Performance of Synchronous or Nonsynchronous Receivers Using Atmospheric Compensation Techniques

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Abstract: We present recent studies on the impact of phase and amplitude fluctuations on free-space links using either synchronous or nonsynchronous detection. We compare options for atmospheric compensation, including conjugate and non-conjugate adaptive optics.

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Evaluating the performance of a heterodyne or homodyne receiver in the presence of atmospheric turbulence is generally difficult because of the complex ways turbulence affects the coherence of the received signal that is to be mixed with the local oscillator. The downconverted heterodyne or homodyne power is maximized when the spatial field of the received signal matches that of the local oscillator. Any mismatch of the amplitudes and phases of the two fields will result in a loss in downconverted power. The use of adaptive compensation of atmospheric wave-front phase distortions to improve the performance of atmospheric systems has been an important field of study for many years. Phase-compensated receivers offer the potential for overcoming atmospheric limitations by adaptive tracking of the beam wave-front and consequent correction of atmospherically-induced aberrations. In particular, the modal compensation method involves correction of several modes of an expansion of the total phase distortion in a set of basis functions.

Here, we study in a unified framework the effects of both phase-front distortion and amplitude scintillation on the performance of synchronous (coherent) and nonsynchronous (noncoherent) receivers utilizing phase-front compensation. First, we have defined a mathematical model for the received signal after propagation through the atmosphere. By noting that the downconverted signal current can be characterized as the sum of many contributions from different coherent regions within the aperture, we have shown that the probability density function (PDF) of this current can be well-approximated by a modified Rice distribution. In our model, the parameters describing the PDF depend on the turbulence conditions and the degree of modal compensation applied to the receiver. Second, we have computed the error probability for digital signals in the presence of multiplicative noise from atmospheric turbulence and additive white Gaussian noise (AWGN).

Figures 1 and 2 show the effect of atmospheric turbulence on QPSK with coherent detection using modal-compensated heterodyne or homodyne receivers. We study the symbol-error rate as a function of several parameters: the average signal-to-noise ratio per symbol, the strength of atmospheric turbulence, the receiver aperture diameter D , and the number of spatial modes J removed by the compensation system. Turbulence effects are described by two parameters. Fried's coherence length r_0 describes the coherent diameter of the distorted wavefront phase. The scintillation index σ_β describes the intensity of amplitude fluctuations. In our modeling, we have chosen typical values of these two parameters. While our model can be applied to various modulation and detection methods, here, we have shown the performance of QPSK using coherent detection in the presence of AWGN. Also, we limit our analysis to receivers that implement the maximum-likelihood decision rule in order to minimize the error probability.

Figure 1 details the dependency of the error rate with turbulence for different degrees of phase compensation. As expected, in the event that atmospheric turbulence is present, the effect of turbulence is to reduce the coherence area of the signal. This in turn reduces the heterodyne or homodyne downconversion detection efficiency and, consequently, the receiver electrical SNR. When phase correction is used and a set of spatial modes is compensated, the downconversion efficiency grows quickly and the improvement caused by the compensation technique is substantial. In most situations, the effect of phase correction is significant even when just a few modes are corrected in the wavefront. Figure 2 considers the effect of receiver aperture on performance. The optimal aperture diameter, which minimizes the error rate, exhibits two different regimes in our studies. When the aperture is relatively small, amplitude scintillation is dominant, and performance is virtually unaffected by phase-front corrections. When the aperture is larger, phase distortion becomes dominant, and high-order phase corrections may be needed to improve performance to acceptable levels. More detailed results and comments on our analysis will be presented at the meeting.

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Fig. 1. For a QPSK signal with coherent detection in the presence of additive white Gaussian noise (AWGN), the symbol-error probability versus available SNR per symbol for different levels of turbulence (left) and as a function of the number of modes J removed by adaptive optics systems (right). In this plots, turbulence is characterized by the Fried's coherence length r_0 describing the coherent diameter of the distorted wavefront phase. For a fixed aperture diameter D , the normalized parameter D/r_0 takes values between 0.1 (weak turbulence effects) and 10 (strong turbulence). Here, the compensating phases are expansions up to tilt ($J=3$) and astigmatism ($J=6$). The no-correction case ($J=0$) is also considered. In both plots, the no-turbulence situation (black line) helps us to clearly identify the effect of atmospheric propagation on the error probability.

Fig. 2. Symbol-error probability versus receiver aperture diameter for different levels of turbulence (left) and as a function of the number of modes J removed by adaptive optics systems (right) for coherent detection of QPSK signals with AWGN. The SNR that would be present in the absence of turbulence is proportional to the aperture diameter. For the smallest aperture shown in the plots, we assume a 10-dB average SNR per symbol. In these plots, turbulence is characterized by the scintillation index σ_p^2 describing the fluctuations in the irradiance of the optical wave. The scintillation index σ_p^2 takes values between 0.3 (weaker turbulence) and 1 (stronger turbulence). The compensating phases presented are expansions up to tilt ($J=3$) and astigmatism ($J=6$). The no-turbulence case is also shown in the plots.