Coherent Detected Secure Point-to-Point Optical Fiber Transmission using Ultra-Dense Optical Spectral Phase Coding (UD-SPC) and Multilevel BCJR Equalization

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Abstract: A secure P2P optical fiber communication scheme based on ultra-dense optical spectral phase coding (UD-SPC) is proposed. The multi-code interference is suppressed by increasing the memory of the multilevel BCJR equalizer as shown by simulations.
OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

With the prevalent of cloud-based applications, e.g. cloud computing/storage, huge amount of data need to be synchronized timely among data centers at different locations. High speed optical fiber communication is considered as a prominent candidate for the point-to-point (P2P) communication between two nodes of the same cloud. The security of such P2P communication system is becoming increasingly important. Recently, some schemes have been proposed to enhance the security of the direct-detected optical fiber communication system [1, 2]. Time domain multi-code parallel coding is employed in [1] to generate an emulated multi-user CDMA signal which is of high security against eavesdropping in P2P communication system.

In this paper, we propose and study a long distance coherent detected P2P secure transmission scheme with multi-code spectral phase coding (SPC)-orthogonal frequency division multiplexing (OFDM) based ultra-dense optical spectral phase coding (UD-SPC). To increase the number of simultaneously transmitted codes, the multilevel BCJR equalization is employed to suppress the cross-talk among non-orthogonal codes.

2. Ultra-Dense Optical Spectral Phase Coding (UD-SPC)

Optical spectral phase coding (SPC) uses the phase of optical carriers to represent the code. In most optical SPC system, a mode lock laser (MLL) is employed to provide a comb of phase locked subcarriers [3]. The encoding and decoding processes take place at the optical domain directly. Unlike these optical SPC systems, we first encode the signal with a comb of orthogonal electrical carriers with frequency spacing equal to baud rate (single code case), i.e. $\Delta f = f_i - f_{i-1} = R$, where $f_i (\mathrm{i} = 1,2,3,\dots,\mathrm{N})$ is the frequency of the $\mathrm{i_{th}}$ electrical carrier. After encoding in the electric domain, the electric encoded signal is electrical-to-optical (E/O) converted to optical encoded signal with a modulator as shown in Fig. 1. At the receiver side, the optical signal after fiber transmission is first optical-to-electrical (O/E) converted to electrical signal either via direct detection or coherent detection. Then, the electrical signal is decoded with a multi-subcarrier phase decoder.

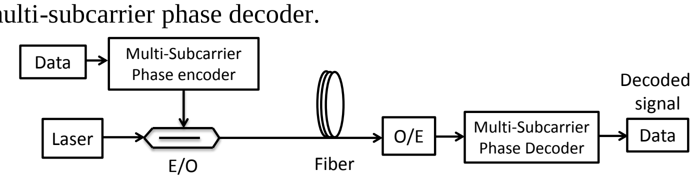

Fig. 1 Schematic diagram of UD-SPC system

The schematic diagrams of the multi-subcarrier phase encoder and decoder are shown in Fig. 2(a) and Fig. 2(b), respectively. The phase of the $\mathrm{i_{th}}$ carrier $\emptyset(C_i^x)$ is determined by the specific code $C^x = \{C_i^x\}$ used. The encoded signal of $\mathrm{k_{th}}$ input symbol S(k) is:

$$S_{enc}(t) = S(k)\mathrm{g}(\mathrm{t}-\mathrm{kT}) \cdot \sum_{i=1}^{N} \mathrm{e}^{j[2\pi f_i(t-kT)+\emptyset(C_i^x)]} \qquad \text{where } \mathrm{g}(\mathrm{t}) = \begin{cases} 1, 0 < \mathrm{t} \le \mathrm{T} \\ 0, \quad \text{other} \end{cases}$$

The samples of $S_{enc}(t)$ $(kT < t \le kT + T)$ with sample rate $R_s = NR = N/T$ are:

$$S_{enc}(k,m) = e^{j2\pi f_1 \frac{m}{N}T} S(k) \sum_{i=0}^{N-1}\left[e^{\mathrm{j}\emptyset(C_i^x)}\right]\mathrm{e}^{j2\pi\frac{im}{N}} \qquad (\mathrm{m}=1, 2, 3\dots, \mathrm{N})$$

As all carriers are orthogonal to each other and assume f_1=0, $S_{enc}(k,m)$ can be described as:

$$S_{enc}(k,m) = \sum_{i=0}^{N-1}\left[S(k)e^{\mathrm{j}\emptyset(C_i^x)}\right]\mathrm{e}^{j2\pi\frac{im}{N}} = \mathfrak{I}^{-1}{}_N^m\left[S(k) \cdot e^{\mathrm{j}\emptyset(C_i^x)}\right]$$

where $\mathfrak{I}^{-1}{}_N^m$ is the $\mathrm{m_{th}}$ output of size N IFFT.

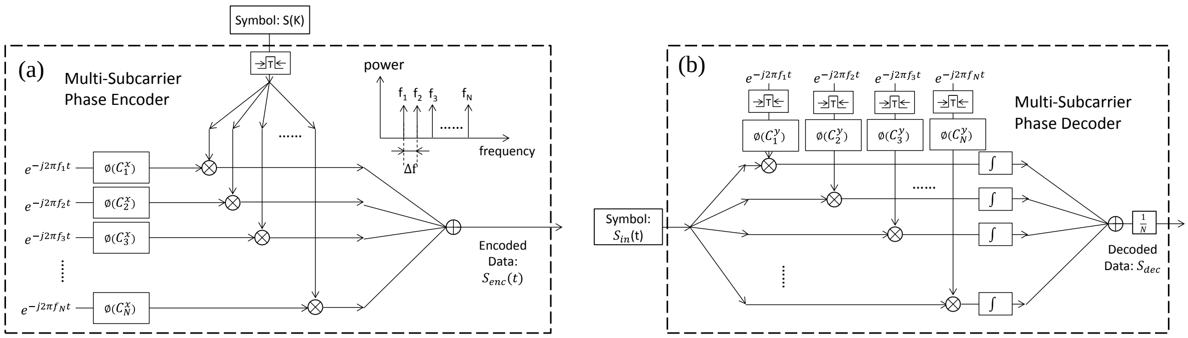

Fig. 2 Schematic diagram of (a) multi-subcarrier phase encoder, and (b) multi-subcarrier phase decoder

For the multi-subcarrier phase decoder, the decoding output of k_{th} input symbol $S_{in}(t)$ $(kT < t \leq kT + T)$:

$$S_{dec}(k) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{T}\int_0^T S_{in}(t)\, e^{j\left[-2\pi f_i t-\emptyset(C_i^y)\right]}dt$$

If $S_{dec}(k)$ is sampled with sample rate $R_s = NR = N/T$ and assume f_1=0, the decoding output can be write as:

$$S_{dec}(k) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{N}\sum_{m=1}^{N} S_{in}(m) e^{j\left[-2\pi f_i \frac{m}{N}T+\emptyset(C_i^y)\right]} = \frac{1}{N}\sum_{i=1}^{N} e^{j\emptyset(C_i^y)}\cdot \Im_N^i[S_{in}(m)]$$

where $C^y = \{C_i^y\}$ is the code of decoder, $S_{in}(m)$ is the m_{th} sample of input symbol, $\Im_N^i$ is the ith output of size N FFT. Therefore, the encoder and decoder can be implemented efficiently with IFFT and FFT in a way similar to orthogonal frequency division multiplexing (OFDM) system [4]. Thus, the encoding and decoding process can be viewed as a combination of CDM and OFDM. The theoretical achievable spectral efficiency (SE) of our system in single code case is:

$$SE_{single\_code}^{\text{UD-SPC}} = \frac{m\cdot R}{R\cdot N} = \frac{m}{N}\ \text{bit/s/Hz}$$

where m is the number of bits per symbol, R is the baud rate, N is the code length. In comparison, the minimal spectral spacing between neighbor subcarriers in traditional optical SPC system equals to the two times of baud rate. Therefore, the maximal spectral efficiency of our system can be two times of the traditional one [3]. In the context of SE, our system is called ultra-dense optical spectral phase coding (UD-SPC) system.

3. Long Distance P2P UD-SPC Secure Optical Fiber Transmission Scheme and Simulation setup

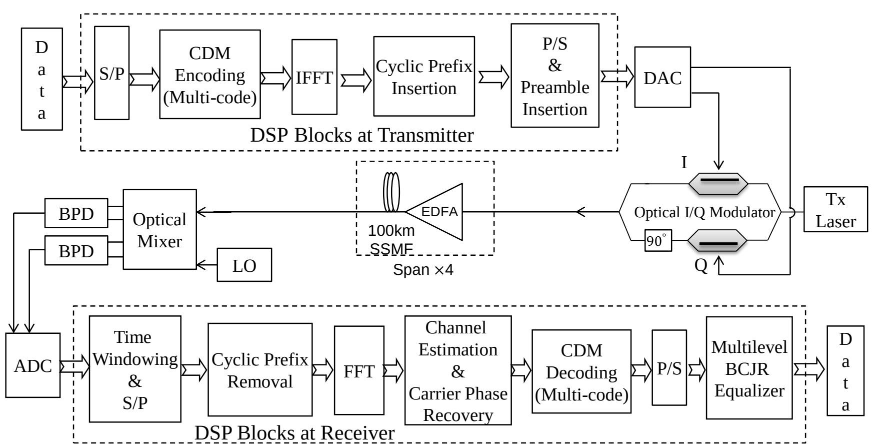

Fig. 3 Long distance P2P UD-SPC secure optical fiber transmission scheme

Table 1 Simulation Parameters

Code length N	511
Block Size M	160
Subcarrier Spacing	10e9/512 Hz
Subcarrier Modulation Format	QPSK
CP/(FFT window)	0.01
Fiber Chromatic Dispersion	16ps/nm/km
Detection Method	Homodyne
Laser Linewidth	(Tx) 100kHz (LO) 100kHz
Total Bit Rate	5.15Gb/s

Fig. 3 depicts our scheme for long distance P2P secure optical fiber transmission. The data first undergoes serial-to-parallel (S/P) conversion with block size M. In the CDM encoding step, each data symbol in the same block is spread with a pre-allocated code of length N, respectively. The spread data of the M symbols are then added up. Notice that the length of combined data equals to the code length N. After CDM encoding, the data is converted to time domain samples by IFFT. Cyclic prefix is inserted after IFFT to combat the accumulated chromatic dispersion of optical fiber transmission. After cyclic prefix insertion, the parallel data block is converted to serial data. Preamble is included at the beginning of communication for channel estimation. Finally the data are converted to electrical signals (in-phase signal I and quadrature signal Q) by a digital-to-analog convertor (DAC). The electrical encoded signals are imprinted on optical carrier with an optical I/Q modulator. The modulated optical UD-SPC signal is launched to fiber for transmission. The fiber link is consisted by several spans of standard single mode fiber

(SSMF) and optical amplifiers (EDFAs). The EDFA fully compensates the fiber transmission loss in each span. No optical dispersion compensation is employed in our simulation. The simulated homodyne system in this paper has a total bit rate of 5.15Gb/s and uses160 non-orthogonal codes. Details of the simulation setup are shown in table 1.

At the receiver side, coherent detection is employed using a laser as local oscillator (LO) and an optical mixer. The electrical signal from balanced photodiodes is sampled and digitalized by an analog-to-digital convertor (ADC). The digitalized signal is then feed into DSP blocks with UD-SPC decoder and multilevel BCJR equalizer. Time window synchronization is done using 'S&C' algorithm [4]. The signal is then S/P converted. Cyclic prefix is removed and the left part is converted to spectral domain by FFT. Carrier phase is recovered by pilot-aided method and channel equalization is done with the help of preamble. The signal is decoded with M different codes in parallel and the M decoded outputs are P/S converted. The decoded data is sent to a multilevel BCJR equalizer for multi-code interference suppression. As M different symbols are transmitted and decoded simultaneously, the multi-code interference can be viewed as inter-symbol-interference (ISI) in the memory channel [5, 6]. Finally, the output of BCJR equalizer can be either send to LDPC decoder for error correction or to slicer for hard decision.

4. Results and Discussion

We use AES encrypted Gold (AES-Gold) sequence with large equivalent code space to further increase the system security. The memory of the channel (i.e. number of employed codes $M \neq 0$) is created intentionally to prevent evasdropper from accessing the transmitted data directly and increasing the total transmission speed. With the increasing of M, the decoded signal in back-to-back become worse due to code interference as shown in Fig. 4(a)-(c). Fig. 4(d) shows the noise-like signal recovered by the eavesdropper with a wrong decoder. By sending 10 equally spaced pilot subcarriers, the phase noise is shown to be well captured when comparing the real carrier phase (Fig. 4(e)) with the estimated carrier phase (Fig. 4(f)).

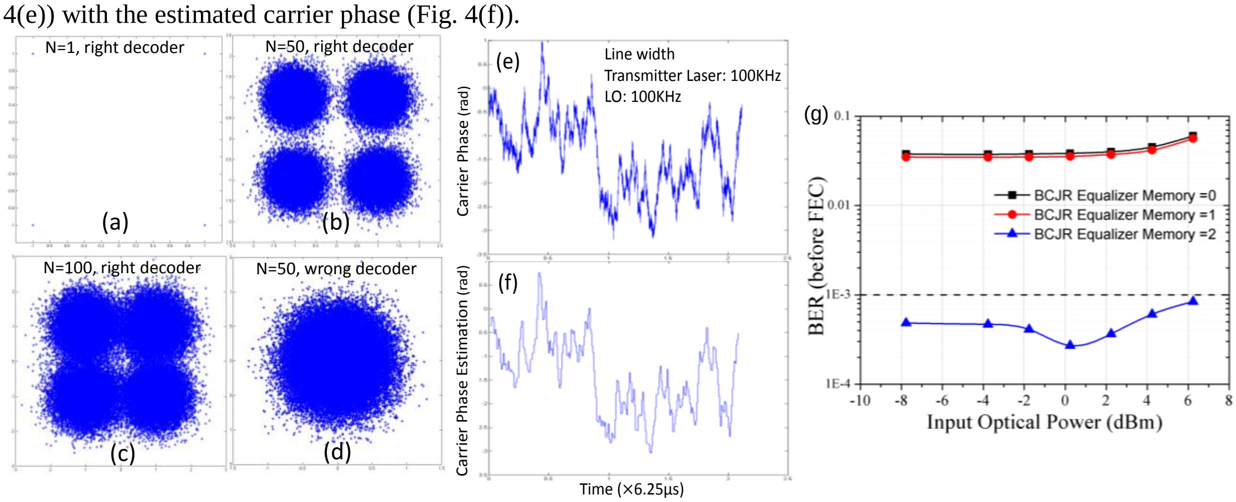

Fig. 4 Simulation results

We also measure the bit-error-rate (BER) results by Monte Carlo simulation. Over 10^5 bits are counted for every BER result. Fig. 4(g) shows the BER after 400km fiber transmission with different equalizer's memories and launch power. With BCJR equalizer's memory>0, the equalizer can help to suppress the multi-code inference. The optimal input power is ~0 dBm for memory=2. As the multilevel BCJR equalizer outputs soft information, i.e. log-likelihood ratio (LLR), strong soft forward error correction (FEC) e.g. LDPC codes can be further employed to improve the overall system performance [5, 6].

Acknowledgments

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5. References

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