# Analysis of Suppressing Turbulence-induced Noise and Fading in Terrestrial Free-space Optical Communications

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# Analysis of Suppressing Turbulence-induced Noise and Fading in Terrestrial Free-space Optical Communications

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**Abstract**: Terrestrial FSO Communication is an alternative and promising telecommunication technology in addition to existing technologies, such as fiber optics and microwave, to provide flexibility in point-to-point telecommunications services. Even though it has flexibility in deployment and has a relatively larger bandwidth than microwave technology, the terrestrial FSOC has major weaknesses in the signal propagation matter due to constantly fluctuating atmospheric conditions in the form of scattering and beam wandering, and simultaneously causes temporal and spatial noise in the receiver side. It is clear that the main weakness of the terrestrial FSOC is the influence of the Turbulence-Induced Noise and Fading effect. Many papers propose suppressing the fading effect with various methods. On the receiver side, a spatial filter technique has been developed using pinholes to suppress fluctuations due to atmospheric turbulence. Multiple receivers are also proposed to compensate for the fading effect. Statistically based detection techniques applied to sampling-and-hold circuits are also widely discussed. This paper proposes a new method of suppressing fading effects by using a CCD sensor and processing algorithm on the receiver side to track the focus point in the receiver, which constantly moves due to beam-wandering by atmospheric turbulence. Solving the problem of intensity fluctuation due to atmospheric turbulence cannot only be solved on the receiver side. Due to the fading effect, the transmitter side must have a feedback channel from the receiver and bit rate setting control to compensate for random intensity fluctuation. With this feedback control, it is expected FSOC becomes feasible technology as an alternative to the existing terrestrial telecommunication technologies.

Keywords: terrestrial; free-space optical communications; turbulence-induced noise; fading; point-to-point communication; CCD sensor; feedback control

## 1. Introduction

The development of business interactions globally increases the need for data communication and drives the quantity of telecommunication technology infrastructure development[1-3]. In the last decades, telecommunications technology has developed rapidly. Starting from copper wire-based network technology, then increasing to terrestrial radio, microwave, and even geosynchronous satellites. Some of these telecommunication technologies were well-developed until the 1960s to meet the various needs of fixed and remote flexible communication. Even in the late 1960s, with the emergence of semiconductor laser technology, the National Aeronautics and Space Administration (NASA) proposed the use of free space optical communications (FSOC), which is believed to have a much more comprehensive bandwidth advantage than the microwave, to be applied in terrestrial and deep space communications. However, because the need was yet to be urgent and the emergence of new fiber optic technology in the early 1970s, the proposal for developing FSOC technology faded.

Since the early 1970s, fiber-optical communication technology has developed rapidly in quality and quantity. In the previous decade, bandwidth was measured in MHz, so with the advent of laser and fiberoptics technology, the bandwidth size became GigaHertz. Furthermore, the range of terrestrial communications becomes unlimited on the earth's surface. Along with the development of fiberoptics from multimode to singlemode, and finally, highspeed lasers with very narrow linewidths of a few kHz, enabling wide bandwidths to carry digital information in several Tbps over hundreds or even thousands of kilometers, as well as defeating the chromatic dispersion effect. Lightwave fiberoptic and cellular RF technologies have together contributed as a foundation for popularizing the internet and any social communication technologies and applications globally today.

Fiberoptic technology far beats microwave technology in terms of communication bandwidth. Nevertheless, in terms of flexibility, microwave technology is much easier to install than fiber optics. Both parameters, namely broad bandwidth capability and installation flexibility, complement each other in supporting telecommunication services. Hence, microwave and satellite technology is still needed to fill areas fiberoptics services have yet to reach.

Since the beginning of the 21st century, space exploration, especially on the Moon and planet Mars, has been carried out by NASA and the European Space Agency (ESA) using various robots operating on the planet's surface or orbiting the intended planet. In its operations, much data and information is exchanged through the control and monitoring of operational and experimental data, including image and video transmission, so a transmission engineering system is needed to support high-speed or large bandwidth communication. Fiberoptics, which is very powerful with significant bandwidth for terrestrial communications, cannot be used for deep-space communication. At the same time, microwave systems have a small bandwidth, hence, the best alternative is using free-space optics to support deep-space communications.

The use of Free-Space Optics as the backbone of deep-space communications in the future is indisputable[4)]. However, this paper will discuss FSOC as an alternative technology for terrestrial telecommunication systems, especially point-to-point communication[5-7)]. FSOC has a bandwidth capability far above the microwave. However, the use of a much shorter wavelength than the microwave causes atmospheric attenuation to be much more significant due to Rayleigh scattering and atmospheric gas absorption. Having mutual strengths and weaknesses, FSOC and microwave systems complement each other to support short and medium-distance telecommunications, which are relatively difficult to use fiberoptics for flexibility.

In this paper, we discuss the potential of FSOC technology as an alternative for point-to-point or line-of-sight terrestrial communications and its problems and weaknesses. There are at least three most significant problems of FSO in terrestrial communication. The first is noise caused by turbulence in atmospheric propagation. As is already well known, due to the influence of local temperature differences, there will be airflow, air turbulence, and differences in the density of the atmosphere distributed along the FSO propagation path. This condition causes the emergence of temporally distributed lenses and even micro lenses along the FSO propagation path. This condition will result in the beam's scattering, deflection, and divergence, which is a time function. The second is scattering caused by pollutants in the air in the form of smoke pollution, dust, and even water vapor. The third is certain types of gas that absorb the beam at the wavelength used. These three effects cause the modulated amplitude and phase signals to arrive in front of the receiver (RX) lens as a noisy modulated wavefront. The wavefront accumulates space and time noise in the form of high-frequency noise fluctuations and fading, which limits the propagation distance capability and FSOC communication bandwidth[8-12)]. The received wavefront in front of the RX aperture lens is then focused on the receiving detector as a combined noise on the received wavefront.

This paper proposes and discusses a new method of suppressing fading effects by using a CCD sensor and processing algorithm on the receiver side to track the focus point in the receiver, which constantly moves due to beam-wandering by atmospheric turbulence so that a fundamental beam with low noise can always be obtained. Solving the problem of intensity fluctuation due to atmospheric turbulence cannot only be solved on the receiver side. A feedback control must be implemented between the receiver (RX) and transmitter (TX) to compensate for fluctuation in intensity due to the fading effect and control bit rate settings. With this feedback control, it is hoped that FSOC will become a feasible alternative to the existing terrestrial telecommunication technologies.

## 2. Theoretical Analysis

The largest problem in terrestrial FSOC are noise and fading caused by atmospheric turbulence. This turbulence-induced noise causes the beam axis between the Transmitter (TX) and the Receiver (RX) to change angle according to the function of time and the amount of turbulence. Apart from the beam axis, the wavefront received at the RX will vary as a function of time and space, manifested in the amplitude and phase modulation of the signal carried by the beam. The effect in the RX detector will be high-frequency noise fluctuations and fading. Several techniques have been developed to model turbulence-induced noise and fading[13-16)]. If averaged on the wavefront, the receiver will experience a signal modulated by amplitude and phase caused by scattering and absorption by the atmosphere.

Atmospheric turbulence-induced noise can be analyzed with an initial approach using additive Gaussian statistics. The lens focuses the wavefront on the receiving end onto the RX detector. The focusing process accumulates all the intensity of the wavefront area on the side of the receiving lens to the RX sensor. In the mathematical model, it is written as follows:

$$I_{RX} = \iint_{(x,y)} I_{rx}(x,y)\, dydx \tag{1}$$

where $I_{RX}$ is the total intensity on the sensor and $I_{rx}(x,y)$ is the intensity at each point on the wavefront of the receiving lens. Assuming that the distance between TX and RX is very far, so that in front of the RX lens is a planar wavefront with lens radius $r$ and area $A = \pi r^2$, the average intensity on the surface of the receiving lens is written as:

$$\overline{I_{rx}} = \frac{I_{RX}}{A} = \frac{1}{2\pi r^2} \iint_{(x,y)} I_{rx}(x,y)\, dydx \quad (2)$$

From the perspective of Gaussian sampling probability, the greater the number of samples $N$, the variance error will be the opposite value of $1/N$. If analogous to the theory of telecommunication systems, this variance error is the noise energy in the system. Suppose the area of $A$ planar wavefront in front of the receiving lens is associated with the number of samples $N$ in the discrete probability function. In that case, we can write the relation between the area of the receiving wavefront and the amount of atmospheric noise that the RX sensor will receive as follows:

$$\sigma_2^2 = \frac{A_1}{A_2}\sigma_1^2 \quad (3)$$

$\sigma_2^2$ is the noise variance on the RX sensor that uses a receiving lens with an area of $A_2$, while $\sigma_1^2$ is the noise variance on the RX sensor that uses a receiving lens with an area of $A_1$. So it can be concluded that expanding the beam and receiving lens will reduce the noise variance in the RX detector. The conclusion is following the understanding of turbulence-induced noise based on the correlation length of random intensity and phase fluctuation, which has been described above. The size of the receiving lens depends on distance, atmospheric disturbances, cost reason, beam wandering, laser safety, and lens care.

However, in the observations we made in the experimental chamber to illustrate atmospheric turbulence effects on FSOC[17,18], using only the additive Gaussian probabilistic noise model is not sufficient. We must consider as well the modulated Gaussian probabilistic noise model. The three signal parameters that the turbulence process can modulate are amplitude, phase, and polarization, while the frequency parameter is relatively unaffected in this turbulence process. Furthermore, due to the use of an RX detector which is not sensitive to changes in polarization, the effect of noise polarization can be ignored in this analysis. Only two wave parameters will be modulated by atmospheric propagation and turbulence, namely amplitude and phase. There are two statistical parameters connected to turbulence-induced noise, namely: (1) $r_0$, the correlation length of random intensity and phase fluctuation, and (2) $\tau_0$, the correlation time of random intensity and phase fluctuation[19]. In order to suppress the effects of turbulence-induced noise and fading, the RX system must be designed such that: (1) RX lens aperture with radius $R > r_0$, much larger would be better; And (2) RX observation interval in the sampling and hold detection circuit $T > \tau_0$, in order to be able to average the noise to 0. Increasing $R$ has consequences for the RX system costs while increasing $T$ will reduce the communication speed capability of the overall system.

The two models, additive and modulated Gaussian probabilistic noise, together form the condition that occurs on the wavefront in front of the RX lens, namely random turbulence-induced noise based on the correlation length and time of random intensity and phase fluctuation. In this paper, we analyze a mathematical model to describe the random fluctuated spatial and time noise wavefront conditions and the methods to reduce them.

### 2.1 RX Receiving Lens Works as Spatial Fourier Transformer

The noisy received wavefront $U(x,y)$ in front of the receiving lens, when analyzed from a wave-optics perspective, is a composite or superposition of multiple planar wavefronts that propagate off the optical axis[20]. If the received wavefront $U(x,y)$ is focused by the receiving lens, various focal points from each of the planar wavefronts that make up the image will be seen in the focal plane of the lens, as shown in Fig. 1 below:

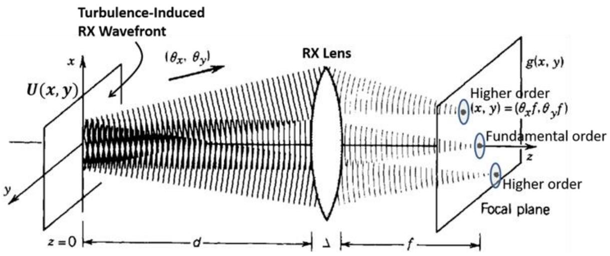



**Fig. 1:** The receiving lens works as a spatial Fourier transformer[20].

$$U(x,y) = \iint F(\nu_x,\nu_y)\exp[-j2\pi(\nu_x x + \nu_y y)]d\nu_x d\nu_y \quad (4)$$

where $\nu_x$ and $\nu_y$ are the spatial frequencies in $x$ and $y$ directions on RX wavefront $xy$ plane, respectively and $F(\nu_x,\nu_y)$ is the amplitude of the mixing spatial frequencies and $U(x,y)$ is the total electromagnetic field at point $(x,y)$.

The receiving lens works as a spatial Fourier transformer. It transforms the temporal-spatial noisy input wavefront to be spatially harmonic focal points on the focal plane. On the focal point plane of the receiving lens exists various focal points of each harmonic planar wavefronts surrounding the center of the fundamental focal point.

The total received power at receiving lens is *Pr* and the fundamental or clean signal power is $P_0$.

$$P_r = \iint |U(x,y)|^2\ dx\,dy \quad (5)$$

The light beam falling around the fundamental focal point is considered as random amplitude phase noise to the fundamental. Meanwhile, those that fall on the fundamental focal point are considered the clean wavefront.

The SNR when the RX detector receives all noisy signals:

$$SNR = \frac{P_0}{P_r - P_0} \quad (6)$$

The focal point is not a singularity point but is an area that, in wave optics, is often referred to as the beam-waist area. The relationship between receiving lens and beam waist diameter at the focal point is formulated in Eq.7 based on Ref.[20].

$$D_0 \approx \frac{4\lambda}{\pi D} f \quad (7)$$

where $D$ is the receiving wavefront diameter right in front of the receiving lens. $D_0$ is the beam waist diameter at focal point, $f$ is the focal length and $\lambda$ is the wavelength.

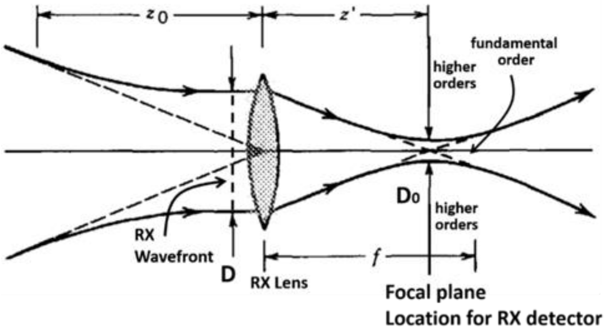



**Fig. 2:** The structure of the RX lens and RX detector, where the RX detector is placed on the RX focal plane[20].

As previously described, in the RX wavefront, there is the accumulation of noise in the form of fluctuations in amplitude and phase at high and low frequencies, also called fading. Fading can be divided into two types: fast fading for high-frequency fading phenomena and slow fading for low-frequency phenomena, as illustrated in Fig. 3 below.

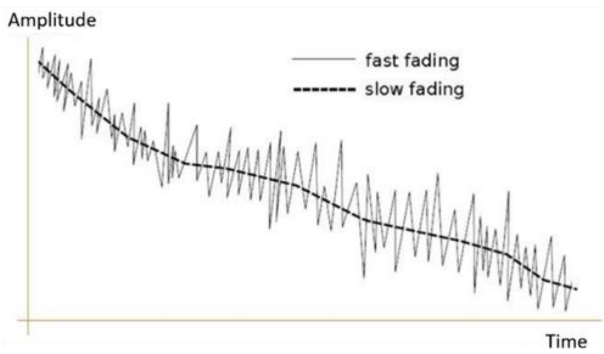
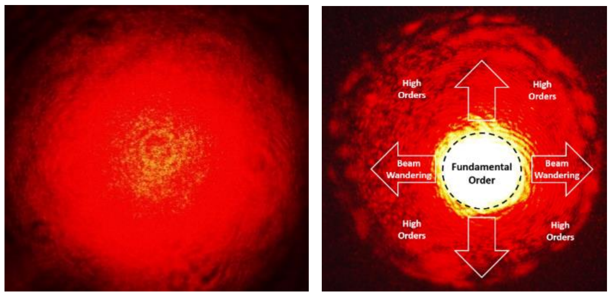



**Fig. 3:** Accumulation of fast and slow fading on the RX detector if all orders (fundamental and higher orders) are received.

Suppose the RX detector receives the entire focused beam through fundamentals and higher orders. In that case, it will be the same as receiving the RX wavefront without using an RX lens because both the fundamental signal and noise will be received entirely. Higher orders signals are part of the clean signals modulated by atmospheric turbulence. Meanwhile, the fundamental order is the clean signal itself which falls precisely on the optical axis of the RX system. The SNR in the fundamental order is much higher than if all the orders were combined into one in the RX detector.

Below is an illustration of the RX wavefront and signal projection spatially Fourier transformed by the RX lens on the RX focal plane:




(a) (b)

**Fig. 4:** (a) Accumulation of noise, fast and slow fading on the RX wavefront in front of the RX lens, and (b) RX lens performs spatial Fourier transforming, fundamental order in the middle can be separated from higher orders.

Fig. 4(a) above shows the wavefront plane in front of the RX lens. All spatial noise orders merge into the fundamental signal. However, after going through the focusing process by the RX lens, as shown in Fig. 4(b), on the focal plane, there will be a separation between the fundamental beam, which is clean from the noise, and the higher-order noises, which are diffracted off. Fig. 4(b) illustrates when beam-wandering occurs, the fundamental order can move from right to left, up and down. The magnitude of the spatial movement depends on the magnitude of the turbulence effect and the distance between TX and RX.

Suppressing spatially turbulence-induced noise is if we only accept fundamental orders and eliminate higher orders. One of the techniques used to suppress higher orders of turbulence-induced noise is to use a pinhole device as a low-pass filter for spatial frequency noise[17),18)] . Pinholes work very well to suppress higher spatial orders, which carry turbulence-induced noise when the fundamental order remains on the optical axis, and there is no beam wandering process. By nature, turbulence-induced noise will cause two things: (1) high-frequency amplitude-phase spatial noise and fading on the RX wavefront and (2) beam wandering, which means that the central axis of the signal shifts and forms an angle to the optical axis of the RX system.

## 3. Discussions

From the description above, to suppress turbulence-induced noise, the cases can be divided into:

1) Turbulence-induced noise and fading without beam wandering.
2) Turbulence-induced noise and fading with beam wandering.

### 3.1 Turbulence-induced noise and fading without beam wandering

The first assumption is that the noise can be modeled as an additive Gaussian noise statistic. As described in Eq. 1-3, when the entire noisy signal is focused on the RX detector, the additive noise effect will be reduced due to the averaging effect of the focusing process. Noise energy will be inversely proportional to the multiple of the RX lens aperture area, which means that the larger the RX lens aperture will proportionally reduce the effect of additive Gaussian Noise.

Based on the observations of turbulence-induced noise and fading, apart from being modeled in additive Gaussian noise, it is considered to be modeled in a modulated Gaussian probabilistic noise model. The two physical signal parameters will be modulated by atmospheric propagation and turbulence, namely amplitude and phase. While the two statistical parameters are connected to turbulence-induced noise, namely: (1) $r_0$, the correlation length of random intensity and phase fluctuation dan (2) $\tau_0$, the correlation time of random intensity and phase fluctuation[17),19)]. In order to surpress turbulence-induced noise and fading, the RX system must be designed accordingly: (1) RX lens aperture radius $R > r_0$, larger is better; this follows what is suggested when using the additive Gaussian noise model; and (2) RX observation interval in sampling and hold detection circuit, $T > \tau_0$, in order to be able to average the noise to 0. Enlarging $R$ (aperture radius or diameter) has a consequence for the RX system cost, while increasing $T$ will reduce the communication speed capability of the overall system.

In addition to increasing the aperture of the RX lens, several suggestions for using spatial diversity in multi-input and multi-output systems[19)], as illustrated in Fig. 5, following:

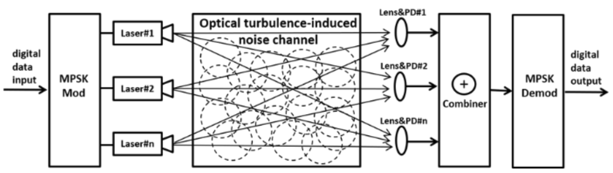



**Fig. 5:** Illustration of the TX-RX FSOC structure based on a spatial diversity multi-input and multi-output (MIMO) system.

The TX-RX structure based on spatial diversity multi-input and multi-output (MIMO) system can suppress turbulence-induced noise and fading effects more than a single TX-RX system. However, if the effect of turbulence-induced noise and fading is very large, then the bit error rate (BER) increases above the threshold, which requires feedback control between TX and RX to overcome $r_0$, $\tau_0$ noise and fading effects.

Overcoming the effects of $r_0$ dan $\tau_0$ can be done with feedback from RX[21)], which tells TX to lower its bit rate. Meanwhile, to reduce the fading effect, this can be done by increasing the intensity of the light sources in the TX. Increasing the gain in RX is recommended if the increase in TX intensity is at its maximum because the increase in RX gain correlates with an increase in the overall noise figure of the RX system. The following Fig. 6 is a modification of Fig. 5. by engaging a feedback control circuit to suppress turbulence-induced noise and fading effects. The feedback channel is illustrated in Fig. 6 below, which does not need to use a high-speed channel, thus preventing this feedback channel from signaling errors.

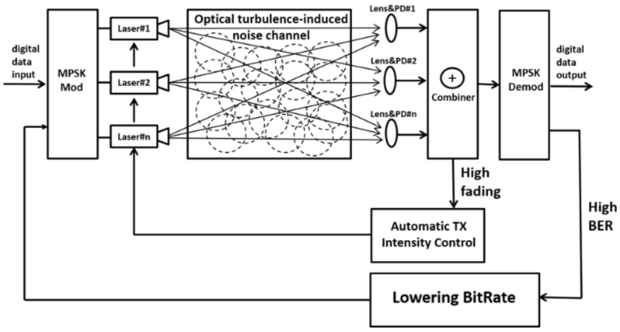



**Fig. 6:** Illustration of the TX-RX FSOC structure based on a spatial diversity multi-input and multi-output (MIMO) system modified with a feedback circuit to suppress turbulence-induced noise and fading effects.

### 3.2 Turbulence-induced noise and fading with beam wandering

Conditions of turbulence-induced noise and fading without beam wandering will only occur if applied at a very close distance of about hundreds of meters. However, in the middle range of 4 to 5 km, the probability of fading caused by beam wandering is very high. Even a minimal change in the TX-RX optical path angle can cause a significant enough shift in the focal point in the RX detector, which causes signal loss[22-28)]. If the shift is slight in the RX detector, it will cause a change in the amplitude of the signal received at the detector, often called fading. The difference in fading here is caused by beam wandering, which causes miss detection by the RX detector.

Meanwhile, the fading discussion in subsection 3.1 (Turbulence-induced noise and fading without beam wandering), more caused by variations in phase changes and noise in the RX wavefront. In contrast, the fading here is caused by beam wandering. Hence, the solution to suppress or avoid fading effects due to beam wandering differs from the previous technique, which used feedback between TX and RX.

As illustrated in Fig. 4(b), the incoming wavefront beam is focused by the RX lens onto the RX detector plane located behind the focal plane. The focused beam is not a point but an area, as illustrated in Fig. 4(b). The area has a diameter, often called the beam waist diameter, written in Eq.7. The cleanest area or fundamental order and the in-phase optical carrier are located in the middle. Meanwhile, around it are higher orders which have phase and amplitude variations. The signal that is less noise and fading is in the fundamental area of the middle order, and only that fundamental area is needed. Meanwhile, those with higher orders must be suppressed or eliminated. Due to the wandering beam effect, the fundamental order area will dance in the RX Detector area according to the shift in the TX-RX optical axis. If the signal is received with a single APD detector, it will likely experience extensive fading during beam wandering. In addition, using a single APD detector causes all orders, both clean signals (fundamental) and those full of turbulence-induced noise (higher orders), to enter the RX processor. There is no suppression of turbulence-induced noise and fading at all except by increasing the aperture of the RX lens and applying the structure of the MIMO system. To further suppress turbulence-induced fading without and with beam wandering, we propose using a Charge Coupled Device (CCD) array as an RX detector[17),29)].

With the CCD, it is possible on the RX side to eliminate signals from higher orders which are full of turbulence-induced noise by programming them only to use the CCD address that gets the fundamental order illumination, as well as predicting focal pointing by programming to determine the location of the fundamental order on the CCD[17),30),31)]. Using the RX CCD is expected to suppress turbulence-induced noise and fading and the beam wandering effect. Structurally, the TX-RX FSOC, which can suppress overall turbulence-induced noise, fading, and beam wandering, is described in Fig. 7. which is a modification of Fig. 6.

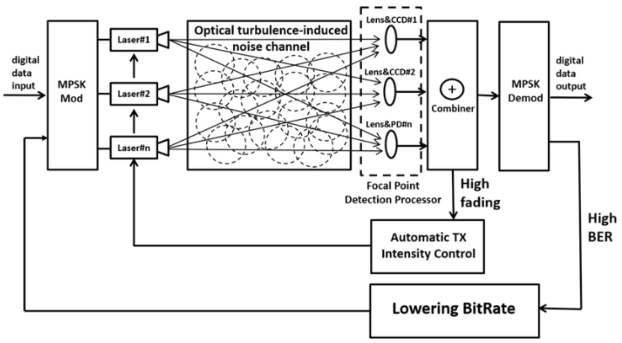



**Fig. 7:** The TX-RX FSOC structure is complete with a spatial diversity multi-input and multi-output (MIMO) system with a feedback circuit and a beam wandering processor to suppress turbulence-induced noise and fading effects.

The system's complexity in suppressing the fading effect depends on the magnitude of the atmospheric turbulence conditions involving differences in temperature, wind, rainfall, and the TX-RX's distance. Atmospheric conditions are, of course, a factor that we cannot control. We can only control the distance TX-RX or distance D and the communication bandwidth B. The product of BD is a constant. If we want to extend the distance D, the consequence is to lower the bit rate or bandwidth B so that BD is always constant.

The BD constant value automatically increases if the TX-RX system has a noise and fading suppression system, as described above. If the turbulence conditions are low, this can be solved minimally by widening the RX aperture. However, if the condition worsens, a more sophisticated system must be used, as illustrated in Fig.6 and even the most sophisticated shown by Fig. 7.

## 4. Conclusions

Terrestrial FSOC System has the advantage of installation flexibility compared to fiber optics and much wider bandwidth than microwave systems; hence, it can be an alternative substitute for the two systems for specific needs. Nevertheless, despite its advantages, the terrestrial FSOC system has fundamental weaknesses, namely the atmospheric turbulence-induced noise and fading effects. Most of the noise present in the terrestrial FSOC system is due to turbulence-induced noise and fading. In this paper, we propose the use of a CCD sensor at the receiver side, which is equipped with a processing algorithm to track the focus point, which is always moving due to beam-wandering by atmospheric turbulence. Hence, it is always assured that the clean fundamental beam can be detected. The intensity fluctuation problem due to atmospheric turbulence cannot be solved merely on the receiver side; a feedback control must be implemented between the receiver (RX) and transmitter (TX) to compensate for intensity fluctuation and bit rate settings due to the fading effect. With this feedback control, it can be expected that FSOC will become a feasible alternative to the existing terrestrial telecommunication technologies.

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