Photonic Pre-Coding for MIMO System in Satellite-Terrestrial Communication

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Abstract In this paper, a photonic based pre-coding for multiple input multiple output (MIMO) satellite communication is realized without digital signal processing (DSP) structure. It should be noted that when the microwave signal transmits through the wireless channel, the distortion is inevitable. Usually, the zero force (ZF) algorithm is considered to mitigate the distortion that introduced by the atmosphere and it is always realized through DSP. Here, we present an all-optical pre-coding structure that may perform the same function of DSP to realize ZF algorithm. The simulation result shows that, the eye diagram shows a clear “eye” and the bit error rate (BER) is about 2.13503E-7, the system capacity is about 0.4276 after using the proposed photonic pre-coding structure. In addition, the influence of the non-ideal parameters on the photonic pre-coding structure is also investigated. The performance of the system is sensitive to the variation of the desired parameters.

Index Terms Microwave photonics, satellite communications, pre-coding, MIMO.

I. INTRODUCTION

Satellite communication plays an important role in fulfilling next generation 5G communication systems [1]. Multiple input multiple output (MIMO) technology, as the key technology of 5G, its exploitation in satellite is a significant technical breakthrough in modern satellite communications due to the advantages of high data rates with low cost of extra spectrum and transmission power [2], [3].

In order to support the next generation high speed satellite mobile communication system, the satellite MIMO system working in the higher frequency bands are significantly needed. However, it is difficult to achieve broad operation bandwidth using electrical payload. In recent years, microwave photonics satellite payload was proposed [4]–[7]. It generates, transmits, and processes microwave signals in optical domain to overcome the bottleneck problems in electrical techniques. The key techniques in microwave photonics satellite payload have also been achieved [8]–[11].

However, it should be noted that most of the previous works only concentrated on how to generate a microwave signal with amplitude or phase been processed, seldom considered whether the algorithm can be realized through photonic method rather than a digital signal processing (DSP) structure. Practically, in order to guarantee the signal transmission quality and efficiency after the satellite to terrestrial channel, a high speed processing algorithm to offset the distortion is very important. It is easier to be achieved by using photonic structure than using electrical method. Although some researchers have verified the feasibility of photonic algorithm for MIMO system [12] recently, it only considered the terrestrial condition, not the satellite to terrestrial background. In MIMO satellite communication system, interference mitigation using pre-coding in the transmit terminal was usually employed to overcome the influence of satellite to terrestrial forward link. There are some pre-coding method have been proposed before [13]. Among these algorithms, zero force (ZF) pre-coding algorithm is widely considered for its direct and easy pre-distortion ability to the signal before launched.
In this paper, we design a photonic structure to perform a single ZF pre-coding. The main devices are some polarizers, optical time delays, optical attenuators and polarization beam combiners/splitters. Two signals in two transmitters are photonic pre-distorted in two polarization directions respectively, which guarantees the excellent isolation. The simulation results show, when the MIMO transmitter equips the optical pre-coding structure, the signal is pre-distorted and the eye diagram emerges a closed “eye” in the transmitting side. After goes through the atmosphere and reach the terrestrial receiver, due to the obvious correcting function of the wireless channel, the eye diagram shows a clear “eye” in the receiving side. Comparing with the previous works, the proposed photonic pre-coding structure can process signals in higher frequency band since it realizes an algorithm through photonic approach instead of electrical method.

II. PRINCIPLE

A. MIMO COMMUNICATION SYSTEM

There are two kinds of MIMO technologies in wireless communications systems, spatial multiplexing and diversity. First of all, although the scatterers in satellite to terrestrial channels are much less than that in terrestrial wireless channels, there are still some possible diversity sources that can be employed in satellite communications and forming the MIMO channel matrix [14]–[17].

In contrast to the traditional communication systems, MIMO communication system integrates \( m_T \) antennas in the transmitter and \( m_R \) antennas in the receiver. It can be regarded as \( m \) couples of transmitters and receivers are parallelly settled and working simultaneously. Here, we only consider a \( 2 \times 2 \) MIMO system. Assuming that the transmit signal vector is \( X=\begin{bmatrix} x_1 \ x_2 \end{bmatrix}^T \), and the receive signal vector is \( Y=\begin{bmatrix} y_1 \ y_2 \end{bmatrix}^T \). In order to well describe the channel properties in MIMO communication system, the channel configuration is necessary. In practice, the channel configuration of MIMO system can be expressed as a matrix form, which is called transmission matrix. If the channel is frequency-flat fading and time-invariant, the relationship between them can be achieved through transmission matrix \( H=\begin{bmatrix} h_{mn} \end{bmatrix} \) and it can be written as \( Y=HX+N \). Here, \( N=\begin{bmatrix} n_{mn} \end{bmatrix} \) is the noise matrix, and the mean is 0, the variance is \( \sigma_h^2 \). \( h_{mn} \) determines the transmission function between \( T_m \) and \( R_n \). In this paper, \( h_{mn} \) is regarded as a composite that include path loss coefficient \( h_p \) and randomly fading coefficient \( h_r \) [18].

Many wireless transmission technologies and researching results can be adopted in MIMO satellite system [2], such as the channel configuration. In clear air, microwave signals with the frequency above 10 GHz may suffer from amplitude and phase fluctuation during transmitting in atmosphere [19]. Usually, \( \chi=\text{ln}(A/A_0) \) is adopted to describe amplitude fading in clear environment. Here \( A \) and \( A_0 \) are the mean of received signal amplitude in \( V/m \) or \( V \), respectively. It should be noted that the amplitude fluctuation \( \chi \) and phase fluctuation \( \phi \) after transmission are all follow Gaussian distribution [19]–[20].

\[
\begin{align*}
\sigma^2_\chi &= 0.307C_n^2(\frac{2\pi}{\lambda})^7L_0^{11/6} - 0.742C_n^2(\frac{2\pi}{\lambda})^7L_0^{17/6}L_0^{-2}
\sigma^2_\phi &= 0.782C_n^2(\frac{2\pi}{\lambda})^2LL_0^{5/3} - 0.307C_n^2(\frac{2\pi}{\lambda})^7L_0^{11/6}
\end{align*}
\]

Here, \( C_n^2 \) is the structure constant with the unit of \( m^{-2/3} \), which relates to the intensity of the refractive-index fluctuations [21]. \( \lambda \) is the wavelength in \( m \). \( L_0 \) and \( L \) are the average outer scale of turbulence and the equivalent path length through turbulence area, they are all in \( m \). It should be noted that for the satellite-terrestrial link, \( L \) can be rewritten as turbulence mean height \( H_T \) in \( m \) (It is assumed to be 1000 m in the ITU-R model and 2000 m in Karasawa, Yamada, and Allnutt’s model [22]) and link elevation angle \( \theta \) in rad [23]:

\[
L = \frac{2H_T}{\sqrt{\sin^2 \theta + 2H_T/8500000 + \sin \theta}}
\]

With the mathematical notations described before, we are going to analyze the satellite MIMO transmission result. Based on the researching results in Ref. [24], the clear environment fading is considered and it can be expressed as

\[
h_{r,\text{clear}mn} = \exp(\chi_{mn})\exp(-j\phi_{mn})
\]

It should be noted that \( h_{r,\text{clear}mn} \) represents the channel fading coefficient between the \( m \)-th transmitting antenna and \( n \)-th receiving antenna in clear environment. As we known, the original signal will be distorted after transmits through the satellite to terrestrial channel. A pre-coding method can be used to pre-distort the original signal to overcome or mitigate the distortion caused by satellite to terrestrial channel. In practical, the zero force (ZF) algorithm is employed to correct the distorted signal. It can be easily realized through designing an inverse transmission matrix \( H^{-1} \) in the transmit side. Before launched to the channel, the MIMO signal is pre-distorted to be \( H^{-1}X \), which will satisfies the principle of \( Y=H(H^{-1}X) \) in the receiver. As shown in Eq. (6), the channel configuration can be expressed through an imaginary form [24], which gives us a new idea to realize the pre-coding...
algorithm through optical processing. Based on elementary row transformation principle, the inverse transmission matrix can be simplified as

$$H_{r, clear}^{-1} = \frac{1}{|H|} \begin{bmatrix} \exp(\chi_{22}) - \exp(\chi_{12}) \exp[-j(\phi_{12} - \phi_{22})] \\ -\exp(\chi_{21}) \exp[-j(\phi_{11} - \phi_{21})] \end{bmatrix}$$

(7)

It shows that all the elements in Eq. (7) can be realized through controlling the amplitude and phase information of optical signal.

**B. PHOTONIC PRE-CODING ALGORITHM FOR MIMO SATELLITE IN CLEAR ENVIRONMENT**

According to the analysis before, a MIMO signal generation structure can be designed and shown in Fig. 1. A laser diode (LD) emits a lightwave with the angular frequency of $\omega_c$ and the amplitude of $E_c$. To simplify the mathematical analysis, it is expressed as $E_c(t) = E_c e^{j\omega_c t}$. The lightwave is led to a dual-polarization binary phase shift keying modulator (DP-BPSKM) and modulated by a microwave source (MS), which can be expressed as $V_{RF}(t) = V_{RF}\sin(\omega_{RF} t + \sigma)$. The DP-BPSKM is an integrated modulator that possesses two dual driven Mach-Zehnder modulators (DMZMx and DMZMy), a 90 degree polarization rotator and a polarization beam combiner (PBC). There are four microwave ports (Upx, Lpx, Upy and Lpy) and two DC bias points (DCx and DCy) in it. The RF signal from the MS is first equally split into two paths ($x$-path and $y$-path) and they are followed by two electrical phase shifters (EPS1 and EPS2) respectively. In order to perform single sideband (SSB) modulation, an electrical 90 degree hybrid coupler is employed to split the microwave signal from $x$-path into two branches (non-shifted branch and shifted branch) with the phase difference of 90 degree. The non-shifted one is used to drive the Upx and the shifted one is input to Lpx. Under the small signal approximation condition, the output signal from the DMZMx can be expressed as

$$E_{DX}(t) = E_c(t) \left[ \exp \left( \frac{j \pi V_{RF}}{4V_\pi} \cos(\omega_{RF} t + \sigma_1) \right) + \exp \left( \frac{j \pi V_{RF}}{4V_\pi} \sin(\omega_{RF} t + \sigma_1) \right) \times \exp \left( \frac{j \pi V_{DCx}}{V_\pi} \right) \right]$$

$$\approx E_c(t) \left[ \sqrt{2} J_0(m_{RF}) + 2J_1(m_{RF}) e^{i(\omega_{RF} t + \sigma_1)} \right]$$

(8)

Eq. (8) shows [30] after Jacobi-anger expansion.

where $m_{RF} = \pi V_{RF}/4V_\pi$ and $V_\pi$ represent the modulation index and the half-wave voltage of DMZMx, respectively. $V_{DCx} = V_{\pi/2}$ is the DC bias voltage. $\sigma_1$ is the phase shift that introduced by EPS1. $J_n(\cdot)$ is the first kind of Bessel function. Different from the DMZMx, the driven signal of DMZMy is separated by a power splitter, and the separated signals are input to Upy and Lpy respectively. If the DCy voltage is set to $V_{DCy} = V_{\pi/2}$, under the small signal approximation condition, the output signal of DMZMy can be written as [30]

$$E_{DY}(t) = E_c(t) \left[ \exp \left( \frac{j \pi V_{RF}}{4V_\pi} \sin(\omega_{RF} t + \sigma_2) \right) + \exp \left( \frac{j \pi V_{RF}}{4V_\pi} \sin(\omega_{RF} t + \sigma_2) \right) \times \exp \left( \frac{j \pi V_{DCy}}{V_\pi} \right) \right]$$

$$\approx \sqrt{2} E_c(t) \left[ J_{-1}(m_{RF}) e^{-i(\omega_{RF} t + \sigma_2)} + J_0(m_{RF}) + J_1(m_{RF}) e^{i(\omega_{RF} t + \sigma_2)} \right]$$

(9)

Here, $\sigma_2$ is the phase shift that introduced by EPS2. Because of the 90 degree polarization rotator, the polarization states of the two modulated signals are orthogonal. They are then combined by the PBC in the integrated modulator and the output signal can be expressed as

$$E_{DP}(t) = E_{DX}(t) \hat{e}_x + E_{DY}(t) \hat{e}_y$$

(10)

Here, $\hat{e}_x$ and $\hat{e}_y$ are the mutually orthogonal basic vectors. After that, the modulated optical signal $E_{DP}(t)$ is controlled...
by the PC2 to align the two orthogonal polarization states to the two principal axes of the polarization modulator (PolM). The PolM is a combination of two phase modulations with opposite modulation indices on the TE and TM components of an optical lightwave [25]. A coding signal $s(t)$ is applied to drive the PolM. According to the principle of polarization modulation, the output signal of PolM can be written as

$$
\begin{bmatrix}
E_{PolMx}(t) \\
E_{PolMy}(t)
\end{bmatrix}
= E_c(t)
\times
\begin{bmatrix}
\sqrt{2} J_0(mRF) + 2jJ_1(mRF) e^{j(\omega RF t + \sigma_1)} e^{j\theta} e^{j\phi} \vec{e}_x \\
\sqrt{2} J_1(mRF) e^{-j(\omega RF t + \sigma_2)} + J_0(mRF) e^{j(\omega RF t + \sigma_2)} e^{-j\theta} \vec{e}_y
\end{bmatrix}
$$

(11)

where, $\theta = \pi s(t)/V_{pp}$ is the phase shift that introduced by coding signal $s(t)$, $V_{pp}$ is the half-wave voltage of the PolM, $\phi$ represents the phase difference between the two principal axes in PolM, which is introduced by PC3. It can be seen from Eq. (11) that the output signal from PolM is also a combined signal, which has two orthogonal polarization states (x-polarization and y-polarization). After controlled by the PC3, the polarization modulated signal is sent to the pre-coding section, whose structure is shown in Fig. 1. It consists of one PBS, two PBCs (PBC1 and PBC2), two PDs (PD1 and PD2), two polarizers (Pol1 and Pol2), two optical time delays (delay 1 and delay 2) and two optical attenuators (Att. 1 and Att. 2). The two orthogonal polarized signals are aligned to the two principal axes of PBS, and then split into two branches with two orthogonal polarization states. In the x-polarization, the optical signal is equally split into two paths and one of them enters in an Att. 1, another one enters in an optical time delay1. The attenuated path is input to the PBC1, while the delayed one is input to PBC2. In the y-polarization, the optical signal is also separated into two paths. Similar to the signal in x-polarization, it is equally split and one Att. 2 is applied to one path, one time delay2 is employed in another path. The attenuated signal is input to PBC2 and the time delayed one is sent to PBC1. After the specially designed combining process, the two output signals in two paths (upper and lower) can be expressed as (12), shown at the bottom of this page.

Here, $A_1$ and $A_2$ are the attenuation coefficients that introduced by Att. 1 and Att. 2, respectively. Two Pols are used in the two output ports respectively to align the orthogonal polarized signals into one polarization state. For convenience, we use $\beta_{2-1} = -(\omega_c - \omega RF)\tau_2$, $\beta_{20} = -\omega_c\tau_2$, $\beta_{21} = -(\omega_c + \omega RF)\tau_2$ to represent the phase shifts of the -1st order, the carrier and the 1st order sidebands respectively introduced by time delay 2. Similarly, use $\beta_{10} = -\omega_c\tau_1$, $\beta_{11} = -(\omega_c + \omega RF)\tau_1$ to represent the phase shifts of the carrier and the 1st order sideband respectively introduced by time delay 1. Thus, the output optical signals can be written as (13), shown at the bottom of this page.

Here, $\alpha_1$ and $\alpha_2$ are the angles of Pol1 and Pol2 relative to the x-polarization, respectively. Finally, the two specially processed optical signals are sent into the photodiodes (PD1 and PD2) to achieve photo-electrical conversion, and the output photo-currents are shown as (14), where, $R_1$ and $R_2$ are the responsivity of the two PDs respectively. $\eta = (\beta_{21} - \beta_{2-1})/2$ and $\delta = (\beta_{21} + \beta_{2-1})/2$. According to Eq. (14) and (15), the generated microwave signals include DC components, fundamental frequency components,
double multiplexing components and the base band components. As for $I_1(t)$, the coefficient of the double multiplexing component contains $J_1(m_{RF})J_{-1}(m_{RF})$, while the fundamental frequency component shows a higher amplitude of $J_1(m_{RF})J_0(m_{RF})$. The amplitude difference can be shown in Fig. 2. According to the calculating results, when the modulation index $m_{RF}$ is low enough, the $J_1(m_{RF})J_{-1}(m_{RF})$ component can be ignored. Besides, the second order harmonics can also be suppressed through an electrical low pass band filter (LBPF). As for $I_2(t)$, The same processing methods can also be carried out.

By using LBPF and the DC blocks, the DC and double multiplexing components can be well suppressed, so that the desired fundamental component reserved. It should be emphasized that the frequency of base band signal is much lower than that of RF signal, so the base band components can be also ignored. After the LBPF, Eq. (14) and (15) can be simplified as shown at the bottom of the this page.

According to the analysis before, Eq. (16), as shown at the bottom of the next page, is the desired component that shows a standard MIMO transmission matrix. However, the second item is not desired. In order to achieve the original coding signal, we only consider the first item in Eq. (17) and adopt coherent demodulation technology. As for the second item in Eq. (17), we will further discuss in the “C. Demodulation” part. Moreover, Eq. (17) also shows that the transmission result has no relation with the two EPSs. Comparing Eq. (7) with Eq. (17), there are

$$I_1(t) = R_1 E_{P_{up}}(t) E_{P_{up}}^*(t) \left[ \begin{array}{c} A_1^2 \cos^2 \alpha_1 (2J_0^2 (m_{RF}) + 4J_1^2 (m_{RF})) \\ +2 \sin^2 \alpha_1 (J_0^2 (m_{RF}) + 2J_1^2 (m_{RF})) \\ +4 \sqrt{2} J_0 (m_{RF}) J_1 (m_{RF}) \left[ A_1^2 \cos^2 \alpha_1 \sin \omega_{RF} t + \sigma_1 + 2\theta + \varphi - \beta_{20} \right] \\ + \sqrt{2} \sin \omega_{RF} t + \varphi_2 + \eta \\ + \sin^2 \alpha_1 \sin (\delta - \beta_{20}) \\ + A_1 \cos \alpha_1 \sin \alpha_1 \sin (\delta - 2\theta - \varphi) \end{array} \right] \right) \right] \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \right) \r
some similarities between them. If the condition below can be satisfied by tuning proper parameters, the optical pre-coding structure is realized.

\[
\begin{align*}
4\sqrt{2} R_1 J_0 (m_{RF}) J_1 (m_{RF}) A_1^2 \cos^2 \alpha_1 \\
= - \frac{1}{|H|} \exp \left( \chi_{22} \right) \\
4\sqrt{2} R_2 J_0 (m_{RF}) J_1 (m_{RF}) \cos^2 \alpha_2 \\
= - \frac{1}{|H|} \exp \left( \chi_{21} \right) \\
4\sqrt{2} R_1 J_0 (m_{RF}) J_1 (m_{RF}) \cos \alpha_1 \sin \alpha_1 \\
= - \frac{1}{|H|} \exp \left( \chi_{12} \right) \\
4\sqrt{2} R_2 J_0 (m_{RF}) J_1 (m_{RF}) \cos \alpha_2 \sin \alpha_2 \\
= - \frac{1}{|H|} \exp \left( \chi_{11} \right) \\
\varphi - \beta_{20} \\
= - (\phi_{12} - \phi_{22}) \text{ and } \varphi + \beta_{11} - (\phi_{11} - \phi_{21})
\end{align*}
\]

In fact, after transmitting through the satellite to terrestrial channel, not only the distortion in amplitude and phase will influence the signal quality, but also the free space loss and other loss factors can deteriorate the signal. Fortunately, the power loss can be compensated through the amplifier.

**C. Demodulation**

After transmission, the received signal should be demodulated to obtain the coding signal. Thanks to the pre-coding structure, the received signal can be expressed as (23), shown at the bottom of the next page.

Usually, as for the phase modulated signal, the coherent demodulation is a priority and widely known technology to extract out coding signal. Here, as shown the second item in Eq. (23), it seems like a “noise” component \( n = [n_1, n_2]^T \) is not desired and will distort the quality of the final signal. We use the parameter controlling to eliminate the undesired component. For convenience, we only consider the noise component \( n_1 \) as a representative. Assuming that the “noise” is also coherent demodulated, the demodulating result can be written as

According to Eq. (24), as shown at the bottom of the next page, the second order harmonics and the base band signal can be obtained in the demodulating result. As for the harmonics, it can be suppressed by an LBPF. But for the base band component, the parameters should be adjusted. It can be noticed that when \( \eta = 0 \) and \( \sigma_2 = 0 \), the base band signal can be eliminated. The same processing is also applied to \( n_2 \).

### III. Simulation Results and Discussion

Since there are a few works investigating satellite based MIMO communication technology [26]–[28], the real link configuration parameters for satellite MIMO communication system in higher frequency bands are not available. In order to investigate the photonic based MIMO satellite communication system with higher frequency bands such as Ka band under condition of clear environment, we set a MIMO communication link according to the scenario and the parameters values that illustrated in Ref. [19]. As Fig. 3 shows, two transmitting antennas located in one satellite, and two receiving antennas work in one terrestrial station. Here, the simulated \( 2 \times 2 \) MIMO satellite system is previously verified in Ref. [24]. So in this paper, we adopt the satellite and
terrestrial station parameters in Ref. [24] to construct the MIMO satellite system and setup a platform to verify the proposed photonic pre-coding. Details are shown in Table 1.

The satellite to terrestrial channel configurations for Ka band signal are shown in Table 2 [27]. According to the parameters information and theoretical analysis before, channel parameters values are $\chi_{11} = 0.1976$, $\phi_{11} = 0.0079$, $\chi_{12} = 0.1977$, $\phi_{12} = 0.0083$, $\chi_{21} = 0.1975$, $\phi_{21} = 0.0068$, $\chi_{22} = 0.1978$, $\phi_{22} = 0.0066$.

Next, the loss factors between the satellites and the terrestrial stations are been investigated. The downlink free space loss for different frequencies in atmosphere are different, here we use the measurement results in Ref. [27] to imitate the real free space loss in the MIMO scenario with the frequency of 30 GHz (Ka band) as Fig. 3 shows. Besides, other power loss factors such as feeder line loss and antenna misalignment loss [32] should also be considered. On the other hand, the signal must go through the atmosphere and suffer from

\[ \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} h_{r,\text{clear}11} & h_{r,\text{clear}12} \\ h_{r,\text{clear}21} & h_{r,\text{clear}22} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + 8J_0(mRF) J_1(mRF) \left( \frac{\sin \omega_{RF} t}{\sin (\omega_{RF} t + 2\theta)} \right) \]

\[ \times \left( \begin{array}{c} \sin^2 \alpha_1 \sin (\delta - \beta_{20}) \\ +A_1 \cos \alpha_1 \sin \alpha_1 \sin (\delta - 2\theta - \varphi) \\ \times \sin (\omega_{RF} t + \eta) h_{r,\text{clear}11} \\ +h_{r,\text{clear}12} A_2 \cos \alpha_2 \sin \alpha_2 \\ \times \sin (2\theta + \varphi + \beta_{10}) \sin (\omega_{RF} t) \end{array} \right) \]

\[ + 8J_0(mRF) J_1(mRF) \left( \frac{\sin \omega_{RF} t}{\sin (\omega_{RF} t + 2\theta)} \right) \]

\[ \times \left( \begin{array}{c} \sin^2 \alpha_1 \sin (\delta - \beta_{20}) \\ +A_1 \cos \alpha_1 \sin \alpha_1 \sin (\delta - 2\theta - \varphi) \\ \times \sin (\omega_{RF} t + \eta) h_{r,\text{clear}21} \\ +h_{r,\text{clear}22} A_2 \cos \alpha_2 \sin \alpha_2 \\ \times \sin (2\theta + \varphi + \beta_{10}) \sin (\omega_{RF} t) \end{array} \right) \]

\[ = 4h_{r,\text{clear}11} J_0(mRF) J_1(mRF) \left( \frac{\sin^2 \alpha_1 \sin (\delta - \beta_{20})}{\sin (2\omega_{RF} t + \eta) + \sin \eta} \right) \]

\[ \times \left( \begin{array}{c} \sin^2 \alpha_1 \sin (\delta - \beta_{20}) \\ +A_1 \cos \alpha_1 \sin \alpha_1 \sin (\delta - 2\theta - \varphi) \\ \times 4h_{r,\text{clear}12} J_0(mRF) J_1(mRF) A_2 \cos \alpha_2 \sin \alpha_2 \sin (2\theta + \varphi + \beta_{10}) \\ \times \sin (2\omega_{RF} t + \sigma_2) + \sin \sigma_2 \end{array} \right) \]
the turbulence. According to the Ref. [33], we can also find the proper refractive-index $C_n^2$ to imitate the atmosphere turbulence when the signal frequency is Ka band. Details are shown in Table 3.

On the basis of the photonics pre-coding MIMO system that shown in Fig. 1, a simulation model using the commercial software “Optisystem” is established to verify the proposed structure. The parameters of the devices in this structure are properly chosen according to a real experimental condition, as shown in Table 4. The generated optical signal is then sent to the photonic pre-coding section to achieve pre-coding for MIMO communication system. In general, the parameters values of the photonic pre-coding structure should match the channel configuration. Parameters (Pol1, Pol2, delay1, delay2, Att. 1 and Att. 2) in the pre-coding structure are also shown in Table 4.

According to the above scenario and parameters, the simulation work is carried out. The simulation results show that the received power in the terrestrial is lower than $-100$ dBm. So an electrical amplifier with a gain of 60 dB is needed. As the theoretical analysis before, the pre-coded signal can well immune to the channel distortion. In order to verify the feasibility, the waveforms of the microwave signal from the transmit side and the receiver side are all demodulated to obtain the coding signals. Comparing with the original coding signal in Fig. 4(a), it can be figured out that in the transmit side, the coding signal (blue line in Fig. 4(b)) distorted greatly. Fortunately, after the satellite to terrestrial channel, it is amended in the receiver side (red line in Fig. 4(b)). It shows that the photonic pre-coding structure improves the transmission quality.

In addition, the eye diagram is another way to observe the signal quality. The simulation results are shown in Fig. 5. It can be seen in Fig. 5(a) that the eye diagram of signal from transmitter side is not clear, which is distorted by the pre-coding structure. Fortunately, after transmission, the channel plays a “correction” function that amends the distorted signal. Just as the result shown in Fig. 5(b), the eye diagram of received signal is very clear and the bit error rate (BER) is about $2.13503E-7$, the system capacity is about $0.4276$. In general, the BER threshold of the satellite communication is assumed to be less than $10^{-6}$ [24]. Based on the simulation results, we can conclude that the photonic pre-coding algorithm is realized without DSP and performs well.

In the previous work, we assume the bit rate as 1 Gbit/s. High transmission rate is desired in future communication system. In this part, we try to increase the bit rate from 2 Gbit/s to 7 Gbit/s with step of 1 Gbit/s, aims to investigate the highest bit rate that this system can provide. According to the simulation results shown in Fig. 6, it can be easily figured out that the eye closed or distorted as the bit rate gets higher. The highest rate is 7 Gbit/s when the frequency of carrier RF is 30 GHz. On the other hand, we continue the simulation work by fix the bit rate at 7 Gbit/s and adjust the
carrier RF frequency from 30 GHz to 38 GHz with a step of 2 GHz. As the simulation results shown in Fig. 7, the eye diagrams get more clear as the carrier frequency gets higher. This result well proves the necessity of higher frequency communication.

For the non-ideal factors, such as the extinction ratio and the inaccurate parameters settlement, they will influence the quality of MIMO communication results in the real experimental system. Thus, the influences of non-ideal factors on the system are investigated. First of all, the extinction ratio is considered. It is an important parameter to identify the quality of electro-optical modulator (EOM). In practice, based on current manufacturing art, the extinction ratio can be improved to 40 dB [30] or even 60 dB [31]. In this work, we change the extinction ratio from 18 dB to 30 dB with the step of 2 dB. For convenience, the BER and the capacity of MIMO system are adopted to show the communication quality. According to the simulation results in Fig. 8(a), the BER is greatly improved as extinction ratio gets higher. However, the capacity shows a decreasing tendency.

It is noticed that the phase shift $\phi$, which is introduced by PC3 supports a phase tuning function when performing pre-coding work. In order to approach the real applications, $\phi$ is adjusted to deviate from desired value with a range of $-10$ degree to 10 degree. As the simulation results shown in Fig. 8(b), the influence of $\phi$ on the BER and the capacity are different. Furthermore, the changing range cannot be neglected. It means that $\phi$ plays a significant role when guarantees the communication quality and should be carefully adjusted.

IV. DISCUSSION

In discussion, according to the theoretical analysis and simulation results before, we can easily find that the algorithm will be realized through microwave photonics technology. Here, we only consider the phenomenon in clear weather and the easy described channel configuration. As for more complex weather condition such as rainfall weather, more
parameters should be introduced or another ingenious photonic pre-coding must be designed. On the other hand, the communication frequency that higher than Ka band will greatly suffer from rainfall mediums and free space loss. The structure should be further improved so that it can satisfy the higher frequency communication requirement and possess multi-weather adaptation. As for the instantaneous channel state information, it should firstly aware that before someone tries to perform the communication task, the channel information is often previously measured and listed as a reference table. It is obvious that different weather determines different channel characteristic. The related channel envelope and phase models for different weathers [27] are shown in Table 5. In order to make the system suitable for different channels, the related parameters in the precoding system should be adjusted according to the matching model shown in Eqs. (18)-(22).

V. CONCLUSION

In this paper, we design a photonic pre-coding structure for MIMO satellite communication system without DSP. According to the result, the obvious signal quality improvement based on photonic pre-coding algorithm can be easily observed through the eye diagram. Before launched from the transmitter, the signal is pre-distorted and the eye diagram shows a closed “eye”. After transmitting from the satellite to terrestrial station, the eye diagram from the receiver emerges a clear open “eye” and the BER is about 2.1350E-3, the system capacity is about 0.4276. Besides, the BER and the system capacity are the efficient tool to evaluate the signal quality. The simulation results depict that when the parameters in the photonic pre-coding structure is altered, it can obviously influence the final communication result. The proposed photonic structure can be well employed in the future MIMO satellite communication system, and take the place of DSP to realize some simple algorithms.

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