Computers and Electrical Engineering 49 (2016) 136–145

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

A study of three-dimensional optical code-division multiple-access for optical fiber sensor networks ☆

Chih-Ta Yen [a,*], Chih-Ming Chen [b]

[a] Department of Electrical Engineering, National Formosa University, Yunlin, Taiwan
[b] Institute of Computer and Communications Engineering, National Cheng Kung University, Tainan, Taiwan

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form 20 February 2015
Accepted 23 February 2015
Available online 16 March 2015

Keywords:
Optical fiber sensors (OFSs)
Three-dimensional (3-D)
Optical code-division multiple-access (OCDMA)
Fiber-Bragg grating (FBG)
Phase-induced intensity noise (PIIN)
Multiple access interference (MAI)

ABSTRACT

This study proposes a novel optical fiber sensor (OFS) network using three-dimensional (3-D) wavelength/time/spatial optical code-division multiple-access (OCDMA) scheme. The proposed 3-D modified quadratic congruence/M-matrix (MQC/M-matrix) coding scheme overcome the restriction of single pulse per row inherent in traditional three-dimensional codes and maintain a high signal-to-noise ratio even when source power is low. The 3-D system is implemented using optical switches (OSW), fiber-Bragg gratings (FBGs), optical splitter and optical combiner. The noises of phase-induced intensity noise (PIIN) and multiple access interference (MAI) in the decoding mechanism can be suppressed by using a spectral spreading scheme and balance-detection in the receivers. By constructing 3-D codes using bipolar pseudorandom (PN) codes rather than unipolar codes provides a significant increase in the maximum permissible number of active sensor nodes.

1. Introduction

Recently, optical fiber sensors (OFSs) have been widely applied in measuring physical parameters, including temperature, pressure, rotation, acceleration, humidity, sound, vibration, and electromagnetic fields. OFSs are also commonly used in civil engineering, environmental and biochemical testing, and clinical biomedical fields. Furthermore, OFSs have advantages of their small size, light weight, low power, high sensitivity, high bandwidth, and ability to resist electromagnetic interference (EMI). In addition, OFSs possess the characteristic of light signal transmission, which enables multiplex measurements from multiple points by combining various multiplex network frameworks such as wavelength division multiplexing (WDM), time division multiplexing (TDM), frequency division multiplexing (FDM), and optical code-division multiple-access (OCDMA) [1,2].

The millimeter-wave radio-over-fiber (RoF) system [3–6] has attracted considerable interest as a potential means of realizing OFSs. Because RoF system can transmit analog sensor signals and seems likely to emerge as a rival to OFS networks in the future. Following the successful application of code-division multiple-access (CDMA) techniques in wireless communications, many researchers have investigated the feasibility of implementing optical CDMA (OCDMA) systems [4–19]. Compared to traditional electrical CDMA schemes, OCDMA systems have the advantage that various types of analog sensor signal can be multiplexed in the optical domain. Furthermore, high processing gains can be obtained using conventional

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. Wen-Hsiang Hsieh.

* Corresponding author.
E-mail address: chihtayen@gmail.com (C.-T. Yen).

http://dx.doi.org/10.1016/j.compeleceng.2015.02.016
0045-7906/

broadband optical devices. OCDMA schemes allow multiple sensor signals in a local area network (LANs) to access the same fiber channel asynchronously without delays or the need for scheduling. Accordingly, OCDMA represents an attractive access technique for OFS networks. In an OFS network with OCDMA access, different node of sensor signals assign different codes. The advantage of the network is easily to add/remove the access points by changing the length of codes or using the specified codes for corresponding network.

The performance of OCDMA systems is mainly degraded by the interference from other simultaneous sensor signals, which is called multiple access interference (MAI). In order to eliminate MAI, the spectral-amplitude coding OCDMA (SAC-OCDMA) system using spectral codes with fixed in-phase cross-correlation were proposed [16]. However, due to the usage of noncoherent broadband light source (BLS), the phase-induced intensity noise (PIIN) exists in these systems and causes considerable performance degradation. In SAC-OCDMA schemes, it is essential to identify the maximum number of serviceable wavelengths since this number dictates the maximum permissible code length and this in turn determines the maximum number of sensor nodes which can be accommodated simultaneously on the network. When the number of sensor nodes is large, it becomes impractical to use limited bandwidth of optical source and optical filters.

Due to the unipolar characteristic of optical signals, the length of one-dimensional (1-D) optical codes must be increased if the maximum permissible number of active RBSs is to be increased. However, long code lengths decrease the data rate and increase the MAI effect at the receiver in time-spreading OCDMA schemes. To overcome the limit of 1-D code and hence multi-dimensional coding method such as two-dimensional (2-D) code [13,14,17] and three-dimensional (3-D) [18,19] code were proposed. The above 3-D coding configuration, the encoding and decoding functions are performed by delaying the optical pulse in the time domain using optical delay lines. Although suitable for optical digital modulation, this technique is less easily applied to the multiplexing of radio signals for transmission over analog links. Previously, Yang and Huang [13] performed optical spectra with fiber-Bragg gratings (FBGs) and spatial coding with star coupler. At nearly same time, Yen and Huang [14] performed time-spreading/wavelength-hopping multiplexing by time-spreading optical pulses with optical switches (OSWs) and spectral coding with arrayed-waveguide grating (AWG). In this study, we combine 1-D time-spreading, wavelength-hopping and spatial coding into 3-D wavelength/time/spatial process.

In the proposed system, we propose new 3-D matrix and associated decoding scheme for a wavelength/time/spatial OCDMA system. We construct 3-D modified quadratic congruence/M-matrix (MQC/M-matrix) codes by extending 1-D MQC codes used for wavelength coding integrated with 2-D M-matrix codes used for time/spatial coding. The performance of multiple-wavelength OCDMA scheme is essentially governed by the PIIN in the receiver. Although various studies have proposed codes with a low in-phase cross-correlation to alleviate this unavoidable effect, the lower code weight leads to a large power loss and therefore these codes perform poorly at low signal power.

The proposed MQC/M-matrix coding scheme overcome the restriction of single pulse per row inherent in traditional 3-D codes and maintain a high signal-to-noise ratio (SNR) even when source power is low. Although the problems of PIIN and MAI still arise in the decoding mechanism of the proposed 3-D scheme, the use of a spectral spreading scheme and balance-detection in the receivers suppress their effects. The rest of this paper is organized as follows. Section 2 provides an overview of the MQC/M-matrix code construction and the system configuration. In Section 3, we analyze the code performance. Acknowledgement section is brief conclusion.

2. Code construction and system description

In the study, we choose low cross-correlation code of MQC as wavelength-hopping code to suppress the PIIN effect. For ensuring the higher transmitted power is obtained in the 3-D OCDMA system, we choose high auto-correlation codes of M-matrices for each time and spatial codes in the OFS network. The 3-D wavelength/time/spatial code can be constructed by employing the following steps: (1) First, we construct MQC codes [9] used for wavelength domain. (2) Second, the M-matrix codes [13] are used for time/spatial domain. (3) We finally combine MQC codes with M-matrix codes to generate 3-D codes.

Let $\boldsymbol{X}_a = [x_a(1)\ldots x_a(h)\ldots x_a(L)]$, $\boldsymbol{Y}_b = [y_b(1)\ldots y_b(t)\ldots y_b(M)]$ and $\boldsymbol{Z}_c = [z_c(1)\ldots z_c(s)\ldots z_c(N)]$ represent ath MQC code, bth M-sequence code and cth M-sequence code used for wavelength, time and spatial domain. The code length for these code sequences are $L = p^2 + p$, M and N. Note that L, M and N need not be in same code length. The 3-D MQC/M-matrix codes can be expressed as $\boldsymbol{R}_{a,b,c} = [x_a(1)\boldsymbol{Y}_b^{\mathrm{T}}\boldsymbol{Z}_c, \ldots, x_a(\lambda)\boldsymbol{Y}_b^{\mathrm{T}}\boldsymbol{Z}_c, \ldots, x_a(L)\boldsymbol{Y}_b^{\mathrm{T}}\boldsymbol{Z}_c]$, where $\boldsymbol{Y}_b^{\mathrm{T}}\boldsymbol{Z}_c$ is an M-matrix. We can use $\boldsymbol{R}_{a,b,c}$ as the wavelength-hopping, time-spreading and spatial codes for the OCDMA network.

The elements of the eight decoding correlation functions at the receiver end for each PD are defined as:

$$\begin{aligned}
&R^{(1)}_{a,b,c}(g,h,l) = X_a Y_b^T Z_c \quad R^{(5)}_{a,b,c}(g,h,l) = X_a Y_b^T \overline{Z}_c\\
&R^{(2)}_{a,b,c}(g,h,l) = \overline{X}_a Y_b^T Z_c \quad R^{(6)}_{a,b,c}(g,h,l) = \overline{X}_a Y_b^T \overline{Z}_c\\
&R^{(3)}_{a,b,c}(g,h,l) = X_a \overline{Y}_b^T Z_c \quad R^{(7)}_{a,b,c}(g,h,l) = X_a \overline{Y}_b^T \overline{Z}_c\\
&R^{(4)}_{a,b,c}(g,h,l) = \overline{X}_a \overline{Y}_b^T Z_c \quad R^{(8)}_{a,b,c}(g,h,l) = \overline{X}_a \overline{Y}_b^T \overline{Z}_c.
\end{aligned} \tag{1}$$

where $\overline{X}$, $\overline{Y}$, and $\overline{Z}$ are the complementary code sequences of X, Y, and Z.