

대용량 광 부호 분할 다중접속(Optical CDMA) 네트워크를 위한 2차원 코드의 공유형 부호기/복호기

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Shared-type Encoder/Decoder Based on 2-D Optical Codes for Large Capacity Optical CDMA Network

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요약

본 논문에서는 대용량 광 부호분할 다중접속(Optical CDMA) 네트워크를 위해, 가변 파장변환기(TWC)와 도파로 열격자(AWG)를 이용한 공유형 부호기/복호기를 제안하였다. 제안한 부호기/복호기는 TWC의 동적 코드 할당 특성과 AWG의 순환(cyclic) 특성을 이용하여 다수의 가입자가 동일한 부호기와 복호기를 공유할 수 있도록 파장 시간의 2차원 코드를 사용한다.

2차원 코드 구성 방법인 GMWPC(Generalized Multi-wavelength Prime Code)와 GMWRSC(Generalized Multi-wavelength Reed-Solomon Code)를 사용한 시뮬레이션을 통해 다수의 가입자를 위해 동적 코드 할당을 할 수 있는 제안한 부호기/복호기 구조의 타당성을 제시하였다

제안한 부호기/복호기는 다중 접속 간섭을 일으키지 않으면서 동시 사용자 수를 증가시키며 상대적으로 짧은 코드 길이를 사용함으로써 채널 효율을 향상시킬 수 있는 장점을 가지고 있다

Key Words : large capacity optical CDMA networks, shared-type encoder/decoder, dynamic code allocation, wavelength/time 2-D code, arrayed waveguide grating(AWG) router.

ABSTRACT

For large capacity optical CDMA networks, we propose a shared-type encoder/decoders based on an tunable wavelength converter(TWC) and an arrayed waveguide grating (AWG) router. 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.

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I. 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 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 arrayed waveguide gratings (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 tunable 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).

II. SHARED-TYPE 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.

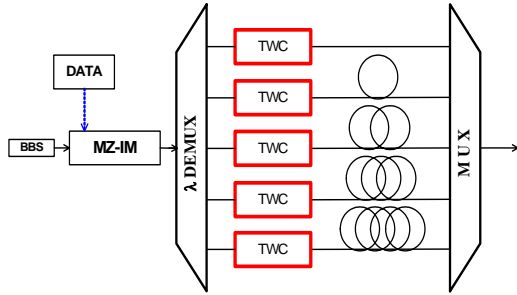


Fig 1. The structure of programmable encoder.

The structure of the proposed programmable encoder is shown in Fig. 1. Optical pulses are generated as return to zero (RZ) signal by modulating a broadband light source (BBS) using Mach-Zehnder intensity modulator (MZ-IM), corresponding to bit rate of data and the number of time chips of code sequence. The generated optical pulse is divided into several wavelengths by the wavelength division multiplexer and converted into appropriate wavelengths by TWCs. The optical pulses with the converted wavelengths are written on correct time chip by optical delay lines. A code is transmitted to a shared medium through an optical coupler.

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 $\lambda_0, \lambda_1, \dots, \lambda_N$ be the N consecutive operating wavelengths of the $N \times N$ AWG. The wavelength that connects the i th input to the j th 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 $q = i + j \pmod{N}$ [10].

	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

Fig 2. The wavelength routing table of 5 x 5 AWG.

An example of wavelength routing of 5×5 AWG is shown in Fig. 2, where the vertical axis and the horizontal axis represent input and output ports, respectively. The output wavelengths corresponding to different input ports are different at any output ports. Using this AWG routing characteristics, several simultaneous users can share the encoder as shown in Fig. 3. The collision between users can be avoided easily by appropriate control of output wavelengths of TWCs. Fig. 4. shows the shared-type 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 wave-

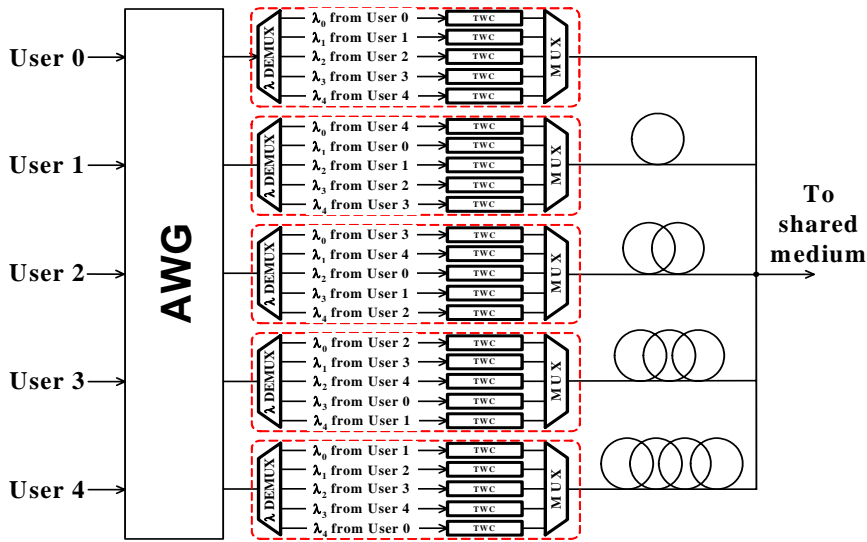


Fig 3. The shared-type encoder configuration.

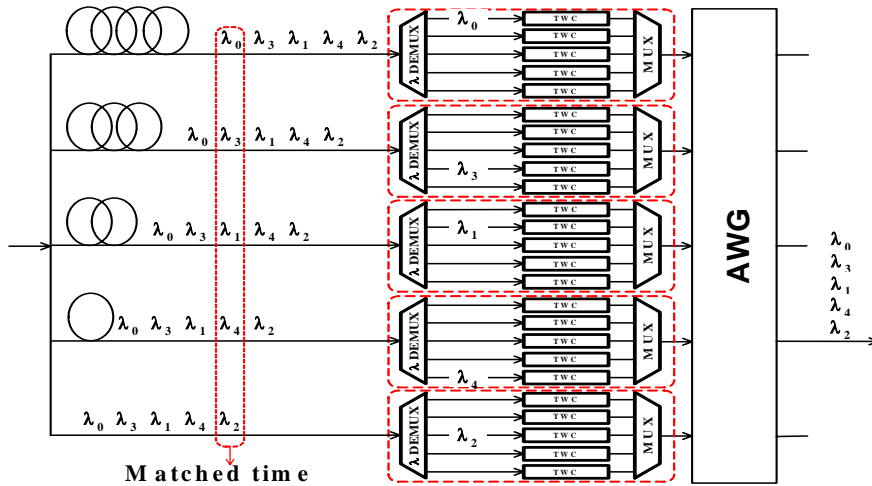


Fig 4. The shared-type decoder configuration.

lengths of encoding signal can be recognized as indicated inside the dashed line vertical circle in Fig. 4. 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.

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.

III. 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 shared-type 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., $(p \times p^2, p, 0, 1)$ GMWPC.

Given a positive integers c and a set of prime numbers $p_k \geq p_{k-1} \geq \dots \geq p_1 \geq c$, a $(c \times p_1 p_2 \dots p_k, c, 0, 1)$ GMWPC with $p_1 p_2 \dots p_k$ codewords of size $c \times p_1 p_2 \dots p_k$, code length $p_1 p_2 \dots p_k$, code weight c , zero autocorrelation sidelobes, and cross-correlation function of at most 1 can be generated[6]. For example, the matrix of codewords of $(5 \times 5, 5, 0, 1)$ GMWPC is shown in Fig. 5. Each ordered pair (t_i, λ_j) represents an optical pulse of wavelength λ_j at time chip t_i . The use of $(5 \times 5, 5, 0, 1)$ GMWPC with time chip reuse in C_0 leads us to modify the encoder and decoder configurations of Fig. 3 and Fig. 4.

Fig. 6. represents the modified encoder/decoder configurations for $(5 \times 5, 5, 0, 1)$ GMWPC. The part A of Fig. 6, 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 op-

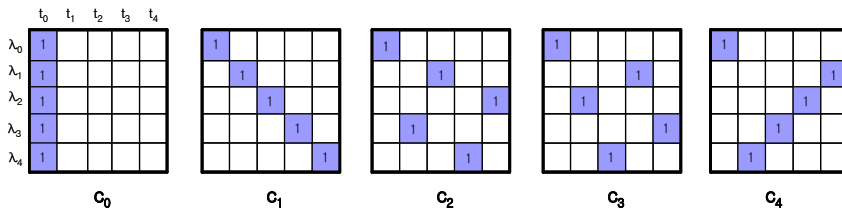


Fig 5. Matrices of codewords for $(5 \times 5, 5, 0, 1)$ GMWPC.

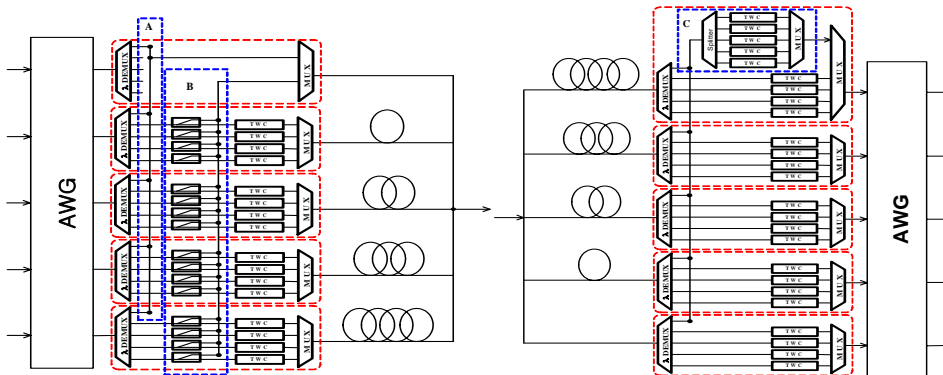


Fig 6. The configuration of the shared-type encoder/decoder with $(5 \times 5, 5, 0, 1)$ GMWPC.

tical switches for code C_0 because every wavelength of code C_0 is positioned at the same time chip. Likewise, the part C is added for common pulses of the codes. As mentioned in Section II, 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. 6. The collision between users can be avoided easily by appropriate control of output wavelengths of TWCs.

Given a set of prime numbers $p_1 p_2 \dots p_k$ such that $p_k \geq p_{k-1} \geq \dots \geq p_2 \geq p_1$, a $p_1 \times (p_1 - 1) p_2 \dots p_k, p_1 - 1, 0, 1)$ GMWRSC with $p_1 p_2 \dots p_k$ codewords of size $p_1 \times (p_1 - 1) p_2 \dots p_k$, zero auto-correlation sidelobes, and cross-correlation functions of at most 1 can be generated[6]. For example, the matrix of codewords for $(7 \times 6, 6, 0, 1)$

GMWRSC is shown in Fig. 7. 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_0 to C_6 . The shared-type encoder and the decoder for 7 simultaneous users is shown in Fig. 8 and Fig. 9, respectively.

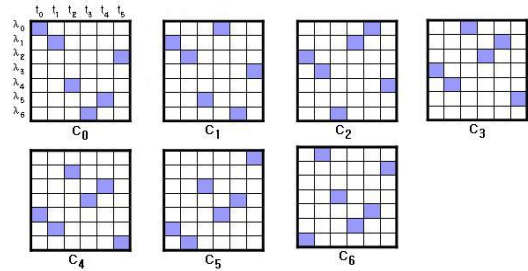


Fig 7. Matrix of codewords for $(7 \times 6, 6, 0, 1)$ GMWRSC.

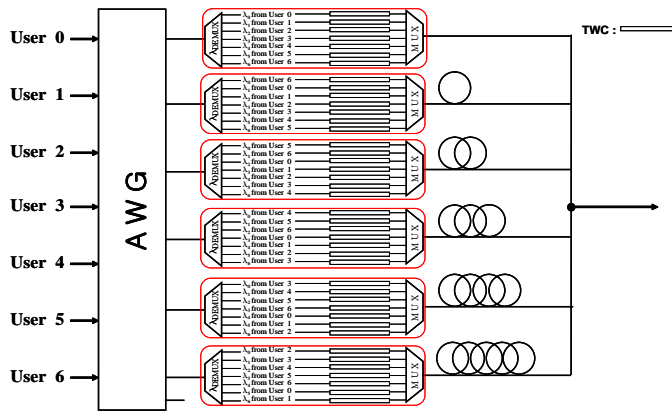


Fig 8. The shared-type encoder configuration with $(7 \times 6, 6, 0, 1)$ GMWRSC.

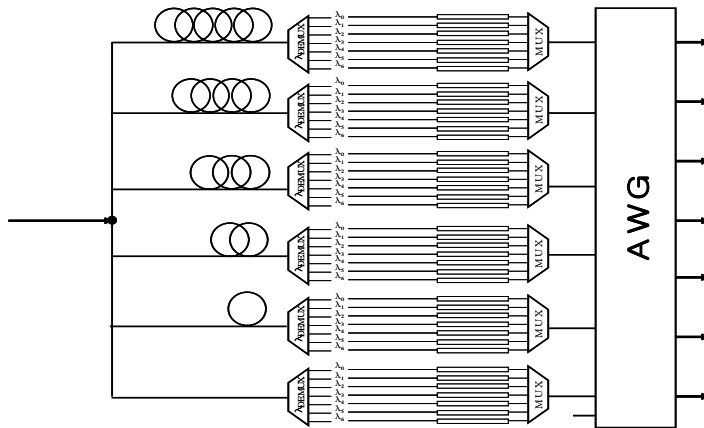


Fig 9. The shared-type decoder configuration with $(7 \times 6, 6, 0, 1)$ GMWRSC.

The used number of AWG, TWC and Mux/Demux based on wavelength channels and code length for $(p \times p, p, 0, 1)$ GMWPC and $(p \times (p-1), p-1, 0, 1)$ GMWRSC are given in Table 1. The complexities of GMWPC and GMWRSC are comparable.

Table 1. System complexity for three codes; $(p \times p, p, 0, 1)$ GMWPC and $(p \times (p-1), p-1, 0, 1)$ GMWRSC.

2-D codes	Parameters	Wavelength channels	Code length	AWGs	TWCs	mux /demux
GMWPC		P	P	2	2P2	4P
GMWRSC		P	P-1	2	2(P-1)P	4(P-1)

IV. SIMULATION RESULTS

Fig. 10 shows the simulation result based on the shared-type encoder/decoder of $(5 \times 5, 5, 0, 1)$ GMWPC for detection of code matrix C_3 for data stream of 111100001010100010001 when other codes are generated discordantly for arbitrary data

stream but with chip synchronization. The threshold level is equal to code weight 5, and signals less than the threshold level are decided as MAI by other simultaneous codes or users.

The captured tree network topologies of GMWPC and GMWRSC for five users using a numerical modeling software package of VPI are shown in Fig. 11 and Fig. 12, respectively. Com-

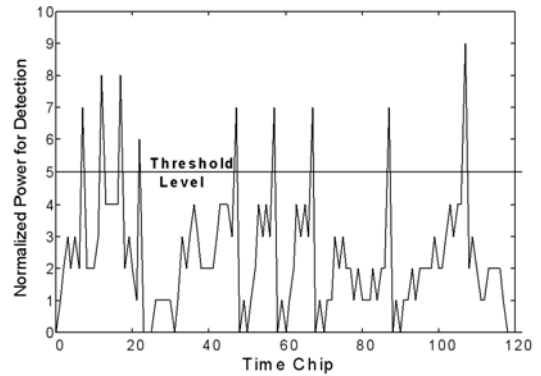


Fig 10. Detection of C_3 for data stream of 111100001010100010001.

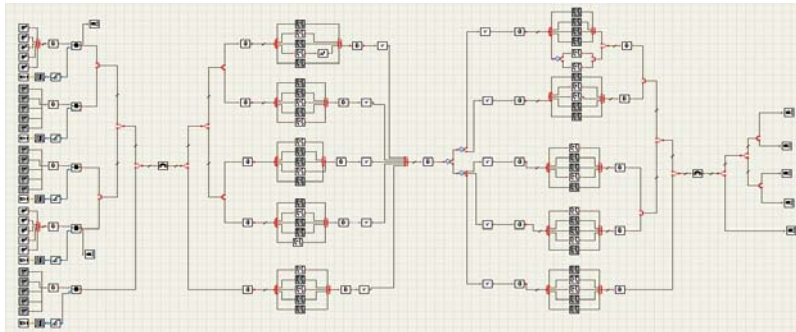


Fig 11. Network topology of GMWPC Encoder/Decoder captured by VPI software.

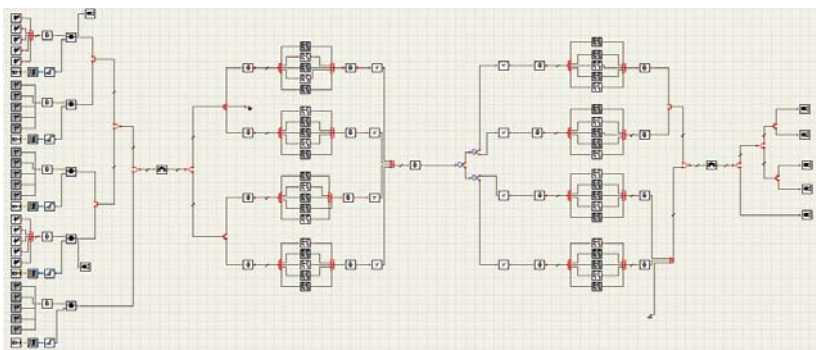


Fig 12. Network topology of GMWRSC Encoder/Decoder captured by VPI software.

pared with the GMWPC, in the network of GMWRSC, one stage of mux/demux and TWC is omitted and the auxiliary extra hardware such as splitters and switches are excluded. This result comes from that there exists only one wavelength for each time chip for GMWRSC.

Simulation results for GMWPC and GMWRSC through running VPI are shown in Fig. 13 and Fig. 14, respectively. The proper choosing of the threshold level at the detector gives the results that the data can be recovered back to its original values.

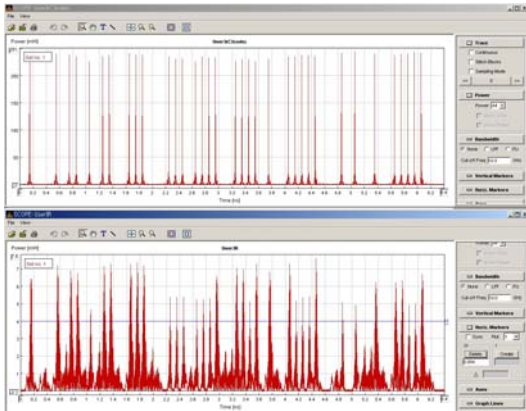


Fig 13. Input and outputs of GMWPC using VPI software.

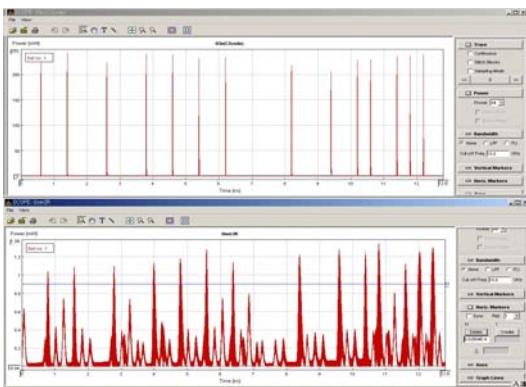


Fig 14. Input and outputs of GMWRSC using VPI software.

V. PERFORMANCE ANALYSIS

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 cir-

cumstance as well as the code size dependent on the code length. The performances of the multi-wavelength 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 short noise in the photodetection 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 short noise, an error occurs only when the accumulative multi-user interference at a particular user, which is receiving data bit “0”, reaches over the decision threshold value.

5.1 Error Probability

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

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

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

Fig. 15 shows the error probability performances versus number of simultaneous users of GMWPC in terms of c and L . We can find that the error probability decreases for the same number of users while the number of simultaneous users increases for the identical error probability 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 error probability. 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 error probability of 10^{-9} , the number of simultaneous users for our shared encoder/decoder becomes 45. For the our system to be more realistic, we might find an optical code that can accommodate more number of simultaneous users with a lower error probability for a given code length.

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

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

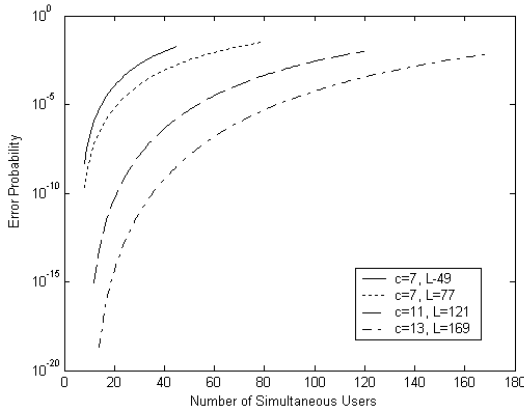


Fig 15. Error probability vs. number of simultaneous users for GMWPC.

Fig. 16 shows the error probabilities versus number of simultaneous users M for GMWPC and GMWRSC for various prime number p based on (2) and (3). Due to the longer code length, the GMWPC performs better than the GMWRSC.

5.2 System Capacity

When N_w wavelength channels and N_t time chips are used to implement the 2-D codes, we have N_w for GMWPC and $N_w N_t / (N_w - 1)$ for GMWRSC, respectively, orthogonal codewords.

For a given N_w , more users can be accommodated by employing a larger number of time chips at the cost of narrower user bandwidth. In this case, however, the number of simultaneous users M also decreases rapidly as the guaranteed error probability becomes lower, and thus the sys-

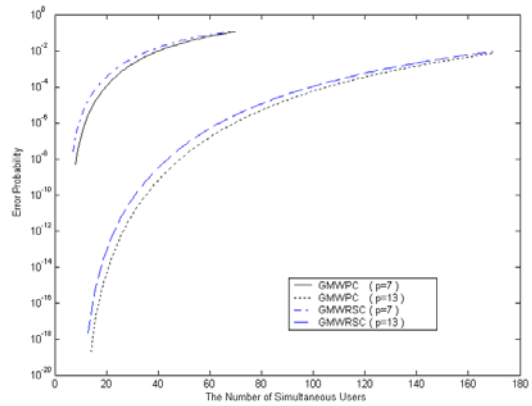


Fig 16. Error probabilities vs. number of simultaneous users for GMWPC and GMWRSC.

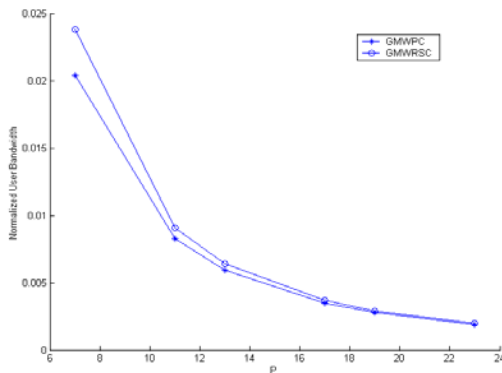


Fig 17. Normalized system capacities for $(p \times p, p, 0, 1)$ GMWPC and $(p \times (p-1), p-1, 0, 1)$ GMWRSC.

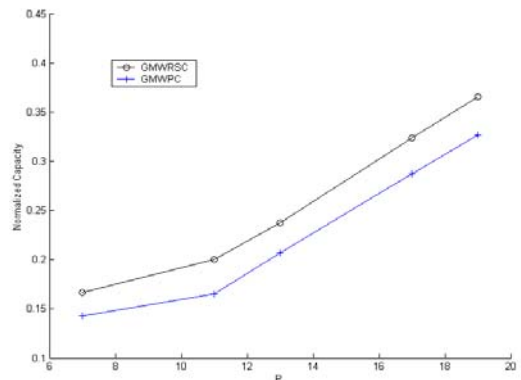


Fig 18. Normalized user bandwidths for $(p \times p, p, 0, 1)$ GMWPC and $(p \times (p-1), p-1, 0, 1)$ GMWRSC.

tem capacity decreases. For the case where $N_w = p$, $N_t = p$ for GMWPC and $N_w = p$, $N_t = (p - 1)$ for GMWRSC with the same error probability of 10^{-9} , the normalized system capacity M/N_t and the normalized user bandwidth $1/N_t$ are plotted as a function of p in Fig. 17. and Fig 18, respectively. We can see that as p increases, the normalized system capacities increase tending to one, while the normalized user bandwidths decrease rapidly. Therefore, in this case, the system capacity and the number of users are limited by user bandwidth rather than N_w [12].

VI. 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 compares 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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