New Code Families for Fiber-Bragg-Grating-Based Spectral-Amplitude-Coding Optical CDMA Systems

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***Abstract*—In this letter, a series of new code families are constructed for spectral-amplitude-coding optical code division multiple access (CDMA) systems at first. Then structures of both the transmitter and the receiver in such a system are also proposed based on tunable chirped fiber Bragg gratings. Our analysis shows that the proposed new code families can suppress the intensity noise effectively and, hence, improve the overall system performance.**

***Index Terms*—Bit-error rate, fiber Bragg gratings, modified quadratic congruence (MQC) code, multiuser interference (MUI), optical code-division multiple access (CDMA), spectral amplitude-coding.**

I. Introduction

Spectral-amplitude-coding optical code division multiple access (CDMA) systems are now receiving more attention because they can completely eliminate multiuser interference (MUI) by using codes with fixed in-phase cross correlation, such as m-sequence and Hadamard code [1]. Let $\lambda = \sum_{i=1}^{N} x_i y_i$ to be the in-phase cross correlation of two different sequences $X = (x_1, x_2, \ldots, x_N)$ and $Y = (y_1, y_2, \ldots, y_N)$. We denote a code by (N, w, λ) where N is the code length, w is the code weight, and λ is its in-phase cross correlation. To suppress the intensity noise, we want the value of λ to be as small as possible. A new code defined as $((q^{m+1}-1/q-1), (q^m-1/q-1), (q^{m-1}-1/q-1))$ has been proposed in [2], using points and hyper-planes of the projective geometry $PG(m, q)$, where q is a prime power and m denotes the finite vector space dimension. It was shown in [2] that this code can effectively suppress the intensity noise and, hence, improve the system performance.

In this letter, we first construct a series of new $(p^2 + p, p + 1, 1)$ code families, where p is a prime number, based on quadratic congruence (QC) code given in [3]. Secondly, we design the structures of both the transmitter and the receiver with fiber Bragg gratings (FBGs) for the use of this code in a spectral-amplitude-coding optical CDMA system. Signal-to-noise ratio of this system is also presented. Finally, the bit-error rate of our system is evaluated by Gaussian approximation and compared with that of a similar system using Hadamard code.

II. Code Construction

The proposed new $(p^2+p, p+1, 1)$ code families, referred to as modified QC (MQC) code, can be constructed using the following steps.

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Step 1) Construct a sequence of integer numbers $y_{d,\alpha,\beta}^{\mathrm{MQC}}(k)$, that are elements of a finite field $GF(p)$ over an odd prime $p(p > 2)$, by using

$$y_{d,\alpha,\beta}^{\mathrm{MQC}}(k) = \begin{cases} \left[d(k+\alpha)^2 + \beta\right] \pmod{p} & k = 0, 1, \ldots, p-1 \\ [\alpha + b] \pmod{p} & k = p \end{cases} \tag{1}$$

where b, α and β are $GF(p)$ elements and d is a nonzero $GF(p)$ element, i.e., $b, \alpha, \beta \in \{0, 1, 2, \ldots, p-1\}$ and $d \in \{1, 2, \ldots, p-1\}$.

In this way we can generate p^2 different sequences for each pair of fixed parameters d and b by changing parameters α and β, and each $y_{d,\alpha,\beta}^{\mathrm{MQC}}(k)$ sequence has $(p+1)$ elements. These p^2 sequences consist of a MQC code family. Therefore, we can totally obtain $p(p-1)$ families when parameters d and b change.

Step 2) Construct a sequence of binary numbers $s_{d,\alpha,\beta}^{\mathrm{MQC}}(k)$ based on the generated sequence $y_{d,\alpha,\beta}^{\mathrm{MQC}}(k)$ by using the mapping method as

$$s_{d,\alpha,\beta}^{\mathrm{MQC}}(i) = \begin{cases} 1, & \text{if } i = kp + y_{d,\alpha,\beta}^{\mathrm{MQC}}(k) \\ 0, & \text{else} \end{cases} \tag{2}$$

where $i = 0, 1, 2, \ldots, p^2 + p - 1$, $k = \lfloor (i/p) \rfloor$, and $\lfloor x \rfloor$ defines the floor function of x, i.e., the largest integer equal to or less than the argument x. Correspondingly, $p(p-1)$ code families can be constructed with different parameters d and b, and in each family there are p^2 code sequences with the following properties:

- Each code sequence has $p^2 + p$ elements that can be divided into $(p+1)$ groups, and each group contains one "1" and $(p-1)$ "0"s.
- In-phase cross correlation λ between any two sequences is always equal to one.

When $m = 2$, the code in [2] becomes a $(q^2+q+1, q+1, 1)$ code, which defers slightly from MQC code only at the code length. Therefore, they have similar properties.

III. Structure of Encoder and Decoder

A detailed function block is proposed in [2] for the use of $((q^{m+1}-1/q-1), (q^m-1/q-1), (q^{m-1}-1/q-1))$ code in the spectral-amplitude-coding optical CDMA systems. Because of the similar properties between the code in [2] and the MQC codes, this function block can also be used for the MQC codes. A novel coherent spectral phase- encoder using FBG has been proposed in [4]. Similarly, we propose the structures of both the transmitter and receiver (shown in Figs. 1 and 2, respectively)

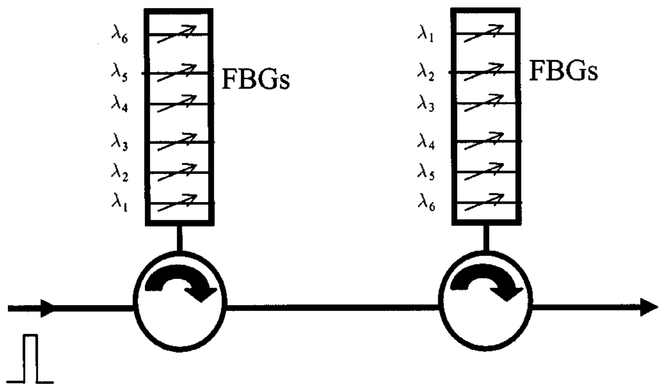

Fig. 1. Encoder ($p = 5$).

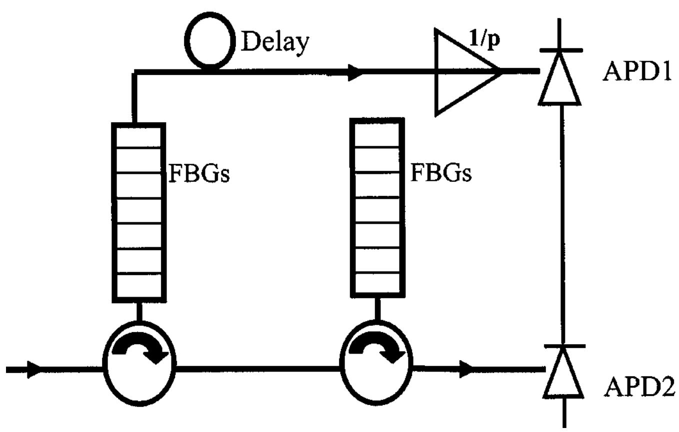

Fig. 2. Decoder ($p = 5$).

for the use of MQC codes in the spectral-amplitude-coding optical CDMA systems.

Let the desired code sequence correspond to a power spectral distribution (psd) as $A(v)$. When a broadband pulse is input into a FBG group, some spectral components are reflected back according to $A(v)$. Then the output at the other end of the grating group will contain all the complementary components corresponding to $\overline{A}(v)$. In the receiver (shown in Fig. 2), the output from the top of the first group of FBGs is used directly as the complementary-code-correlated output $R(v)\overline{A}(v)$ [where $R(v)$ is the overall psd of the received signals and $\overline{A}(v)$ is the psd corresponding to the complementary code of the receiver address sequence]. In this way, we can avoid the loss incurred by an extra $1 : \alpha$ coupler as in [2], and utilize all the received optical power efficiently.

When data bit is "1," we send an optical pulse from the broadband source; and nothing is sent if the data bit is "0." The optical pulse is input into the first fiber-grating group and correspondent spectral components are reflected. For the reconfiguration of the destined address code, the gratings in the encoder are all tunable, which means the central wavelength of the reflected spectral component can be changed. This change can be realized by either fiber stretching using piezoelectric devices or temperature adjustment. If we use MQC code, the changing range of each FBG is the same and equal to only $1/(p+1)$ of the totally available source bandwidth. Therefore, the required tunable range of each FBGs can be greatly reduced. The second group of FBGs in the transmitter is used to compensate the round-trip delay of different spectral components so that all the reflected components have the same time delay and can be incorporated into a pulse again. At the receiver, each grating is fixed according to the receiver's address sequence. In such a system, MUI can be completely eliminated by balanced detection because the in-phase cross correlation between any two code-sequences is always equal to 1.

IV. Performance Analysis

The noises that exist in the receiver include FBG noise, incoherent intensity noise, as well as shot noise and thermal noise of APD. FBG noise is generated due to the imperfect characteristics of FBG. When $\kappa L \geq 3$ (where κ is the coupling coefficient of the FBG, L is the grating length) we can obtain a grating reflectivity as $R = \tanh^2(\kappa L) \geq$ 99.01%. Also, we can reduce the reflectivity of undesired spectral components by adjusting the FBG parameters, such as pitch period, effective refraction index, and so on.

Because intensity noise is the dominating noise and increasing the received optical power cannot reduce its effect, we have only considered this noise in our analysis. For mathematical simplification we have assumed that: 1) each light source is unpolarized and its spectrum is ideally flat over the bandwidth $[v_0 - \Delta v/2,\ v_0 + \Delta v/2]$, where v_0 is the central frequency and Δv is the optical bandwidth in Hertz; 2) each power spectral component has identical spectral width; 3) each user has equal power at the receiver; and 4) each bit-stream from each user is synchronized. Applying the same method as in [5] and taking into account that the probability of sending data bit "1" is $(1/2)$ for each user, the signal-to-noise ratio (SNR) due to intensity noise can be expressed as

$$\mathrm{SNR} = \frac{2\Delta v(p+1)}{BK[(K-1)/p + p + K]} \quad (3)$$

where

- B noise equivalent electrical bandwidth of the receiver;
- K number of simultaneous users;
- p prime number used in the MQC-code construction.

Assuming that the noise is Gaussian-distributed, we can obtain the corresponding bit-error rate (BER) by $P_e = (1/2)\mathrm{erfc}(\sqrt{\mathrm{SNR}/8})$, which is shown in Fig. 3. In this graph, we use the following parameters: $\Delta v =$ 2.5 THz (which is equivalent to 20-nm line width), $B =$ 80 MHz, $p = 11$, and the operation wavelength is 1550 nm. The BER using Hadamard code is also shown as a reference with same Δv, B and similar code length ($N = 128$). Equation (3) clearly shows that the two curves will overlap when $p = 1$.

Also (3) reveals that the proposed system performance improves as p increases. However, larger value of p will cause a larger power loss in the encoder (see Fig. 1). If we use a laser array that consists of $(p+1)$ tunable lasers, we can keep a large optical power. In this case the required tunable range of the laser is only $1/(p+1)$ of the total encoded optical bandwidth. Therefore, this bandwidth can be greatly enlarged and a much better BER results.

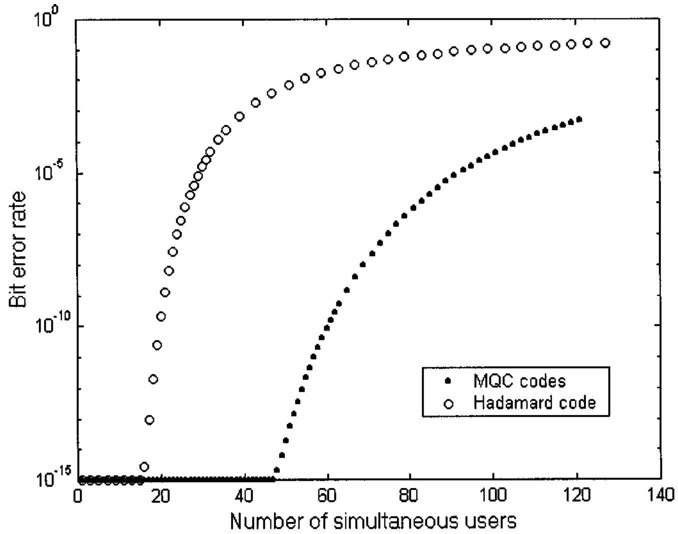

Fig. 3. Bit-error probability against number of simultaneous user.

V. Conclusion

We have proposed a construction method of a series of new code families and corresponding transmitter and receiver structures based on FBGs for spectral-amplitude-coding optical CDMA systems. The new code families can suppress intensity noise effectively and, hence, improve the overall system performance.

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