BER analysis of FSO system with Airy beam as carrier over exponentiated Weibull channel model

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Abstract
Average Bit Error Rate (BER) expression of free-space optical (FSO) communication links with Airy beam as signal carrier under weak atmospheric turbulence and on–off keying modulation scheme is derived based on scintillation index of Airy beam and Exponentiated Weibull channel model. The average BER has been evaluated at different transverse scale factors and exponential decay factors of Airy beam and link distances. And comparison of the average BER of FSO links with Airy beam and Gaussian beam as signal carrier has been carried out. The simulation results show that the average BER of FSO links with Airy beam as carrier decreases with the increase of mean signal to noise ratio and increases with the increase of transmission distance. When the transverse scale factor is about 1.5 cm, a lower average BER can be obtained. And the smaller the exponential decay factor is, the lower the average BER is. Under the same atmospheric turbulence condition, the average BER of FSO links with Airy beam as carrier is obviously better than that of FSO links with Gaussian beam as carrier. The results of this research have some significance for the application of Airy beam in FSO system.

Keywords Free-space optical communication · Airy beam · Exponentiated Weibull channel model · Bit error rate

1 Introduction

Free-space optical (FSO) communication is a promising communication technology for high-data-rate information transmission that is available at optical frequencies (Chaaban et al. 2016; Sun and Djordjevic 2016). For FSO links using Gaussian beam as signal carrier, beam spreading and atmospheric turbulence are two main factors that deteriorate their performances, particularly over link distance of 1 km or longer (Bosu and Prince 2019; Mahdieh and Pournoury 2010). To solve these problems, researchers have proposed many methods, such as adaptive optics (Jiawei and Weibiao 2016), multi-beam transmission (Peleg and Moloney 2007), partial coherent beam transmission (Vorontsov et al. 2013)
and modulation encoding in different ways (Chaudhary et al. 2014; Zhang 2019) have reduced the influence of atmospheric effect to a certain extent. But the actual effect to suppress the atmospheric turbulence is not good enough. For this reason, it is a natural thought to replace conventional Gaussian beam with non-diffracting Airy beam for improving the properties of FSO links (Xingchun et al. 2016).

As a new type of non-diffracting beam, Airy beam is solution of the Helmholtz wave equation and has unique non-diffracting, self-accelerating and self-healing properties (Yifan and Tao 2020; Siviloglou et al. 2008, 2007; Siviloglou and Christodoulides 2007). Compared with the traditional Gaussian beam, Airy beam can keep its transverse intensity distribution invariant over a longer propagation distance and has a smaller scintillation index (Chu et al. 2018; Gu and Gbur 2010). These features make Airy beam has potential applications in optical communication and optical design to reduce diffractive spreading and the effects of atmospheric turbulence. Therefore, properties of Airy beam travelling in atmospheric turbulence have been widely investigated from several aspects such as propagating evolution (Chu 2011; Ji and Eyyuboğlu 2013; Chen et al. 2014; Wen et al. 2015a), far-field divergence (Yiqing and Zhou 2012; Tao et al. 2013), scintillation behavior (Eyyuboğlu 2013; Jiaan et al. 2017; Qiang et al. 2017) and beam wander (Wen and Chu 2014; Wen et al 2015b, 2018) etc. And applications of Airy beam in optical route (Rose et al. 2013), image signal transmission (Liang et al. 2015), label-free imaging (Nagar et al. 2018) and obstacle evasion in FSO links (Zhu et al. 2018) have been reported. However, to the best of our knowledge, no one has yet discussed the link performance, such as BER, channel capacity and interrupt probability etc., of FSO links with Airy beams as optical carrier in the published literatures.

In this paper, we explored the average BER performance of FSO links with Airy beam as signal carrier under weak atmospheric turbulence. Firstly, we derived the average BER expression based on scintillation index of Airy beam, Exponentiated Weibull channel model and on–off keying(OOK) modulation scheme. Secondly, we evaluated the average BER at different transverse scale factors and exponential decay factors of Airy beam and link distances, and compared it with that of FSO links with Gaussian beam as carrier under the same condition. Simulation results show that the average BER of FSO links with Airy beam as carrier decreases with the increase of mean signal to noise ratio (SNR) and increases with the increase of transmission distance. When the value of transverse scale factor of Airy beams is selected to be 1.5 cm, a minimum average BER can be obtained. And the smaller the exponential decay factor is, the lower the average BER is. Under the same atmospheric turbulence condition, the average BER of FSO links with Airy beam as carrier is significantly lower than that of FSO links with Gaussian beam as carrier. This research has certain significance for extending the application of Airy light to FSO communication field.

2 Scintillation index of Airy beam

Scintillations (intensity fluctuations due to turbulence) are one of the fundamental limitations in the development of free-space optical communication systems. The fluctuations increase the Bit Error Rate(BER) of the communications system. Scintillation index $\sigma^2$ of Airy beam based on first order Rytov approximation deduced by Eyyuboğlu at (2013) is represented by Eyyuboglu (2013), Jiaan et al. (2017)
\[ \sigma_i^2 = 0.4147k^2C_n^2 \int_0^L dp \int_0^{2\pi} d\phi_k \int_0^\infty d\kappa \kappa \exp \left[ -\kappa^2 \left( \frac{l_0}{5.92} \right)^2 \right] \frac{1}{\left[ \kappa^2 + (2\pi/L_0)^2 \right]^{1/6}} \]

\[ \times \left\{ \exp \left[ \frac{2(L - p)}{k w_x} a_x \kappa \cos \phi_k \right] \frac{|Ai_{x1}|^2 |Ai_{x1}|^2}{|Ai_x|^2 |Ai_x|^2} \right\} \]

\[ -\text{Re} \left\{ \exp \left[ -\frac{j(L - p)}{k} \kappa^2 \cos^2 \phi_x \right] \frac{Ai_{x1}Ai_{x2}Ai_{y1}Ai_{y2}}{Ai_x^2Ai_y^2} \right\} \] (1)

with \( Ai_x = Ai \left\{ \frac{r_x}{w_x} + \frac{ja_x L}{k w_x^2} - \frac{L^2}{4k^2w_x^4} \right\} \) (2)

\[ Ai_{x1} = Ai \left\{ \frac{r_x}{w_x} + \frac{1}{k w_x^2} \left[ j a_x L - \kappa w_x (L - p) \cos \phi_x \right] - \frac{L^2}{4k^2w_x^4} \right\} \] (3)

\( Ai_y \) is simply the \( y \) equivalent of Eq. (2). \( Ai_{x2} \) is simply \( Ai_{x1} \) with sign of \( k \) inverted. \( Ai_{y1} \) and \( Ai_{y2} \) are the \( y \) counterparts of \( Ai_{x1} \) and \( Ai_{x2} \), additionally with cosine changed to sine.

Where \( Ai(\cdot) \) is the Airy function, \( w_x, w_y \) and \( a_x, a_y \) are the coordinate dependent transverse scale factors and exponential decay factors, \( r_x \) and \( r_y \) are the transverse coordinates on receiver plane, \( L \) is the distance of the receiver plane away from the source plane, \( \kappa \) is the magnitude of spatial wave number and \( \phi_k \) indicates its angular orientation, \( k = 2\pi/\lambda \) is the wave number being related to the wavelength \( \lambda \), \( p \) is the axial propagation distance, \( C_n^2 \) is the atmospheric refractive index structure constant, \( l_0 \) and \( L_0 \) are the inner and outer scales of turbulence respectively.

The scintillation index of Airy beam at the position coincide with the peak of the beam on the receiver plane can be calculated by Eq. (1). While the scintillation index of Gaussian beam has been widely discussed in literatures and its formulation can refer to Eq. (23) in chapter 8 of reference (Larry 2005).

### 3 System and channel model

#### 3.1 System model

On–off-keying (OOK) modulation scheme is commonly used in FSO system because of its simplicity and low cost (Yulong et al. 2019; Giri and Patnaik 2018). The OOK based communication system is assumed to have an Airy beam generator and an amplitude modulator. Airy beam is launched from the Airy beam generator and then modulated by the modulator. Received optical signal is guided into an optical amplifier, and then the amplified amplitude modulated optical signal is converted into electrical signal and passed on to the decision circuit. Block diagram of FSO link with Airy beam as optical carrier is shown in Fig. 1.
In the absence of atmospheric effects, signal to noise ratio (SNR) of a FSO link is defined by

$$SNR_0 = \frac{i_s}{\sigma_N}$$  \hspace{1cm} (4)

where $i_s$ is the detector signal current and $\sigma_N$ is the root-mean-square noise power.

The mean signal current is represented by

$$\langle i_s \rangle = \eta e\langle P_s \rangle$$  \hspace{1cm} (5)

where $\langle P_s \rangle$ is the mean signal power in watts, $\eta$ is the detector quantum efficiency in electrons/photon, $e$ is the electric charge in coulombs, $h$ is Plank’s constant, and $v$ is optical frequency in hertz.

The output current variance of the photodetector is defined by

$$\sigma_{SN}^2 = \langle i_s^2 \rangle - \langle i_s \rangle^2 = \left( \frac{\eta e}{h v} \right)^2 \langle \Delta P_s^2 \rangle + \frac{2\eta e^2 B \langle P_s \rangle}{hv}$$  \hspace{1cm} (6)

where $\langle \Delta P_s^2 \rangle = \langle P_s^2 \rangle - \langle P_s \rangle^2$ represents power fluctuations in the signal that become a contributor to the detector shot noise.

Taking optical turbulence into account, the SNR above for a shot-noise limited is defined by the mean SNR (Zhao et al. 2016)

$$\langle SNR \rangle = \frac{SNR_0}{\sqrt{\left( \frac{P_{s0}}{\langle P_s \rangle} \right) + \sigma_I^2 SNR_0^2}}$$  \hspace{1cm} (7)

where $P_{s0}$ is the signal power in the absence of atmospheric effects, $P_s$ is the instantaneous input signal power on the photodetector.

The mean SNR can be rearranged as

$$\langle SNR \rangle = \frac{SNR_0}{\sqrt{\frac{1}{1+1.33\sigma_R^2} + \sigma_I^2 SNR_0^2}}$$  \hspace{1cm} (8)

where $\sigma_R^2 = 1.23C_n^2k^{7/6}L^{11/6}$ is the Rytov variance, $\Lambda$ denotes the nondimensional diffractive beam parameter at the receiver. Due to the non-diffracting feature of Airy beam in a certain propagation distance, $\Lambda$ is assumed to 1 for Airy beam analyzed in next sections.
3.2 Exponentiated Weibull (EW) channel model

Many distributions have been proposed to model the probability density function of irradiance fluctuations in FSO channels. The most widespread models are the Lognormal (LN) and Gamma–Gamma (GG) distributions. Albeit these models comply with the actual PDF data most of the time, neither of them works in all scenarios. The LN model is only valid in weak turbulence regime for a point receiver. The GG model is accepted to be valid in all turbulence regimes for a point receiver, nevertheless, it does not hold when aperture averaging takes place. EW distribution was first proposed by Barrios to model the distribution of the irradiance in FSO links. And it is valid through the whole weak-to-strong turbulence regime in the presence of aperture averaging. The probability density function (PDF) of a random variable $I$ described by the EW distribution is given by Barrios and Dios (2013)

$$f(I) = \frac{\alpha \beta}{\eta} \left( \frac{I}{\eta} \right)^{\beta-1} \exp \left[ -\left( \frac{I}{\eta} \right)^{\beta} \right] \left\{ 1 - \exp \left[ -\left( \frac{I}{\eta} \right)^{\beta} \right] \right\}^{\alpha-1}$$  \hspace{1cm} (9)

where $\alpha > 0$ and $\beta > 0$ are shape parameters related to the scintillation index $\sigma_i^2$, $\eta > 0$ is a scale parameter and is related to the mean value of the irradiance. Using standard curve fitting techniques the parameters $\alpha, \beta$ and $\eta$ are given by Barrios and Dios (2013)

$$\alpha \approx \frac{7.220 \sigma_i^{2/3}}{\Gamma\left(2.487 \sigma_i^{2/6} - 0.104\right)}$$  \hspace{1cm} (10)

$$\beta \approx 1.012 \left( \alpha \sigma_i^2 \right)^{-13/25} + 0.142$$  \hspace{1cm} (11)

$$\eta = \frac{1}{\alpha \Gamma(1 + 1/\beta) g_1(\alpha, \beta)}$$  \hspace{1cm} (12)

where $g_n(\alpha, \beta)$ is defined by

$$g_n(\alpha, \beta) = \sum_{i=0}^{\infty} \frac{(-1)^i \Gamma(\alpha)}{i!(i + 1)\Gamma(\alpha - i)}$$  \hspace{1cm} (13)

Equation (18) is easily computed numerically as the series converges rapidly, and usually as much as 10 terms or less are sufficient for the series to converge (Barrios and Dios 2013).

4 BER over the EW channel model

The average BER of IM/DD with OOK modulation scheme can be expressed by Lyke et al. (2009)

$$\langle \text{BER} \rangle_{\text{OOK}} = \Pr(E) = \frac{1}{2} \int_0^{\infty} f(I) \text{erfc}\left( \frac{\langle \text{SNR} \rangle I}{2} \right) dI$$  \hspace{1cm} (14)

where $\text{erfc}(\cdot)$ is the complementary error function.
Using Eq. (9) in Eq. (14) gives

\[
P_e = \frac{1}{2} \int_0^\infty \frac{\alpha^\beta}{\eta} \left( \frac{I}{\eta} \right)^{\beta-1} \exp \left[ -\left( \frac{I}{\eta} \right)^\beta \right] \left\{ 1 - \exp \left[ -\left( \frac{I}{\eta} \right)^\beta \right] \right\}^{a-1} \times \text{erfc} \left( \frac{\langle \text{SNR} \rangle I}{2} \right) \, dI
\]

(15)

The \text{erfc}(\cdot) and \exp(\cdot) functions can be represented by Meijer’s G function as Kolbig et al. (1985)

\[
\text{erfc}(x) = \frac{1}{\sqrt{\pi}} G_{2,0}^{1,2} \left[ x^2 \mid \frac{1}{0}, \frac{1}{2} \right]
\]

(16)

\[
\exp(x) = G_{0,1}^{1,0} \left[ -x \mid -1 \right]
\]

(17)

Using Eq. (16) in Eq. (15), the average BER can be given as

\[
P_e = \frac{1}{2\sqrt{\pi}} \int_0^\infty G_{1,2}^{2,0} \left[ \frac{(\langle \text{SNR} \rangle I)^2}{4} \mid \frac{1}{0}, \frac{1}{2} \right] \frac{\alpha^\beta}{\eta} \left( \frac{I}{\eta} \right)^{\beta-1} \exp \left[ -\left( \frac{I}{\eta} \right)^\beta \right] \left\{ 1 - \exp \left[ -\left( \frac{I}{\eta} \right)^\beta \right] \right\}^{a-1} \, dI
\]

(18)

The last item in Eq. (18) can be expanded using Newton’s general binomial theorem as

\[
\left\{ 1 - \exp \left[ -\left( \frac{I}{\eta} \right)^\beta \right] \right\}^{a-1} = \sum_{j=0}^{\infty} \frac{(-1)^j \Gamma(a)}{j! \Gamma(a-j)} \exp \left[ -j \left( \frac{I}{\eta} \right)^\beta \right]
\]

(19)

Combining Eqs. (17–19), the average BER represented by Meijer’s function can be expressed by

\[
P_e = \frac{\alpha^\beta}{2\eta \sqrt{\pi}} \sum_{j=0}^{\infty} \frac{(-1)^j \Gamma(a)}{j! \Gamma(a-j)} \int_0^\infty \left( \frac{I}{\eta} \right)^{\beta-1} G_{1,2}^{2,0} \left[ \frac{(\langle \text{SNR} \rangle I)^2}{4} \mid \frac{1}{0}, \frac{1}{2} \right] \times G_{0,1}^{1,0} \left[ (j+1) \left( \frac{I}{\eta} \right)^\beta \mid 0 \right] \, dI
\]

(20)

Setting \( y = (I/\eta)^2 \), yields

\[
P_e = \frac{\alpha^\beta \sqrt{m \pi}}{2\sigma(2\pi)^{3/2}} \left( \frac{l}{\sigma} \right)^{\delta-1} \sum_{j=0}^{\infty} \frac{(-1)^j \Gamma(a)}{j! \Gamma(a-j)} G_{2,m+1}^{m+l} \left[ \left( \frac{\omega}{k} \right)^{m} \left( \frac{l}{\sigma} \right)^{l} \frac{\Delta(l,1-\frac{\beta}{2}), \Delta(l,1-\frac{\beta}{2})}{\Delta(m,0), \Delta(l,-\frac{\beta}{2})} \right]
\]

(21)

where \( \omega = 1 + j, \sigma = (\eta \langle \text{SNR} \rangle)^2 / 8, \Delta(K,A) = \frac{A}{k}, \frac{A+1}{k}, \ldots, \frac{A+k-1}{k}, l \) and \( m \) are integer numbers that should meet \( l/m = \beta/2 \). Equation (21) is in the form of an infinite series but converges rapidly, and usually as much as 30 terms or less are sufficient for the series to converge.
5 Numerical results and discussion

5.1 Average BER analysis for FSO link with Airy beam as carrier

In this section, the average BER of FSO link with Airy beam as carrier is numerically evaluated and compared with that of FSO link with Gaussian beam as carrier. In the following numerical evaluations, wavelength, structure constant, inner and outer scales of turbulence are set as $\lambda=1550\text{nm}$, $C_n^2=10^{-15}\text{m}^{-2/3}$, $l_0=0$, $L_0=\infty$. And $x$, $y$ symmetry is assumed, hence only the $x$ parameter settings are quoted. Additionally, the receiver plane position is selected to coincide with the peak of the Airy beam at the particular propagation distances because Airy beam experiences propagation distance and source parameters dependent bending (Eyjuboglu 2013).

Figure 2 shows the average BER versus the mean SNR at selected propagation distances and at a single setting of the transvers scale factor $w_x=2\text{cm}$ and the exponential decay factor $a_x=0.5$. As seen from Fig. 2, the average BER decreases with the increase of the mean SNR and increases with the increase of the transmission distance. When the average SNR is less than 8 dB, the influence of different propagation distances on the average BER is very small, and the average BER is higher than $1.7\times10^{-3}$. With the increase of mean SNR, the influence of propagation distance on average BER becomes more and more obvious. For example, when the mean SNR is 20 dB, the average BER is about $2.32\times10^{-19}$ when the propagation distance is $L=1000\text{m}$. When the propagation distance increases to 2000 m, the average BER increases by 3 orders of magnitude compared with $L=1000\text{m}$, which is about $5.13\times10^{-16}$. When the propagation distance increases to 3000 m, the average BER increases by 4 orders of magnitude compared with $L=1000\text{m}$, which is about $8.86\times10^{-15}$. When the propagation distance increases to 4000 m, the average BER increases by 5 orders of magnitude compared with $L=1000\text{m}$, which is about $4.16\times10^{-14}$.

Figure 3 shows the average BER versus the mean SNR at selected transvers scale factors and at a single setting of the propagation $L=3000\text{m}$ and the exponential decay factor $a_x=0.5$. As can be seen from the figure, when the transvers scale factor $w_x \leq 1\text{cm}$, the average BER is higher than that when $w_x=1.5\text{cm}$ and $w_x=2\text{cm}$, but lower than that when $w_x=3\text{cm}$. When $w_x>1\text{cm}$, the average BER increases with the increase of $w_x$. For example, when the mean SNR is 20 dB, the average BER is about $2.78\times10^{-16}$ at the selected value of $w_x=1.5\text{cm}$. When $w_x=2\text{cm}$, the average BER increases by an order of magnitude, about $8.86\times10^{-15}$. When $w_x=3\text{cm}$, the average BER increases by 4 orders
of magnitude, about $1.29 \times 10^{-12}$. Therefore, when the transverse scale factor is 1.5 cm or 2 cm, FSO link with Airy beam as carrier can obtain a lower average BER.

In Fig. 4, we fix the propagation distance $L = 3000$ m, the transverse scale factor $w_x = 2$ cm and take the selective values of the exponential decay factor $a_x$, then plot the average BER against mean SNR. Figure 4 reveals that the average BER increases with the exponential decay factor $a_x$. For example, when the average SNR is 20 dB, the average BER is about $6.73 \times 10^{-16}$ when $a_x = 0.2$. When $a_x = 0.5$, the average BER increased by an order of magnitude, about $8.86 \times 10^{-15}$. When $a_x = 1$, the average BER increased by 4 orders of magnitude, about $1.01 \times 10^{-12}$. When $a_x = 1.5$, the average BER increased by 5 orders of magnitude, about $4.08 \times 10^{-11}$. Therefore, when the exponential decay factor $a_x \leq 1$, the change of $a_x$ has a great influence on the average BER. This is due to the fact that when the exponential decay factor of Airy beam decreases, more side lobe is present and Airy beam would travel much farther without diffracting.

### 5.2 Comparison of average BER of FSO links with Airy and Gaussian beams as carrier

In order to compare the average BER of FSO links with Airy and Gaussian beam as carrier, we assume the light sources are one dimensional Airy and Gaussian beams. And one
dimensional Airy beam source power can be calculated as follow (Siviloglou and Christodoulides 2007)

$$P_{AS} = \int_{-\infty}^{\infty} A^2 \left(\frac{s_x}{w_x}\right) \exp\left(\frac{2a_x s_x}{w_x}\right) ds_x = \frac{w_x}{\sqrt{8\pi a_x}} \exp\left(\frac{2a_x^2}{3}\right)$$  \hspace{1cm} (22)

While the source power of one dimensional Gaussian beam with waist radius $\omega_x$ can be expressed as (Eyyuboglu 2013)

$$P_{GS} = \int_{-\infty}^{\infty} \exp\left(-\frac{s_x^2}{\omega_x^2}\right) ds_x = \sqrt{\pi} \omega_x$$  \hspace{1cm} (23)

Firstly, we consider the case that the source powers of Airy and Gaussian beam are the same. In this case, Eqs. (22) and (23) are equal, and we can obtain

$$\omega_x = \pi^{-0.5} P_{AS} = \frac{w_x}{2\pi \sqrt{2a_x}} \exp\left(\frac{2a_x^2}{3}\right)$$  \hspace{1cm} (24)

Therefore, when the source parameters of Airy beam (the transverse scale factor $w_x$ and the exponential decay factor $a_x$) are given, the source parameters of Gaussian beam (the waist radius $\omega_x$) can be calculated by Formula (24), and then its scintillation index can be calculated by relevant theory.

Figure 5 shows the average BER of FSO links with Airy and Gaussian beam as carriers against the mean SNR under the same source power condition. We fix the propagation distance $L = 3000$ m, the exponential decay factor $a_x = 0.5$ and take the selective values of the transverse scale factor $w_x$, then calculate the waist radius of equipower Gaussian beams. We can see that within the given range of transverse scale factor, the average BER of Airy beam link increases with the increase of transverse scale factor, while that of equipower Gaussian beam link is basically unchanged. If the transverse scale factor $w_x$ is less than 2.5 cm, the average BER of Airy beam link is significantly lower than that of equipower Gaussian beam link. But when the transverse scale factor goes up to 3 cm, the average BER of Airy beam link is higher than that of equipower Gaussian beam link. For example, when the mean SNR is 20 dB, the average BER of Airy beam link with $w_x = 1.5$ cm is about $2.78 \times 10^{-16}$, and that of equipower Gaussian beam link is about $4.02 \times 10^{-12}$,
which is 4 orders of magnitude higher. When $w_x = 2\text{cm}$, the average BER of Airy beam link is about $8.86 \times 10^{-15}$, and that of equipower Gaussian beam link is about $3.31 \times 10^{-12}$, which is 3 orders of magnitude higher. When $w_x = 2.5\text{cm}$, the average BER of Airy beam link is about $1.46 \times 10^{-12}$, and that of equipower Gaussian beam link is about the same of $2.69 \times 10^{-12}$. When $w_x = 3\text{cm}$, the average BER of Airy beam link is about $1.55 \times 10^{-11}$, and that of equipower Gaussian beam link is about $2.14 \times 10^{-12}$.

Secondly, we consider the case that the transverse scale factor of Airy beam is the same as the waist radius of Gaussian beam and we call it source width. In this case, the source power can be calculated respectively according to Eqs. (22) and (23).

Figure 6 shows the average BER of FSO links with Airy and Gaussian beam as carriers against the mean SNR under condition of the selected source width value of 1.5 cm. The propagation distance is selected to $L = 3000\text{m}$ and take the selective values of the exponential decay factor $a_x$. It can be seen that the average BER of Gaussian beam link is higher than that of corresponding Airy beam links. For example, when the mean SNR is 20 dB, the average BER of Gaussian beam link is about $1.47 \times 10^{-13}$. While that of Airy beam links are about $2.34 \times 10^{-18}$ and $2.78 \times 10^{-16}$ for the case of exponential decay factor value of 0.2 and 0.5 respectively.

Figure 7 gives comparison curve of the average BER between Airy and Gaussian beam links when the source width value is 2 cm. And the results are similar to those in Fig. 6. When the mean SNR is 20 dB, the average BER of Gaussian beam link is about
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6.26 × 10⁻¹⁴, which is lower than that of Gaussian beam link with source width of 1.5 cm. For Airy beam link with \( a_x = 0.2 \) and \( w_x = 2 \text{cm} \), the corresponding average BER is about 6.73 × 10⁻¹⁶. And for Airy beam link with \( a_x = 0.5 \) and \( w_x = 2 \text{cm} \), the corresponding average BER is about 8.86 × 10⁻¹⁵. Comparing the results of Figs. 6 and 7, we can see that the average BER of Gaussian beam link decreases with the increase of source width. While the average BER of Airy beam links with source width of 2 cm is lower than that of Airy beam links with source width of 1.5 cm.

6 Conclusion

The average BER performance of FSO ink with Airy beam as carrier under weak turbulence was analyzed. Based on scintillation index model of Airy beam and EW channel model, we derived the expression of the average BER of FSO link with Airy beam as carrier. The BER performance of FSO link with Airy beam as carrier was then numerically evaluated and compared with that of FSO link with Gaussian beam as carrier. The results show that the average BER of FSO with Airy beam as carrier decreases with the increase of mean SNR and increases with the increase of transmission distance. When the transverse scale factor of Airy beam is about 1.5 cm, a relatively low average BER can be obtained. Decreasing the exponential decay factor of Airy beam, a better average BER of FSO link with Airy beam as carrier can be achieved. Under condition of the same source power, when the transverse scale factor of Airy beam is about 1.5 cm, the average BER of FSO link with Airy beam as carrier is significantly lower than that of corresponding FSO link with Gaussian beam as carrier. When the source width of Airy and Gaussian beam are the same, if the transverse scale factor of Airy beam is less than 2 cm and its exponential decay factor less than 1, the average BER of FSO link with Airy beam as carrier is still lower than that of corresponding FSO link with Gaussian beam as carrier. To sum up, FSO link with Airy beam as carrier has better average BER performance than FSO link with Gaussian beam as carrier. The results can be used as a reference for application of Airy beam in the design of FSO communication link.

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