared with other codes like MQC, RD codes. Furthermore, there are no overlapping chips for different users.

The total MD code sequence will be:

$$MD = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{4x12} \tag{10}$$

Where $K = 4$, $N = 12$.
So, the codeword for each user according to the above example would be:

Hybrid SCM- SAC-OCDMA system based on MD code

In this section, we demonstrate a hybrid SCM- SAC-OCDMA based on the MD code. Figure 1 illustrates the schematic diagram of the SCM- SAC-OCDMA system. As shown in Figure 1, the electrical data are modulated with the subcarrier frequencies where all the modulated subcarriers are combined using an electrical adder. The Optical External Modulator (OEM) is then used to modulate the combined modulated subcarrier frequencies with the distinct code sequence.
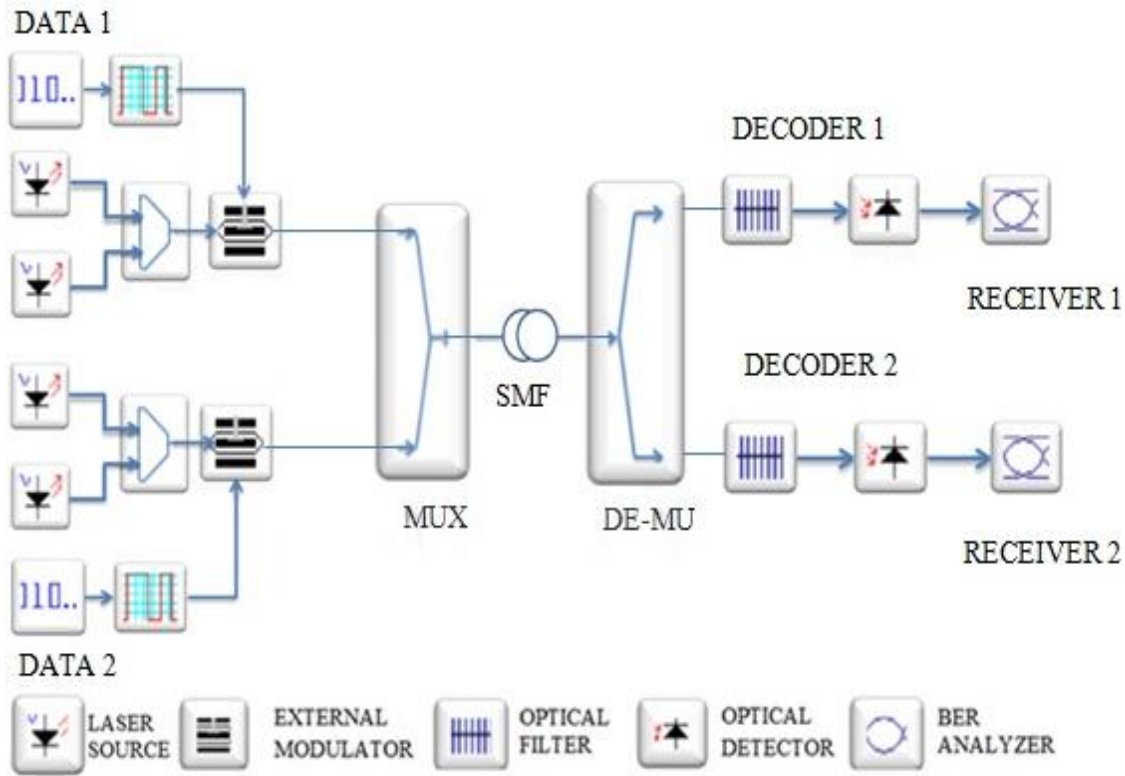
Figure 2. Illustrations of the block diagram of an MD code system with direct detection technique.

Each codeword of the SAC-OCDMA based on MD code consists of different wavelengths. An optical combiner is used to combine all modulated code sequence and send out through optical fiber.

On the receiver side, a de-multiplexer is used to separate the different modulated codewordcodeword. The received code sequence will be filtered out by using the Fiber Bragg Grating (FBG) filter. After filtration, the photo detector, electrical splitter and Band Pass Filter (BPF) are used to split the SCM signals and reject the unwanted signals. To retrieve the original sending data, a local microwave frequency f_i is mixed electrically with the incoming signal, and filtered by Low Pass Filter (LPF).

SCM- SAC-OCDMA receiver based on direct detection technique

The hybrid SCM-SAC-OCDMA receiver using the direct detection technique for two users is illustrated in Figure 2. Only one pair of decoders and detectors is required compared to other techniques which require two branches of inputs to the receiver like those in complementary subtraction techniques.

There is also no subtraction process involved. This is achievable for the simple reason that the information is assumed to be adequately recoverable from any of the chips that do not overlap with any other chips from other code sequences, since MD code is designed with no overlapping chips. Thus the detector will only need to filter through the clean chips (no overlapping chips) to be directly detected by the photo diode as normal intensity modulation within the direct detection scheme. The MAI effect has been successfully and completely suppressed because only the required signal spectra in the optical domain will be filtered.

Analysis of hybrid SCM SAC-OCDMA system

1. System performance analysis

For analysis of our system, Gaussian approximation is used for calculation of BER [4, 8]. We have considered the effect of thermal noise $\left(I_{th}^2 \right)$, shot noise $\left(I_{sh}^2 \right)$ and Inter-Modulation Distortion $\left(I_{IMD}^2 \right)$ in the photo-detector. The SNR of an electrical signal is defined as the average signal power to noise power $SNR = \left| I^2 \middle/ \sigma^2 \right|$. Due to the zero cross-correlation property of MD code, there is no overlapping in spectra of different users. For that reason, the effect of incoherent intensity noise has been ignored. The variation of photo-detector as a result of the detection of an ideally unpolarized thermal light, which is generated by spontaneous emission, can be expressed as:

$$\sigma^2 = I_{sh}^2 + I_{th}^2 + I_{IMD}^2 \tag{11}$$

Let $C_K(i)$ denote the ith element of the Kth MD code sequences, and according to the properties of MD code, the direct detection technique can be written as:

$$\sum_{i=1}^{N} C_K(i) C_l(i) = \begin{cases} W, & For \quad K = l, \\ 0, & Else. \end{cases} \tag{12}$$
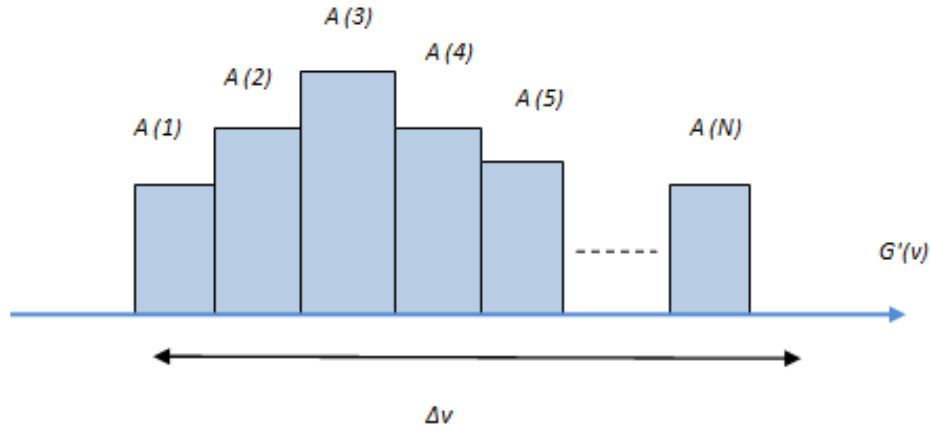
Figure 3. The PSD of the received signal *r(v)*.

The following assumptions are made (Smith et al., 1998; Wen et al., 2006):

1. Each light source is ideally unpolarized and its spectrum is flat over the bandwidth [$v_0-\Delta v/2$, $v_0+\Delta v/2$] where v_0 is the central optical frequency and Δv is the optical source bandwidth expressed in Hertz.
2. Each power spectral component has an identical spectral width.
3. Each user has equal power at the receiver.
4. Each bit stream from each user is synchronized.

The above assumptions are important for mathematical straightforwardness. Devoid of these assumptions, it is difficult to analyze the system; for example, if the power for each spectral component is not identical and each user has a different power at the receiver.

The power spectral density (PSD) of the received optical signals can be written as (Chao-Chin et al; 2004):

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{K=1}^{K} d_K \sum_{i=1}^{N} c_K(i)rect(i) \qquad (13)$$

Where P_{sr} is the effective power of a broadband source at the receiver, K is the active users , N is the MD code length, and d_K is the modulation data of nth subcarrier channel on the Kth optical codeword, which can be expressed as (Sahbudin et al., 2009):

$$d_k(t) = \sum_{n=1}^{Nc} u_{n,K}(t)m_{n,K}\cos(w_n t) \qquad (14)$$

$u_{n,K}(t)$ is the normalized digital signal at the nth subcarrier channel of the Kth codeword. w_n is the angular subcarrier frequency, $m_{n,K}$ is the modulation index of the nth subcarrier of the Kth users. Where is N_c is the number of the subcarrier channel on each codeword. Sahbudin et al. (2009), Koshy and Shankar (1999), Koshy and Shankar (1999) assume an identical modulation index for all subcarrier channels as:

$$0 \le m_{n,K} \le \frac{1}{N_c},$$

The $rect(i)$ function in Equation(13) is given by

$$rect(i) = u\left[v-v_0-\frac{\Delta v}{2N}(-N+2i-2)\right] - u\left[v-v_0-\frac{\Delta v}{2N}(-N+2i)\right] = u\left[\frac{\Delta v}{N}\right] \quad (15)$$

Where $u(v)$ is the unit step function expressed as:

$$u(v) = \begin{cases} 1, & v \ge 0 \\ 0, & v < 0 \end{cases} \qquad (16)$$

To compute the integral of $G(v)$, let us first consider an example of the PSD (denoted by $G^{'}(v)$ of the received superimposed signal), which is shown in Figure 3, where $A(i)$ is the amplitude of the signal of the ith spectral slot with width of $\frac{\Delta v}{N}$.

The total power incident at the input of the photo-detector of Figure 2 is given by:

$$\int_0^\infty G(v)dv = \int_0^\infty \left[\frac{P_{sr}}{\Delta v}\sum_{K=1}^{K}d_K(t)\sum_{i=1}^{N}C_K(i)C_l(i)rect(i)\right]dv \quad (17)$$

$$\int_0^\infty G(v)dv = \int_0^\infty \left[\frac{P_{sr}}{\Delta v}\sum_{K=1}^{K}d_K(t)\sum_{i=1}^{N}C_K(i)C_l(i)\left[\frac{\Delta v}{N}\right]\right]dv$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}W}{\Delta v}\right]\left[\frac{\Delta v}{N}\right]\sum_{K=1}^{K}d_K(t)\sum_{i=1}^{N}C_K(i)C_l(i)$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}W}{N}\right].\sum_{K=1}^{K}d_K(t)\sum_{i=1}^{N}C_K(i)C_l(i)$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}W}{N}\right].\sum_{K=1}^{K}d_K(t) + \left[\frac{P_{sr}}{N}\right]\sum_{K=1,K\neq l}^{N}d_K(t)$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}W}{N}\right].d_l \tag{18}$$

The photocurrent I can be found as:

$$I = \Re\int_0^\infty G(v)dv \tag{19}$$

Where, $\Re$ is the responsivity of the photo-detectors given by $\Re = \frac{\eta e}{hv_c}$ (Smith et al., 1998).

Here, η is the quantum efficiency, h is Planck's constant, and vc is the central frequency of the original broad-band optical pulse. Then Equation (19) can be expressed as:

$$I = \Re\int_0^\infty G(v)dv = \frac{\Re P_{sr}W}{N}\sum_{n=1}^{Nc}u_{n,K}(t)m_{n,K}\cos(w_n t) \tag{20}$$

At the RF demodulator, the signal coherently mixed with a local oscillator $2\cos(w_n t)$ (Sahbudin et al., 2009)

Therefore, Equation (20) will be expressed as:

$$I = \frac{\Re P_{sr}W}{N}\sum_{n=1}^{Nc}u_{n,K}(t)m_{n,K}\cos(w_n t)\left[2\cos(w_n t)\right],$$

$$I = \frac{\Re P_{sr}W}{N}\sum_{n=1}^{Nc}u_{n,K}(t)m_{n,K}\left[1+\cos(2w_n t)\right],$$

While, the frequency double component will be filtered out by using LPF, as a result the modulator output is:

$$I = \frac{\Re P_{sr}W}{N}u_{n,K}(t)m_{n,K}. \tag{21}$$

The noise power of shot noise can be written as (Zou et al., 2001):

$$I_{sh}^2 = 2eB\Re\left[\int_0^\infty G(v)dv\right], \tag{22}$$

$$= 2eB\Re\left[\frac{\Delta v}{N}\right].\left[\frac{P_{sr}W}{\Delta v}\right],$$

$$= \frac{2eB\Re P_{sr}W}{N}, \tag{23}$$

Note the probability of sending bit "1" at any time for each user is $\frac{1}{2}$, thus Equation(23) becomes

$$I_{sh}^2 = \frac{eB\Re P_{sr}W}{N}. \tag{24}$$

Thermal noise is given as (Zou et al., 2001; Fadhil et al., 2009)

$$I_{th}^2 = \frac{4K_b T_n B}{R_L}. \tag{25}$$

where $K_b, T_n, B, \text{and } R_L$ is the Boltzmann Constant, Absolute receiver noise temperature, Noise–equivalent electrical bandwidth of the receiver and Receiver load resistor, respectively. The intermediation distortion is given as (Koshy and Shankar, 1999)

$$I_{IMD}^2 = P_{sr}^2\Re^2 m_{n,K}^6\left[\frac{D_{1,1,1}}{32}+\frac{D_{2,1}}{64}\right]. \tag{26}$$

Where $D_{1,1,1}$ is the three-tone third order intermediation at, $f_i + f_K - f_l,$

$$D_{1,1,1} = \frac{N_s}{2}(N_c - N_s + 1) + \frac{1}{4}\{(N_c-3)^2 - 5 - \frac{1}{2}[1-(-1)^{N_c}](-1)^{N_c+Ns}\}.$$

$D_{2,1}$ is the two-tone third order inter-modulation at $2f_i - f_K,$

$$D_{1,2} = \frac{1}{2}\{N_c - 2 - \frac{1}{2}[1-(-1)^{N_c}](-1)^{Ns}\}.$$

Lastly from Equations (21), (24), (25) and (26) we can compute the average Signal to Noise Ratio of the SCM-SAC-OCDMA system for the MD code as:

$$SNR = \frac{\left[\frac{\Re P_{sr}W}{N}u_{n,K}(t)m_{n,K}\right]^2}{\frac{eB\Re P_{sr}W}{N}+\frac{4K_b T_n B}{R_L}+P_{sr}^2\Re^2 m_{n,K}^6\left[\frac{D_{111}}{32}+\frac{D_{21}}{64}\right]} \tag{27}$$

Using Gaussian approximation, the Bit Error Rate (BER) can be expressed as (Zou et al., 2001):

$$BER = P_e = \frac{1}{2}erfc\left(\sqrt{\frac{SNR}{8}}\right). \tag{28}$$

RESULTS

Analytical evaluation

The performance of MD code has been compared

Table 1. Typical parameter used in the numerical analysis calculation.

| Symbol	Parameter	Value
η	Photo detector quantum efficiency	0.6
P_{sr}	Broadband effective power	-10 dBm
B	Electrical bandwidth	311 MHz
λ_0	Operating wavelength	1550 nm
R_b	Data bit rate	622 M bit/s
T_n	Receiver noise temperature	300 K
R_L	Receiver load resistor	1030 Ω
e	Electron charge	1.6×10^{-19} C
h	Planck's constant	6.66×10^{-34} Js
K_b	Boltzmann's constant	1.38×10^{-23} J/K
N_c	Number of carrier	3-8
N_s	Number of subcarrier	2-26
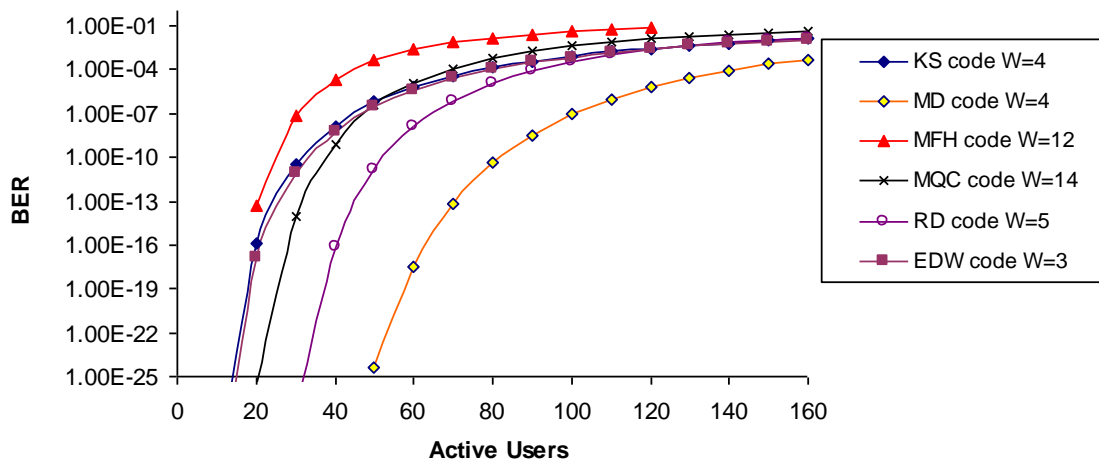
Figure 4. BER against the number of active users for various codes employing the SAC-OCDMA technique.

mathematically with other recent codes, such as KS code, EDW code, MFH code and MQC code. We evaluate the BER and SNR by using Equations (27) and (28), respectively. The parameters used in our numerical calculation are reported in Table 1.

Figure 4 shows the variation of BER against the number of active users for various codes employing the SAC-OCDMA technique for different values of K (number of active users). It is shown that the performance of the MD code is better compared to others, even though the weight of other codes is equal or greater than the MD code weight. The maximum acceptable BER of 10^{-9} is achieved by the MD code with 92 active users compared

to 55 active users achieved by RD code, 43 active users achieved by MQC code, 39 active users by KS code, 34 active users by EDW code and 27 active users by MFH code. This is good considering the small value of weight used. This is evident from the fact that MD code has zero cross-correlation properties with a diagonal matrix design, while other codes have a variable cross-correlation between 1 and zero, also very long code length. However, a few code-specific parameters were chosen based on the published results for these practical codes (Ahmad et al., 2009; Hasson et al., 2008; Zou et al., 2001). The calculated BER for KS code was $W = 4$, EDW code $W = 3$, MD code $W = 4$, RD code $W=5$, MFH
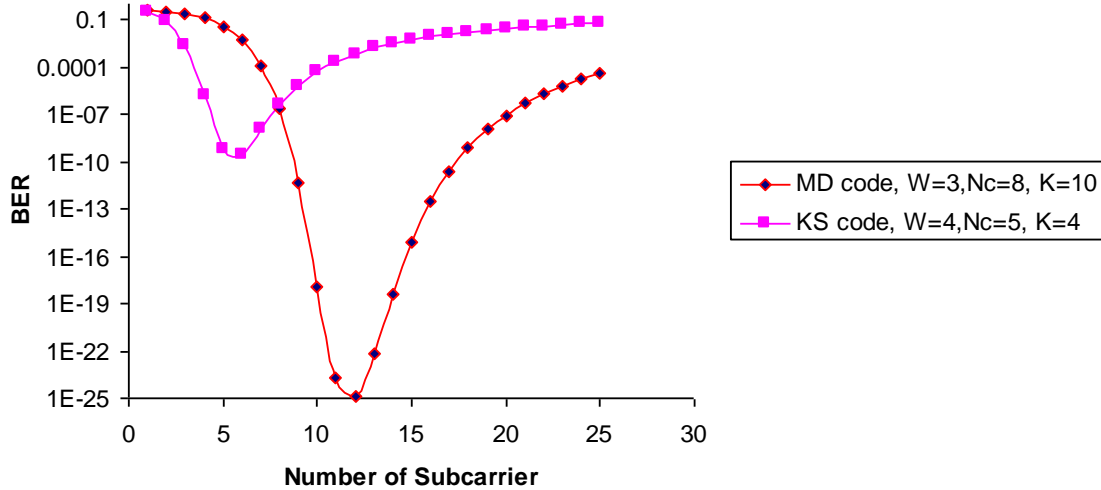
Figure 5. BER against the number of subcarriers for the hybrid system at Psr= -10dBm employing MD code and KS code.

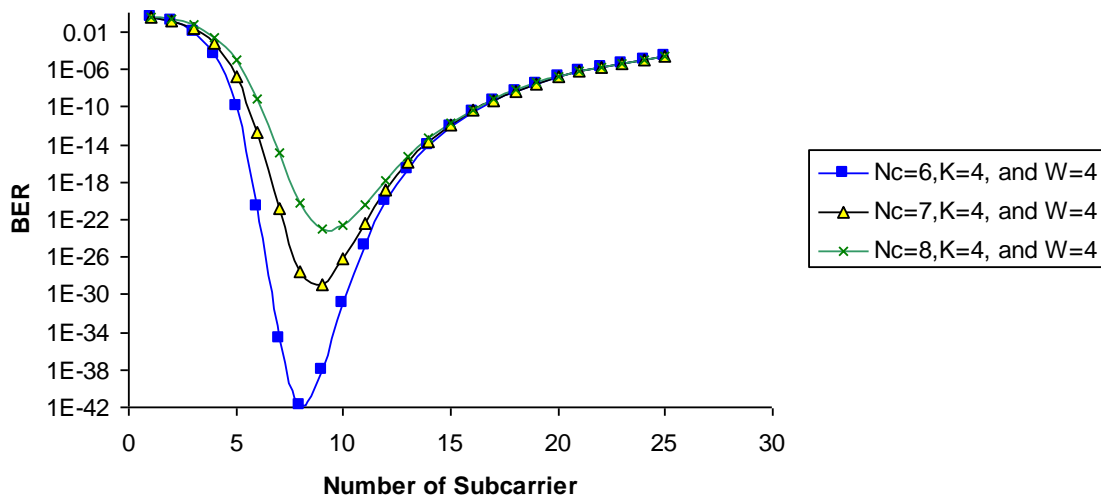**Figure 6.** BER against the number of subcarriers for the hybrid system at Psr= -10dBm employing MD code.

code W=12 and W= 14 for MQC code.

Figure 5 shows the variation of BER against the number of subcarriers for MD and KS codes employing the SCM/SAC-OCDMA technique. It is shown that the performance of the MD code is better compared to KS code even though the weight value of KS code is greater than the MD code weight. The performance of the MD code is still better even when the number of codewordcodewords and numbers of the carrier are greater than that used in the hybrid KS code system. However, the maximum number of subcarriers carried on each codeword with BER of 1×10^{-9} is 19 subcarriers, compared to 6 subcarriers with BER of 1×10^{-9} achieved by KS code. That is achieved due to the zero cross-correlation properties of MD code and eliminates the overlap between the code sequences. Nevertheless, it can be clearly observed that the hybrid system utilizing MD code improves the performance of the SCM/SAC-OCDMA system.

Figure 6 depicts the performance of the hybrid system using direct detection technique for various numbers of carriers and subcarriers. The number of weight of the MD codes is designed at a fixed $W = 4$, while the number of users is 5 in order to observe the effect of number of carriers and subcarriers on the hybrid system capability. It is clearly observable that the variation of BER with the increase in the number of carriers and subcarriers results in an effect of two-tone third order and third-tone third order inter-modulation distortion. On the other hand, the number of subcarrier with an acceptable BER (Maximum
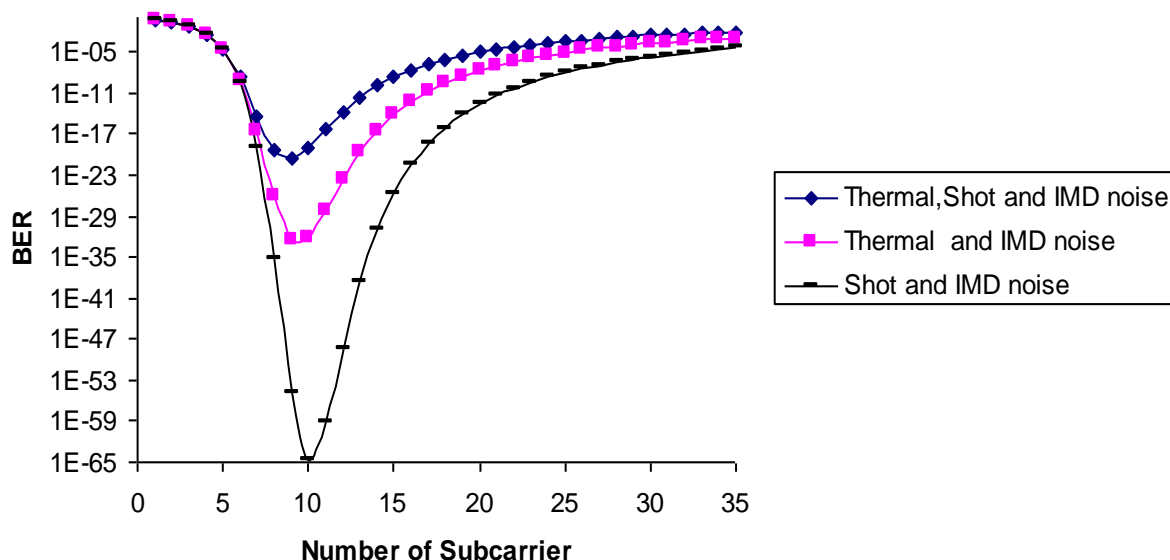
Figure 7. Illustrates the variation of BER with respect to the number of carriers and subcarriers at Psr= -10 dBm.

10^{-9}) is 18 with the minimum carrier. It should be noted that although the BER can go down to the value (10^{-42}) when the number of carrier is 6 (which is practically worthless), it does not contradict the objective of this study in comparing the performance of the hybrid system when the number of carriers is more than 6.

Figure 7 illustrates the variation of BER with respect to the number of carriers and subcarriers under different noise conditions when P_{sr} = -10 dBm, W= 4 and the number of active users is 5 while the number of carriers is 7. We can easily recognize from Figure 7 that the main factor limiter in the system performance is the thermal noise. We also observe that the effect of shot noise is smaller compared to thermal noise at the power source Psr=-10 dBm.

Simulation analysis

The hybrid system is simulated using *Optisystem* ver. 9. The simulation design was implemented based on MD code for two and four subcarrier channels, respectively, where the data rates carry out at 155 M bit/s for each subcarrier channel. Furthermore, the subcarrier frequencies are set at ≥2 (Niquest frequency) times the bit rate. In contrast each optical channel has a spectral width of 0.4 nm.

The simulation was carried out employing the ITU-T G.652 standard single-mode optical fiber (SMF). All the attenuation α (i.e., 0.25 dB/km), dispersion (i.e., 18 ps/nm km), non-linear effects such as four wave mixing and self-phase modulation were activated and specified according to the typical industrial values to simulate the real environment as close as possible. The noise generated

at the receivers was set to be random and totally uncorrelated. The dark current value was set as 5 nA, and the thermal noise coefficient was 1.8×10^{-23} W/Hz for each of the photo-detectors. The performance of the system was characterized by referring to the BER and eye diagram pattern.

Figure 8 shows the effect of the fiber distance on the system performance with two and four subcarrier frequencies. It can be clearly observed from the figure that the BER decreases as the fiber distance increases due to the attenuation and dispersion of fiber length. Furthermore, in the case of increasing the subcarrier channels, the system performance is expected to be decreased as the fiber length increases. In contrast, the BER 4.4×10^{-10} has been achieved for 45 km with four subcarrier channel at 1.21 GHz.

Conclusion

In this paper, we have numerically analyzed a SCM/SAC-OCDMA system, using MD code as a signature sequence code. The performance of the system improved significantly because the total loss is reduced as the direct detection technique required a fewer numbers of filters in the decoder. Therefore, the complexity of the overall system is reduced.

In addition, the system has been simulated using Optisystem software. The simulation results show that the system performance with two and four subcarrier frequencies is affected by the attenuation and dispersion of fiber length. Using MD code as a signature sequence for the SCM/SAC-OCDMA system shows a promising solution to suppression of the Multi Access Interference
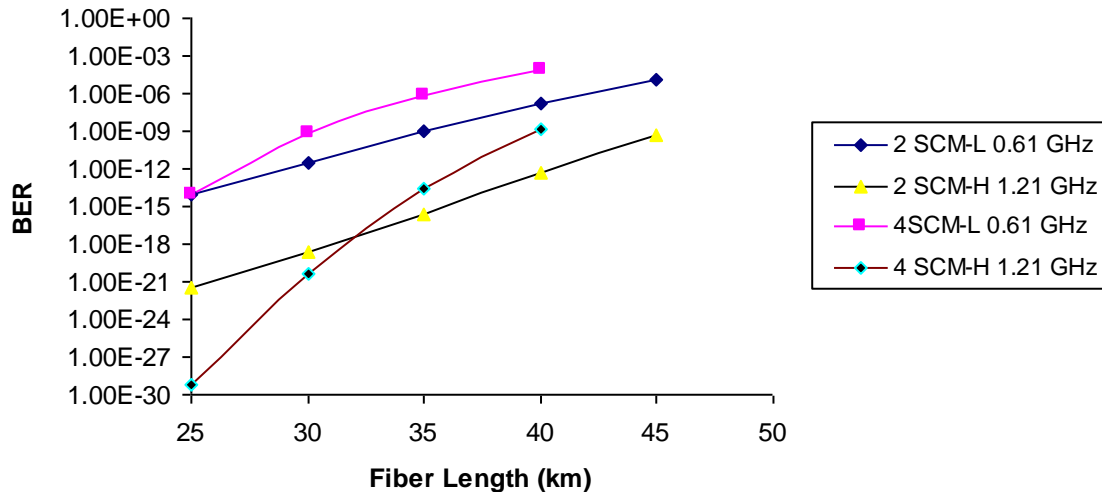
Figure 8. illustrates the variation of BER with respect to fiber length for hybrid SCM SAC-OCDMA.

(MAI) as compared to the ones using other SAC-codes, and carrying a large number of codewords and multiplexed subcarriers.

REFERENCES

Ahmad ASB, Abdullah MK, Mokhtar M, Aljunid SA, Walker SD (2009). Optical domain service differentiation using spectral-amplitude-coding. J. Optical Fiber Technol., 15(1): 26-32.

Bao LD, Niemegeers I (2005). Analysis of IEEE 802.11 in radio over fiber home Networks.

Chao-Chin Y, Jen-Fa H, Shin-Pin T (2004). Optical CDMA network codecs structured with M-sequence codes over waveguide-grating routers. IEEE Lett. J.Photonics Technol., 16(2): 641-643.

Dang BL, Larrode MG, Prasad RV, Niemegeers I, Koonen AM J (2007). Radio-over-Fiber based architecture for seamless wireless indoor communication in the 60 GHz band. J. Comput. Commun., 30(18): 3598-3613.

Fadhil HA, Aljunid SA, Ahmad RB (2009). Performance of random diagonal code for OCDMA systems using new spectral direct detection technique. J. Optical Fiber Technol.,15(3): 283-289.

Hasson FN, Aljunid SA, Samad MDA, Abdullah MK, Shaaris (2008). Spectral amplitude coding OCDMA using AND subtraction technique: J. Appl. Optics., 47: 1263-1268.

Hui R, Zhu B, Huang R, Allen CT, Demarest KR, Richards D (2002). Subcarrier Multiplexing for High Speed Optical Transmission, J. Lightwave Technol., 20: 417-427.

Kaszubowska A, Barry LP, Anandarajah P, Hu L (2006). Characterization of Wavelength Interleaving in Radio-over-Fiber Systems Employing WDM/SCM. Commu J. Optics., 260: 144-149.

Khaleghi F, Kavehrad M (1995). A subcarrier multiplexed CDM optical local area network, theory and experiment. J. IEEE. Trans. Commun., 43(1): 75-87.

Koshy BJ, Shankar PM (1999). Efficient Modeling and Evaluation of Fiber-fed Microcellular Networks in a Land Mobile Channel using a GMSK Modem Scheme. J. IEEE. Selected Areas Commun.,15: 694-705.

Koshy BJ, Shankar PM (1999). Spread Spectrum techniques for fiber-fed microcellular networks. J. IEEE. Trans. Vehicul. Technol., 48: 847-857.

Palais JC (2005). Fiber optic communication," fifth ed., Pearson/Prentice Hall.

Sahbudin RKZ, Abdullah MK, Mokhtar M (2009). Performance improvement of hybrid subcarrier multiplexing optical spectrum code division multiplexing system using spectral direct decoding detection technique. J. Optical Fiber Technol., 15(3): 266-273.

Smith EDJ, Blaikie RJ, Taylor DP (1998). Performance enhancement of spectral-amplitude-coding optical CDMA using pulse-position modulation., J. IEEE. Trans. Commun., 46(9): 1176-1185.

Stok A, Sargent EH (2000). Lighting the local network: Optical code division multiple access and quality of service provisioning IEEE.J. Network, 14: 42-46.

c PK, Ong LC, Alphones A, Luo B, Fujise M (2004). PER and EVM measurements of a radio-over-fiber network for cellular and WLAN system applications. J. Lightwave Technol., 22(11): 2370-2376.

Wen JH, Jhou JS, Li CP (2006). Optical spectral amplitude coding CDMA systems using perfect difference code and interference estimation, IEE Proc. Optoelectron., 153: 152-160.

Zou W, Ghafouri-Shiraz H, Shalaby HMH (2001). New code families for fiber-Bragg-grating-based spectral-amplitude-coding optical CDMA systems. IEEE Lett. J. Photonics Technol., 13(8): 890-892.

Zou W, Shalaby HMH, Ghafouri-Shiraz H (2001). Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems. J. Lightwave Technol., 19(9): 1274-1281.