MIMO communication system capacity in random visible light channel

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Abstract

Being a promising one, optical information transmission standard expands capabilities of communication systems in the conditions of heavy frequency band load. Optical communication system efficiency in a room can be improved by multi-antenna systems. The aim of this paper is a theoretical study of MIMO Li-Fi communication system capacity. The calculation of ergodic capacity is performed for MIMO optical communication system in terms of various scenarios of light propagation. Receiving and transmitting system is modeled in the form of receivers and transmitters randomly placed in a room with randomly oriented light-emitting and photo diodes. A matrix of channel parameters is modeled using corresponding probability density functions and additive Gaussian noise at receiver inputs. The paper also considers various scenarios of optical signal propagation and their influence on optical channel capacity. The comparison of various methods of power distribution between original modes of MIMO optical communication system as well as their influence on capacity is carried out. Optimal power distribution between MIMO system eigenmodes is determined by maximum capacity criterion.

Keywords: light fidelity, discrete-continuous channel, optical signal processing, signal-to-noise ratio, MIMO channel capacity.

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Introduction

Widespread application of wireless communication systems with channel frequency division creates difficulties in allocating frequency spectrum sections for various systems to operate. The problem of frequency resource shortage in cellular mobile communication systems, Internet of Things (IoT) systems and devices is especially relevant. To solve this problem, various methods are used, among which the most promising is MIMO technology which allows transmitting a larger amount of information due to spatial diversity in the same frequency band. With high concentration of various radio devices mutual interference leading to channel capacity limitation inside and outside the room takes place. To solve this problem the electromagnetic radiation of various wavelength ranges: radio frequency and optical range is offered to be used. Extensive bibliography is devoted to the study of information transmission using optical signals [1 – 12]. MIMO system advantages are realized with the condition that channel matrix is measured with the help of various algorithms [13 – 15].

The possibility of wide application of IEEE 802.11bb Li-Fi communication standard is provided by the distribution of lighting devices based on LED lamps. For any LED, a fundamental possibility to simultaneously illuminate the room and broadcast arrays of binary data exists. For example, Li-Fi tests were carried out by Beamcaster employees reaching data transfer rate of 1.25 Gbit/s, as well as Sisoft, carrying out data transfer at a speed of 10 Gbit/s.

To realize the advantages of MIMO technology, it is necessary to ensure synchronization in the conditions of frequency selective and frequency non-selective fading channel. The authors also recommend to create and study highly effective wireless interfaces by using methods and equipment of radiophotonics, as well as to ensure wave, spatial, and angular separations of optical signals. The processing of optical frequency signals at thermal noise background can be performed using statistical methods. A well-known approach for processing is Gaussian models of thermal noise [4 – 6, 8 – 9].

The paper [17] provides a classification of various MIMO optical wireless communication technologies and discusses their key distinctive features. Various architectures of MIMO optical systems are considered and information transfer rate is compared. Spatial multiplexing is proven to provide highest information transfer rate. Incoherent transmission of optical signals has become the most widespread, for which optical DC-biased carrier or, in simpler case, on-off keying (OOK) method is used. An example of power level bias of optical carrier is hybrid Hy-Fi system [8] which combines light-based communication (LiFi) and radio frequency at physical 802.11 (WiFi) layer using MIMO capabilities, as the IEEE 802.11bb proposes. Under these conditions, in order to obtain high-rank MIMO signal resulting in high capacity the authors propose to orient several photo detectors at different angles of inclination forming a pyramidal or a hemispherical receiver [3].

MIMO communication system capacity depends on channel coefficients matrix, as well as the parameters of transmitter, receiver, modulation and coding methods. The expression for limiting value of capacity is given in [18], and depends on signal power distribution over its eigenmodes.

The aim of the work is to increase the capacity of optical Li-Fi communication channel by optimal power distribution over its eigenmodes comparing it with the capacity in case of non-optimal power distribution.

1. Architectures of Li-Fi information transmission systems

The development of information transmission systems in visible radiation range has been carried out in various scientific and technical organizations around the world for several years [1 – 3]. The advantage of Light Fidelity (Li-Fi) technology is high data rate. If we take 224 Gbit / s as a basis [16], then Li-Fi exceeds limit speed of Wi-Fi of IEEE 802.11ax standard by 22.4 times, and IEEE 802.11ac by 30 times. Li-Fi 802.11bb communication standard (2023) is currently in effect. The basic concept of 802.11bb standard is the optimal use of 802.11 standard parameters and the introduction of only relevant functions for the visible radiation to be used. The 802.11bb standard, as well as Wi-Fi, uses existing signal generation methods – orthogonal frequency division multiplexing (OFDM). But OFDM cannot be used directly in optical communication systems that use intensity modulation and direct detection method to transmit data. To provide an OFDM-based approach, DC biased optical OFDM (DCO-OFDM) is used. This is an intensity modulation based on optical carrier, in which transmitter emits a carrier by periodically changing light intensity and modulates this carrier using conventional OFDM. Compared to simpler pulse intensity modulation used in 802.15.7 and 802.15.13, DCO-OFDM is less susceptible to intersymbol interference, thus supporting higher data rates. To convert a complex and bipolar OFDM signal into a real and non-negative DCO-OFDM signal, the device converts an original OFDM signal into a real signal, and then shifts it by some positive amount.

Following this method, for a theoretical analysis of optical channel maximum capacity, it is assumed that the technical implementation uses multilevel modulation of optical radiation intensity with constant carrier offset (DC).

2. Problem statement and basic ratios

Let's consider a discrete-continuous information transmission channel. The channel can be represented as several independent channels of information transmission as a result of applying MIMO spatial encoding and decoding. The optical signal emitted has amplitude modulation with a discrete message taking values $\mathbf{X}=\{0,1\}$ with probabilities p_0, p_1, respectively. The signal at the output of continuous channel is described by expression $y=\sqrt{P}Hx+v$, where P is a power of emitted optical signal, $H>0$ is a coefficient of optical signal transmission from transmitter to receiver, v is thermal Gaussian noise with variance σ_V^2.

The problem of estimating the amount of conditional information in a discrete-continuous channel is solved in [19]. Maximum capacity is observed with equal bits probabilities $p_0=p_1=1/2$ and with Gaussian probability distribution of noise v. The amount of mutual information is determined by entropy difference $I=h(y)-h(y|x)$. Probability density function (PDF) of the observed process y is the sum of PDF at discrete values of message: $w(y)=p_1w_1(y)+p_0w_0(y)$, where PDF in absence and at presence of a signal is equal respectively [19]

$$w_0(y)=\frac{1}{\sqrt{2\pi}\sigma_V}\exp\left(-\frac{y^2}{2\sigma_V^2}\right),$$

$$w_1(y)=\frac{1}{\sqrt{2\pi}\sigma_V}\exp\left(-\frac{\left(y-\sqrt{P}H\right)^2}{2\sigma_V^2}\right).$$

Conditional PDF has the form:

$$w(y\,|\,x)=\frac{1}{\sqrt{2\pi}\sigma_V}\exp\left(-\frac{\left(y-\sqrt{P}Hx\right)^2}{2\sigma_V^2}\right).$$

Single channel capacity in a MIMO system is determined by expression [19]

$$C=\frac{1}{2}\int_{-\infty}^{\infty}w(y\,|\,0)\log_2\left(\frac{w(y\,|\,0)}{w(y)}\right)dy+$$
$$+\frac{1}{2}\int_{-\infty}^{\infty}w(y\,|\,1)\log_2\left(\frac{w(y\,|\,1)}{w(y)}\right)dy.$$

By entering a normalized variable $z=y/\sigma_V$, signal-to-noise ratio $q_1=PH^2/\sigma_V^2$, a priori bit probabilities $p_0=p_1=0.5$ we get an expression for channel capacity for a given case:

$$C_H=\frac{1}{2}\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}}e^{-\frac{z^2}{2}}\log_2\left(\frac{2e^{-\frac{z^2}{2}}}{e^{-\frac{z^2}{2}}+e^{-\frac{1}{2}\left(z-\sqrt{q_1}\right)^2}}\right)dz+$$
$$+\frac{1}{2}\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}\left(z-\sqrt{q_1}\right)^2}\log_2\left(\frac{2e^{-\frac{1}{2}\left(z-\sqrt{q_1}\right)^2}}{e^{-\frac{z^2}{2}}+e^{-\frac{1}{2}\left(z-\sqrt{q_1}\right)^2}}\right)dz. \quad (1)$$

The dependence of capacity on signal-to-noise ratio is shown in Fig. 1. It is clear that with a large signal-to-noise ratio, the capacity tends to 1.

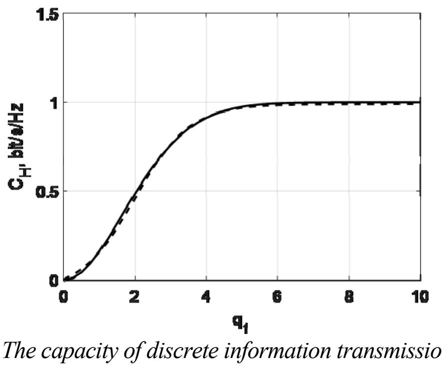

Fig. 1. The capacity of discrete information transmission channel

Let's consider MIMO communication system based on optical radiation, which consists of N_{TX} transmitting and N_{RX} receiving devices. Optical signals are incoherent. Propagation channel is modeled as power transmission coefficients of a signal for each pair of receiver and transmitter. Thus, optical signal transmission matrix $\mathbf{H}=\{h_{nm}, n=1,\ldots,N_{\mathrm{RX}}, m=1,N_{\mathrm{TX}}\}$ is formed and its coefficients satisfy the conditions $h_{nm}>0$, $n=1,\ldots,N_{\mathrm{RX}}$, $m=1,N_{\mathrm{TX}}$.

The signal observed from the outputs of optical sensor system is equal to

$$\mathbf{Y}=\mathbf{HS}(\mathbf{X})+\mathbf{V},$$

where $\mathbf{S}(\mathbf{X})$ is a signal at the outputs of transmitting system, $\mathbf{V}$ is a thermal noise vector of receiving system in the form of Gaussian random variables with correlation matrix $\mathbf{R}_V=\sigma_V^2\mathbf{I}$. DC offset of optical carrier is assumed to be removed in a transimpedance amplifier.

Let's apply spatial encoding and decoding using channel matrix decomposition into singular numbers $\mathbf{H}=\mathbf{U\Sigma Q}^{\mathrm{H}}$ [13–15]:

$$\mathbf{Y}=\mathbf{H\Phi QX}+\mathbf{V},\quad \hat{\mathbf{X}}=\mathbf{U}^{\mathrm{H}}\mathbf{Y},$$

where $\mathbf{U}$, $\mathbf{Q}$ are unitary matrices size of $N_{\mathrm{TX}}\times N_{\mathrm{RX}}$ and $N_{\mathrm{RX}}\times N_{\mathrm{TX}}$ respectively, $\mathbf{\Sigma}=\{\sigma_k, k=1,\ldots,K\}$ is a diagonal matrix of singular numbers, $K\leq\min(N_{\mathrm{TX}},N_{\mathrm{RX}})$ is a rank of matrix $\mathbf{H}$.

In this expression $\mathbf{\Phi}=\{\varphi_k, k=1,\ldots,K\}$ is a diagonal matrix, the elements of which set the signal strength in each eigenmode. Thus, we obtain that the transformation of optical signals in a multipath channel can be represented as K parallel independent channels:

$$\hat{x}_k=\sigma_k\varphi_k x_k+\tilde{v}_k,\quad k=1,\ldots,K,$$

where $\tilde{v}_k$ is Gaussian random variables with the same statistical properties as noise v_k. Therefore, the ratio of signal to noise power in each eigenmode is equal to $q_k=\sigma_k^2\varphi_k^2 q$, where $q=P/\sigma_V^2$ is a ratio of total power of all transmitters to noise power in each receiver.

Entire MIMO system capacity is equal to the sum of each eigenmode capacity C_k:

$$C_H=\sum_{k=1}^{K}C_k \tag{2}$$

each being calculated using formula (1) for discrete channel.

Thus, MIMO system is a communication system with channel matrix $\mathbf{H}$. It can be represented as several virtual transmission channels, formed by eigenmodes with capacity $C_k, k=1,\ldots,K$, each being defined by expression (1). In case of fixed total power of all eigenmodes

$$P=\sum_{k=1}^{K}P_k=P\sum_{k=1}^{K}\varphi_k^2$$

the task is to distribute the power over a separate eigenmode using coefficients $\mathbf{\Phi}=\{\varphi_k, k=1,\ldots,K\}$.

If there is no information about channel matrix on a transmitting side, the best strategy is to distribute the power evenly [18]

$$\mathbf{\Phi}=\left\{1/\sqrt{K},\ k=1,\ldots,K\right\}.$$

If MIMO system with closed-loop transmit diversity is used, then power distribution in a continuous Gaussian channel is performed according to maximum capacity criterion (2) in accordance with the principle of "water filling" [18]:

$$\mathbf{\Phi}=\left\{\varphi_k,\ k=1,\ldots,K\right\}=\left\{\sqrt{\left(\mu-\frac{1}{q\sigma_k^2}\right)^{+}},\ k=1,\ldots,K\right\}, \tag{3}$$

where μ is undetermined Lagrange multiplier,

$$(x)^{+}=\begin{cases}x, & x\geq 0\\ 0, & x<0\end{cases}.$$

For a discrete channel, carrying out optimal power distribution is difficult due to the complexity of analytical expression (1). Therefore, we introduce the approximation of Fig. 1 dependence $C_H(q_1)$ by a hyperbolic tangent function

$$C_H(q_1)\approx 0.53\,\mathrm{th}(0.65q_1-1.3)-0.46.$$

Approximate capacity dependence on signal-to-noise ratio is shown in Fig. 1 with a dotted line.

Auxiliary quality functionality to optimize power distribution between its eigenmodes has the form:

$$F=$$
$$=-\sum_{k=1}^{K}\left[0.53\,\mathrm{th}\left(0.65\sigma_k^2\varphi_k^2 q-1.3\right)-0.46+\lambda_k\varphi_k^2-\mu\varphi_k^2\right],$$

where μ is undetermined Lagrange multiplier, and power distribution in channels φ_k^2 satisfy normalization condition

$$\sum_{k=1}^{K}\varphi_k^2=1. \tag{4}$$

Necessary and sufficient optimum conditions have the form:

$$\frac{dF}{d\varphi_k^2}=-0.53\frac{4\exp(2(0.65\sigma_k^2\varphi_k^2 q-1.3))}{\left(\exp(2(0.65\sigma_k^2\varphi_k^2 q-1.3))+1\right)^2}\times$$
$$\times 0.65\sigma_k^2 q-\lambda_k+\mu=0.$$

Solving this equation with respect to λ_k, we obtain:

$$\lambda_k=\mu-0.53\times 0.65\sigma_k^2 q\times$$
$$\times\frac{4\exp(2(0.65\sigma_k^2\varphi_k^2 q-1.3))}{\left(\exp(2(0.65\sigma_k^2\varphi_k^2 q-1.3))+1\right)^2}.$$

To solve equation $\lambda_k=0$ with respect to φ_k^2, we produce variable replacement:

$$z=\exp(2\left(0.65\sigma_k^2\varphi_k^2 q-1.3\right)) .$$

After substituting and solving the equation with respect to z_k, we get:

$$z_k\left(\mu\right)=\left(0.689\sigma_k^2 q/\mu-1\right)+\sqrt{\left(0.689\sigma_k^2 q/\mu-1\right)^2-1} .$$

As a result of solving this equation, we obtain optimal distribution of power across its eigenmodes:

$$\varphi_k^2=\frac{1}{q\sigma_k^2}\times\left(\frac{\ln z_k\left(\mu\right)+2.6}{1.3}\right)^+ ,\ k=1,...,K . \tag{5}$$

In conclusion, we define parameter μ that must satisfy normalization condition (4)

$$\sum_{k=1}^{K}\frac{1}{q\sigma_k^2}\times\left(\frac{\ln z_k\left(\mu\right)+2.6}{1.3}\right)^+=1 .$$

Capacity depends on channel matrix **H**, which is not known before and can take a variety of values depending on location and orientation of optical emitters, the nature of reflective surfaces and obstacles, and contamination of optical radiation propagation medium. Therefore, objective characteristic of information efficiency of MIMO information transmission system is a capacity value averaged over an ensemble of N channel matrix implementations called ergodic capacity [19]:

$$C_{\mathrm{E}}=\overline{C_H\left(i\right)}\approx\frac{1}{N}\sum_{i=1}^{N}C_H\left(i\right) . \tag{6}$$

3. Light radiation propagation model

Since matrix transmission coefficient of channel **H** is a random variable, the characteristics of efficiency are ergodic capacity C_{E} obtained by averaging over channel matrix **H** implementations. To describe optical signal attenuation in free space, we use the Lambert model given in [7]

$$H=\frac{m+1}{2\pi d^2}\cos^{m-1}\left(\phi\right)A\left(\psi\right) , \tag{7}$$

where m is Lambert mode number of emitted optical signal, d is Euclidean distance between transmitter and receiver, ϕ and ψ are angular directions, $A(\psi)$ is the aperture of photocell receiving part. In this case, attenuation losses of optical signal in the environment are equal to zero, them being determined by surface aperture of receiving photodiode.

Many papers [2–7, 20] present signal propagation modeling method where the aperture of receiving photodiode is taken into account. To describe the transmission coefficient of channel **H** fully, it is necessary to determine the loss of optical signal during propagation in the environment from transmitter to receiver. Let's denote the power of emitted optical signal P_{TX}, including the characteristics of emitter and lens, equal to signal power on receiver photodiode lens P_{RX}. Then, under the condition of modeling a signal transmitter as a point source, the optical signal received will have power [21]

$$P_{\mathrm{RX}}=I_0\frac{A_{\mathrm{TX}}^2 A_{\mathrm{RX}}}{\lambda^2 f^2 d^2} ,$$

where I_0 is source radiation intensity, A_{TX} and A_{RX} are lens apertures on transmitting and receiving sides, λ is optical carrier signal wavelength, f is focal length of lenses, d is the distance between transmitter and receiver lenses.

A transmitter with non-zero aperture generates signal power at photodiode aperture according to the following expression [21]

$$P_{\mathrm{RX}}=\frac{P_{\mathrm{TX}}A_{\mathrm{TX}}A_{\mathrm{RX}}}{\lambda^2 d^2} .$$

Considering optical signal propagation, it is possible to identify various approaches to describing signal paths from transmitter to receiver. We can suppose a transmitter with photodiodes being arranged in a circle and representing emitters of optical signal with sector pattern. Transmitter and receiver are located indoors. Let's consider three scenarios for signal propagation:

- signal transmission from a transmitter to a receiver is only along a line of sight (LOS); reflections and diffraction are neglected, the matrix of channel coefficients of multi-antenna system is equal to $\mathbf{H}_{\mathrm{LOS}}$;
- only diffusive scattering of optical radiation, when power transmission coefficient from each emitter to each optical radiation receiver has independent Rayleigh values $\mathbf{H}_{\mathrm{DIF}}$;
- line-of-sight (LOS) propagation and diffusive propagation of optical radiation, when probability distribution of optical radiation has Rice's law, and the matrix of channel coefficients is equal to

$$\mathbf{H}=\sqrt{\frac{1}{1+K_{\mathrm{R}}}}\mathbf{H}_{\mathrm{DIF}}+\sqrt{\frac{K_{\mathrm{R}}}{1+K_{\mathrm{R}}}}\mathbf{H}_{\mathrm{LOS}} , \tag{8}$$

where K_{R} is Rice factor. This paper does not consider multiple reflection of signal from walls, floor, room ceiling and other objects. The reflections of such signal are supposed to be much weaker than the rest part and their contribution to generated radiation intensity at photodiode can be neglected.

If we take into account only diffraction effects which lead to optical signal attenuation in space, then radiation power incident on photo detector is described by range equation

$$P_{\mathrm{RX}}=0.45\frac{P_{\mathrm{TX}}D_{\mathrm{TX}}D_{\mathrm{RX}}\tau}{\lambda^2 d^2} ,$$

where D_{TX} and D_{RX} are lenses diameters on transmitting and receiving sides, τ is a transmission coefficient of propagation environment, $\tau=e^{-\alpha d}$. Exponent α is determined by two components: absorption coefficient of optical radiation by the environment (Bouguer coefficient) α_B and scattering coefficient α_S: $\alpha = \alpha_B + \alpha_S$. The coefficient of absorption by the environment is equal to α_B. In the atmosphere~~,~~ it is determined by its composition and has different values at different wavelengths of radiation. Minimal absorption is typical for "transparency windows" in the vicinity of wavelengths $0.4 \ldots 0.8, 1.5, 2, 3.5, 10.5$ microns. Scattering coefficient α_S is equal to the sum of Rayleigh scattering coefficients α_{SR}, determining the scattering of optical signal on atmospheric particles with the dimensions smaller than the wavelength of carrier signal and the scattering of Mi α_{SM}, corresponding to scattering by particles of a larger size compared to carrier signal wavelength: $\alpha_S = \alpha_{SR} + \alpha_{SM}$ [16].

Let the system of optical emitters and the system of receivers be located in a square-shaped room with side size S. The coordinates of their location center are given as independent uniformly distributed random values

$$w(x_{TX}) = w(x_{RX}) = w(y_{TX}) = w(y_{RX}) = 1/S . \quad (9)$$

The delays of optical signal are considered insignificant compared to the duration of optical pulses.

The angular orientation of emitter system and receiver system relative to the center of their location is also random with a uniform distribution law:

$$w(\gamma_{TX}) = w(\gamma_{RX}) = 1/2\pi . \quad (10)$$

Let radiation and reception diagrams be uniform within the angular sector of size $\Delta\gamma_{TX} = 2\pi / N_{TX}$, $\Delta\gamma_{RX} = 2\pi / N_{RX}$. Power attenuation during propagation in the environment is directly proportional to distance square. The reflections from various surfaces, as well as scattering by atmospheric particles, are modeled by independent Rayleigh values in a matrix of coefficients $\mathbf{H}_{DIF}$.

4. Optical channel capacity evaluation

We will analyze optical MIMO channel capacity by statistical modeling. Communication system is supposed to use multilevel modulation of optical radiation intensity with constant carrier offset. Channel matrix **H** is described in chapter 3 by formula (8). Fig. 2 shows dependences of capacity (6) and (8) of a discrete optical channel with independent Rayleigh fades, $K_R = 0$, $\mathbf{H} = \mathbf{H}_{DIF}$ on signal-to-noise ratio at different values of the number of optical transmitters and the number of receivers, $N_{TX} = N_{RX}$. The lower family of graphs is calculated at $q = 2$ dB and the higher family of graphs is calculated at $q = 10$ dB.

The dots indicate graphs for optimal power distribution between eigenmodes in accordance with expression (5) for a discrete channel. A dotted line indicates graphs with uniform power distribution between eigenmodes, and a solid line indicates graphs with optimal power distribution for continuous Gaussian channel in accordance with expression (3). It can be noted that optimal power distribution for a continuous channel generally gives good results for a discrete channel. Moreover, optimization of power distribution increases capacity by 15...30 % depending on signal-to-noise ratio.

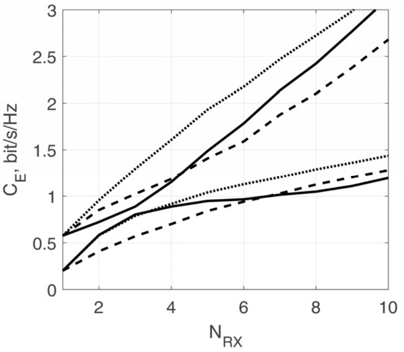

Fig. 2. Discrete channel capacity for Rayleigh model

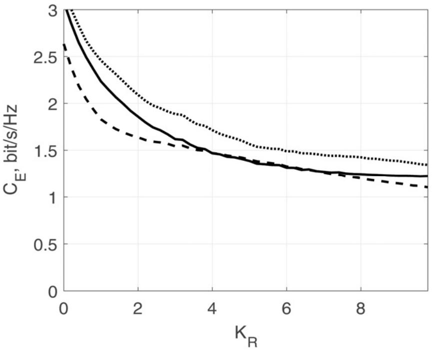

Fig. 3. Discrete channel capacity for Rice model

With the Rayleigh channel model, location and orientation of receiving photo diodes and transmitting LEDs do not affect capacity.

Fig. 3 shows dependences of capacity (1) and (6) of a discrete optical channel on signal-to-noise ratio at $N_{TX} = N_{RX} = 10$, $q = 10$ dB and various values of Rice factor. Rice factor increase is shown to lead to capacity decrease, but our method of optimal power distribution allows to increase capacity in any case comparing with other methods.

Let's consider matrix **H** of transformation coefficients from each optical transmitter to each optical receiver at given values of their coordinates and rotation angles of transmitter system $x_{TX}, x_{rX}, y_{TX}, y_{RX}, \gamma_{TX}, \gamma_{RX}$ in accordance with expressions (9) and (10). Figure 4 shows the capacity of communication channel (6) for different values of Rice factor $K_R = 0; 2; 5$, $N_{TX} = N_{RX} = 4$, angular sector of size $\Delta\gamma_{TX} = \Delta\gamma_{TX} = \pi/2$.

It has been established that the location of optical signal transmitters and receivers in space significantly affects rank conditionality of channel matrix and, consequently, optical MIMO communication system capacity.

The influence of the characteristics of optical signal propagation environment on MIMO communication system capacity is studied. The increase in capacity reaches 25 % in case of $K_R = 0$, which is equivalent to a gain in signal-to-noise ratio of 3 dB, as shown in Fig. 4.

Conclusion

In this paper we use obtained formulas for calculating the capacity of discrete-continuous communication channel of optical MIMO communication system. These formulas allow us to justify the number of transmitters and receivers of optical signals. It has been established that optimization of power distribution over MIMO system eigenmodes allows increasing capacity comparing with other optimization methods.

The results obtained are planned to be used for efficiency evaluation of communication channel models of various types.

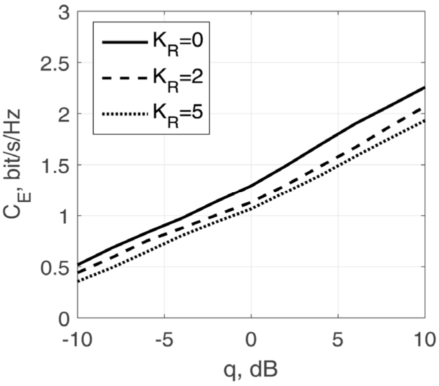

Fig. 4. MIMO optical communication channel capacity at various Rice factors

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