# Data-Driven Modeling in Dynamic Networks

**Proposal for a tutorial session during the 2021 European Control Conference.**

**Lecturers**:

- Prof. Paul M.J. Van den Hof, Eindhoven University of Technology, The Netherlands (Organizer).
- Dr. Xiaodong Cheng, Cambridge University, UK.
- Dr. Arne Dankers, University of Calgary, Canada and Hifi Engineering, Calgary, Canada.
- Karthik Ramaswamy MSc, Eindhoven University of Technology, The Netherlands.

## Description

Many of our current technological systems are composed of subsystems that have local dynamic behaviour and that interact with each other in some kind of network structure. Typical examples are found in e.g., power systems (smart grids), biological systems, flexible mechanical structure, robotic networks, autonomous driving and other transportation systems, gas and water distribution networks, etcetera. The distributed and/or multi-agent control and optimization of such network is one of the serious challenges for the systems and control domain. Motivated by this challenge, in recent years increasing attention has been given to the development of new tools for the data-driven dynamic modeling of large-scale interconnected systems, also known as dynamic networks. These networks are typically thought of as a set of measurable signals (the node signals) interconnected through linear dynamic systems (the modules), possibly driven by external excitations (the reference signals). Among the literature on this topic, we can distinguish three main categories of developments. The first one focuses on identifying the topology of the dynamic network. The second category concerns identification of the full network dynamics, including aspects of identifiability, while the third one deals with identification of a specific component (module) of the network, assuming that the network topology is known (the so called local module identification). There are many important aspects involved in this development.

- First, an appropriate framework has to be built for addressing data-driven modeling questions in a networked environment. The structural (graph-related) properties that are present in networks require a revision and extension of the standard identification framework, including a reconsideration of the prime aspects as data informativity and identifiability.
- An important aspect concerns the selection of signals that are available for measurement, together with the selection of locations where probing signals might be added to the network for guaranteeing data-informativity and identifiability, allowing for drawing appropriate conclusions on the estimated targets.

- Even if the target to be estimated is a single module, the complexity of the estimation algorithm can grow substantially, requiring a more efficient use of resources and optimization tools than is typically present in classical (prediction error) identification methods. Methods that find their motivation in the machine learning domain, like kernel-based regularized (Bayesian) methods, can effectively be used for handling this complexity, arriving at estimates with improved mean square errors, and with a computational complexity that allows scalability to larger-sized networks.
- The incorporation of prior knowledge is an important aspect that plays a role in all of the above problems: this can include prior knowledge on the topology of the network, on the correlation properties of the process disturbances, on the order of dynamic modules, but also on the actual dynamics of some modules, as e.g., controllers that are designed by the user and therefore known a priori.

In this tutorial session, an introduction and overview will be given of the developments in data-driven modeling in dynamic networks, where attention is focussed on the domain of prediction error and machine learning methods, applied to linear dynamic networks. Four lecturers will present tutorial contributions on their domain of expertise:

1. Paul M.J. Van den Hof will provide an introduction to the field, present the modeling framework, introduce the relevant data-driven modeling problems and basic concepts like identifiability, [6], [7], [8].
2. Xiaodong Cheng will present a graph-based method for analysing generic identifiability of a full network, as well as an algorithm for allocating external excitation signals that warrant identifiability of the network, [1].
3. Arne Dankers will present an effective and scalable identification algorithm for full network identification and discuss the results of a technology project performed in Canada on pipeline monitoring in gas pipelines in which the tools for network identification have been applied successfully [2].
4. Karthik Ramaswamy will present conceptual and algorithmic solutions for the data-driven modeling of a single dynamic module in a network, including the appropriate choice of graph nodes to be measured, the handling of confounding variables, and machine-learning based algorithms to master computational complexity [3],[5],[4].

## References


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[5] K. R. Ramaswamy and P. M. J. Van den Hof. A local direct method for module identification in dynamic networks with correlated noise. *IEEE Trans. Automatic Control*, 66, 2021.

[6] P. M. J. Van den Hof, A. G. Dankers, P. S. C. Heuberger, and X. Bombois. Identification of dynamic models in complex networks with prediction error methods - basic methods for consistent module estimates. *Automatica*, 49(10):2994–3006, 2013.

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Except for paper [2], all other papers are available through:
http://publications.pvandenhof.nl.

## Lecturers

**Paul M.J. Van den Hof** received the M.Sc. and Ph.D. degrees in electrical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1982 and 1989, respectively. In 1986 he moved to Delft University of Technology, where he was appointed as Full Professor in 1999. From 2003 to 2011, he was founding co-director of the Delft Center for Systems and Control (DCSC). As of 2011, he is a Full Professor in the Electrical Engineering Department, Eindhoven University of Technology. His research interests include data-driven modeling, identification for control, dynamic network identification, and model-based control and optimization, with applications in industrial process control systems and high-tech systems. He holds an ERC Advanced Research grant for a research project on identification in dynamic networks. Paul Van den Hof is an IFAC Fellow and IEEE Fellow, and Honorary Member of the Hungarian Academy of Sciences, and IFAC Advisor. He has been a member of the IFAC Council (1999–2005, 2017-2020), the Board of Governors of IEEE Control Systems Society (2003–2005), and an Associate Editor and Editor of Automatica (1992–2005). In the triennium 2017-2020 he served as Chair of the Executive Board and Vice-President of IFAC.

**Xiaodong Cheng** received his B.S. and M.S. degrees in system and control engineering from the Northwestern Polytechnic University, Xi'an, China, in 2011 and 2014, respectively. In 2018, he received the Ph.D. degree in system and control from the University

of Groningen, the Netherlands. From 2019-2020 he was a postdoctoral researcher with the Control Systems Group of the Department of Electrical Engineering, Eindhoven University of Technology, the Netherlands. Currently he is a Research Associate with the University of Cambridge, UK. His main research interests include system identification, model reduction and distributed control in large-scale dynamic networks. He is the recipient of the Paper Prize Award from the IFAC Journal Automatica in the triennium 2017-2019 and the Outstanding Paper Award from IEEE Transactions on Control Systems Technology in 2020.

**Arne G. Dankers** received B.Sc. and M.Sc. degrees from the Department of Electrical and Computer Engineering at the University of Calgary in Calgary, Canada, and a Ph.D. degree from the Delft Center for Systems and Control at the Delft University of Technology in Delft, The Netherlands. He was awarded with the Best Student Paper Award of the 2013 European Control Conference for a paper on dynamic network identification. He completed a Post-Doc position at the University of Calgary in partnership with Hifi Engineering Inc. Currently he is employed full time at Hifi Engineering where he applies system identification for leak detection in pipelines. His current research interests include system identification, dynamic networks, acoustic modelling and leak detection in pipelines.

**Karthik Raghavan Ramaswamy** was born in 1989. He received his Bachelor's in Electrical and Electronics Engineering (with Distinction) in 2011 from Anna University and Master's in Systems and Control (with great appreciation) from Eindhoven University of Technology in 2017. From 2011 to 2015 he was Control & Automation engineer at Larsen & Toubro. Currently, he is a PhD researcher with the Control Systems research group, Department of Electrical Engineering, Eindhoven University of Technology, The Netherlands. His research interests are in the area of data driven modeling, dynamic network identification and machine learning.