광 부호 분할 다중접속 네트워크를 위한 파장/시간 2차원 코드의 새로운 부호기/복호기

New Encoder/Decoder with Wavelength/Time 2-D Codes for Optical CDMA Network

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Abstract – We propose a new encoder/decoders based on an tuneable wavelength converter (TWC) and an arrayed waveguide grating (AWG) router for large capacity optical CDMA networks. The proposed encoder/decoder treats codewords of wavelength/time 2-D code simultaneously using the dynamic code allocation property of the TWC and the cyclic property of the AWG router, and multiple subscribers can share the encoder/decoder in networks. Feasibility of the structure of the proposed encoder/decoder for dynamic code allocation is tested through simulations using two wavelength/time 2-D codes, which are the generalized multi-wavelength prime code (GMWPC) and the generalized multi-wavelength Reed-Solomon code (GMWRSC). Test results show that the proposed encoder/decoder can increase the channel efficiency not only by increasing the number of simultaneous users without any multiple-access interference but by using a relatively short length CDMA codes.

Key Words : Optical CDMA networks, New encoder/decoder, Dynamic code allocation, Wavelength/time 2-D code, Arrayed waveguide grating (AWG) router.

1. INTRODUCTION

The optical code division multiple access (CDMA) technique has been raised as a novel technology which enables effective usage of broadband characteristics of already installed optical communication infrastructure. Due to its inherent characteristics of orthogonality, the length of optical CDMA code increases as the size of network expands, which is not desirable in system implementation. In order to solve this problem, multiple-dimensional code generation schemes which utilize the combination of wavelength, space, or time domain at the same time are widely being investigated. However, due to the limited number of usable wavelengths and the rapid increase of optical loss in generating multiple- dimensional codes, the maximum number of optical codes becomes limited, and as a result, the number of subscribers in the system becomes confined.

In general, optical CDMA systems are classified as incoherent and coherent systems. The coherent systems in which the generated optical pulses are phase coherent allow the use of bipolar code sequences and offer good correlation properties since they use phase information[1],[2]. However, the coherent systems have high sensitivity to environmental changes, such as relative phase shifts, polarization states, and amplitudes. On the other hand, since the incoherent optical systems[3],[4],[5] allow only optical pulses with intensity levels corresponding to light ON/OFF, the systems are simpler and less sensitive to environmental changes.

Another classification factor of optical CDMA systems is the dimension of code signature or domains of spreading signal. Typically, in one-dimensional (1-D) optical CDMA systems, encoding the information according to a proper code sequence results in time-spreading of the signal. In other words, to support many simultaneous users with good correlation properties in 1-D optical CDMA system, very long CDMA codes should be used. This requires a very large bandwidth expansion, creating a stringent requirement on the speed of encoding and decoding hardware[6]. One possible way to lessen this problem is to use two-dimensional (2-D) codes in wavelength/time optical CDMA systems[5],[6],[7],[8], where each code sequence or matrix carries information in time and wavelength simultaneously. Wavelength/time 2-D optical CDMA system has several advantages, such as inherently high cardinality, high information spectral density, and ease of adapting wavelength division multiplexing technique.

In this paper, we propose a new structure of incoherent wavelength/time 2-D optical encoder and

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decoder system which adapts a new dynamic code allocation technique. In conventional 2-D optical CDMA system, each user needs to have its own specific fixed encoder/decoder which results in very lengthy CDMA codes or huge amount of hardware for a large system[3],[4]. The proposed system uses a group of encoder/decoder for many simultaneous users to share by employing AWGs. Since many users share the encoder/decoder in the system, the amount of hardware can be decreased dramatically. The users which share the encoder/decoder can cause collision between the users when each user transmits the same code simultaneously. We solved this problem by employing a new dynamic code allocation scheme based on the control of code wavelength by tuneable wavelength converters (TWCs).

Feasibility of the structure of the proposed encoder/decoder for dynamic code allocation is tested through simulations using two wavelength/time 2-D codes, which are the generalized multi-wavelength prime code (GMWPC) and the generalized multi-wavelength Reed-Solomon code (GMWRSC).

2. NEW ENCODER/DECODER STRUCTURE

In order to develop a novel technique for minimizing the length of optical CDMA code, we introduce a dynamic code allocation technique so that the optical CDMA encoder/decoder can handle large number of subscribers by using only limited number of optical codes. Dynamic code allocation technique not only makes us overcome the problem of limited number of optical codes but also gives us a huge advantage of saving large amount of hardware by allowing many subscribers to share the same encoder/decoder.

In order to generate desired code, output wavelengths of TWCs are controlled according to the code sequence or matrix generated by dynamic code allocation scheme. The number of TWCs of the encoder depends on the properties of the code used in the system[9]. In case of GMWPC, the number of wavelengths is equal to the weight of the code and the code length, i.e., the number of time chips is greater or equal to the code weight. When GMWPC is used in our system, the number of TWCs is equal to the code length, not the code weight.

Many simultaneous users can share the structure of the group of encoders with the dynamic code allocation by using AWG. In order to explain the operation of an AWG, we now consider the wavelength routing model of a $N \times N$ AWG. Let $\lambda 0$, $\lambda 1$, $\cdots$, λN be the consecutive operating wavelengths of the $N \times N$ AWG. The wavelength that connects the ith input to the jth output of the $N \times N$ AWG can be expressed by

$$\lambda(i, j) = \lambda_q \tag{1}$$

where the subscript q is determined by $q = i+j$ (modulo N)[10].

An example of wavelength routing of 5×5 AWG is shown in Table 1, where the vertical axis and the horizontal axis represent input and output ports, respectively.

Table 1 The wavelength routing table of 5 x 5 AWG

	port 0	**port 1**	**port 2**	**port 3**	**port 4**
port 0	λ_0	λ_1	λ_2	λ_3	λ_4
port 1	λ_1	λ_2	λ_3	λ_4	λ_0
port 2	λ_2	λ_3	λ_4	λ_0	λ_1
port 3	λ_3	λ_4	λ_0	λ_1	λ_2
port 4	λ_4	λ_0	λ_1	λ_2	λ_3

Using this AWG routing characteristics, several simultaneous users can share the encoder as shown in Fig. 1. The collision between users can be avoided easily by appropriate control of output wavelengths of TWCs.

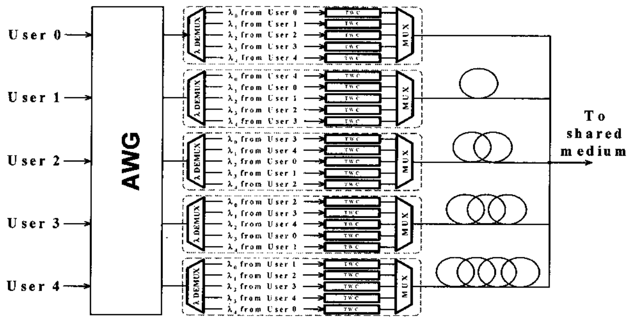


Fig. 1 New encoder configuration

Fig. 2 shows the new decoder configuration. The decoder also has TWCs for dynamic code allocation and uses AWG for sharing function. Optical CDMA spreading signal enters into optical delay lines after duplication through an optical coupler. Through different length delay lines, the duplicated signals are rearranged as an opposite order comparing with the case of time chip signature of encoding code.

When the duplicated signals are matched by delay lines, a time chip which has all of the wavelengths of encoding signal can be recognized as indicated inside the dashed line vertical circle in Fig. 2. The wavelengths inside the duplicated signal are separated after demultiplexing coupler. The separated wavelength is converted to proper wavelength by TWC so that it can be routed to an intended destination through AWG.

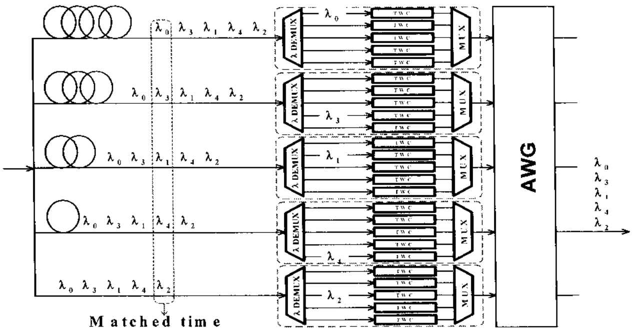


Fig. 2 New decoder configuration

In this process only the wavelength signals inside the time chip becomes dominant, and the other wavelength signals outside the time chip spread out to not intended users, and detected as unmatched signals less than threshold level. In other words, these other simultaneous codes are uncorrelated to the intended user, and treated as noise or multiple access interference(MAI).

The decoder as well as the encoder has dynamic code allocation and sharing function by TWCs and AWGs. Due to dynamic code allocation structure of the encoder, the codes become changeable and we can do programmable decoding according to encoding information. In addition, easy control of collision is possible due to sharing structure of the decoder as well as the encoder.

3. CONSTRUCTION OF WAVELENGTH/TIME 2-D CODES

The multi-wavelength approach in the incoherent 2-D optical CDMA system imbeds multiple wavelengths inside optical codes, providing a second degree of coding dimension[6]. The scheme can be viewed as a wavelength-hopping system, in which the wavelength hop takes place at each pulse of a code sequence. This code allows every pulse in a two-dimensional code sequence to be encoded in a distinct wavelength. Utilizing the same number of code length, the code has a larger cardinality than the conventional one-dimensional codes.

We now use GMWPC and GMWRSC[6] as wavelength/time 2-D codes, which are called multiwavelength optical orthogonal codes, for our new encoder/decoder. The GMWPC and the GMWRSC are constructed by modifying frequency-hop sequences such as the prime code and the Reed-Solomon code, respectively. The cardinality of these codes has been shown asymptotically optimal in [6]. Note that the prime-hop code, which has $p(p-1)$ codewords for a given prime number p, is a "subset" of the choice $k=2$ and $c=p_1=p_2=p$ in construction, i.e., GMWPC.

Given a positive integers c and a set of prime numbers $p_k \ge p_{k-1} \ge \cdots \ge p_1 \ge c$, a $(c\times p_1p_2\cdots p_k,c,0,1)$ GMWPC with $p_1p_2\cdots p_k$ codewords of size $c\times p_1p_2\cdots p_k$, code length $p_1p_2\cdots p_k$, code weight c, zero autocorrelation sidelobes, and crosscorrelation function of at most 1 can be generated [6]. For example, the matrix of codewords of (5×5,5,0,1)GMWPC is shown in Fig. 3. Each ordered pair (t_i,λ_j) represents an optical pulse of wavelength λ_j at time chip t_i. The use of (5×5,5,0,1)GMWPC with time chip reuse in C_o leads us to modify the encoder and decoder configurations of Fig. 1 and Fig. 2.

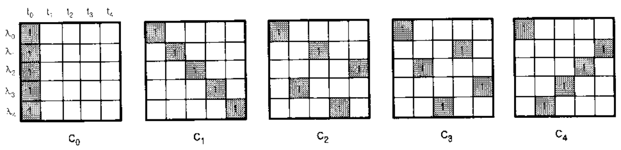


Fig. 3 Matrices of codewords for (5×5,5,0,1)GMWPC

Fig. 4 represents the modified encoder/decoder configurations for (5×5,5,0,1)GMWPC. The part A of Fig. 4, which is indicated as dashed-line vertical box, is due to pulses of codes with the same wavelength λ_0 in the same time chip t_0, while the part B is constructed by insertion of 1×2 optical switches for code C_o because every wavelength of code C_o is positioned at the same time chip. Likewise, the part C is added for common pulses of the codes.

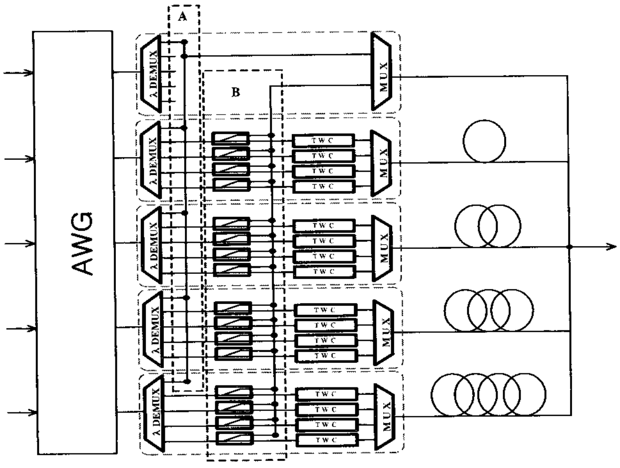


Fig. 4 The configuration of the new encoder/decoder with (5×5,5,0,1)GMWPC

As mentioned in Section 2, the separated wavelength is converted to proper wavelength by TWC so that it can be routed to an intended destination through AWG. Five simultaneous users can share the encoder/decoder as shown in Fig. 4. The collision between users can be avoided easily by appropriate control of output wavelengths of TWCs.

Given a set of prime numbers $p_1p_2\cdots p_k$ such that $p_k \ge p_{k-1} \ge \cdots \ge p_2 \ge p_1$, a $(p_1\times(p_1-1)p_2\cdots p_k, p_1-1, 0, 1)$GMWRSC with $p_1p_2\cdots p_k$ codewords of size $p_1\times(p_1-1)p_2\cdots p_k$, zero autocorrelation sidelobes, and cross-correlation functions of at most 1 can be generated[6]. For example, the matrix of codewords for (7×6,6,0,1)GMWRSC is shown in Fig. 5. Note that the wavelength of optical pulse in each time chip shows cyclic shift for different codewords. For example, the wavelength of the optical pulse at time chip 3 varies cyclically from λ_6 to λ_5 as the codeword changes from C_o to C_6. Configurations of the new encoder and decoder of (7×6,6,0,1)GMWRSC for 7 simultaneous users are omitted for simplicity.

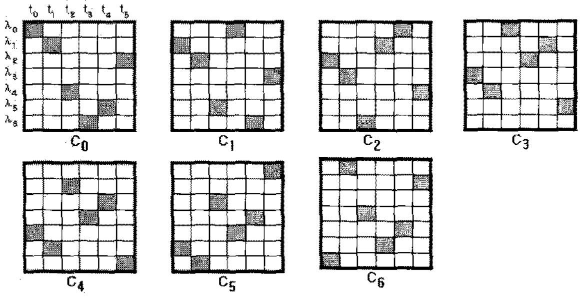
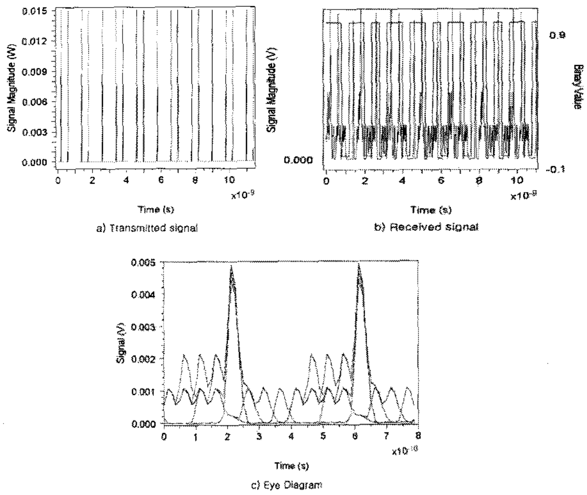


Fig. 5 Matrix of codewords for (7×6,6,0,1)GMWRSC

4. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

Based on the tree network topologies of GMWPC and GMWRSC for 5 users using OptSim software package, simulation results for detection of any specific user code show that the proper choosing of the threshold level at the detector gives the results that the data can be recovered back to its original values. The threshold level is equal to code weight 5 for GMWPC, and signals less than the threshold level are decided as MAI by other simultaneous codes or users. Fig. 6 and Fig. 7 represent the detection results of the code matrix C_3 with bit stream of "11011010" for GMWPC and GMWRSC, respectively, when other code is generated discordantly for arbitrary data stream but with chip synchronization.

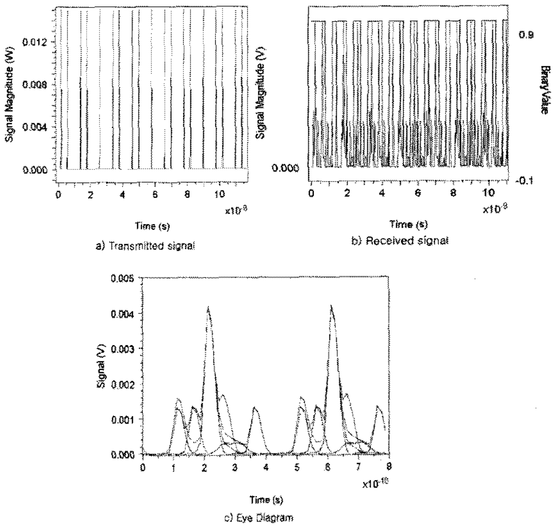


a) Transmitted signal

b) Received signal

c) Eye Diagram

Fig. 6 Detection of C_3 with bit stream of "11011010" for GMWPC



a) Transmitted signal

b) Received signal

c) Eye Diagram

Fig. 7 Detection of C_3 with bit stream of "11011010" for GMWRSC

The performance of encoder/decoder is determined by the band- width efficiency of the used optical codes which is closely related with the error probability of the code in multiple user circumstance as well as the code size depending on the code length. The performances of the multiwavelength CDMA system based on the GMWPC and GMWRSC codes are analyzed. The exact influences due to the interferences of multiple users are the focus of the analysis while the negative effects of thermal noise and the shot noise in the photo detection process are neglected. The results, therefore, represent an asymptotic limit on the system performance as the signal-to-noise ratio approaches infinity. Chip synchronization is also assumed here for the sake of mathematical convenience. This assumption has been demonstrated to result in an upper bound of the performance[11]. Without thermal noise and shot noise, an error occurs only when the accumulative multiuser interference at a particular user, which is receiving data bit "0", reaches over the decision threshold value.

The probability of one of the pulses in a signature code at any time chip is assumed to be $q=(1/2)(c/L)$, where c is the code weight, i.e., the number of pulses in a code, L is the code length, and the received data bit of 1 or 0 is equally probable. The error probability of $(p\times p^2, p, 0, 1)$GMWPC is given by

$$P_e=\frac{1}{2}\sum_{i=Th}^{M-1}\binom{M-1}{i}q^i(1-q)^{M-1-i} \qquad (2)$$

where Th and M are threshold level and total number of simultaneous users, respectively.

Fig. 8 shows the bit error rate (BER) performance versus number of simultaneous users of GMWPC in terms of c and L. We can find that the BER decreases for the same number of users while the number of simultaneous users increases for the identical BER when the code length L increases with the same code weight, i.e., the same number of used wavelengths of $c=7$. If the number of wavelengths increases, the number of simultaneous users increases for the identical BER. However, in this case, the code length also increases due to the properties of GMWPC.

The curve with $c=13$, $L=169$ indicates that for the allowable BER of 10^{-9},the number of simultaneous users for our new encoder/decoder becomes 45. For our system to be more realistic, we might find or devise an optical code that can accommodate more number of simultaneous users with a lower BER for a given code length.

The result in (2) can be modified to the error probability of $(p\times(p-1)p, p-1, 0, 1)$GMWRSC by simply replacing q by $(p-1)/p^2$. Hence, the error probability of GMWRSC is given by

$$P_e=\frac{1}{2}\sum_{i=Th}^{M-1}\binom{M-1}{i}\left(\frac{p-1}{2p^2}\right)^2\left(1-\frac{p-1}{2p^2}\right)^{M-1-i} \qquad (3)$$

Fig. 9 shows the error probabilities versus number of simultaneous users M for GMWPC and GMWRSC for various prime number p based on Eq. (2) and (3). Due to the longer code length, the GMWPC performs better than the GMWRSC.

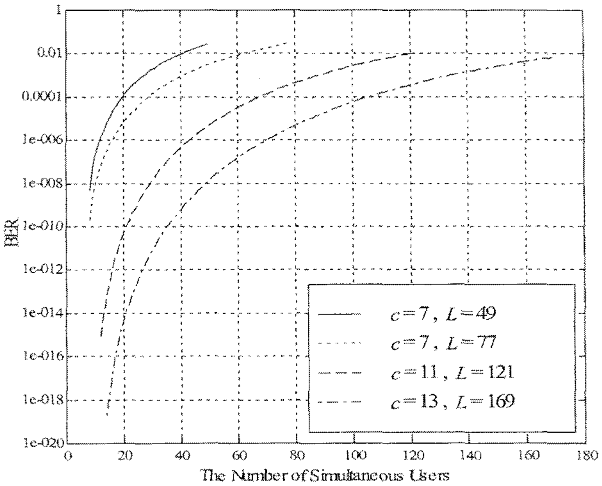


Fig. 8 Error probability vs. number of simultaneous users for GMWPC

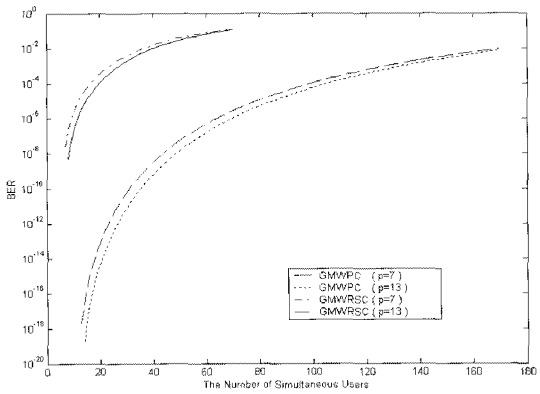


Fig. 9 Error probabilities vs. number of simultaneous users for GMWPC and GMWRSC

5. CONCLUDING REMARKS

The proposed encoder/decoder has the structure of providing dynamic code allocation and sharing through the TWCs and AWG for increasing channel efficiency with a relatively short code length. This was confirmed through simulations using two classes of 2-D wavelength/time codes. The number of simultaneous users can be increased with minimum modification of network configuration depending on the used code.

We analyzed the error probabilities of the used 2-D optical codes and compare them in terms of code length, system capacity, and user bandwidth in multiple user circumstances. For the proposed system to be able to support more number of users, we need to find an optical code which can generate a different network configuration from the used codes so that more number of simultaneous users with a lower error probability for a given code length can be accommodated.

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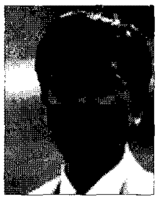

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