

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 25-02-2016		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 27-Mar-2013 - 26-Mar-2015	
4. TITLE AND SUBTITLE Final Report: Approximation of Quantum Stochastic Differential Equations for Input-Output Model Reduction			5a. CONTRACT NUMBER W911NF-13-1-0064		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Hideo Mabuchi			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Stanford University Office of Sponsored Research 3160 Porter Drive, Suite 100 Palo Alto, CA 94304 -8445			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 60701-MA.3		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT We have completed a short program of theoretical research on dimensional reduction and approximation of models based on quantum stochastic differential equations. Our primary results lie in the area of modeling systems with time delays. We have developed a technique to approximate the dynamics of a linear passive QSDE network with time delays, within given limits on the complex plane, by truncation of an expansion in scattering poles.					
15. SUBJECT TERMS quantum probability, quantum stochastic differential equations					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Hideo Mabuchi
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 650-723-0201

Report Title

Final Report: Approximation of Quantum Stochastic Differential Equations for Input-Output Model Reduction

ABSTRACT

We have completed a short program of theoretical research on dimensional reduction and approximation of models based on quantum stochastic differential equations. Our primary results lie in the area of modeling systems with time delays. We have developed a technique to approximate the dynamics of a linear passive QSDE network with time delays, within given limits on the complex plane, by truncation of an expansion in scattering poles.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received

Paper

02/25/2016 4.00 Yeong Dae Kwon, Michael Armen, Hideo Mabuchi. Femtojoule-Scale All-Optical Latching and Modulation via Cavity Nonlinear Optics, PHYSICAL REVIEW Letters, (11 2013): 203002. doi:

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

(c) Presentations

"Algorithms and software for quantum engineering," H. Mabuchi and R. Balu, Review Management Board meeting for the Advanced High Performance Computing Research Center, Stanford, CA, 13 Jan 2016

"Coherent feedback in photonic signal processing," H. Mabuchi, System-X Annual Review Meeting, Stanford, CA 19 Nov 2015

"Quantum dynamical networks and architectures," H. Mabuchi, ARO/ARL Workshop on Theoretical Foundations for Modeling of Open Quantum Systems, Adelphi, MD, 3 Aug 2015

"Coherent feedback in photonic signal processing and computation," H. Mabuchi, International Workshop on Principles and Applications of Control in Quantum Systems, Sydney, Australia, 21 Jul 2015

"Quantum information science and engineering," H. Mabuchi, seminar at Qualcomm, Santa Clara, CA, 4 May 2015

"Quantum engineering and coherent feedback," H. Mabuchi, seminar at Google, Venice, CA, 4 Feb 2015

"Architectures for autonomous quantum memories - coherent feedback and the small volume limit," H. Mabuchi, IARPA Workshop on Quantum Noise and Model Reduction, Laurel, MD, 26 Jan 2015

"Coherent feedback in quantum photonic circuit theory," H. Mabuchi, Optics and Electronics Seminar, Stanford, CA 5 Jan 2015

"Quantum information science and engineering," H. Mabuchi, seminar at Amazon, Seattle, WA, 20 Nov 2014

"Quantum photonic engineering: From single-device experiments to large-scale circuit architectures," H. Mabuchi, seminar at ARL, Adelphi, MD, 6 Nov 2014

"Quantum nonlinear optics and the renaissance of photonic computing," H. Mabuchi, physics colloquium at USF, San Francisco, CA, 29 Oct 2014

"Coherent feedback in quantum optical networks," H. Mabuchi, SECANT advisory board meeting, Albuquerque, NM, 9 Sep 2014

"Coherent feedback control of photonic circuits," H. Mabuchi, DARPA/MTO Meso Program Review, Monterrey, CA, 19 Aug 2014

"Coherent feedback and photonic engineering," H. Mabuchi, SPIE, Baltimore, MD, 7 May 2014

"Coherent feedback and quantum photonic circuit theory," H. Mabuchi, physics colloquium at Univ. of Utah, Salt Lake City, NV, 14 Nov 2013

"Physics with photons: from quantum to bio," H. Mabuchi, Statistics seminar, Stanford, CA, 5 Nov 2013

"Coherent feedback and quantum photonic circuit theory," Stanford-USTC-MIT Conference at USTC, Hefei, China, 17 Sep 2013

"Embedded control for smart photonics," H. Mabuchi, AFOSR Future Directions in Control, Arlington, VA, 19 Jun 2013

"Coherent feedback control and quantum photonic circuit theory," H. Mabuchi, Coherent Quantum Dynamics Summer School, Okinawa, Japan, 8 May 2013

Number of Presentations: 19.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

02/25/2016	2.00	Gil Tabak, Hideo Mabuchi. Trapped Modes in Linear Quantum Stochastic Networks with Delays, EPJ Quantum Technology (10 2015)
10/10/2013	1.00	Hideo Mabuchi, Dmitri S. Pavlichin. Photonic circuits for iterative decoding of a class of low-density parity check codes, ArXiv e-prints (06 2013)
TOTAL:		2

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Dmitri Pavlichin	0.50	
Jie Wu	0.13	
Ryan Hamerly	0.00	
Nikolas Tezak	0.00	
Gil Tabak	0.00	
FTE Equivalent:	0.63	
Total Number:	5	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Dmitri Pavlichin	0.50
FTE Equivalent:	0.50
Total Number:	1

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Hideo Mabuchi	0.09	No
FTE Equivalent:	0.09	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Dmitri Pavlichin
Total Number:

Names of other research staff

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

During the initial months of the award period we focused our efforts on the development and implementation of new computational methods for simulation (without approximation) of QSDE models that incorporate strong quantum noise and component nonlinearities, but minimal buildup of large-scale coherences. We applied this new method in a study of photonic circuit architectures for decoding low-density parity check codes, which have novel and important features. The results were reported in manuscript #1 (uploaded), which has been published in New Journal of Physics.

We then turned to the development of QSDE model reduction techniques for approximate simulation of large-scale optical computing networks. Our approach was to use QSDEs to construct a master equation model of the network, then to transform the master equation into a Wigner Equation framework, and finally to apply systematic Gaussian approximations to the PDE that governs time evolution. By doing so we obtained a set of coupled stochastic differential equations that can reproduce the circuit behavior up to leading order in quantum nonlinear effects. We extended this approach to include not only quantum nonlinear optical models based on ideal (instantaneous, Kerr-type) nonlinearities, but also to models for free

carrier-based nonlinearities in optical semiconductors. The resulting sets of coupled SDEs include both photonic and electronic quantum fluctuations, and we are working to formulate near-term-feasible experimental tests for these models. In collaboration with Charles Santori at HP Labs, we applied the new model-reduction approach to a latch-based model of a 4-bit optical binary logic ripple counter. This enabled us to understand the impact of quantum fluctuations on circuit performance and to identify a critical switching-energy scale for this architecture of about 30 photons, below which quantum stochastic errors propagate and spoil the computation but above which the computation can be performed robustly.

In the final year of the award period we have focused on the challenge of modeling QSDE networks with time delays. The difficulty of accurately modeling dynamical systems with time delays is well known from classical theory; time delays technically add infinite-dimensional PDE-like degrees of freedom to a network model and must be treated carefully in dimensional reduction. In order to make progress on the quantum analogue we began with linear passive models representing the optical "skeleton" of the network, with the physical intuition (which still needs to be proved mathematically) that nonlinear interactions could be added to the reduced skeleton in a straightforward fashion. Building upon results from the classical literature in electromagnetic scattering and circuit theory, we showed how to derive a Blaschke-Potapov expansion for linear stochastic QSDE models with time delays and feedback, and developed a systematic procedure for truncating the expansion to arrive at a finite-dimensional model capturing the effects of the time delays within a desired window of timescales. We encountered a subtlety related to pure-feedforward channels in QSDE networks with time delays, and related this to an entire term that factors out of the Blaschke-Potapov expansion. We developed an approach to computing this term via systematic transformation of the QSDE model. The results of this work are described in manuscript #2 (uploaded), which has very recently been accepted for publication in EPJ Quantum Technology. We believe that these results will be of critical importance for modeling distributed quantum information processing networks.

Technology Transfer

Our ideas about quantum circuit architecture and modeling of networks with time delays have been discussed at length with Dr. Rad Balu and his team at ARL/Adelphi. The time delay approximation procedure is being incorporated into our QNET software package, which is being ported to DOD/HPC platforms by the ARL/Adelphi team.