Fault Detection and Diagnosis using the Dynamic Network Framework

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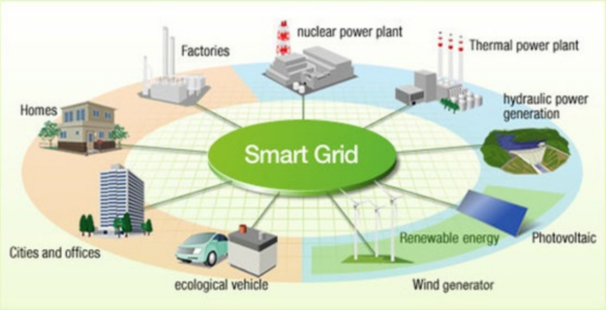
Authors: Yibo Shi, Stefanie J. M. Fonken, Paul M. J. Van den Hof
Presenter: Paul M. J. Van den Hof

European Research Council

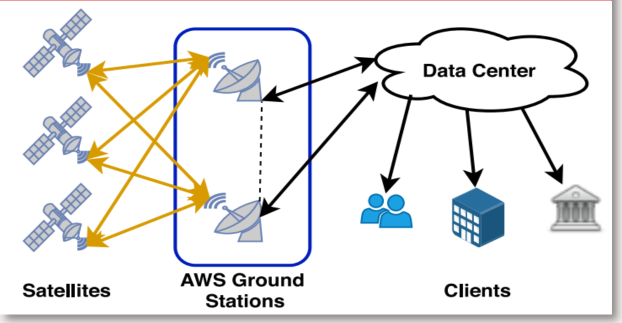
Department of Electric Engineering, Control System Group
EINDHOVEN UNIVERSITY OF TECHNOLOGY

Large-scale network systems

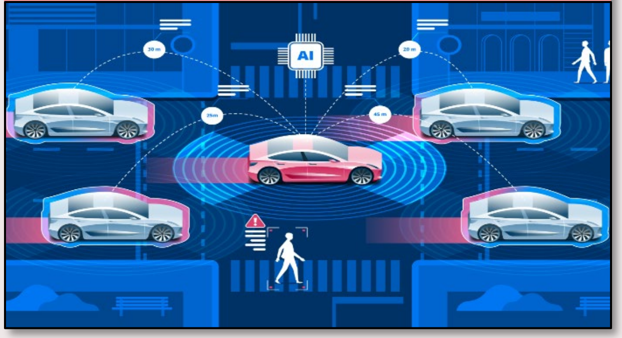
Power grid [1]

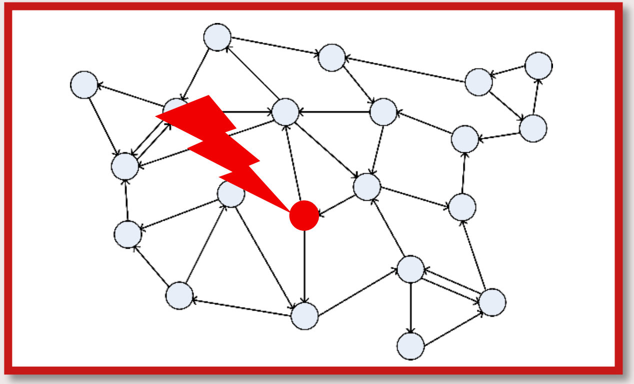


Satellite communication [2]



Autonomous driving network





[1] www.marketexpert24.com
[2] O. Kodheli et al., IEEE Communications Surveys & Tutorials, 2020

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Fault detection and diagnosis (FDD)

FDD methods become challenging as the size and complexity of the systems grow

Model-free FDD methods:

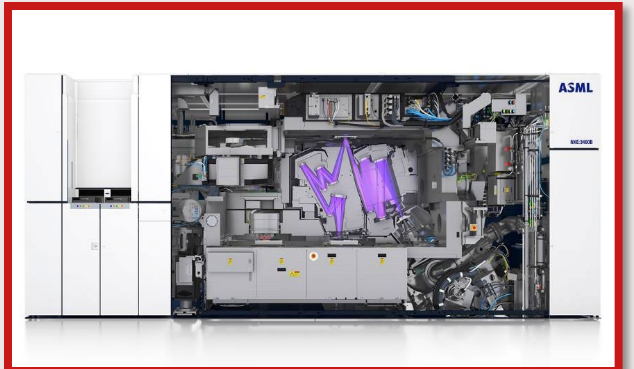
- *Data-driven: AI & machine-learning* [1]
- *Knowledge-based methods* [2]

Not explainable

Heavily rely on data

Model-based FDD methods:

- *State observer, parameter estimation* [3], [4]
- *Residual analysis*



[5]

Challenge

- ***Exploit interconnection structure***

[1] G. Milis et al., IJCNN, 2016
[2] M. He et al., IEEE Transactions on Smart Grid, 2011
[3] S. Simani, *Model-based fault diagnosis*, 2003
[4] R. Isermann, *Fault detection and diagnosis*, 2006
[5] D. Nikitas

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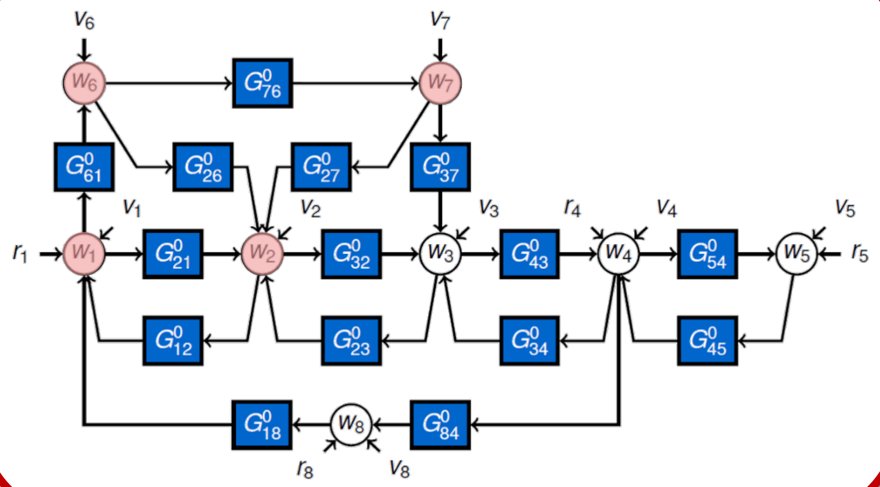
Dynamic network framework

Dynamic network setup:

- $w_i(t)$: *measured node signals*
- G_{ij}^0: *modules, LTI transfer functions*
- $v_i(t) = H_i^0 e_i(t)$: *process noise signals*
- $r_i(t)$: *external excitation signals*

Dynamic network identification:

- *Local module or full network identification* [1-6]

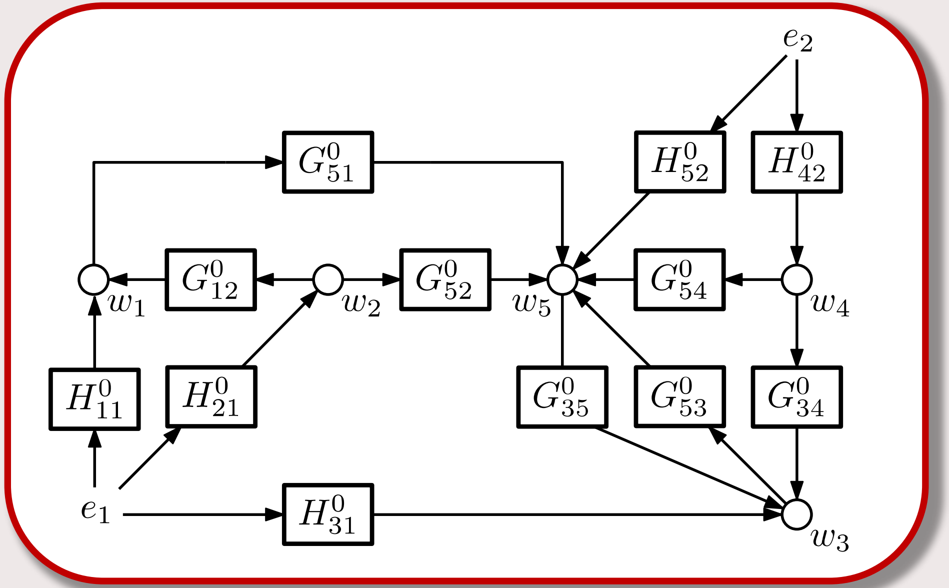


When given a model of a dynamic network, can we detect and diagnose a fault in a local module by confronting the model with the data of the faulty system (including probing the faulty system)?

[1] P. Van den Hof et al., Automatica, 2013
[2] A. Dankers et al, IEEE-TAC, 2016
[3] H. Weerts et al. Automatica, 2018
[4] M. Gevers, SYSID, 2018
[5] K. Ramaswamy et al., TAC, 2021
[6] S. Fonken et al., Automatica, 2022

Research question and problem statement

*How to perform **local fault detection and diagnosis** for an interconnected **network system**, using its model in the **dynamic network framework**?*



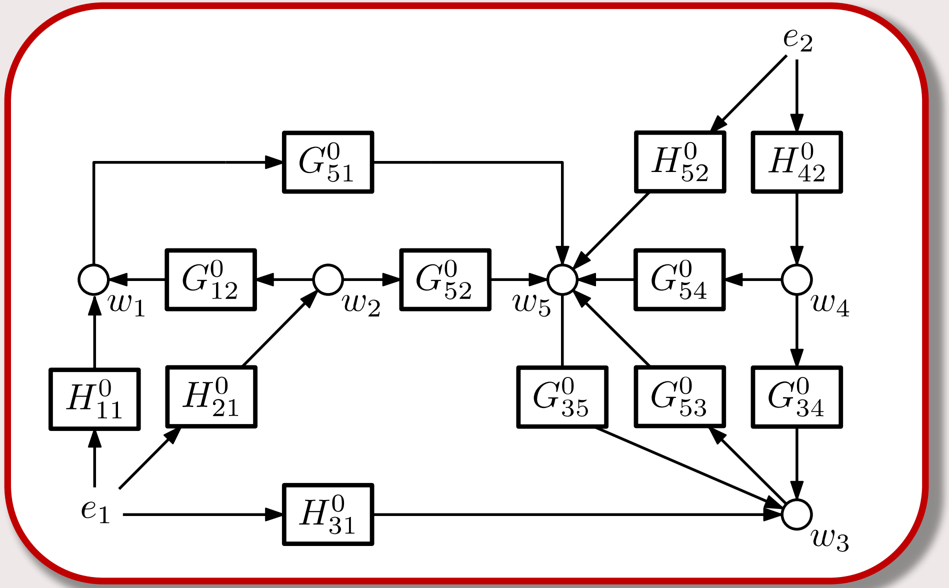
Start point:

- *A fault is $G^0_{ji} \rightarrow G^f_{ji}$*
- *Local subnetwork model $\hat{G}$*
- *Full network topology $\mathcal{T}_G$*
- *Possible noise information:*
  - *Noise model H^0*
  - *Noise topology $\mathcal{T}_H$*

Assumption: *Every node in w is affected by a single noise source e only.*

Research question and problem statement

*How to perform **local fault detection and diagnosis** for an interconnected **network system**, using its model in the **dynamic network framework**?*



Model-based FDD

↓

Model invalidation

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Residual analysis

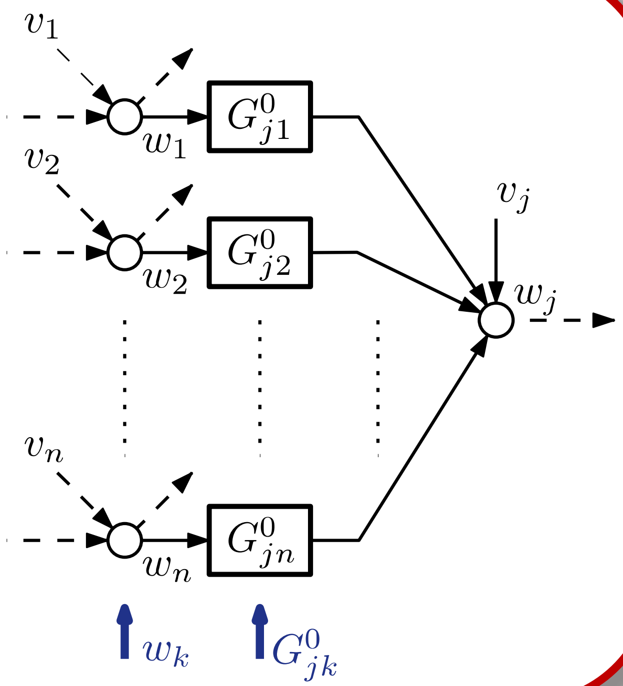
Contents

Residual in a local node

MISO Subnetwork

Prediction Error

In-neighbor nodes of w_j in set $\mathcal{N}_j$



$\hat{\varepsilon}_j := w_j - \hat{w}_j$

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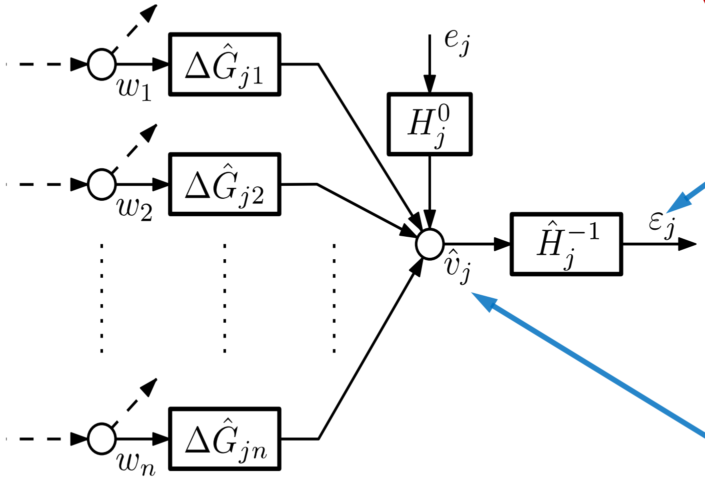
Residual in a local node

MISO Subnetwork

Prediction Error

In-neighbor nodes of w_j in set $\mathcal{N}_j$



$$\Delta\hat{G}_{jk} = G^0_{jk} - \hat{G}_{jk}$$

With noise model $\hat{H}_j$

$\hat{\varepsilon}_j := w_j - \hat{w}_j$

No noise model $\hat{H}_j$

Residual analysis for model validation: Correlation test

Null Hypothesis $\mathcal{H}_0 : \widehat{G} = G^0$

SISO System

Test statistics [1]:

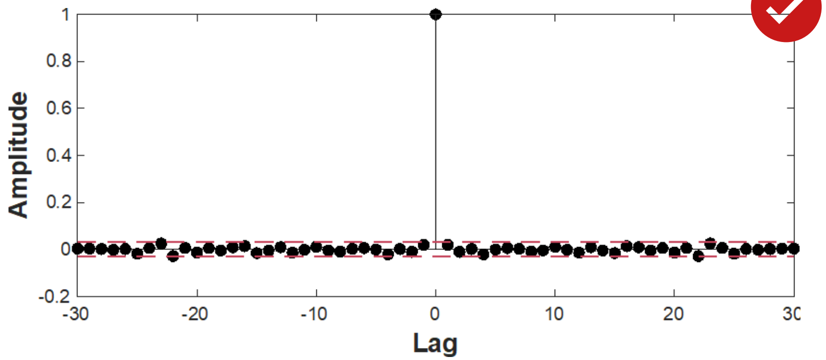
- *Autocorrelation* $R_{\hat{\varepsilon}}(\tau)$
- *Cross-correlation* $R_{\hat{\varepsilon},u}(\tau)$

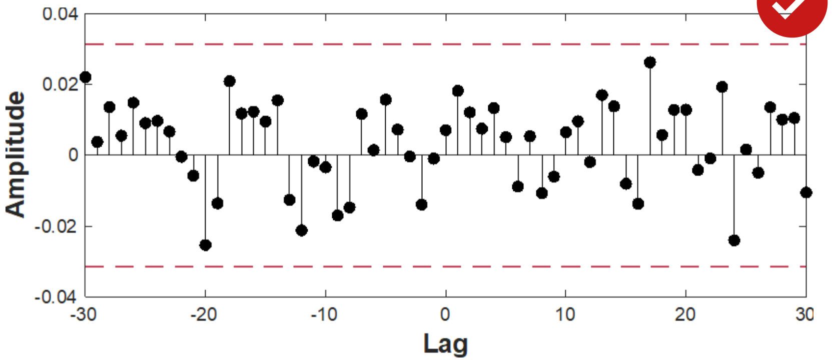
Accept $\mathcal{H}_0$

- $R_{\hat{\varepsilon}}(\tau)$, $R_{\hat{\varepsilon},u}(\tau)$ ***Uncorrelation***

Reject $\mathcal{H}_0$

- $R_{\hat{\varepsilon}}(\tau)$, $R_{\hat{\varepsilon},u}(\tau)$ ***Correlation***



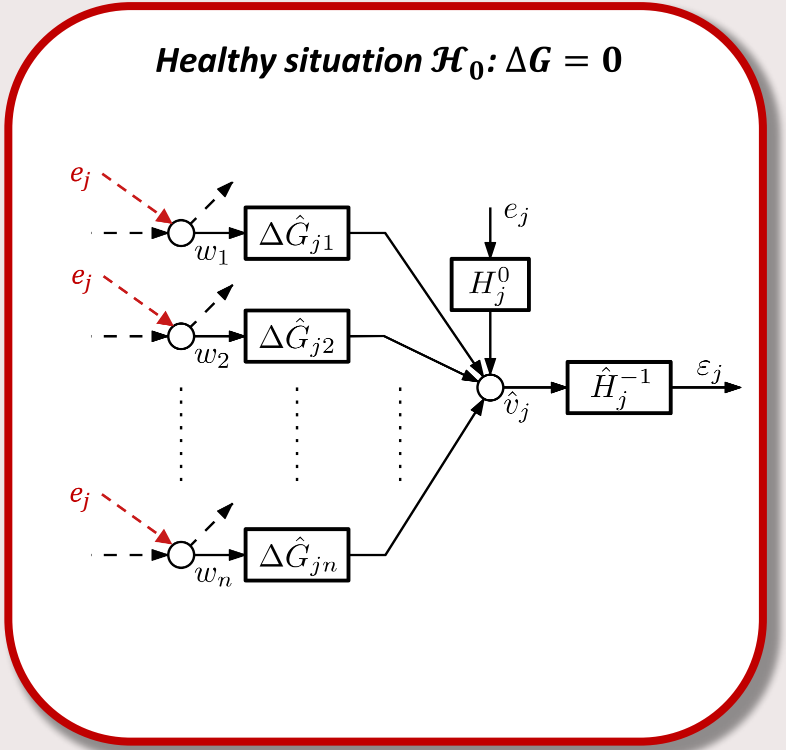


[1] L. Ljung, *System Identification: Theory for the User*, 1999

Correlation tests for dynamic networks

- *Autocorrelation test:* R_{ε_j}
- *Cross-correlation test:* $R_{\varepsilon_j w_i}$
- *Cross-correlation test:* $R_{\varepsilon_j r_i}$

If the noise model is not available then the cross-correlations, $R_{\varepsilon_j r_i}$, $R_{\varepsilon_j w_i}$ ***are replaced by*** $R_{v_j r_i}$, $R_{v_j w_i}$



Correlation tests for dynamic networks

- *Autocorrelation test: R_{ε_j}*
- *Cross-correlation test: $R_{\varepsilon_j w_i}$*
- *Cross-correlation test: $R_{\varepsilon_j r_i}$*

(a) Noise model $\hat{H}_j$ and noise topology $\mathcal{T}_H$

- R_{ε_j}, $R_{\varepsilon_j w_i}$, $R_{\varepsilon_j r_i}$

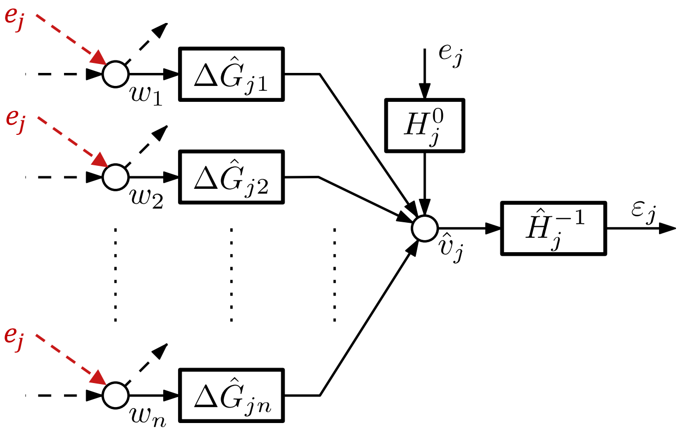
(b) Noise topology $\mathcal{T}_H$

- *Some* $R_{\varepsilon_j w_i}$, $R_{\varepsilon_j r_i}$

(c) No noise information

- $R_{\varepsilon_j r_i}$

Healthy situation $\mathcal{H}_0$: $\Delta G = 0$



Target module set $\mathcal{S}$:

The set that contains all modules related to a correlation test.

Test is passed → *Target modules validation*

Test fails → *Invalidation among target modules*

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Target module sets

- ***Autocorrelation test*** R_{ε_j} : $\mathcal{S}_{\hat{\varepsilon}_j} = \{G_{jk} \mid k \in \mathcal{N}_j\}$
- ***Cross-correlation test*** $R_{\varepsilon_j w_i}$: $\mathcal{S}_{\hat{\varepsilon}_j w_i} = \mathcal{S}_{\hat{v}_j w_i} = \{G_{jk} \mid k \in \mathcal{N}_j \cap \mathcal{C}_i\}$
- ***Cross-correlation test*** $R_{\varepsilon_j r_i}$: $\mathcal{S}_{\hat{\varepsilon}_j r_i} = \mathcal{S}_{\hat{v}_j r_i} = \{G_{jk} \mid k \in \mathcal{N}_j \cap \mathcal{J}_i\}$

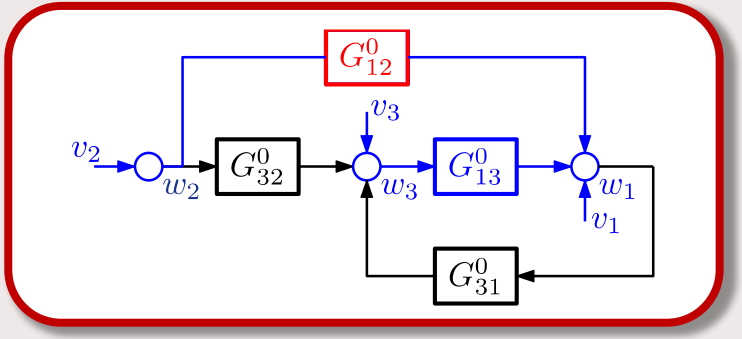
- $\mathcal{C}_i$: *the set of all node signals that are correlated with* w_i
- $\mathcal{J}_i$: *the set of node indices k, including i, for which a directed path exists from* w_i *to* w_k

Target module sets / Noise information / Tests	(a) $H_j^0(q)$ & $\mathcal{T}_H$	(b) $\mathcal{T}_H$	(c) None
Autocorrelation test with $\hat{\varepsilon}_j$	$\mathcal{S}_{\hat{\varepsilon}_j}, \forall j$	$\emptyset$	$\emptyset$
Cross-correlation test with $\hat{\varepsilon}_j$ (or $\hat{v}_j$) and w_i	$\mathcal{S}_{\hat{\varepsilon}_j w_i}, i \in \mathcal{N}_j$	$\mathcal{S}_{\hat{v}_j w_i}, i \in \mathcal{N}_j \setminus \mathcal{V}_j$	$\emptyset$
Cross-correlation test with $\hat{\varepsilon}_j$ (or $\hat{v}_j$) and r_i	$\mathcal{S}_{\hat{\varepsilon}_j r_i}, i \in \mathcal{N}_j$	$\mathcal{S}_{\hat{v}_j r_i}, i \in \mathcal{N}_j$	$\mathcal{S}_{\hat{v}_j r_i}, i \in \mathcal{N}_j$

- $\mathcal{V}_j$: *the set of node indices k, for which a path exists from the innovation source e of* w_j

Contents

Example



Detect/diagnose possible fault in G_{12}

$\mathrm{j} = 1 \quad \mathcal{N}_1 = \{2,3\} \quad \mathcal{V}_1 = \{1\}$

$\mathcal{C}_2 = \mathcal{J}_2 = \{1,2,3\} \quad \mathcal{C}_3 = \{1,2,3\} \quad \mathcal{J}_3 = \{1,3\}$

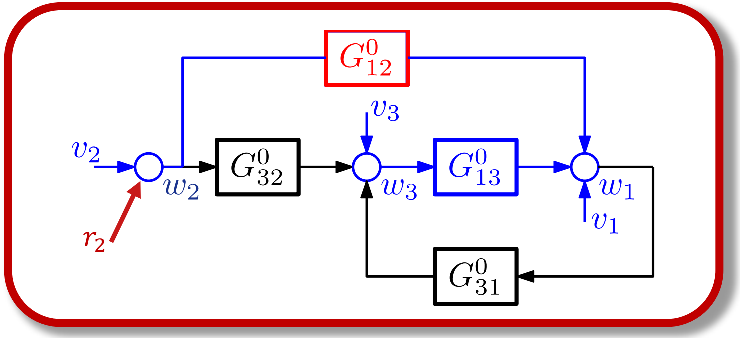
Available tests	R_{ε_1}	$R_{\varepsilon_1 w_2}$	$R_{\varepsilon_1 r_2}$	$R_{\varepsilon_1 r_3}$	…
Target module sets	$\{G_{12}, G_{13}\}$	$\{G_{12}, G_{13}\}$	$\{G_{12}, G_{13}\}$	$\{G_{13}\}$	…

Adding r_2 ***does not help, but adding*** r_3 ***allows for diagnosis of the correct fault.***

Example

Experiments with different noise information:

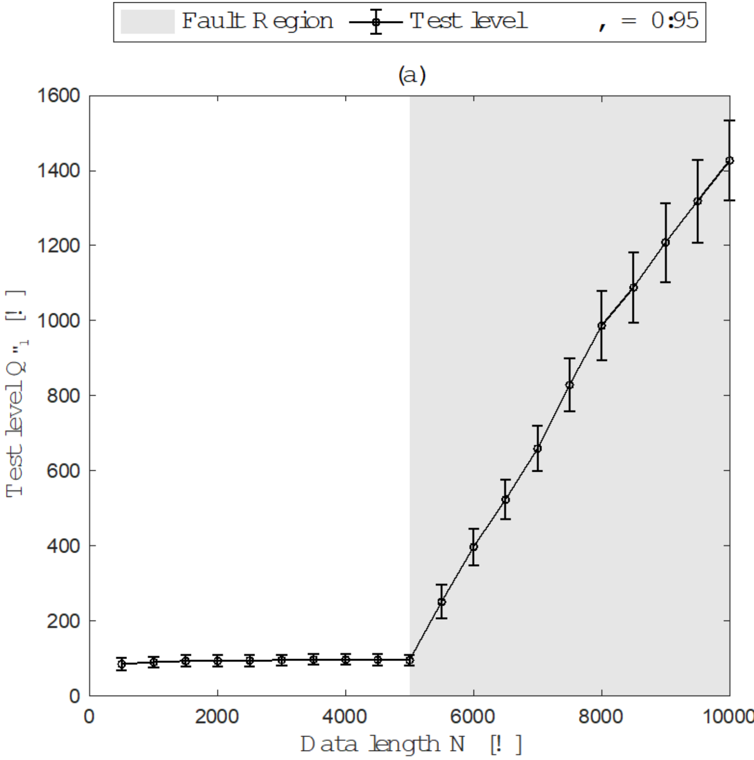
- *(a) With noise model $\widehat{H}_1$ and noise topology $\mathcal{T}_H$:* R_{ε_1}
- *(b) With noise topology $\mathcal{T}_H$:* $R_{\varepsilon_1 w_2}$
- *(c) No noise information:* $R_{\varepsilon_1 r_2}$



100 MC runs

All tests show fault after $N = 5000$

Fault location?



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Vector valued correlation test:

The Correlation test using statistic Q (Q test):

If $\mathcal{H}_0$ is true, it follows from a variant of the central limit theorem that the following distribution holds[1]*:*

$$Q_a(N,M) = \frac{N}{\left(R^N_{\hat{\varepsilon}_j}(0)\right)^2} \sum_{\tau=1}^{M} \left(R^N_{\hat{\varepsilon}_j}(\tau)\right)^2 \sim As\ \chi^2(M)$$

The autocorrelation test is for $\mathcal{H}_0$ is:

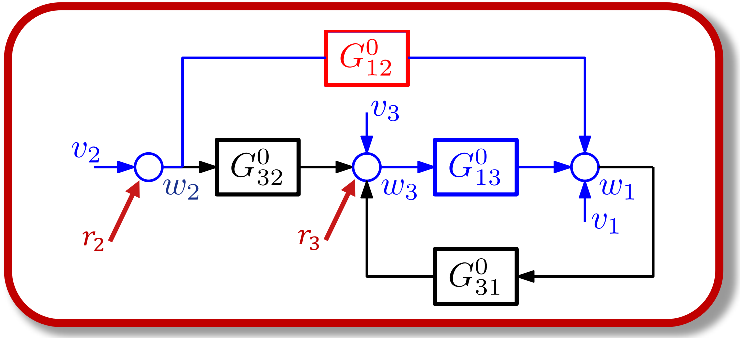
$$\begin{cases} \text{if } Q_a(N,M) \leq c_\chi(\alpha, M), \text{ then accept } \mathcal{H}_0 \\ \text{otherwise, reject } \mathcal{H}_0 \text{ with a risk equal to } \alpha \end{cases}$$

[1] S. Douma et al., Automatica, 2008

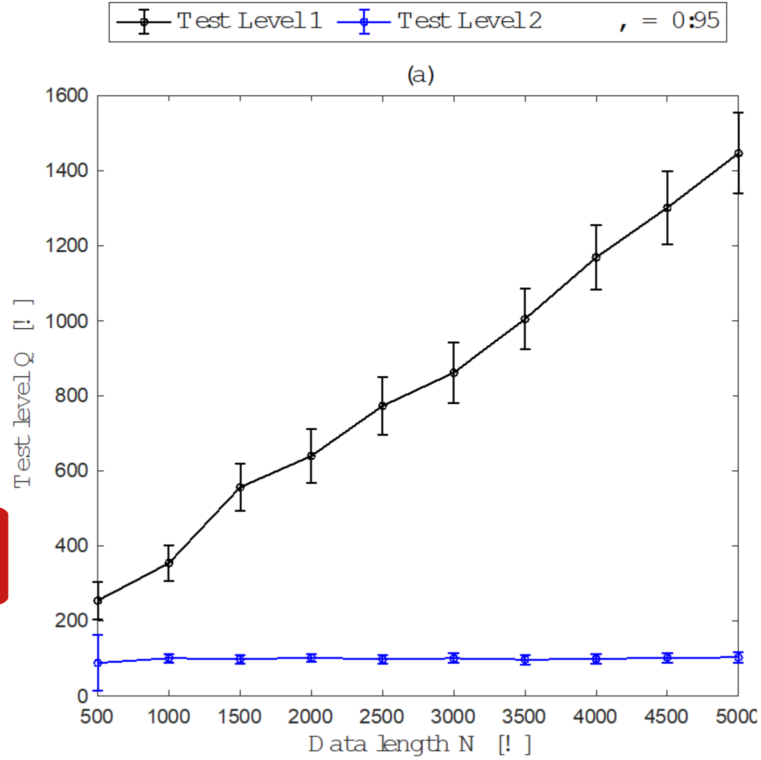
Example

Experiments with different noise information:

- *(a) With noise model $\widehat{H}_1$ and noise topology $\mathcal{T}_H$: R_{ε_1} , $R_{\varepsilon_1 r_3}$*
- *(b) With noise topology $\mathcal{T}_H$: $R_{\varepsilon_1 w_2}$, $R_{\varepsilon_1 r_3}$*
- *(c) No noise information: $R_{\varepsilon_1 r_2}$, $R_{\varepsilon_1 r_3}$*



Fault on G_{12}



The selection of the appropriate tests for a particular target module can be automated

Conclusion

*How to perform **local fault detection and diagnosis** for an interconnected **network system**, using its model in the **dynamic network framework**?*

- Designed model-based **procedure** for local MISO subnetwork FDD
- that can exploit topology information on the network
- It shows how to (in)validate local modules in a network
- and indicates whether it is attractive/necessary to add excitation signals for diagnosis.

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Thanks for your attention!

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