ULTRAVIOLET PULSE POSITION MODULATION IN THE PRESENCE OF SCATTERING LOSSES

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ABSTRACT

Ultraviolet (UV) communication systems allow non-line-of-sight mode of communications. This is made possible due to the scattering of UV signals from the molecules and aerosols present in the atmosphere. In this paper, a UV system employing pulse position modulation (PPM) is studied. The receiver uses avalanche photodiode detectors in the Geiger mode. The effects of fog and dust aerosols on the bit error rate performance are presented. Results are given for varying distances between the transmitter and the receiver. For the parameters considered, the results show a significant improvement in the bit error rate performance with an increase in the fog particle density.

INTRODUCTION

Ultraviolet (UV) communications allow non-line-of-sight (NLOS) mode of data communications. In this context, the deep UV band of 200-300 nm is interesting as this band is nearly noise free closer to the earth's surface due to the significant absorption of the solar UV radiations occurring in the atmosphere [1]. The UV signal transmitted from a communications source too undergoes significant atmospheric attenuation. However, they also interact with the molecules and aerosols in the atmosphere, and these interactions can result in the scattering of some of the transmitted photons. The scattered photons, therefore, can reach the receiver placed at relatively short distances ranging from a few tens of meters to a few kilometers. With the use of sensitive photon counting receivers, these links can operate even with a highly attenuated received signal. A UV link also offers other advantages that include reduced interference and less susceptibility of eavesdropping unlike in the case of radio frequency (RF) channels where special techniques are needed to reduce eavesdropping possibilities [2], [3]. UV communication links can be used in both civilian and military applications including unattended ground sensor networks where RF emissions are unavailable or undesirable [4].

UV systems employing different modulation techniques have been studied in the literature. Although on-off keying (OOK) is a promising modulation technique, one of its disadvantages is that the optimal threshold needed for its demodulation depends on the channel state information. The threshold selection issue can be avoided using M-ary pulse position modulation (PPM) systems

that use M time slots to transmit each symbol. The demodulation of M-PPM involves comparison of the signal values over all the M slots and finding the largest value without requiring any threshold. However, there are a few disadvantages that include an increase in the transmitter peak power requirement and the need for both slot and symbol synchronization [5].
During the transmission of UV signals, particles much smaller than the signal wavelength cause molecular scattering and this is modeled using the Rayleigh phase function. The scattering caused by aerosols is modeled using the Mie theory. The presence of the Mie particles and their density in the atmosphere can either help or degrade the path loss depending on their characteristics [6], [7]. The large path loss in NLOS UV systems also require the use of highly sensitive receivers such as the photomultiplier tube (PMT) and the avalanche photodiode (APD). The bit error rate (BER) performance of PMT and linear mode APD receivers is studied in various articles, for e.g., [8].
In this paper, we use M-PPM UV signals to explore the effects of fog and dust particles in the atmosphere. The purpose is to quantify the communication range and the data rate possible under various scenarios. The receiver uses a Geiger mode (GM) APD. The effect of the APD dead time is included. As the considered data rate is low, the effect of intersymbol interference is not considered. The results demonstrate that significant benefit can be obtained by using higher order M-PPM under both dust and fog conditions. As the density of dust or fog particles increases in the atmosphere, the BER performance is found to improve under the parameters used in the study. Fog provides significantly better performance than dust. As a result, the possible range of communication for a given data rate increases significantly under foggy conditions.

SYSTEM MODEL

A UV source generating a uniform radiation pattern over its transmit aperture is considered. We assume the transmitter to be inclined at an angle of θ_T as shown in Fig. 1. Its beamwidth is β_T. The receiver has a field of view of β_R, and it is inclined at an angle of θ_R. The receiver's field of view is assumed to be uniform. The azimuth angles (not shown in the figure) for the transmitter and the receiver are ϕ_T and ϕ_R respectively. The distance between the transmitter and the receiver is r. As shown in the figure, the transmitter and the receiver cones intersect at some distance producing a common volume. A photon emitted from the transmitter can encounter scattering at any point along its path. If this happens in the common volume, then there is a probability that the photon can reach the receiver from this single scattering event. Otherwise, multiple scattering events can also allow photons to arrive at the receiver and be counted. The impact of molecules and aerosols on the scattering and absorption of photons will be discussed in more detail in the next section.
The system uses an M-ary PPM transmission technique, where each group of $\log_2 M$ bits is mapped to an M-ary PPM symbol of duration T. Each PPM symbol consists of M time slots and a pulse is transmitted in only one of the slots depending on the group of the transmit bits. We can call this an active slot. No signal is transmitted during the other slots in the symbol. Let the slot duration be T_s so that $T = MT_s$. For an average transmit power of P_{avg} over the symbol duration, the power over the active slot is MP_{avg}.
To detect weak arriving signals, the receiver uses GM-APDs that can detect even a single photon. A GM-APD device is operated by reverse-biasing it above the breakdown voltage. Once this happens, even a single photon can cause an avalanche of electric charge carriers due to the cascading

effects of impact ionization and hence the photon gets detected. Subsequently, the rapid rise in avalanche current is brought down below the breakdown voltage using a quenching circuit. After the quenching process, the APD is reverse-biased again above the breakdown voltage to be able to detect the next photon. Every time a photon is detected and the quenching process runs, the APD cannot respond to another incident photon resulting in a so called dead time. There are two types of quenching circuits: active and passive. While photons arriving during the dead time in passive quenching can lengthen the dead time, they do not affect the dead time for actively quenched circuits [9]. Our work assumes active quenching.

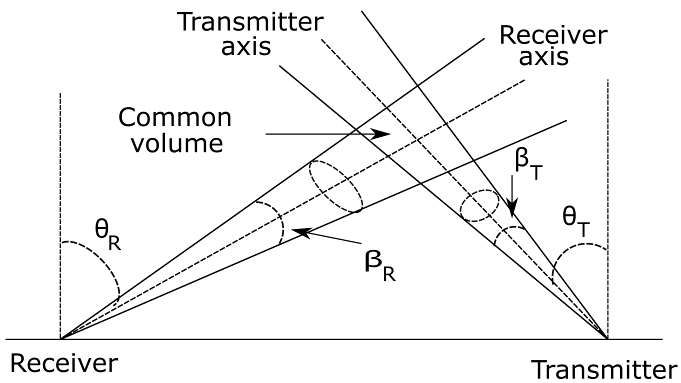

Figure 1: Transmitter/Receiver configuration in NLOS mode of operation

In a GM APD, a thermally generated electron or hole can also trigger an avalanche. Unfortunately, this avalanche is indistinguishable from an avalanche triggered by an incident photon. Therefore, this contributes to errors in the total photon count and is described by dark count rate which is the rate at which the avalanche events are triggered by the dark current. Another important parameter describing a GM APD is the single photon detection efficiency. This represents the probability that an incident photon will cause an electron-hole pair and that this will trigger an avalanche event. Finally, a GM APD can be operated in a free-running or a gated mode. The gated mode allows the APD to detect photons only during the gate-on period. When the gate signal is off, incident photons cannot be detected by the APD.

UV CHANNEL EFFECTS

Let P_t be the average transmit power during an active slot. Considering a path loss of L from the transmitter to an APD, the average received power over an active PPM slot is P_t/L. For simplicity, consider a single gate-on pulse in each slot of the PPM symbol and that the gate duration is $T_g = T_s - T_d$, where T_d is the dead time. The photon arrival at a receiving APD due to the transmit signal during an active slot is modeled as Poisson and the average rate per unit time is $\lambda_s = P_t/(Lh\nu)$, where h is the Planck's constant and ν is the frequency. Considering a background rate of λ_b and a dark count rate of λ_d, the total effective rate per unit time during an active slot is $\eta(\lambda_s + \lambda_b) + \lambda_d$, where η is the APD detection efficiency. During an inactive slot, the effective rate is $\eta\lambda_b + \lambda_d$. Due to the presence of dead time, the photon counting from the APD is no longer Poisson.

Since all the photons emitted by the transmitter do not reach the receiver, the system incurs a path loss factor L. When a photon leaves the transmitter, it travels an exponentially distributed random distance before interacting with air molecules or aerosols. This interaction can contribute to path loss if it results in the photon being absorbed. This probability is k_a/k_e, where k_a and k_e are the absorption and extinction coefficients respectively. Alternatively, the photon interaction can result in the photon being scattered with a probability of k_s/k_e, where k_s is the scattering coefficient and $k_e = k_a + k_s$. If the scattering occurs in the common volume, then the photon can reach the receiver with a finite probability if there is no further scattering or absorption and the photon directly approaches the receiver collecting area. The photon can also undergo multiple scattering events to finally arrive at the receiver. Alternatively, the photon can get absorbed during one of these interactions or can move away from the receiver. This contributes to path loss.

When a photon is scattered by particles much smaller than the wavelength λ, the rotation angle θ is described by the Rayleigh phase function

$$p_{ray}(\theta, \phi) = \frac{3(1 + 3\gamma_R + (1 - \gamma_R)\omega^2)}{16\pi(1 + 2\gamma_R)}$$

where $\omega = \cos\theta$ and γ_R is an atmospheric model parameter. Large size particles, on the other hand, cause aerosol or Mie scattering with a different phase function $p_{mie}(\theta, \phi)$ so that the total phase function is obtained as

$$p_{tot}(\theta, \phi) = \frac{k_{s,ray}}{k_s} p_{ray}(\theta, \phi) + \frac{k_{s,mie}}{k_s} p_{mie}(\theta, \phi)$$

where $k_s = k_{s,ray} + k_{s,mie}$ so that $k_{s,ray}$ and $k_{s,mie}$ represent the Rayleigh and Mie contributions to scattering respectively. Similarly, $k_a = k_{a,ray} + k_{a,mie}$, where $k_{a,ray}$ and $k_{a,mie}$ represent the Rayleigh and Mie contributions to k_a respectively. The Mie coefficients depend on the nature of the particles, their size and density. The function $p_{mie}(\theta, \phi)$ also depends on the nature of the particles. The Mie phase function and the coefficients can be obtained as described in [7], [10].

NUMERICAL RESULTS

Results are obtained through numerical simulations. We use $\beta_T = 17^o$, $\beta_R = 30^o$ and a detector area of $S_R = 4.9 \times 10^{-8}$ m^2 corresponding to a diameter of about 250 μm. The wavelength is $\lambda = 250$ nm. The transmitter and receiver orientations are kept fixed in an NLOS setting with parameters: $\theta_T = 70^o$, $\phi_T = -80^o$, $\theta_R = 60^o$ and $\phi_R = 90^o$. The dark count rate is assumed to be 5000 Hz and the background rate is 100 Hz. The detector efficiency is fixed at 30%. Two types of aerosols are considered: dust and fog. The particle radius is assumed to be 0.5 μm. For dust, the refractive index is a complex number given by $\mu = 1.53 + j0.03$, and for fog, $\mu = 1.362$. The following atmospheric parameters are used $k_{a,ray} = 1.0926 \times 10^{-3}$ m^{-1}, and $k_{s,ray} = 3.2117 \times 10^{-4}$ m^{-1}. The transmit power P_{avg} is 150 mW. The other parameters are as specified in [7]. Although the dead time is included in the simulation results, we have found that its impact is negligible due to the use of low data rates. Further, only single scattering events are considered since the contributions from the higher order scattering are very small. Therefore, the results might slightly underestimate the true performance when multiple scattering events are considered although the error is typically only a fraction of a dB.

Figure 2 demonstrates the impact of using an array of APDs in a foggy condition with a particle density of 10^8 m^{-3} for $M = 2, 4$ and 8-ary PPM systems. The distance is $r = 60$ m and the data rate is 10 kbit/s. A single APD has a very small receiver area and thus incurs a severe path loss. By using an array of APDs, the loss can be significantly reduced. In the figure, it is observed that using an array of 144 APDs the BER can be reduced by 10^5 times over using only 4 APDs for $M = 8$ PPM. Less gain is obtained for $M = 2$ and $M = 4$ cases.

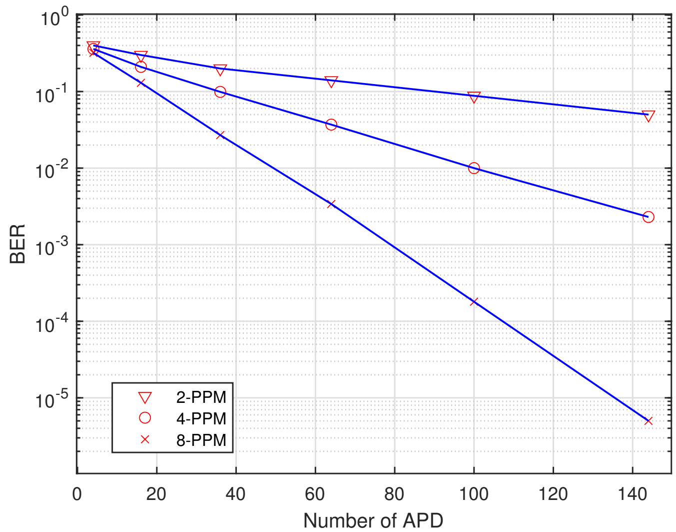

Figure 2: BER performance versus the number of APDs

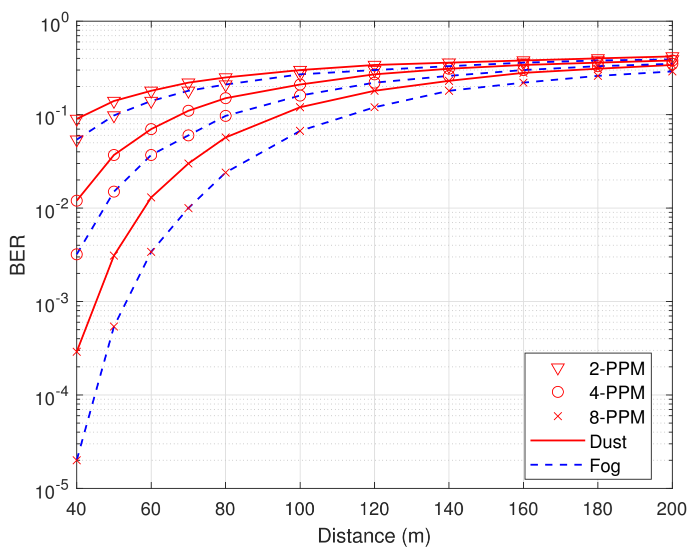

Figure 3: BER performance versus the distance between the transmitter and the receiver

Figure 3 demonstrates the BER performance as the distance (r) between the transmitter and the receiver increases. We use an array of 64 APDs. The data rate is 10 kbit/s and the particle density

is 10^8 m^{-3}. In all cases, the BER is observed to increase rapidly with distance. The path loss for a single receiving APD varies from about 135 dB to 144 dB over the distances used in the figure.
In Fig. 4, we show how far away the receiver can be placed from the transmitter when the data rate increases so that the BER stays less than 10^{-3}. An array of 100 APDs is used and the particle density is 5×10^8 m^{-3}. These results correspond to a foggy weather. For 2-PPM, lowering the data rate from 50 kbit/s to 5 kbit/s allows the range to increase from 20 m to 75 m. A similar trend is observed for other values of M although the range is much higher for higher values of M as expected.

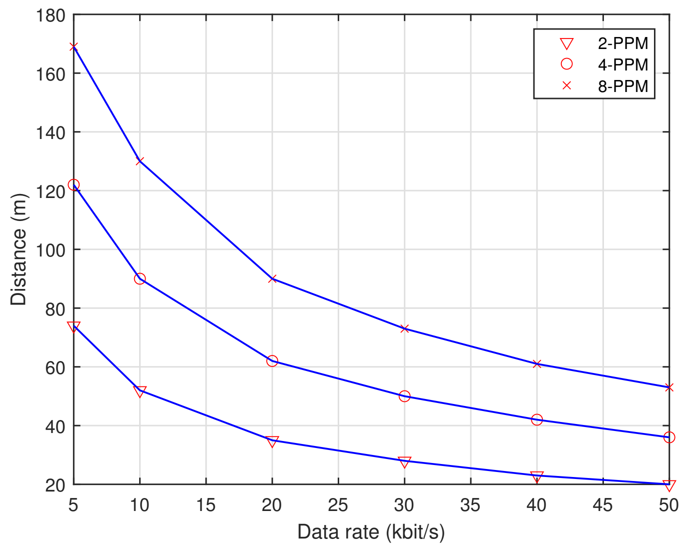

Figure 4: Distance allowed for a given data rate under fog condition.

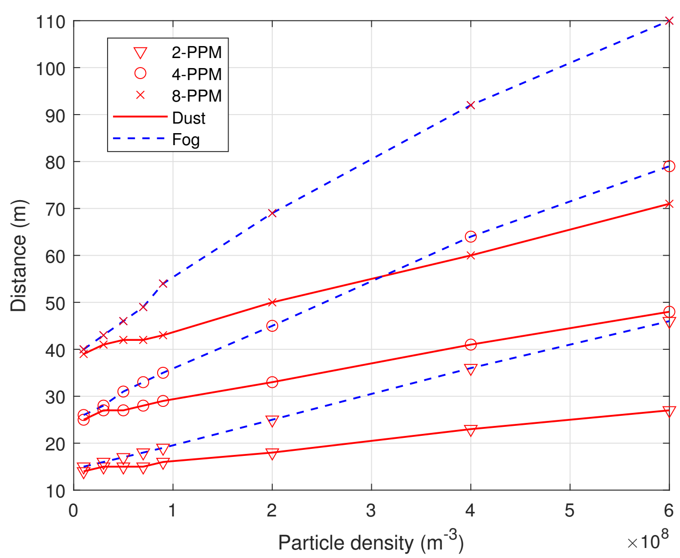

Figure 5: Distance allowed versus particle density.

Finally, Fig. 5 studies the effect of the weather on the transmitter/receiver distance (r) for maintaining a BER of 10^{-3} by varying the particle density in the atmosphere. An array of 64 APDs is considered and the data rate is 10 kbit/s. It is seen that under the low particle density condition, both dust and fog allow almost the same distance for communications. This is because the role of the particles is insignificant. However, as the particle density increases, fog conditions provide significantly better range of coverage than dust conditions. When using 8-PPM in fog, the range of coverage increases nearly 2.8 times as the particle density increases from 10^7 m^{-3} to 6×10^8 m^{-3}. For a similar increase in the dust particle density when using 8-PPM, the range increases only by about 1.8 times.

CONCLUSIONS

This paper studies a UV communication system in the NLOS mode using pulse position modulation (PPM). The receiver uses avalanche photodiode detectors in the Geiger mode. The weather effect is included using molecular and aerosol interactions based on Rayleigh and Mie theory models. The effects of fog and dust aerosols on the bit error rate performance are presented. Receiver results are given to show the impact of the distance between the transmitter and the receiver, the number of APDs, and the aerosol densities. For the parameters considered, the results show a significant improvement in the bit error rate performance with an increase in the fog particle density.

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