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Performance analysis of orthogonal optical chaotic division multiplexing utilizing semiconductor lasers

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ABSTRACT

In this paper, we numerically investigate the performance of orthogonal optical chaotic division multiplexing (OOCDM) based on active–passive decomposition utilizing semiconductor lasers. To the best of our knowledge, it is the first time that two necessary conditions including chaotic synchronization condition and orthogonal condition of chaotic carriers are defined to quantify the performance of OOCDM. The chaotic characteristics of the output optical powers, including time traces, RF power spectra, and auto-correlation function, are numerically analyzed. The effects of spontaneous emission noise and the following *internal and external* parameter mismatch on the performance of OOCDM are analyzed in detail, which include gain saturation coefficient, photon lifetime, carrier decay rate, carrier number at transparency, differential gain, linewidth enhancement factor, and pumping current. The numerical results show that the proposed OOCDM system is robust towards spontaneous emission noise and parameter mismatch for certain relative mismatch ratios.

1. Introduction

Chaotic optical communications is an encryption protocol for fiber-optic communications at the physical layer. For this encryption protocol, a message is embedded within a chaotic carrier generated by a transmitter, and recovered by a receiver upon synchronization with chaotic transmitter [1]. Chaotic carrier generation and chaotic synchronization have been realized utilizing CO_2 lasers, fiber lasers, solid-state lasers, semiconductor lasers and so on. Due to the following merits of semiconductor lasers: low cost, small size, high efficiency, low power consumption, and so on, chaotic optical communications using semiconductor lasers has attracted extensive research interest during the past decade [1–14]. Argyris et al. successfully realized a field trial chaotic optical communications for transmission rate of 1 Gbits/s, and bit error rate of 10^{-7} in a 120-km commercial single optical fiber [1]. This is a milestone opening the door to the practical applications of chaotic optical communications. During recent years, the practical issues for chaotic optical communications mainly focus on the chaotic photonic integrated circuits (PICs) [15], multiplexing [16], bidirectional communications [17], bandwidth enhancement [18], security analysis [19,20], transmission rate increase [21], generation of novel chaotic carriers [22–24], etc.

Multiplexing is an important aspect for this technique, which can realize multiple-channel transmission in a single optical fiber to economize link resources. WDM for chaotic optical communications includes two aspects: WDM between chaotic optical channel and conventional optical channel, and WDM among multiple chaotic optical channels. For the former, Zhang et al. numerically studied the DWDM transmission between chaotic optical channel and conventional optical channel [25]. Argyris et al. experimentally demonstrated the corresponding results [26]. For the later, Zhao et al. studied the performance for DWDM among triple chaotic optical channels [27]. However, the orthogonal optical chaotic division multiplexing (OOCDM) can obviously economize the optical link resources. Rontani et al. pointed out that OOCDM can be realized utilizing active–passive decomposition (APD) [28]. Nevertheless, to the best of our knowledge, the orthogonal performance of optical chaotic division multiplexing, including necessary conditions, robust orthogonality, chaotic synchronization against parameter mismatch, has not yet been analyzed in detail.

In this paper, the performance for OOCDM based on APD is demonstrated numerically. The necessary conditions for OOCDM are proposed and analyzed by quantifying the system performance with the variation of the parameter values of the transmitters and spontaneous emission noise.

2. Necessary conditions

The setup for OOCDM using semiconductor lasers is shown in Fig. 1. The output optical powers of transmitters LDT_1, LDT_2,…, and LDT_i are combined by an optical coupler. Optical feedback is

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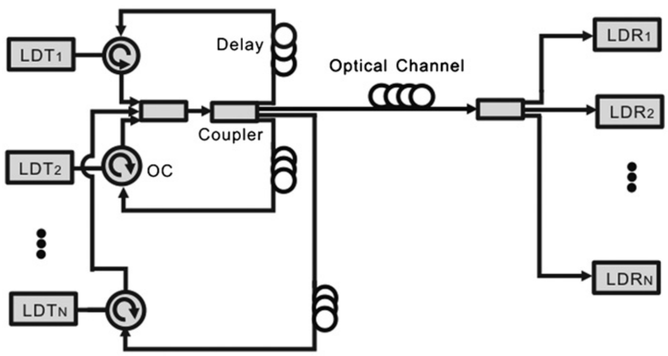

Fig. 1. Setup for orthogonal optical chaotic division multiplexing. OC: optical circulator.

realized by the feedback loops to drive the transmitters. Meanwhile one beam of the combined optical signal is sent to the optical channel. Therefore, the receivers are also driven by the combined optical signal, which is the so-called active–passive decomposition. As demonstrated previously, a matched receiver with the chaotic transmitter can synchronize. While the carriers generated by the transmitters can be orthogonal under the condition of APD. Consequently, the OOCDM is achieved. Note that feedback loops consisting of optical fiber instead of optical devices in the free space are adopted to realize chaotic optical communications utilizing optical fiber. The feedback light propagated in the fiber loops operates in coherent state [29,30]. This is due to the small optical power of the transmitter laser, which causes the light propagated in fiber locating in the linear propagation regime. Hence no nonlinear effects of fiber occur [31].

The active–passive decomposition is adopted to achieve OOCDM. During the following part, the corresponding mathematical analyses are demonstrated.

A dynamical system containing N semiconductor lasers can be expressed as follows:

$$\dot{x}_i = f_i(x_i(t),\, s(t)), \quad i = 1,2,\ldots,N, \tag{1}$$

where $x \in R^3$. This three-dimensional physical space of the slowly varying complex electric field amplitude E and the carrier number N is the so-called (E, N) space.

The driving signal $s(t)$ is expressed as

$$s(t) = g(x_1, x_2, \ldots, x_N) = g(E_1^{\mathrm{T}}, E_2^{\mathrm{T}}, \ldots, E_N^{\mathrm{T}}). \tag{2}$$

For the receiver side

$$\dot{y}_i = f_i(y_i(t),\, s(t)), \quad i = 1,2,\ldots,N. \tag{3}$$

Therefore, the decomposition of f and g is the active–passive decomposition of the system described by Eq. (1) containing N semiconductor lasers, which ensures the realization of OOCDM.

The optical power is adopted to quantitatively measure the necessary conditions for OOCDM in this paper. The relationship between the optical power P and the electric field amplitude E can be expressed as follows [32]:

$$P = [hc\omega\alpha_m/(4\pi\mu_g)]\|E\|^2, \tag{4}$$

where h is the Planck's constant, c is the speed of light in vacuum. $\omega = 2\pi c/\lambda$ is the angular frequency corresponding with the central wavelength. α_m is the facet loss, μ_g is group refractive index. The parameter values used in the following simulation are $\alpha_m = 4500\ \mathrm{m}^{-1}$, $\mu_g = 4$.

We use the correlation coefficient to quantify the similarity of two chaotic time traces, which is defined as [33]

$$\mathrm{CC} = \frac{\langle [P_1(t) - \langle P_1(t)\rangle][P_2(t) - \langle P_2(t)\rangle]\rangle}{\sqrt{\langle |[P_1(t) - \langle P_1(t)\rangle]|^2\rangle}\sqrt{\langle |[P_2(t) - \langle P_2(t)\rangle]|^2\rangle}}, \tag{5}$$

where $P_1(t)$ and $P_2(t)$ are the optical powers of chaotic time traces 1 and 2, and $\langle \bullet \rangle$ denotes the time average. The greater the CC, the higher similarity is.

The following two necessary conditions are defined to quantify the performance of OOCDM.

3. Synchronization condition

The matched transmitter $\dot{x}_i = f_i(x_i(t), s(t))$and receiver $\dot{y}_i = f_i(y_i(t), s(t))$should be synchronous for any driving $s(t)$ and any initial condition $x_i(0)$ and $y_i(0)$. Mathematically, the definition of synchronization is

$$\|x_i - y_i\| \to 0, \quad t \to \infty. \tag{6}$$

Eq. (6) can be expressed by correlation coefficient as follows:

$$\mathrm{CC}(x_i, y_i) \to 1, \quad t \to \infty. \tag{7}$$

The structure and parameters for the transmitter and receiver should be matched very well for the chaotic synchronization defined by Eq. (7). This is the so-called complete synchronization, which is difficult to achieve for practical experiment implementations. In contrast, generalized synchronization is more feasible and effortless for practical applications owing to the injection locking between transmitter and receiver. Therefore generalized synchronization is more tolerant of parameter mismatch and less sensitive to the variation of parameters [34]. The type of chaotic synchronization adopted in this paper is generalized synchronization. The synchronization condition for OOCDM is given as follows:

$$\mathrm{A} = \{\mathrm{CC}(P_i^{\mathrm{T}}, P_i^{\mathrm{R}}) \,|\, 0.9 < \mathrm{CC}(P_i^{\mathrm{T}}, P_i^{\mathrm{R}}) \le 1\} \tag{8}$$

where T and R denote transmitter and receiver, respectively. The lower limit of the synchronous condition is set to 0.9 for a certain span of parameter mismatch can be tolerated by generalized synchronization [35].

4. Orthogonal condition

Mathematically, the chaotic carriers of any pair of transmitters should be orthogonal, which can be defined as follows:

$$|\langle x_i, x_j\rangle| = \frac{1}{\Delta T}\left|\int_0^{\Delta T} x_i(t)x_j(t)\mathrm{d}t\right| \ll 1, \text{ for } i \ne j, \tag{9}$$

where $x(t)$ denotes the chaotic carrier of transmitter and ΔT is time interval. This indicates that any pair of chaotic carriers $x_i(t)$ and $x_j(t)$ is orthogonal when the similarity of the temporal waveforms is far less than one. The orthogonal condition can be defined by correlation coefficient

$$\mathrm{B} = \{\mathrm{CC}(P_i^{\mathrm{T}}, P_j^{\mathrm{T}}) \,|\, 0 < \mathrm{CC}(P_i^{\mathrm{T}}, P_j^{\mathrm{T}}) < 0.1\} \tag{10}$$

where T denotes transmitter. From the mathematical point of view, the upper limit 0.1 is not far less than one. But this limit can satisfy the orthogonal condition in practice [28]. During the following numerical simulations, synchronization condition Eq. (8) and orthogonal condition Eq. (10) are adopted to quantify the performance of the proposed OOCDM.

5. Numerical simulation

The dynamical characteristics of each pair of transmitter and receiver can be described by the well-known Lang–Kobayashi rate