6. Optical Propagation and Communication

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The central theme of our programs has been to advance the understanding of optical and quasi-optical communication, radar, and sensing systems. Broadly speaking, this has entailed: developing system-analytic models for important optical propagation, detection, and communication scenarios; using these models to derive the fundamental limits on system performance; and identifying, and establishing through experimentation the feasibility of, techniques and devices which can be used to approach these performance limits.

6.1 Atmospheric Optical Communications in Local Area Networks

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A local area network is prototypically a high-bandwidth (1-10 Mb/s) geographically compact (0.1-5 km diameter) packet-switched network that employs twisted pair, coaxial cable, or fiber optics as its transmission medium. These networks interconnect host computers within a single company, often within a single building. They are distinguished from wide-area packet networks in that the high-bandwidth, short delay, low-cost transmission media employed in local area networks permit the use of simplified protocols and control strategies.

Atmospheric optical communication links are a natural choice for certain high-bandwidth short-haul terrestrial transmission applications in which cable rights-of-way are unobtainable, or frequent link and network reconfiguration is necessary. The utility of these links will be limited, primarily, by the occasional outages they experience due to local adverse weather conditions.

The natural advantages of atmospheric optical links make them attractive candidates for such local area network (LAN) applications as bridges between buildings containing cable subnetworks, and temporary quick-connects for new outlying hosts for which cable runs are initially unavailable. In this program, we have undertaken a combined analytical and experimental study of the use of atmospheric optical communications in local area networks. A brief summary of these efforts follows.

Theory

In Nguyen's doctoral dissertation,[1] we presented an initial network analysis of the use of variable transmission-rate atmospheric optical links, with appropriate protocols and control strategies, as an improvement on a simple on/off approach to coping with weather-related performance degradations. This analysis was framed in terms of the ~10 Mb/s data rate ring, star, and bus network topologies now in use. Its principal conclusion is that, with the appropriate control strategy and load reduction procedure, transmission-rate reduction at an atmospheric optical link in an LAN is a strongly recommended technique for achieving significantly better bad weather network performance than would otherwise be available.

Future developments in LANs will likely occur in the area of very high speed (100 Mb/s - 1 Gb/s) systems based on single-mode optical fiber. Atmospheric optical communications can still be considered as an adjunct to such networks, only now the impact of atmospheric propagation on network performance will be more severe. In a new study,[2] we are exploring the impact of inserting an atmospheric optical link into some of the proposed very high speed fiber-optic LANs, such as FASNET.[3] Here, a bad weather optical link outage will force the network to divide into sub-networks. Also, clear weather fading due to atmospheric turbulence, which was not a severe problem for Mb/s systems owing to their greater power margin, will affect atmospheric link performance in a way that may require protocol modifications.

We have also addressed the possible development of an all-optical broadcast network, serving a community of users within line-of-sight of an elevated central site.[4] In this study, clear weather power budgets were evaluated to establish baseline feasibility of the concept, and queueing studies were performed on busy-tone multiple access protocols for segmented and universal coverage schemes.

Finally, we have begun a study[5] to systematically investigate various fiber-optic alternatives for providing very high speed bus communications within a computer. The principal objective of this study is to determine the trade-offs between serial (bit by bit) and parallel (byte by byte) implementations.

Experiment

The purpose of the experimental portion of our program has been to develop an atmospheric optical communication/LAN test bed with which to buttress the theoretical work via actual user experience in LANs on the M.I.T. campus. Two optical transceivers, based on continuous-wave GaAℓAs laser diodes and Silicon APD/preamplifier modules, have been constructed[6] and adapted,[7] for initial network experimentation in the PROTEON proNET cable ring network already in use in M.I.T.'s Laboratory for Computer Science (LCS). The proNET is a 10 Mb/s token passing ring structure which admits to extensive interconnection through what are called wire centers.

In recent bench tests, our atmospheric optical realization of a 2-node proNET ring (with optical attenuators employed to simulate the loss encountered on an outdoor path) performed with excellent reliability. Indeed, the optical links gave packet transmission performance that was indistinguishable from that obtained with wire connections. We are now moving toward 2-node operation over a 150 meter outdoor path from LCS in building NE43 to the Research Laboratory of Electronics in building 36 on the M.I.T. campus.

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6.2 Squeezed States of Light

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Recent work has highlighted the potential applications of squeezed states, also known as two-photon coherent states (TCS), in optical communications and precision measurements. These states have an asymmetric noise division between their quadrature components, with the low-noise quadrature exhibiting lower fluctuation strength than that of a coherent state. We are engaged in a program to: generate and verify the quantum noise behavior of squeezed state light; and analyze the physics and applications of such light. Our recent progress is summarized below.

Squeezed State Generation

Efforts aimed at squeezed state generation are now underway at a number of laboratories. Our approach is via forward degenerate four-wave mixing (DFWM)[1,2] in a Sodium vapor cell pumped by a dye laser at the 589 nm D lines. Using this arrangement, and a single-beam pumping configuration, we have observed phase-sensitive noise spectra,[3] with our noise minimum reaching, but not going below, the coherent state level. Limited amounts of squeezing in an intracavity Sodium beam DFWM experiment have recently been reported by AT&T Bell Laboratories.[4] We are now making noise measurements on a two-beam pump DFWM configuration in Sodium vapor, and are preparing for intracavity work using the 555.6 nm line of Ytterbium.

In support of the preceding experimental work, we have been developing a vector-field quantum theory for squeezed state generaton via DFWM.[5] This analysis, which extends the scalar work of Reid and Walls,[6] assumes a four-level atomic system comprising a ground state and three degenerate excited states such as encountered with the 555.6 nm Ytterbium line.

Quantum Photodetection

We have previously provided full multi-mode quantum treatment of direct detection, homodyne detection, and heterodyne detection for photon-flux driven detectors.[7,8] This work presumed open-loop operation, in which there is no feedback path from the detector output to the light beam at its input. There is now interest in using closed-loop photodetection, in conjunction with quantum non-demolition techniques, to generate squeezed states.[9-11] We have thus turned our attention to such systems. In particular, we have shown that generally accepted open-loop distinctions between the photodetection statistics of classical and non-classical light beams do not carry over to closed-loop configurations.[12]

Squeezed State Applications

We have developed multi-mode phase and amplitude uncertainty results for heterodyne detection,[13] extending our earlier single-mode work.[14] The new work is relevant to phase-sensing interferometry, and squeezed state frequency-modulated communication.

Squeezed State Workshop

We hosted a one day workshop on squeezed states that drew participants from nearly all major squeezed-state research efforts.[15]

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6.3 Laser Radar System Theory

U.S. Army Research Office - Durham (Contract DAAG29-84-K-0095)

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Coherent laser radars represent a true translation to the optical frequency band of conventional microwave radar concepts. This program is aimed at developing a system theory for the emerging technology of multifunction coherent CO_2 laser radars. It includes a collaboration arrangement with the Opto-Radar Systems Group of M.I.T. Lincoln Laboratory whereby the experimental portions of the research are carried out with measurements from their CO_2 laser radar test beds. Our recent work in this program is summarized below.

Speckle Correlations

In order to understand the impact of laser speckle on the full panoply of coherent laser radar measurements, we have derived the transverse and longitudinal degrees of coherence for speckle targets observed via heterodyne detection.[1] This work elucidates hitherto unidentified interactions between various measurement-configuration parameters that impact speckle-target correlation scales. Moreover, these results differ significantly from those of earlier direct detection studies[2] in operating regimes that are experimentally accessible.[3] Thus our analysis is the appropriate basis for coherent laser radar system calculations involving decorrelation times, e.g., for frame averaging pulsed imagers, and Doppler radar velocity and vibration sensing.

Peak-Detection Systems

In both 2-D pulsed imager and 2-D Doppler imager laser radars, the intermediate-frequency (IF) return signals are filtered, envelope detected, and peak detected in a pre-processor subsystem. The input to the peak detector is often thresholded, so that these systems are subject to dropouts. Moreover, for speckle targets both systems are prone to detecting anomalous peaks. We have developed results for the dropout, anomaly, and accuracy performance of peak detection pre-processors.[4] The effect of the pre-processor on reflectivity determination has also been determined, and the essential features of the theory were verified experimentally.[5]

Multipixel Detection Theory

We have made substantial progress in multipixel detection theory for multidimensional radars.[6] Quasi-optimum range-only and intensity-only processors have been derived for the detection of an extended speckle target located at unknown range, azimuth, and elevation, within a speckle (ground) background of known terrain profile. The receiver operating characteristics for these processors have also been obtained. They are now being used to quantify a variety of resolution/performance trade-offs for these systems.

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6.4 Fiber-Coupled External-Cavity Semiconductor High Power Laser

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Last year's annual report described the operation of five diode gain elements (diode lasers with one facet anti-reflection coated) as a coherent ensemble by placing a spatial filter between the AR-coated facet and the end mirror of an external cavity which provides feedback for laser operation.[1] In 1985, these results were further quantified. The linewidth of the output of the coherent ensemble has been shown to be less than 7.5 MHz ($\sim 2 \times 10^{-8}$ of the center frequency) and the output has been shown to be stable to 7.5 MHz (1.7×10^{-5} nm) over a period of a minute.[2] The line-width measurements are limited by the resolution of the Fabry-Perot interferometer spectrum-analyzer used to obtain the results.

A first order monochromatic theory of the cw operation of the external cavity and its stablility has been developed. The spatial filter is in the Fourier transform plane of the five emitting gain elements. When operating coherently with each other, these elements produce an interference pattern in the Fourier plane in which most of the light is concentrated in fringes with widths that are 30% of the spacing between them. The theory implemented in Fortran and synthesizing the active and passive parts of the cavity using matrix representations indicates that binary filters with duty cycles of 0.3 yield the optimum combination of maxima for output power, stability, and wavelength tuning sensitivity.

Pulsed operation of the external cavity laser has been extensively investigated experimentally. One case which may be of significant practical importance involves operating three alternate gain elements cw and pulsing the intermediate two elements. When only alternate gain elements are operating, the ensemble is below laser threshold because the spacing between the intensity peaks in the Fourier plane is decreased by a factor of two and significant radiation hits the opaque areas of the filter halfway between the open slits, causing high loss. Pulses on the intermediate gain elements eliminate this loss, and bring the ensemble above threshold. The resulting pulsed output spectrum is chirpless (does not change output wavelength during the pulse) to the 1.7×10^{-5} nm resolution of the Fabry-Perot spectrum analyzer used for the measurement.[3,4] Chirpless operation is desirable when the optical pulses are transmitted through dispersive media such as fiber optics.

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