**Final Report: Multivariate Heavy Tail Phenomena: Modeling and Diagnostics**

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrived as an official Department of the Army position, policy or decision, unless so designated by other documentation.

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   16-Aug-2012 - 30-Sep-2018

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   U.S. Army Research Office
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13. **SUPPLEMENTARY NOTES**
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Begin Performance Period: 16-Aug-2012
End Performance Period: 30-Sep-2018

Report Date: 31-Dec-2018
Report Term: 0-Other

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Major Goals: This project develops reliable diagnostic, inferential and model validation tools for heavy tailed multivariate data; generates new classes of multivariate heavy tailed models that highlight the implications of dependence and tail weight; and applies these statistical and mathematical developments to the key application areas of network design and control, social network analysis, and cloud computing. Our application interests also include network security, anomaly detection, mobile application scheduling and risk analysis.

To understand and exploit multivariate heavy tail phenomena in relevant application areas, our project contributes statistical, mathematical and software tools that provide: (a) Flexible and practical representations of multidimensional heavy tail distributions that permit reliable statistical analysis and inference; allow model discovery, selection and confirmation; quantify dependence; and overcome the curse of dimensionality.
(b) Heavy tailed mathematical models that can be calibrated; which clearly exhibit the influence of dependence and tail weight; and which are appropriate to the applied context.
(c) Exploitation of the new tools of multivariate heavy tail analysis to study social networks; mobile networks; network design and control; application scheduling in mobile devices and cloud computing; and robust network search.

Accomplishments: See pdf document in "Upload" section.
Training Opportunities: Training opportunities, for the most part, have been addressed through working with PhD students and occasionally undergraduates. There have been Post-Docs supported on the MURI at Columbia and Ohio State as well as unsupported post-docs who have been mentored by MURI PI's; eg. Jaakko Lehtomaa mentored by Sidney Resnick at Cornell.

Seminars, short courses, conference lectures and papers by MURI PI's all serve to educate the professional public about our work. This is all detailed in our annual progress reports.

Results Dissemination: Reports and talks are publicly posted at

https://www.orie.cornell.edu/research/research-groups/multivariate-heavy-tail-phenomena-modeling-and-diagnostics

and there are also links to software that has been developed through the 5 years; this has been reported in the yearly progress reports. Each of the PI’s maintained an active speaking schedule at seminars, workshops and conferences as well as active publication activities.

Results are also reported at conferences and workshops and submitted to leading journals. This has been archived in yearly progress reports as well.

Samorodnitsky published a book about a year ago on related topics. Nolan is about 80% done with volume 1 about multivariate stable laws.
Honors and Awards: Richard Davis was elected to the council of the Institute of Mathematical Statistics 2013. Richard Davis was selected to deliver the 2014 Hotelling Lectures at the University of North Carolina
Zhi-Li Zhang was awarded the McKnight Distinguished University Professor by the University of Minnesota 2013, Board of Regents in 2013
R. Srikant gave the Keynote Lecture at ACM MobiHoc 2013
R. Srikant was chosen to be the Editor-in-Chief of the IEEE/ACM Transactions on Networking, starting from July 2013
D. Towsley gave a Keynote Lecture at IFIP Networking 2013
D. Towsley won best paper awards at IEEE ICDCS 2013 and IEEE VTC- Spring '13
L. Tong is selected to give a plenary lecture at 2013 IEEE Global Conference on Signal and Information Processing
L. Tong is selected to give a plenary lecture at The Fifth IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing
Van Dantzig Seminar, Jan 23, 2014, University of Delft, The Netherlands (http://www.few.vu.nl/~bkk320/vandantzig/)
Shroff 2014: received the IEEE INFOCOM achievement award for "seminal contributions to scheduling and resource allocation in wireless networks”.
-listed on Most highly cited researchers Thomson Reuters ISI (http://highlycited.com/), ranking among the top 1% most cited for their subject field.
Towsley 2014 Distinguished Lectures related to project (Towsley):
Kelly Distinguished Lecture,
--Pennsylvania State University (October 2013)
--University of North Carolina – Charlotte (April 2014)
Shroff was recently listed on Most highly cited researchers Thomson Reuters ISI ranking among the top 1% most cited for their subject field.
Shroff is noted in the List of The World's Most Influential Scientific Minds in 2014.
Gong/Towsley: Distinguished Lecture, BBN April 2015 “Sampling Node Pairs in Large Graphs”
Zhang: Best Paper Award, SIMPLEX’15
Srikant: IEEE INFOCOM Achievement Award, 2015
Srikant: IEEE INFOCOM Best Paper Award, 2015
Srikant: IIT Madras Distinguished Alumnus Award, 2015
Towsley: BBN April 2015 “Sampling Node Pairs in Large Graphs
Gong: Univ Distinguished Professor of UofMass - Oct 2016
Towsley: Elected corresponding member of Brazilian Academy of Science 2016
Shroff: IEEE Communications Society William R. Bennett Prize 2016 (postdoc Joohyun Lee)
Davis: President, Institute of Mathematical Statistics 2016
Ness B. Shroff
Best student paper award at ACM Sigmetrics 2017 (Sinong Wang, and Ness B. Shroff), Urbana-Champaign, IL, Jun. 2017.
Srikant:Plenary Speaker, 2017 Applied Probability Society Conference
Phyllis Wan, JSM Student Travel Award presented by Section on Business and Economic Statistics. JSM 2017
Elected Fellow of International Engineering and Technology Institute, 2018
Chosen as Jubilee Professor, Department of Mathematical Sciences, Chalmers University of Technology, Göteborg, Sweden. (Position takes place in 2019.)
Conference Organizer (with Serena Ng and Ruey Tsay): NBER/NSF Workshop on Time Series Analysis, Northwestern University, Sept 8–9, 2017.

Protocol Activity Status:

Technology Transfer: Ness Shroff was one of 3 authors for patent application T2016-095, 62/281,244 entitled “A highly energy-efficient context-aware scheduler on background applications in mobile systems”.

Public domain information about papers, talks and software is at our MURI webstite https://www.orie.cornell.edu/orie/research/research-groups which contains a fairly complete record of the intellectual output from the group.

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National Academy Member: N
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International Collaboration:
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International Collaboration:
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Project Contribution:
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Funding Support:

Project Contribution:
International Collaboration:
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Other Collaborators:

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Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

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Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

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**Project Contribution:**
**International Collaboration:**
**International Travel:**
**National Academy Member:** N

Other Collaborators:

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**Project Contribution:**
**International Collaboration:**
**International Travel:**
**National Academy Member:** N

Other Collaborators:

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**Project Contribution:**
**International Collaboration:**
**International Travel:**
**National Academy Member:** N

Other Collaborators:

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**Project Contribution:**
**International Collaboration:**
**International Travel:**
**National Academy Member:** N

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**Funding Support:**

**Project Contribution:**
**International Collaboration:**
**International Travel:**
**National Academy Member:** N

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**Funding Support:**

**Project Contribution:**
**International Collaboration:**
International Travel:
National Academy Member: N
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**Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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**Participant Type:** Graduate Student (research assistant)
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**Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Braulio Dumba
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**Funding Support:**
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International Travel:
National Academy Member: N
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**Participant Type:** Graduate Student (research assistant)
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**Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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**Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Julian Sun
**Person Months Worked:** 7.00
**Funding Support:**
Project Contribution:
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
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Funding Support:

Project Contribution:
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International Travel:
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Project Contribution:
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International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Participant: Fabricio Murai
RPPR Final Report
as of 31-Dec-2018

**Person Months Worked:** 8.00  
**Funding Support:**

**Project Contribution:**  
**International Collaboration:**
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**National Academy Member:** N
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**Project Contribution:**  
**International Collaboration:**
**International Travel:**
**National Academy Member:** N
**Other Collaborators:**

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**Funding Support:**

**Project Contribution:**  
**International Collaboration:**
**International Travel:**
**National Academy Member:** N
**Other Collaborators:**

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**Project Contribution:**
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**International Travel:**
**National Academy Member:** N
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**Funding Support:**

**Project Contribution:**
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**International Travel:**
**National Academy Member:** N
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**Funding Support:**

**Project Contribution:**
**International Collaboration:**
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International Collaboration:
International Travel:
National Academy Member: N
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Participant: Bin Li
Person Months Worked: 3.00
Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:
Participant Type: Graduate Student (research assistant)
Participant: Yuelin Sun
Person Months Worked: 11.00
Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Xiaoyang Liu
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Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Lifan Wu
Person Months Worked: 2.00
Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 2.00
Funding Support:
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:
Publication Type: Journal Article
Peer Reviewed: Y
Publication Status: 1-Published
Journal: Astin Bulletin
Publication Identifier Type:
Publication Identifier:
Volume: 43 Issue: 2 First Page #: 245
Date Submitted: Date Published:
Publication Location:
Article Title: Multivariate tail measure and the estimation of CoVar
Authors:
Keywords: extremes, tail estimation, tail measure, spectral measure, CoVar, tail region
Abstract: The quality of estimation of multivariate tails depends significantly on the portion of the sample included in the estimation. A simple approach involving sequential statistical testing is proposed in order to select which observations should be used for estimation of the tail and spectral measures. We prove that the estimator is consistent. We test the proposed method on simulated data, and subsequently apply it to analyze CoVar for stock and index returns.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:
Financial modeling with heavy-tailed stable distributions

Stable distributions with elliptical contours are a class of distributions that are useful for modeling heavy tailed multivariate data. This paper describes the theory of such distributions, presents formulas for calculating their densities, and methods for fitting the data and assessing the fit. Efficient numerical routines are implemented and evaluated in simulations. Applications to data sets of a financial portfolio with 30 assets and to a bivariate radar clutter data set are presented.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support:

An analytical framework to characterize the efficiency and delay in a mobile data offloading system

Smart mobile devices are generating a tremendous amount of data traffic that is putting stress on even the most advanced cellular networks. Delayed offloading has recently been proposed as an efficient mechanism to substantially alleviate this stress. The idea is simple. It allows a mobile device to delay transmission of data packets for a certain amount of time, while it searches WiFi (or similarly femtocell) networks to offload the data during the time. When the time expires, it completes the remaining portion of the delayed transmission through the cellular network that is available at the moment. In this paper, we develop an analytical framework using an embedded Markov process for the delayed offloading system. We provide a closed-form expression for estimating how much data generated by the users can be offloaded to WiFi networks from cellular networks even when there are non-Markovian data arrivals and service interruptions. We conduct extensive numerical studies with various ra

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Publication Type: Journal Article  Peer Reviewed: Y  Publication Status: 1-Published
Journal: ACM SIGMETRICS Performance Evaluation Review
Publication Identifier Type: DOI  Publication Identifier: 10.1145/2591971.2591989
Volume: 0  Issue: 0  First Page #: 0
Date Submitted:  Date Published:  
Publication Location:  
Article Title: Stochastic bandits with side observations on networks
Authors:  
Keywords: Multi-arm bandits, stochastic analysis, social networks.
Abstract: We study the stochastic multi-armed bandit (MAB) problem in the presence of side-observations across actions. In our model, choosing an action provides additional side observations for a subset of the remaining actions. One example of this model occurs in the problem of targeting users in online social networks where users respond to their friends’ activity, thus providing information about each other’s preferences. Our contributions are as follows: 1) We derive an asymptotic (with respect to time) lower bound (as a function of the network structure) on the regret (loss) of any uniformly good policy that achieves the maximum long term average reward. 2) We propose two policies - a randomized policy and a policy based on the well-known upper confidence bound (UCB) policies, both of which explore each action at a rate that is a function of its network position. We show that these policies achieve the asymptotic lower bound on the regret up to a multiplicative factor independent of network
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article  Peer Reviewed: Y  Publication Status: 1-Published
Journal: IEEE/ACM Transactions on Networking
Publication Identifier Type: DOI  Publication Identifier: 10.1109/TNET.2013.2288973
Volume: 0  Issue: 0  First Page #: 0
Date Submitted:  Date Published:  
Publication Location:  
Article Title: Scheduling Jobs With Unknown Duration in Clouds
Authors:  
Keywords: Cloud computing, performance evaluation, queueing theory, resource allocation, scheduling.
Abstract: We consider a stochastic model of jobs arriving at a cloud data center. Each job requests a certain amount of CPU, memory, disk space, etc. Job sizes (durations) are also modeled as random variables, with possibly unbounded support. These jobs need to be scheduled nonpreemptively on servers. The jobs are first routed to one of the servers when they arrive and are queued at the servers. Each server then chooses a set of jobs from its queues so that it has enough resources to serve all of them simultaneously. This problem has been studied previously under the assumption that job sizes are known and upper-bounded, and an algorithm was proposed that stabilizes traffic load in a diminished capacity region. Here, we present a load balancing and scheduling algo- rithm that is throughput-optimal, without assuming that job sizes are known or are upper-bounded.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:
The goal of this paper is two-fold: (1) We review classical and recent measures of serial extremal dependence in a strictly stationary time series as well as their estimation. (2) We discuss recent concepts of heavy-tailed time series, including regular variation and max-stable processes. Serial extremal dependence is typically characterized by clusters of exceedances of high thresholds in the series. We start by discussing the notion of extremal index of a univariate sequence, i.e. the reciprocal of the expected cluster size, which has attracted major attention in the extremal value literature. Then we continue by introducing the extremogram which is an asymptotic autocorrelation function for sequences of extremal events in a time series. In this context, we discuss regular variation of a time series. This notion has been useful for describing serial extremal dependence and heavy tails in a strictly stationary sequence. We briefly discuss the tail process coined by Basrak and Segers.
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Publication Type: Conference Paper or Presentation
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Conference Name: Proceedings of the International Teletraffic Congress (ITC),
Date Received: 26-Dec-2018   Conference Date: 04-Sep-2012   Date Published:
Conference Location: Krakow, Poland
Paper Title:Heavy traffic optimal resource allocation algorithms for cloud computing clusters.
Authors: Siva Theja Maguluri, R. Srikant, Lei Ying
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation
Publication Status: 0-Other
Conference Name: the First Workshop
Date Received: 30-Aug-2017   Conference Date: 30-Jun-2016   Date Published:
Conference Location: Singapore, Singapore
Paper Title: Mining Spatial-Temporal
Authors: Arvind Narayanan, Saurabh Verma, Zhi-Li Zhang
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation
Publication Status: 0-Other
Conference Name: IEEE INFOCOM 2016 - IEEE Conference on Computer Communications
Date Received: 30-Aug-2017   Conference Date: 10-Apr-2016   Date Published:
Conference Location: San Francisco, CA, USA
Paper Title: Understanding security group usage in a public IaaS cloud
Authors: Cheng Jin, Abhinav Srivastava, Zhi-Li Zhang
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation
Publication Status: 0-Other
Conference Name: IEEE INFOCOM 2016 - IEEE Conference on Computer Communications
Date Received: 30-Aug-2017   Conference Date: 10-Apr-2016   Date Published:
Conference Location: San Francisco, CA, USA
Paper Title: SAMPO: Online subflow association for multipath TCP with partial flow records
Authors: Yang Zhang, Hesham Mekky, Zhi-Li Zhang, Fang Hao, Sarit Mukherjee and T V Lakshman
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation
Publication Status: 3-Accepted
Conference Name: 2015 ACM Information Centric Network Conference
Date Received: 30-Aug-2017   Conference Date: 31-Aug-2016   Date Published: 25-Aug-2016
Conference Location: San Francisco
Paper Title: On the Analysis of Caches with Pending Interest Tables
Authors: Mostafa Dehghan, Bo Jiang, Ali Dabirmoghaddam, Don Towsley
Acknowledged Federal Support: N

Publication Type: Conference Paper or Presentation
Publication Status: 3-Accepted
Conference Name: 2016 ACM SIGMETRICS/IFIP Performance Conference
Date Received: 30-Aug-2017   Conference Date: 25-Aug-2016   Date Published: 25-Aug-2016
Conference Location: France
Paper Title: On the Duration and Intensity of Competitions in Nonlinear Pólya Urn Processes with Fitness
Authors: Bo Jiang, Daniel Figueiredo, Bruno Ribeiro, Don Towsley
Acknowledged Federal Support: N
Publication Type: Conference Paper or Presentation  
Publication Status: 0-Other

Conference Name: The 2016 International Conference on Image Processing
Date Received: 30-Aug-2017  
Conference Date: 23-Sep-2016  
Date Published: 25-Aug-2016
Conference Location: Phoenix Arizona
Paper Title: IMAGE FEATURE EXTRACTION BASED ON SPECTRAL GRAPH INFORMATION
Authors: Jieqi Kang, Shan Lu, Weibo Gong, Patrick A. Kelly
Acknowledged Federal Support: N

Publication Type: Conference Paper or Presentation  
Publication Status: 1-Published

Conference Name: 2016 American Control Conference (ACC)
Date Received: 30-Aug-2017  
Conference Date: 06-Jun-2016  
Date Published: 25-Aug-2016
Conference Location: Boston, MA
Paper Title: Poisson Process Driven Stochastic Differential Equations for Bivariate Heavy Tailed Distributions
Authors: Shan Lu, Gennady Samorodnitsky, Weibo Gong, Bo Jiang, Jieqi Kang, Don Towsley
Acknowledged Federal Support: N

Publication Type: Conference Paper or Presentation  
Publication Status: 1-Published

Conference Name: New England Statistical Symposium
Date Received: 30-Aug-2017  
Conference Date: 22-Apr-2017  
Date Published: 25-Aug-2016
Conference Location: Univ of Conn
Paper Title: An R package for modeling and simulating generalized spherical and related distributions
Authors: John Nolan
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 3-Accepted

Conference Name: IEEE INFOCOM'16
Date Received: 30-Aug-2017  
Conference Date: 10-Apr-2016  
Date Published: 26-Aug-2016
Conference Location: San Francisco, CA
Paper Title: Heavy-Ball: A New Approach to Tame Delay and Convergence in Wireless Network Optimization
Authors: J. Liu, A. Eryilmaz, N. B. Shroff, E. Bentley
Acknowledged Federal Support: N

Publication Type: Conference Paper or Presentation  
Publication Status: 0-Other

Conference Name: ACM UbiComp
Date Received: 30-Aug-2017  
Conference Date: 12-Sep-2016  
Date Published: 26-Aug-2016
Conference Location: Heidelberg, Germany
Paper Title: Context-aware Application Scheduling in Mobile Systems: What Will Users Do and Not Do Next
Authors: J. Lee, K. Lee, E. Jeong, J. Jo, N. B. Shroff
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 3-Accepted

Conference Name: 50th Conference on Information Sciences and Systems (CISS)
Date Received: 30-Aug-2017  
Conference Date: 16-Mar-2016  
Date Published: 26-Aug-2016
Conference Location: Princeton University
Paper Title: Battle of Opinions over Evolving Social Networks
Authors: I. Koprulu, Y. Kim, N. B. Shroff
Acknowledged Federal Support: N
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<td>Most Calls are Local (but Some are Regional): Dissecting Cellular Communication Patterns</td>
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Date Received: 30-Aug-2017  
Conference Date: 11-Jan-2017  
Conference Location: University of Lancaster  
Paper Title: Extreme Value Theory without the extremes: What can be done?  
Authors: Jingjing Zou, Richard Davis, Gennady Samorodnitsky  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Conference Name: New England Statistics Symposium  
Date Received: 30-Aug-2017  
Conference Date: 21-Apr-2017  
Conference Location: University of Connecticut  
Paper Title: Threshold Selection for Multivariate Heavy-Tailed Data  
Authors: P. Wan, R.A. Davis  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Conference Name: Singapore University of Technology and Design  
Date Received: 30-Aug-2017  
Conference Date: 25-Jan-2017  
Conference Location: Singapore University  
Paper Title: Multivariate Power Laws in a Preferential Attachment Network Model; Model Calibration  
Authors: P. Wan, T. Wang, R. Davis, S. Resnick  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Conference Name: College of Business and Economics  
Date Received: 30-Aug-2017  
Conference Date: 15-Feb-2017  
Conference Location: Australian National University, Canberra  
Paper Title: Multivariate Power Laws in a Preferential Attachment Network Model; Model Calibration  
Authors: P. Wan, T. Wang, R. Davis, S. Resnick  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Conference Name: Working Group on Risk  
Date Received: 30-Aug-2017  
Conference Date: 19-Apr-2017  
Conference Location: ESSEC Business School, Paris France  
Paper Title: Multivariate Power Laws with Strong Asymptotic Dependence  
Authors: B. Das, S. Resnick  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Conference Name: Working Group on Risk  
Date Received: 30-Aug-2017  
Conference Date: 19-Apr-2017  
Conference Location: ESSEC Business School, Paris France  
Paper Title: Fitting the Linear Preferential Attachment Model  
Authors: P. Wan, T. Wang, R. Davis, S. Resnick  
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**Publication Type:** Conference Paper or Presentation  
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**Date Received:** 30-Aug-2017  
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**Paper Title:** ParaBox: Exploiting Parallelism for Virtual Network Functions in Service Chaining  
**Authors:** Yang Zhang, Bilal Anwer, Vijay Gopalakrishnan, Bo Han, Joshua Reich, Aman Shaikh, Zhi-Li Zhang  
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**Date Received:** 30-Aug-2017  
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**Paper Title:** Magneto: Unified Fine-grained Path Control in Legacy and OpenFlow Hybrid Networks  
**Authors:** Cheng Jin, Cristian Lumezanu, Qiang Xu, Hesham Mekky, Zhi-Li Zhang, Guofei Jiang  
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**Conference Name:** the First Asia-Pacific Workshop  
**Date Received:** 30-Aug-2017  
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**Paper Title:** When Raft Meets SDN  
**Authors:** Yang Zhang, Eman Ramadan, Hesham Mekk, Zhi-Li Zhang  
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**Conference Name:** 2017 IEEE Symposium on Security and Privacy (SP)  
**Date Received:** 30-Aug-2017  
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**Paper Title:** Multi-touch Authentication Using Hand Geometry and Behavioral Information  
**Authors:** Yunpeng Song, Zongmin Ca, Zhi-Li Zhang  
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**Conference Name:** IEEE INFOCOM 2017  
**Date Received:** 30-Aug-2017  
**Conference Date:** 01-May-2017  
**Conference Location:** Atlanta, GA  
**Paper Title:** Network Function Virtualization Enablement Within SDN Data Plane  
**Authors:** Hesham Mekky, Fang Hao, Sarit Mukherjee, T. V. Lakshman, Zhi-Li Zhang  
**Acknowledged Federal Support:** Y  
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**Conference Name:** In Proc. of ITC’29 conference  
**Date Received:** 30-Aug-2018  
**Conference Date:** 04-Sep-2016  
**Conference Location:** Genoa, Italy  
**Paper Title:** Multi-Low-Rank Approximation For Traffic Matrices  
**Authors:** Saurabh Verma, Arvind Narayanand, Zhi-Li Zhang  
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<td>Authors</td>
<td>Yinghua Dong, Gennady Samorodnitsky</td>
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<td>Authors</td>
<td>Joohyun Lee, Fang Liu, Kyunghan Lee, N Shroff</td>
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Publication Status: 0-Other  
Conference Name: the 2017 ACM  
Date Received: 30-Aug-2018  
Conference Date: 06-Nov-2017  
Conference Location: Singapore, Singapore  
Paper Title: From Fingerprint to Footprint  
Authors: Huandong Wang, Chen Gao, Yong Li, Zhi-Li Zhang, Depeng Jin  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 0-Other  
Conference Name: SIGSPATIAL 17  
Date Received: 30-Aug-2018  
Conference Date: 07-Nov-2017  
Conference Location: Redondo Beach CA  
Paper Title: CityLines: Hybrid Hub-and-Spoke Urban Transit System  
Authors: Guanxiong Liu, Yanhua Li, Zhi-Li Zhang, Jun Luo, Fan Zhang  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 5-Submitted  
Conference Name: NIPS 2017  
Date Received: 30-Aug-2018  
Conference Date: 04-Dec-2017  
Conference Location: Long Beach Convention Center, Long Beach  
Paper Title: Hunt For The Unique, Stable, Sparse And Fast Feature Learning On Graphs  
Authors: Saurabh Verma, Zhi-Li Zhang  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 5-Submitted  
Conference Name: Workshop on Quantum Techniques in Machine Learning  
Date Received: 30-Aug-2018  
Conference Date: 06-Nov-2017  
Conference Location: Verona Italy  
Paper Title: Quantum Walk Inspired Neural Networks for Graph-Structured Data  
Authors: Stefan Dernbach, Arman Mohseni-Kabir, Siddharth Pal, Don Towsley, Miles Gepner  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 3-Accepted  
Conference Name: 2017 IEEE56 Annual Conference on Decisions and Control  
Date Received: 30-Aug-2018  
Conference Date: 12-Dec-2017  
Conference Location: Melbourne Australia  
Paper Title: Relation generation and fast similarity testing for unsupervised learning  
Authors: Bo Jiang, Weibo Gong  
Acknowledged Federal Support: Y

Publication Type: Conference Paper or Presentation  
Publication Status: 5-Submitted  
Conference Name: 2018 European Control Conference  
Date Received: 30-Aug-2018  
Conference Date: 12-Jun-2018  
Conference Location: Limassol Cyprus  
Paper Title: On concept abstraction algorithms  
Authors: Weibo Gong  
Acknowledged Federal Support: Y
**Publication Type:** Conference Paper or Presentation  
**Conference Name:** Linear Algebra and Applications 2018  
**Date Received:** 30-Aug-2018  
**Conference Date:** 01-Aug-2018  
**Conference Location:** Rio de Janeiro  
**Paper Title:** Markov Tensor Theory and Cascade, Reachability, and Routing in Complex Networks  
**Authors:** Zhi-Li Zhang

**Publication Type:** Conference Paper or Presentation  
**Conference Name:** 25th ACM SIGSPATIAL (SIGSPATIAL’17)  
**Date Received:** 30-Aug-2018  
**Conference Date:** 07-Nov-2017  
**Conference Location:** Redondo Beach, California, USA  
**Paper Title:** CityLines: Designing Hybrid Hub-and-Spoke Transit System with Urban Big Data  
**Authors:** Yanhua Li, Guanxiong Liu, Zhi-Li Zhang, Jun Luo, Fan Zhang

**Publication Type:** Conference Paper or Presentation  
**Conference Name:** FERM 2018  
**Date Received:** 30-Aug-2018  
**Conference Date:** 13-Jun-2018  
**Conference Location:** Fudan University  
**Paper Title:** Inference on the tail process with application to financial time series modelling  
**Authors:** Richard A. Davis, Holger Drees, Johan Segers, Michal Warchol

**Publication Type:** Conference Paper or Presentation  
**Conference Name:** Financial Econometrics Conference  
**Date Received:** 30-Aug-2018  
**Conference Date:** 04-May-2018  
**Conference Location:** Toulouse  
**Paper Title:** Inference on the tail process with application to financial time series modelling  
**Authors:** Richard A Davis, Holger Drees, Johan Segers, Michal Warchol

**Publication Type:** Conference Paper or Presentation  
**Conference Name:** HKUST2018  
**Date Received:** 30-Aug-2018  
**Conference Date:** 01-Jul-2018  
**Conference Location:** Hong Kong  
**Paper Title:** Extreme Value Analysis Without the Largest Values: What Can Be Done?  
**Authors:** Jingjing Zou, Richard A. Davis, Gennady Samorodnitsky

**Dissertations:**

**Publication Type:** Thesis or Dissertation  
**Institution:**  
**Date Received:** 29-Aug-2013  
**Completion Date:**  
**Title:** Characterizing Diverse Link Patterns in Complex Networks: Theory and Applications  
**Authors:**  
Acknowledged Federal Support:
Publication Type: Thesis or Dissertation
Institution: University of Minnesota
Date Received: 31-Aug-2018
Completion Date: 3/2/18 7:19AM
Title: Towards More Manageable and Secure Enterprise and Data-Center Networks
Authors: Cheng Jin
Acknowledged Federal Support: Y

Publication Type: Thesis or Dissertation
Institution: University of Minnesota
Date Received: 30-Aug-2018
Completion Date: 7/1/18 8:00AM
Title: Analysis of the Structural Properties and Scalability of Complex Networks
Authors: Braulio Gabriel Dumba
Acknowledged Federal Support: Y

Publication Type: Thesis or Dissertation
Institution: University of Minnesota
Date Received: 31-Aug-2018
Completion Date: 12/1/17 3:00PM
Title: Markov Tensor Theory and Cascade, Reachability, and Routing in Complex Networks
Authors: Golshan Golnari
Acknowledged Federal Support: Y

Publication Type: Thesis or Dissertation
Institution: Cornell University
Date Received: 31-Aug-2018
Completion Date: 7/31/18 4:29PM
Title: MODELLING AND INFEERENCE FOR EXTREMAL EVENTS: METHODS AND TECHNIQUES
Authors: Julian, Sun
Acknowledged Federal Support: N
WEBSITES:

URL:  http://www.orie.cornell.edu/orie/research/groups/multheavytail/
Date Received:  29-Aug-2017
Title:  Cornell MURI website and archive
Description:  Repository for talks, papers and software arising out of the Cornell MURI project.

PATENTS:

Intellectual Property Type:  Patent
Date Received:  31-Aug-2018
Patent Title:  A Highly Energy-Efficient Context-Aware Scheduler on Background Applications in Mobile Systems
Patent Abstract:  This is a scheduling algorithm that balances memory needs, energy conservation and app open
Patent Number:  62/281,244
Patent Country:  USA
Application Date:  27-Aug-2018
Application Status:  1
Date Issued:  

Accomplishments

(1) Foreword:
The organization of the research effort has been in these categories:

[A] Core theory, modeling, statistical methodology, numerical techniques for multivariate heavy tailed phenomena.

[B] Applications of heavy tailed techniques to modeling, discovery, and control of mobile and social networks; scheduling in cloud computing and wireless networks.

(2) Results

(2A) Core theory: Multivariate tail inference, risk estimation, dependence measures.

- Risk methodology: We developed practical methods for assessing risk with multivariate data. Measures of dependence have been devised which can guide understanding of concurrence of risks as well as test for various types of asymptotic or extremal independence. Alternatives to numerical summaries of dependence depend on estimating the support of the heavy tail limit measure and this estimation is based on a grid method suitable for high dimensional data. Several R-based packages are running; some of these are linked to the MURI website https://www.orie.cornell.edu/research/research-groups/multivariate-heavy-tail-phenomena-modeling-and-diagnostics.

- Assessing risks often depends on extreme value tail estimation methods. These methods require a threshold selection beyond which the modeled tail is assumed to begin. We have investigated several approaches:
  - a. averaging over various thresholds to minimize information loss due to discarded observations;
  - b. automated procedures based on minimum distance minimization between fitted tails and empirical tails;
  - use of a robust tool called distance covariance.
Each method can be fooled but each offers guidance in appropriate circumstances.

- The importance of large dimensional data in finance, insurance and risk necessitated finding methods for dealing with heavy tailed dimension reduction
both from the point of view of parametric standard stable models and more
general regularly varying models. Graphical methods and numerical summaries
offer guidance about which vector components possess enough dependence to
create systemic risk worries.

- **Statistical methodology:** We created extreme value methods for
analyzing data when extremes are omitted from the sample. For example,
this can occur when users mask their behavior or presence on a network.
Despite the unknown quantity of missing data, tail descriptors are still
required for prediction.

  Distance covariance was further applied to the issue of testing
goodness of fit of traditional time series models such as ARMA, ARCH,
GARCH. The fact that much network data is count data which is discrete
required research on extremes from discrete data; associated inference
methods result in more accurate estimation methods than the currently
used practice of ignoring the discrete nature of observations.

  In the parametric class of multivariate stable laws, we developed
a new method for parameter estimation based on fractional moments
(since few or no integral moments exist). We developed related fitting
methods for multivariate extreme value distributions using dense classes
of models such as discrete spectral measures and generalized logistic.
An accompanying R-package *mvevd* (linked through the MURI web site)
now exists and can run simulations and evaluate methods.

- **More Core theory:** We now understand the joint behavior of Levy
process jumps and the trimmed process with the jumps removed. This is part of
a stream of work that provides robust estimation methods for continuous time
risk models with jumps and relates to trimming in classical statistics. We
now understand extreme behavior of random fields in important cases with
important spinoffs to environmental modeling.

- **Software:** Nolan packages are updated and posted to the R-repository
CRAN and linked to our MURI site. They give the ability to do various
calculations with multivariate heavy tailed distributions. One can calculate
multivariate stable probabilities, likelihoods and densities of ratios of stable
random variables. Also on the MURI website are links to software for
simulating preferential networks and fitting parameters.

[2B] Engineering and networks
Network model calibration. Preferential attachment is an explanatory mechanism for describing social network growth. A series of papers gave methods for fitting a simple parametric growth model and three methods were given: a) MLE when a history with time stamps of edge creation is available; b) a single snapshot (SN) method when only the structure of the network is available at a single time point; c) a robust extreme value (EV) method when one suspects data corruption or model error. Companion work developed simulation methods that allowed extensive experimentation to show the advantages and weaknesses of each method. The estimation techniques were tested on real data revealing how data needed to be cleaned and the methodology modified.

Estimation for networks: Degree indices are typically estimated in CS and network science by a common method that is essentially standard Hill estimation from extreme value theory. This was adapted from the extremes literature where it was developed for repeatedly sampled data but not network degree data. We now know the estimator is consistent for tail indices for particular network growth models both in the directed and undirected cases. Asymptotic normality still eludes us but we have made significant progress justifying a widely used method.

Network search: We developed search techniques that allow discovery of nodes with desirable characteristics within a graph. For example, this could be used to identify potential donors within a social network. The technique uses multi-armed bandit methods where arms correspond to different models of unknown nodes based on their known local neighborhoods.

Graph classification: We created a graph neural network for the purpose of performing regression and classification tasks based on a quantum walk. Experiments indicate that quantum walks provide better models than classical random walks for small problem instances; however a limitation remains that computational effort increases substantially with heavier degree distributions.

Network sampling. Multidimensional random walk sampling algorithms have been developed for the purpose of characterizing large directed graphs. These algorithms take advantage of the heavy-tail nature of the joint in- out-degree distribution to reduce sampling errors.

Uncovering network structure: Big data efforts focussed on identifying the
core structure of the Google+ network serving as a practical test of proposed algorithms. This suggested general methods for uncovering the nucleus that supplement the k-shell method. Further work exposed weaknesses to standard graph capsule convolutional neural network methods and gave solutions.

- **Power management.** Ness Shroff and coworkers were awarded a patent for a highly energy efficient context aware scheduler on background applications in mobile systems. This complimented his work on minimizing latency time when launching apps in a mobile context as well as minimizing power usage when switching between wifi and 4G networks.

- **Parallel or cloud computing:** How do you reduce job latency across multiple servers for either parallel processing or cloud computing? The commonly used strategy of replication and task assignment across multiple servers induces dependence across servers, which makes it difficult to quantify the performance benefit of such strategies. However, replication/task assignment improves performance dramatically especially when the task service-time distributions have a large variance or are heavy-tailed provided the task delays in different servers are independent.

- **Graph matching:** The network deanonymization problem has the goal of inferring node identities in an anonymized graph by observing the node identities and topology of a dependent graph. Label the nodes of the anonymized graph so that the adjacency matrix of the anonymized graph matches the adjacency matrix of the correlated graph as closely as possible. Given certain connectivity and sparsity constraints, and assuming a noisy estimate of the true label matching, a proposed algorithm corrects errors provided the noisy estimate contains a certain number of correct matches. The algorithm works well on random graph models as well on publicly available real network datasets.

- **Image recognition:** Scaling phenomena in natural images suggest new feature vectors for scale invariant object recognition. Our approach develops relational information and retrieving methods.

- **Networking:** Age-of-Information and How to Keep Data Fresh. How do we balance freshness of data with network throughput, minimal delay for updates, and energy consumption in heterogeneous transmission environments where packet transmission times and job sizes could be heavy tailed? We devised alternatives to the zero-wait update policy in which the source node submits a fresh update once the previous update is
delivered and the channel becomes free which achieves the maximum throughput and the minimum delay. But the zero-wait policy does not always minimize age. This problem was specialized to mobile devices where application freshness is balanced with energy requirements, base station overloading and freshness in an environment where inter-launch times of an application are heavy tailed.