Network Optimization and Control

Network Optimization and Control

Srinivas Shakkottai

Texas A&M University
USA

R. Srikant

University of Illinois
Urbana-Champaign
USA
rsrikant@uiuc.edu

the essence of knowledge

Boston – Delft

Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
USA
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is S. Shakkottai and R. Srikant, Network Optimization and Control, Foundation and Trends® in Networking, vol 2, no 3, pp 271–379, 2007

ISBN: 978-1-60198-102-8

Foundations and Trends® in Networking

Volume 2 Issue 3, 2007

Editorial Scope

Foundations and Trends® in Networking will publish survey and tutorial articles in the following topics:

- Ad Hoc Wireless Networks
- Sensor Networks
- Optical Networks
- Local Area Networks
- Satellite and Hybrid Networks
- Cellular Networks
- Internet and Web Services
- Protocols and Cross-Layer Design
- Network Coding
- Energy-Efficiency Incentives/Pricing/Utility-based
- Games (co-operative or not)
- Security
- Scalability
- Topology
- Control/Graph-theoretic models
- Dynamics and Asymptotic Behavior of Networks

Information for Librarians

Foundations and Trends® in Networking, 2007, Volume 2, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in
Networking
Vol. 2, No. 3 (2007) 271–379

DOI: 10.1561/1300000007

Network Optimization and Control

Srinivas Shakkottai[1] and R. Srikant[2]

[1] *Texas A&M University, USA*
[2] *University of Illinois, Urbana-Champaign, USA, rsrikant@uiuc.edu*

Abstract

We study how protocol design for various functionalities within a communication network architecture can be viewed as a distributed resource allocation problem. This involves understanding what resources are, how to allocate them fairly, and perhaps most importantly, how to achieve this goal in a distributed and stable fashion. We start with ideas of a centralized optimization framework and show how congestion control, routing and scheduling in wired and wireless networks can be thought of as fair resource allocation. We then move to the study of controllers that allow a decentralized solution of this problem. These controllers are the analytical equivalent of protocols in use on the Internet today, and we describe existing protocols as realizations of such controllers. The Internet is a dynamic system with feedback delays and flows that arrive and depart, which means that stability of the system cannot be taken for granted. We show how to incorporate stability into protocols, and thus, prevent undesirable network behavior. Finally, we consider a futuristic scenario where users are aware of the effects of their actions and try to game the system. We will see that the optimization framework is remarkably robust even to such gaming.

Contents

1 Introduction **1**

2 Network Utility Maximization **5**

2.1 Utility Maximization in Networks 6
2.2 Resource Allocation in Wireless Networks 12
2.3 Node-Based Flow Conservation Constraints 15
2.4 Fairness 16

3 Utility Maximization Algorithms **21**

3.1 Primal Formulation 22
3.2 Dual Formulation 34
3.3 Extension to Multi-Path Routing 38
3.4 Primal–Dual Algorithm for Wireless Networks 41

4 Congestion Control Protocols **53**

4.1 TCP-Reno 55
4.2 Relationship to Primal Algorithm 58
4.3 A Generalization of TCP-Reno 59
4.4 TCP-Vegas: A Delay Based Algorithm 60
4.5 TCP-Vegas as a Resource Allocation Algorithm 62
4.6 Relation to Dual Algorithms and Extensions 64

5 Network Stability **69**

5.1 Stability of the Primal Algorithm with Delays 71
5.2 Stability Under Flow Arrivals and Departures 80

6 Game Theory and Resource Allocation **87**

6.1 VCG Mechanism 88
6.2 Kelly Mechanism 91
6.3 Strategic or Price-Anticipating Users 93

Conclusions **101**

Acknowledgments **105**

References **107**

1

Introduction

The Internet has been one of the most conspicuous successes of the communications industry, and has permeated every aspect of our lives. Indeed, it is a testimony to its relevance in modern lifestyle that Internet connectivity is now considered an essential service like electricity and water supply. The idea that a best-effort data service could attain such significance was perhaps difficult to imagine a couple of decades ago. In fact, the Internet was initially envisioned as a decentralized data transmission network for military use. The argument was that if there were no centralized control, such as in a telephone network, and if much of the intelligence was at the edges of the system, it would make the network that much harder to destroy. Concurrent with the indestructibility requirements of the military was the need of scientific laboratories which required a network to exchange large data files of experimental results with each other. They envisioned high-speed links for transferring data between geographically distant data sources. The two requirements, coupled with statistical multiplexing ideas that illustrated the efficiency of using packetized data transmission gave rise to the Internet.

As the network grew, it was clear that unrestricted data transfer by many users over a shared resource, i.e., the Internet, could be bad for the end users: excess load on the links leads to packet loss and decreases the effective throughput. This kind of loss was experienced at a significant level in the 1980s and was termed *congestion collapse*. Thus, there was a need for a protocol to control the congestion in the network, i.e., control the overloading of the network resources. It led to the development of a congestion control algorithm for the Internet by Van Jacobson [34]. This congestion control algorithm was implemented within the protocol used by the end hosts for data transfer called the Transmission Control Protocol (TCP). Even though TCP is a lot more than just a congestion control algorithm, for the purposes of this review, we will use the terms "TCP" and "TCP congestion control algorithm" interchangeably.

Congestion control can also be viewed as a means of allocating the available network resources in some fair manner among the competing users. This idea was first noted by Chiu and Jain [13] who studied the relationship between control mechanisms at the end-hosts which use one-bit feedback from a link and the allocation of the available bandwidth at the link among the end-hosts. In fact, some of the details of Jacobson's congestion control algorithm for the Internet were partly influenced by the analytical work in [13]. The resource allocation viewpoint was significantly generalized by Kelly et al. [41] who presented an optimization approach to understanding congestion control in networks with arbitrary topology, not just a single link. The purpose of this review is to present a state-of-the-art view of this optimization approach to network control. The material presented here is complementary to the book [89]. While the starting point is the same, i.e., the work in [41], this review focuses primarily on the developments since the writing of [89]. The purpose of this review is to provide a starting point for a mature reader with little background on the subject of congestion control to understand the basic concepts underlying network resource allocation. While it would be useful to the reader to have an understanding of optimization and control theory, we have tried to make the review as self contained as possible to make it accessible to a large audience. We have made it a point to provide extensive references, and the interested reader could consult these to obtain a deeper understanding of the topics covered. We hope that by providing a foundation for understanding the analytical approach to congestion control, the review will encourage both analysts and systems designers to work in synergy while developing protocols for the future Internet.

The review is organized as follows. We state the resource allocation objective in Section 2 and present the optimization formulation of the resource allocation problem. In Section 3, we will study decentralized, dynamic algorithms that solve the optimization problem. The section explains the framework for the design of such algorithms and proves the convergence of these algorithms. We then study current and recently proposed congestion control protocols, and their relationship to the optimization framework in Section 4. We then proceed to study the question of network stability in Section 5. We study two concepts of stability — that of convergence of algorithms to the fair allocation in the presence of feedback delays, and the question of whether the number of flows in the system would remain finite when flows arrive and depart. Finally, in Section 6, we study resource allocation from a game-theoretic viewpoint. In all the previous sections, it was assumed that the users cooperate to maximize network utility. In Section 6, we study selfish users whose goal is to maximize their own utility and their impact on the total network utility.

References

[1] T. Alpcan and T. Başar, "A utility-based congestion control scheme for internet-style networks with delay," in *Proceedings of IEEE Infocom*, San Francisco, California, March–April 2003.

[2] F. Baccelli and D. Hong, "A.I.M.D., fairness and fractal scaling of TCP traffic," in *Proceedings of IEEE INFOCOM*, 2002.

[3] F. Baccelli, D. R. McDonald, and J. Reynier, "A mean-field model for multiple TCP connections through a buffer implementing red," *Performance Evaluation*, vol. 49, no. 1/4, pp. 77–97, 2002.

[4] D. Bertsekas and R. Gallager, *Data Networks*. Englewood Cliffs, NJ: Prentice Hall, 1987.

[5] D. P. Bertsekas, *Nonlinear Programming*. Athena Scientific, 1999.

[6] T. Bonald and L. Massoulie, "Impact of fairness on internet performance," in *Proceedings of ACM Sigmetrics*, 2001.

[7] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[8] L. Bramko and L. Peterson, "TCP Vegas: End-to-end congestion avoidance on a global internet," *IEEE Journal on Selected Areas in Communications*, pp. 1465–1480, October 1995.

[9] M. Bramson, "Stability of networks for max–min fair routing," presented at INFORMS Applied Probability Conference, 2005.

[10] L. Bui, R. Srikant, and A. L. Stolyar, "Optimal resource allocation for multicast flows in multihop wireless networks," in *Proceedings of the IEEE Conference on Decision and Control*, December 2007.

[11] M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, "Layering as optimization decomposition: A mathematical theory of network architectures," *Proceedings of IEEE*, January 2007.

[12] M. Chiang, D. Shah, and A. Tang, "Stochastic stability of network utility maximization: General file size distribution," in *Proceedings of the Allerton Conference on Communication, Control and Computing*, 2006.

[13] D. Chiu and R. Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks," *Computer Networks and ISDN Systems*, vol. 17, pp. 1–14, 1989.

[14] E. H. Clarke, "Multipart pricing of public goods," *Public Choice*, 1971.

[15] A. Das and R. Srikant, "Diffusion approximations for models of congestion control in high-speed networks," in *IEEE Conference on Decision and Control*, Tampa, FL, December 1998.

[16] G. de Veciana, T.-J. Lee, and T. Konstantopoulos, "Stability and performance analysis of networks supporting elastic services," *IEEE/ACM Transactions on Networking*, vol. 9, no. 1, pp. 2–14, February 2001.

[17] S. Deb and R. Srikant, "Congestion control for fair resource allocation in networks with multicast flows," in *Proceedings of the IEEE Conference on Decision and Control*, 2001.

[18] S. Deb and R. Srikant, "Global stability of congestion controllers for the internet," *IEEE Transactions on Automatic Control*, vol. 48, pp. 1055–1060, June 2003.

[19] S. Deb and R. Srikant, "Rate-based versus queue-based models of congestion control," in *Proceedings of ACM Sigmetrics*, 2004.

[20] S. Deb and R. Srikant, "Rate-based versus queue-based models of congestion control," *IEEE Transactions on Automatic Control*, April 2006.

[21] C. A. Desoer and Y. T. Wang, "On the generalized Nyquist stability criterion," *IEEE Transactions on Automatic Control*, vol. 25, pp. 187–196, April 1980.

[22] A. Eryilmaz and R. Srikant, "Fair resource allocation in wireless networks using queue-length-based scheduling and congestion control," in *Proceedings of IEEE INFOCOM*, 2005.

[23] A. Eryilmaz and R. Srikant, "Joint congestion control, routing and MAC for stability and fairness in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1514–1524, August 2006.

[24] S. Floyd, "TCP and explicit congestion notification," *ACM Computer Communication Review*, vol. 24, pp. 10–23, October 1994.

[25] S. Floyd and V. Jacobson, "Random early detection gateways for congestion avoidance," *IEEE/ACM Transactions on Networking*, pp. 397–413, August 1993.

[26] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*. Prentice-Hall, 2002.

[27] C. Fulton, S.-Q. Li, and C. S. Lim, "Ut: Abr feedback control with tracking," in *IEEE Infocom*, April 1997.

[28] L. Georgiadis, M. J. Neely, and L. Tassiulas, "Resource allocation and cross-layer control in wireless networks," *Foundations and Trends in Networking*, vol. 1, pp. 1–144, 2006.

[29] T. Groves, "Incentives in teams," *Econometrica*, pp. 617–631, 1973.

[30] H. Han, S. Shakkottai, C. V. Hollot, R. Srikant, and D. Towsley, "Multi-path TCP: A joint congestion control and routing scheme to exploit path diversity on the internet," *IEEE/ACM Transactions on Networking*, vol. 14, December 2006.

[31] D. Heyman, T. V. Lakshman, and A. Niedhart, "A new method for analyzing feedback-based protocols with applications to engineering web traffic over the Internet," in *Sigmetrics 97*, pp. 24–38, 1997.

[32] C. Hollot, V. Misra, D. Towsley, and W. Gong, "On designing improved controllers for AQM routers supporting TCP flows," in *Proceedings of IEEE Infocom*, pp. 1726–1734, Anchorage, Alaska, April 2001.

[33] C. V. Hollot and Y. Chait, "Nonlinear stability analysis for a class of TCP/AQM schemes," in *Proceedings of the IEEE Conference on Decision and Control*, December 2001.

[34] V. Jacobson, "Congestion avoidance and control," *ACM Computer Communication Review*, vol. 18, pp. 314–329, August 1988.

[35] J. M. Jaffe, "A dentralized "optimal" multiple-user flow control algorithm," *IEEE Transactions on Communications*, pp. 954–962, 1981.

[36] C. Jin, D. Wei, S. H. Low, G. Buhrmaster, J. Bunn, D. H. Choe, R. L. A. Cottrell, J. C. Doyle, W. Feng, O. Martin, H. Newman, F. Paganini, S. Ravot, and S. Singh, *FAST TCP: From Theory to Experiments*. April 2003.

[37] R. Johari and J. N. Tsitsiklis, "Efficiency loss in a network resource allocation game," *Mathematics of Operations Research*, vol. 29, pp. 407–435, March 2004.

[38] R. Johari and J. N. Tsitsiklis, "Communication requirements of VCG-like mechanisms in convex environments," in *Proceedings of the Allerton Conference on Control, Communications and Computing*, 2005.

[39] K. Kar, S. Sarkar, and L. Tassiulas, "A scalable low-overhead rate control algorithm for multirate multicast sessions," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 8, pp. 1541–1557, October 2002.

[40] F. Kelly and T. Voice, "Stability of end-to-end algorithms for joint routing and rate control," *Computer Communication Review*, vol. 35, 2005.

[41] F. P. Kelly, "Charging and rate control for elastic traffic," *European Transactions on Telecommunications*, vol. 8, pp. 33–37, 1997.

[42] F. P. Kelly, "Models for a self-managed Internet," *Philosophical Transactions of the Royal Society*, vol. A358, pp. 2335–2348, 2000.

[43] F. P. Kelly, "Mathematical modelling of the Internet," in *Mathematics Unlimited — 2001 and Beyond*, (B. Engquist and W. Schmid, eds.), pp. 685–702, Berlin: Springer-Verlag, 2001.

[44] F. P. Kelly, A. Maulloo, and D. Tan, "Rate control in communication networks: Shadow prices, proportional fairness and stability," *Journal of the Operational Research Society*, vol. 49, pp. 237–252, 1998.

[45] T. Kelly, *Scalable TCP: Improving Performance in Highspeed Wide Area Networks*. December 2002.

[46] S. Keshav, *An Engineering Approach to Computer Networks*. Reading, MA: Addison-Wesley, 1997.

[47] H. Khalil, *Nonlinear Systems*. Upper Saddle River, NJ: Prentice Hall, Second ed., 1996.

[48] A. Kherani, B. Prabhu, K. Avrachenkov, and E. Altman, "Comparative study of different adaptive window protocols," *Telecommunication Systems*, pp. 321–350, 2005.

[49] S. Kunniyur and R. Srikant, "End-to-end congestion control: Utility functions, random losses and ECN marks," in *Proceedings of IEEE Infocom*, Tel Aviv, Israel, March 2000.

[50] S. Kunniyur and R. Srikant, "Analysis and design of an adaptive virtual queue algorithm for active queue management," in *Proceedings of ACM Sigcomm*, pp. 123–134, San Diego, CA, August 2001.

[51] S. Kunniyur and R. Srikant, "A time-scale decomposition approach to adaptive ECN marking," in *Proceedings of IEEE Infocom*, Anchorage, AK, April 2001.

[52] S. Kunniyur and R. Srikant, "Stable, scalable, fair congestion control and AQM schemes that achieve high utilization in the internet," *IEEE Transactions on Automatic Control*, vol. 48, pp. 2024–2028, 2003.

[53] S. Kunniyur and R. Srikant, "End-to-end congestion control: Utility functions, random losses and ECN marks," *IEEE/ACM Transactions on Networking*, vol. 7, no. 5, pp. 689–702, October 2003.

[54] D. E. Lapsley and S. H. Low, "Random early marking for Internet congestion control," in *Proceedings of IEEE GLOBECOM*, pp. 1747–1752, 1999.

[55] T.-J. Lee and G. de Veciana, "A decentralized framework to achieve max–min fair bandwidth allocation for ATM networks," in *Proceedings of IEEE GLOBECOM*, pp. 1515–1520, 1998.

[56] X. Lin and N. Shroff, "The multi-path utility maximization problem," in *Proceedings of the Allerton Conference on Communications, Control and Computing*, Monticello, IL, October 2003.

[57] X. Lin and N. Shroff, "Joint rate control and scheduling in wireless networks," in *Proceedings of the IEEE Conference on Decision and Control*, 2004.

[58] X. Lin and N. Shroff, "On the stability region of congestion control," in *Proceedings of the Allerton Conference on Communications, Control and Computing*, 2004.

[59] X. Lin, N. Shroff, and R. Srikant, "A tutorial on cross-layer optimization in wireless networks," *IEEE Journal on Selected Areas in Communications*, pp. 1452–1463, August 2006.

[60] X. Lin, N. B. Shroff, and R. Srikant, "On the connection-level stability of congestion-controlled networks," to appear in the *IEEE Transactions on Information Theory*, 2006.

[61] S. Liu, T. Başar, and R. Srikant, "Exponential red: A stabilizing AQM scheme for low- and high-speed TCP protocols," *IEEE/ACM Transactions on Networking*, pp. 1068–1081, October 2005.

[62] S. Liu, T. Basar, and R. Srikant, "TCP-illinois: A loss and delay-based congestion control algorithm for high-speed networks," in *Proceedings of First International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS)*, Pisa, Italy, October 11–13 2006.

[63] S. H. Low, "Optimization flow control with on-line measurement or multiple paths," in *Proceedings of the 16th International Teletraffic Congress*, Edinburgh, UK, 1999.

[64] S. H. Low and D. E. Lapsley, "Optimization flow control, I: Basic algorithm and convergence," *IEEE/ACM Transactions on Networking*, pp. 861–875, December 1999.

[65] S. H. Low, F. Paganini, and J. C. Doyle, "Internet congestion control," *IEEE Control Systems Magazine*, vol. 22, pp. 28–43, February 2002.

[66] S. H. Low, L. Peterson, and L. Wang, "Understanding Vegas: A duality model," *Journal of ACM*, vol. 49, no. 2, pp. 207–235, March 2002.

[67] R. T. Maheswaran and T. Basar, "Efficient signal proportional allocation (espa) mechanisms: Decentralized social welfare maximization for divisible resources," *IEEE Journal on Selected Areas in Communications*, pp. 1000–1009, May 2006.

[68] L. Massoulie, *Structural Properties of Proportional Fairness: Stability and Insensitivity*. Preprint.

[69] L. Massoulie and J. Roberts, "Bandwidth sharing: Objectives and algorithms," in *Proceedings of Infocom*, New York, NY, March 1999.

[70] S. P. Meyn, *Control Techniques for Complex Networks*. Cambridge University Press, 2007.

[71] V. Misra, W. Gong, and D. Towsley, "A fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED," in *Proceedings of ACM Sigcomm*, Stockholm, Sweden, September 2000.

[72] J. Mo, R. J. La, V. Anantharam, and J. Walrand, "Analysis and comparison of TCP Reno and Vegas," in *Proceedings of Infocom*, pp. 1556–1563, March 1999.

[73] J. Mo and J. Walrand, "Fair end-to-end window-based congestion control," in *SPIE International Symposium*, Boston, MA, 1998.

[74] J. Mo and J. Walrand, "Fair end-to-end window-based congestion control," *IEEE/ACM Transactions on Networking*, vol. 8, pp. 556–567, October 2000.

[75] J. Nash, "The bargaining problem," *Econometrica*, vol. 18, pp. 155–162, 1950.

[76] M. J. Neely, E. Modiano, and C. Li, "Fairness and optimal stochastic control for heterogeneous networks," in *Proceedings of IEEE INFOCOM*, 2005.

[77] F. Paganini, "A global stability result in network flow control," *Systems and Control Letters*, vol. 46, no. 3, pp. 153–163, 2002.

[78] F. Paganini, J. Doyle, and S. Low, "Scalable laws for stable network congestion control," in *Proceedings of the IEEE Conference on Decision and Control*, pp. 185–190, Orlando, FL, December 2001.

[79] A. Papachristodoulou, "Global stability analysis of a TCP/AQM protocol for arbitrary networks with delay," in *Proceedings of the IEEE Conference on Decision and Control*, December 2004.

[80] L. L. Peterson and B. Davie, *Computer Networks: A Systems Approach*. Morgan-Kaufman, 1999.

[81] G. Raina and D. Wischik, "Buffer sizes for large multiplexers: TCP queueing theory and instability analysis," in *Proceedings of EuroNGI Conference on Next Generation Internet Networks*, 2005.

- [82] K. K. Ramakrishnan and R. Jain, "A binary feedback scheme for congestion avoidance in computer networks with a connectionless network layer," in *Proceedings of ACM Sigcomm*, pp. 303–313, 1988.
- [83] P. Ranjan, R. J. La, and E. H. Abed, "Characterization of global stability conditions for rate control with an arbitrary communication delay," *IEEE/ACM Transactions on Networking*, pp. 94–107, February 2006.
- [84] J. Rawls, *A Theory of Justice*. Belknap Press, 1971.
- [85] J. Roberts and L. Massoulie, "Bandwidth sharing and admission control for elastic traffic," in *Proceedings of ITC specialists seminar*, Yokohama, Japan, 1998.
- [86] S. Shakkottai and R. Srikant, "How good are fluid models of internet congestion control?," in *Proceedings of IEEE Infocom*, June 2002.
- [87] S. Shakkottai and R. Srikant, "Mean FDE models for internet congestion control under a many-flows regime," *IEEE Transactions on Information Theory*, pp. 1050–1072, June 2004.
- [88] R. N. Shorten and D. J. Leith, "H-TCP: TCP for high-speed and long-distance networks," in *Proceedings of PFLDnet*, 2004.
- [89] R. Srikant, *The Mathematics of Internet Congestion Control*. Birkhauser, 2004.
- [90] R. Srikant, "Models and methods for analyzing internet congestion control algorithms," in *Advances in Communication Control Networks in the Series Lecture Notes in Control an Information Sciences (LCNCIS)*, (C. T. Abdallah, J. Chiasson, and S. Tarbouriech, eds.), Springer, 2004.
- [91] R. Srikant, "On the positive recurrence of a Markov chain describing file arrivals and departures in a congestion-controlled network," presented at the IEEE Computer Communications Workshop, October 2004.
- [92] R. Stevens, *TCP/IP Illustrated*. Vol. 1, Addison-Wesley, 1994.
- [93] A. L. Stolyar, "Maximizing queueing network utility subject to stability: Greedy primal-dual algorithm," *Queueing Systems*, vol. 50, pp. 401–457, 2005.
- [94] P. Tinnakornsrisuphap and A. M. Makowski, "Limit behavior of ECN/RED gateways under a large number of TCP flows," in *Proceedings of Infocom*, pp. 873–883, San Francisco, CA, April 2003.
- [95] W. Vickrey, "Counter speculation, auctions, and competitive sealed tenders," *Journal of Finance*, pp. 8–37, 1961.
- [96] G. Vinnicombe, "On the stability of end-to-end congestion control for the internet," University of Cambridge Technical Report CUED/F-INFENG/TR.398. Available at http://www.eng.cam.ac.uk/~gv, 2001.
- [97] G. Vinnicombe, "On the stability of networks operating TCP-like congestion control," in *Proceedings of the IFAC World Congress*, Barcelona, Spain, 2002.
- [98] Z. Wang and F. Paganini, "Global stability with time-delay in network congestion control," in *Proceedings of the IEEE Conference on Decision and Control*, 2002.
- [99] D. X. Wei, C. Jin, S. H. Low, and S. Hegde, "Fast TCP: Motivation, architecture, algorithms, performance," *IEEE/ACM Transactions on Networking*, December 2006.
- [100] J. Wen and M. Arcak, "A unifying passivity framework for network flow control," in *Proceedings of IEEE Infocom*, April 2003.

[101] F. Wirth, R. Stanojevic, R. Shorten, and D. Leith, "Stochastic equilibria of AIMD communication networks," *SIAM Journal of Matrix Theory and Its Applications*, 2006.

[102] H. Yaiche, R. R. Mazumdar, and C. Rosenberg, "A game-theoretic framework for bandwidth allocation and pricing in broadband networks," *IEEE/ACM Transactions on Networking*, vol. 8, pp. 667–678, October 2000.

[103] S. Yang and B. Hajek, "VCG-kelly mechanisms for allocation of divisible goods: Adapting VCG mechanisms to one-dimensional signals," *IEEE Jounal of Selected Area in Communications, Special Issue on Non-Cooperative Behavior in Networking*, vol. 25, August 2007.

[104] L. Ying, G. Dullerud, and R. Srikant, "Global stability of Internet congestion controllers with heterogeneous delays," in *Proceedings of the American Control Conference*, Boston, MA, June 2004.

[105] L. Ying, G. Dullerud, and R. Srikant, "Global stability of Internet congestion controllers with heterogeneous delays," *IEEE/ACM Transactions on Networking*, June 2006.