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Resilient Sensor Placement for Faults and Attacks in Water Distribution Networks

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Motivation

Motivation:

* Leakages in urban water networks can cause huge economic losses, and health risks.
* Sensors for network monitoring are vulnerable to cyber attacks

Objective:

Sensor placement for an efficient and **resilient localization** of pipe failures in the presence of faults and attacks.

Challenges:

Pipe failure uncertainty, budget constraints, sensor errors, event detection and localization.

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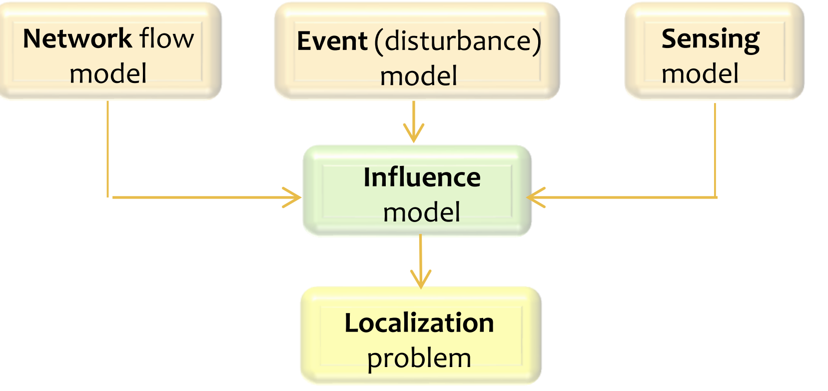
Contributions

Previous Work:

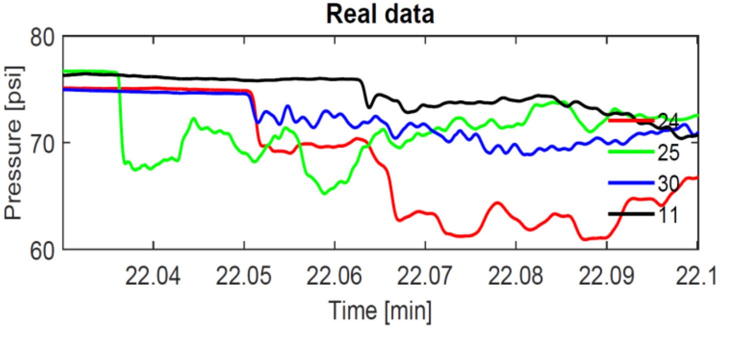
* Using combinatorial optimization, an efficient sensor placement algorithm for the localization of failure events in water networks. *(Automatica 2016)*
* Improved localization through multi-level sensing *(ACM BuildSys 2015)*



Current

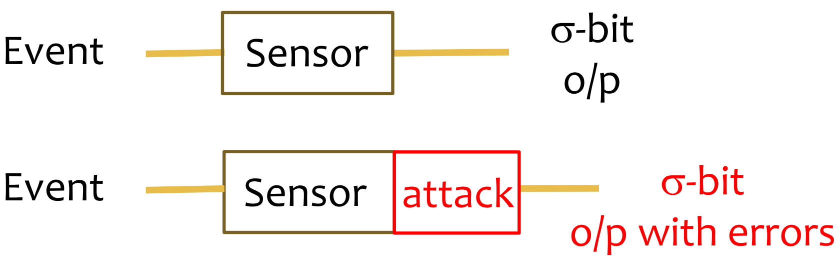
* Localization in the presence of sensor errors (faults and attacks)

W. Abbas, L. Perelman, S. Amin, and X. Koutsoukos, "Resilient Sensor Placement for Fault Localization in Water Distribution Networks" ***(ACM/IEEE ICCPS 2017)***



Attacks and Faults Resulting in Sensor Errors

Single sensor error



Error (attack): One or more of the output bits are flipped.

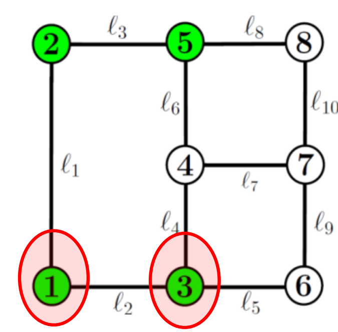
Error Sources: Sensor degradation, Cyber attacks

- At most e sensors can give incorrect outputs.
- The error model can be used to model a class of attacks in which an attacker takes control of at most e sensors and changes their output in any possible way.

Multiple sensors errors

Given a set of m sensors, at most e of them can give incorrect outputs for an event.

Example:



e = 2

Sensors	S_1	S_2	S_3	S_5
Correct o/p	0 1	1 0	0 0	0 0
Possible o/p with 2 errors	1 0	1 0	1 1	0 0
	…	…	…	…

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Problems

Problem 1: (Resilient Sensor Placement)
How to place **m** sensors, each with a σ-bit output, to maximize the number of events that can be localized accurately, even if **e** of the deployed sensors give errors? At the same time, how can we evaluate such a sensor placement in water distribution networks?

	Explanation
m	No. of sensors
σ	No. of output bits (features)
e	No. of erroneous sensors
L	Localization performance

Problem 2: (Tradeoffs Between System Variables)
What is the trade-off between **m, e, σ**, and the localization performance in the context of sensor placement for fault localization. In particular, fixing any two variables, what is the relationship between the remaining two?

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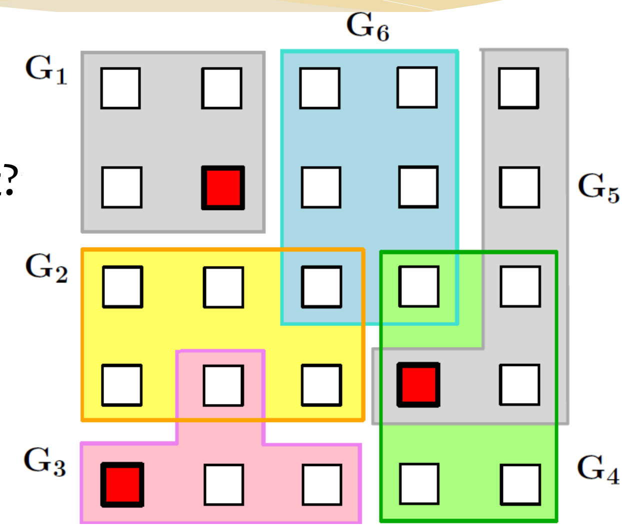
Non-adaptive Group Testing (NAGT) and Resilient Sensor Placement

Group Testing (GT):

- Set of elements with some defective ones.
- Elements are divided into groups.
- Questions are asked, "If G_i contains a defective element?
- Answers are either "yes" or "no".

Non-adaptive GT: All groups are made a priori.

Non-adaptive GT with Unreliable Tests: Some questions may be answered incorrectly.



Objective:

Design groups (queries) so that defective elements could be identified by asking the minimum number of queries.

Results:

Various results are known, e.g., at least $O((d^2/\log d)\log n)$ queries are always required, and there exist schemes that can achieve NAGT in $O(d^2 \log n)$ queries, e.g., *(Macula 1997, Porat and Rothschild 2011, Mazumdar and Mohajer 2014)*

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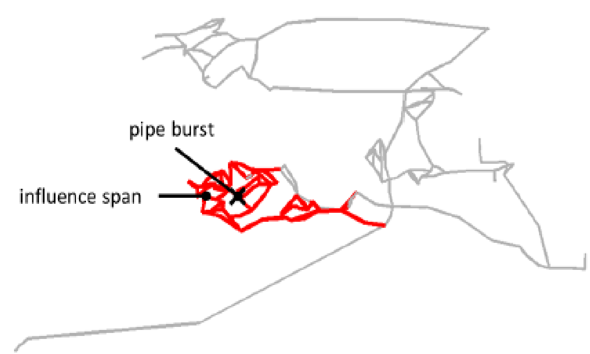
NAGT and Resilient Sensor Placement- Impact of physical dynamics

NAGT		Resilient Sensor Placement
Elements	→	Pipes
Defective elements		Pipes with bursts and leakages
Groups		Sensors
Tests (queries)		Sensors outputs
Unreliable tests		Sensors outputs with errors

However, there is a major difference.

- Typically in NAGT, any set of elements can be grouped together to make a test.
- In sensor placement, groups (tests) are coming from the physical system, i.e., any set of pipes cannot be grouped together.



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Localization with Sensor Errors

Events	S_1	S_2	S_3	S_4	…	…	S_{total}
Pipe 1	0 0 0 1	1 0 0 1	1 0 1 0	0 1 0 1	…	…	1 1 1 0

Events	S_1	S_4	…	S_m
Pipe 1	0 0 0 1	0 1 0 1	…	0 1 0 1

← Signature of pipe 1 failure.

At most e sensors can be erroneous.

Two events can be distinguished in the presence of at most **e erroneous sensors** as long as the hamming distance between their signatures is at least **(2e + 1).**

Therefore, select sensors such that pairs of signatures that are at least (2e+1) hamming distance away from each other is maximized.

Set Multi-Cover for Localization with Errors

Pair-wise influence matrix:

Pair-wise events	S_1	S_2	S_3	S_4	…	S_{total}
Pipes (1,2)						

Set Multi-Cover Problem

Given a set of elements L, and a collection C of subsets of L. Select the minimum number of subsets in C such that each element in L is contained in at least k of selected subsets. For our problem, k = 2e+1.

* Simple greedy gives (1+ln a)-approximation algorithm *(Vazirani 2001)*
* A randomized algorithm with an approximation ratio *(Berman et al. 2007)*

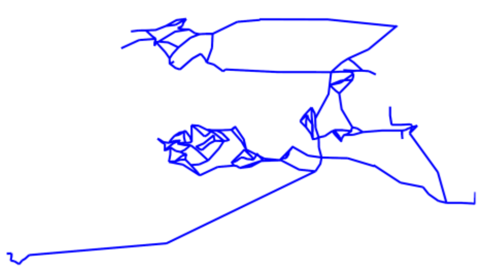
$$(1 + o(1)) \ln (a / k) \quad \text{if } (a / k) \geq 7.39$$

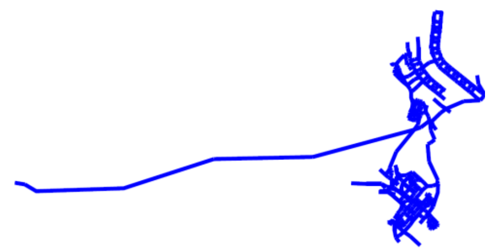
$$1 + 2(a / k)^{1/2} \quad \text{if } (a / k) < 7.39$$

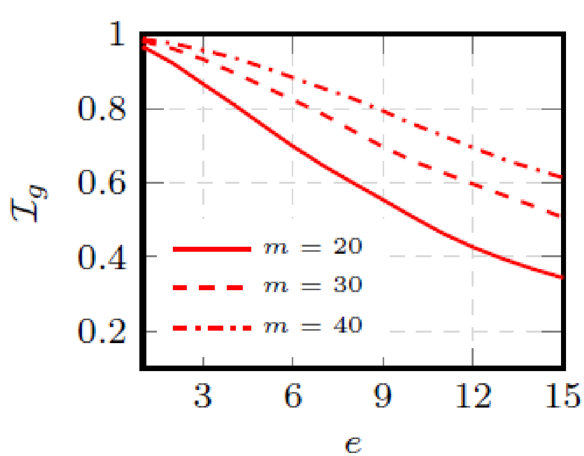
We solve the set multi-cover problem on the pair-wise influence matrix.

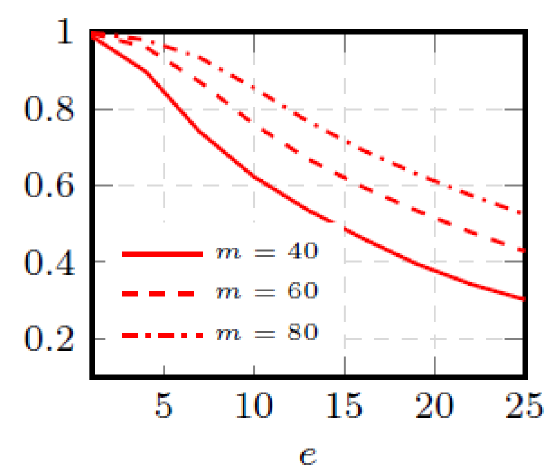
Numerical Evaluation

Generalized Identification Score:









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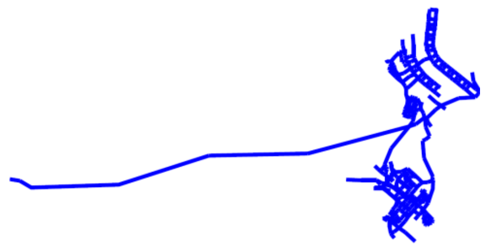
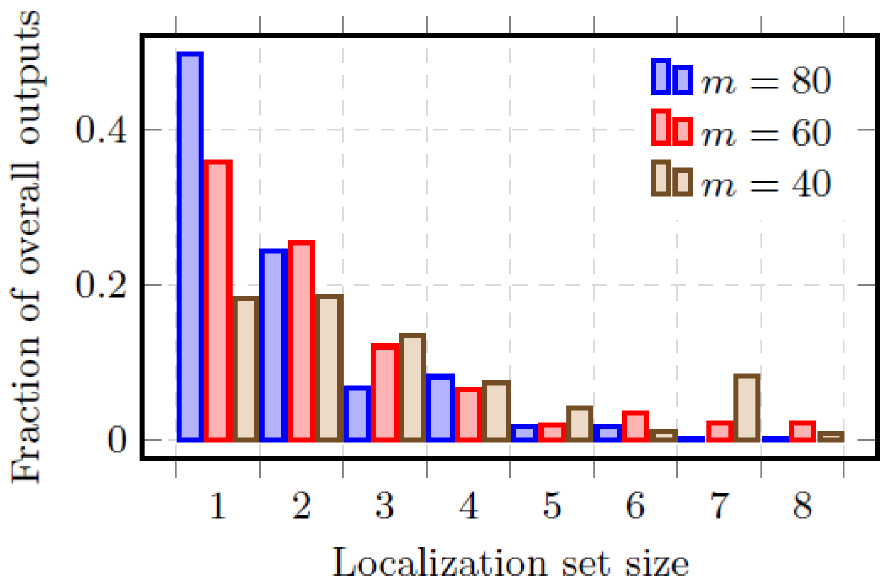
Numerical Evaluation

Localization Set Size:





The percentage of outputs that have localization sets of size at most 5 is about 90%, 80%, and 58% for m = 80, 60, and 40 respectively.

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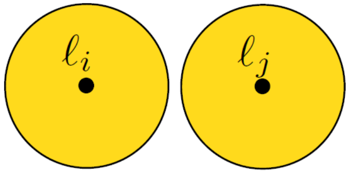
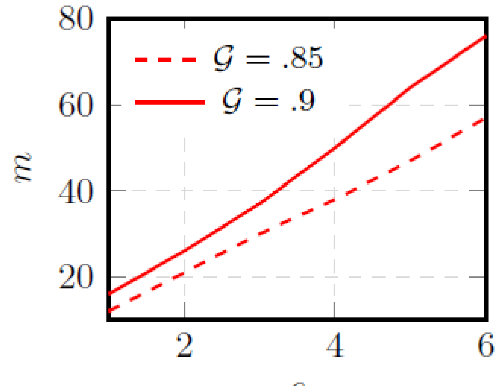
Numerical Evaluation

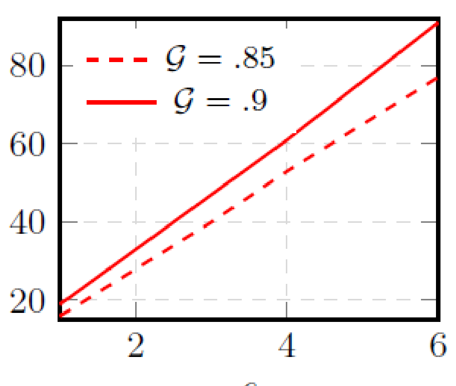
G = fraction of pair-wise events whose signatures are at least (2e+1) hamming distance apart.



For a fixed G, the ratio e/m (approximately) remains the same, i.e., m increases almost linearly with e.



(a) Water network 1



(b) Water network 2

Example:
In water network 2,
For G = .85, the ratio e/m = .08,
and for G = 0.9, e/m = .065

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Thank you