# 28. 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.

## 28.1 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 to 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. Such systems will experience occasional outages due to local adverse weather conditions, but via the results of our prior work,[1,2] low-visibility atmospheric optical communication links can now be analyzed with some confidence. It turns out that exploitation of scattered light can permit useful link operation beyond the limit set by extinction of the direct beam. However, although technology development can help extend scattered-light operating range, true all-weather capability at high data rates over kilometer or longer path lengths cannot be guaranteed.

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. Nevertheless, atmospheric optical communications are not now in widespread use in LANs. This, we believe, is due to a substantial gap that exists between link-understanding and network-understanding of atmospheric optical communications. We have undertaken a combined analytical and experimental effort to attack these network problems. A brief summary of the status of these efforts follows.

## Theory

In our view, the impact of atmospheric optical communications is felt primarily at the four lowest layers of LAN architecture, namely, from the bottom up: at the physical layer, where one or more atmospheric optical links (with their uncontrollable weather-dependent transmission problems) take the place of reliable cable communications; at the data-link layer, where the protocols make the higher layers perceive packet transmission as being error-free; at the network layer, where load management issues are dealt with; and at the transport layer, where job management occurs.

In Nguyen's doctoral dissertation[3] we have presented 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. The rationale here is that by allowing the atmospheric optical links to reduce their data rates, in response to deteriorating visibility conditions, limited transmission-rate low error probability link capability can be maintained into far worse weather conditions before the link must be regarded as inoperable. Within the layered architecture described above, the achievements of[3] are as follows.

Starting at the physical layer, we have extracted from[1,2] the weather-dependent single bit and single packet error probabilities for the semiconductor laser diode transmitter/avalanche photodiode (APD) direct-detection receiver atmospheric link arrangement that we think is appropriate for LAN applications. Next, at the data-link layer, we have shown, assuming constant transmission load at the atmospheric optical link, that transmission rate reduction is far superior to simple full-rate packet repetition as a means for maintaining information flow as the visibility decreases. Additional data-link layer studies included an analysis of the tradeoff between buffer capacity available and transmission delay incurred at the atmospheric optical link after that link has made an unannounced transmission-rate reduction with an assumed constant transmission load.[4] Also, a state-control procedure has been devised for the atmospheric optical link, which relies on an independent channel estimate to keep the optical link operating at the appropriate (weather-dependent) transmission rate with high probability without inducing a state-oscillation problem.[4,5]

The constant transmission load assumed in the lower layer studies cannot prevail after a transmission-rate reduction at the atmospheric optical link unless the rest of the network is informed of this link status change, and network load reduction procedures are then invoked for traffic requiring transmission through this link. In network layer studies, we have devised and evaluated three procedures for disseminating the status information, and we have compared two approaches to load reduction.

The preceding layered analysis was developed without particular assumptions as to the network topology in which the atmospheric optical link was embedded. Specific examination was thus given later to topological considerations; star networks, ring networks, and bridge/gateway operation were treated.

In brief, the overall conclusion from the theory developed in[3] 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 attainable.

## 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 atmospheric optical transceivers have been constructed and tested.[4-6] The transmitters use 2 mW continuous-wave GaAℓAs laser diodes, and the receivers employ Silicon APD/preamplifier modules. These electro-optical elements were selected because they represent choices consistent with operation at rates up to 10 Mb/s over paths as long as 1 km in good weather, subject to the constraints of eye safety, reliability, inexpensive components, and stand-alone operation. They are also consistent with the philosophy of sharing technology with present-day data rate fiber-optic LANs.

The transceivers were designed for binary pulse-position modulation (PPM) transmission, with phase-locked loop (PLL) clock recovery and optimum (integrate-and-compare) demodulation. For link communication and test purposes, two pairs of special transmitting and receiving rate-converting buffers were constructed. The transmitter buffer accepts (and stores) a packet from a PDP 11/23 minicomputer at a 9.6 kb/s terminal communication rate. This packet is then routed to (and stored by) the receiving buffer, via an optical transceiver, at a selectable data rate of up to 10 Mb/s. Finally, the receiving buffer relays the packet to another PDP 11/23 at 9.6 kb/s where error statistics are accumulated.

Initial link tests were performed over a 150 m outdoor path from the Laboratory for Computer Science (LCS) in Building NE43 to the Research Laboratory of Electronics (RLE) in Building 36 on the M.I.T. campus.[5,6] The clear-weather packet error probability was found to be about $2 \times 10^{-4}$, limited primarily by clock-recovery problems; during clear-weather conditions with a stable clock the observed bit error probability has been $10^{-9}$ or less.

Based on the initial test results, plans were made to simultaneously upgrade the clock-recovery circuit and to move toward operation of our transceivers as a 2-node ring network, basically an atmospheric optical version of the PROTEON proNET cable ring network already in use in LCS. Modification of our transceivers to accommodate the proNET differential pulse-position modulation (DPPM) signal set, and to use a 75% gate first-order PLL clock recovery circuit has been completed.[7] We are now bench testing our equipment using the PDP 11/23, equipped with a proNET interface card, and an IBM-PC similarly proNET equipped.

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## 28.2 Two-Photon Coherent State Light

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Recent work has highlighted the applications of two-photon coherent states (TCS), also known as squeezed states, in optical communications and precision measurements. These states have non-classical noise statistics, and their predicted generation schemes include degenerate parametric amplification (DPA), degenerate four-wave mixing (DFWM), the free-electron laser, and multi-photon optical bistability. The preceding generation schemes have been analyzed to varying degrees of approximation, but no experimental observation of TCS has been reported as of yet. We are engaged in a program to: generate and verify the quantum noise behavior of TCS light; and analyze the physics and applications of such light. Our recent progress is summarized below.

## TCS Generation and Detection

Our approach to generate TCS is via DFWM.[1] We reported an extension of the TCS generation theory[1] to encompass pump quantum noise and probe/conjugate loss in backward DFWM.[2] Also described therein were results of a pulsed-beam sodium vapor backward DFWM experiment, which successfully demonstrated quantum-limited transmitted-probe and phase-conjugate beam measurements, but failed to exhibit non-classical light effects. In this pulsed work, we developed a technique to reduce excess noise effects in DFWM,[3] and observed previously unresolved lineshape behavior.[4] More recently, our attention has turned to forward DFWM for TCS generation,[5] with cw beams and optical homodyne detection. We have also experimented with the use of an optical cavity to enhance the DFWM interaction, and discovered an unexpected Raman process that dominates DFWM in our experimental configuration.[6]

## Quantum Photodetection

The basic quantum descriptions for multi-spatiotemporal mode direct detection, homodyne detection, and heterodyne detection were treated under a quasimonochromatic assumption.[7] We relaxed that assumption[8,9] by appealing to the photon-flux driven nature of the detection process.[10] Furthermore, we provided full multi-mode quantum treatment of the recently suggested dual-detector (balanced-mixer) arrangement[11] for suppressing local-oscillator excess noise in coherent optical detection.[9]

## TCS Applications

We have considered the use of TCS light in phase-sensing interferometers.[12] In particular, we developed an optimum phase-conjugate interferometer for single-frequency measurements. We also showed how use of a multi-frequency interferometer in a gravity-wave detecting interferometer can circumvent the previously held standard quantum limit (SQL) on such measurements. It turns out that obtaining sub-SQL performance is intimately related to the photon-flux view of photodetection.

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## 28.3 Laser Radar System Theory

*U.S. Army Research Office - Durham (Contracts DAAG29-80-K-0022 and 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.

1) The use of high time-bandwidth product signal waveforms for 3-D laser radar imaging was studied theoretically.[1] The work concentrated on the effects of range-spread speckle targets and assumed simple practical signal processors. It was shown that chirped signals enjoy a definite advantage over sinusoidally-modulated waveforms in environments with multiple targets lying within a single azimuth/elevation bin.

2) In an earlier study of Doppler-radar target statistics, Mesite[2] found that near-field measurements of flame-sprayed aluminum (speckle target) calibration plates mounted on a moving truck and observed with the Lincoln Laboratory test bed showed a tenfold reduction in fluctuations that was absent from similar far-field measurements, and could not be explained by scanning-induced decorrelation alone. We are now using computer simulation to learn whether random target tilts (due to vibration of the plates) in conjunction with the scanning can provide a theoretical basis for the observed near-field speckle reduction.[3]

3) Partly to buttress the preceding near-field Doppler radar study, and more generally to understand the impact of speckle fluctuations 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.[4] This work elucidates hitherto unidentified interactions between various measurement-configuration parameters that impact speckle-target correlation scales, and hence laser radar performance.

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## 28.4 Fiber-Coupled External-Cavity Semiconductor High Power Laser

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Five diode gain elements (diode lasers with one facet anti-reflection coated) have been controlled to operate coherently with each other by a spatial filter placed between the anti-reflection coated facet and the mirror of an external cavity which provides the feedback for laser operation.[1] The locking of the lasers is relatively insensitive to phase adjustment in each laser path. Locking has occurred with lasers whose output wavelength when operating individually differed by 60 Å. It is expected that the maximum tolerance to wavelength difference is much larger because lasers used were selected so simple individual temperature control could bring them into wavelength coincidence. These results point to the feasibility of placing well over a thousand diode lasers in an external cavity with coherent output.

As the output power is increased (above about one to five watts c.w.) with the concurrent increase in the density of power dissipated, it has been proposed to physically separate the diode gain elements in groups and couple each element into the cavity in series with an optical fiber.[2] The external cavity control of the operation of the series combination of a semiconductor diode gain element and an optical fiber has previously been demonstrated[3] under this contract.

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