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14. ABSTRACT
The goals of this project are to improve the understanding of multi-scale Features of networks and to use that understanding to developed improved protocols.

The theoretical contributions of this work include sparse models of long-range dependency in network, a stochastic approximation theory for long range dependent processes, techniques to learn the characteristics of losses in wireless networks, stochastic gradient algorithms for wireless ad hoc networks, sampling techniques to estimate the

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Report Title

Analysis and Design of Complex Networks

ABSTRACT

The goals of this project are to improve the understanding of multi-scale Features of networks and to use that understanding to developed improved protocols.

The theoretical contributions of this work include sparse models of long-range dependency in network, a stochastic approximation theory for long range dependent processes, techniques to learn the characteristics of losses in wireless networks, stochastic gradient algorithms for wireless ad hoc networks, sampling techniques to estimate the features of complex graphs, and improved models of transmission protocols.

The practical contributions include media access control algorithms for maximum throughput in ad hoc networks, protocols for higher throughput and lower delays in WiFi, protocols for generating secret keys in wireless networks.

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
07/31/2013	49.00	Yong He, Jie Sun, Xiaojun Ma, Athanasios V. Vasilakos, Ruixi Yuan, Weibo Gong. Semi-Random Backoff: Towards Resource Reservation for Channel Access in Wireless LANs, IEEE/ACM Transactions on Networking, (02 2013): 0. doi: 10.1109/TNET.2012.2202323
08/29/2011	2.00	Amin Aminzadeh Gohari, Venkat Anantharam. Evaluation of Marton's Inner Bound for the General Broadcast Channel, IEEE Transactions on Information Theory, (03 2012): 0. doi:
08/29/2011	3.00	Venkat Anantharam, Takis Konstantopoulos. Integral representation of Skorokhod reflection, Proceedings of the American Mathematical Society, (03 2012): 0. doi:
08/30/2011	4.00	Juan Jose ? Jaramillo, R. Srikant, Lei Ying. Scheduling for Optimal Rate Allocation in Ad HocNetworks With Heterogeneous Delay Constraints, IEEE Journal on Selected Areas in Communications, (05 2011): 979. doi:
08/30/2011	6.00	Mathieu Leconte, Jian Ni, R. Srikant. Improved Bounds on the Throughput Efficiency ofGreedy Maximal Scheduling in Wireless Networks, IEEE/ACM Transactions on Networking, (06 2011): 709. doi:
08/31/2011	9.00	Yan Cai, Patrick P.C. Lee, Weibo Gong, Don Towsley. Analysis of traffic correlation attacks on router queues, Computer Networks, (02 2011): 734. doi:
08/31/2011	31.00	Zhenhua Liu, Minghong Lin, Adam Wierman, Steven H. Low, Lachlan L. H. Andrew. Geographical Load Balancing with Renewables, ACM SIGMETRICS Performance Evaluation Review, (03 2012): 0. doi:
08/31/2011	27.00	BO JIANG, ROGER BROCKETT, WEIBO GONG, DON TOWSLEY. STOCHASTIC DIFFERENTIAL EQUATIONS FOR POWER LAWBEHAVIORS, Journal of Applied Probability, (02 2012): 0. doi:
08/31/2011	14.00	B. Jiang, Y. Cai, D. Towsley. On the Resource Utilization and Traffic Distribution of MultipathTransmission Control, Performance Evaluation, (01 2012): 0. doi:
10/01/2012	34.00	Venkat Anantharam , Vivek Borkar. Stochastic approximation with long range dependentand heavy tailed noise, Queueing Systems, (06 2012): 221. doi:
10/01/2012	46.00	Yong He, Jie Sun, Xiaojun Ma, Athanasios V. Vasilakos, Ruixi Yuan, Weibo Gong. Semi-Random Backoff: Towards ResourceReservation for Channel Access in Wireless LANs, IEEE/ACM Transactions on Networking, (12 2012): 0. doi:
10/01/2012	36.00	Amin Aminzadeh Gohari, Venkat Anantharam. Evaluation of Marton's Inner Boundfor the General Broadcast Channel, IEEE TRANSACTIONS ON INFORMATION THEORY, (02 2012): 608. doi:
10/21/2014	39.00	Barlas Oguz, Venkat Anantharam. Hurst Index of Functions of Long-Range-Dependent Markov Chains, Journal of Applied Probability, (06 2012): 451. doi:

10/21/2014 48.00 Z. Liu, A. Wierman, Y. Chen, B. Razon, N. Chen. Data Center Demand Response: Avoiding the Coincident Peak via Workload Shifting and Local Generation,
, (09 2013): 0. doi:

12/02/2014 78.00 PINGHUI WANG, JOHN C. S. LUI, BRUNO RIBEIRO, DON TOWSLEY, JUNZHOU ZHAO, XIAOHONG GUAN. Efficiently Estimating Motif Statistics of Large Networks,
ACM Transactions on Knowledge Discovery from Data, (09 2014): 81. doi:

12/02/2014 66.00 Barlas Oguz, Venkat Anantharam. Hurst Index of functions of long-range-dependent Markov chains,
Journal of Applied Probability, (07 2012): 451. doi:

TOTAL: 16

Number of Papers published in peer-reviewed journals:

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

Received	Paper

12/02/2014 77.00 Yan Cai, Xiaolin Wang, Weibo Gong, Don Towsley. A Study on the Performance of a Three-StageLoad-Balancing Switch,
IEEE/ACM Transactions on Networking, (02 2014): 52. doi:

12/02/2014 74.00 . Real-Time Peer-to-Peer Streaming Over MultipleRandom Hamiltonian Cycles,
IEEE TRANSACTIONS ON INFORMATION THEORY, (09 2013): 5763. doi:

TOTAL: 2

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

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

Received	Paper
07/31/2013 53.00	Sudeep Kamath, Venkat Anantharam. Non-interactive simulation of joint distributions: the Hirschfeld-Gebelein-Renyi correlation and the hypercontractivity ribbon, Annual Allerton Conference on Communications, Control, and Computing. 10-JAN-12, . : ,
07/31/2013 57.00	Q. Peng, A. Walid, S. H. Low. Multipath TCP Algorithms: Theory and Design, ACM Sigmetrics. 17-JUL-13, . : ,
08/31/2011 26.00	Sheng Xiao, Weibo Gong, Don Towsley. From Uncertainty to Secrecy: A Dynamic Approach, Asilomar conference on signals and systems. 08-NOV-10, . : ,
10/01/2012 40.00	Barlas Oguz, Venkat Anantharam. Long range dependent Markov chains with applications, Information Theory and Applications Workshop. 05-FEB-12, . : ,
10/01/2012 43.00	Weibo Gong. Can one hear the shape of a concept?, Chinese Control Conference. 27-JUL-12, . : ,
10/01/2012 42.00	Narayana Santhanam, Venkat Anantharam. Prediction over countable alphabets, Conference on Inforamtion Sciences and Systems. 21-MAR-12, . : ,
12/02/2014 72.00	Varun Jog, Venkat Anantharam. The Entropy Power Inequality and Mrs. Gerber's Lemma for Groups of order 2^n, IEEE International Symposium of Information Theory. 07-JUL-13, . : ,
12/02/2014 80.00	Kun Tu, Bruno Ribeiro, David Jensen, Don Towsley, Benyuan Liu, Hua Jiang, Xiaodong Wang. Online Dating Recommendations: Matching Markets and Learning Preferences, International World Wide Web Conference. 07-APR-14, . : ,
12/02/2014 64.00	Varun Jog, Venkat Anantharam. Convex relative entropy decay in Markov chains, 48th Annual Conference on Information Science and Systems. 19-MAR-14, . : ,
TOTAL:	**9**

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

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

Received		Paper
07/31/2013	52.00	Varun Jog, Venkat Anantharam. The Entropy Power Inequality and Mrs. Gerber's Lemma for Groups of Order 2^n, IEEE International Symposium on Information Theory. 07-JUL-13, . : ,
07/31/2013	59.00	B. Jiang, R. Brockett, W. Gong, D. Towsley. Stochastic Differential Equations for Power Law Behaviors, IEEE Conference on Decision and Control. 12-DEC-12, . : ,
07/31/2013	56.00	Venkat Anantharam, Amin Gohari, Chandra Nair. Improved cardinality bounds on the auxiliaryrandom variables in Marton's inner bound, IEEE International Symposium on Information Theory, Istanbul, Turkey. 07-JUL-13, . : ,
07/31/2013	54.00	Barlas Oguz, Venkat Anantharam, Ilkka Norros. Stable, distributed P2P protocols based on random peer sampling, Annual Allerton Conference on Communications, Control, and Computing, Urbana, Illinois. 10-JAN-12, . : ,
08/31/2011	8.00	Yeon-sup Lim, Bruno Ribeiro, Daniel S. Menasche, Prithwish Basu, Don Towsley. Online Estimating The Top k Nodes Of A Network, IEEE Network Science Workshop. 24-JUN-11, . : ,
08/31/2011	33.00	Assane Gueye, Jean Walrand, Venkat Anantharam. A Network Topology Design Game: How to Choose Communication Links in an Adversarial Environment?, GameNets2011, 2nd International ICST Conference on Game Theory for Networks, . 16-APR-11, . : ,
08/31/2011	32.00	Assane Gueye, Jean Walrand, Venkat Anantharam. Design of Network Topology in an Adversarial Environment, GameSec2010, Conference on Decision and Game Theory for Security. 22-NOV-10, . : ,
08/31/2011	30.00	Venkat Anantharam, Narayana Santhanam. What risks lead to ruin, 2010 48th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 28-SEP-10, Monticello, IL, USA. : ,
08/31/2011	29.00	Sudeep Kamath, David Tse, Venkat Anantharam. Generalized Networki Sharing Outer Bound and the Two-Unicast Problem, NetCod 2011, The 2011 International Symposium on Network Coding. 25-JUL-11, . : ,
08/31/2011	28.00	Venkat Anantharam, Sudeep Kamath. A new dual to the Gacs-Korrner common information defined via the Gray-Wyner system, 2010 48th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 28-SEP-10, Monticello, IL, USA. : ,
08/31/2011	22.00	Somayeh Sojoudi, Steven H. Low, John C. Doyle. Effect of Buffers on Stability of Internet Congestion Controllers, Infocom 2011. 10-APR-11, . : ,
08/31/2011	21.00	Zhenhua Liu, Minghong Lin, Adam Wierman, Steven H. Low, Lachlan L. H. Andrew. Greening Geographical Load Balancing, Proc. ACM Sigmetrics, 2011. 08-JUN-11, . : ,
08/31/2011	15.00	Sheng Xiao, Weibo Gong. Mobility Can Help: Protect User Identity withDynamic Credential, International Conference on Mobile Data Management. 23-MAY-11, . : ,

08/31/2011	12.00	Bruno Ribeiro, Don Towsley. Estimating and Sampling Graphs withMultidimensional Random Walks, ACM SIGCOMM Internet Measurement Conference. 04-NOV-11, . : ,
08/31/2011	11.00	Wei Zeng, Xian Chen, Alexander Russell, Sudarshan Vasudevan, Bing Wang, Wei Wei. Neighbor Discovery in Wireless Networks with MultipacketReception, Mobihoc 2011. 16-MAY-11, . : ,
10/01/2012	35.00	Jean Walrand, Longbo Huang. A Benes Packet Network, IEEE Infocom. 14-APR-13, . : ,
10/01/2012	41.00	Barlas Ogus, Venkat Anantharam. Pointwise lossy source coding theorem for sourceswith memory, International Symposium on Information Theory. 01-JUL-12, . : ,
10/01/2012	38.00	Michael Krishnan, Ehsan Haghani, Avideh Zakhor. Packet Length Adaptation in WLANs with Hidden Nodes and Time-Varying Channels, IEEE Globecom. 05-DEC-11, . : ,
10/01/2012	37.00	Amin Gohari, Chandra Nair, Venkat Anantharam. On Marton's inner bound for broadcast channels, International Symposium on Information Theory. 01-JUL-12, . : ,
10/21/2014	58.00	J. R. Marden, A. Wierman, R. Gopalakrishnan. Potential Games are Necessary to Ensure Pure Nash Equilibria in Cost Sharing Games, EC '13 Proceedings of the fourteenth ACM conference on Electronic commerce. 16-JUN-13, . : ,
12/02/2014	79.00	Shan Lu, Jieqi Kang, Weibo Gong. Complex Network Comparison Using Random Walks, International World Wide Web Conference. 07-APR-14, . : ,
12/02/2014	76.00	Chandramani Singh, Angelia Nedic, R. Srikant. LP-relaxation based Distributed Algorithms for Scheduling in Wireless Networks, IEEE Infocom. 27-APR-14, . : ,
12/02/2014	71.00	Venkat Anantharam, Amin Gohari, Chandra Nair. Improved cardinality bounds on the auxiliary random variables in Marton's inner bound, IEEE Internation Symposium on Information Theory. 07-JUL-13, . : ,
12/02/2014	73.00	Narayana Prasad Santhanam, Venkat Anantharam. Universal algorithms in probabilistic setups: building a case for pointwise convergence over model classes. , Annual Allerton Conference on Communications, Control, and Computing, Urbana. 01-OCT-12, . : ,
TOTAL:	**24**	

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

(d) Manuscripts

Received	Paper
07/31/2013 50.00	Fabricio Murai, Bruno Ribeiro, Don Towsley, Pinghui Wang. On Set Size Distribution Estimation and the Characterization of Large Networks via Sampling, IEEE Journal on Selected Areas in Communications (06 2013)
07/31/2013 51.00	B. Jiang, J. Tian, W. Wei, N. Shroff, D. Towsley. Heavy tails in queuing systems: impact of parallelism on tail performance, Journal of Applied Probability, 50(1), 127-150, March 2013. (03 2013)
10/21/2014 60.00	Longbo Huang, Jean Walrand. A Benes packet Network, (04 2013)
10/21/2014 61.00	Longbo Huang, Jean Walrand. Transient Response Functions , (04 2013)
12/02/2014 75.00	Siva Theja Maguluri, Bruce Hajek, R. Srikant. The Stability of Longest-Queue-First Scheduling With Variable Packet Sizes, IEEE TRANSACTIONS ON Automatic Control (10 2014)
12/02/2014 70.00	Amin Aminzadeh Gohari, Venkat Anantharam. Converses For Discrete Memoryless Multiterminal Networks, IEEE TRANSACTIONS ON Information Theory (07 2010)
12/02/2014 65.00	Javad Ghaderi, R. Srikant. The impact of access probabilities on the delay performance of Q-CSMA algorithms in wireless networks., IEEE/ACM Trans. on Networking (10 2012)
12/02/2014 69.00	Venkat Anantharam, Amin Gohari, Sudeep Kamath, Chandra Nair. On Maximal Correlation, Hypercontractivity, andthe Data Processing Inequality studied by Erkip and Cover, IEEE TRANSACTIONS ON Information Theory (04 2013)
12/02/2014 67.00	Venkat Anantharam, Justin Salez. The densest subgraph problem in sparse random graphs, Annals of Applied Probability (12 2013)
12/02/2014 68.00	Narayana Santhanam, Venkat Anantharam. Agnostic insurability of model classes, Journal of Machine Learning Research (10 2013)

TOTAL: 10

Number of Manuscripts:

Books

Received	Book	
07/31/2013	63.00	S. Xiao, W. Gong, D. Towsley. Dynamic Secrets in Communication Security, English: Springer, (07 2013)

TOTAL: **1**

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Jean Walrand, ACM Sigmetrics Achievement Award, 2013

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Venkat Anantharam	0.25	
John Doyle	0.05	
Weibo Gong	0.05	
Steven Low	0.05	
Ryadurgam Srikant	0.05	
Don Towsley	0.05	
Jean Walrand	0.10	
Avideh Zakhor	0.10	
FTE Equivalent:	**0.70**	
Total Number:	**8**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
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: .....

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

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:.....

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

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

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

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: .....

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

I. Maxmin fair rate control in wireless networks

Rate adaptation and power control are two key resource allocation mechanisms in multiuser wireless networks. In the presence of interference, how do we jointly optimize end- to-end source rates and link powers to achieve weighted max-min rate fairness for all sources in the network? This optimization problem is hard to solve as physical layer link rate functions are nonlinear, nonconvex, and coupled in the transmit powers. We show that the weighted max-min rate fairness problem can, in fact, be decoupled into separate fairness problems for flow rate and power control. For a large class of physical layer link rate functions, we have characterized the optimal solution analytically by a nonlinear Perron-Frobenius theory (through solving a conditional eigenvalue problem) that captures the interaction of multiuser interference. We have given an iterative algorithm to compute the optimal flow rate that converges geometrically fast without any parameter configuration. Numerical results show that our iterative algorithm is computationally fast for both the Shannon capacity, CDMA, and piecewise linear link rate functions. [Cai2012-infocom]

II. Energy efficient congestion control

Various link bandwidth adjustment mechanisms are being developed to save network energy. However, their interaction with congestion control can significantly reduce throughput, and is not well understood. We have proposed an easily implementable link dynamic bandwidth adjustment (DBA) mechanism. In DBA, each link updates its bandwidth according to an integral control law to match its average buffer size with a target buffer size. We prove that DBA reduces link bandwidth without sacrificing throughput—DBA only turns off excess bandwidth—in the presence of congestion control. Preliminary ns2 simulations confirm this result. [Gan-2012-EECC-Sigmetrics]

III. Geographical load balancing

Given the significant energy consumption of data centers, it is important to improve their energy efficiency. However, energy efficiency is necessary but not sufficient for sustainability, which demands reduced usage of energy from fossil fuels. We have studied the feasibility of powering internet-scale systems using (nearly) entirely renewable energy. We have performed a trace-based study to evaluate three issues related to achieving this goal: the impact of geographical load balancing, the role of storage, and the optimal mix of renewables. Our results highlight that geographical load balancing can significantly reduce the required capacity of renewable energy by using the energy more efficiently with “follow-the-renewables” routing. Further, our results show that small-scale storage can be useful, especially in combination with geographical load balancing, and that an optimal mix of renewables includes significantly more wind than photovoltaic solar. We have also designed online algorithms for geographical load balancing (GLB). A commonly suggested algorithm for this setting is “receding horizon control” (RHC), which computes the provisioning for the current time by optimizing over a window of predicted future loads. We have shown that RHC performs well in a homogeneous setting, in which all servers can serve all jobs equally well, but can perform poorly when propagation delays, servers, and electricity prices are different. We have introduced variants of RHC that are guaranteed to perform as well in the face of such heterogeneity. [Liu-2012-GLB-PER, Lin-2012-GLB-IGCC]

IV. Network effect in large-scale systems

Online services today are characterized by a highly congestion sensitive user base, that also experiences strong positive network effects. A majority of these services are supported by advertising and are offered for free to the end user. We study the problem of optimal capacity provisioning for a profit-maximizing firm operating such an online service in the asymptotic regime of a large market size. We show that network effects heavily influence the optimal capacity provisioning strategy, as well as the profit of the firm. In particular, strong positive network effects allow the firm to operate the service with fewer servers, which translates into increased profit.

V. Contention window adaptation using the concept of busy/idle signal for 802.11 networks.

VI. Use of directional busy/idle signals to discover topology and improve throughput in WLAN networks with multi-antenna beam-forming nodes.

VII. Use of busy/idle signals for discovering optimum AP association

VIII. Characterization of set size distributions

Consider the problem of estimating the set size distribution for a collection of sets based on the random sampling of elements from the sets. This problem has applications to network capacity planning, network theory, among other areas. Examples include characterizing in-degree distributions in large graphs and characterizing flow size distributions in the Internet. We show that it is difficult to estimate the original set size distribution unless the sampling probability is large. The recoverability of original set size distributions presents a sharp threshold with respect to the fraction of elements that are sampled. If this fraction remains below this threshold then the original set size distribution is unrecoverable. Moreover, this threshold is highly

dependent on the set size distribution. It is one half when set sizes are characterized by power laws, and 1/(a+1) when the distribution has an exponential tail and average a. The threshold is zero when the distribution has a lighter than exponential tail. Details are found in

F. Murai, B. Ribeiro, D. Towsley, P. Wang. “On set Size Distribution Estimation and the Characterization of Large Networks via Sampling”, submitted for publication.

IX. Design of scalable network

Using the theory of Lyapunov drift, we designed a modular scalable network with at most four queues per modules. The network maximizes the utility of the flows and has a delay logarithmic in the size.

X. Stochastic Differential Equation Models for Power Law.

We develop simple stochastic differential equations that lead to lower-tail and/or upper tail power law behaviors. We also present a model with bi-directional Poisson counters that exhibits power law behavior near a critical point, which has implications in understanding phase transitions in statistical physics and other areas [JiangBrockettGongTowsley-CDC2012].

XI. Power Law Graph as Concept Representations

We develop algorithms based on the random walks on power law graphs for concept abstraction in high intelligence [Gong-CCC2012].

Technology Transfer