Non-reciprocity compensation correction and antenna selection for optical large MIMO system*

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This paper exploits an optical large multiple input multiple output (MIMO) system. We first establish the non-reciprocity compensation correction factor to solve the channel non-reciprocity problem. Then we propose an antenna selection algorithm with the goal of realizing maximum energy efficiency (*EE*) when satisfying the outage *EE*. The simulation results prove that this non-reciprocity compensation correction factor can compensate beam energy attenuation gap and spatial correlation gap between uplink and downlink effectively, and this antenna selection algorithm can economize the number of transmit antennas and achieve high *EE* performance. Finally, we apply direct current-biased optical orthogonal frequency division multiplexing (DCO-OFDM) modulation in our system and prove that it can improve the bit error rate (*BER*) compared with on-off keying (OOK) modulation, so the DCO-OFDM modulation can resist atmospheric turbulence effectively.

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Atmospheric turbulence is an important harmful influencing factor in free space optical (FSO) communication[1]. Massive multiple input multiple output (MIMO) can effectively resist the atmospheric turbulence and has much more benefits than conventional MIMO[2,3]. Therefore, it is an attractive scene to combine FSO link with massive MIMO. In this paper, we exploit two key issues in an optical large MIMO system, which are the non-reciprocity compensation correction and the antenna selection.

Most massive MIMO systems use time-division duplex (TDD) operation[4]. TDD operation relies on channel reciprocity, but actually the channel is not completely reciprocal between uplink and downlink. The calibration error of hardware chains[2] and the correlation difference between the base station (BS) and terminal transceivers may make the channel non-reciprocal. This phenomenon will be more serious in FSO links.

In massive MIMO system, the signal processing and hardware cost become a heavy burden. Transmit antenna selection technique is a simple and effective solution which can reduce the hardware cost and meanwhile retain most of the diversity or multiplexing benefit of all antennas[5,6].

In this paper, the proposed optical large MIMO system can operate in TDD mode, so that the downlink channel state information (CSI) can be estimated through that of uplink. However, the acquired uplink CSI is imperfect to be applied to downlink precoding and antenna selection. Therefore, we design the non-reciprocity compensation correction factor to achieve the optimal CSI. Then, we propose the antenna selection algorithm which can improve the maximum energy efficiency (*EE*). Finally, we apply the direct current-biased optical orthogonal frequency division multiplexing (DCO-OFDM) modulation in this system, and prove that it can resist atmospheric turbulence.

We consider a multiuser downlink optical large MIMO system with one BS and K active terminals. The BS is equipped with N_t transmit antennas satisfying N_t>10K, while each terminal performs as a receiver with a single antenna. The distance between adjacent transmit antennas is less than the coherence distance d_0, while the distance between terminals is much larger than d_0. The schematic diagram of the system is shown in Fig.1.

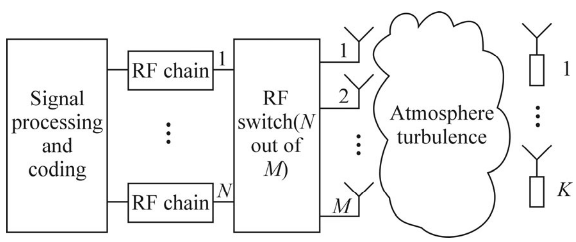

Fig.1 Schematic diagram of the proposed system

The received signal vector at terminals can be represented as[6]

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$$y=\sqrt{P_{\mathrm{tx}}}\boldsymbol{H}\zeta\boldsymbol{F}\boldsymbol{x}+\boldsymbol{n},\qquad(1)$$

where $\boldsymbol{y}$ is the $K\times1$ received vector for each terminal, P_{tx} is the total transmitting (TX) power of forward link, $\boldsymbol{H}$ is a $K\times N_{\mathrm{t}}$ fading channel matrix between N_{t} BS antennas and K terminals, and ζ is the TX power normalization factor which is approximated as $\zeta\approx\sqrt{N_{\mathrm{t}}/K}$. $\boldsymbol{F}$ is the $N_{\mathrm{t}}\times K$ precoding matrix, and in this paper, we use zero-forcing (ZF) precoding, i.e., $\boldsymbol{F}=\boldsymbol{H}^{\mathrm{H}}(\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}})^{-1}$. $\boldsymbol{x}$ is the $K\times1$ transmitting signal vector, and $\boldsymbol{n}$ is additive white Gaussian noise with variance of σ_n^2.

The fading channel matrix $\boldsymbol{H}$ arises due to two factors: geometric spread and pointing errors h_{p} and atmospheric turbulence h_{a}. In this paper, we only consider weak turbulence, so we make h_{a} follow lognormal distribution. The fading channel coefficient from the mth transmit aperture to the nth receiver is given by

$$h_{mn}=h_{\mathrm{p}}h_{\mathrm{a}}=\frac{E_{I_L,(\omega_L,R_0)}}{E_{I_0,\omega_0}}h_{\mathrm{a0}}\exp(2X_{mn}),\qquad(2)$$

where I_0 and ω_0 are the beam intensity and beam waist width at the transmit apertures, and I_L and ω_L are the beam intensity and beam waist width when the transmission distance is L km. R_0 is the size of receive aperture. $E_{I,\omega}$ stands for the beam energy. X_{mn} is identically (independent for downlink while not for uplink) distributed normal random variable with mean of μ_x and variance of σ_x, so h_{a} follows a lognormal distribution as

$$f(h_{\mathrm{a}})=\frac{1}{2h_{\mathrm{a}}}\frac{1}{\sqrt{2\pi\sigma_x^2}}\exp\left\{-\frac{\left[\ln(h_{\mathrm{a}}/h_{\mathrm{a0}})-2\mu_x\right]^2}{8\sigma_x^2}\right\}.\qquad(3)$$

To ensure that h_{a} does not attenuate or amplify the average power, we normalize the fading coefficient as $E\{[h_{\mathrm{a}}/h_{\mathrm{a0}}]\}=1$, which requires the condition of $\mu_x=-\sigma_x^2$[7]. The variances of log-amplitude fluctuation of plane and spherical waves along a slant path are expressed as

$$\sigma_x^2\big|_{\mathrm{plane}}=0.563\left(\frac{2\pi}{\lambda}\right)^{7/6}\times$$

$$(\sec\phi)^{11/6}\int_0^L C_n^2(h)(L-h)^{5/6}\mathrm{d}h,\qquad(4)$$

$$\sigma_x^2\big|_{\mathrm{spherical}}=0.563\left(\frac{2\pi}{\lambda}\right)^{7/6}(\sec\phi)^{11/6}\times$$

$$\int_0^L C_n^2(h)\left[\frac{h(L-h)}{L}\right]^{5/6}\mathrm{d}h,\qquad(5)$$

where λ is the wavelength, ϕ is the zenith angle, and L is the link distance in meters[8]. $C_n^2(h)$ is the refractive index structure coefficient varying with the height h, and in slant atmospheric turbulence it usually uses Hufnagle-Valley (HV) model as[9]

$$C_n^2(h)=0.005\,94(v/27)^2(10^{-5}h)^{10}\exp(h/1\,000)+$$

$$2.7\times10^{-6}\exp(-h/1\,500)+C_n^2(0)\exp(-h/100),\qquad(6)$$

where v is the wind speed, and $C_n^2(0)$ is the refractive index structure coefficient on the ground. We use HV-21 model in calculation, where v=21 m/s and $C_n^2(0)=1.7\times10^{-14}\ \mathrm{m}^{-2/3}$.

Based on $\hat{\boldsymbol{H}}$ which is estimated through uplink pilots, we give the corrected $\boldsymbol{H}$ as[10]

$$\boldsymbol{H}=c\hat{\boldsymbol{H}}^{\mathrm{T}}+\sqrt{1-c^2}\boldsymbol{E},\qquad(7)$$

where c is the non-reciprocity compensation correction factor which is established as

$$c=r_E\boldsymbol{R}^{-1}.\qquad(8)$$

$\boldsymbol{E}$ is the error matrix following identically independent distributed Gaussian variables with mean of zero and variance of $1-c^2$.

Our key work is to establish the non-reciprocity compensation correction factor c. In the process of establishing c, we consider two influence factors, one is beam energy attenuation gap, and the other is spatial correlation gap. The first factor r_E which is the received beam energy ratio of uplink to downlink is given as

$$r_E=E_{\mathrm{d}}/E_{\mathrm{u}}=\begin{cases}\int_{-R_0}^{R_0}I_{\mathrm{d}}\times\pi\rho^2\,\mathrm{d}\rho\Big/\int_{-R_0}^{R_0}I_{\mathrm{u}}\times\pi\rho^2\,\mathrm{d}\rho, & \text{if } R_0<\omega_{\mathrm{d}}\\ \int_{-\omega_{\mathrm{d}}}^{\omega_{\mathrm{d}}}I_{\mathrm{d}}\times\pi\rho^2\,\mathrm{d}\rho\Big/\int_{-R_0}^{R_0}I_{\mathrm{u}}\times\pi\rho^2\,\mathrm{d}\rho, & \text{if } R_0>\omega_{\mathrm{d}} \text{ and } R_0<\omega_{\mathrm{u}}\\ \int_{-\omega_{\mathrm{d}}}^{\omega_{\mathrm{d}}}I_{\mathrm{d}}\times\pi\rho^2\,\mathrm{d}\rho\Big/\int_{-\omega_{\mathrm{u}}}^{\omega_{\mathrm{u}}}I_{\mathrm{u}}\times\pi\rho^2\,\mathrm{d}\rho, & \text{if } R_0>\omega_{\mathrm{u}}\end{cases},\qquad(9)$$

where I_{u}, I_{d}, ω_{u} and ω_{d} represent the beam intensity and beam waist width of uplink and downlink, respectively. The beam intensity and the beam waist width can be expressed as[9]

$$I(\boldsymbol{\rho},L)=\frac{k^2(D^2\rho^2+C)}{4L^2AC^3}\exp\left[-\left(\frac{D^2}{C}-D\right)\rho^2\right]-$$

$$\frac{k^2\pi^2\omega_0^2(G^2\rho^2+F)}{32L^2F^3}\exp\left(\frac{G^2\rho^2}{F}\right),\qquad(10)$$

$$\omega(L)=\left[\omega_0^2+\left(\frac{4}{k^2\omega_0^2}+\frac{2}{k^2\sigma_0^2}\right)L^2+\frac{2L^2B_3}{k^2}\right]^{1/2},\qquad(11)$$

where the relative parameters are

$$C=\frac{2}{\omega_0^2}+\frac{k^2}{4AL^2},\qquad(12)$$

$$F=A+\frac{k^2\omega_0^2}{8L^2},\qquad(13)$$

$$D=\frac{k^2}{4AL^2}, \tag{14}$$

$$G=\frac{\mathrm{i}k}{2L}, \tag{15}$$

$$L=\left(h_1-h_0\right)\sec\left(\phi\right), \tag{16}$$

$$A=\frac{1}{2\omega_0^2}+\frac{1}{2\sigma_0^2}+\frac{B_3}{2}, \tag{17}$$

$$B_3=3.279\ 6k^2 l_0^{-1/3}\sec\left(\phi\right)\times\int_{h_0}^{h_1}C_n^2\left(h\right)\eta^2\mathrm{d}h, \tag{18}$$

where h_1 and h_0 are the heights of BS and terminal, ϕ is zenith angle, l_0 is turbulence inner scale, λ is wavelength, σ_0 is spatial correlation length, ω_0 is beam waist width, and k=2π/λ. The key factor which causes the difference between I_u and I_d or between ω_u and ω_d is η. In uplink transmission, $\eta=1-(h-h_0)/(h_1-h_0)$, while in downlink transmission, $\eta=(h-h_0)/(h_1-h_0)$.

The second factor $\boldsymbol{R}$ is the receive correlation matrix of uplink. In our research, the spatial correlation is simply caused by the distance between adjacent antennas. Therefore, we need to multiply $\hat{\boldsymbol{H}}$ by $\boldsymbol{R}^{-1}$ to get rid of correlation for downlink $\boldsymbol{H}$. The element of $\boldsymbol{R}$ is established as

$$b\left(d_{xy}\right)=\begin{cases}1, & \text{if } d_{xy}<d_0/g\\ \frac{1}{s}\frac{g}{g-1}\left(1-\frac{d_{xy}}{d_0}\right), & \text{if } d_0/g\le d_{xy}<d_0\\ 0, & \text{if } d_{xy}\ge d_0\end{cases}, \tag{19}$$

where d_{xy} is the distance between x and y antennas, s is the turbulence factor, and g is the scale factor.

We first derive the threshold number of transmit antennas N_t^{thr} for obtaining the maximum EE when satisfying outage EE. We use the power consumption model defined in Ref.[6] as

$$P_{sum}=P_{PA}+P_{BB}+N_t P_{RFfront}, \tag{20}$$

where P_{PA} is the power amplifier (PA) power consumption, P_{BB} is the baseband power consumption, and $P_{RFfront}$ is the radio frequency (RF) front-end power consumption which includes mixer, filter, and digital-to-analog converter (DAC) power consumption. The simple relation between P_{tx} and P_{PA} can be represented as

$$P_{tx}=\kappa P_{PA}, \tag{21}$$

where κ=22% is the PA efficiency. The relationship between P_{BB} and χ(Gflops) can be represented as

$$P_{BB}=\frac{\chi\left(\text{Gflops}\right)}{\vartheta\left(\text{Gflops/W}\right)}, \tag{22}$$

where ϑ is the very large scale integration (VLSI) processing efficiency. We use large scale MIMO baseband computation model, χ(Gflops), which is presented as

$$\chi=N_t B\left[\left(\frac{T_u}{T_s}\right)\log_2\left(T_u B\right)+\left(\frac{T_u}{T_s}\right)\left(1-\frac{T_p}{T_{sl}}\right)K+\left(\frac{T_u}{T_s}\right)\left(\frac{T_p}{T_{sl}}\right)\log_2\left(\frac{T_u T_p}{T_s T_d}\right)+\left(\frac{T_d}{T_{sl}}\right)K^2\right]. \tag{23}$$

The description of each parameter is shown in Tab.1[6].

Tab.1 Baseband power consumption parameters

Parameter	Description	Power consumption
B	Bandwidth	10 MHz
T_{sl}	Slot length	0.5 ms
T_p	Pilot length in one slot	0.214 ms
T_s	Symbol duration	71.4 μs
T_g	Guard interval (GI)	4.7 μs
T_u	Symbol without GI	66.7 μs
T_d	Delay spread	4.7 μs

We simulate 10 MHz DCO-OFDM system with 600 subcarriers, so we also reference the values of relative parameters in long term evolution (LTE) system[6] as shown in Tab.1. P_{tx}=40 W, $P_{RFfront}$=97.5 mW, and ϑ=50 Gflops/W.

As our system uses ZF precoding, EE can be represented as

$$EE=C/P_{sum}\approx\alpha BK\left[\log_2\left(1+\frac{P_{tx}N_t}{N_0 BK}\right)\right]\Big/P_{sum}. \tag{24}$$

Different from achieving maximum EE, the main idea of our algorithm is only to satisfy the quality of service (QoS) requirement under the given outage probability. We reference the LTE QoS requirement index in 3GPP TS23.203[11] which shows us the packet error rate (PER) index of standardized QoS class identifiers (QCIs). But we need the bit error rate (BER) index rather than the PER index. So we have to derive BER index through the relationship between BER and PER[12]. We consider the traffic, such as conversational video (live streaming) and real time gaming. The PER threshold of this kind traffic is 10^{-3}, and we can derive their BER threshold is about 10^{-6}. With the signal-to-noise ratio (SNR) threshold of SNR_{thr}=12 dB, which is mentioned below, and the outage probability of p_{out}=5%, we can calculate the threshold number of transmit antennas N_t^{thr}, as shown in Fig.2. It can achieve the maximum EE when the users' SNR is larger than SNR_{thr} with the probability of $1-p_{out}$. The optimal number of transmit antennas N_t^{opt} obtained in Ref.[6] is also shown in Fig.2 for comparison. Then we compare the relative EE performance with the selected number of transmit antennas of N_t^{thr} and N_t^{opt} as shown in Fig.3. We define the outage EE as

$$EE_{out}=C_{thr}/P_{sum}\approx\alpha BK\left[\log_2\left(1+SNR_{thr}\right)\right]/P_{sum}. \tag{25}$$

Figs.2 and 3 show that our selected number of transmit antennas N_t^{thr} is much smaller than N_t^{opt}, and our antenna selection can achieve higher *EE* performance. The *EE* improvement is because P_{tx} and N_t are decreased at the same time in our antenna selection algorithm, it also makes P_{sum} decreased, and the decrease magnitude of P_{sum} is larger than that of system capacity *C*.

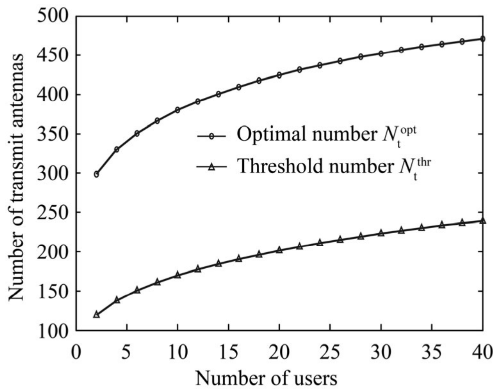

Fig.2 The selected number of antennas of N_t^{thr} and N_t^{opt} versus the number of users *K*

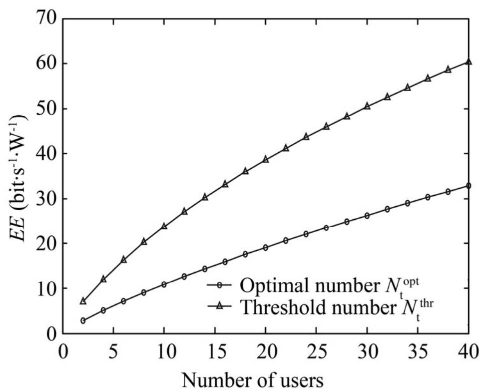

Fig.3 Relative *EE* performances with the selected numbers of transmit antennas of N_t^{thr} and N_t^{opt}

With the significant decrease of selected number of transmit antennas, the random antenna selection algorithm becomes imperfect because the complexity of optimal selection algorithm is decreased to a large extent. In addition, the optical channel fading and varying are more serious than those in RF environment. So the maximum norm method and the antenna cyclic reduction method can be combined together as the preferable antenna selection algorithm.

Then we firstly prove that our non-reciprocity compensation correction can compensate beam energy attenuation gap and spatial correlation gap between uplink and downlink effectively. The values of calculation parameters are h_1=2 km, h_0=0, ϕ =60°, l_0=0.01 m, λ=1.55 μm, σ_0=2.5 cm, ω_0=3 cm, R_0=10 cm, d_0=6 cm, g=6 and s=3. Our system is a 200×4 (N_t×K) optical large MIMO system using on-off keying (OOK) modulation. Considering linear minimum mean-square error (MMSE) based channel estimation is commonly used in massive MIMO and can provide near-optimal performance with low complexity[4,13], we use linear MMSE and least squares (LS) estimation in our system. Fig.4 shows the mean-square error (*MSE*) performances of uncorrected and corrected fading channel matrices with MMSE and LS estimation. Fig.5 shows the downlink *BER* performances with and without our non-reciprocity compensation correction.

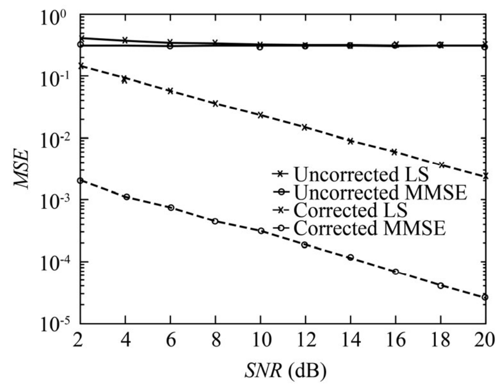

Fig.4 *MSE* performances of uncorrected $\hat{H}$ and corrected *H* with LS and MMSE channel estimation, respectively

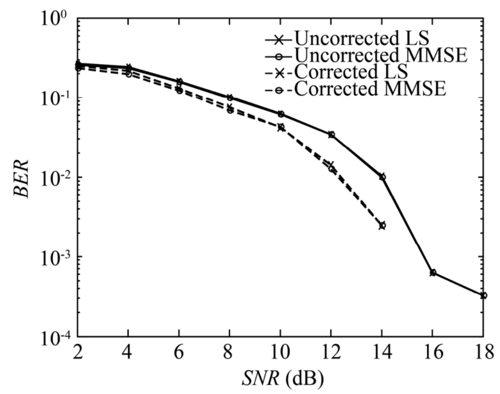

Fig.5 Downlink *BER* performances with and without our non-reciprocity compensation correction, respectively

We can see from Fig.4 that the *MSE* of uncorrected $\hat{\boldsymbol{H}}$ is much higher than that of corrected $\boldsymbol{H}$, which means that there is non-reciprocity between uplink and downlink. On the other hand, the *MSE* of uncorrected $\hat{\boldsymbol{H}}$ does not change with the increase of *SNR*, and the key reason may be the correlation difference between uplink and downlink. In our system, there hardly exists any correlation in the downlink. From Fig.5, we can see after using our non-reciprocity compensation correction, *BER* performance of the system is obviously improved.

Finally, we compare the performances of OOK modulation and DCO-OFDM modulation in our large optical MIMO system. The DCO-OFDM simulation result can give reference to the improvement of antenna selection algorithm and provide guidance to our antenna selection. The DCO-OFDM modulation process is referenced from Ref.[14], and its block diagram is shown in Fig.6. The downlink *BER* performances under OOK modulation and DCO-OFDM modulation using the proposed non-reciprocity compensation correction are shown in Fig.7. We can find from Fig.7 that DCO-OFDM modulation can improve the *BER* compared with OOK modulation, so we draw a conclusion that DCO-OFDM can resist the atmospheric turbulence effectively. Moreover, we can achieve the *SNR* threshold of about 12 dB from Fig.7, which is used above for improving the antenna selection algorithm.

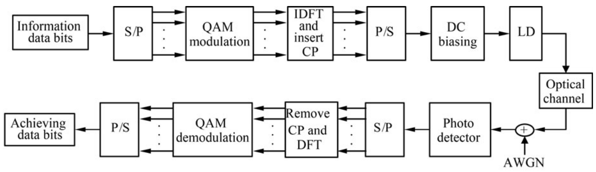

Fig.6 Block diagram of DCO-OFDM modulation

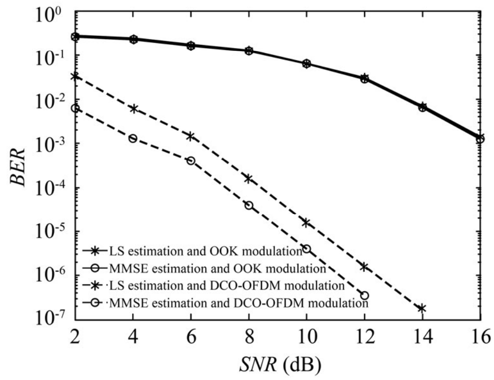

Fig.7 Downlink *BER* performances under OOK modulation and DCO-OFDM modulation when using our non-reciprocity compensation correction

In this paper, an optical large MIMO system with imperfect CSI is proposed, and for its channel non-reciprocity problem, we establish the non-reciprocity compensation correction. Simulation results prove that it can compensate the beam energy attenuation gap and the spatial correlation gap between uplink and downlink effectively. We also propose an antenna selection algorithm with the goal of obtaining the maximum *EE* when satisfying outage *EE*, which can not only economize the number of transmit antennas, but also achieve high *EE* performance. Finally, we compare the OOK modulation and DCO-OFDM modulation performance in our system, and find that the DCO-OFDM modulation can resist the atmospheric turbulence effectively.

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