Numerical Studies on Time-Domain Responses of ON/OFF-Keyed Modulated Optical Signals Through a Dense Fog

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There is an increasing interest in Free Space Optics (FSO) communication systems among data service providers. The cost of installing a new fiber network in an urban environment is often very expensive, and a less expensive method is needed. A high-speed data link, for example, can be designed using either optical or millimeter-wave (MMW) point-to-point communication systems. The optical system is often the preferred method because of its simplicity and security. The data rate for short distance FSO systems in an ideal condition can exceed one Gbit/sec. However, both MMW and optical links are susceptible to adverse weather conditions.

The traditional method to estimate the effects of an atmospheric channel is to calculate the attenuation characteristics based on the size distribution and concentration of particles along the signal path length. From the signal attenuation rate, the bit-error rate is usually estimated. This approach, however, does not consider the propagation characteristics of modulated signals. The signal dispersion and eye-diagram distortion can only be obtained by studying the propagation of modulated signals. In addition, the signal dispersion is due to the multiple scattering effects. If the first-order single scattering approximation is used for analysis, the signal dispersion of optical signals cannot be estimated. In this paper, we will give a numerical method to calculate the waveform of an intensity modulated optical signal through a layer of fog and cloud. Our approach takes into account the multiple scattering effects and reveals a substantial amount of waveform distortion.

It is assumed that a laser (λ = 0.8 μm or λ = 1.5 μm) is used as a transmitter and the ON/OFF modulation frequency f_{mod} are 200 MHz and 2 GHz. The ON/OFF keyed modulated signal (square wave) is modeled by a Fourier series expansion with the fundamental, 3rd, 5th, 7th and 9th harmonics of the modulation frequency. We assume the transmitted light has a left-hand circular (LHC) polarization. The fog is modeled by a uniform layer of randomly distributed water particles with a size distribution. The refractive index of a fog particle is n_{fog} = 1.3289 + $i0$.0013289 at λ = 0.8 μm and 1.319 + $i0$.001319 at λ = 1.5 μm. The fog layer (path length) is assumed to be L = 1 km and the concentration of fog particles is varied according to the optical depth τ_0 defined by $\tau_0 = \rho\sigma_t L$ where ρ is the number of density, σ_t is the total scattering of a single particle. The scattering and attenuation by single particle is obtained using the Mie solution. The transmitted intensity as a function of angle is calculated using the numerical solutions of the vector radiative transfer (RT) equation. The receiver has a finite field-of-view (FOV) and the received intensity must be obtained by integrating over the receiver FOV. By summing the average (DC) and harmonic components, we can estimate the time-domain responses of the ON/OFF-keyed modulated signal. The waveform of the received signal is strongly dependent on the receiver FOV.

0-7803-8196-3/03/$20.00 ©2003 IEEE

The main task is to develop a method which can simulate the propagation channel including multiple scattering effects. For a plane wave incident on a homogeneous layer of particles, the most accurate results can be obtained with the numerical solution of the vector radiative transfer equation. Recently, we have developed a technique to include the envelope modulated light or "photon density wave" in the radiative transfer equation. This new method will be applied for analyzing the communication channels. To simulate the propagation characteristics of the ON/OFF-keyed modulated signal, we need to calculate four different cases as shown in Fig. 1. The ON/OFF-keyed modulated light is separated into the average (DC) and modulated (AC) signals. Both DC and AC signals can be separated into the coherent (reduced incident light) and incoherent (scattered) light. Each will be calculated separately using the radiative transfer equation. The incident light is assumed to be a plane wave, and the FOV of the receiver has no effect on the coherent (unscattered) signal. However, the scattered light arrives from different angles and the total incoherent intensity is given by integrating the specific intensity over the receiver FOV. Figure 2 shows one example of the optical waveform distortion due to fog.

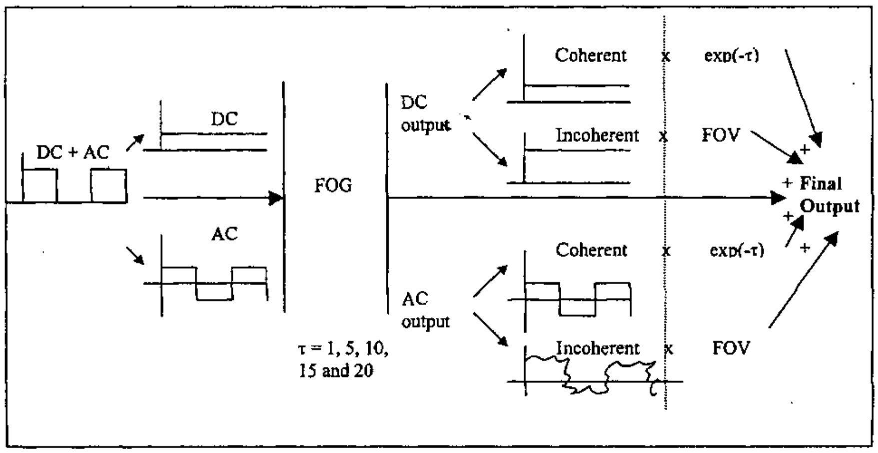

Fig. 1: Method to solve for the ON-OFF key modulated optical system. DC: Constant intensity. AC: Modulated intensity.

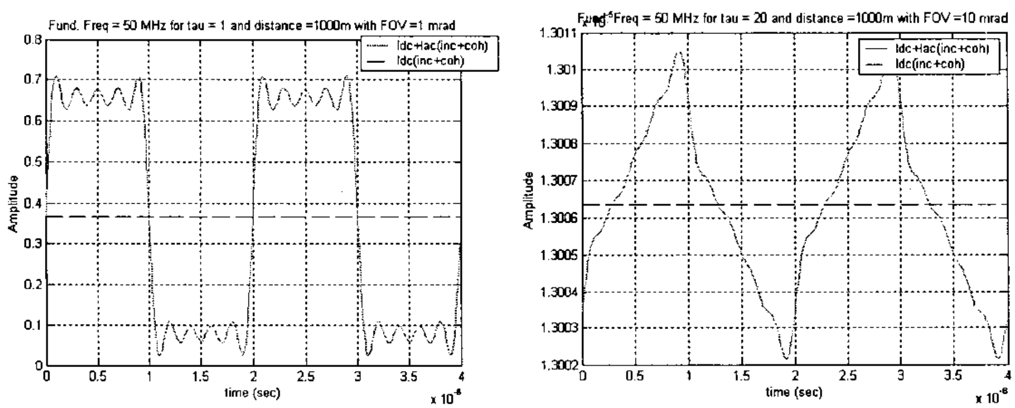

Fig.2: Received signals through fog. Left: Very light fog (τ=1). Right: Heavy fog (τ =20).