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Capacity enhancement of wavelength/time/space asynchronous optical CDMA with relaxed cross-correlation

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ABSTRACT

The analysis of a three-dimensional (3-D) wavelength/time/space (W–T–S) asynchronous optical CDMA code family is presented considering MAI only under relaxed cross-correlation ($\lambda_c \geqslant 1$). Based on the code performance, it is shown that for code-limited systems (when W and/or T are non-prime), the number of generated codes and hence the supported users can be significantly increased by relaxing the cross-correlation constraint if a slight degradation in code performance can be tolerated.

1. Introduction

For quite some time now, Optical CDMA has been an area of extensive research due to its numerous benefits such as asynchronism; graceful performance failure under increased loads; simpler protocols and data security [1–9] which make it a very suitable choice for access networks, next generation PONs (NG-PONs) and long distance networks as well. With a number of code families having been proposed for optical CDMA [1–7], a larger code set has always been the first objective of code design besides the near-ideal correlation properties since a larger code set can offer a number of gains such as larger number of supported users and increased data security. Efforts made towards improving the code characteristics i.e. the code correlation properties and code cardinality [1–7] as well as improving the data security of optical CDMA systems [8–14] have regularly been reported in the literature. Codes using variety of sequences such as Prime sequences [2], Golomb sequences [3,6], Pseudo-noise sequences [4,5] etc., have been proposed in order to improve the code characteristics. Two-code keying for secure-data communication has been proposed in [8], techniques such as reconfigurable coders based on code-swapping [10,11], wavelength conversion using PPLN [12] and optical steganography [13,14] have been recently proposed. These significant advancements have enabled optical CDMA as a strong candidate to be used in technologies such as NG-PONs [15–17] and for IP transmission over optical CDMA networks [18,19].

Still, the fundamental strength (the ability to support ever-increasing number of subscribers) behind the success of all these applications lies in the cardinality of an optical CDMA system. To this end, the three-dimensional (3-D) codes are most suited since they give better system performance as well as a larger code set compared to the 1-D/2-D codes, while the requirement of fiber ribbons and the multiple star couplers is eliminated with the 2-D implementation of 3-D codes [2].

The second major issue is the flexibility in selection of code dimensions as demanded by the system constraints such as available optical bandwidth, availability of system components, non-uniform channel spacing (for controlling the non-linearities in fiber-optic CDMA) etc. In some codes, the wavelengths (W) and time slots (T) have been taken as prime [2] or taken to be multiple of 'two' (i.e. 2, 4, 8, 16) due to the photonic component characteristics (matrix codes [3] and pseudo-random noise codes [4,5]). Restricting the code dimensions to be multiple of '2' or prime only cannot hence result in optimal coder design given the limited system bandwidth and other issues as described above. The design flexibility increases when W and T can be prime (P) or non-prime (NP) independently. Addressing the above two concerns, the number of codes in the 3-D optical CDMA systems can be increased (over all the categories of codes formed by prime or non-prime W and/or T) by relaxing the cross-correlation constraint without sacrificing the BER performance.

The procedure for generating the 3-D W–T–S prime codes with 'unity' peak cross-correlation ($\lambda_c = 1$) was explained in [6] where differential detection along with antipodal signaling was considered. The code set becomes limited when the W and/or T dimensions are non-prime.

Based on the code performance, it is shown that for code-limited systems (when wavelengths, W, and/or time-slots, T, are non-prime), the number of supported users can be increased by relaxing the peak cross-correlation constraint while the system can operate at 10^{-9} or even larger users may be supported if BER due to MAI can be further traded for as shown by the results obtained.

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A generalized optical CDMA system is described in Section 2. The improvement in the code cardinality is discussed in Section 3. The BER analysis for code-limited code families (when W and/or T are non-prime) considering MAI only is given in Section 4. In the end, the findings are concluded in Section 5.

2. Optical code division multiple access system

Fig. 1 shows the scheme of optical code division multiple access system. The user data is fed to an electrical to optical converter in the transmitter. A tunable encoder converts the data into coded message and transmits it to the network. A pair of codes is assigned to each user so that both '1' and '0' bits are transmitted using two different codes. A matched decoder in the receiver (that uses differential detection to minimize MAI) can only receive the data correctly by de-spreading the signal intended for it since it uses the same code-pair that has been used in the encoder. The multiple access interference signals from other users are further spread by the decoder. The decoder output is threshold-detected and the desired data is recovered.

3. 3-D *W–T–S* codes when *W*/*T* can be independently prime or non-prime (P/NP)

The 3-D W–T–S Codes are the $W \times T \times S$ matrices of code weight c_w with a single '1' element per plane. Fig. 2 shows a 3-D W–T–S code in which both wavelength and time dimensions are prime while S is non-prime.

In general, $W(r_v + 1)$codes are generated where r_v is the value of r for which the peak cross-correlation exceeds λ_c, and r denotes the number of zeroes inserted to the positions of elements in the Golomb ruler used. The procedure for generating the 3-D W–T–S codes can be found in [6] where the analysis was carried out for $\lambda_c = 1$.

The effect of relaxed peak cross-correlation ($\lambda_c \geqslant 1$) on the code set size r_v and the code dimensions W and T is discussed in the following section.

3.1. Code set size and $\lambda_c \geqslant 1$

The number of generated codes is given by $W(rv + 1)$ and r_v is determined for the different code dimensions and λ_c as discussed below.

3.1.1. W and T are both prime

Extending the results obtained for $\lambda_c = 1$ in [6] to $\lambda_c > 1$, where for two codes corresponding to $r = 0$ and $r = r_v$(corresponding to λ_c) and the same wavelength shift, an overlap in the nth plane will occur when

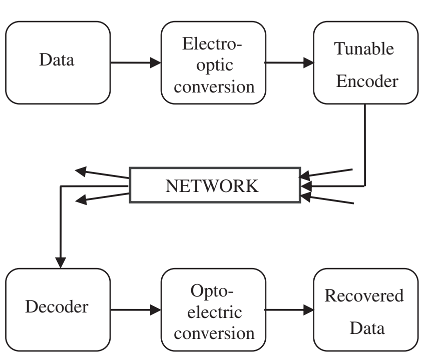

Fig. 1. A generalized star-connected optical CDMA system.

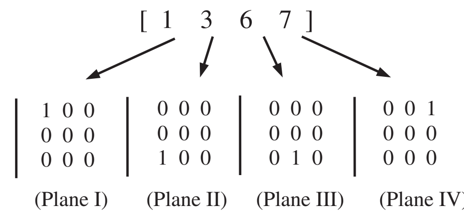

Fig. 2. A 3-D W–T–S code with weight = 4 based on Golomb ruler [1 3 6 7] of order 4 when W/T are prime/prime (P/P).

$$Rem\left[\frac{g'_n}{W \times T}\right] = g_n \tag{1}$$

where g_n and g'_n are the pulse positions in the nth planes of the two codes corresponding to $r = 0$ and $r = r_v$ where g'_n is given as [6]

$$g'_n = (g_n + (n-1) \times r)_{\text{mod}(W \times T)}. \tag{2}$$

The peak cross-correlation increases by unity each time Eq. (1) is satisfied between any two codes; the number of such overlaps giving the value of cross-correlation peak. Specifically, r_v and the plane p containing an overlap are related as

$$r_v(p-1) = k \times (W \times T) \tag{3}$$

where p is the plane containing another overlap and is the largest integer < S such that the above equation is true and k is an integer. Table 1 gives the values for r_v for different S and λ_c. It is seen that for code-limited cases (when W and/or T are non-prime), r_v can be increased by increasing λ_c. The expressions given in Table 1 can be easily obtained from (3). This can be illustrated with the help of some examples.

To illustrate the $max(W,T) < S$ case, let us consider a code $(5 \times 7 \times 16)$ for which the $W \times T = 35$ with $S = 16$. For $\lambda_c = 1$ is violated, and the second and third overlaps occur in the 8th and the 15th planes as per (3) when $r_v \times (8-1) = W \times T = 35$ which gives $r_v = 5$ [i.e. $r_v = min(W \times T)$]. The condition $1 < \lambda_c \leqslant S/W$ is violated when $\lambda_c > S/W$; let say $\lambda_c = 3$ (>S/W), which means that as per (3), second, third and fourth overlaps occur for $r_v = 7$ [i.e. $r_v = max(W,T)$] in the 11th, 8th and 6th plane respectively.

Similarly considering a code $(5 \times 11 \times 7)$ as an example of $min(W,T) < S \leqslant max(W,T)$, the $W \times T = 55$ with $S = 7$. For $\lambda_c = 1$ is violated, and the second overlap occurs in the 6th plane so that as per (3), $r_v \times (6-1) = W \times T = 55$ which gives us $r_v = 11$ [i.e. $r_v = max(W,T)$]. The remaining expressions in Table 1 can be obtained and verified by the same reasoning so the illustration for the remaining expressions will be a repetition and hence has been avoided.

3.1.2. W and/or T are non-prime and $\lambda_c \geqslant 1$

Table 2 gives r_v for different peak cross-correlation λ_c. As for case 1, peak cross-correlation increases by unity each time Eq. (1) is satisfied. The expressions given in Table 2 can be easily obtained from (3) so the illustration for the remaining expressions will be a repetition and hence has been avoided.Subsequently, for $\lambda_c = 1$, $r_v = \frac{W \times T}{(\text{largest integer} < S)}$ such that division is complete with zero remainder.

Table 1
r_v for prime W and T and $1 \leqslant \lambda_c < S$.

No. of space channels, S	r_v		
	$\lambda_c = 1$	$1 < \lambda_c \leqslant S/W$	$S/W < \lambda_c < S$
$max(W,T) < S$	$min(W,T)$	$max(W,T)$	$W \times T$
$min(W,T) < S \leqslant max(W,T)$	$max(W,T)$	$max(W,T)$	$W \times T$
$S \leqslant min(W,T)$	$W \times T$	$W \times T$	$W \times T$