Controlling Complex Networks: When Control Theory Meets Network Science

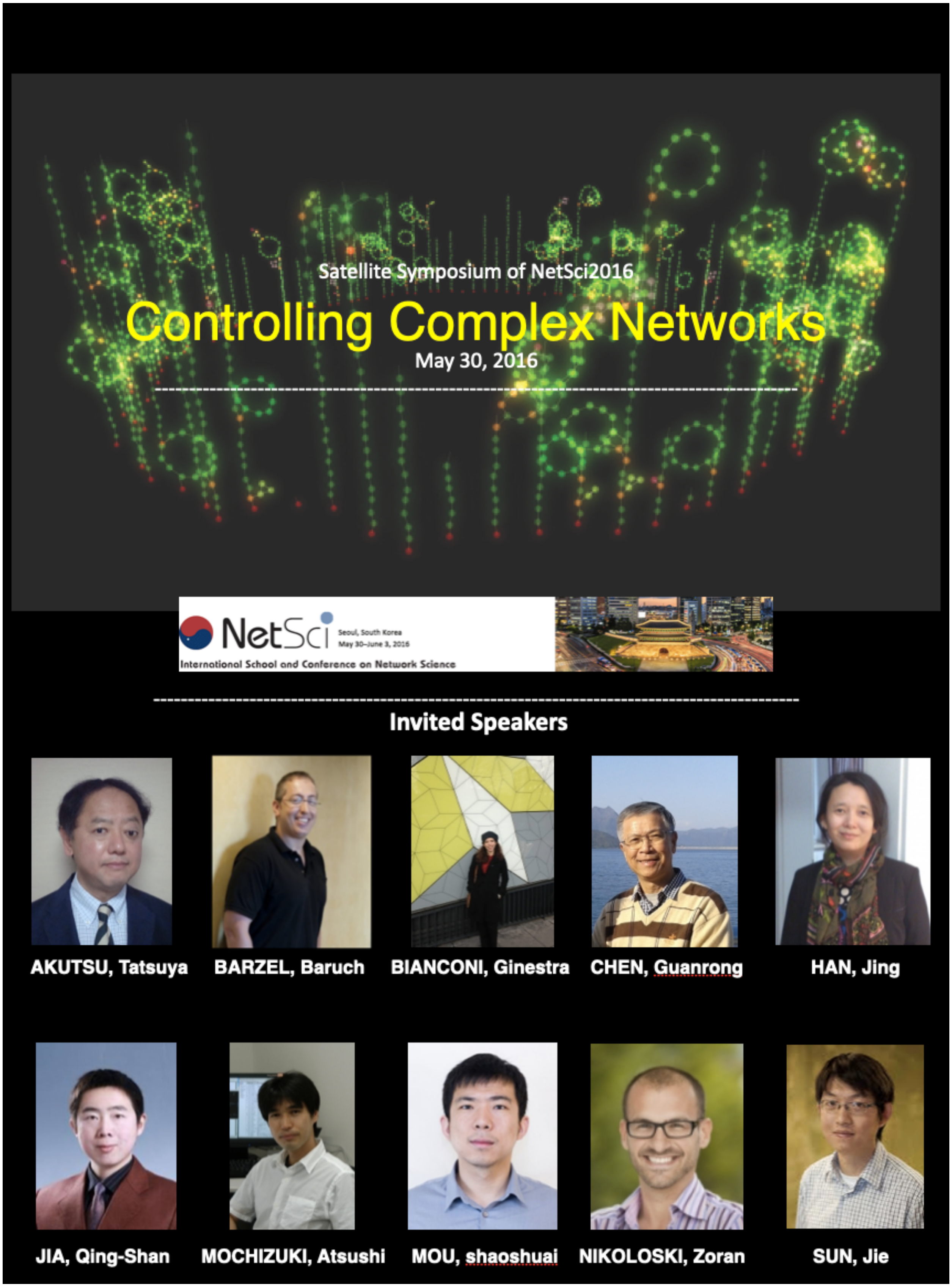
Satellite symposium of NetSci2016, Seoul, South Korea

Date: May 30, 2016

Venue: **K-hotel, Cystal Ballroom A**

Registration of this symposium is free of charge. Yet, symposium participants still need to register for the NetSci main conference.

Organizers:
Yang-Yu Liu
Gang Yan
Marco Tulio Angulo
Pau Vilimelis Aceituno


Satellite Symposium of NetSci2016
Controlling Complex Networks
May 30, 2016
NetSci
Seoul, South Korea
May 30–June 3, 2016
International School and Conference on Network Science
Invited Speakers
AKUTSU, Tatsuya
BARZEL, Baruch
BIANCONI, Ginestra
CHEN, Guanrong
HAN, Jing
JIA, Qing-Shan
MOCHIZUKI, Atsushi
MOU, shaoshuai
NIKOLOSKI, Zoran
SUN, Jie

NetSci Satellite Symposium – ***Controlling Complex Networks***

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Program

8:30-8:50	Sign in
8:50-9:00	Welcome address (Yang-Yu Liu)
	Session I (Chair: Gang Yan)
9:00-9:40	**Qing-Shan Jia**: *Event-Based Optimization for Controlling Complex Networks with Multi-Scale Dynamics*
9:40-10:20	**Jie Sun**: *Information-theoretic Reverse Engineering of Biological Networks*
10:20-11:00	**Shaoshuai Mou**: *Distributed control of Multi-Agent Networks*
11:00-11:20	Coffee Break
11:20-11:40	**Session II** (Chair: Pau Vilimelis Aceituno) **(Contributed Talk 1)**: **Aming Li**: *The Advantages of Temporal Networks*
11:40-12:20	**Tatsuya Akutsu**: *Extensions and Applications of the Minimum Dominating Set-Based Approach to Controllability of Complex Networks*
12:20-1:00	**Baruch Barzel**: *A Perturbative Theory of Network Dynamics*
1:00-2:30	Lunch (on your own)
	Session III (Chair: Marco Tulio Angulo)
2:30-3:10	**Atsushi Mochizuki**: *Dynamics of complex biological systems determined/controlled by minimal subsets of molecules in regulatory networks*
3:10-3:50	**Zoran Nikoloski**: *Control of Fluxes in Metabolic Networks*
3:50-4:30	**Jing Han**: *Soft-control of networked multi-agent systems*
4:30-4:50	Coffee Break
4:50-5:10	**Session IV** (Chair: Gang Yan) **(Contributed Talk 2)**: **Yan Zhang**: *Value of peripheral nodes in controlling multilayer networks*
5:10-5:50	**Ginestra Bianconi**: *Control of Multilayer Networks*
5:50-6:30	**Guanrong Chen**: *Recent Progress on Network State Controllability*
6:30-6:35	Conclusion (Yang-Yu Liu)

Abstracts

AKUTSU, Tatsuya
Professor, Bioinformatics Center, Institute for Chemical Research, Kyoto University, Japan

Extensions and Applications of the Minimum Dominating Set-Based Approach to Controllability of Complex Networks

Several years ago, we showed a relationship between the minimum dominating set (MDS) and structural controllability of complex networks, where MDS is a well-known concept in graph theory. It is summarized that if nodes in MDS are selected as control nodes and each of these nodes can control its connecting edges independently, the system is structurally controllable. Since then we have been extending this MDS-based approach as follows [1].

(1) Since many networks have bipartite network structure such as drug-disease networks and ncRNA-protein networks, we extended the MDS-based approach to bipartite networks in which controls are given for nodes in only one side.
(2) Jia et al. introduced the concepts of critical and redundant nodes in the maximum matching-based approach to controllability of complex networks. We applied these concepts to the MDS-based approach in both unipartite and bipartite networks.
(3) We introduced the robust MDS using which a network remains structurally controllable against arbitrary failures of up to a constant number of communication links.

MDS has also been applied to analysis of various kinds of biological networks by us and several other groups, which include protein-protein interaction networks, drug-target protein network, non-coding RNA-protein network, and cancer metabolic network [1]. In this talk, we overview these extensions and applications of the MDS-based approach.

[1] J. C. Nacher and T. Akutsu, Minimum dominating set-based methods for analyzing biological networks, Methods, in press.

BARZEL, Baruch
Assistant Professor, Department of Mathematics, Bar Ilan University, Israel

A Perturbative Theory of Network Dynamics

Capturing the underlying geometry of complex systems, network science has uncovered many universal properties, such as the scale-free degree distribution and the small world phenomena, observed from sub-cellular networks to social systems. The ultimate goal of these research efforts, however, is to translate the topological findings into an understanding of the system's dynamic behavior: how does the small world structure impact the patterns of spread in the system? Or how does the presence of hubs affect the distribution of influence? In essence, whether its communicable diseases, genetic regulation or the spread of failures in an infrastructure network, these questions pertain to the patterns of information spread in the network, and how this spread is mediated by the network's topology and the nonlinear dynamics of the system's interaction. Hence we developed a formalism to track such information spread by following the system's dynamic response to perturbations. We discovered a set of universal response patterns, which expose the dynamic role of properties such as the scale-free degree distribution or the small world phenomena, and, most importantly, the interplay of these topological characteristics and the system's internal dynamics.

BIANCONI, Ginestra
Reader, Director of the MSc in Network Science, School of Mathematical Sciences, Queen Mary University of London, UK

Control of Multilayer Networks

The controllability of a network is a theoretical problem of relevance in a variety of contexts ranging from financial markets to the brain. Until now, network controllability has been characterized only on isolated networks, while the vast majority of complex systems are formed by multilayer networks. In fact the vast majority of complex systems is not described by a single isolated networks but by several interacting networks.Extending our knowledge of single networks to multilayer networks provides often a completely new paradigm to understand complexity. Here we build a theoretical framework for the linear controllability of multilayer networks by mapping the problem into a combinatorial matching problem. We found that correlating the external signals in the different layers can significantly reduce the multiplex network robustness to node removal, as it can be seen in conjunction with a hybrid phase transition occurring in interacting Poisson networks. Moreover we observe that multilayer networks can stabilize the fully controllable multiplex network configuration that can be stable also when the full controllability of the single network is not stable.

CHEN, Guanrong
Chair Professor, Department of Electronic Engineering City University of Hong Kong, China

Recent Progress on Network State Controllability

In this talk, we discuss the complete state controllability of networked higher-dimensional linear time-invariant dynamical systems coupled by directed and weighted higher-dimensional communication channels. We show how the network topology, node-system dynamics, external control inputs, and inner interactions affect the controllability of such a complex network. We present precise necessary and sufficient conditions for the network controllability in a general topology, as well as in some special configurations such as chains and cycles with more subtitle details.

HAN, Jing
Associate Professor, Associate Director of Complex Systems Research Center
Academy of Mathematics and Systems Science, Chinese Academy Science, China

Soft-control of networked multi-agent systems

How do we control the collective behavior of networked multi-agent systems (MAS) without changing the local rule of the existing agents in the system ? We proposed a new method called 'Soft Control': by adding special agents, called 'shills', into the system, we control the collective behavior by controlling the shills. It is a nondestructive intervention method, because shills are still treated as normal agents by normal ones in the system. Three case studies are presented in this talk to show the feasibilities and power of soft-control: (1) adding one intelligent shill into the Vicsek' model based system to help the system reach consensus; (2) adding some shills into a multi-person prisoner dilemma game system to increase the cooperation level; (3) adding some shills into an opinion dynamical Degroot model system to change the convergent collective opinion value. We believe the soft-control method can be applied to many other networked systems, and it will bring out more interesting issues and challenges.

JIA, Qing-Shan (Samuel)
Associate Professor, Center for Intelligent and Networked Systems, Tsinghua University, Beijing, China

Event-Based Optimization for Controlling Complex Networks with Multi-Scale Dynamics

Large-scale complex networks usually involve dynamics in multiple spatial and temporal scales. This is especially true in many cyber-physical systems and Internet of Things, in which systems follow not only physical laws but also man-made rules. For example, technological advances now allow us to connect multiple buildings into a micro grid in which the renewable energy such as solar power and wind power are generated locally in the building, stored in the building, and consumed in the building by plug-in loads and electric vehicles. There are models to predict the power generation and consumption in minutes, hours, and days. And there are models to predict the power generation and consumption in individual buildings or a group of buildings. In order to well control the dynamics in such complex networks, domain knowledge and problem structure in multiple scales should be explored. In this talk, we consider this important problem. First, we motivate the study by real-life engineering problems. Second, we formulate the problem into a multi-scale event-based optimization problem where control decisions are made only when certain events occur. Third, we develop a simulation-based policy improvement approach which uses policy projection and state and action aggregation to connect the models in multiple scales. Fourth, we demonstrate the performance of this approach on the power management problem in a micro grid of buildings in which decisions are made to best utilize the renewable energy to charge the electric vehicles. Our approach found control policies which are better than the base ones. We hope this work sheds light to the control of complex networks with multi-scale dynamics.

MOCHIZUKI, Atsushi
Chief Scientist, Theoretical Biology Laboratory, Riken, Japan

Dynamics of complex biological systems determined/controlled by minimal subsets of molecules in regulatory networks

Modern biology provides many networks describing regulations between a large number of species of molecules. It is widely believed that the dynamics of molecular activities based on such regulatory networks are the origin of biological functions. In this study we develop a new theory to provide an important aspect of dynamics from information of regulatory linkages alone. We show that the "feedback vertex set" (FVS) of a regulatory network is a set of "determining nodes" of the dynamics. It assures that i) any long-term dynamical behavior of the whole system, such as steady states, periodic oscillations or quasi-periodic oscillations, can be identified by measurements of a subset of molecules in the network, and that ii) the subset is determined from the regulatory linkage alone. For example, dynamical attractors possibly generated by a gene regulatory network for ascidian cell-differentiation with more than100 molecules can be identified by measurement of the activity of only 5 genes, if the information on the network structure is correct. We also show that controlling the dynamics of the FVS is sufficient to switch the dynamics of the whole system from one attractor to others.

Further Reading: Mochizuki A. *et al.* (2013) Dynamics and control at feedback vertex sets. II: A faithful monitor to determine the diversity of molecular activities in regulatory networks. *J. Theor. Biol.* **335**, 130-146.

MOU, shaoshuai

Assistant Professor, School of Aeronautics and Astronautics, Purdue University, USA

Distributed Control of Multi-Agent Networks

This talk aims to address two problems in the area of distributed control of multi-agent networks, the goal of which is to achieve global objectives through local coordinations. One is about a distributed algorithm for solving large linear algebraic equations, which is applicable to all linear equations; converges exponentially fast; works asynchronously; does not involve any small stepsize for convergence; works for time-varying networks. The other one is about distributed formation control. We have analytically proved that the gradient method is not robust in the sense that in the presence of small measurements inconsistencies, undirected formations under the gradient method will display dramatic misbehavior. Impact of this research will be well beyond formation control considering the fact that the gradient method severs as a powerful tool in many other field.

NIKOLOSKI, Zoran
Research Group Leader "Mathematical Modelling and Systems Biology", Max Planck Institute of Molecular Plant Physiology, Germany

Control of Fluxes in Metabolic Networks

Understanding the control of large-scale metabolic networks is central to biology and medicine. However, existing approaches either require specifying a cellular objective or can only be used for small networks. We introduce new coupling types describing the relations between reaction activities, and develop an efficient computational framework, which does not require any cellular objective for systematic studies of large-scale metabolism. We identify the driver reactions facilitating control of 23 metabolic networks from all kingdoms of life. We find that unicellular organisms require smaller degree of control than multicellular organisms. Driver reactions are under strong transcriptional regulation in Escherichia coli, indicating their preeminent role in facilitating cellular control. In human cancer cells driver reactions play pivotal roles in malignancy and represent potential therapeutic targets. The developed framework helps us gain insights into regulatory principles of diseases and facilitates design of engineering strategies at the interface of gene regulation, signaling, and metabolism.

SUN, Jie
Assistant Professor, Department of Mathematics, Clarkson University, USA

Information-theoretic Reverse Engineering of Biological Networks

Understanding the dynamics and functioning of biological systems is one of the most challenging tasks faced in modern science. An important problem in practice regards how to accurately infer the underlying cause-and-effect (i.e., causal) network from observational data, especially when the underlying system consists of a large number of interacting components and the dynamics is intrinsicaly nonlinear. Utilizing our recently developed theory of causation entropy (J. Sun, D. Taylor, and E. M. Bollt, SIAM Journal on Applied Dynamical Systems 14, 73–106, 2015), we devised an efficient computational approach of optimal causation entropy (oCSE) to infer causal networks from data, and demonstrate its effectiveness using both synthetic and experimental data.

WANG, Xingang
Professor of Physics, School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710062, China

Topological control of synchronous patterns in systems of networked chaotic oscillators

Recent studies of network science have revealed the sensitive dependence of network collective behaviors on structures; here we employ this feature of topological sensitivity for the purpose of pattern control. By simple models of networked chaotic oscillators, we are able to argue and demonstrate that, by manipulating just a single link in the network, the synchronous patterns of the system can be effectively adjusted or controlled. In particular, by changing the weight or the connection of a shortcut link in the network, we find not only that various stable synchronous patterns can be generated from the system but also that the synchronous patterns can be successfully switched among different forms. The stability of the synchronous patterns is analyzed by the method of eigenvalue analysis, and the feasibility of the control is verified by numerical simulations. Our study provides a step forward to the control of sophisticated collective behaviors in more complex networks, as well as insights to the evolution and function of some realistic complex systems.

ZHANG, Yan

Chair of Systems Design, ETH Zurich, Weinbergstrasse 58, 8092 Zurich, Switzerland
Value of peripheral nodes in controlling multilayer networks

Control of large-scale complex networks is an outstanding challenge. In addition to the sheer size of such systems, there can be constraints in accessing all of the driver nodes necessary to control the system. This limitation motivates our research, namely to understand how control can be achieved with a rather small number of driver nodes. With our work, we extend the scope from single-layer to multilayer networks. Such networks consist of multiple layers that each contain a complex network, and additional links between nodes of different layers. We further consider, as an additional challenge, restricted access to only one layer of a multilayer network. We combine the in-degree and out-degree values to assign an importance value w to each node, and distinguish between peripheral nodes with low w and central nodes with high w. Based on numerical simulations, we find that, the controllable part of the network is larger when choosing low w nodes to connect the two layers. The control is as efficient when peripheral nodes are driver nodes as it is for the case of more central nodes. However, if we assume a cost to utilize nodes which is proportional to their overall degree, utilizing peripheral nodes to connect the two layers or to act as driver nodes is not only the most cost-efficient solution, it is also the one that performs best in controlling the two-layer network among the different interconnecting strategies we have tested.

Ref: Yan Zhang, Antonios Garas, and Frank Schweitzer, Phys. Rev. E 93, 012309 – Published 27 January 2016