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Research on Space Diversity Technique of Laser Atmospheric Communication Based on MIMO

Li Dashe[1,2], *Liu Shue*[3], *Wang Bin*[1,2] ,*Li Guangwen*[1,2]

[1]School of Computer Science and Technology, Shandong Institute of Business & Technology, Yantai 264005, China
[2]Key Laboratory of Intelligent Information Processing in Universities of Shandong (Shandong Institute of Business and Technology),Yantai 264005,China
[3] School of Computer Science and Technology, Binzhou Medical University, Yantai 264003, China

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Abstract: Space diversity is one of the important techniques of overcoming the influence of atmospheric turbulence on laser communication. Having analyzed the theory of diversity technique, the paper has focused on researching the space diversity technique and established the joint probability density function of the threshold value. Outage probability is studied in laser communication and get the variation curve of power gain and the number of antenna in different atmospheric turbulence. Based on the BPSK modulation mode, the bit error ratio mode of the multi-input multi-output (MIMO) is set up and reach the conclusions that maximum power gain is obtained with an equal amount of transmitting antenna and receiving antenna and the total amount should be not greater than nine. The space diversity technology can effectively reduce the bit error ratio of the system.

Keywords: Laser atmospheric communication,space diversity, MIMO, bit error ratio.

1 Introduction

Current free-space optical systems are unable to support reliable low-cost gigabit class communication over tens of kilometers.In free-space optical communication links using intensity modulation and direct detection (IM/DD), atmospheric turbulence-induced intensity fluctuations can significantly impair link performance. Communication techniques can be applied to mitigate turbulence-induced intensity fluctuations in the regime in which the receiver aperture D0 is smaller than the fading correlation length d0 and the observation interval T0 is smaller than the fading correlation time $\tau 0$. If the receiver has knowledge of the joint temporal statistics of the fading, maximum-likelihood sequence detection (MLSD) can be employed, but at the cost of high computational complexity. Frequency-diversity can provide some additional robustness but is costly because of the broadband components required. These components must be broadband because of the large frequency coherence of atmospheric turbulence. Thus we are motivated to explore architectures with a high degree of spatial diversity. This requires systems with many transmit and receive apertures. Such systems can be readily implemented due to the relatively short coherence length of the atmosphere at optical wavelengths. Previous work on sparse aperture coherent detection systems has not included wavefront predistortion, and assumes the turbulence is in the near field of only the receiver [1, 10]. The transmission of laser through the atmospheric channel generates atmospheric attenuation and atmospheric turbulence, inducing such phenomena as energy attenuation and the flickering, curving, excursion and distortion of light beam. The randomness of occurrence and intensity of such influences have impacts on the quality of communication or even causes suspension of communication. As an effective way to overcome the influence of atmosphere especially the atmospheric turbulence, space diversity technique is capable of improving the performance of photo-communication with a relatively low cost for the improvement of the receiving signals SNR, the reduction of bit error ratio and the improvement of communication reliability.

* Corresponding author e-mail: lidashe@126.com

2 THEORY OF DIVERSITY TECHNIQUE

To effectively overcome the impacts of atmospheric turbulence on laser communication, diversity technique is often used to improve the performance of system. The diversity technique is to receive terminal and optical signals transmitted from different routes simultaneously and to constitute overall receipt signals through the modulation and combination of received optical signals so as to reduce the influences of atmospheric absorption and atmospheric turbulence. Frequently used diversity techniques include time diversity, frequency diversity and space diversity. Time diversity is, in terms of the random fading signal, to transmit the same signal with an interval longer than the coherence time of channels to provide the time domain redundancy for the receiver so that the signal can be received by the receiver with independent fading conditions. Frequency diversity is to transmit the same information with laser of different wavelength (namely different frequencies) to realize the frequency domain redundancy of the receivers signal. Space diversity is to guarantee the signals space domain redundancy with multiple transmitting and receiving antennas meeting certain conditions in terms of spatial distance (normally the space between the antennas is larger than the coherence length of the channel) for the improvement of the receivers SNR, the reduction of the systems bit error ratio and the improvement of the systems performance. Space diversity is used in offshore laser atmospheric communication [11–13].

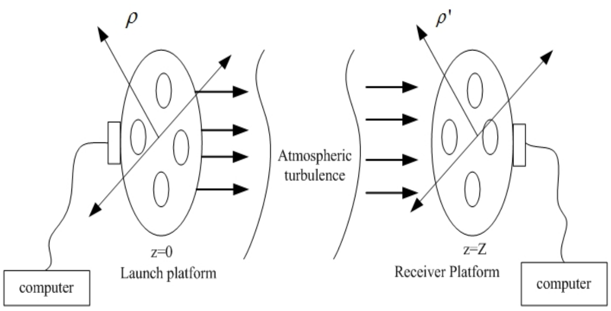

Fig. 2.1 The structural diagram of space diversity

3 RESEARCH ON SPACE DIVERSITY TECHNIQUE

Compared with the conventional diversity technique, space diversity of laser atmospheric communication is easier to practice. In atmospheric turbulence, the coherence length for atmospheric turbulence: $r_0 \approx (1.46k^2{C_n}^2L)^{-3/5}$. In normal circumstances, the transmission range Ł $= 8000m$, optical maser wavelen gth $\lambda = 1060nm$ If the typical value of ${C_n}^2$ in offshore transmission ${C_n}^2 = 5 \times 10^{-16}$ then $r_0 = 4.1cm$ which means the dimension of the coherence length is centimeter level. Therefore, so long as the space between the transmitting and receiving antennas remains on the level of centimeter, the laser transmitted along different channels is independent and irrelevant.

The number of transmitting antennas is n_t , the number of receiving antennas is n_r . Moreover, at least one of them is larger than 1. (that means one of the mode among MISO, SIMO and MIMO) The launched light beams reach the receiving end after the atmospheric turbulence. The transmitting and receiving antennas are uniformly distributed on the circle with an R radius. The distance between the transmitting terminal and receiving end is Z. The transmitting and receiving antennas locate on the transmitting and receiving platforms respectively and their activities are under the command of the main controlling computer. For the convenience of discussion, we have made the following hypothesis: //

(1) The system is under the BPSK modulation mode;

(2) The distance between the receiving antennas, transmitting antennas and the transmitting and receiving antennas is longer than the atmospheric coherence length. The transmission of all light beams meet the same law (With the same atmospheric attenuation, the impacts caused by atmospheric turbulence remains the same.)

(3) The noise resulted from noise source is AWGN;

(4) The channel gain from the ith transmitting antenna to the jth receiving antenna is h_{ij} which conforms to normal distribution;

(5) The total transmitting power P_t remains the fixed value which is not subject to the change of the transmitting antenna number.

(6) The atmospheric turbulence meets the Rog off condition, namely the isotropic atmosphere.

(7) $n_{\min} = \min(n_t, n_r)$, $n_{\max} = \max(n_t, n_r)$

Based on the hypothesis above, we define the transmission equation from laser transmission terminal to the laser receiving end a linear equation

$$\vec{y} = \frac{1}{\sqrt{n_{\max}}}\vec{H}\vec{x} + w \tag{1}$$

$\vec{x}$ is the vector of the transmitting surface, $\vec{y}$ the vector of the receiving surface,
w is the AWGN resulted from the noise source of the system (noise from the receiver, background and dark current) .

$\vec{H}$ is the atmospheric transmission channel. From the Huygens-Fresnel theorem:

$$h_{ij} = \frac{1}{j\lambda z}\exp[\frac{j2\pi z}{\lambda}(1 + \frac{|\rho_i - {\rho_j}'|^2}{2z^2}] \tag{2}$$

λ is the wavelength of the transmitting laser. With the perturbation method, the gain of light beam can be formulated as the following:

$$h_{ij} = \frac{1}{j\lambda z}\exp[\frac{j2\pi z}{\lambda}(1+\frac{|\rho_i-\rho_j'|^2}{2z^2}] \times \exp[\chi(\rho_i,\rho_j')+j\phi(\rho_i,\rho_j')] \quad (3)$$

(ρ_i,ρ_j') , (ρ_i,ρ_j') are respectively the amplitude and the variation of phase, which are combined Gaussian scalars. $\chi(\rho_i,\rho_j') \propto N(m_\chi,\sigma_\chi{}^2)$, m_χ is the mean value of amplitude and $\sigma_\chi{}^2$ the variance of amplitude. φ distributes uniformly in $[0,2\pi]$. From the SVD theory, the eigenmode can be dissolved into the following:

$$\frac{1}{\sqrt{n_{\max}}}\vec{H}\vec{H}^{+} = \Phi\Gamma\Phi^{+} \quad (4)$$

The ith row of the Φ is the output eigenmode. The eigen value or diffraction gain value on the ith line of the diagonal matrixΓ is related to the eigen mode value on the ith row. The ith eigenmode value is γ_i . The diffraction gain can be written in the following form:

$$y_i = \sqrt{\gamma_i}x_i + w_i \quad (5)$$

x_i , y_i , and $\vec{x}$, $\vec{y}$,
w correspond with one another.
w conforms with the Gaussian distribution and its variance is σ^2 . The probability density function of the diffraction gain can be written as:

$$f_\beta(\gamma) = \frac{\sqrt[3]{p(\gamma,\beta)((1+\sqrt{\beta})^2-\gamma)}}{2\pi\gamma} \quad (6)$$

Among them,

$$p(\gamma,\beta) = \begin{cases} \gamma-(1-\sqrt{\beta})^2 & \gamma \geq (1-\sqrt{\beta})^2 \\ (1-\sqrt{\beta})^2\text{-}\gamma & \gamma \leq (1-\sqrt{\beta})^2 \end{cases},$$

$$\beta = n_{\min}/n_{\max} \text{ , } \gamma_{\max} = (1+\sqrt{\beta})^2$$

As is seen from above, the relationship between the value of probability density function and the eigenmode under different β value is shown. The bigger the β value, the closer between $n_{\min}$ and $n_{\max}$ value, the bigger the value of probability density function. When $\beta = 1$ ($n_{\min} = n_{\max}$ or $n_t = n_r$), the function value reaches the maximum. Therefore, in the system, the number of the transmitting and receiving antennas should be the same ($n = 4$)[14,16].

4 ANALYSIS OF SPACE DIVERSITY TECHNIQUE

In multiple beam transmission, some beams out of nm light beams may greatly attenuate the energy (lower than the responsiveness requirements) or cause beam distortion due to factors like atmospheric turbulence and atmospheric absorption. Other light beams with relatively weak attenuation maintain great amount of energy when they reach the receiving end, so these signals can be easily recognized and applied. Under equal conditions, the more the light beams, the higher the SNR of the receiving end. The Isaac K.I. experiment has demonstrated that the SNR of the system rise by 7-10dB owing to the application of space diversity technique. Thus, the space diversity technique is used in this system[17,18].

4.1 Space diversity in weak turbulence

In weak turbulence, the light power can be simplified as

$$p(I) = \frac{1}{<I>}\exp(-I/<I>) \quad (7)$$

The statistic characteristics of the light intensity I_k $k = (1,2,...m)$ on the receiving point of the n beams comply with the same distribution. And the I_k is used for calculating the independence which has the same contribution to I . Then

$$I = I_1+I_2+\cdots I_n = \sum_{k=0}^{n} I_k \; I_k = <I>/n \quad (8)$$

And the characteristic function of the I_k distribution is

$$\phi_{I_k}(\omega) = \int_0^\infty \exp(j\omega I_k)p(I_k)dI_k = \frac{1}{1-j\omega<I>/n} \quad (9)$$

Then normalizing the characteristic function of the I_k distribution and setting $<I>/n = 1$ so $\phi_{I_k}(\omega) = \int_0^\infty \exp(j\omega I_k)p(I_k)dI_k = \frac{1}{1-j\omega<I>/n} = \frac{1}{1-j\omega}$ Under the multiple beams transmission, they transmit n beams laser; and then the characteristic function generated by the m scattering elements is

$$\phi_I = \phi_{I_1}(\omega)\times\phi_{I_2}(\omega)\cdots\phi_{I_m}(\omega) = (\frac{1}{1-j\omega})^{nm} \quad (10)$$

To conduct the Fourier inversion to the last expression and get the probability density function of the total light intensity as :

$$P_I(I) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\exp(-j\omega I)\phi_I(\omega)d\omega = \frac{I^{nm-1}}{\Gamma(nm)}\exp(-I) \quad (11)$$

Where n is the number of transmitting antenna. In the formula,
m is the number of incoherent scatters. The computational formula is as follows :

$$m \approx \begin{cases} D_{re}/\rho_0 & (D_{re}/\rho_0) > 1 \\ 1 & (D_{re}/\rho_0) \leq 1 \end{cases}$$

Suppose the threshold value of light intensity is I_{th} (the system cannot detect when the receiving light intensity is lower than this value), the probability of the light intensity being lower than the threshold value in each circuit branch of the receiving end is:

$$P_1{}^n(I<I_{th}) = \int_0^{I_{th}} P_I(I)dI = \int_0^{I_{th}} \frac{I^{n-1}}{\Gamma(n)} \exp(-I)dI \quad (12)$$

After the deduction, the above formula can be written as:

$$P_1{}^n(I<I_{th}) = \exp(-I)\sum_{r=0}^{n-1}(-1)^r \frac{(n-1)!I^{n-1-r}}{(n-1-r)!}\Bigg|_0^{I_{th}}$$

If there are m scatters in the transmission space, the joint probability density function of the power value of all the n transmitting light beams being lower than the threshold value is:

$$P_n{}^m(I<I_{th}) = [P_1{}^n(I<I_{th})]^m \quad (13)$$

The probability of at least one light beam reaching the threshold value is:

$$P(I>I_{th}) = 1-[P_1{}^n(I<I_{th})]^m \quad (14)$$

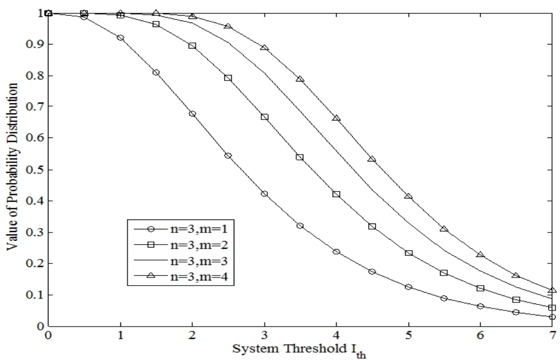

Fig. 4.1 Probability distribution in weak turbulence

Figure 4.1 is the probability distribution curve as the number of transmitting light beams $n = 3$ and there are $m = 1,2,3,4$ number of scatters in the transmission space. It can be seen from table 1 that the more the branches are, the bigger the probability distribution value is under the same threshold value of the system, the easier the realization of the system is. When the number of branches reaches 9, the probability value reaches 100%. Therefore, normally the number of transmitting light beams in the system is lower than 10.

For the same light beam, the lower the threshold value, the bigger the probability distribution value, the easier the realization of the system is. Thus, the system has the tendency of choosing components with low threshold value is there is suppression of background light[19,20].

Table 4.1 Function values under Different branches

branches	erobability valup	bracnhes	probabulity valie
1	67.6%	6	99.8%
2	89.5%	7	99.9%
3	96.6%	8	99.9%
4	98.9%	9	100%
5	99.6%	10	100%

4.2 Space diversity in strong turbulence

As it is known in the document, in the strong turbulence, when the related parameters $\rho \to 0$; then the probability density of the light intensity I is

$$P_{I_k}(I_k) = \frac{2}{\Gamma(m)} m^{(m+1)/2} I_k{}^{(m-1)/2} K_{m-1}[2(mI_k)^{1/2}]$$

Wherein, K_{m-1} is the modified Bessel function and the m is the scattering elements amount. The definition is the same as the formula (14). The statistic characteristics of the light intensity $I_k(k = 1,2,...m)$ on the receiving point of the n beams are complied with the same distribution. And I_k is used for calculating the independence which has the same contribution to I , then

$$I = I_1 + I_2 + \cdots I_n = \sum_{k=0}^{n} I_k$$

And the characteristic function of the I_k distribution is

$$\phi_{I_k}(\omega) = \int_0^{\infty} \exp(j\omega I_k)p(I_k)dI_k = n^{(n-1/2)} \times (j\omega)^{-n} \times \exp(jn/\omega) \quad (15)$$

Because the I_k is used for calculating the independence; and the characteristic function of overlapping light intensity I distribution is

$$\phi_I = \phi_{I_1}(\omega) \times \phi_{I_2}(\omega) \cdots \phi_{I_m}(\omega) = [\phi_{I_k}(\omega)]^n \quad (16)$$

To conduct the Fourier inversion to the formula (16) and after getting strong turbulence, the probability density function of the light intensity I under the multi-beams transmission is

$$P_I(I) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \exp(-j\omega I)\phi_I(\omega)d\omega = m^{\frac{m-1}{2}n} \times I^{-\frac{mn}{2}} \times (mn)^{\left(\frac{1}{2}\right)^{mn}} \times K_{nm+1}[2(nmI)^{1/2}]$$

Suppose the threshold value of light intensity is I_{th} (the system cannot detect when the receiving light intensity is lower than this value), the probability of the light intensity being lower than the threshold value in each circuit branch of the receiving end is:

$$P_1{}^n(I<I_{th}) = \int_0^{I_{th}} P_I(I)dI = \int_0^{I_{th}} I^{-\frac{n}{2}} \times (n)^{\left(\frac{1}{2}\right)^n} \times K_{n+1}[2(nI)^{1/2}]dI \quad (17)$$

Likewise, if there are m scatters in the transmission space, the joint probability density function of the power value of all the n transmitting light beams being lower than the threshold value is:

$$P_n{}^m(I < I_{th}) = [P_1{}^n(I < I_{th})]^m \quad (18)$$

The probability of at least one light beam reaching the threshold value is:

$$P(I > I_{th}) = 1 - [P_1{}^n(I < I_{th})]^m \quad (19)$$

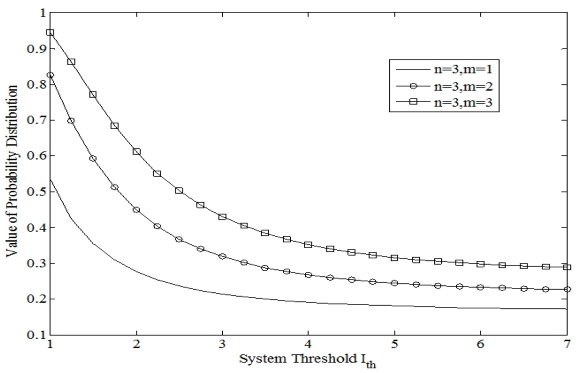

Fig. 4.2 Probability distribution in strong turbulence

Figure 4.2 is the probability distribution curve as the number of transmitting light beams $n = 3$ and there are $m = 1, 2, 3$ number of scatterers in the transmission space. It can be seen that the more the branches are, the bigger the probability distribution value is under the same threshold value of the system, the easier the realization of the system is. For the same light beam, the lower the threshold value is, the bigger the probability distribution value is, the easier the realization of the system is. It can be seen through the comparison of figure 4.1 and figure 4 that under the condition of $n = 3, m = 2$, in weak turbulence, .In strong turbulence, $P(I > I_{th}) = 34.51\%$. The value in weak turbulence is much bigger than that in strong turbulence.

5 RESEARCH ON THE BER OF THE SPACE DIVERSITY SYSTEM

The laser atmospheric communication system is under the BPSK modulation mode with the code element period as T. To set the detectors integration time inside each bit interval as $T_0 < T$, when the transmitting bit value is "1", the detected signal is I_a ; when the transmitting bit signal is "0", the detected signal is $-I_a$. The description upon signal receipt is as follows:

$$x(t) = \begin{cases} I_a + n_c \;\; transmitting\text{"1"} \\ -I_a + n_c \; transmitting\text{"0"} \end{cases}$$

Among them, n_c is the mean value which equals 0, the variance is the AWGN of N/2, which has nothing to do with the transmitting and receiving code element being equal to "1" or "0". But in normal circumstances, the value is so small that it can be overlooked. The receivers function of detecting the circuit is to confirm whether the bit value is 1 or 0 according to the received signal. But it should be noticed that when transmitting "1", the value of $x(t)$ is lower than 0 at the time of detection owing to the noise superposition, the value of "1" can thus be mistakenly detected as "0" . So the error probability P_{e1} of detecting "1" as "0" is

$$P_{e1} = P(x < 0, transmitting\text{"1"}) \quad (20)$$

Likewise, the error probability P_{e2} of detecting "0" as "1"is

$$P_{e2} = P(x > 0, transmitting\text{"0"}) \quad (21)$$

For MIMO, in long-distance transmission, the probability density function of I_a should satisfy:

$$P_I(I) = \frac{I^{nm-1}}{\Gamma(nm)} \exp(-I)$$

Thereupon, its mean value and variance are:

$$a = E[I] = \frac{\Gamma(nm+1)}{\Gamma(nm)}$$

$$\sigma_n{}^2 = \frac{\Gamma(nm)\Gamma(nm+2) - \Gamma^2(nm+1)}{\Gamma^2(nm)}$$

Within a relatively long period of observation, the channel mode can be seen as the multiplicative interference channel mode with a Gaussian distribution. x , as the mean value equals a . The variance is the normal random variable of $\sigma_n{}^2$. Therefore:

$$P_{e1} = \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma_n} e^{-(x-a)^2/2\sigma_n{}^2} dx = \frac{1}{2} erfc(\sqrt{r})$$

Among them,

$$r = \frac{a^2}{2\sigma_n{}^2} = \frac{\Gamma^2(nm+1)}{\Gamma(nm)\Gamma(nm+2) - \Gamma^2(nm+1)}$$

Suppose there is equal distribution probability of "0" and "1" in the transmitting code element, namely $P(0) = P(1) = 1/2$ and $P_{e1} = P_{e2}$.

To neglect the inter-symbol interference, the bit error ratio of laser atmospheric communication system modulated in BPSK mode is:

$$P_e = P(0)P_{e1} + P(1)P_{e2} = P_{e1} = \frac{1}{2} erfc(\sqrt{r}) \quad (22)$$

It can be seen from the figure that diversity gain of the system has greatly improved the bit error performance. When the bit error ratio is 10^{-6} , four light beams can obtain approximately 6dB SNR gain[20-24]

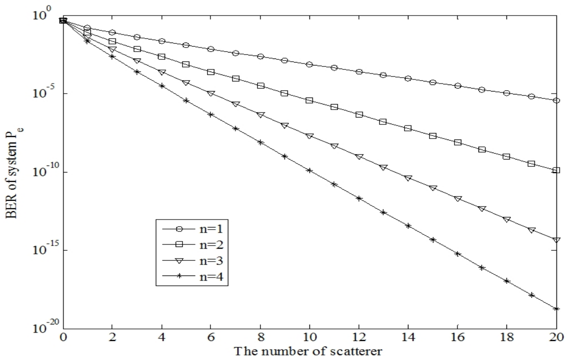

Fig. 5.1 Curve of the systems bit error ratio

Conclusion

BER model is built based on BPSK modulation.From the probability density function, maximum power gain is obtained with an equal amount of transmitting antenna and receiving antenna and the total amount should be not greater than nine. Outage probability is established.From the model based on MIMO,we can get that space diversity technology can effectively reduce the bit error ratio of the system.

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Li Dashe was born in Linyi, Shandong Province, China, on July 23, 1978. He received his B.S degree from Qufu Normal University of China in 2002 and Master degree form Yantai University in 2005. Currently, he is a PH.D research candidate at China University of Mining & Technology since 2008. His research interest is wireless communication.

Liu Shue was born in Yantai, Shandong Province ,China, on November 17,1977. She received her B.S degree from Qufu Normal University of China in 2002 and Master degree form Yantai University in 2006.Currently, she is a lecturer of Binzhou Medical University of China and conducts research in the areas of power electronics and power transmission.

Wang Bin was born in Linyi, Shandong Province ,China, on January 22,1977. He received his B.S degree from Chongqing University of Posts and Telecommunications of China in 2003 and Master degree form Shandong University in 2012.Currently, He is a lecturer of Shandong Institute of Business And Technology of China and conducts research in the areas of power electronics and power transmission.

Li Guangwen was born in Jinan, Shandong Province ,China, on October 18,1972. He received his B.S degree from Shandong University of China in 1993 and Master degree form Shandong University in 2001 and Doctor degree form Nanjing University of Posts and Telecommunications of China in 2009.Currently, He is a lecturer of Shandong Institute of Business And Technology of China and conducts research in the areas of power electronics and power transmission.