Multipath dispersion of pulse signals in a non-line-of-sight optical scattering channel

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Multipath-induced pulse broadening in a non-line-of-sight (NLOS) optical scattering channel is investigated. Expressions for impulse response and digital signal-to-noise ratio (DSNR) penalty induced by intersymbol interference (ISI) of a NLOS ultraviolet (UV) scattering communication are introduced based on a single-scattering model, and simulated results for some typical atmospheric condition and configuration of geometry are given in the paper. It is shown that the multipath dispersion is one of the most important factors limiting the system performances, and return-to-zero (RZ) format is more suitable for the optical scattering communications than non-return-to-zero (NRZ) format. The method proposed here can be used to predict available bandwidth and data rate of the communication system operating in a NLOS optical scattering channel.

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A short range, non-line-of-sight (NLOS) free space optical (FSO) communication link can be achieved based on atmospheric scattering of ultraviolet (UV) light[1]. Particularly, the channel in solar-blind UV region has unique merit, since there is little background of solar radiation in the spectral region owing to the absorption of atmospheric ozone layer. The absence of background light makes it possible to utilize wide field-of-view (FOV) receiver to increase received signals. The communication systems through optical scattering channel will relax the rigorous requirements of the line-of-sight FSO link such as precise pointing and tracking, and obstacle-free. Additionally, the UV communication systems provide secure, covert data links with low probability of jam and intercept. The features make UV communication a candidate for tactical military applications, and civil applications in some particular situations.

In the optical scattering channel, optical pulse signals will undergo multipath propagation, since the received photons have been scattered by different atmospheric molecules and aerosols spreading over some large volume. The multipath propagation will cause pulse broadening and consequently limit the available bandwidth of the channel. It is found that the multipath-induced pulse broadening has received little attention in past correlated literatures. The reason possibly is that now available UV communications operate at relatively low data rate since UV lamps are used as transmitter sources. UV laser sources, however, have been developed rapidly, and may hopefully be applied to communications in future to increase data rate. Accordingly, multipath-induced pulse broadening must be taken into consideration. In this paper, multipath impulse response of a NLOS UV optical scattering channel is investigated, and digital signal-to-noise ratio (DSNR) penalty caused by intersymbol interference (ISI) is evaluated. The effort here is focusing on estimating available bandwidth of a NLOS optical scattering channel and predicting attainable data rate of communications.

A general NLOS optical scattering geometry is illustrated in Fig. 1. A transmitter is located at point F_1, and a receiver is at point F_2 with a distance of r to F_1. The amount of photons reaching the receiver is determined by the system geometry, including transmitter divergence, receiver FOV, apex angles of the transmitter and receiver, distance between the transmitter and receiver, and the atmospheric attenuation and scattering properties. Obviously, photons scattered by the particles in scattering volume, which is enclosed by the intersection of the cones of the transmitter and receiver, will arrive at receiver at different time. The experimental research[2] suggests that the received scattered signal is insensitive to atmospheric turbulence, because the receiver in a NLOS system must collect scattered photons as many as possible, and a large receiving angle has to be used, then the actual received signal will be an averaged one over multiplicity in paths and in scatters as well. In order to analyze the received power as a function of time, given an impulse of energy emitted by the transmitter, the NLOS single-scattering propagation model developed by Luettgen *et al.* is used[3], which has been validated by the field tests[4]. The model is based on a prolate-spheroidal coordinate system with a radial coordinate ξ, an angular coordinate η, an azimuthal coordinate ϕ, and with two foci at F_1 and F_2, as illustrated in Fig. 2. Obviously photons scattered by points on the prolate-spheroidal surface will arrive at receiver at the same time. Thus, the received energy of scattered signal at a given time

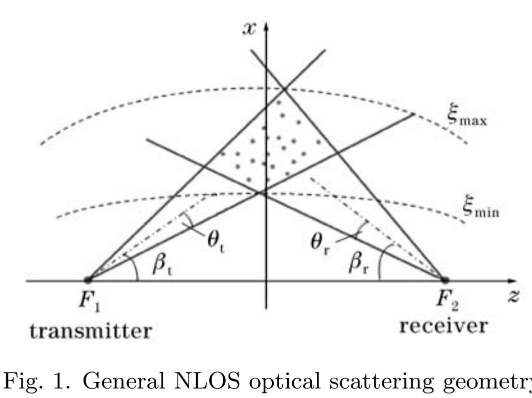

Fig. 1. General NLOS optical scattering geometry.

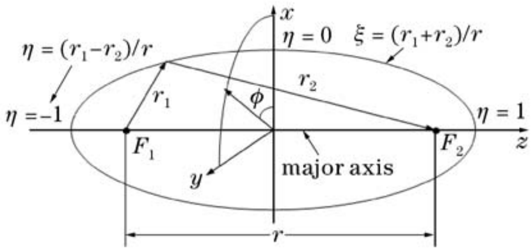

Fig. 2. Prolate-spheroidal coordinates.

$t = (r_1 + r_2)/c$ can be calculated simply through an integration over the prolate-spheroidal surface for a given ξ.

Assume that an impulse of energy $Q_{\rm t}$ is emitted at $t = 0$ uniformly over the transmitter solid cone angle from the transmitter. For simplicity, it is assumed that the axes of the transmission and reception cones lie in a common plane, thus the integration volume is symmetric over coordinate ϕ. Then the received singly scattered light power at time t can be expressed as

$$h\left(t\right) = \frac{Q_{\rm t} A_{\rm r} c k_{\rm s} \exp\left(-k_{\rm e} c t\right)}{2\pi\Omega_{\rm t} r^2} \times \int_{\eta_1(ct/r)}^{\eta_2(ct/r)} \frac{2G\left[\phi\left(ct/r,\eta\right)\right] p\left(\theta_{\rm s}\right)}{\left(ct/r\right)^2 - \eta^2} {\rm d}\eta, \quad (1)$$

where $\Omega_{\rm t} = 4\pi \sin^2\left(\theta_{\rm t}/2\right)$ is transmitter solid cone angle; $A_{\rm r}$ is area of the receiver aperture; $k_{\rm s}$ and $k_{\rm e}$ are atmospheric scattering coefficient and extinction coefficient respectively; $p\left(\theta_{\rm s}\right)$ is the single-scatter phase function with scattering angle $\theta_{\rm s}$; $\eta_1(ct/r)$, $\eta_2(ct/r)$, and $G\left[\phi\left(ct/r,\eta\right)\right]$ are expressions related to the boundary of integration over the scattering volume which depends on the geometry of optical scattering channel shown in Fig. 1. Detailed derivations of these expressions can be found in Ref. [3]. The NLOS optical scattering channel can be regarded as a linear and time-invariant system, then Eq. (1) can be used to analyze the effects induced by multipath propagation. One can evaluate the NLOS optical scattering channel's transmission function by Fourier transforming the impulse response of Eq. (1).

The propagation properties of UV light in atmosphere are necessary in calculating multipath dispersion for a NLOS UV scattering channel. Scattering and absorption coefficients in solar-blind region vary widely under different atmospheric conditions, and have been examined through a combination of experiments and theory[5−7]. The primary scattering mechanism near the ground can be divided into Rayleigh scattering by atmospheric molecules and Mie scattering by aerosols. Assuming independent scattering, the scattered intensity from each type of particle may be computed separately and then summed to obtain the composite result. The Rayleigh phase function has a simple analytic expression. For lack of analytic resolution, the Mie phase function can be approximated by use of the modified Henyey-Greenstein phase function proposed by Cornette *et al.*[8].

Consider a NLOS optical scattering channel in a typical atmosphere with a 5-km visual range. Wavelength of the source is assumed to be 266 nm in the solar-blind spectrum region. Figure 3 illustrates the normalized

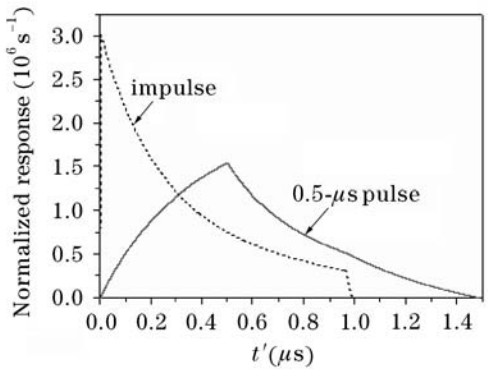

Fig. 3. Normalized response of the NLOS optical scattering channel.

impulse response for the channel with the following parameters: $r = 0.5$ km, $\beta_{\rm t} = \beta_{\rm r} = \pi/4$, $\theta_{\rm t} = 5$ mrad, $\theta_{\rm r} = \pi/8$. The time axis is defined by $t' = t - \xi_{\rm min} r/c$, so that the response is zero for $t' < 0$. We can see from Fig. 3 that transmitted impulse is broadened significantly after propagating in the NLOS optical scattering channel. For a input pulse of arbitrary shape, the output of the channel can be obtained by convolving the input pulse with the impulse response for the channel. The broadened profile of a 0.5-μs square pulse transmitted from the source is also shown in Fig. 3.

The pulse broadening induced by multipath will cause ISI in digital communication systems. A baseband on-off keying (OOK) system is considered to evaluate the adverse effects of multipath dispersion on performance of a NLOS optical scattering communication. The bit error rate (BER) associated with the OOK system for an optimal threshold receiver without ISI is[9]

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{\text{DSNR}}{\sqrt{2}}\right). \quad (2)$$

To evaluate the BER degradation of the system in the presence of ISI, an equivalent discrete-time impulse response of the system is expressed as[9,10]

$$h_k = h_{\rm TR}\left(t\right) \otimes h_{\rm N}\left(t\right) \otimes h_{\rm RE}\left(t\right)|_{t=kT}, \quad (3)$$

where $\otimes$ denotes convolution; $h_{\rm TR}(t)$ and $h_{\rm RE}(t)$ are impulse response of transmitter and receiver filter respectively; $h_{\rm N}(t)$ is the normalized impulse response of NLOS channel. T is the bit duration, and the bit rate is denoted by $R_{\rm b} = 1/T$. The normalization of $\sum_k h_k = 1$ is included in Eq. (3). It is also assumed that the sample time at receiver is shifted to maximize h_0[9]. The BER can be obtained by averaging over all possible M bit sequences, where M is the length of tail of the impulse response h_k, and can be expressed as follows for an optimal threshold condition[10],

$$\text{BER} = \frac{1}{2^{M+1}} \sum_a \text{erfc}\left[\frac{\text{DSNR}}{\sqrt{2}}\left(1 - 2\sum_{i \neq k} a_i h_{k-i}\right)\right], \quad (4)$$

where $a_i \in \{0, 1\}$ is the data symbols, and factor $2\sum_{i\neq k} a_i h_{k-i}$ represents the ISI. It is found from Eq. (4) that a higher value of DSNR is required in case of ISI presence to achieve a desired BER as without ISI.

For low values of BER, the degradation due to ISI caused by multipath is dominated by the degradation of the worst-case bit sequences, which consist of a single one bit preceded and followed by long zeros and the complement of that sequence[10]. Thus, Eq. (4) reduces to

$$\mathrm{BER} \approx \frac{1}{2^{M+1}} \mathrm{erfc}\left[\frac{\mathrm{DSNR}}{\sqrt{2}}(2h_0 - 1)\right]. \tag{5}$$

The ISI-induced DSNR penalty is defined as the increase in DSNR necessary to maintain the same BER as a link transmitting over a nondispersive channel having the same path loss[9], given by

$$\mathrm{penalty} = 10\log_{10}\left[\frac{\mathrm{erfc}^{-1}\left(2^{M+1}\mathrm{BER}_0\right)}{(2h_0 - 1)\,\mathrm{erfc}^{-1}\left(2\mathrm{BER}_0\right)}\right], \tag{6}$$

where BER_0 is the BER defined as Eq. (2) for without ISI.

ISI-induced DSNR penalties for non-return-to-zero (NRZ) and return-to-zero (RZ) formats with duty cycle of 50% are calculated by assuming that ISI occurs only between adjacent bits, as illustrated in Fig. 4. It is shown that, as the bit rate increases, the DSNR penalty increases significantly. The figure also illustrates that, compared with NRZ-OOK system, RZ-OOK system suffers a less DSNR penalty for a given bit rate. For a penalty requirement of 1 dB, bit rate as high as 1 Mb/s can probably be realized by RZ format. Although a RZ system generally requires a larger bandwidth, this is not an important barrier for UV scattering channel since it is usually used in relatively low data rate and narrower pulse UV sources are available, especially with solid state lasers. It should be noted that multipath dispersion is dependent on the geometry of the NLOS optical communication system. It is expected that, for example, reduction of the receiver FOV can diminish the time dispersion of pulse and alleviate the ISI consequently. However, this results in less photons received, and then larger path loss of the system. Hence, the communication engineers have to make a tradeoff between the bit rate and path loss of the system.

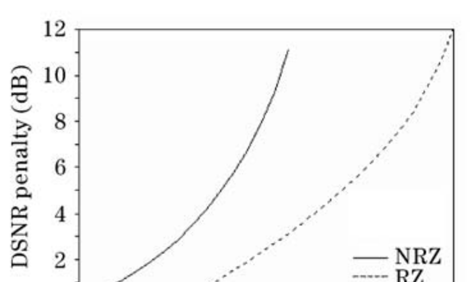

Fig. 4. DSNR penalty as a function of the bit rate for the NLOS optical scattering communication system.

In conclusion, multipath propagation of light in a NLOS optical scattering channel has been investigated, and the formulas for temporal response, ISI and BER in the NLOS communication channel are introduced. Taking scattering from both atmospheric molecules and aerosols into account, impulse response and ISI-induced DSNR penalty of a typical UV scattering channel have been calculated. It is shown that multipath-induced pulse broadening should be considered as one of the most important factors limiting the system performance. The results also show that RZ format is more suitable for the optical scattering communications than NRZ format. The method proposed here can be used to predict available bandwidth and data rate of the communication system operating in a NLOS optical scattering channel. The simulation result presented in this paper is an example system configuration, and other configurations can also be calculated by using the method proposed here. It should be noticed that multiple-scattering process may not be neglected in low-visibility weather, and then larger pulse broadening and higher loss may result. Further investigations, including experimental measurements, are being undertaken.

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