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On Performance of Optical Wireless Communication With Spatial Multiplexing Towards 5-G

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ABSTRACT Optical wireless communication (OWC) with orbital angular momentum (OAM)-based spatial multiplexing enables to offer ultra-high information capacity as well as high spectral and energy efficiencies, which is a promising alternative to establish the fronthaul toward the fifth generation (5-G) wireless communication networks. The air turbulence in the optical wireless channel, however, would result in adverse effect in the performance of OWC with spatial multiplexing. We study the impact of air turbulence on the purities of multiplexed OAM states. The split step propagation scheme combining with the Monte-Carlo phase screen method is employed to accurately emulate the OWC link with OAM-based spatial multiplexing. The numerical results reveal that the air turbulence-induced cross-talk among the parallel OAM spatial channels would severely degrades the performance of the fronthaul in 5-G which is established by the OWC with OAM-based spatial multiplexing.

INDEX TERMS 5-G mobile communication, optical wireless communication, spatial multiplexing.

I. INTRODUCTION

The demand of wireless communication, in the past two decades, has strikingly increased; while this continuous increment has been aggravating by the wideband mobile services originating from plenty of wireless devices, like smartphones, laptops and tablets etc., as well as the internet of things (IoT). As such, it results in an explosive growth in the bandwidth requirement of mobile networks. Therefore, a new scheme offering high data rate and quality of service (QoS) with low cost is highly desired to solve such severe network congestion. The fifth (next) generation (5G) wireless communication networks are expected to meet those requirements above [1], [2].

In 5G, there exists 1000 times increase with respect to the capacity compared to the current wireless communication networks, which consists of 10 times growth in data rate, 10 times growth in spectral efficiency and 10 times growth in energy efficiency [3]. Accordingly, to establish the fronthaul in 5G among wireless network nodes or mobile stations, an extremely large bandwidth needs to be offered. Despite the traditional radio frequency (RF) technique is mature, it does not appear to be an ideal approach to realize the fronthaul in 5G due to its limited bandwidth, interference effect and relative-high energy consumption. Optical wireless communication (OWC), also known as the free-space optical (FSO) communication, has been proposed and regarded as one of the most promising alternative techniques [4]. OWC can provide extremely high data rate as well as electromagnetic interference-free. Its spectrum is unregulated. In addition, OWC is a green technique with low energy consumption and reduced mobile stations while with low deployment cost.

In order to improve the information capacity of OWC, the multilevel modulation formats, such as M-ary phase-shift keying modulation (M-PSK) and quadrature-amplitude modulation (M-QAM), and multiplexing schemes have been employed up to date. Those multiplexing techniques involve the time, frequency, spatial and polarization domain. With respect to the spatial multiplexing, the orbital angular momentum (OAM) based scheme has attracted considerable attention. The OAM, as a newly explored freedom degree of optical-beam/single-photon, can be used in the optical communication to increase the capacity [5]–[9]. The OAM

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modes are the eigenstates of optical-beam/single-photon in free-space channel within the paraxial area. They span an infinite-dimensional Hilbert space, thus enabling to offer a potential scheme to multiply the information capacity of the OWC by the multiplexing at the single wavelength with extremely high spectrum efficiency. Moreover, the OAM based Spatial-division multiplexing (SDM) does not increase the complexity of fronthual [3]. More precisely, it does not need the complex multiple-input multiple-output (MIMO) processing.

A large amount of literatures have studied the OWC with the use of OAM based spatial multiplexing. An aggregated 80 Gbits/s transmission data rate could be provided by the use of 4-OAM-mode SDM with each carrying a 20 Gbits/s signal of quadrature phase-shift keying (QPSK) modulation format at single wavelength transmitted ∼1 m optical wireless path over the lab table [10]. Reference [11] experimentally demonstrated 9 OAM modes propagating through an outdoor optical wireless link of 1.6 km, and analyzed the degradation in channel fidelity. Up to 200 OAM modes spatial multiplexing has been realized in the lab environment with a single hologram device [12], which offers potential application in the OWC with the spatial multiplexing scheme in 5G. In parallel, [13] demonstrated the OWC with 400 Gbits/s data rate operating over a 120 m optical wireless link by using the quadrature phase-shift keying (QPSK) modulation format and the 4-OAM-state SDM scheme. Beyond [13], a higher data rate of 2.2 Tbits/s was achieved by the combination of multicarrier transmission strategy and 16-QAM modulation format propagating through a 11.5 m optical wireless path [14].

Although the progress above has been completed so far, the performance of OWC with spatial multiplexing strongly relies on the outdoor free-space channel conditions [15]–[17]. The air turbulence in the optical wireless channel results in the wavefront distortions of the spatially multiplexed OAM modes which carry the optical signals after they propagate through certain long optical wireless link, thus contaminating the purities of OAM modes. The crosstalk among the parallel OAM mode spatial channels would be induced [6]–[9]. Accordingly, the performance of OWC adopting the OAM-based SDM scheme towards 5G would be degraded. However, to the best of our knowledge, its concrete analysis has been rarely evaluated to date. In this paper, we study the influence of air turbulence effects on the parallel multiplexed-OAM modes by employing the split step propagation approach, and eventually evaluate the performance of OWC with OAM-based SDM scheme by dint of the numerical calculated crosstalk among the OAM modes spatial channels.

The remainder of this paper is organized as follows. In section 2, the optical wireless link in 5G fronthaul with the use of spatial multiplexing and the air turbulence-induced cross-talk among the parallel OAM mode spatial channels are introduced concretely. Subsequently, the numerical simulations as well as the results are presented in the section 3. Finally, the conclusion is drawn in the section 4.

II. PERFORMANCE OF OWC WITH OAM-BASED SPATIAL MULTIPLEXING

The sketch of OWC with OAM-based SDM scheme towards 5G is demonstrated in Fig. 1. We assume that the number of mobile user is M. Each one communicates with the remote radio head (RRH) by employing the OWC/radio-frequency (RF) technique to transmit and receive data. The RF is conventional scheme; while the OWC is recently proposed one with higher information capacity and lower energy consumption. The OWC serves as the indoor communications in 5G [18], well-known as the Light Fidelity (Li-Fi) [4], [19]. Due to the huge number of mobile user, the throughput capacity between the RRH and base band unit (BBU) would be extremely heavy. The OWC with OAM-based SDM scheme is adopted to establish the fronthaul in 5G, which enables to offer ultra-high information capacity so that the traffic congestion could be relieved effectively. Eventually the BBU pool is connected with the core network by the use of optical fiber channel [20]. As the Fig.1 presents, both OWC with OAM based SDM scheme and LI-FI would be the one of most promising techniques to establish the fronthaul towards 5G.

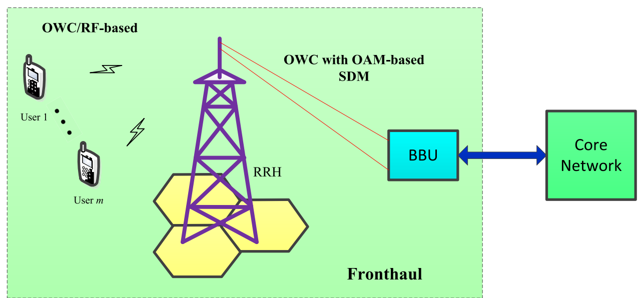

FIGURE 1. Sketch of OWC with OAM based spatial multiplexing scheme towards 5-G. RF: radio frequency; RRH: remote radio head; BBU: base band unit.

A. OPTICAL WIRELESS LINK IN 5G WITH THE USE OF SPATIAL MULTIPLEXING

To prevent from the traffic congestion, the fronthaul in 5G requires novel technique to provide strikingly high information capacity. As the preceding advantages, the OWC with OAM-based SDM scheme will be the desired one since it offers high data rate, spectrum efficiency and energy efficiency without increasing the complexity. The multiple parallel OAM mode spatial channels enable to provide fold capacity improvement. However, the helical wavefront of OAM mode is vulnerable to disturbance, thus resulting in contamination of its purity. Accordingly, the performance of OWC with OAM-based SDM scheme will be degraded severely.

The resources of disturbance mainly include the system imperfection and the air turbulence. The former produces the tilt distortion, which can be well-compensated by alignment; while the latter presents extremely complex mechanisms. Due to the existence of wind, temperature gradient and humidity difference, the air turbulence is generated in the optical wireless channel, which leads to the random fluctuations of air refractive index. Therefore, after the optical beam carrying OAM propagates through the turbulent air channel, its wavefront phase and amplitude are perturbed accordingly. Since the perturbations have the nature of accumulation, the total distortions in wavefront phase and amplitude could be significant over certain long optical wireless link propagation. In order to analyze the impact of air turbulence on the parallel OAM spatial channels, the statistical characters of random-fluctuated air refractive index and the corresponding perturbations of OAM mode wavefront have to be explored.

Several mathematical models have been proposed to characterize the statistics of air refractive index fluctuation. The Kolmogorov model is the original one [21] by simply assuming that the outer scale of air turbulence is up to infinite, while the inner scale reaches to 0. However, it has been well-known that the large air turbulence cells are unstable eventually splitting into many smaller ones; while with respect to the small turbulence cells, their energies are decreased eventually reaching 0 because of the dissipation effect. Consequently, the original Kolmogorov model is appropriate within the initial subrange only, namely the turbulence spatial range between the outer scale and the inner scale. To establish the realistic turbulence model, besides the initial subrange, the preceding effects of the turbulence outer and inner scales have to also be taken into account so that the entire range of spatial frequencies would be applicable. Along this line, the Pump model has been presented. Also, its accuracy has been validated by the field experimental data. The Pump model is regarded as the most realistic one to assess the statistics of refractive index fluctuation. Given that the air is isotropic and homogeneous, the power spectrum density (PSD) of air refractive index is considerably reduced, which is a function of scalar spatial frequency with the expression [21] of

$$\Phi_n(\kappa, z) = 0.033C_n^2(z)\left[1+1.802\left(\frac{\kappa}{\kappa_l}\right) - 0.254\left(\frac{\kappa}{\kappa_l}\right)^{7/6}\right] \times\frac{\exp\left(-\kappa^2/\kappa_l^2\right)}{\left(\kappa^2+\kappa_0^2\right)^{11/6}}, \quad \text{for } 0 \le \kappa < \infty, \tag{1}$$

where κ denotes the spatial frequency; $\kappa_l = 3.3/l_0$ and $\kappa_0 = 2\pi/L_0$ are related to the turbulence inner and outer scale parameters l_0 and L_0, respectively; $C_n^2(z)$ is the air refractive index structure parameter in unit of $m^{-2/3}$, which measures the strength of air turbulence. In general case, C_n^2 changes as the optical wireless path distance z. But for the special case of horizontal-path link that is concerned in this paper, C_n^2 can be treated as be independent with z, namely, a constant. Further, the PSD function of turbulence-induced phase distortions can be simply derived by multiplying the factor of $2\pi k^2 L$ on $\Phi_n(\kappa)$ only, where $k = 2\pi/\lambda$ is the wavenumber with λ indicating the optical wavelength and L being the optical wireless propagation distance between the RRH and BBU. In terms of Eq. (1), the PSD function of phase distortions can be written as

$$\Phi_\phi(\kappa) = 0.49r_0^{-5/3}\left[1+1.802\left(\frac{\kappa}{\kappa_l}\right) - 0.254\left(\frac{\kappa}{\kappa_l}\right)^{7/6}\right] \times\frac{\exp\left(-\kappa^2/\kappa_l^2\right)}{\left(\kappa^2+\kappa_0^2\right)^{11/6}}, \quad \text{for } 0 \le \kappa < \infty, \tag{2}$$

where $r_0=[0.423k^2C_n^2L]^{-3/5}$ represents the air coherent diameter.

Now we proceed to the emulation of optical wireless link by employing the numerical techniques. Theoretically, the air turbulence-induced phase distortions can be written as the summation of the Fourier series [22]

$$\phi(x, y) = \sum_{i=-\infty}^{\infty}\sum_{j=-\infty}^{\infty} c_{ij}\exp\left[i2\pi\left(f_{x_i}x + f_{y_j}y\right)\right], \tag{3}$$

where f_{x_i} and f_{y_j} represent the sampled spatial frequencies along x and y axis, respectively; c_{ij} is the coefficient of Fourier-series. Obviously, c_{ij} is the key to emulate the turbulence-induced phase distortions. Based on the fact that all air turbulent cells are independent, c_{ij} follows a specific normal distribution with mean zero by the central-limit theorem. Further, in light of the Parseval's theorem, we have

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|\phi(x, y)|^2dxdy = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|\Phi_\phi\left(f_x, f_y\right)\right|^2df_xdf_y. \tag{4}$$

Combination of Eq. (3) and Eq. (4), the variance of c_{ij} can be given as

$$\sigma^2 = \Phi_\phi\left(f_{x_n}, f_{y_m}\right)\frac{1}{\Delta x}\frac{1}{\Delta y}, \tag{5}$$

where Δx and Δy are the sampled spacing in x-direction and y-direction, respectively. With $c_{ij} \sim N(0, \sigma^2)$, the turbulence-induced phase distortions now can achieved by merely performing the Inverse Fast Fourier Transform (IFFT),

$$\phi(x, y) = F^{-1}\{C \cdot \sigma\}, \tag{6}$$

where C denotes an array of complex random numbers, and its real part and imaginary part follow the standard normal distribution.

By employing the numerical techniques described above, the optical wireless link can be emulated. Specifically, an array of the randomly sampled points whose statistics agrees with the theoretical phase PSD function of Eq. (2) represents the wavefornt phase distortions induced by the air turbulence in the optical wireless channel.

B. PERFORMANCE EVALUATION

Optical beams carrying OAM are generally referred to as the optical vortices due to the nature of helical transverse-spatial wavefront structure. Their intensities at the center vanish since the phase there is discontinuous. The wave vector normal to the vortex wavefront follows a spiral trajectory along the propagation direction $+z$ axis, which is characterized by an index proportional to the number of wave vector turns propagating one optical wavelength distance. This index can be used to characterize specific OAM state. Since the Laguerre-Gaussian (LG) beams carrying OAM modes can be generated readily [23], they are usually used in practical applications. The field distribution of LG mode can be expressed by [24]

$$u(r,\theta,z) = \sqrt{\frac{2p!}{\pi\,(p+|m|!)}}\frac{1}{w(z)}\left[\frac{r\sqrt{2}}{w(z)}\right]^{|m|} L_{p,m}\left[\frac{2r^2}{w^2(z)}\right] \times \exp\left[\frac{-r^2}{w^2(z)}\right]\exp\left[\frac{-jkr^2z}{2\left(z^2+z_R^2\right)}\right] \times \exp\left[j\,(2p+|m|+1)\tan^{-1}\left(\frac{z}{z_R}\right)\right] \times \exp\left(-jm\theta\right), \quad (7)$$

where $(r,\ \theta,\ z)$ represents the cylindrical coordinate with r denoting radial distance, θ being the azimuthal angle, and z denoting the $+z$ axis; $w(z) = w_0\sqrt{1+(z/z_R)^2}$ is the beam radius at the distance z with w_0 being the radius of the zero-order Gaussian beam (i.e. the TEM_{00} mode) at its waist, $z_R = \pi w_0^2/\lambda$ being the Rayleigh range; $L_{p,m}(\cdot)$ denotes the generalized Laguerre polynomial with p and m being the radial and angular mode numbers, respectively. Note that Eq. (7) is reduced to the TEM_{00} mode when p=0 and m=0.

As one can clearly see from the Eq. (7), LG modes consist of a complete orthogonal basis, thus spanning an infinite-dimensional Hilbert space. They can be considered as the parallel spatial signal components which are suitable for multiplexing to increase information capacity in the OWC based fronthaul. Note that in the Eq. (7), the angular mode index m corresponds to the OAM state index. The OAM mode spatial channels are mutually orthogonal, which is the key reason why they can be considered for multiplexing in the OWC. The orthogonality principle of OAM modes means that the integral of overlapping fields satisfy

$$\int u_m^*(r,\theta,z)\cdot u_n(r,\theta,z)\,dr d\theta dz = \begin{cases} 0, & \text{if } m \neq n \\ I, & \text{if } m = n \end{cases} \quad (8)$$

where I is the intensity of LG mode with OAM index m. However, in the presence of air turbulence, the orthogonality is disrupted due to turbulence effects so that the Eq. (8) is not equal to 0 even when $m \neq n$, which means that the spatial channel of OAM mode with index m leaks its energy into other OAM mode spatial channels. Therefore, the cross-talk among the parallel OAM mode spatial channels would be induced due to the wavefront distortions caused by the air turbulence when these OAM modes are spatially demodulated by the mode sorter. The cross-talk is measured by the conditional probability

$$P(m|n) = \frac{1}{I}\int u_m^*(r,\theta,z)\cdot u_n(r,\theta,z)\,dr d\theta dz, \quad (9)$$

which characterizes the energy of original OAM mode channel with index m transferring into other OAM mode channels with index n.

III. SIMULATION RESULTS AND DISCUSSIONS

In terms of the theories above, now we perform the corresponding numerical simulations to specifically evaluate the performance of OWC with OAM based multiplexing towards 5G. Here, we use the Monte-Carlo phase screen method to generate the phase distortions resulting from the air turbulence. Also, to emulate the air turbulence effects more concretely, the split step beam propagation strategy [22], [25] is applied, which is presented explicitly in Fig.2.

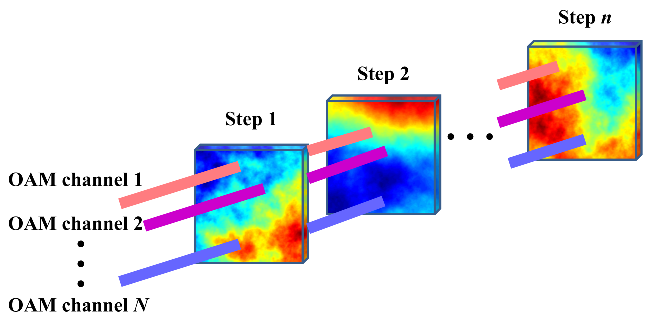

FIGURE 2. Split step beam propagation scheme. The *N* multiplexed OAM spatial channels together propagate through the optical wireless link by *n* split steps.

As the Fig.2 demonstrates, N parallel OAM spatial channels are multiplexed by the mode multiplexer. Subsequently they together propagate through the turbulent air. The optical wireless channel is split into n steps. Each subdivided step can be regarded as a slab, thus enabling one to emulate the turbulence-induced phase distortions by the use of Monte-Carlo phase screen method which has been described in the section 2.1. On the other side, the optical beam propagation during each step is expressed with the Fresnel diffraction. By use of the accumulated n phase screens, the wavefront distortions of N OAM states can be derived. Eventually, we can employ the Eqs. (7-9) to evaluate the cross-talk among the N parallel OAM mode spatial channels.

To perform the simulations, the air parameters are adopted as follows. The air refractive index structure parameter C_n^2=10^{-15} $\mathrm{m}^{-2/3}$ and distance L from RRH to BBU is 2 km, which corresponds to the medium air turbulence scenario. The inner and outer scales of air turbulence are 6×10^{-3} m and 5 m, respectively. In addition, the optical wavelength of OAM state is 1550 nm, which is compatible with the optical fiber communication based core network. We pay attention to the parallel OAM mode spatial channels with index $m = -10, -9, \cdots, 0, \cdots 9, 10$, namely N=21. Also, the number of split steps is 10, which means each step corresponds to a distance of 0.2 km. As an example, Fig.3 illustrates the emulated phase distortions in the presence of air turbulence by using the Monte-Caro phase screen method for two subdivided steps of 5 and 9. As one can clearly see, the phase

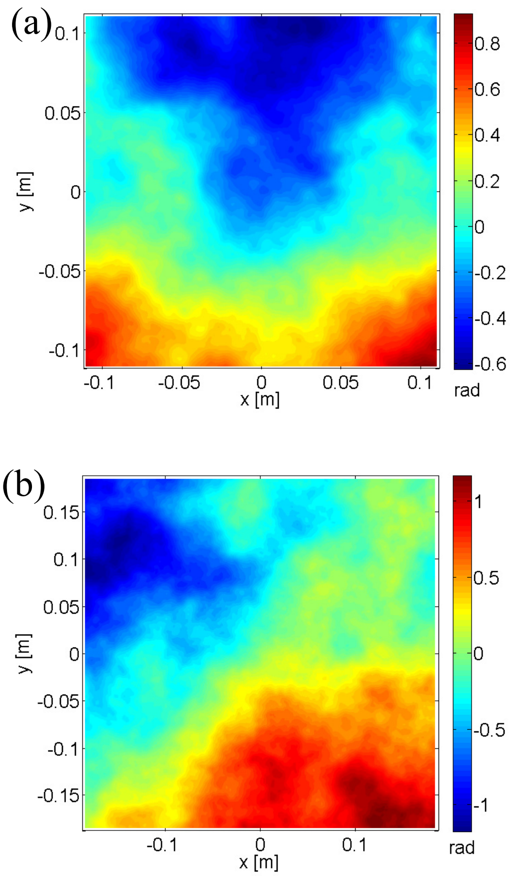

FIGURE 3. Phase distortions reduced by air turbulence for the step (a) 5 and (b) 9, respectively. The phase screen size is 512×512 with sampled spacing of (a) 4.32×10^{-4} m and (b) 6.65×10^{-4} m, respectively.

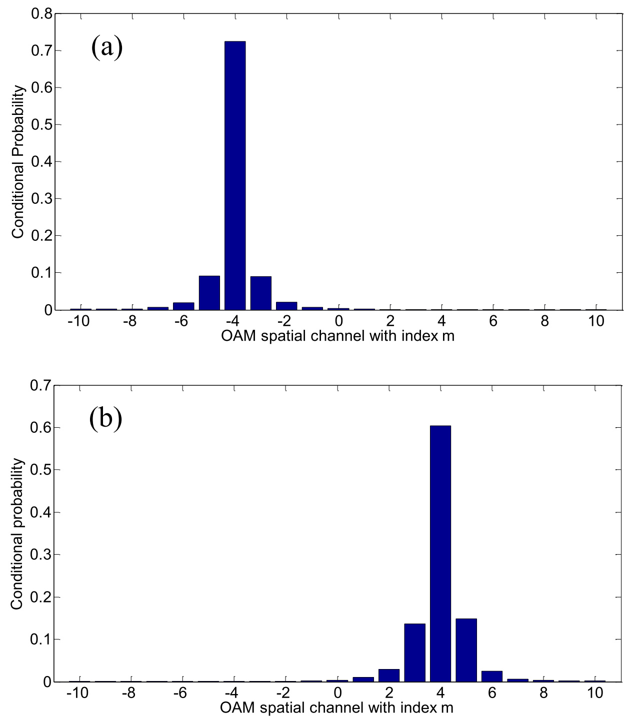

FIGURE 4. Energy leaks in the presence of air turbulence for the OAM mode spatial channels with index (a) $m = -4$ and (b) $m = 4$, respectively.

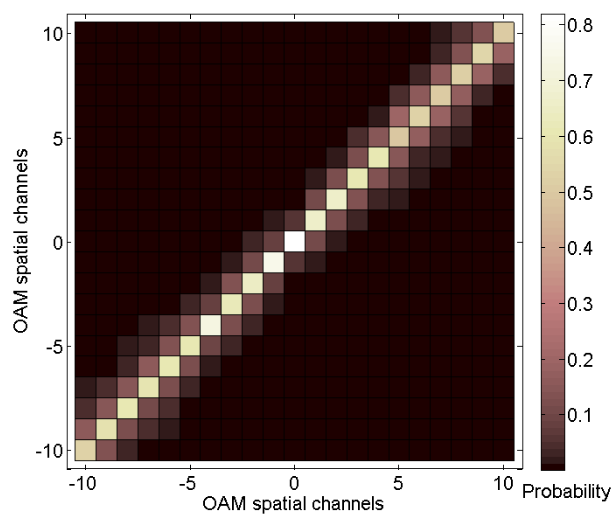

FIGURE 5. Cross-talk among the entire OAM mode spatial channels.

distortions are of significantly difference between two steps due to their nature of randomness. For each step, the phase distortions are small. Nevertheless, after n steps, the phase distortions are significant since those phase distortions can be accumulated. Note that the sizes of two phase screens are not identical. This is attributed to that the beam radius of OAM state diverges along the optical wireless path $+z$ so that the size of phase screen will become larger.

The wavefront distortions showed in Fig. 3 will cause the degradation of OAM mode purity. After the propagation over optical wireless channel, the multiplexed OAM modes are contaminated. Now they can be regarded as the superposition of all OAM states with each having a weighted coefficient. The square of weighted coefficient measures the energy leaks into the specific OAM mode spatial channel, which is characterized by the conditional probability of Eq. (9). As an example, Fig. 4 presents the energy leaks for the OAM mode spatial channel with index $m = \pm 4$. Obviously, the air turbulence impacts the wavefront of OAM mode significantly, thus leading to severe energy leak into other OAM modes. In the presence of air turbulence, the probabilities of preserved energy are 0.73 and 0.62 for the OAM mode spatial channels with index $m = -4$ and $m = 4$, respectively; while the rest of energy is transferred into other OAM mode spatial channels, which produces the cross-talk.

Since the air turbulence presents a random process, we take the ensemble average over 100 executions of split step propagation emulation. Eventually, the averaged cross-talk among the entire OAM mode spatial channels are obtained, which is showed in the Fig. 5. As one can see, the energy leak for each OAM mode spatial channel has the similar behavior, which is that the original OAM mode spatial channel transfers its energy into the neighboring OAM mode channels with much higher probabilities than other channels. Accordingly, by dint of the averaged cross-talk among the parallel OAM mode spatial channels, one can achieve the channel transfer matrix, and eventually evaluate the performance of OWC with spatial multiplexing in the fronthual towards 5G. Clearly, one can also anticipate that the stronger air turbulence will result in severer cross-talk. Thus, to improve the performance, certain schemes have to be taken in place to mitigate such turbulence effects. Fortunately, some formidable approaches have been proposed for compensation, for instance, adaptive optics [6], [8], [26], [27], Gerchberg–Saxton algorithm based phase correction [28].

IV. CONCLUSION

OWC with the use of OAM based spatial multiplexing enables to offer ultra-high data rate, spectral efficiency and energy efficiency, as well as low-complexity of reception without MIMO signal processing, which is a promising alternative to establish the fronthaul towards 5G. We evaluated the cross-talk among the entire parallel OAM mode spatial channels induced by the air turbulence in the optical wireless channel by employing the split step propagation scheme and Monte-Carlo phase screen method. The crosstalk-based channel transfer matrix would be utilized for the evaluation of performance of OWC with spatial multiplexing in the fronthaul towards 5G. Note that the OWC requires a line-of-sight scenario, which could post a challenge in practical application. The combination of RF and OWC could be as a promising strategy to establish the fronthaul in 5G.

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