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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE		3. DATES COVERED *(From - To)*
03/02/2009	Final		4/1/06-11/30/08

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
IONS: Information-theory and Optimization of Networked Systems	FA9550-06-1-0297
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Chiang, Mung	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Mung Chiang Princeton University Olden Street, Engineering Quadrangle Princeton, NJ 08544	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR 875 N Randolph St Arlington, VA 22203 Dr. Robert Bonneau/NL	
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for Public Release

20090610623

13. SUPPLEMENTARY NOTES

14. ABSTRACT

In this project of Information-theory and Optimization of Networked Systems (IONS), we developed the approaches of geometric programming, information-control duality, erasure information, and stochastic network optimization for communication networks. Pathfinder applications to missile defense, telecommunications, and biological networks are studied. Several major awards were received by the team of co-PIs, including Shannon Award, IEEE Hamming Medal, Presidential Early Career Award for Scientists and Engineers, and Technology Review TR35 Young Innovator Award.

15. SUBJECT TERMS

Optimization, Information, Control, Networks

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Mung Chiang
U	U	U	UU		19b. TELEPHONE NUMBER *(Include area code)* (609)258-5071

Standard Form 29B (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

IONS Information-theory and Optimization of Networked Systems
Final Technical Report, February 2009

1. Project Participants

1.1 Principal Investigator

Mung Chiang
Associate Professor of Electrical Engineering
Princeton University

1.2 Co-Principal Investigator

Bob Fry
Systems Engineering Group (SEG)

Sergio Verdu
Professor of Electrical Engineering
Princeton University

2. Activities and Findings

2.1 Major Research and Education Activities

- Layering as optimization decomposition and alternative decomposition for NUM
- Stochatsic network utility maximization
- Erasure information and Lautum information
- Information-control duality

2.2 Major Findings

- Completed a comprehensive survey paper in the Proceedings of IEEE on "Layering As Optimization Decomposition", the first mathematically rigorous, top-down, first-principled method for network architectural decision: who does what and how to connec them, based on optimization modeling and decomposition methods.
- Developed the methodology of enumerating and comparing alternative decompositions to derive alternative network protocol stacks.
- Developed a comprehensive framework of Stochastic Network Utility Maximization at session, packet, channel, and topology level, proving the strongest results so far on session level stability for general workload distribution, nonconvex and time-varying constraint set.
- Reverse engineered widely deployed wireless random access protocols as a selfish game, with protocol details determining the utility function shape and user

strategies, motivated the search for and development of utility optimal medium access control protocols.
- Proved robustness of duality-based resource allocation algorithms in the presence of stochastic feedback noise and characterized rate of convergence in these practical settings.
- Developed the theory of information lost in erasures and the new measure of Lautum information.
- Developed the duality notion between information and control with pathfinder applications to neural processing and missile defense.

2.3 Awards and Recognitions

Based on results in part sponsored by this project, Chiang has received the following awards: Presidential Early Career Award for Scientists and Engineers 2007 from the White House, TR35 Young Technologist Award 2007 from Technology Review Magazine (35 top innovators in biology, material, and information technologies in the world under the age of 35), Young Researcher Competition Runner-up 2007 from Mathematical Programming Society (one of 3 researchers in continuous optimization under the age of 35, selected once every 3 years), and Young Investigator Award 2007 from the Office of Naval Research. Verdu received Shannon Award from Information Theory Society and IEEE Hamming Medal, and was elected to the U.S. National Academy of Engineering.

2.4 Outreach Activities

Extensive research collaborations are established with Arizona State University and Bell Labs through this project. Over 15 tutorials and special sessions organized on the topics in IEEE, ACM, MPS, and INFORMS international conferences.

3. Publications

3.1 Journal Papers

1. M. Chiang, "Geometric programming for communication systems", *Foundations and Trends in Communications and Information Theory*, vol. 2, no. 1-2, pp. 1-154, August 2005. **(One of top 3 papers by authors under the age of 35 in the field of continuous optimization during 2004 – 2007 selected by Mathematical Programming Society)**

2. M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, "Layering as optimization decomposition: A mathematical theory of network architectures", *Proceedings of the IEEE*, vol. 95, no. 1, pp. 255-312, January 2007. **(Top 100 downloaded papers in IEEE Xplore in March – May 2007.)**

3. M. Chiang, C. W. Tan, D. Palomar, D. O'Neill, and D. Julian, "Power control by geometric programming", *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 2640-2651, July 2007.

4. D. Palomar and M. Chiang, "Alternative distributed algorithms for network utility maximization: Framework and applications", *IEEE Transactions on Automatic Control*, vol. 52, no. 12, pp. 2254-2269, December 2007.

5. J. Zhang, D. Zheng, and M. Chiang, "The impact of stochastic noisy feedback on distributed network utility maximization", *IEEE Transactions on Information Theory*, vol. 54, no. 2, pp. 645-665, February 2008.

6. Y. Yi and M. Chiang, "Stochastic network utility maximization: A tribute to Kelly's paper published in this journal a decade ago", *European Transactions on Telecommunications*, vol. 19, no. 4, pp. 421-442, June 2008

7. M. Chiang, P. Hande, T. Lan, and C. W. Tan, "Power control in wireless cellular networks", *Foundations and Trends in Networking*, vol. 2, no. 4, pp. 381-533, July 2008.

8. P. Hande, S. Rangan, M. Chiang, and X. Wu, "Distributed uplink power control for optimal SIR assignment in cellular data networks", *IEEE/ACM Transactions on Networking*, vol. 16, no. 6, pp. 1430-1443, November 2008.

9. C. W. Tan, D. Palomar, and M. Chiang, "Robustness-energy tradeoff in cellular network power control", To appear *IEEE/ACM Transactions on Networking*, 2009.

10. H. Mohsenian Rad, J. Huang, M. Chiang, and V. Wong, "Utility-optimal random access Part I: Reduced complexity, fast convergence, and robust performance", *IEEE Transactions on Wireless Communications*, January 2009.

11. H. Mohsenian Rad, J. Huang, M. Chiang, and V. Wong, "Utility-optimal random access Part II: Algorithms without explicit message passing", *IEEE Transactions on Wireless Communications*, January 2009.

12. S. Verdu and T. Weissman, "The information lost in erasures", IEEE Transactions on Information Theory, vol. 54, no. 11, pp. 5030-5058, November 2008.

13. D. Palomar and S. Verdu, "Lautum information", IEEE Transactions on Information Theory, vol. 54, no. 3, pp. 964-975, March 2008.

3.2 Selected Conference Papers

1. T. Lan, X. Lin, M. Chiang, and R. B. Lee, "How bad is suboptimal rate allocation?" *Proc. IEEE INFOCOM, Phoenix, AZ,* April 2008.

2. J. Zhang, D. Zheng, and M. Chiang, "The impact of stochastic noisy feedback on distributed network utility maximization", *Proc. IEEE INFOCOM*, Anchorage, Alaska, May 2007.

3. L. Chen, T. Ho, S. H. Low, M. Chiang, and J. C. Doyle, "Optimization based rate control for multicast with network coding", *Proc. IEEE INFOCOM*, Anchorage, Alaska, May 2007.

4. D. Palomar and M. Chiang, "Alternative decompositions for distributed maximization of network utility: framework and applications", *Proc. IEEE INFOCOM*, Barcelona, Spain, April 2006.

5. Y. Yi, A. Proutiere, and M. Chiang, "Complexity of wireless scheduling: Impact and tradeoffs", *Proc. ACM Mobihoc*, May 2008.

6. R. Fry, "The engineering of intelligent weapon systems," *Proc. 2007 National Fire Control Symposium*, SECRET, San Diego, CA, August 2007.

7. R. Fry, "Intelligent BMD systems, algorithms, and firecontrol," *Proc. 6th MDA Ballistic Missile Conference*, SECRET, April 2008.

8. R. Fry, "Computation by neural and cortical systems," paper given at the 2008 Computational Neuroscience meeting CNS*2008, Portland, OR, July 2008.

9. R. Fry, "Computation and design of autonomous weapon systems," *Proc. SPIE Defense and Security Conference*, Orlando, FL, March 2008.

3.3 Invited Presentations

1. *Caltech*, Information Sciences Seminar, "Recent Results in Power Control", January 2006.

2. *Arizona State University*, ECE Department Seminar, "Layering As Optimization Decomposition", January 2006.

3. *UCSD*, ECE Department Seminar, "Layering As Optimization Decomposition", May 2006.

4. *IEEE Communication Theory Workshop*, "Layering As Optimization Decomposition", May 2006.

5. *Hong Kong University of Science and Technology*, EE Department Seminar, "Layering As Optimization Decomposition", June 2006.

6. *Chinese University of Hong Kong*, Information Engineering Seminar, "Power Control in Broadband Access", July 2006.

7. *Boston University*, CISE Colloquium, "Layering As Optimization Decomposition", September 2006.

8. *INFORMS Annual Meeting*, "FAST Copper for Broadband Access", November 2006.

9. *INFORMS Annual Meeting*, "Geometric Programming for Communication Systems", November 2006.

10. *University of Maryland*, HyNet Colloquium, "Optimization of Communication Networks: Challenges, Progress, and New Ideas", December 2006.

11. *University of Pennsylvania*, EE Department Seminar, "Optimization of Communication Networks: Challenges, Progress, and New Ideas", December 2006.

12. *Caltech*, Information Sciences Seminar, "Nonconvexity from an Engineering Point of View", January 2007.

13. *Rutgers*, WINLAB Seminar, "Nonconvexity from an Engineering Point of View", February 2007.

14. *International Conference on Complementarity, Duality, and Global Optimization*, "Optimization Beyond Optimality: New Trends in Networking Applications", February 2006.

15. *IEEE 3rd Workshop on Resource Allocation in Wireless Networks*, **Keynote Talk**, "Power Control in Cellular Networks", April 2007.

16. *Stanford University*, Information Systems Laboratory Colloquium, "Beyond Optimality: New Trends in Network Optimization", May 2007.

17. *Hong Kong University of Science and Technology*, EE Seminar, "Beyond Optimality: New Trends in Network Optimization", May 2007.

18. *Chinese Univesity of Hong Kong*, Information Engineering Seminar, "Beyond Optimality: New Trends in Network Optimization", May 2007.

19. *University of Cambridge*, Statistics Laboratory Seminar, "Beyond Optimality: New Trends in Network Optimization", June 2007.

20. *University of Illinois, Urbana Champaign*, "Nonconvex Optimization in Networking from Engineering Viewpoints", July 2007.

21. *International Conference on Continuous Optimization*, Young Researcher Award Session, "Geometric Programming for Communication Systems", August 2007.

22. *NSF Workshop on Wireless Networking Research and Funding*, "Architecture, Complexity, and Robustness", August 2007.

23. *Annual Emerging Technologies Conference at MIT*, "Network Optimization: From Theory to Impacts", September 2007.

24. *Bell Labs Wireless Research Center*, "Beyond Optimality: New Trends in Network Optimization", October 2007.

25. *University of Washington Optimization Seminar Series*, "Beyond Optimality: New Trends in Network Optimization", April 2008.

26. *Center for Theoretical Information and Computer Science*, Hong Kong, "Content-Pipe Divide and Network Distribution Capacity", April 2008.

27. *Hong Kong University of Science and Technology*, "Content-Pipe Divide and Network Distribution Capacity", April 2008.

28. *Office of Naval Research Workshop on Communications*: "Simplicity in Complex Communication Networks", May 2008.

29. *SIAM 8th Conference on Optimization*, "Optimization and Game in Cellular and DSL Communications", May 2008.

30. *USC Invited Workshop on Wireless Networks*, "Bridging Theory Practice Gap", May 2008.

31. *Microsoft Research Lab*, "Simplicity in Complex Communication Networks", June 2008.

32. *IEEE 5th Workshop on Sensor Array and Multichannel Signal Processing*, **Keynote talk,** "Beyond Optimality: New Trends in Network Optimization", Darmstadt, Germany, July 2008.

33. *Institute of Pure and Applied Mathematics Workshop on Network of Networks*, "Content-Pipe Divide", November 2008.

34. *Institute of Pure and Applied Mathematics Workshop on Mathematical Frontiers of Networking Research*, "Distributed Scheduling", November 2008.

35. *UCLA EE Department Seminar*, "Two Open Problems in Networking: Random Access Performance and P2P Streaming Capacity", December 2008.

36. MIT Lincoln Lab MKV program, "Joint discrimination, fusion, and weapon-target assignment framework," Apri 2007.

37. Air Force Institute of Technology, "Engineering intelligent systems", May 2007.