Signaling-Embedded Preamble Design for Flexible Optical Transport Networks

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***Abstract*—Coherent optical orthogonal frequency division multiplexing (CO-OFDM) is a promising technique for future elastic optical transport networks. In CO-OFDM systems, the preamble is usually used for timing and frequency synchronization, and dedicated pilots are adopted to carry signaling for flexible system configurations. In this paper, we propose a judicious signaling-embedded preamble design to simultaneously achieve the exact timing synchronization based on the ideal Delta-like timing metric, the accurate frequency synchronization with sufficient estimation range, as well as reliable signaling transmission. This is achieved by designing the preamble in the frequency, i.e., two identical training sequences with a specific distance occupy the even subcarriers of the preamble, whereby the system signaling is carried by the combination of different training sequences and different distances between two sequences. Such frequency-domain design would result in the time-domain preamble having conjugate symmetric property and two repetitive parts. The former property is used to produce the ideal Delta-like correlation function for exact timing synchronization, while the latter one is used for accurate frequency synchronization. Simulation results also show that the improved signaling detection performance can be achieved.**

I. INTRODUCTION

Enhancing the spectrum utilization is intensively demanded and becomes more challenging when next-generation optical transport networks is evolving from 10 Gb/s to beyond 100 Gb/s [1]. The pioneering work by Shieh [2] has suggested coherent optical orthogonal frequency division multiplexing (CO-OFDM) to provide spectrum-efficient and elastic long-haul high-speed optical transmissions, whereby variable signal bandwidth and data rate could be easily and flexibly configured in a *gridless* fashion [3]–[6].

To further enhance the system flexibility and improve the spectrum efficiency for future optical transport networks, it is highly expected that CO-OFDM could support a number of working modes, which are indicated by different inverse fast Fourier transform (IFFT) sizes, guard interval lengths, constellation modulations, channel coding schemes, code rates, etc [4]. However, extra dedicated resources (e.g., frequency-domain pilots) are usually required to reliably convey those important system signaling, which suffers from loss in spectrum efficiency.

Additionally, in most CO-OFDM systems, the preamble at the beginning of the transmission frame is used for timing and frequency synchronization [7]–[10]. The most widely used preamble is the one proposed by Schmidl [7], [8], but it suffers from performance degradation since the timing metric used for synchronization has a plateau even over single-path channels. This problem can be resolved by Minn's preamble [9], [10], wherein multiple repetitive parts with specifically designed signs yield a well-behaved timing metric, but the timing metric of the Minn's preamble is not sharp enough to acquire the exact timing of the transmission block, and the frequency synchronization estimation accuracy is reduced.

Motivated by the requirements of signaling-based system flexibility and preamble-based synchronization, in this paper we propose a novel signaling-embedded preamble design to simultaneously achieve the exact timing synchronization based on the ideal Delta-like timing metric, the accurate frequency synchronization with sufficient estimation range, as well as reliable signaling transmission. Those merits are achieved by the following design method in the frequency domain: two identical Hadamard sequences with a specific distance occupy the even subcarriers of the preamble, whereby the system signaling is carried by the combination of different Hadamard sequences and different sequence distances. Such frequency-domain design would result in the time-domain preamble having conjugate symmetric property and two repetitive parts. The former property is used to produce the ideal Delta-like correlation function for exact timing synchronization, while the latter one is used for accurate frequency synchronization.

The remainder of this paper is organized as follows. The proposed signaling-embedded preamble design is described in Section II. The corresponding timing/freqeuncy synchronization and signaling detection are presented in Section III. Numerical results are shown in Section IV. Finally, conclusions are drawn in Section V.

Notation: We use the upper and lower boldface letters to denote matrices and column vectors, respectively; $\mathbf{F}_N$ denotes the normalized $N \times N$ fast Fourier transform (FFT) matrix whose $(n+1, k+1)$th entry is $\exp(-j2\pi nk/N)/\sqrt{N}$; $(\cdot)^*$ amd $(\cdot)^T$ denote the complex conjugate and transpose, respectively; $\text{angle}\{x\}$ means the angle of the complex-valued x; Finally, $\widetilde{x}$ indicates that x is a frequency-domain signal.

II. SIGNALING-EMBEDDED PREAMBLE DESIGN

In this section, we propose a novel signaling-embedded preamble design to simultaneously achieve the following three merits: 1) Ideal Delta-like timing metric for very accurate timing synchronization; 2) Accurate frequency synchronization

978-1-4799-4482-8/14/$31.00

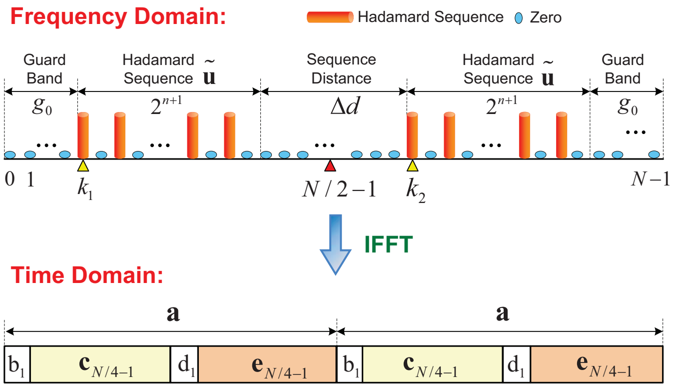

Fig. 1. Frequency-domain and time-domain structures of the signaling-embedded preamble.

with sufficient estimation range; 3) Reliable system signaling transmission. The signal structure of the proposed preamble in the frequency and time domains are illustrated by the top and bottom parts of Figure 1, respectively.

In the frequency domain, the preamble $\widetilde{\mathbf{p}} = [\widetilde{p}_0, \widetilde{p}_1, \cdots, \widetilde{p}_{N-1}]^T$ of length N is composed of three distinct parts: 1) Two guard bands filled with zero subcarriers are located at high frequency band and low frequency band (including the DC subcarrier), and each guard band has g_0 subcarriers; 2) Two identical Hadamard sequences occupy two separated regions with the distance of Δd, and each region has 2^{n+1} subcarriers; 3) In the middle, Δd zero subcarriers are used to separate the two Hadamard sequences.

The Hadamard sequence $\widetilde{\mathbf{u}}$ of length 2^n is extracted from any column of the n-order real-valued Hadamard matrix $\mathbf{H}_n$ recursively generated by [11]

$$\mathbf{H}_1 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}_{2\times 2}, \mathbf{H}_n = \begin{bmatrix} +\mathbf{H}_{n-1} & +\mathbf{H}_{n-1} \\ +\mathbf{H}_{n-1} & -\mathbf{H}_{n-1} \end{bmatrix}_{2^n \times 2^n}. \quad (1)$$

Then, the Hadamard sequence $\widetilde{\mathbf{u}} = \{\widetilde{u}_k\}_{k=0}^{2^n-1}$ is mapped on the even subcarriers of two regions with the frequency-domain distance Δd as below

$$\widetilde{p}_k = \begin{cases} \widetilde{u}_{(k-k_1)/2}, & \mathrm{mod}(k,2) = 0, k_1 \leq k < k_1 + 2^{n+1}, \\ \widetilde{u}_{(k-k_2)/2}, & \mathrm{mod}(k,2) = 0, k_2 \leq k < k_2 + 2^{n+1}, \\ 0, & \text{others}, \end{cases} \quad (2)$$

where $k_1 = g_0 + \Delta d/2$, and $k_2 = k_1 + 2^{n+1} + \Delta d$.

Unlike conventional preambles mainly used for timing and frequency synchronization, we propose to embed the system signaling in the preamble so that no extra dedicated overhead will be required to carry the system parameters. This is achieved by the combination of selected Hadamard sequence and the specific sequence distance according to the configured signaling. More specifically, different signaling corresponds to distinct Hadamard sequences and/or sequence distances, both of which could be detected by the receiver to recover the transmitted signaling. First, when one specific Hadamard sequence $\widetilde{\mathbf{u}}$ has been selected, one specific sequence distance Δd could convey certain signaling. For example, in Figure 1 we assume the following values $N = 2048, 2^{n+1} = 512, g_0 = 128$, so the value of Δd could be configured to vary within the range $(256, 768]$ (the minimum sequence distance $\Delta d_{\min}$ should be larger than zero, e.g., 256 mentioned here, so virtual subcarriers located in the middle of the signal bandwidth can be used to alleviate the carrier leakage effect [12]). Bear in mind that only the even subcarriers are used in the preamble, Δd should be an even number, so the distance range $(256, 768]$ could carry 8-bit signaling (notice that $(768 - 256)/2 = 2^8$). Second, since Δd can carry no more than 9-bit signaling even when $g_0 = 0$ and $\Delta d_{\min} = 0$, more signaling bits could be provided by selecting different Hadamard sequences. For example, the signaling bits could be increased from 8 to 10 if four possible Hadamard sequence candidates can be used. The receiver can easily identify which one is selected due to the orthogonality of different Hadamard sequences. Since sequence discrimination via correlation has higher complexity than sequence distance detection, using sequence distance to carry signaling is preferred if the sequence distance could provide the required signalling bits. Note that if no signaling is embedded in the preamble, the fixed Hadamard sequence $\widetilde{\mathbf{u}}$ and sequence distance Δd will be assigned.

In the time domain, the preamble $\mathbf{p} = [p_0, p_1, \cdots, p_{N-1}]^T$ is obtained by applying IFFT to the frequency-domain preamble $\widetilde{\mathbf{p}}$, yielding

$$\mathbf{p} = \alpha \mathbf{F}_N^H \widetilde{\mathbf{p}}, \quad (3)$$

where α is a power scaling factor to make the preamble have the same average power as data symbol with N subcarriers, e.g., $\alpha = \sqrt{N/2^{n+1}}$. The time-domain preamble follows the form

$$\mathbf{p} = [\underbrace{\mathrm{b}_1 \ \mathbf{c}_{N/4-1} \ \mathrm{d}_1 \ \mathbf{e}_{N/4-1}}_{\mathbf{a}} \underbrace{\mathrm{b}_1 \ \mathbf{c}_{N/4-1} \ \mathrm{d}_1 \ \mathbf{e}_{N/4-1}}_{\mathbf{a}}]^T, \quad (4)$$

where $\mathbf{a} = [\mathrm{b}_1 \ \mathbf{c}_{N/4-1} \ \mathrm{d}_1 \ \mathbf{e}_{N/4-1}]$ of length $N/2$ is composed of four parts: both b_1 and d_1 have only one entry, while $\mathbf{c}_{N/4-1}$ and $\mathbf{e}_{N/4-1}$ have the length of $N/4 - 1$. In practical CO-OFDM systems, the preamble $\mathbf{p}$ will be protected by its cyclic prefix to avoid the interference due to optical impairments including chromatic dispersion (CD) [3].

Compared with Schmidl's and Minn's preambles [7], [9], the proposed preamble $\mathbf{p}$ simultaneously enjoys the following two time-domain features: 1) Similar to Schmidl's design, $\mathbf{p}$ is also composed of two identical time-domain parts, e.g., $\mathbf{p} = [\mathbf{a} \ \ \mathbf{a}]^T$, because only the even subcarriers are occupied by non-zero signals in the frequency domain; 2) Meanwhile, within part $\mathbf{a}$, $\mathbf{c}_{N/4-1}$ and $\mathbf{e}_{N/4-1}$ are conjugate symmetric, i.e.,

$$c_n^* = e_{N/4-1-n}, \quad 0 \leq n \leq N/4 - 1. \quad (5)$$

The first feature is useful for accurate frequency synchronization, and the second one is essential for accurate timing synchronization, both of which will be addressed in detail in the following Section.

III. PREAMBLE-BASED JOINT TIMING/FREQUENCY SYNCHRONIZATION AND SIGNALING DETECTION

In this section, the specially designed preamble will be used to achieve accurate timing/frequency synchronization as well as physical layer signaling transmission.

A. Joint Timing and Frequency Synchronization

Using the conjugate symmetric property of the preamble, the exact starting point d_0 of the CO-OFDM symbol is acquired by maximizing the timing metric $M(d)$ as below

$$d_0 = \arg\left\{\max_{d}\{M(d)\}\right\} = \arg\left\{\max_{d}\{\frac{|P(d)|^2}{R^2(d)}\}\right\}, \quad (6)$$

where

$$P(d) = \sum_{n=1}^{N/2-1} q^*_{d+n} q_{N+d+n}, \quad (7)$$

denotes the correlation function of the received preamble $\{q_n\}_{n=0}^{N-1}$, and

$$R(d) = \sum_{n=1}^{N/2-1} |q_{d+n}|^2 \quad (8)$$

represents the average power of the received preamble [13] used to normalize the correlation function $P(d)$ in (6).

After timing synchronization, carrier frequency offset (CFO) estimation (or frequency synchronization) should be performed before further processing. In CO-OFDM systems with intradyne receiver front end, the CFO Δf between the local optical laser oscillator (OLO) and the incoming signal is at most equal to the OFDM symbol rate $1/T$ (or one subcarrier spacing) [14], i.e., the normalized CFO denoted by $\Omega = \Delta f T$ satisfies $|\Omega| \leq 1$ (CFO in optical OFDM systems is most likely to be about 10%-20% of one subcarrier spacing [14], so $|\Omega| \leq 0.2$ is usually valid). Thus, the receiver only needs to perform the fine (fractional) CFO estimation. Similar to Schmidl's method [7], the CFO estimate $\widehat{\Omega}$ can be obtained by exploiting the time-domain structure of the proposed preamble with two identical halves as below

$$\widehat{\Omega} = \frac{1}{\pi}\text{angle}\left\{P'(d_0)\right\}, \quad (9)$$

where

$$P'(d_0) = \sum_{n=0}^{N/2-1} q^*_{d_0+n} q_{N/2+d_0+n}. \quad (10)$$

Due to the phase ambiguity issue, the estimation range of (9) is $(-1, +1]$, which is sufficient for CO-OFDM systems since only the fine CFO estimation is required as mentioned above. On the other hand, the proposed preamble can also deal with CFO much larger than one subcarrier spacing, e.g., by exploiting the property that the integral CFO results in the frequency-domain shifting of the active subcarriers but can be easily determined by comparing the received preamble with the local known preamble in the frequency domain [15].

Note that the correlation function $P'(d_0)$ in (10) is used for both timing and frequency synchronization in Schmidl's method [7], while $P'(d_0)$ is only used for CFO estimation but $P(d_0)$ in (6) is used for timing synchronization in our proposed scheme.

B. Signaling Detection

After timing synchronization and CFO compensation, the received time-domain preamble $\{q_n\}_{n=0}^{N-1}$ is then converted to the frequency-domain preamble $\{\widetilde{q}_k\}_{k=0}^{N-1}$ by using N-point FFT. Afterwards, the cross-correlation between the received preamble and the local known preamble in the frequency domain is calculated by

$$Q(m) = \frac{\sum\limits_{k=0,\ \text{mod}\ (k,2)=0}^{2^{n+1}-2} \widetilde{q}^*_{m+k/2}\widetilde{u}_{k/2}}{2^n\alpha^2}, \qquad \text{mod}\ (m,2) = 0, g_0 \leq m \leq g_0 + \frac{\Delta d}{2}, \quad (11)$$

where only the even subcarriers of the received frequency-domain preamble are used, and $\widetilde{\mathbf{u}} = \{\widetilde{u}_k\}_{k=0}^{2^n-1}$ denotes one possible Hadamard sequence candidate. Since there are two identical Hadamard sequences in the frequency-domain preamble, two correlation peaks are expected at the subcarrier locations k_1 and k_2 when the local Hadamard sequence matches the transmitted one, and the distance between the two correlation peaks should be $k_2 - k_1 = 2^{n+1} + \Delta d$. Finally, the system signaling is detected by the sequence selection combined with the observed distance Δd, and the correct signaling can be used by the receiver for further processing.

Unlike the conventional signaling scheme based on the actual detection of the transmitted known training signal, the proposed signaling detection mainly relies on the distance of correlation peaks associated with two known training sequences. Since distance detection is usually more robust to channel impairments than signal detection, more reliable signaling detection can be expected by the proposed preamble, which will be verified later in Section IV.

C. Computational Complexity

For correlation-based timing synchronization (6) and CFO estimation (9), computation of the correlation function is similar to that used in conventional CO-OFDM systems [8], [10], although the proposed preamble has better synchronization performance. Additionally, the proposed preamble can also be used for signaling detection with low complexity, because the multiplication required to calculate the cross-correlation function (11) in the frequency domain can be simplified to direct addition/subtraction due to the real-valued Hadamard sequence as indicated by (1) and (2). In summary, the proposed scheme has low computational complexity.

D. Extension Discussion

The proposed signaling-embedded preamble with Delta-like timing metric can be directly used by coherent optical single-carrier frequency domain equalization (CO-SC-FDE) systems to improve the timing synchronization performance. In addition, the capability of conveying the system parameters

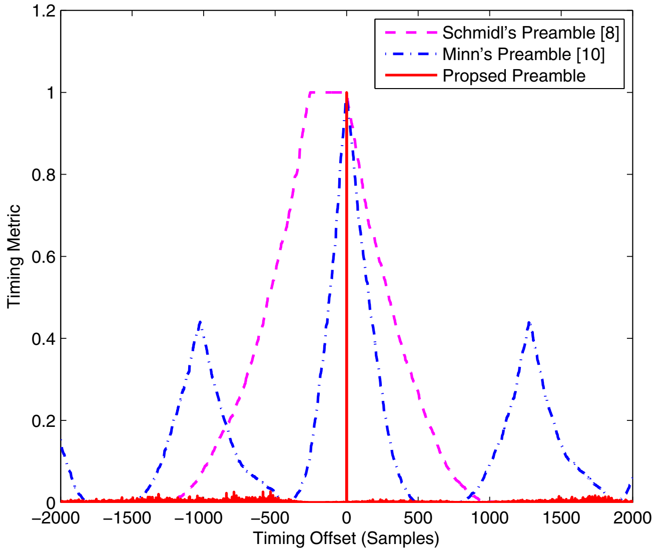

Fig. 2. Comparison of the timing metric behaviors in the absence of noise and channel distortion. The timing offset 0 indicates the exact timing point.

can be exploited to reliably deliver physical layer signaling without extra dedicated overhead.

IV. NUMERICAL RESULTS

In this section, the performance of the proposed signaling-embedded preamble is numerically evaluated through simulations. The simulation setup is similar to the CO-OFDM system in [16]: The IFFT length is 2048, the guard interval length is 512; The transmission link is composed of 16 optically amplified 80-km fiber spans, and the electronic dispersion compensation (EDC) via one-tap filter is performed prior to channel estimation at the receiver. The polarization-diversity optical hybrid detector has the optical local oscillator with the line bandwidth of 100 kHz. The optical signal-to-noise ratio (OSNR) at the receiver is defined with the 0.1 nm noise bandwidth. Refer to [16] for more details of the simulation setup.

Figure 2 compares the timing metric behavior of the proposed preamble with those of the classical Schmidl's and Minn's preambles in the absence of noise and channel distortion. A plateau for Schmidl's preamble [8] is observed, and much sharper timing metric is achieved by Minn's preamble [10]. However, neither of them is as sharp as the proposed preamble that enjoys the ideal Delta-like timing metric, indicating that very precise timing synchronization can be achieved by the proposed preamble both in the singlepath and multipath channels.

The robustness of the timing metric to CFO is usually desirable. It is examined by Figure 3 that shows the impact of the normalized CFOs on the timing metric under different conditions. The timing metric is still a Delta-like function which indicates that successful timing synchronization can be achieved even with CFO distortion.

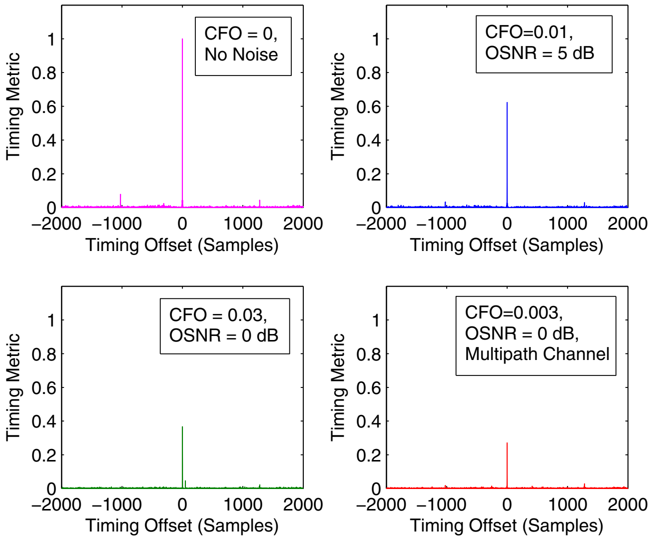

Fig. 3. Timing metric of the proposed preamble under different CFOs and OSNRs. The first three subplots are obtained over an AWGN channel, while the last subplot over a multipath channel.

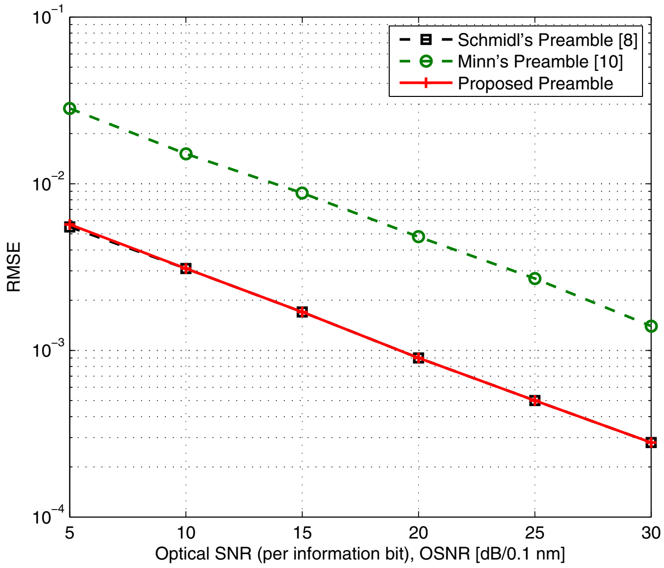

Fig. 4. Comparison of the RMSE performance of the normalized CFO estimation.

Figure 4 compares the performance of the normalized CFO estimator (9) with those of the conventional schemes in terms of root mean squared error (RMSE). We can observe that the proposed CFO estimator performs similarly as Schmidl's method [8] but much better than Minn's solution [10]. The CFO can be estimated at a very small error, for example, the RMSE is 0.0031 when OSNR is 10 dB.

Figure 5 shows the false signaling detection probability of the proposed preamble. For comparison, the performance of

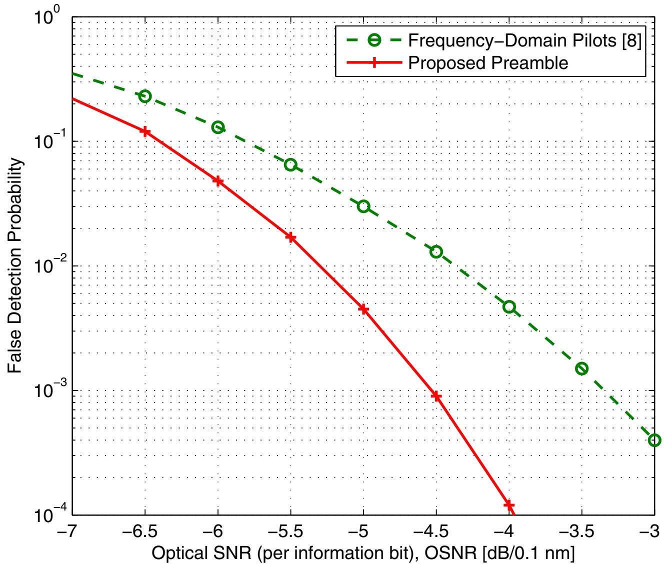

Fig. 5. Comparison of false signaling detection probability.

the conventional signaling scheme based on frequency-domain pilots [8] has also been provided. As has been addressed in Section III, since the conventional signaling schemes rely on the actual detection of the transmitted signal in the frequency domain, while the proposed signaling detection relies on the distance of correlation peaks associated with two known training sequence, better signaling detection performance can be expected by the proposed scheme due to distance detection is usually more robust to channel impairments. For example, when the target false detection probability of 10^{-3} is considered, the proposed preamble outperforms the conventional scheme by about 1.3 dB, which demonstrates the reliable transmission of the important system signaling.

V. CONCLUSIONS

Motivated by the requirements of signaling-based system flexibility and preamble-based synchronization for CO-OFDM optical transport networks, we propose a novel signaling-embedded preamble design to simultaneously achieve accurate timing/frequency synchronization as well as reliable signaling detection. In the frequency domain, two identical Hadamard sequences with a specific distance occupy the even subcarriers of the preamble, and the system signaling is carried by the combination of different Hadamard sequences and different sequence distances. The corresponding preamble in the time domain has conjugate symmetric property and two repetitive parts, which produces the ideal Delta-like correlation function for exact timing synchronization and accurate frequency synchronization. Additionally, the distance-based signaling detection is robust to channel impairments, and outperforms the conventional scheme by about 1.3 dB for the false detection probability of 10^{-3}. The proposed signaling-embedded preamble can be also directly used by coherent optical single-carrier frequency domain equalization (CO-SC-FDE) systems to improve the systme performance.

ACKNOWLEDGEMENT

This work was supported by National Key Basic Research Program of China (Grant No. 2013CB329201), National Natural Science Foundation of China (Grant Nos. 61271266 and 61201185), and ZTE fund project CON1307250001.

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