10Gb/s Two-User Spatial Diversity FSO-CDMA Wiretap Channel Based on Reconfigurable Optical Encoder/Decoders

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ABSTRACT Due to the effect of atmospheric turbulence, the transmission reliability and physical-layer security of free space optical (FSO) communication system are facing many challenges. In this paper, for the first time, we design and investigate a 10 Gb/s reconfigurable FSO wiretap channel based on spatial diversity and optical code division multiple access (OCDMA). Reconfigurable two-dimensional optical encoder and decoder are constructed by wavelength selective switch and optical delay lines, and reconfigurable one-dimensional optical encoder and decoder are constructed by couplers and tunable optical delay lines. Under three different turbulence conditions, bit error rates (BER) of legitimate user and eavesdropper are measured. It can be seen that under turbulence effects, BER of legitimate user in spatial-diversity is lower than that of non-diversity system. By the rapid code reconfiguration of legitimate users, the eavesdropper can only use unmatched decoder. Thus, the eavesdropping methods of code interception and brute-force searching can be avoided. Experimental results show that this scheme can ensure the reliable transmission of legitimate users, and the eavesdropper can’t crack the information when the extraction ratio is 1%. Hence, reliability and physical-layer security can be enhanced simultaneously.

INDEX TERMS Free space optical communication, optical code division multiple access, spatial diversity, atmospheric turbulence.

I. INTRODUCTION
Free space optical (FSO) communications have been employed in commercial and military communication systems for image transmission. Image transmission has been widely applied for image processing, and so on [1], [2]. However, FSO are highly susceptible to atmospheric turbulence, which occurs as a result of the variations in the refractive index due to inhomogeneities in temperature and pressure changes. These index inhomogeneities can cause fluctuations in both the intensity and the phase of the received signal [1], [4], which limits the performance of FSO system. Diversity techniques, including time diversity [5], spatial diversity [6] and frequency diversity [7], have been proposed to alleviate these problems. Spatial diversity is widely used because of its high diversity gain, which can effectively counter the effects of multipath fading and is accessible to implement [8]. Aperture averaging and spatial diversity techniques are used to improve the error probability of atmospheric system [9], [10]. Analysis results show that spatial diversity can improve performance in presence of turbulence and different weather conditions [11].

On the other hand, FSO communications can still suffer from optical tapping risks [12], especially when the main lobe of laser beam is considerably wider than the size of the receiver [13], [14]. A plausible mechanism for interception arises when part of the beam radiation is reflected by small particles, and then is detected by an external observer not in the light-of-sight of both communication peers. Since the laser beam experiences divergence due to optical diffractions, one possibility for a successful eavesdropping is to locate eavesdropper (Eve) in the divergence region of the beam.
For long distances FSO communication, Eve has a stronger chance for eavesdropping on the FSO link by collecting the power not captured by legitimate peers.

Optical code division multiple access (OCDMA) is considered as a good candidate to provide physical-layer security [15]–[17]. The physical-layer security of OCDMA-based optical fiber communication system is analyzed in [18], and authors use security leakage factor to evaluate the physical-layer security level. OCDMA based hybrid FSO/fiber wiretap channel is proposed in [19], and the physical-layer security is analyzed theoretically, using the conditional secrecy outage probability as the performance metric. A novel type of OCDMA network for 2-D image transmission based on optical orthogonal signature pattern codes is proposed in [20].

However, OCDMA systems are found to provide less data confidentiality than cryptography, and the confidentiality provided is found to be highly dependent on system design and implementation. As pointed out in [15], for an OCDMA based on on-off keying (OOK), Eve can use a simple energy detector to detect whether energy is present or not in each bit interval if he can isolate individual user’s signals. In this case, there is no security at all due to the energy detector output contains the user’s data stream. Brute force searching of different codewords is not an efficient attack when the code space is large enough. But Eve can derive the user’s code from this waveform and use this code to detect subsequently transmitted data until the user changes the code [21]. One simple and straightforward approach to improve the system’s security is to change the code periodically [15], [21], [22]. By the rapid code reconfiguration of legitimate users, Eve can only use unmatched decoder. Thus, the eavesdropping methods of code interception and brute-force searching can be avoided.

On the other hand, spatial diversity technology can improve the performance of the transmission link [23], [24]. In [25], a 10 Gb/s FSO wiretap channel based on spatial diversity scheme and OCDMA is experimentally demonstrated. In weak and middle turbulence cases, bit error rate (BER) of legitimate user can be decreased and physical-layer security can be enhanced simultaneously. However, for single-user spatial diversity FSO-CDMA system, Eve can recover user signals directly by energy detection without optical decoder, so the system has security risk. In order to avoid the eavesdropping method of energy detection, an effective method is to adopt multi-user OCDMA scheme.

To the best of our knowledge, experimental investigation of multi-user reconfigurable FSO-CDMA wiretap channel using spatial diversity reception has not been reported yet. In this paper, we design and investigate a 10 Gb/s two-user reconfigurable FSO wiretap channel based on spatial diversity and OCDMA. Experiments show that reliability and security of spatial diversity FSO-CDMA can be enhanced simultaneously.

This paper is organized as follows. In Section 2, we will build an experimental system of 10 Gb/s two-user reconfigurable spatial diversity FSO-CDMA wiretap channel. The reliability and security of spatial diversity FSO-CDMA are tested and analyzed in Section 3. The experimental results of code reconfiguration are analyzed in Section 4. This paper is concluded in Section 5.

II. EXPERIMENTAL SYSTEM

Fig. 1 shows the model of two-user spatial diversity FSO-CDMA wiretap channel based on reconfigurable optical encoding, where two legitimate users want to communicate over the FSO transmission link, and Eve observes their transmission in the divergence region of the beam. At the transmitter, data bits of each user are encoded by OCDMA encoder 1 and encoder 2 respectively. Then, two encoded signals are coupled and transmitted by two transmitting collimator lens. At the receiver, two receiving collimator lens are adopted to receive optical signals. A coupler is used to deliver the optical signals to each user. Then, each user can employ matched decoder to recover data respectively. At the same time, Eve extracts a certain proportion of optical signals and uses unmatched decoder to eavesdrop data.

Fig. 2 shows the experimental system of 10 Gb/s two-user spatial diversity FSO-CDMA wiretap channel based on reconfigurable optical encoding. 10G BER tester SeBERT-10S sends the signal to the optical transmitter for OOK modulation. The optical transmitter outputs optical pulses with a width of 15ps and a spectrum of 1548.7-1550.1 nm, corresponding to the wavelength selective switch (WSS) wavelength of 53 (1549.72 nm), 54 (1550.12 nm). The output power is −6.1 dBm. The modulated optical signal is amplified by an erbium doped fiber amplifier (EDFA). Then, the optical signal is split by
a coupler. Two different optical encoders are used to encode signals respectively. Among them, optical encoder 1 is a two-dimensional optical encoder, and optical encoder 2 is a one-dimensional optical encoder. Tunable attenuator 1 is used to ensure the same signal power after encoding. Then, two encoded signals are coupled and amplified by an EDFA. The amplified signals are divided into two signals through a coupler and transmitted by two different collimating lenses respectively. The two signals are uncorrelated when the aperture distance between transmitter lens is larger than the fading correlation length $\sqrt{\lambda L}$, with $\lambda$ and $L$ denoting the wavelength and link distance respectively [4]. In this experiment, the transmission distance of FSO is 1.8m, and two collimator lenses are 12 cm apart. In order to simulate the atmospheric turbulence effect, a 40 cm $\times$ 40 cm $\times$ 80 cm box is designed. The holes at the left and right ends are used for optical signal transmission. Different temperature and wind speed correspond to different turbulence effects.

At the receiving end, optical signals received by collimating lens are coupled and amplified by an EDFA, and divided into two signals for matched decoding respectively. In this experiment, a polarizer is used to stabilize the waveform of combined signal. By adjusting attenuators, the optical power of two decoded signals will be the same. After photodetector, 1G BER tester is used for error detection. At the same time, tunable attenuator 2 can be used to simulate different atmospheric attenuation.

According to Kerckhoff’s principle, Eve knows what types of OCDMA signals are being sent, but does not know the optical code of the legitimate user. Hence, we can assume that the optical code of the legitimate user should not be available for Eve. Therefore, Eve should employ unmatched decoder. In this experiment, the optical power of Eve is changed by tunable attenuator and the extraction ratio is 1%. Then, Eve can use a tunable EDFA to amplify the optical signal, so that the receiving power is consistent with that of the legitimate user.

As shown in Fig. 3, reconfigurable two-dimensional optical encoder consists of WSS and optical fiber delay lines (ODL). Each port of WSS corresponds to different wavelengths to realize wavelength-domain encoding. Different ports connect different lengths of ODL to achieve time-domain encoding. At the decoding end, the matched decoder is realized by controlling the wavelength setting of WSS. Similarly, the delay of each port of the decoder is complementary to the delay of the corresponding port of the encoder.

As shown in Fig.4, reconfigurable one-dimensional optical encoder is constructed by couplers and tunable optical delay lines (TODL). Different ports connect different lengths of TODL to achieve time-domain encoding. At the decoding end, the delay of each port is complementary to the delay of the corresponding port of the encoder.

Fig.5 shows the encoding waveform of WSS encoder corresponding to $\{(0,0) (1, \lambda_{53}), (2,0) (3,0) (4, \lambda_{54}) (5,0) (6,0)\}$. The x label (100 ps/div) represents the time, and the y label (50 mV/div) indicates the signal amplitude. Here, $(i, j)$ denotes the position of the $i$th chip pulse and the $j$th wavelength.

Fig.6 shows the waveform of TODL encoder corresponding to code [0101010]. Delay setting of TODL is 14.3, 42.9, 71.4ps respectively. The x label (100 ps/div) represents
the time, and the y label (50 mV/div) indicates the signal amplitude.

Fig.7 shows the combined encoding waveform of WSS and TODL encoders, employing \{(0,0) (1,\lambda_{53}), (2,0) (3,0) (4,\lambda_{54}) (5,0) (6,0)\} and \{0101010\} respectively. The x label (100 ps/div) represents the time, and the y label (50 mV/div) indicates the signal amplitude. From Fig.5 and Fig. 6, it can be seen that for single-user FSO-CDMA system, Eve can recover user data directly by bit energy detection without optical decoder. Therefore, for single-user FSO-CDMA system, physical-layer security is the same as that of uncoded system. As can be seen from Fig. 7, for the combined waveform of WSS and TODL encoders, Eve cannot directly recover the original signal by energy detection. Therefore, the physical-layer security can be improved.

When the number of reconfigurable codes increases, the physical-layer security of the system will be improved. For example, if code length is 169, code weight is 7, and the number of wavelengths is 30, the number of WSS reconfigurable codes will be

$$C_7^{169}C_7^{30} \approx 1.40 \times 10^{18}.$$  

For such a large capacity of reconfigurable codes, as long as the code reconstruction rate (5ms) is less than Eve’s cracking time, Eve not only cannot intercept the code, but also cannot take the eavesdropping method of brute-force searching.

III. RESULT AND ANALYSIS OF RELIABILITY AND SECURITY EXPERIMENT

Different turbulence conditions can be simulated by controlling hot wind temperature and wind speed. Fig.8 shows the received signal waveforms for three different turbulence cases. The test time is 10s and the sampling interval is 0.01ms. The variance can be calculated by

$$\sigma^2 = \langle I_1^2 \rangle / \langle I_1 \rangle^2 - 1,$$

where \(I_1\) is the received intensity after passing through the turbulent channel [26]. Then, we can obtain the refractive index structure coefficient

$$C_n^2 \approx \frac{\sigma^2}{1.38 \times L^{-\frac{11}{6}}}.$$  

In this context, \(\sigma^2\) represents the variance of the received intensity, \(I_1\) the received intensity, \(L\) the link distance in meters, and \(C_n^2\) the refractive index structure coefficient.
experiment, the refractive index structure coefficients are 1.51E-13, 3.41E-14 and 4.96E-15 in strong turbulence, middle turbulence and weak turbulence respectively.

Fig. 9(a)-(c) shows eye diagrams of user 1 (WSS encoder/decoder) in spatial diversity at receiving power $-15$ dBm. Fig. 9(d)-(f) shows eye diagrams of user 1 in non-diversity system. The x label (100 ps/div) represents the time, and the y label (50 mV/div) indicates the signal amplitude.

It can be seen that under the same turbulence conditions, the eye diagrams under spatial diversity are better than that of non-diversity, which indicates that reliability of FSO-CDMA system can be improved by spatial diversity.

Fig. 10 shows BERs of legitimate user and Eve in diversity and non-diversity systems. From Fig. 10 (a) and (c), it can be seen that for legitimate user using WSS encoder/decoder, BER of spatial diversity system is lower than that of non-diversity system. At the received power of $-15$ dBm in weak turbulence, BERs of WSS encoder/decoder are 4.1E-9 and 6.25E-9 in spatial diversity and non-diversity, respectively. In case of middle turbulence, BERs are 9.5E-9 and 2.4E-8 in spatial diversity and non-diversity, respectively. In case of strong turbulence, BERs are 4.96e-8 and 1.61E-7 in spatial diversity and non-diversity, respectively. For TODL user, BERs are 1.17E-8 and 1.38E-8 in weak turbulence, 4.41E-8 and 5.64E-8 in middle turbulence, and 6.87E-8 and 2.33E-7 in strong turbulence, respectively. Therefore, spatial diversity can improve the reliability of the two-user FSO-CDMA system.

It can be seen from Fig. 10 (b) and 10 (d) that BERs of Eve are almost the same under the conditions of diversity and non-diversity system. The reason is that in spatial diversity and non-diversity systems, Eve can detect the same combined signal of two encoders. Therefore, at the same receiving power, BER of spatial diversity will be the same as that of non-diversity system.

Moreover, it can be seen from Fig. 10 that with the enhancement of turbulence, the BER of legitimate and Eve will increase. At the same time, with the decrease of receiving power, the BER of legitimate and Eve increases gradually. Therefore, on the premise of ensuring the reliability of
legitimate users, the physical-layer security can be enhanced by reducing the transmitting power.

IV. EXPERIMENT RESULTS AND ANALYSIS OF RECONFIGURABLE ENCODER

Since the delay of TODL encoder is tunable and the wavelength of WSS encoder can be selected by computer, it is easy for the legitimate user to change the optical code. Thus, the eavesdropping methods of code interception and brute-force searching can be avoided. In the following experiments, we present different encoding waveforms of reconfigurable WSS and TODL encoders. Then, system performances under different encoding conditions are tested.

Fig. 11 shows the waveforms of reconfigurable WSS and TODL encoders. Fig. 11(a) and (b) are the encoding waveforms of WSS encoders corresponding to \{0,0,1,0,2,\(\lambda_{53}\),3,\(\lambda_{54}\),4,0,5,0,6,0\} and \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} respectively. Fig. 11(c) and (d) are the waveforms of TODL encoders corresponding to codeword \{0110010\} and \{0101100\} respectively.

Fig. 12 shows the combined encoding waveforms with WSS and TODL encoders. The x label (100 ps/div) represents the time, and the y label (50 mV/div) indicates the signal amplitude. 12(a) is the waveform of \{0,0,1,0,2,\(\lambda_{53}\),3,\(\lambda_{54}\),4,0,5,0,6,0\} and \{0101010\}. 12(b) is the waveform of \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} and \{0101010\}. 12(c) is the waveform of \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} and \{0110010\}. 12(d) is the waveform of \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} and \{0101100\}.

Fig. 13 shows BERs of different reconfigurable WSS encoder/decoders with TODL \{0101010\}. WSS codes are \{0,0,1,0,2,\(\lambda_{53}\),3,\(\lambda_{54}\),4,0,5,0,6,0\}, \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\}, \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} respectively. It is shown that BERs of legitimate user are almost the same with different codes. For example, in weak turbulence and receiving power −15dBm, BERs of legitimate user are 4.5E-9 and 4.1E-9 for \{0,0,1,0,2,\(\lambda_{53}\),3,\(\lambda_{54}\),4,0,5,0,6,0\} and \{0,0,1,\(\lambda_{53}\),2,0,3,0,4,\(\lambda_{54}\),5,0,6,0\} respectively. Thus, employing WSS code reconfiguration,
The legitimate user can recover user data with matched decoder. However, Eve must use unmatched optical decoder. As shown in Fig.13(b), in weak turbulence and receiving power $-15$dBm, BER of Eve is larger than $2.5 \times 10^{-2}$, which is over the soft-decision forward-error-correction (SD-FEC) threshold $2 \times 10^{-2}$ [27]. Hence, Eve cannot recover user data correctly.

Fig.14 is BERs of different reconfigurable TODL encoder/decoders with WSS $\{(0,0), (1, \lambda_{53}), (2,0), (3,0), (4, \lambda_{54}), (5,0), (6,0)\}$ (a) BER of legitimate user (b) BER of Eve.

In this experiment, a tunable attenuator is used to simulate different FSO link distances, and different temperatures and wind speeds are employed to simulate different atmospheric turbulence effects. The experimental results of the system are consistent with different system parameters, which can show the validity of the proposed scheme.

Our scheme can improve both reliability and physical-layer security of FSO system. Therefore, it provides a good candidate for secure image transmission system [28]–[30]. In future research, we will realize long distance transmission of multi-user spatial diversity FSO-CDMA wiretap channel based on reconfigurable encoder/decoders.

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