

COMMUNICATION SCIENCES
AND
ENGINEERING

XVII. OPTICAL PROPAGATION AND COMMUNICATION

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The broad objectives of our program are to (i) formulate propagation models for important optical channels from the underlying physical processes, (ii) determine the fundamental limits on detection and communication performance that can be realized with these channels, (iii) develop techniques for optical detection and communication which achieve or approach these limits, and (iv) establish, by means of experiment, the validity of the theoretical results and guide their further development.

1. QUANTUM COMMUNICATION THEORY

National Aeronautics and Space Administration (Grant NGR 22-009-013)
U. S. Navy – Office of Naval Research (Contract N00014-76-C-0605)
Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Horace P. H. Yuen, Robert S. Kennedy, Jeffrey H. Shapiro

Our main concern in this work is the extent to which commonly accepted conclusions concerning the limitations imposed by quantum effects upon system performance are correct. The issue is important because such effects often contribute the dominant "noise" in the optical communication systems that are now contemplated. Our goal is to determine whether the limits encountered thus far are fundamental in nature, or merely associated with the specific systems that have been considered. If they are not fundamental, there may be opportunities for substantial improvement in the performance of optical systems.

To determine the extent of possible improvement in performance, three major questions are being addressed:

- (i) Assuming that we are only limited by physical laws rather than by present-day technology, what are the situations in which the performance of the systems now being considered falls substantially short of the performance of an optimum system?
- (ii) What is the structure of the optimum quantum system for any given application, expressed in the abstract language of quantum physics?
- (iii) How can a desired optimum quantum system be realized or approximated in

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situations wherein it offers a significant performance advantage?

Our major effort during the past year was concentrated on determining the advantages of producing fields associated with two-photon coherent states and the advantages of optimal quantum receivers for coded communication systems.

The photodetection statistics for two-photon coherent states were determined for single-mode fields. It was also shown that ordinary homodyne detection is a realization of the optimum quantum measurement for these states.

The practical possibilities of realizing two-photon coherent states, in the form of ultrashort pulses, were further developed during the past year. We found that dissipation does not significantly alter the pulse formation, and that, to a first approximation, two-photon cascade systems, such as stimulated spin-flip Raman scattering, lead (both classically and quantum mechanically) to the desired two-photon behavior. This greatly increases the possibility of realizing stimulated two-photon emission experimentally. Detailed analysis of such cascade systems will be carried out during the coming year.

We have developed the general theory of quantum field propagation between a transmitter and a receiver. This work, in combination with previous work on channel modeling, yields a general framework for the representation of quantum channels. The results were applied to free-space propagation to obtain the two-photon results that we have described. We are also determining the extent to which an optimum quantum decoder can improve the performance of coded optical communication systems. A bound to the performance of such systems has been developed and will be compared with the performance attainable with existing systems.

2. IMPROVED LOW-VISIBILITY COMMUNICATION

National Science Foundation (Grant ENG74-00131-A02)

U. S. Air Force – Electronic Systems Division (Contract F19628-76-C-0054)

Robert S. Kennedy, Jeffrey H. Shapiro, Cardinal Warde

This investigation, which is carried out jointly with the M. I. T. Center for Materials Science and Engineering, is concerned with the performance of terrestrial line-of-sight communication systems under conditions of low visibility. Our aim is to determine the extent to which performance can be improved through appropriate system design, and to develop the devices for achieving this improvement. The potential for improvement resides in the energy and information contained in the scattered component of the received field.

The collection of data to establish the frequency, variability, and the regularity of the key channel parameters has been our major concern during the past year. Measurements taken on a 13-km line-of-sight path at 0.69 μm and 2 μm wavelengths have shown

little dispersion of the field, either in time or angle for optical thicknesses as large as ten. Measurements at larger optical thicknesses have been limited by system sensitivity. Efforts to correlate the experimental data with various propagation models are now in progress.

3. OPTICAL PROPAGATION AND COMMUNICATION THROUGH ATMOSPHERIC TURBULENCE

National Science Foundation (Grant ENG74-03996-A01)

Jeffrey H. Shapiro

Random spatiotemporal fluctuations in refractive index that result from turbulent mixing in the Earth's atmosphere have a profound effect on optical wave propagation. In particular, turbulence-induced optical phase perturbations restrict the resolution attainable in long-exposure telescopic photography to a few seconds of arc. The same phase perturbations gradually destroy the spatial coherence of a laser beam as it propagates through the atmosphere, and thus they limit the effectiveness of collimated or focused laser transmitters in communication and radar systems. Furthermore, atmospheric optical receivers are subject to severe temporal fading caused by turbulence-induced optical amplitude fluctuations. We have been working to quantify the performance limitations imposed by atmospheric turbulence on specific imaging and communication systems, and to develop system configurations that are immune to atmospheric fluctuations.

During the past year, several advances have been made toward realizing the preceding objectives. In research for a Master's thesis, Raymond J. Staron¹ studied and simulated phase-estimation procedures for mode-compression communication receivers. This work provides a useful quantitative sensitivity analysis for direct-detection linear least-squares phase estimation, and includes computer simulation results that offer some valuable insights into the nonlinear phase estimation performance. In other Master's thesis research, Mahmoud Tebyani² analyzed various diversity-combining techniques. His results have led us to an analytical framework for parametric performance comparisons between diffraction-limited, photon-bucket, channel matched-filter, and phase-compensated reception.³ Finally, we have prepared a review article that unifies recent results on propagation, imaging, and communication through atmospheric turbulence;⁴ some novel results are presented in this article.

In the coming year, we plan to develop Markov process (state-variable) models for atmospheric statistics, and use these models to study the ultimate limits on phase-tracking performance in imaging and communication systems.

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4. ULTRAVIOLET COMMUNICATION

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Robert S. Kennedy, Horace P. H. Yuen

This investigation is concerned with determining whether broadcast (omnidirectional) optical systems can operate in low-visibility scattering atmospheres. The potential exists because in an omnidirectional system the power level at the receiving aperture is much less reduced by the presence of scattering than in a line-of-sight collimated system. To utilize this power the field of view of the receiver must be increased with an attendant increase in collected noise power. By operating in the 0.2-0.3 μm wavelength region, where detector and background noise is negligible, the noise limitation is greatly relaxed and the major limitations become multipath spread and boundary losses.

During the past year, the magnitude of the multipath spread and the width of the received angular spectrum for omnidirectional scatter have been estimated theoretically. The angular spectrum broadens quickly to fill the hemisphere as the optical thickness increases to approximately one. The multipath spread is of the order of $3\beta r^2/c$ seconds when there is no absorption. Here β is the scattering coefficient, r is the path length, and c is the velocity of light. A small amount of absorption changes this to approximately $0.5 \sqrt{r/\beta} [(\alpha/\beta) - 1]^{-3/4}/c$, where α is the extinction coefficient (absorption plus scatter).

Our theoretical results will be extended to include other scattering functions. A propagation experiment to confirm the results is also planned.