6.453 Quantum Optical Communication
Spring 2009

Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science

6.453 Quantum Optical Communication

Term-Paper Rules and Potential Topics

Fall 2008

Date: Thursday, October 16, 2008

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 per formed. 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:

Thursday, 10/16/08: Term paper rules and suggested-topics list distributed, in class.

10/16/08–11/6/08: Preliminary reading in support of topic selection; consultation with Prof. Shapiro as necessary.

Thursday, 11/6/08: One paragraph term-paper proposals due, in class.

11/6/08–12/9/08: Reading, and term-paper preparation.

Tuesday, 12/9/08: 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 measure ments. 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 computa tion, 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.[9]

1. J.A. Wheeler and W.H. Zurek, eds., *Quantum Theory and Measurement,* (Prince ton 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://isiknowledge.com/wos[1]

8. http://libraries.mit.edu

9. http://arXiv.org/archive/quant-ph

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 that would remove this unappealing feature of standard quantum mechanics. Bell's inequalities afford experimental tests that can discriminate quantum theory (as it stands) from any such de terministic, 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 refer ences 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

1 The Web of Science® Citation Index requires a subscription.

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 min imum 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]; an on-line journal special focus is also of interest [12].

- **Quantum Detection Theory:**
  When discrete-valued classical information is conveyed by quantum states, quan tum 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 decom position 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 more 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 the Kolobov book [23] for more information and [24] 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 possi ble to do quantum computing. The foundation reference for this topic is [25]. Much additional work—including experiments—has appeared since then, con sult [26] and [27].

- **Sources of Polarization-Entangled Photon Pairs** There is a considerable literature on the generation of polarization-entangled photon pairs using spon taneous parametric downconversion in bulk crystals or in waveguides with $\chi^{(2)}$ nonlinearities or in optical fiber with its $\chi^{(3)}$ nonlinearity. See [28] for a re cent summary of $\chi^{(2)}$ work with references to other schemes for entanglement generation.

- **Quantum Precision Measurements** The use of quantum resources—entanglement and squeezing—for improved precision measurements is a topic of continuing interest. See [29] for a relevant survey of this field.

References

[1] J.S. Bell, "On the Einstein Podolsky Rosen Paradox," Physics **1**, 195–200 (1964); reprinted in 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] 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).

[4] M.A. Nielsen and I.L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).

[5] C.M. Caves, "Quantum Nondemolition Measurements," in P. Meystre and M.O. Scully, eds. *Qunatum Optics, Experimental Gravitation, and Measurement Theory* (Plenum, New York, 1982).

[6] G.M. D'Ariano, U. Leonhardt, and H. Paul, "Homodyne Detection of the Density-Matrix of the Radiation-Field," Phys. Rev. A **52**, R1801–R1804 (1995).

[7] M. Vasilyev, S.K. Choi, P. Kumar, and G.M. D'Ariano, "Tomographic Measurement of Joint Photon Statistics of the Twin-Beam Quantum State," Phys. Rev. Lett. **84**, 2354–2357 (2000).

[8] C.H. Bennett and P.W. Shor, "Quantum Information Theory," IEEE Trans. Inform. Theory **44**, 2724–2742 (1998).

[9] P.W. Shor, "Scheme for Reducing Decoherence in Quantum Computer Memory," Phys. Rev. A **52**, R2493–R2496 (1995).

[10] S. Lloyd and J.-J.E. Slotine, "Analog Quantum Error Correction," Phys. Rev. Lett. **80**, 4088–4091 (1998).

[11] D. Bouwmeester, A. Ekert, and A. Zeilinger, eds. *The Physics of Quantum Information* (Springer, Berlin, 2000).

[12] New J. Phys. **4**, Articles 41–47 (2002): http://www.njp.org.

[13] C.W. Helstrom, *Quantum Detection and Estimation Theory,* (Academic, New York, 1976).

[14] P. Carruthers and M.M. Nieto, Rev. Mod. Phys. **40**, 411 (1968).

[15] R. Lynch, "The Quantum Phase Problem: A Critical Review," Phys. Reports **256**, 367–436 (1995).

[16] W. Schleich and S.M. Barnett, eds., *Special Issue on Quantum Phase and Phase Dependent Measurements,* Phys. Scripta, **T48** (1993).

[17] H.A. Haus and Y. Yamamoto, "Theory of Feedback-Generated Squeezed States," Phys. Rev. A **34**, 270–292 (1986).

[18] J.H. Shapiro, G. Saplakoglu, S.-T. Ho, P. Kumar, B.E.A. Saleh, and M.C. Teich, "Theory of Light Detection in the Presence of Feedback," J. Opt. Soc. Am. B, **4**, 1604–1620 (1987).

[19] M.D. Levenson, R.M. Shelby, M.D. Reid, D.F¿ Walls, and A. Aspect, "Gener ation and Detection of Squeezed States of Light by Nondegenerate Four-Wave Mixing in an Optical Fiber," Phys. Rev. A **32**, 1550 (1985).

[20] Y. Lai, "Quantum Theory of Soliton Propagation: A Unified Approach Based on the Linearization Approximation," J. Opt. Soc. Am. B **10**, 475–484 (1993).

[21] K. Bergman, C.R. Doerr, H.A. Haus, and M. Shirasaki, "Sub-Shot-Noise Mea surement with Fiber-Squeezed Optical Pulses," Opt. Lett. **18**, 643–645 (1993).

[22] D. Levandovsky, M. Vasilyev, and P. Kumar, "Soliton Squeezing in a Highly Transmissive Nonlinear Optical Loop Mirror," Opt. Lett. **24** 89–92 (1999); errata: **24**, 423 (1999).

[23] M.I. Kolobov, ed., *Quantum Imaging,* (Springer, Berlin, 2007).

[24] http://www.bu.edu/qil/publications.html

[25] E. Knill, R. Laflamme, and G.J. Milburn, "A scheme for efficient quantum com putation with linear optics," Nature **409**, 46 (2001).

[26] http://isiknowledge.com/wos[1]

[27] http://www.arXiv.org/archive/quant-ph

[28] F.N.C Wong, J.H. Shapiro, and T. Kim, "Efficient Generation of Polarization-Entangled Photons in a Nonlinear Crystal," Laser Phys. **16,** 1517 (2006).

[29] V. Giovannetti, L. Maccone, and S. Lloyd, "Quantum-Enhanced Measurements: Beating the Standard Quantum Limit," Science **306,** 1330 (2004).

1 The Web of Science® Citation Index requires a subscription.