Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science

6.453 QUANTUM OPTICAL COMMUNICATION

## Term-Paper Rules and Potential Topics

Fall 2004

**Date:** Wednesday, October 20, 2004

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**General Remarks:**

As part of 6.453, each student must do a term paper consisting of: (1) outside reading on a topic relevant to quantum optical communication, and (2) preparation and submission of a written report based on this reading.

It is *not* the intent of the term-paper requirement that original research be performed. You *may* choose a topic related to your thesis work, but the term paper should *not* be a reproduction of work already done for that thesis.

In what follows there is a list of potential topics, each with some brief remarks and one or more (very) preliminary references to get you started. You are encouraged to seek topics that are not on this list, if you so desire. Please feel free to consult with Prof. Shapiro regarding any term-paper topic, whether or not it is listed below. In order to help you plan your time outlay, the following schedule has been established:

**Wednesday, 10/20/04:** Term paper rules and suggested-topics list distributed, in class.

**10/20/04–11/8/04:** Preliminary reading in support of topic selection; consultation with Prof. Shapiro as necessary.

**Monday, 11/8/04:** One paragraph term-paper proposals due, in class.

**11/8/04–12/8/04:** Reading, and term-paper preparation.

**Wednesday, 12/8/04:** Term papers due, in class.

Before turning to the potential topics themselves, it is worth noting some useful general references. The reprint volume edited by Wheeler and Zurek[1] includes many of the early, classic papers in quantum measurement theory, as well as works from the 1960's and 1970's on Bell's inequalities, quantum non-demolition measurements, etc. Mandel and Wolf[2] cover the fundamentals of quantum optics through work in the 1980's and 1990's on squeezing, and optical quantum non-demolition measurements. The book by Hermann Haus[3] has a wealth of information on quantum noise, squeezing, and quantum non-demolition measurements. Bennett and Shor[4] provide a review of quantum information theory, touching on many topics in quantum computation, quantum coding, etc. Bouwmeester, Ekert, and Zeilinger[5] cover theoretical and experimental work in quantum cryptography, quantum teleportation, and quantum computation. Nielsen and Chuang[6] is a comprehensive text on quantum computation and quantum information. The Web of Science[7] makes it easy to search for recent relevant articles, many of which are available on-line in .pdf form through the MIT libraries' VERA service[8]. If you want to see the very latest preprints, you can consult the quant-ph archive run by the Los Alamos National Laboratory.[9]

1. J.A. Wheeler and W.H. Zurek, eds., *Quantum Theory and Measurement,* (Princeton University Press, Princeton, 1983).
2. L. Mandel and E. Wolf *Optical Coherence and Quantum Optics,* (Cambridge University Press, Cambridge, 1995).
3. H.A. Haus, *Electromagnetic Noise and Quantum Optical Measurements* (Springer, Berlin, 2000).
4. C.H. Bennett and P.W. Shor, "Quantum Information Theory," IEEE Trans. Inform. Theory **44**, 2724–2742 (1998).
5. D. Bouwmeester, A. Ekert, and A. Zeilinger, eds. *The Physics of Quantum Information* (Springer, Berlin, 2000).
6. M.A. Nielsen and I.L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).
7. http://isi2.isiknowledge.com/portal.cgi
8. http://libraries.mit.edu
9. http://www.arXiv.org/archive/quant-ph

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**Potential Topics:**

- **Hidden Variables and Bell's Inequalities:**
  In the early days of quantum mechanics, the disturbing, fundamental presence of randomness in its theory of measurement led a number physicists to seek more complete, "hidden-variable" theories which would remove this unappealing feature of standard quantum mechanics. Bell's inequalities afford experimental tests which can discriminate quantum theory (as it stands) from any such deterministic, hidden-variable theory. Moreover several optical experiments have been performed which confirm these inequalities, i.e., which confirm quantum mechanics and exclude hidden-variable theories. Bell's original paper can be found in [1]. A readable short treatment is given in [2, Sect. 12.14], with references to both theoretical and experimental work, see also [4, Sect. 2.6]

- **Quantum Non-Demolition Measurements:**
  The photodetection measurements that we will discuss in class are annihilative, so the controversial projection postulate does not play a major role. Quantum non-demolition measurements do *not* destroy the optical field, and are of interest

in quantum mechanics more broadly. The early, fundamental work on this topic can be found in [3]. Additional theory appears in [5]. A readable short treatment in the quantum optics setting is given in [2, Sect. 22.6], with references to both theoretical and experimental work.

- **Quantum-State Tomography:**
  A collection of optical homodyne measurements made at a variety of local-oscillator phase angles can be used measure the quantum state of a light beam via a tomographic reconstruction technique. For some theoretical work see [6]; for some experimental work see [7]. See [4, Sect. 8.4.2] for the related topic of quantum process tomography.

- **Quantum-State Source Coding:**
  In classical communication theory, Shannon's source-coding theorem sets a minimum value to the number of bits that must be used to represent the output of an information source. There is a corresponding theory of source coding for quantum states, viz., there is a minimum number of qubits needed to represent a quantum state. For a brief discussion of this problem, with references, see [8].

- **Quantum-State Channel Coding:**
  In classical communication theory, Shannon's noisy-channel coding theorem sete the channel-capacity limit on reliable (error-free) communication. There is a corresponding theory being developed for qubit communication. For a brief discussion of this problem, with references, see [8]. For a text book treatment see [4, Chap. 12].

- **Quantum Error-Correcting Codes:**
  Both digital and analog quantum codes for error correction have been described. See [9],[10]; more references are given in [8]. For more information go to [11, Chap. 7]; for a text book treatment see [4, Chap. 10]

- **Quantum Cryptography:**
  Our upcoming presentation in class will barely scratch the surface of the theory of quantum cryptography. For a brief discussion, with references, see [8]. For much more information go to [11, Chap. 2]; the text book treatment can be found at [4, Chap. 10]; a recent on-line journal special focus is also of interest [12].

- **Quantum Detection Theory:**
  When discrete-valued classical information is conveyed by quantum states, quantum detection theory can be used to provide optimum decision rules and their performance. We will only treat the binary case. For much more information on this topic see [13].

- **Quantum Estimation Theory:**
  When continuous-valued classical information is conveyed by quantum states, quantum estimation theory can be used to provide optimum estimation rules and universal bounds on their performance. For much information on this topic see [13].

- **Quantum Phase:**
  Our treatment of the harmonic oscillator has focused on the quadrature decomposition of its annihilation operator, $\hat{a} = \hat{a}_1 + j\hat{a}_2$, viz., the quantized version of the classical harmonic oscillator's quadrature decomposition, $a = a_1 + ja_2$. The classical harmonic oscillator's polar decomposition, $a = |a|e^{j\phi}$ leads to the problem of quantum phase. Some early work on this problem can be found in [14]. More recent and very extensive treatments appear in [15],[16]

- **Feedback Photodetection:**
  In class we will only treat open-loop photodetection, i.e., we will not consider the case in which the photocurrent is fedback to control the state of the light beam that is being detected. Feedback photodetection has an interesting theory, see, e.g., [17],[18].

- **Nonclassical Light-Beam Generation in Optical Fiber:**
  Our presentation of nonclassical light-beam generation will concentrate on second-order nonlinearities, i.e., on optical parametric amplification. Nonclassical light has also been generated in optical fiber, via its third-order nonlinearity. Early work on continuous-wave (cw) squeezed-state generation in fiber appears in [19]. The cw experiments proved to be very difficult, so most recent work has concentrated on soliton squeezing, see [20]–[22].

- **Quantum Imaging** Combining Fourier optics with non-classical light sources leads to interesting new paradigms known as quantum imaging; see [23] for an extensive set of publications on this topic by the Boston University quantum optics group.

- **Linear Optics Quantum Computing** By combining single-photon sources with linear optics—beam splitters and mirrors—and photodetectors it is possible to do quantum computing. The foundation reference for this topic is [24]. Much additional work—including experiments—has appeared since then, consult [25] and [26]

# References

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[3] V.B. Braginsky, Y.I. Vorontsov, and K.S. Thorne, "Quantum Nondemolition Measurements," Science **209**, 547–557 (1980); reprinted in J.A. Wheeler and W.H. Zurek, eds., *Quantum Theory and Measurement,* (Princeton University Press, Princeton, 1983).

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