Diversity reception and equalization techniques for laser communication in space

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The principle of band-limited space optical communication system using the techniques of space diversity methods and time domain Rake receiver is analyzed. The joint channel equalizer method combining diversity reception and equalization technique is presented in space laser communication. By computer simulation, the bit error rates of noncoherent space optical on-off keying signal using different space diversity methods, Rake reception with different inter-symbol interferences, joint diversity equalizations with different signal noise rates and different channel numbers are analysed. The results identify that joint diversity equalization method can enhance space optical communication performance evidently.

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Laser communication in free space is attractive due to its high speed, flexible, and security[1,2]. When laser pulse is transmitted through atmospheric and oceanic channel, the laser beam is temporal and spatial spreading owing to the multi-scattering effects of media. Therefore, the signal intensity fading and the pulse width broadening are introduced into the received laser pulse[3]. Stochastic interference caused by atmospheric turbulence also make the received optical field scintillation[4]. In order to compensate the transmission channel impacts, the temporal and spatial diversity reception techniques are presented. The combination of both diversity reception and equalization for band limited space optical channel is proposed in this letter[5].

For laser communication in atmosphere or ocean, the received laser pulse is suffered from the channel fading, pulse broaddening, time delay, and background noise. The space diversity reception method is to collect the signal energy from M receiving channels. The total signal is summed with different weights of all channels

$$S = a_1 s_1 + a_2 s_2 + \cdots + a_M s_M, \tag{1}$$

where α_i $(i = 1, 2, 3, \cdots, M)$ is the weight coefficient, s_i is the separate channel independent signal.

If the on-off keying (OOK) signal format with bit rate $R = 1/T$ is considered, the effect of atmosphere on the channels can be modeled by an intensity-fading factor β_i[6,7]

$$\beta_i = \exp(2x_i), \tag{2}$$

where x_i is independently identically distributed Gaussian random variable as a function of laser wavelength, optical path length, and refractive index structure constant[8].

There are three candidates for weight-summing. The first one is equal-gain (EG) summing, and each receiving channel has same weight $\alpha_i = 1/M$. The second option is called the selection-combination (SC) where the channel with the largest instantaneous signal-to-noise ratio (SNR) is selected. The difficulty of adopting this method is the estimation of instantaneous SNR. The last one is similar to the maximum ratio combination (MRC) of radio communication, the weight is proportional to signal intensity or signal SNR, the total SNRs after combining can be equal to the sum of SNRs of all channels. According to this method, the optimal coefficient for shot-noise-limited Poisson channel is given as[9,10]

$$\alpha_i = \ln(m_1^{(i)}/m_0^{(i)}), \tag{3}$$

where $m_1^{(i)}$ and $m_0^{(i)}$ are the mean optical intensities of signal bits "1" and "0". In the case of log-normal intensity-fading channel, the coefficients can be written as[11]

$$\alpha_i = \exp(2x_i), \tag{4}$$

where α_i equals channel intensity-fading factor β_i, it is evident that the weight is directly related to each branch SNR.

Figure 1 is the comparison of the three different space diversity methods in log-normal optical intensity-fading channel. In the simulation, the optical signal is OOK modulation format. The received bit error rate (BER) is assumed to be 0.1 if only one channel is used. If the signals of eight channels are combined, the receiver performance is improved as much as 10—20 dB as shown in

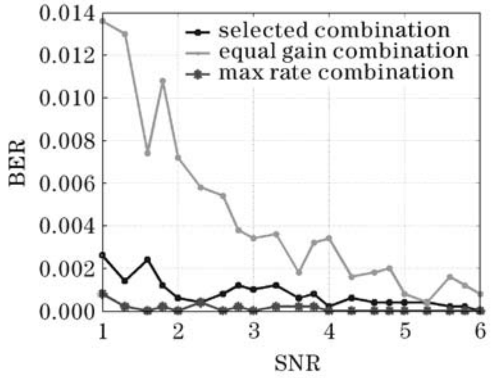

Fig. 1. Comparison of different space diversity combination methods.

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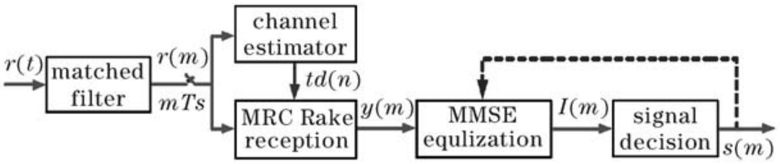

Fig. 2. Rake receiver with equalization model.

Fig. 1, the best space diversity method is MRC. While in practice, both the instant SNR and instant channel fading amplitude are hard to be measured accurately. Equal gain combination (EGC) is a very simple method even if its performance is slightly inferior.

A Rake receiver is a kind of time domain multi-path energy combination method for the time-delay signal waveforms[12]. It is suited for time domain separable multi-path channel, in which the received signal waveform is the time-delayed transmission pulse. Therefore, only the pulse-matched filters are required, and the output signal of the Rake receiver is the combination of the outputs of matched filters at the different time delay moments. While in the case of the received signal with inter-symbol interference (ISI), the output of matched filter is mixed with the multi-path energy of other data bits, the performance of Rake reception structure to collect time domain signal energy degrades. In this letter, a Rake receiver is followed by an equalizer to reduce the effect of ISI[13]. The proposed Rake receiver with the adaptive equalization structure is shown in Fig. 2, least mean square (LMS) algorithm of equalizing is used.

The performances of a Rake receiver with or without equalizing are shown in Fig. 3 when the ISI exist in the received signal. Supposing that output pulse of the space optical channel is composed of two separate scattering components with the same intensity, in which time domain pulse shape is general impulse decay. The each scattering component is sampled by 20 points with the same time slot width, analog waveform is turned into discrete signal sequence. Figure 3 analyzed three receiver system structure performances with different time sampling point distances of the two components. It can be seen that in the front of 17 point distance, the BER curves wave slightly and then rises, under this conditon the movement of multi-path components does not generate ISI interference. Behind 17 point, performance curve of the equalizer receiver separates from the other two curves obviously, its original BER value is kept. It means that the equalizer begins to conflict with ISI, so the receiver can make its performance unchange. The other two receiver structure do not possess capability of the conflicting ISI, and the performance falls continually.

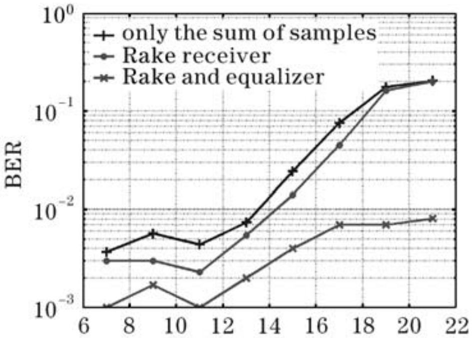

Fig. 3. Performance of time domain diversity receiver with different ISIs.

Although Rake receiver structure can collect signal energy in time domain, the total SNR of the receiver cannot increase. Therefore, two practical special diversity equalization techniques are investigated. One is the space equalizer combiner (SEC), there is a minimum mean-squared error (MMSE) equalizer behind the matched filter in each receiving channel, and the output of each equalizer is summed with diversity combiner weights. The other is called the jointed channel equalizer (JCE), in which the equalizer coefficients are adjusted by equalization algorithm. As adaptive equalization algorithm has the ability to track channel variations, therefore the above two techniques not only have the merits of space diversity to compensate channel fading, but also can adjust the filter coefficients to reduce the effect of multipath time delay. So the space diversity equalization receiver can process received data in both time and space domain[14−16]. The configuration of JCE model is shown in Fig. 4.

Supposing the same laser pulse sequence is transmitted through D different optical space channels, the received signal at terminal is mixed with additive noise and channel effects. The outputs of all diversity channels are taken as a general input sent to the jointed channel equalizer. The JCE optimizes its coefficients according to the multi-input single-output (MISO) system. The optimum criteria for equalizer is MMSE, where the MSE is defined as

$$\varepsilon^2 = \langle \left| I_k - \hat{I}_k \right|^2 \rangle, \qquad (5)$$

where I_k is the sent symbol, $\hat{I}_k$ is the estimated symbol, the bracket means statistical average.

According to the orthogonality principle, the MMSE

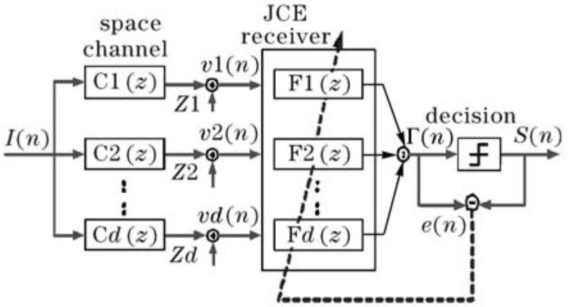

Fig. 4. Joint channel equalizer model for space diversity receiving.

equalizer coefficient is the solution of the following equation[17]

$$\sum_{j=-\infty}^{\infty} c_j \langle v_{k-j} v_{k-l}^* \rangle = \langle I_k v_{k-l}^* \rangle, \tag{6}$$

where c_j is the coefficient of the channel equalizer and v_k is the time discrete sampling input to the equalizer. If the general channel discrete response length is $2L+1$, the single channel equalizer weight length is $2k+1$, and the noise is spatially independent that the noise in each reception branch is uncorrelated, when the JCE is employed, the received data sequence is given by

$$v_k^{(d)} = \sum_{n=-L}^{L} f_n^{(d)} I_{k-n} + z_k^{(d)}, \tag{7}$$

where $f_n^{(d)}$ denotes general channel sampling response, $Z_k^{(d)}$ is additive noise, and the superscript (d) denotes the dth channel.

According to MMSE criteria, if $\langle \left| I_k - \hat{I}_k \right|^2 \rangle$ is minimized, $(2k+1)D$ taps will be solved simultaneously. By the orthogonality principle, $\langle (I_k - \hat{I}_k) \cdot v_{k-l}^{(d2)} \rangle = 0$ is assumed, then

$$\sum_{d=1}^{D} \sum_{m=-k}^{k} c_m^{(d1)} \langle v_{k-l}^{(d2)} v_{k-m}^{(d1)} \rangle = \langle I_k v_{k-l}^{(d2)} \rangle, \tag{8}$$

where $d1, d2 \in [1, D]$, and $(2k+1)D$ taps correspond to a set of $(2k+1)D$ equations. These equations can be expressed in matrix format

$$\vec{\Gamma} \cdot \vec{C} = \vec{\xi}. \tag{9}$$

Matrix inversion can directly solve out the optimal filter tap vector $\vec{C}$ of JCE, where correlation matrix $\vec{\Gamma}$ is composed of the self sub-correlation matrix $\Gamma_{d1,d2}$, any component of which is expressed as

$$\Gamma_{lj} = \begin{cases} \sigma_i^2 \sum\limits_{m=1}^{2k+1-|l-j|} f_m^{(d1)} f_{m+|j-l|}^{(d2)*} + 2N_0 \delta_{lj} \delta_{d1d2} \\ \qquad\qquad |l-j| \le L \\ 0 \qquad\qquad \text{otherwise} \end{cases},$$

$$\langle I_{n-j-m} I_{n-l-m'} \rangle = \begin{cases} \sigma_i^2 & m' = j - l + m \\ 0 & \text{otherwise} \end{cases},$$

$$\langle z_{k-j} z_{l-j}^* \rangle = \begin{cases} N_0 & l = j \\ 0 & l \neq j \end{cases}. \tag{10}$$

The cross correlation matrix $\vec{\xi}$ between the inputs v_k^d of equalization filter and the sent symbol I_k is

$$\xi_l = \sum_{n=-\infty}^{+\infty} f_n^* \langle I_k I_{k-l-n} \rangle = \begin{cases} \sigma_i^2 f_{-l}^{(d)*} & |l| < L \\ 0 & \text{others} \end{cases}. \tag{11}$$

The cross correlation matrix is made up of D subvectors of length $2k+1$, JCE has $(2k+1)D$ taps in all. The Γ matrix inversion operation needs to inverse a $(2k+1)D * (2k+1)D$ matrix, it requires a long time. In this letter, an adaptive iterative algorithm based on stochastic gradient method is used, then the filter can combine the space separate received signals and track the variation of optical channel automatically at same time.

The Poisson optical channel with ISI disturbance is assumed, and the MMSE adaptive equalization algorithm is used in this numerical simulation. The space equalizer combiner and the joint channel equalizer are compared in Fig. 5 with the different channel numbers and SNRs. The BER decreases with the increases of SNR, and the more the channels, the lower the BER. JCE method is better than SEC one under all conditions, especially for larger channel number. It is also shown that the difference is larger when the channel number increases. The reason is that JCE takes all received signals as a general equalizer to input, SEC has only one reception branch. However, JCE needs much longer computing time instead.

From Fig. 5, we can see that the performances of laser communication in atmospheric and ocean channels can be enhanced by the techniques of space receiver array and equalization no matter how much of that SNR is. Whether or not the enhancement of systme performance by increasing channel number has a limitation? To answer this question, we do a simulation according to the channel number. The results is illustrated in Fig. 6, there does not exist the limitation. If SNR is 6, the original BER of one channel equalization is 0.1, and the total 25 channels are combined with JCE technique, the BER is reduced to be 10^{-4}. It is close to the performance of

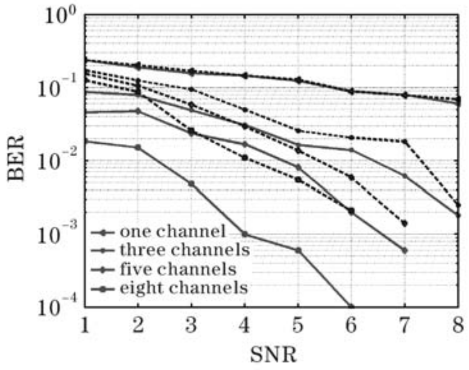

Fig. 5. BERs of two diversity equalization model under different SNRs. Dashed lines: SEC; solid lines: JCE.

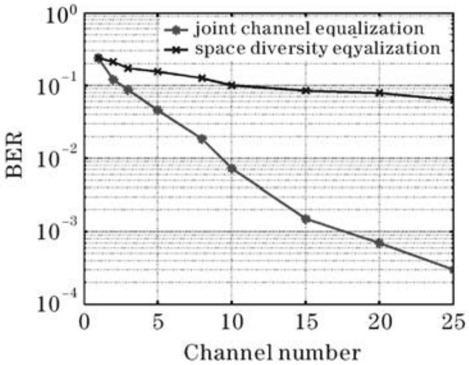

Fig. 6. BERs of two diversity equalization versus channel numbers under SNR = 6.

communication system with the most complex and advance coding. It is implied that JCE is one of the powerful tools for laser communication in atmospheric and oceanic channel.

In summary, the temporal and spatial diversity receiving technique is introduced into the laser communication in atmospheric and oceanic channels. And a jointed channel equalizer with MMSE adaptive equalization algorithm for space diversity is proposed. The numerical simulation shows that the communication performance is enhanced significantly with this technique.

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