Adaptive Optical Transmitter and Receiver for Optical Wireless Communication System with Multiscattering Channel

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ABSTRACT

Optical wireless communication from tower to tower on the earth's surface consists of heavy rain, snow, hail, haze etc. are part of optical channel. Propagation of optical signals through these atmospheric turbulence channels causes attenuation and scattering of the transmitted beam. These effects reduce the received signal quality and decrease the information bandwidth of the system. The atmospheric effects are analyzed and proposed an adaptive optical transmitter and receiver under multiscattering condition. Based on the value of visibility in the atmosphere, the transmitter is adapted by changing its transmitted power. Intensity Modulation (IM)/Direct Detection (DD) links using On-Off Keying (OOK) is applied in this paper. The transmitted optical signals are scattered more by the atmospheric turbulence channel and considered as reflected signals. Multiple optical receivers are placed with small space diversion then combined by maximum-likelihood sequence detection (MLSD) techniques. The adaptive optical transmitter was designed to meet the worst climatic conditions. From the receiver point of view, the receiver sensitivity can be improved based on atmospheric turbulence effects. So, the adaptive optical receiver was designed by implementing matched filter in the front-end of the optical receiver. This matched filter response will be adaptive in nature to improve the performance of the optical receiver under worst climatic conditions. Hence, the entire Optical Wireless Communication System model was derived and obtained the results for various climatic conditions. This Optical Wireless Communication links are very much useful to meet the high availability requirements of the telecommunication industries. For, Laser power through the atmosphere, the exponential Beers-Lambert law was used and for simulation MATLAB 6.1 software with Pentium-IV personal computer was used.

Keywords: optical wireless, adaptive system, attenuation and scattering, turbulence channel, hail, haze.

I. INTRODUCTION

The Optical Wireless Communication is the only solution to the next generation Wireless Communication due to some of the advantages over the existing RF wireless systems are (1) large information bandwidth (THz-range), (2) low transmitted power (mW-range), (3) high directivity (beamwidth mrad), (4) high speed data transmission (Gbps), (5) high signal security, (6) free from electromagnetic interference, (7) very less Bit Error Rate ($10^{-12}$), (8) size and weight of the optical components are very small etc. Fig(i) and (ii) represents the general block diagram of optical wireless communication system for point to point optical link for both clear sky and heavy rain conditions respectively.

![Fig (1). Optical wireless communication system under clear sky condition.](image-url)
In the optical wireless communication systems, the Laser Beam from the source is used as the carrier wave and is transmitted through the free-space( atmosphere) directly. Because of highly directional beam, the transmitted signal is traveling in the straight line with long distance. The transmitter and receiver should be in face-to-face, i.e., line of sight (LOS) condition to be applied for optical wireless communication system. Even though optical wireless communication system has great potential, there are some limitations to overcome the existing optical wireless communication becomes highly efficient one. The major problem in the available optical wireless communication system is multiscattering effect, i.e., in the presence of fog, haze, rain, mist etc. in the atmosphere causes serious signal degradation in the propagation path. Under clear sky condition, the optical wireless communication system has very less attenuation and scattering effects, but in the fog or snows form condition, the attenuation and scattering effects are more. This effect limits the maximum system bandwidth and increases bit error rate (BER). The use of optical wireless communication can be improved only when the environmental effects are controlled or overcome by system performance. In the existing research papers, the impulse response function of atmospheric clouds for optical pulses is derived and modeled the optical wireless communication system. This system can be used only for earth to low earth orbit (LEO) satellites, geo synchronous orbit (GEO) satellites and downwards. In this paper, we propose the optical wireless communication system under worst climatic condition, is considered as atmospheric turbulence channel, on the Earth’s surface between tower to tower or high building to building. So, we have to analyze these effects by extension search of the literature survey, we propose a novel approach to overcome these problems.

II. ADAPTIVE TRANSMITTER AND RECEIVER WITH CHANNEL DESCRIPTION

The changes in the parameters of the channels, like atmospheric attenuation coefficient, radius of the scattering particle, visibility, the size distribution of the scattering particles etc. can be measured and the optical transmitter can be adapted to these changes. The optical transmitter receives information about the channel conditions through reflected signal from channel itself. Based on the amount of reflected signals, it is observed that the visibility and reflected energies are inversely proportional to each other, and derived the mathematical equation for it. This reflected power is processed in the optical transmitter by the way of calculating signal level, time delay between transmitted and reflected powers and fixing the threshold level. Depends upon this processed reflected signal, the control unit was asked to control the laser power output by signal processor. Hence, the output laser power can be increased or decreased, depends upon the reflected signal. So, the optical transmitter can be adaptive in transmission.
In this paper we describe an engineering model of an adaptive transmitter for optical wireless communication through atmospheric turbulence channel with system approach and analysis of climatic effects on atmosphere. The engineering model of an adaptive optical wireless communication system that deals with the variation of the reflected power from the snow or rain like effects of the transmitted power and the variation of the attenuation of the environmental conditions[4]. We strongly believed that this approach of an adaptive optical transmission system for rainy channel should improve the performance of optical wireless communication system. Here, we explain the principles of the proposed adaptive optical wireless communication system and present the mathematical analysis of the adaptive system.

In the Fig(3), the adaptive optical transmitter includes a laser source in which the output power can be varied according to climatic conditions. The optical signal processor consists of delay calculation unit, comparator, decision threshold, amplifiers etc. which process the reflected signals from the turbulence channel and gives the instruction to the control unit. All these operations are performed in the optical domain itself by the optical signal processor. So that we choose the operating wavelength of 1550nm which is suitable for optical wireless communication[5] and the optical components are available in that wavelength also[6]. The control unit, also receives the data or message electrical signal input from the source, controls the laser source power according to the instructions coming from signal processor. Hence, the adaptiveness of the optical transmitter is maintained.

Similarly the optical receiver is designed for adaptive in nature under various climatic conditions. The front end of adaptive optical receiver consist the optical beam forming unit and MLSD units similar to adaptive transmitter and the functions are also same. After combining all these received signals, the combined signal is sent to the matched filter. This matched filter plays major role in the adaptive optical receiver and the response of this filter is varying depends upon the strength of the received signal. In order to maintain the sensitivity of the receiver above 1 µm, the response of the matched filter is varying. So that the matched filter is designed by the function as,

$$F(f) = \left[ (Y_1 - Y_0) / (Z^2 + 2Z + 1) \right] G_1 \left[ \left( k_1 (k_2/2\pi)^2 \right) + \left( k_3 (k_4/2\pi)^2 \right) + \ldots \ldots + \left( k_6 (k_7/2\pi)^2 \right) \right] \exp(-j2\pi ft_d)$$

Where, $F(f)$ is the adaptive filter transfer function, $Y_1$ & $Y_0$are functions of receiver parameters and transmitter power for receiving 1 and 0 respectively, $k_1,k_2,\ldots,k_6$ are double gamma function constants depends upon the visibilities, f is the frequency, and $t_d$ is the time at which signal is at the filter output, and $Z^2 = (G_0/G_1)$, where $G_0$&$G_1$ are the noise spectral densities of the receiver for receiving 0 and 1 respectively.
Fig (4). Adaptive Optical Receiver

After received the signal by the matched filter, it is passed through optical detector then processes it like ordinary optical receiver

III. NUMERICAL ANALYSIS

By neglecting the optical efficiencies, detector noises etc, the link equation for optical wireless communication system using Beers-Lambert law is given by,

\[ P_r = P_t \left( \frac{A_r}{(D.R)^2} \right) \exp(-sR) \]  

(1)

Where, \( P_r \) is the received power at the optical receiver in Watts, \( P_t \) is the transmitted power at the optical transmitter in Watts, \( A_r \) is the receiver aperture area in cm\(^2\) with the radius of \( r = 20\) cm, the transmit beam divergence \( D = 2\) mrad, the distance between the optical transmitter and receiver (range) \( R = 2\) km and \( s \) is the atmospheric attenuation coefficient in km\(^{-1}\) is given by

\[ s = \begin{cases} 3.91/V \left( \frac{?}{550 \text{ nm}} \right)^q & \text{for } V > 50 \text{ km} \\ 1.6 & \text{for } V = 50 \text{ km} \\ 1.3 & \text{for } 6 \text{ km} < V < 50 \text{ km} \\ 0.16V + 0.34 & \text{for } 1 \text{ km} < V < 6 \text{ km} \\ V - 0.5 & \text{for } 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases} \]

From this equation the amount of received power is directly proportional to the amount of transmitted power and area of the collection aperture. It is inversely proportional to the square of the beam divergence and link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient times the link range. In the above equation the variables \( P_r, A_r, D \) and \( R \) are controllable and \( s \) is uncontrollable and depends upon climatic conditions, also independent of wavelength in heavy attenuation (worst climatic conditions). But, \( P_r \) is exponentially decreases with the product of \( s \) and \( R \). Hence, \( s \) and \( R \) play major role in the amount of \( P_r \), but \( s \) is not controllable and \( R \) should be maintained at moderate level, otherwise the entire optical wireless communication system becomes highly expensive. The equ (1) is used to calculate the \( P_r \) at the \( R_r \), under various climatic conditions. From the datas, the receiver sensitivity should be greater than 1\( \mu \)w and up to this minimum level the optical receiver is able to detect the received signal. Hence the adaptiveness can be applied to this minimum received power level under worst atmospheric conditions.

It is assumed that the atmospheric turbulence effects occurred for entire transmission path and the range \( R \) is taken as 1m. So the received power at the atmospheric turbulence channel is calculated using the equ.

\[ P_{\text{ATC}} = P_t \left( \frac{A_{\text{ATC}}}{(D.R)^2} \right) \exp(-sR) \]  

(2)

Where, \( P_{\text{ATC}} \) is the received power at atmospheric turbulence channel in Watts, \( P_t \) is the transmitted power at Transmitter towards channel in Watts, \( A_{\text{ATC}} \) is the area of the atmospheric scattering particles like fog, rain drops, snow, hail, etc and it varies from 20\( \mu \)m to 50 mm depends upon climatic conditions and \( D \) is the transmit beam divergence of Laser source = 2mrad.

The received power at the atmospheric turbulence channel are scattered to many directions. A portion of this scattered signals are received at the transmitter itself. Based on the reflectivity of the atmospheric turbulence channel, the reflected power is received in the transmitter by Maximum–Likelihood Sequence Detection (MLSD) techniques. The reflected power obtained in the transmitter is given by the equ.
\[ P_{\text{reflect}} = P_{\text{ATC}} \left[ A_T / (D \cdot R)^2 \right] \exp(-sR) \]  

(3)

Where \( P_{\text{reflect}} \) is the reflected power and received at the transmitter in W, \( P_{\text{ATC}} \) is the received power at atmospheric turbulence channel and considered as the transmitted power in W, \( A_T \) is the receiver aperture area of radius \( r=5\text{cm} \) which is the transmitter itself, \( D \) is the beam divergence and highly important one, because the scattered beam is obtained here, so that \( D \) is considered as high value of 200 mrad, \( R \) is the range =1m and \( s \) is the attenuation coefficient under worst climatic conditions (V=0.5km).

A part of the reflected/scattered beams received in the transmitter are processed in the optical signal processor. The optical signal processor collects the reflected beams from many directions by placing multiple optical detectors and combines these signals by Maximum–Likelihood Sequence Detection (MLSD) techniques using optical beam former. Then compare this reflected power with original transmitted beam using the comparator. The output of the comparator is high when the reflected power is low and vice versa. The decision threshold unit, which is maintained at some fixed threshold level \( (D_{th}) \), compares the output of the comparator and if it is less than fixed threshold level, it is considered as the reflected power is very high and the control unit was asked to increase the Laser output power till the comparator output becomes greater than fixed threshold level and vice versa. This process is continuous depends upon the outputs of the comparator and decision threshold \( (D_{th}) \) unit, hence the adaptiveness of the optical transmitter is maintained.

**IV. MAXIMUM–LIKELIHOOD DETECTION OF REFLECTED SIGNAL**

Here, we consider Intensity Modulation and Direct Detection (IM/DD) links using On-Off Keying (OOK). The noise present in the optical wireless communication system can be modeled to high accuracy as additive, white Gaussian noise that is statistically independent of the desired signal. The transmitted optical signals are scattered more by the atmospheric turbulence channel and this scattered signals are considered as reflected signals. A part of these reflected signals, towards the transmitter, are detected by the transmitter itself. Since, we received multiple signals reflected from turbulence channel of various directions, we are in need of special algorithm to detect these signals. So, that Maximum–Likelihood Sequence Detection (MLSD) is used to detect the reflected signal from the turbulence channel.[7] In order to collect multiple reflected signals from the atmospheric turbulence channel, we placed multiple optical receivers with small space diversion, then we combine these reflected signals by maximum-likelihood sequence detection (MLSD) techniques which is most effective method in this situation. For a sequence of ‘\( n \)’ transmitted bits the MLSD computes the likelihood ratio of each of the \( 2^n \) possible bits sequence \( s = [s_1 \ s_2 \ s_3 \ ... \ s_n] \) and chooses,

\[
s = \arg \max_s \ P(r/s) = \arg \max_s \ \sum_{i=1}^{n} f_i(X) \exp[-? \ { r_i - ? s_i } \ I_o( \exp(2X_i - 2E[X_i])) / N_i] dX
\]

Since we used OOK techniques each \( s_i \) can take the value OFF or ON, so that \( s \in \{0,1\} \)

\[
f_i(X) = \frac{1}{(2\pi)^{n/2}} \left| C_X \right|^{n/2} \exp\left[ -\frac{1}{2} \sum_i \left( X_i - E[X_i] \right)^2 \right] \]

The MLSD requires computing an \( n \)-Dimensional integral for each of the \( 2^n \) bit sequences, so that the complexity is proportional to \( n \cdot 2^n \). Even though MLSD is more complex but, in this turbulence channels we don’t know anything about this fluctuating environmental effects, the MLSD in the most effective method in this condition.

**V. RESULTS AND DISCUSSION**

In fig(5) the graph is drawn between visibility Vs received power at the constant transmitted power \( P=100\text{mW} \) with the distance of \( R=2\text{km} \). It is observed that for clear sky conditions (V>50km) the received power is nearly 75% of transmitted power, but in the worst case, the received power is only \( 1.26 \cdot 10^{-8} \text{W} \), which is not detectable by the optical receiver. The optical receiver sensitivity should be greater than 1µW, so that high transmitter power is required to meet the above condition. So, we are in need of more transmitted power to meet 1µW in the receiver.
In fig(6), the results are plotted by calculating the received power in the receiver for various visibility conditions with the distance of 2km. From fig.(7) it is observed that the required transmitted power is increased from 0.1 W to 10W to get at least 1µW power in the receiver in the worst climatic condition.
In fig(8) the graph is plotted between transmitted power and reflected power with the visibility of $V<0.5\text{km}$, and assumed the atmospheric turbulence effects occurred in the entire transmission path. It is observed that, when transmitted power is increased then reflected power is decreased almost linearly and at transmitted power becomes 10W, the reflected power approaches to 0W, i.e., there is no reflected power and all the transmitted power are transmitted (penetrated) through the atmospheric turbulence channel.
VI. CONCLUSION

The presence of snow or heavy rain between the optical transmitter and receiver causes heavy attenuation and scattering of optical signals. This limits the performance of the optical wireless communication system.[9]. Simulation of optical propagation through atmospheric turbulence channels makes it possible to derive mathematical models for optical wireless communication system. By using the derived model, the adaptive optical transmitter system was developed which performs better on rainy days compared with clear sky conditions.[10] Also, it is observed that when critical weather conditions, (i.e., for heavy snow or rain) the (V<500m) atmospheric attenuation is independent of wavelength(\lambda). But, the operating wavelength plays major role when V>6km, the atmospheric attenuation is inversely proportional to wavelength. So, that we choose wavelength is high value of 1550nm. Similarly the optical receiver is designed for adaptive in nature by placing matched filter whose response is varying to meet the minimum sensitivity of the receiver. These optical wireless communication links are must for the next generation wireless communication to meet the increased availability requirements. By overcome these atmospheric turbulence effects, the optical wireless communication system become more popular than existing RF wireless communication links.

REFERENCES