Generalized sensing and actuation schemes for local module identification in dynamic networks

Karthik R. Ramaswamy , **Paul M.J. Van den Hof, Arne G. Dankers**

k.r.ramaswamy@tue.nl
www.sysdynet.eu

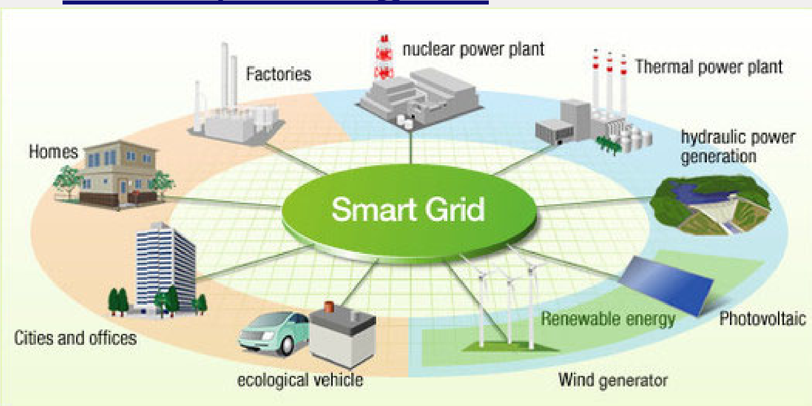
58th IEEE Conference on Decision and Control, Nice, France, December 11-13, 2019

EINDHOVEN UNIVERSITY OF TECHNOLOGY

European Research Council

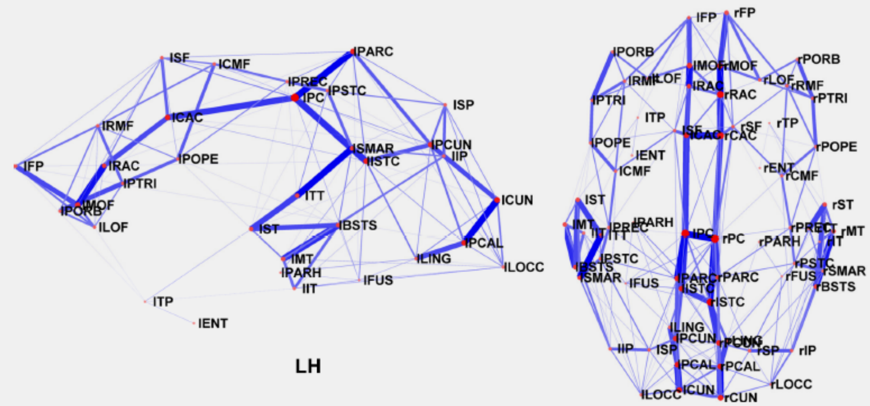
Dynamic Networks

Smart power grids

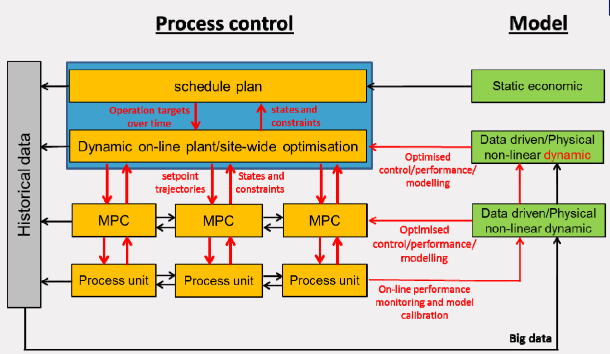


www.betterworldsolutions.eu

Brain networks



Brain networks from human MRI [1]



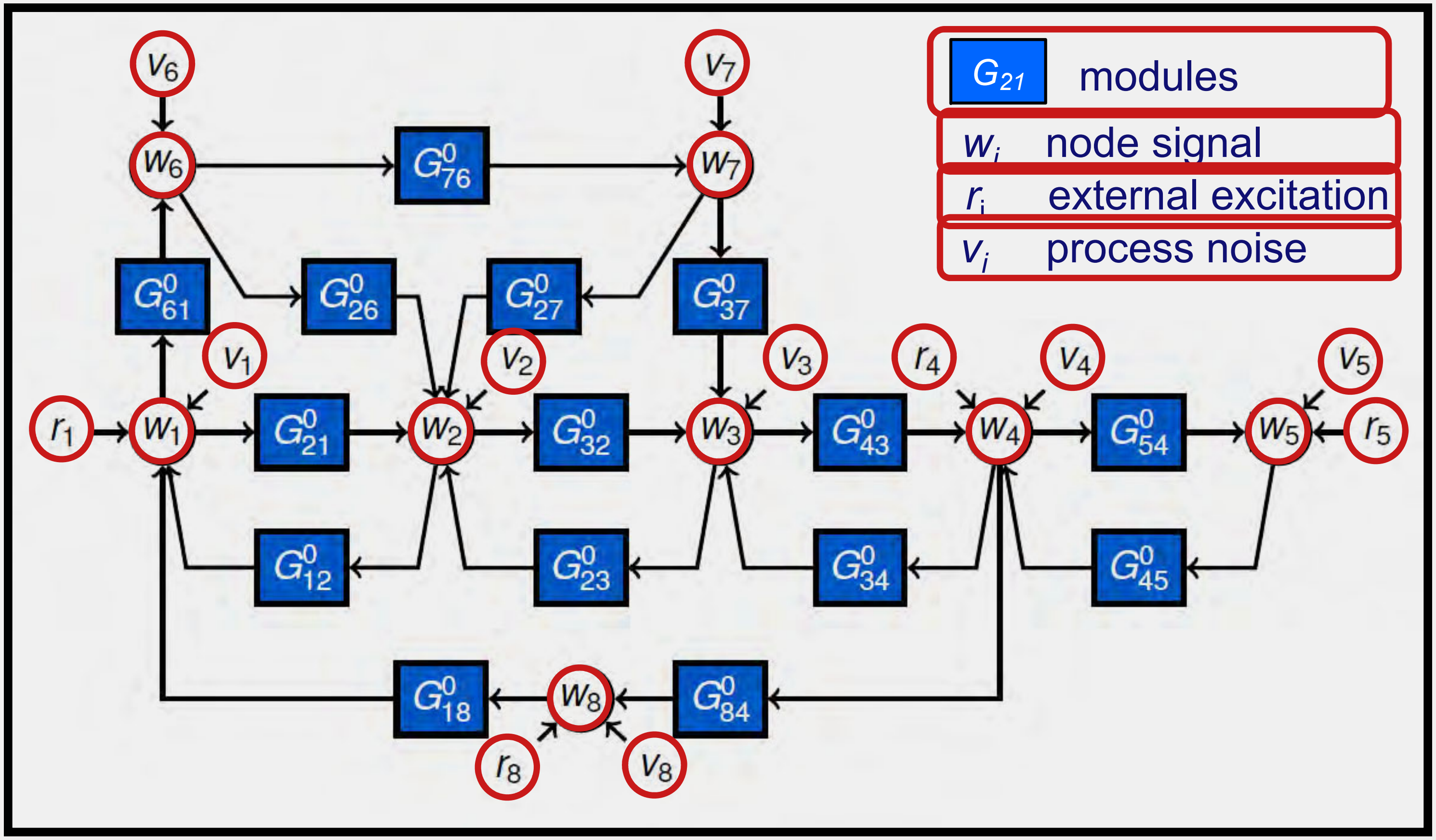
Distributed/Decentralized process control

Many examples for dynamically interconnected systems…

[1] P. Hagmann, L. Cammoun, X. Gigandet, R. Meuli, C. J. Honey, V. J. Wedeen, and O. Sporns. PLoS biology, 6(7):e159, 2008.

TU/e

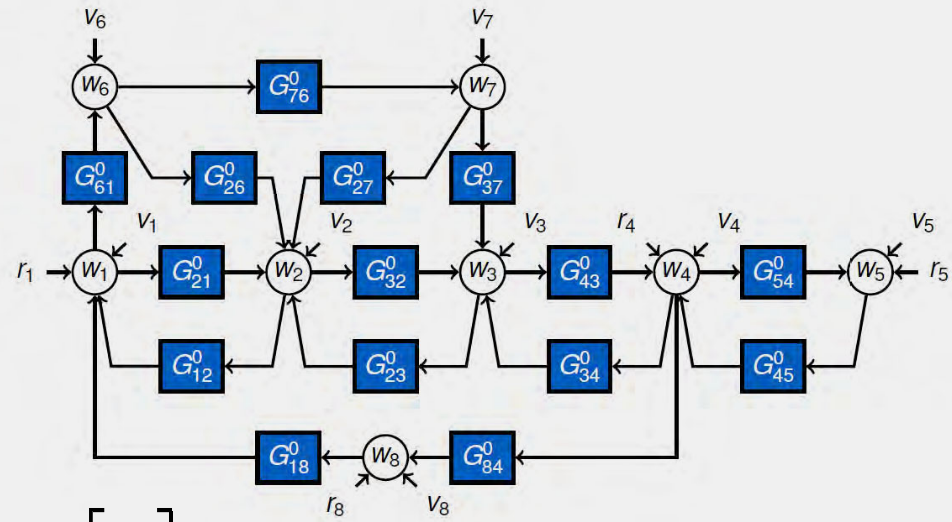
Dynamic network setup



Dynamic network setup

Assumptions:

- Known topology
- Network is stable and well posed
- Disturbances are stationary stochastic and can be correlated



$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_L \end{bmatrix} = \begin{bmatrix} 0 & G^0_{12} & \cdots & G^0_{1L} \\ G^0_{21} & 0 & \cdots & G^0_{2L} \\ \vdots & \ddots & \ddots & \vdots \\ G^0_{L1} & G^0_{L2} & \cdots & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_L \end{bmatrix} + \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_L \end{bmatrix} + H^0 \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_L \end{bmatrix}$$

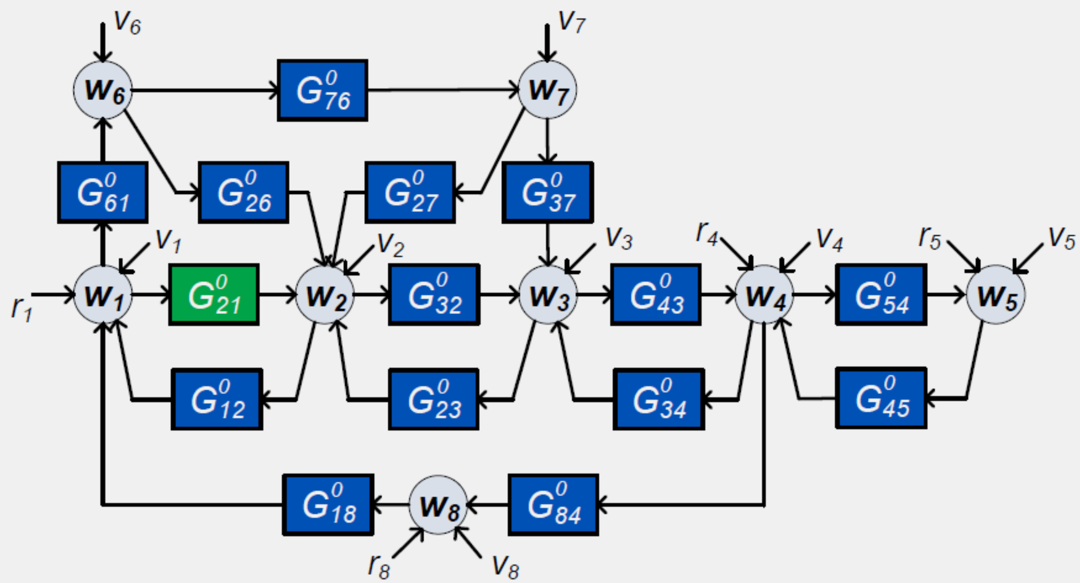
- **Elements of r can be zero (i.e. the nodes without excitation)**

$$w = G^0(q)w + r + v \qquad\qquad w = (I - G^0)^{-1}(r + v)$$

P. M. J. Van den Hof, A. G. Dankers, P. S. C. Heuberger, and X. Bombois. Automatica, 49(10):2994–3006, 2013.

Single module identification

- For a network with known topology, identify a single module in a dynamic network based on the given data
- For example, identify G^0_{21} on the basis of measured signals



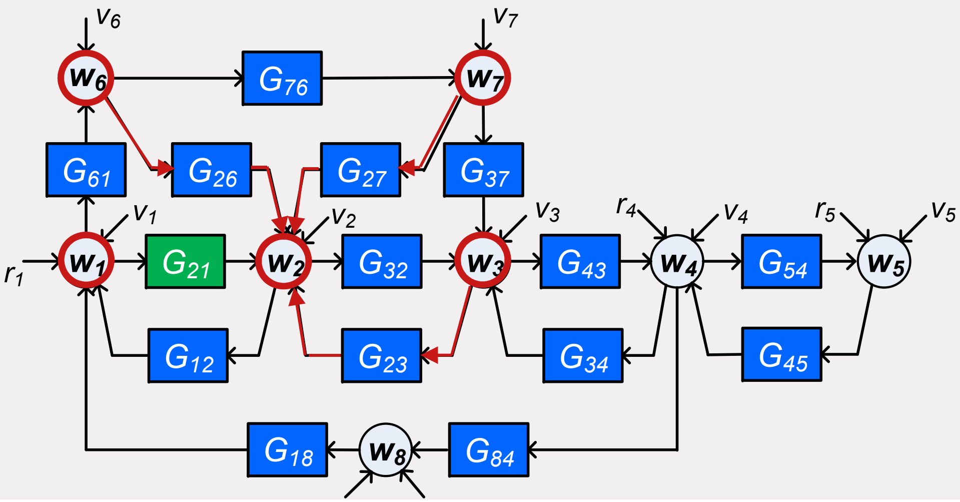
Identifying options

- Identify the MIMO system – from measured $\boldsymbol{r}$ and $\boldsymbol{w}$

$$\boldsymbol{w} = (\boldsymbol{I} - \boldsymbol{G}^0)^{-1}[\boldsymbol{r} + \boldsymbol{v}]$$

A global approach that we wish to avoid. Why???

- Identify a subset of modules from a subset of signals in $\boldsymbol{r}$ and $\boldsymbol{w}$ (Local)

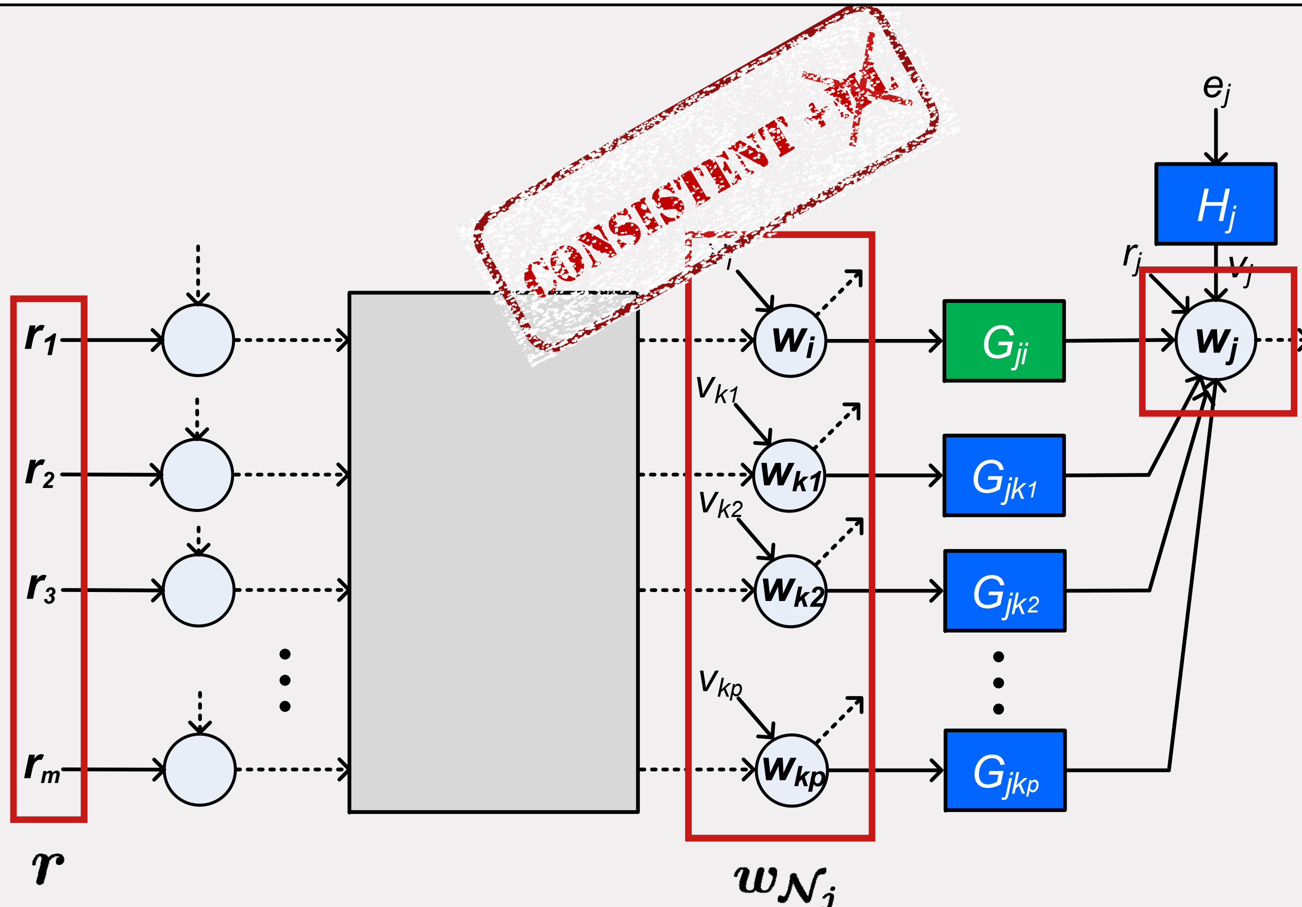


- Indirect Method
- Direct Method

P. M. J. Van den Hof, A. G. Dankers, P. S. C. Heuberger, and X. Bombois. Automatica, 49(10):2994–3006, 2013.

Indirect method

- Uses external excitation signals $\boldsymbol{r}$ as predictor inputs
- Estimate consistently dynamics from $\boldsymbol{r}$ to nodes.
- *Post-process* it to get the target module. $\hat{G}_{j\mathcal{N}_j} = \hat{T}_{j\boldsymbol{r}}[\hat{T}_{\mathcal{N}_j\boldsymbol{r}}]^{-1}$
- Flexibility in location of actuators ($\boldsymbol{r}$ signals)



However, requires sufficient number of excitations and conditions on excitation of certain nodes.

[1] M. Gevers, et al. In Proc. 18th IFAC Symposium on System Identification (SYSID2018), 2018.

[2] A. Bazanella et al., CDC 2019.

Direct method

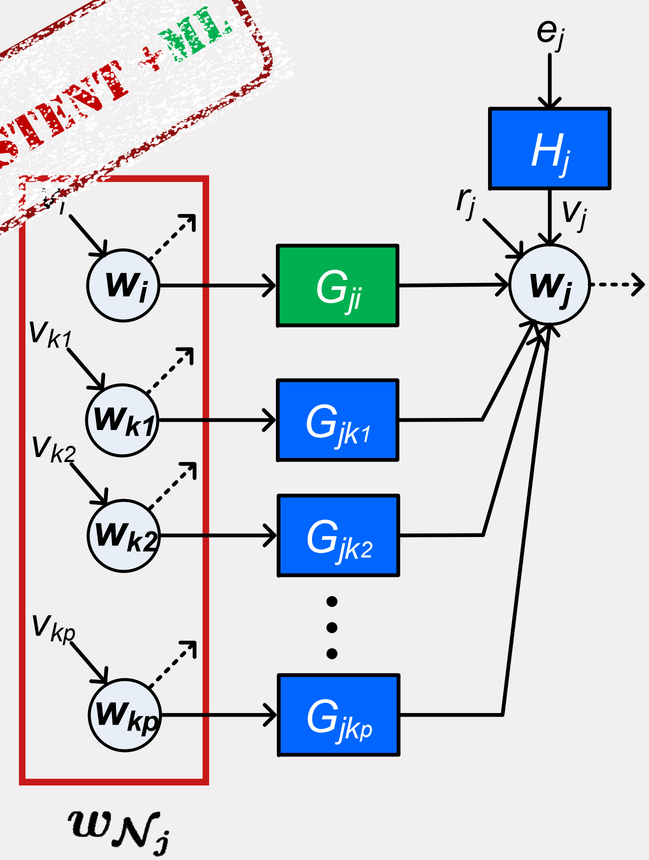
- $\mathcal{N}_j = \{i, k_1, \ldots, k_p\}$ → in-neighbors

- Assuming measurements of w's available and v_j uncorrelated with other v's

- Minimize the power of prediction error :

$$\varepsilon_j(t,\theta) = H_j^{-1}(\theta)\left(w_j(t) - \sum_{k\in\mathcal{N}_j} G_{jk}(q,\theta)w_k(t) - r_j(t)\right)$$

- Flexibility in selection of input node signals. Number of inputs can be reduced [2].



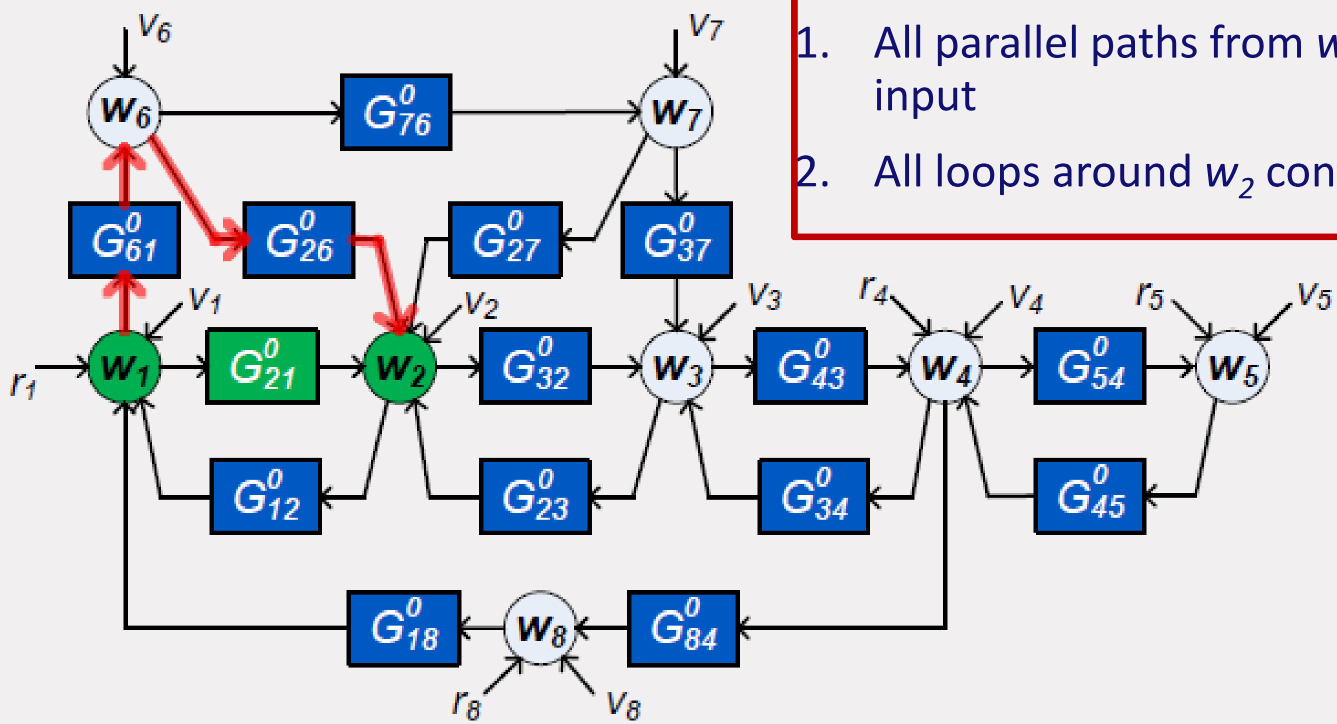
However, requires parallel path/loop conditions to be satisfied that requires certain nodes to be measured

[1] P. M. J. Van den Hof *et al*. Automatica, 49(10):2994–3006, 2013.

[2] A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

TU/e

Parallel paths and loops

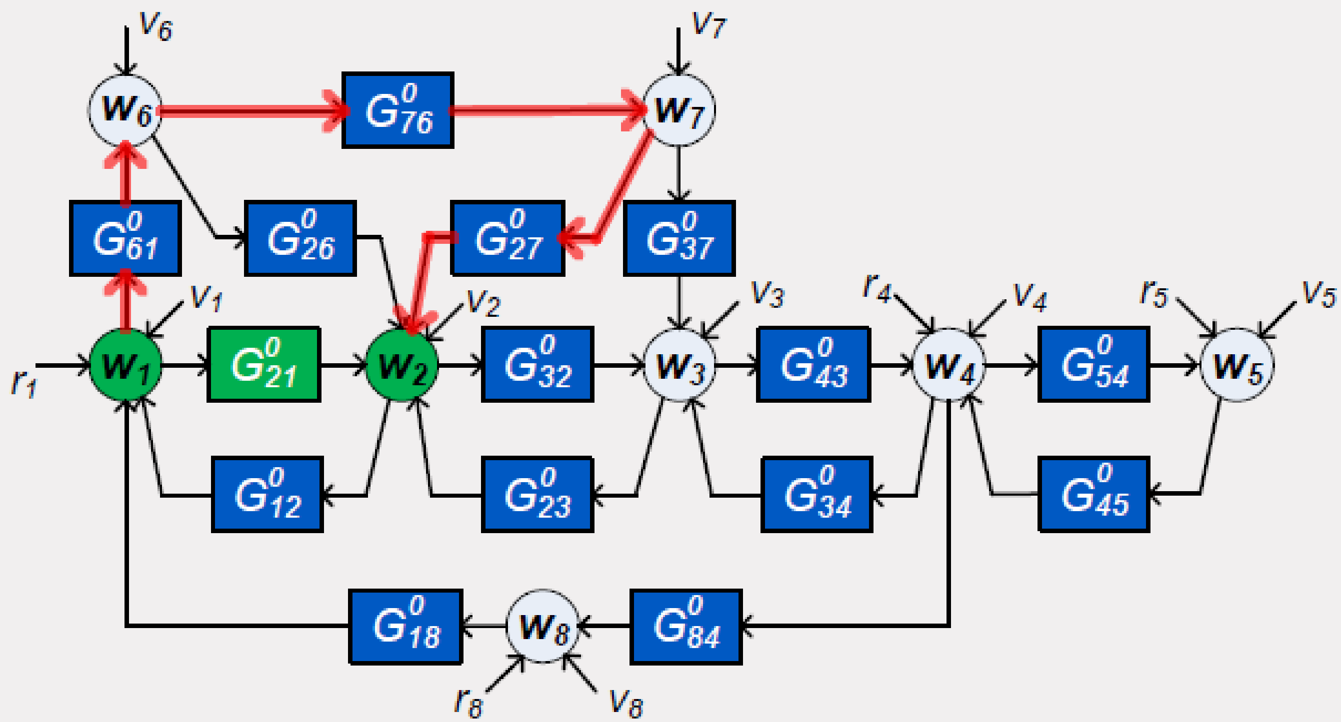


Selection of predictor input signals:

1. All parallel paths from w_1 to w_2 contain an input
2. All loops around w_2 contain an input

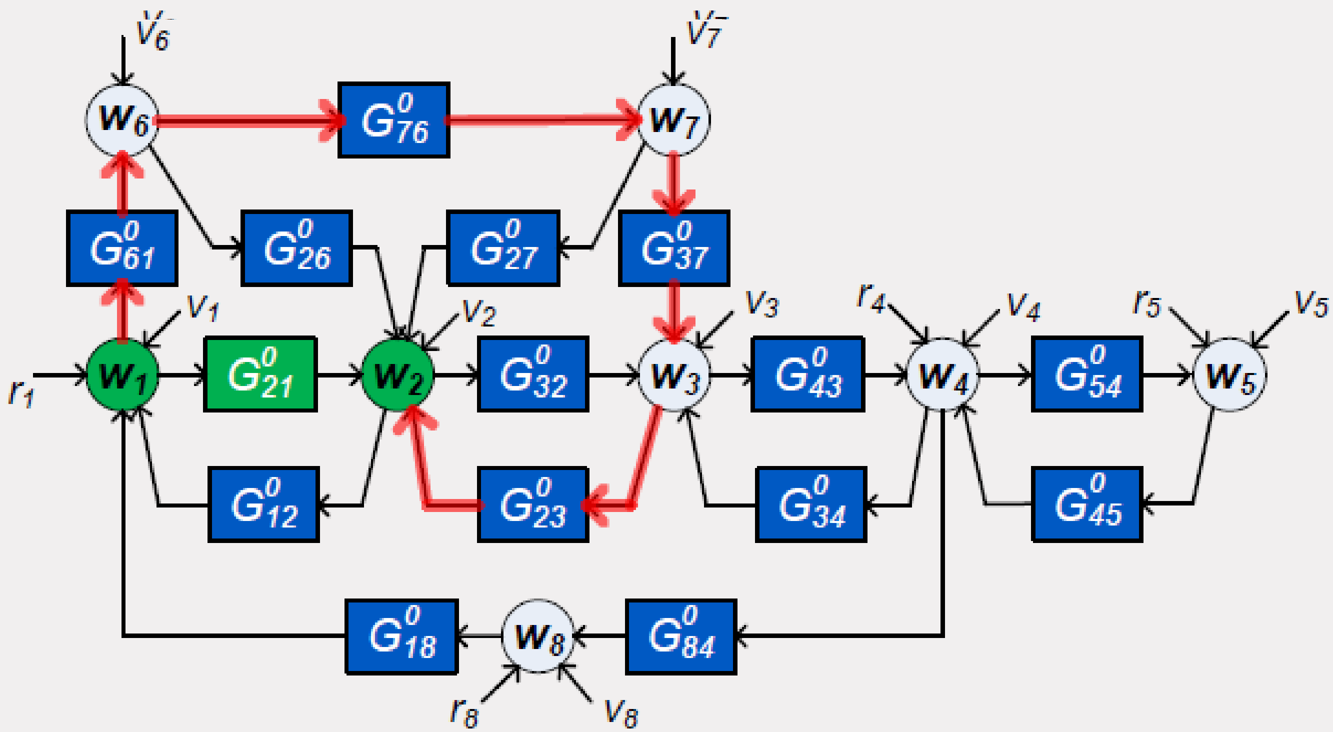
A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

Parallel paths and loops



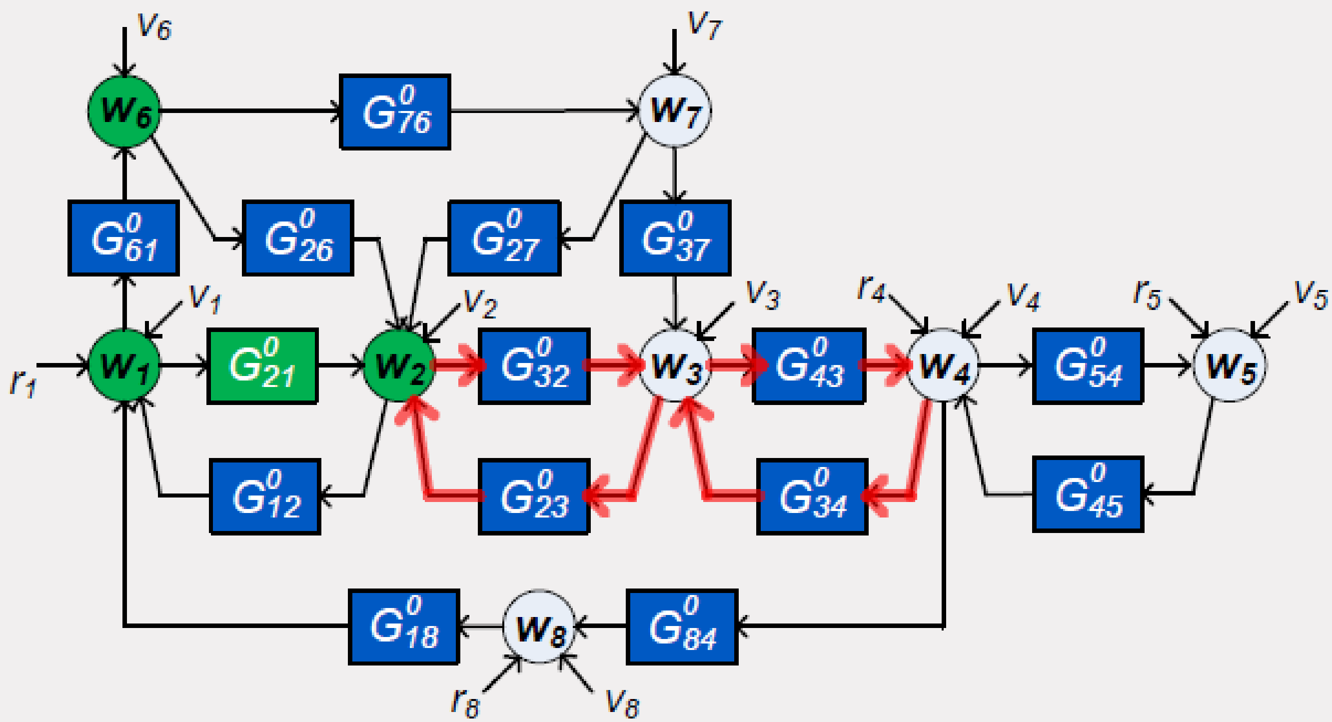
A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

Parallel paths and loops



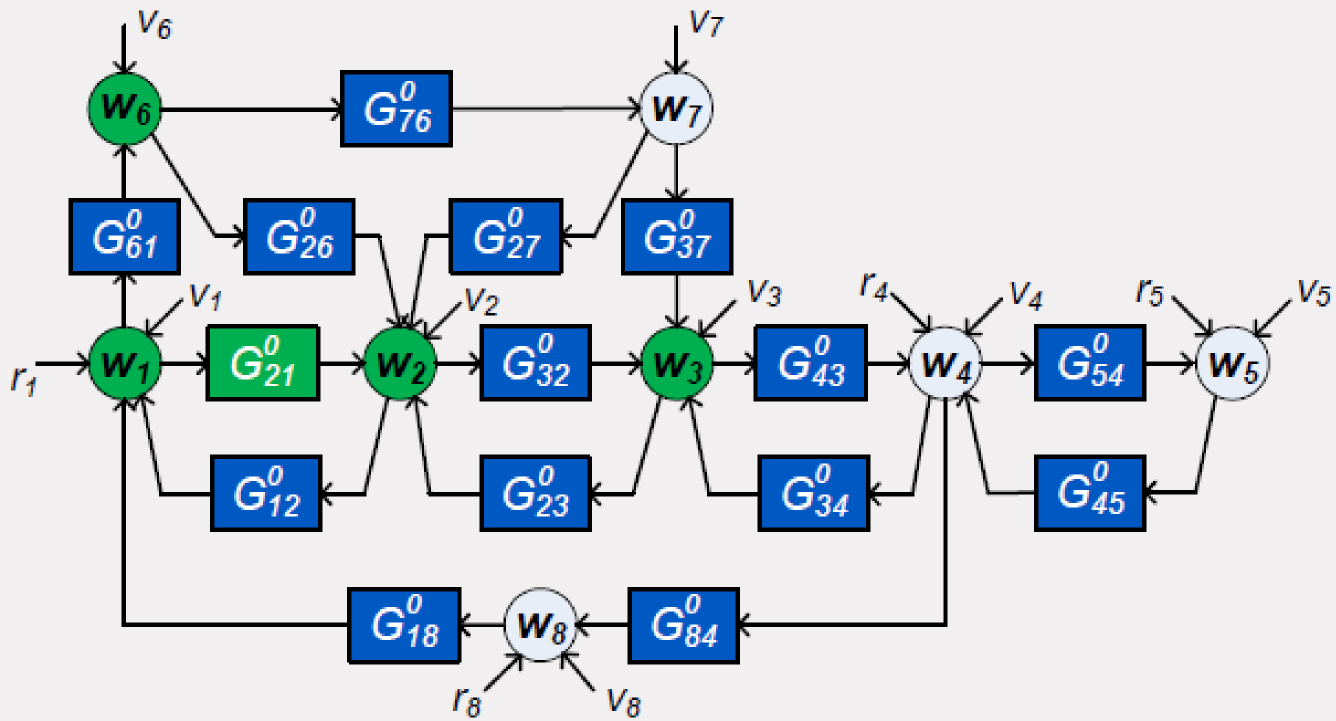
A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

Parallel paths and loops



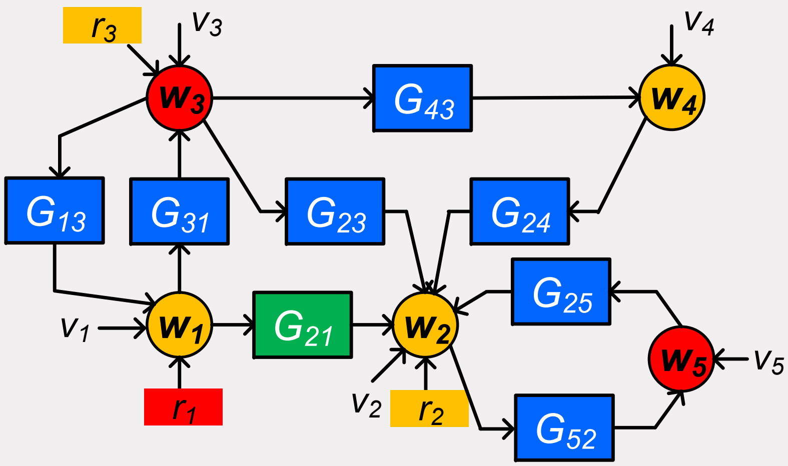
A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

Parallel paths and loops



A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

Example



$$\underbrace{\{w_1, {\color{red}w_3}, {\color{red}w_5}\} \to \{w_2\}}_{Direct\ \ method}{}^{[1]}$$

$$\underbrace{\{{\color{red}r_1}, r_2, r_3\} \to \{w_2, w_3\}}_{indirect\ \ method}{}^{[2]}$$

- What can we do if parallel path/loop conditions cannot be satisfied?
- What can we do if certain nodes cannot be excited?

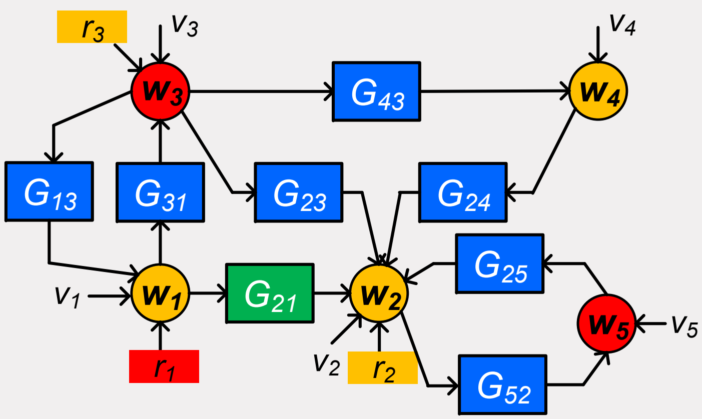
We combine the ideas of direct and indirect methods to relax the restrictive situations on sensing and actuations

[1] A. Dankers *et al*. IEEE Transactions on Automatic Control, 61(4):937–952, 2016.

[2] M. Gevers, et al. In Proc. 18th IFAC Symposium on System Identification (SYSID2018), 2018.

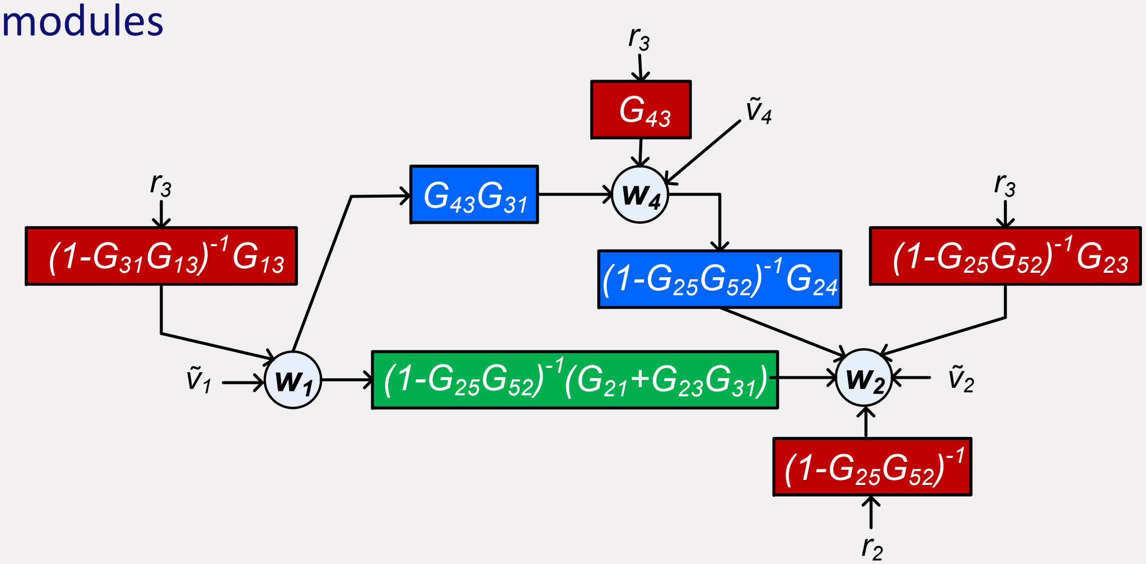
General philosophy

- Include both internal nodes and external excitation as predictor inputs
- Use a MIMO identification approach
- We use "post-processing" of estimated modules

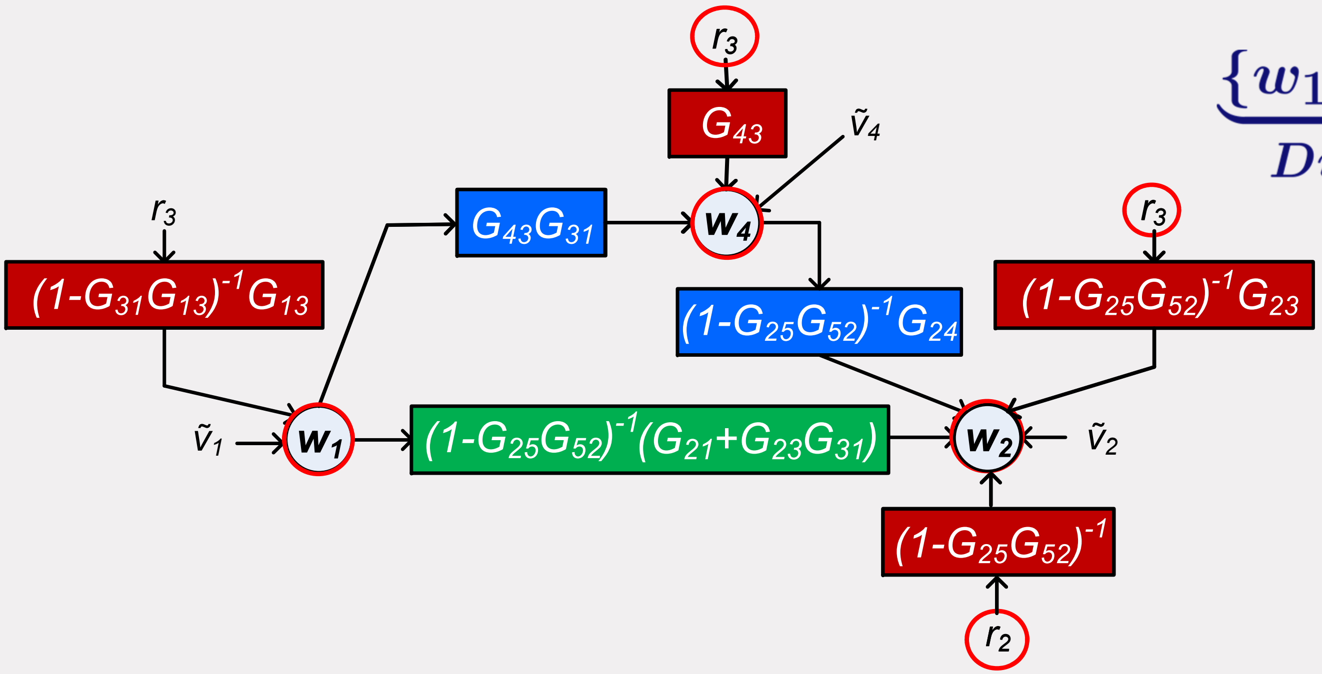


The same example !!!

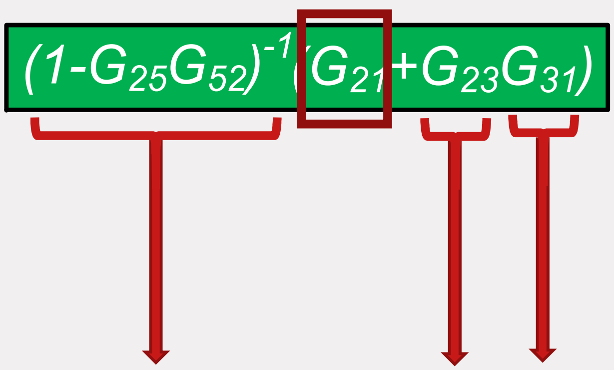
immersion



General philosophy



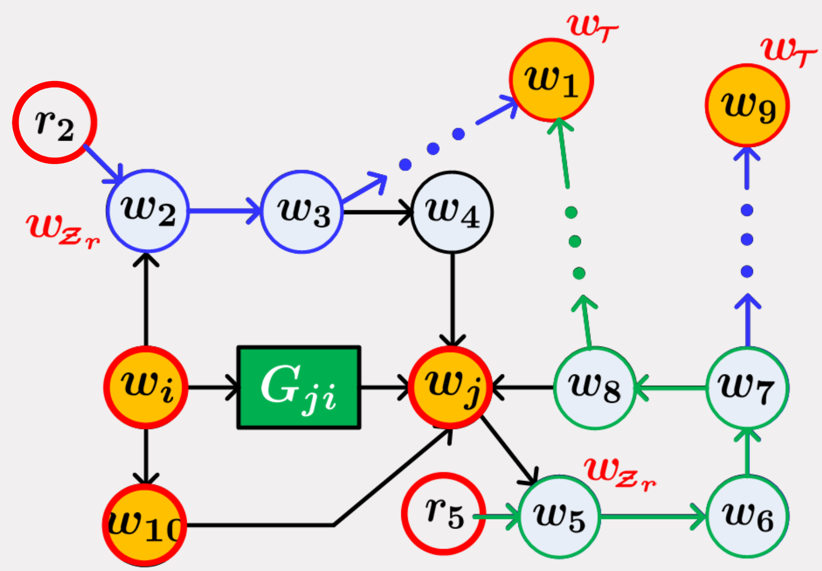
$$\underbrace{\{w_1, w_4, r_2, r_3\} \rightarrow \{w_2, w_4\}}_{Direct\ +\ Indirect\ \ method}$$



How to select the MIMO identification setup?

MIMO identification setup

- Start with input and output of the target module
- Add predictor inputs that block the parallel paths/loops
- Violation of parallel path condition
  - excite the path and add the excitation as input
  - measure a descendent and include in output
- Violation of loop condition and if w_j not excited
  - excite the loop and add the excitation as input
  - measure a descendent and include in output
- Each excitation for parallel path/loops should have at least one independent descendent measured
- Add an output also as input if it has unmeasured paths to any of the outputs



Identification

- $\bar{G}$ and $\bar{R}$ can be consistently estimated using the MIMO identification setup :
  - under persistence of excitation conditions satisfied
  - some delay conditions satisfied
  - all external excitations $\boldsymbol{r}$ are uncorrelated with each other and with noise

- Using the elements of $\bar{G}$ and $\bar{R}$, a consistent estimate of the target module is obtained. Analytical expression is provided in the paper.

- Noise correlations and confounding variables can be handled by adding outputs [1],[2].

[1] K. R. Ramaswamy, *et al*. A local direct method for module identification in dynamic networks with correlated noise. ArXiv.

[2] P. M. J. Van den Hof, *et al*. Local module identification in dynamic networks with correlated noise – the full input case. in CDC 2019.

Summary

- Generalized sensing and actuation scheme for consistent local module identification
- Merger of direct and indirect identification approaches
- Use of external signals and node signals as predictor inputs
- Relaxation of parallel path and loop conditions
- Higher flexibility in choice of signals
- A priori known modules can be accounted for

Generalized sensing and actuation schemes for local module identification in dynamic networks

Karthik R. Ramaswamy , **Paul M.J. Van den Hof, Arne G. Dankers**

k.r.ramaswamy@tue.nl
www.sysdynet.eu

58th IEEE Conference on Decision and Control, Nice, France, December 11-13, 2019

EINDHOVEN UNIVERSITY OF TECHNOLOGY

European Research Council