Design and Cost Performance of Decoding Technique for Hybrid Subcarrier Spectral Amplitude Coding-Optical Code Division Multiple Access System

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Abstract: Problem statement: A hybrid technique combining subcarrier multiplexed and Spectral Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA) deploying the Khazani-Syed code was proposed. It was proposed as a mean of increasing the maximum number of simultaneous active users by increasing the subcarrier and/or the SAC-OCDMA code word. Multiple Access Interference (MAI) is the most dominant cause of performance degradation in SACOCDMA systems. **Approach:** A decoding technique which was simple and easy to build named Spectral Direct Decoding (SDD) technique was proposed for the hybrid system of subcarrier SACOCDMA. **Results:** The comparison between the complementary subtraction and proposed SDD techniques for hybrid subcarrier SAC-OCDMA system in terms of cost performance was presented here. Results showed that the cost performance of the SDD technique offers a significant improvement over the complementary subtraction detection technique. **Conclusion:** It is shown that the cost performance of the hybrid system using SDD technique is significantly better than using the Complementary subtraction technique.

Key words: Cost performance, SDD technique, hybrid subcarrier, Spectral Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA), Spectral Direct Decoding (SDD), communication systems, decoding technique

INTRODUCTION

The tremendous growth of the Internet and the World Wide Web, has made telecommunications one of the leading growth sectors in the world economy. Thus, the infrastructures need to be able to meet the increasingly high user's expectation. The vast bandwidth of the optical fiber enables a large number of simultaneous communication channels to be carried by a single optical fiber by any one of a number of multiplexing techniques. Therefore, in this study, a hybrid technique between subcarrier multiplexed and SAC-OCDMA deploying the Khazani-Syed (KS) (Sahbudin *et al.*, 2009) code is proposed. It is proposed as a means of increasing the maximum number of simultaneous active users by increasing the subcarrier and/or the SAC-OCDMA codeword. Thus the resulting hybrid system is robust against interference, possesses high transmission security and increases the channel capacity in the existing optical fibers.

The SAC-OCDMA systems with good design of the code sequences and detection or decoding technique were proposed as a means of increasing the maximum number of simultaneous active users and reduce the effect of Multiple Access Interference (MAI) (Ab-Rahman *et al.*, 2009; Al-Galbi *et al.*, 2009) at the same time. MAI is the main cause of performance degradation in SAC-OCDMA systems. The effect of MAI can be eliminated by using Complementary subtraction technique, which is also known as balanced detection technique (Tsai *et al.*, 2009) if the spectral amplitude is flat across the whole spectrum. However, in practical, this does not happen and it will still cause MAI. Consequently, it is extremely important to design decoding technique in such a way that MAI is minimized regardless of the number of users and

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maintain the performance of the system at a minimal cost. Alternatively, the subcarrier multiplexed technology is simple and cost-effective. (Kosek *et al.*, 2007). It provides a way to take advantage of the huge bandwidth of the optical fiber using well-known microwave techniques for which components are established and commercially available (Kourtessis *et al.*, 2007).

Researches Yang (2006) and Huang and Chang (2006) use Complementary method at the receiver side to recover the original signal. A decoding technique which is simple and easy to build named SDD technique is proposed for the hybrid system of subcarrier SAC-OCDMA. This technique reduces the receiver complexity, cost and at the same time improves the system performance. In this study, we present the design and cost performance between the Complementary subtraction and SDD decoding techniques for the hybrid subcarrier SAC-OCDMA system.

Hybrid subcarrier SAC-OCDMA system: The block diagram of the hybrid subcarrier SAC-OCDMA system is shown in Fig. 1. At the transmitter, the data (user) is mixed with a different microwave carrier frequency f_i.

The subcarriers are combined and optically modulated onto the code sequence c_i, using an Mach Zehnder Optical External Modulator (OEM). Then m

modulated code sequences are combined together via the optical combiner and transmitted through the optical fiber. So in this hybrid system, each user is assigned with a particular code sequence c_i and subcarrier frequency f_i, where the pair of (c_i, f_i) is unique with respect to every other user. At the receiver, an optical splitter is used to separate the different modulated code sequences. Only the intended receiver is able to correctly demodulate the detected signal, made possible by using a matched code sequence and the unmatched signals are filtered out. Then, the photodetector is used to detect the decoded signal. A splitter and an electrical Band Pass Filter (BPF) are used to split the subcarrier multiplexed signals and to reject the unwanted signals, respectively. In order to recover the original transmitted data, the incoming signal is electrically mixed with a local microwave frequency f_i and filtered using Low-Pass Filter (LPF). Hence, the proposed hybrid system has a high transmission security since each receiver must tune to the correct pair of (c_i, f_i) to receive the desired data.

In this study, optical bandpass filters are used as the encoders and decoders that are discussed. The number of filters needed is equal to the number of 'ones' in the code sequence. Assumption is made here that separate filters are used for different chip wavelength, as been widely proposed in SAC-OCDMA implementation (Anas *et al.*, 2009).
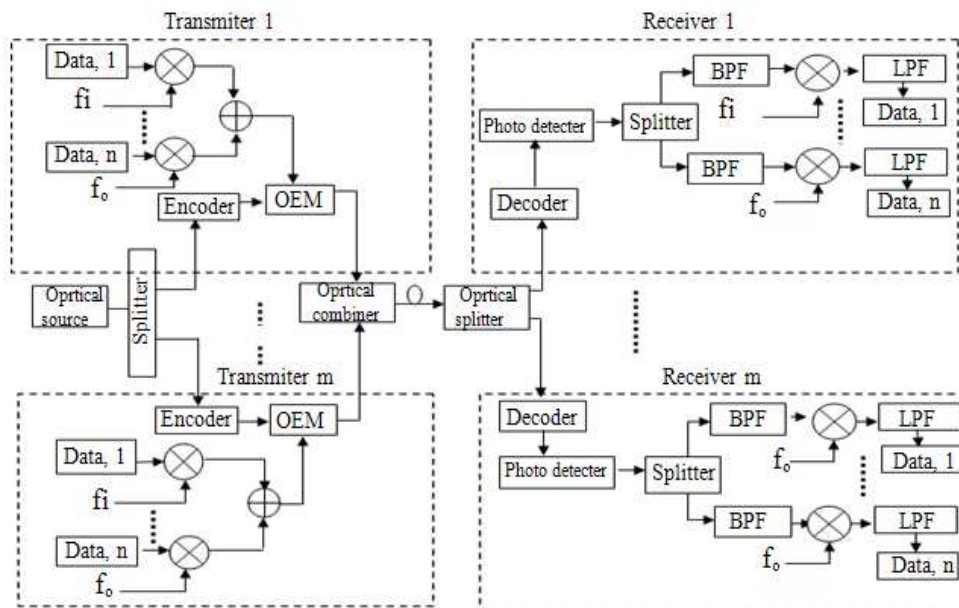

Fig. 1: Block diagram of subcarrier SAC-OCDMA system

In the KS code, two chips (wavelengths) always occur next to each other, while in other codes published Prucnal (2006), two adjacent wavelengths are separated. Since chip 'ones' always occurs in pairs, one filter of a larger bandwidth (doubled) could be used instead of using two filters to represent two distinct 'ones'. Hence, the number of filters at the encoder and decoder for a system employing KS code is reduced by half (Sahbudin and Abdullah, 2009).

MATERIALS AND METHODS

Complementary Subtraction Detection Technique: For example, let us consider the KS code sequences as shown in Table 1.

Note that λ_i where i is 1,2, ...N, represents the spectral position of the chips in the KS code sequence.

The implementation of a hybrid subcarrier SAC-OCDMA system using Complementary subtraction technique is shown in Fig. 2.

The optical pulses are encoded according to the KS code sequences denoted as X = (1100) and Y = (0110). The subcarrier signal is then optically modulated with the KS code sequence. The outputs of the two Mach Zehnder External Modulators (OEM) are combined and transmitted through an optical fiber. As shown in Receiver 1, the signals are split and decoded separately by two Complementary decoders. The outputs from the Complementary filters are detected by the two photo detectors (PIN) connected to a subtractor. In order to decode the KS code and detect the signal, this technique requires five filters, four photodetectors and two subtractors. Three filters with the bandwidth twice the chip width for 'ones' at the position of λ_1 and λ_2, λ_3 and λ_4, λ_2 and λ_3 and two separate filters for λ_1 and λ_4. To eliminate the MAI from undesired users, an attenuator is required at PIN 2 and PIN 4. This is explained below.

Let $C_k(i)$ denote the ith element of the kth KS code sequence with $\overline{C}_1(i)$ as its complement. The code properties for the Complementary detection technique can be written as (Sahbudin and Abdullah, 2009):

$$\sum_{i=1}^{N} C_k(i)C_1(i) = \begin{cases} W, & \text{For } k=1 \\ 1, & \text{For } k \neq 1 \\ & \text{in the same sector} \\ 0, & \text{For } k \neq 1 \\ & \text{not in the same sector} \end{cases} \quad (1)$$

Table 1: Example of KS code with weight, W = 2

	Code sequence			
	l1	l2	l3	l4
X	1	1	0	0
Y	0	1	1	0

And:

$$\sum_{i=1}^{N} C_k(i)\overline{C}_1(i) = \begin{cases} 0, & \text{For } k=1 \\ W-1, & \text{For } k \neq 1 \\ & \text{in the same sector} \\ W, & \text{For } k \neq 1 \\ & \text{not in the same sector} \end{cases} \quad (2)$$

The condition of k and l in the same sector meaning that both code sequences are in C(1), C(2) or C(M) as shown in Eq. 3. For the condition of k and l not in the same sector meaning that one of the code sequences might be in C(1) and the other code sequence is in C(2) or C(M).

$$C(m) = \begin{bmatrix} C(1) & 0 & 0 & 0 \\ 0 & C(2) & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & C(M) \end{bmatrix} \quad (3)$$

The matrix size of each 0 and C(m), $1 < m \leq M$ is the same as C(1) matrix size. For a fixed value of weight, when the number of mapping is increased, the code size is extended by $(m \times K_B)$ and the basic code is extended diagonally as shown in Eq. 3. K_B is given by (Sahbudin and Abdullah, 2009):

$$K_B = \frac{W}{2} + 1 \quad (4)$$

In order to eliminate the MAI, the complement cross correlation $C_k(i)\overline{C}_1(i)$ must be multiplied by an attenuator with a transmission coefficient, **T** so that the cross correlation $C_k(i)\overline{C}_1(i)$ subtracted from $C_k(i)C_1(i)$ is equal to zero. Therefore, the subtraction can be written as:

$$\sum_{i=1}^{N} C_k(i)C_1(i) - T \sum_{i=1}^{N} C_k(i)\overline{C}_1(i)$$
$$= \begin{cases} W, & k=1 \\ 0, & k \neq 1 \end{cases} \quad (5)$$

Where:

$$T = \frac{1}{\left[(W-1) + \dfrac{WK_B(m-1)}{(K_B-1)}\right]} \quad (6)$$
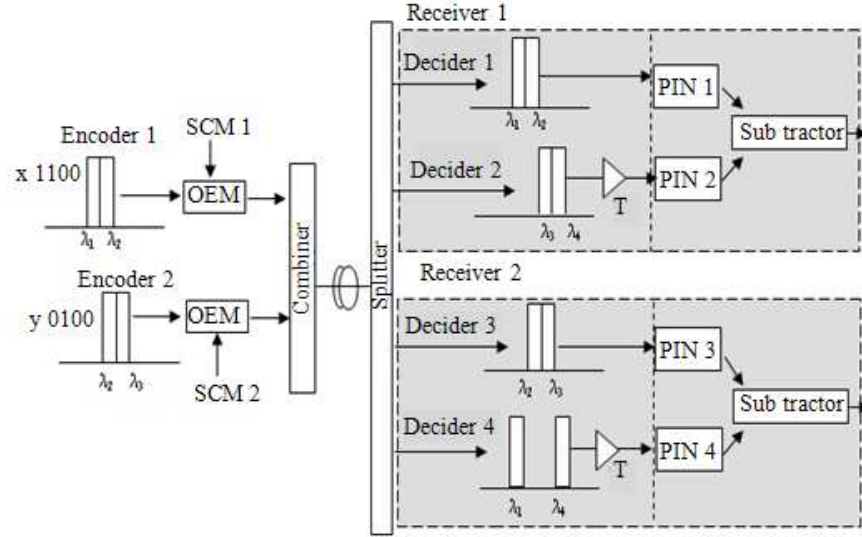
Fig. 2: Hybrid system using Complementary subcarrier SAC-OCDMA subtraction technique

Eq. 6 is when the number of mapping is greater than 1. Without the mapping or m = 1, Eq. 6 becomes:

$$T = \frac{1}{\left[(W-1)\right]} \tag{7}$$

Thus for W>>1, Eq. 7 becomes:

$$T = \frac{1}{W} \tag{8}$$

Eq. 5 shows that when the code sequence is matched, the weight W is obtained. However when the code sequences are unmatched, the weight is zero, meaning that the MAI is eliminated in this system.

Spectral Direct Decoding (SDD) technique: The hybrid subcarrier SAC-OCDMA system using SDD technique is shown in Fig. 3. For two KS code sequences as shown in Fig. 3, it requires only two filters for the decoders, which are used to filter the non-overlapping chips, λ_1 and λ_3 because the overlapping chips of the two code sequences may cause interference at the receiver (Khaleghi *et al.*, 2010). The number of photodetectors is reduced to two. It does not require any subtractor and attenuator at the receiver. Note that it is assumed that the power per chip is sufficient for the data recovery.

If $C_k(i)$ denotes the ith element of the kth KS code sequence, the code properties for SDD technique can be written as:

$$\sum_{i=1}^{N} C_k(i)C_l(i) = \begin{cases} \dfrac{W}{2}, & \text{For} \quad k=1 \\ 0, & \text{For} \quad k \neq 1 \end{cases} \tag{9}$$

When the code sequences are unmatched, the weight is zero, meaning that the MAI can be eliminated using the SDD technique.

In the analysis, the light source of each user is assumed to be unpolarized and has a flat spectrum over bandwidth Δv Hz with magnitude $P_{sr}/\Delta v$, where P_{sr} is the effective power from the source at the decoder. The desired signal for this technique is:

$$I = \Re \left[\frac{P_{sr}}{N}\right] \cdot \left[\frac{W}{2} d_l\right] \tag{10}$$

$$I = \frac{\Re P_{sr} W}{N2} \, m_{n,k} u_{n,k}(t) \tag{11}$$

N is the KS code length, $\Re$ is the responsivity of the photodetectors and $u_{n,k}(t)$ is the normalized digital signal at the nth subcarrier channel of the kth code, where 0 and 1 are represented as digital signal "0" and "1", respectively. $m_{n,k}$ is the modulation index of the nth subcarrier of the kth code. Assuming an identical modulation index for all subcarrier channels, it is necessary that $0 < m_{n,k} \leq \dfrac{1}{N_c}$ (Stern *et al.*, 2008).

Since only the non-overlapping chip is filtered through for SDD technique, PIIN noise is eliminated thus is not considered. PIIN noise occurs only when more than one optical signal is incident on the photodetector surface (Rad and Salehi, 2006; Capman, *et al.*, 2006).
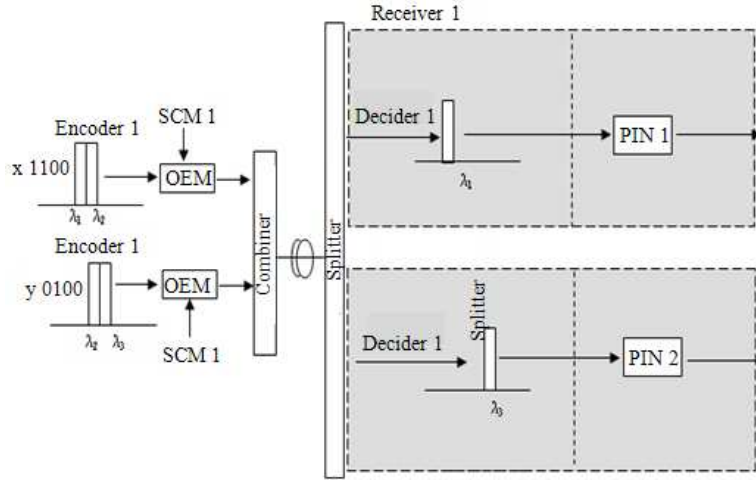
Fig. 3: Hybrid subcarrier SAC-OCDMA system using SDD technique

The total noise here is considered to be only the sum of shot noise, thermal noise and inter-modulation distortion noise as shown in Eq. 12, respectively.

$$\langle I^2 \rangle = eB\mathfrak{R} \cdot \left[\frac{P_{sr}}{N} \left(\frac{W}{2} \right) \right] + \frac{4K_b T_n B}{R_L}$$
$$+ P_{sr}^2 \mathfrak{R}^2 m_{n,k}^6 \left[\frac{D_{111}}{32} + \frac{D_{21}}{128} \right] \tag{12}$$

where, D_{111} and D_{21} are the number of inter-modulation terms of the type $f_i + f_k - f_l$ and $2f_i - f_k$ falling on the nth subcarrier with N_c number of subcarrier channels, respectively. They are given as (Al-Raweshidy and Komaki, 2002):

$$D_{111} = \frac{n}{2} (N_c - n + 1) + \frac{1}{4} \left[(N_c - 3)^2 - 5 \right]$$
$$- \frac{1}{8} \left[1 - (-1)^{N_c} \right] (-1)^{N_c + n} \tag{13}$$

$$D_{21} = \frac{1}{2} \left[N_c - 2 - \frac{1}{2} \left\{ 1 - (-1)^{N_c} \right\} (-1)^n \right] \tag{14}$$

The SNR of the hybrid system using the SDD technique can be expressed as:

$$SNR = \frac{(I_{dd})^2}{\langle I^2 \rangle} \tag{15}$$

$$SNR = \frac{\dfrac{\mathfrak{R}^2 P_{sr}^2 \left(\dfrac{W}{2} \right)^2 m_{n,k}^2}{N^2}}{\dfrac{eB\mathfrak{R}P_{sr}}{N} \left[\dfrac{W}{2} \right] + \dfrac{4K_b T_n B}{R_L} + P_{sr}^2 \mathfrak{R}^2 m_{n,k}^6 \left[\dfrac{D_{111}}{32} + \dfrac{D_{21}}{128} \right]} \tag{16}$$

RESULTS AND DISCUSSION

The design of Complementary subtraction and SDD techniques has been described. It is obvious that the advantage of SDD is that fewer numbers of filters are required for the decoders. The number of filters that is needed in the decoders depends on the code weight, W and the basic code's row size or the basic number of codes, K_B. Eqs. 17 and 18 show the number of filters that are required at the decoder for the Complementary subtraction and SDD technique, respectively.

$$F_{Comp} = 2 K_B^2 - K_{B-} 2 \tag{17}$$

$$F_{SDD} = K_B^2 - K_B \tag{18}$$

Moreover SDD technique does not require subtractor and attenuator to eliminate MAI. Therefore, the use of fewer components to implement the SDD technique leads to a substantial cost reduction of the overall system.

Figure 4 clearly shows that the SDD technique requires fewer filters at the decoders than the Complementary subtraction technique as the number of weight increases. For an example, for weight equals to 10, SDD and Complementary subtraction techniques require 30 and 64 filters, respectively.

Figure 5-6 show the number of filters and costs required for the implementation of both techniques as the number of codes increases, respectively. The weight W is set at 4. The costs are calculated base on the number of filters and attenuators that are required for the decoders. It does not take into account other components such as the encoders, optical sources and fibers, which are considered as similar to both of the systems.
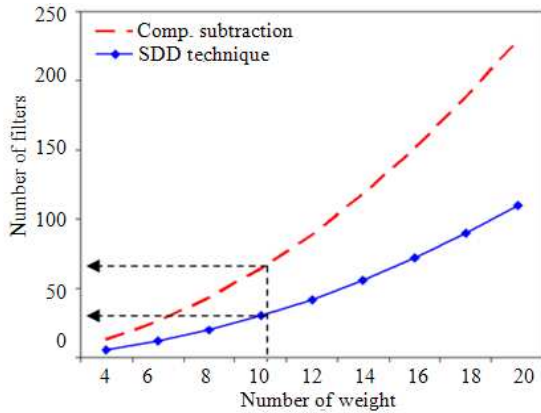
Fig. 4: Number of filters required for Complementary subtraction and SDD techniques as the code weight increases
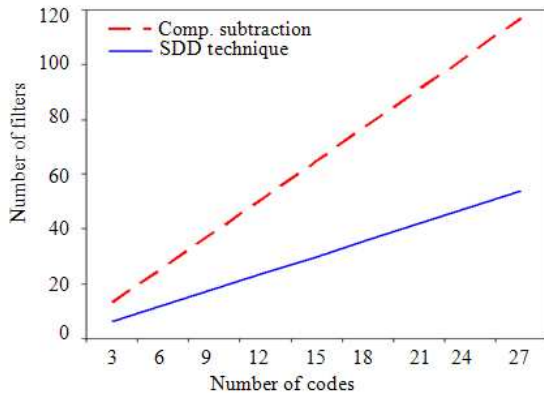

Fig. 5: Number of filters required for Complementary subtraction and SDD techniques as the number of codes increases
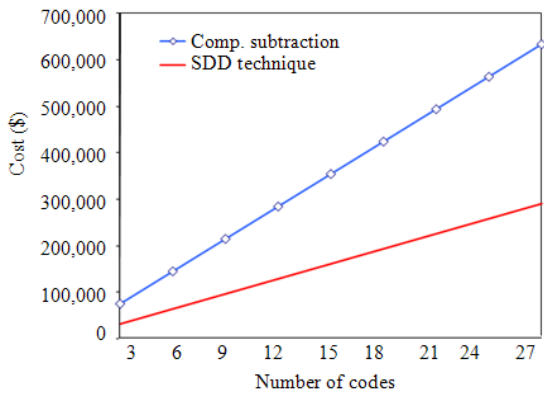

Fig. 6: Cost ($) required for Complementary subtraction and SDD techniques as the number of codes increases
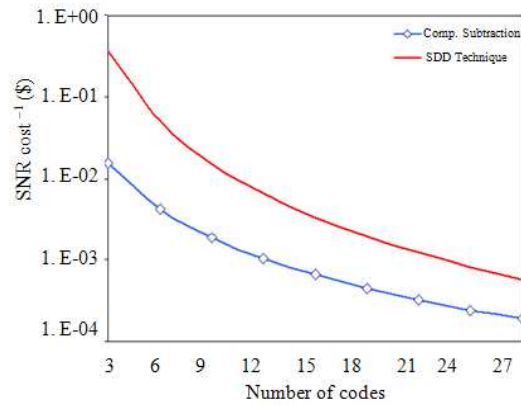

Fig. 7: Performance SNR/Cost ratio for hybrid system using Complementary subtraction and SDD techniques as the number of codes increases

In the economical evaluations, the cost for commercially available tunable optical filter and attenuator that has been provided by the manufacturer is $5366 and $2590, respectively. It is obvious that the SDD technique requires fewer filters than that using the Complementary subtraction as the number of codes increases, thus leads to a substantial reduction in cost of the overall hybrid system. Furthermore, it does not require attenuator to eliminate the MAI.

Figure 7 shows the performance signal-to-noise ratio (SNR)/cost ratio for the hybrid system employing the two decoding techniques. The performance SNR/cost ratio is defined as the SNR divided by the total price of all filters and attenuators. As larger SNR and/or lower cost are desirable, the larger the ratio the better. This is a new parameter proposed to represent the performance-cost relationship for the hybrid subcarrier SAC-OCDMA system. The performance SNR/cost ratio for the hybrid system using SDD technique has been found to be greater than that using the Complementary subtraction technique as the number of codes increases, as shown in Fig. 7. It shows that theoretically it is advantageous to use the SDD technique.

CONCLUSION

The design and cost performance of decoding technique for the hybrid subcarrier SAC-OCDMA system have been presented in this study. It is shown that with the reduced number of filters and photodetectors required for the SDD technique, the complexity of the overall hybrid system is also reduced. It has been proven that the cost performance of the hybrid system using the SDD technique is improved significantly. The proposed hybrid system offers a great potential as a flexible and powerful technique as it can accommodate more users to access the network simultaneously.

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