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Resilient Fault Localization in Water Networks Using Multi-level Sensing

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Resilient Localization of Leakages in Water-Distribution Networks

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 cyber-attacks.

Challenges:

Pipe failure uncertainty, budget constraints, sensor errors etc.

Contributions:

- 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)***
- Localization in the presence of sensor attacks (errors)

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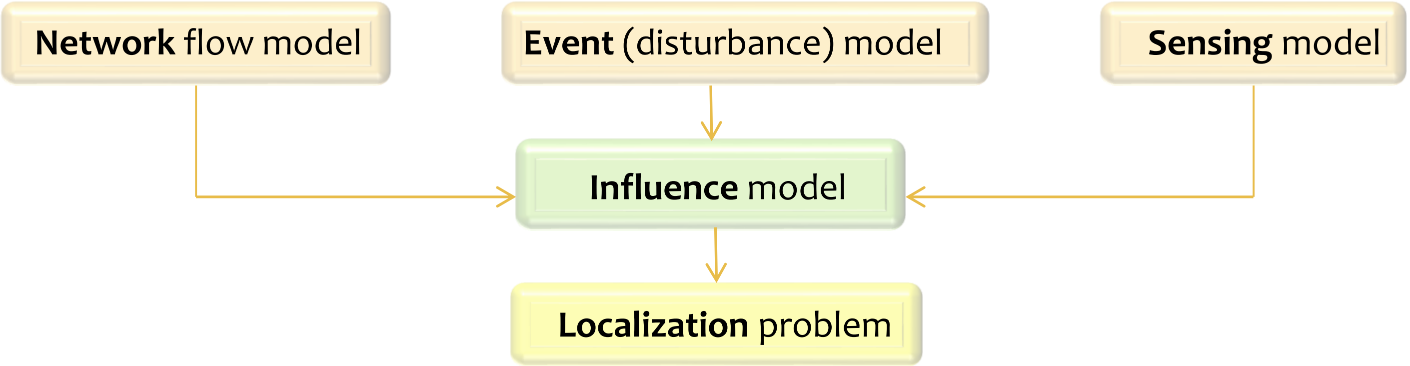
Localization of Failure Events



Network flow model

Event (disturbance) model

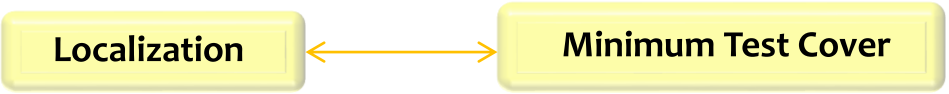
Sensing model

Influence model

Localization problem

Localization Problem:

Find the minimum number of sensors and their locations so that the maximum number of link failures can be uniquely detected and can be distinguished from one another.



Localization

Minimum Test Cover

NP-hrad

To solve the minimum test cover problem, we proposed an approximate algorithm that is faster as compared to the other known solutions. (Automatica 2016)

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Localization Using Multi-level Sensing

In **single-level sensing (1-bit),** output of the sensor is

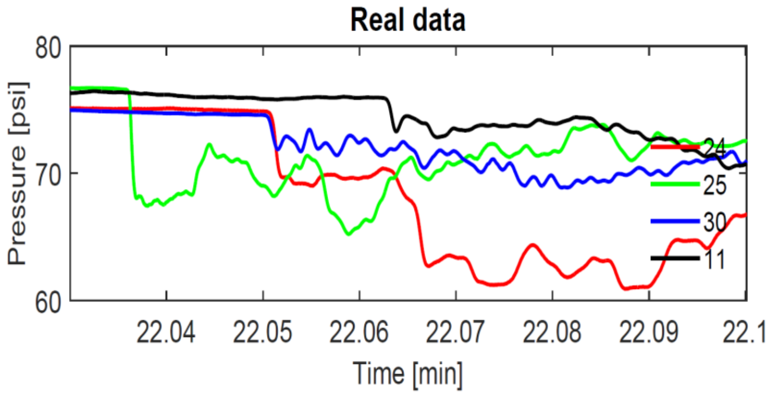
$$\begin{cases} 1 & \text{if failure event is detected, or} \\ 0 & \text{otherwise.} \end{cases}$$

In **multi-level sensing (σ - bit)** , a sensor in case of detection, captures some *extra information* about the failure event, such as time taken to detect the event etc.

Output of sensor consists of *multiple bits*.

Case: Bi-level sensing

$$\begin{cases} 0 \quad 0 & \text{failure event is not detected,} \\ 1 \quad 0 & \text{event is detected early, i.e., in } [0 \quad t1) \\ 0 \quad 1 & \text{event is detected later, i.e., in } [t1 \quad T] \end{cases}$$



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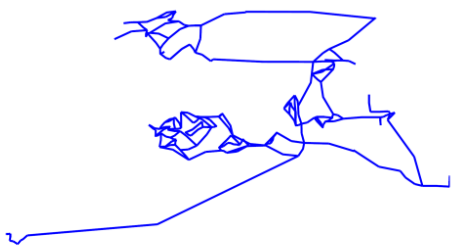
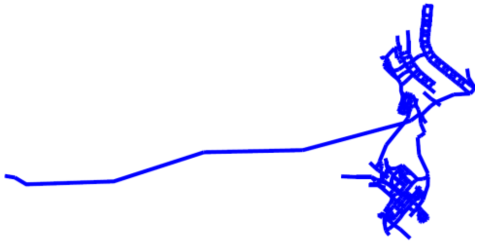
Simulations: Bi-Level Sensing

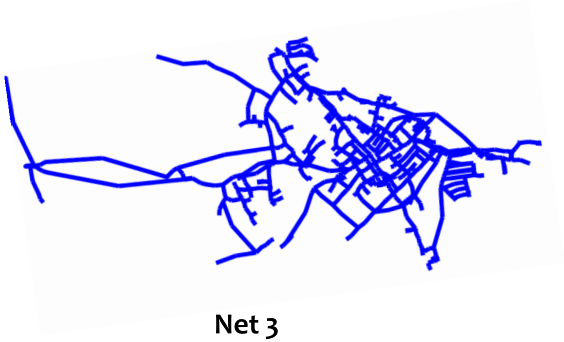
The **number of pair-wise link failures** that can be detected by σ-bit sensors is greater than in the case of 1-bit sensors.



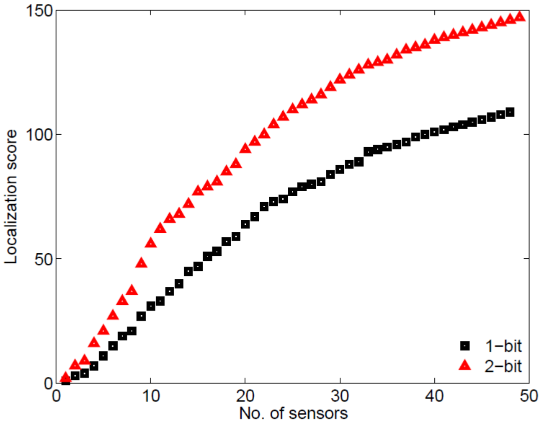
Net 1

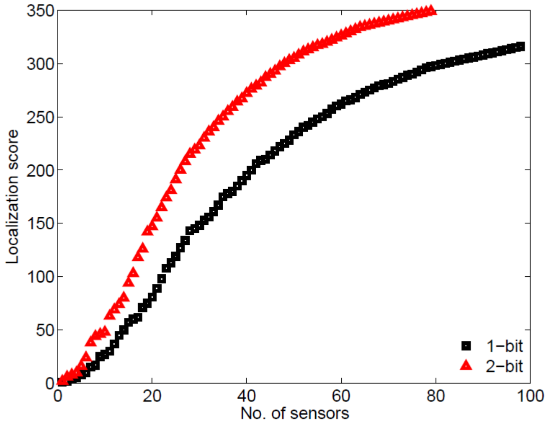


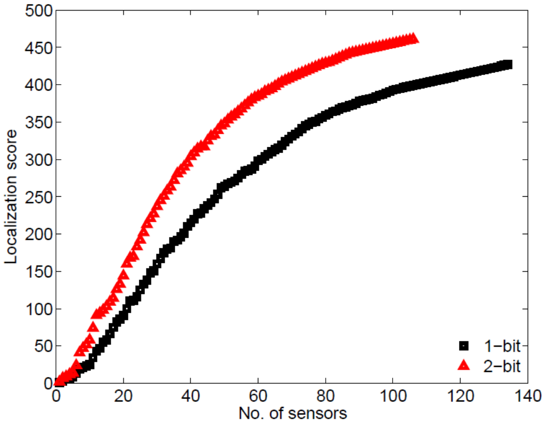
Net 2



Net 3

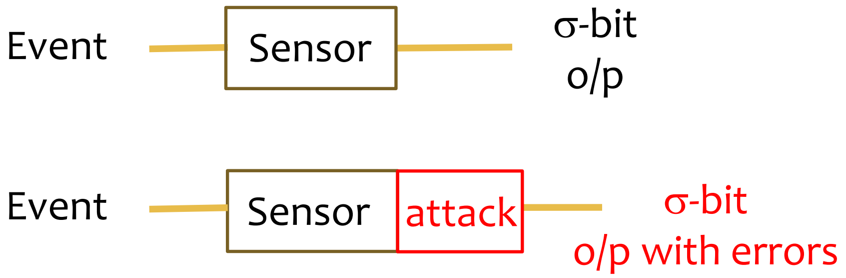






Attacks Resulting in Sensor Errors

Single sensor attack



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

Example:

Correct 2-bit output: 0 1

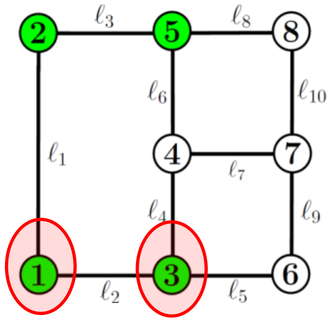
2-bit output with error can be any of the

0 0
1 0
1 1

Multiple sensors attack

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
	…	…	…	…

Localization with Sensor Errors

Objective:

Design a resilient placement algorithm for a set of m sensors with multiple output bits to maximize the localization of n events given that at most e of the m sensors are attacked and can give incorrect outputs.

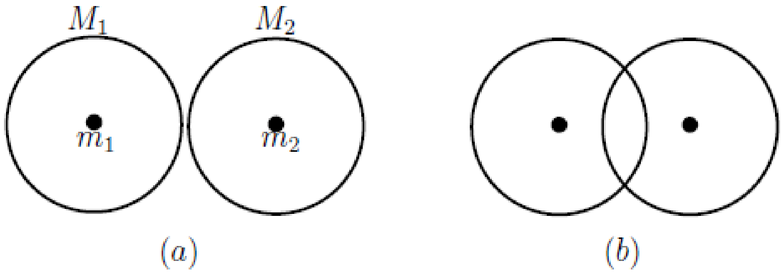
Two events can be distinguished in the presence of at most **e sensor errors (attacks)** as long as the hamming distance between their signatures is at least **(2e + 1).**

Example:

$m_1 = 0\ 0\ 0\ 1$

$m_2 = 1\ 1\ 0\ 0$

$e = 1$



Select m sensors such that the number of event pairs that have a hamming distance of at least (2e+1) between their signatures is maximized.

Set Multi-Cover for Localization with Errors

Select m sensors such that the number of event pairs that have a hamming distance of at least (2e+1) between their signatures is maximized.

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 d)-approximation algorithm ***(Vazirani 2001)***
- A randomized algorithm with an approximation ratio ***(Berman et al. 2007)***

$$\begin{cases} (1 + o(1)) \ln (d / k) & \text{if } (d / k) \geq 7.39 \\ 1 + 2(d / k)^{1/2} & \text{if } (d / k) < 7.39 \end{cases}$$

High versus Low Level Sensing

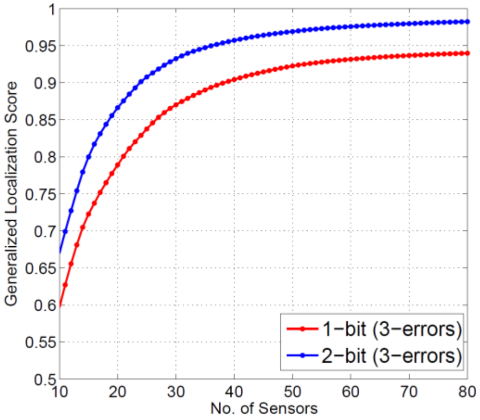
Let $\sigma' > \sigma$

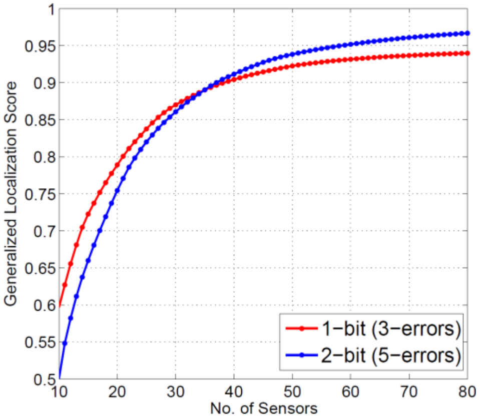
Fixing number of sensors and e,

Localization score in σ'-bit (high level) sensing is at least as good as in σ-bit (low level) sensing

Fixing number of sensors and localization score,

σ'-bit (high level) sensing can handle at least as many sensor errors (attacks) as σ-bit (low level) sensing





How many more errors (attacks) σ'-bit sensing can handle as compared to σ-bit sensing?

Thank You

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Localization Using Multi-level Sensing

The **maximum number of pair-wise link failures** that can be detected by σ-bit sensors is greater than in the case of 1-bit sensors.

1-bit

k : No. of ***link failures*** detected

$\mathcal{P}_1$: No. of ***pair-wise link failures*** detected

$$\mathcal{P}_1 = k(n-k)$$

σ- bit $(\sigma > 1)$

k_i : No. of link ***failures detected*** by the i^{th} bit such that $\sum_{i=1}^{\sigma} k_i = k$

$\mathcal{P}_\sigma$: No. of ***pair-wise link failures*** detected

$$\mathcal{P}_\sigma = \mathcal{P}_1 + \left(\sum_{x=1}^{\sigma-1} \sum_{y>x}^{\sigma} k_x k_y \right)$$

e.g, for 2-bit: $\mathcal{P}_2 = \mathcal{P}_1 + k_1 k_2$

$$\mathcal{P}_1 + (\sigma - 1)\left(k - \frac{\sigma}{2}\right) \leq \mathcal{P}_\sigma \leq \mathcal{P}_1 + \left(\frac{k^2(\sigma-1)}{2\sigma} \right)$$

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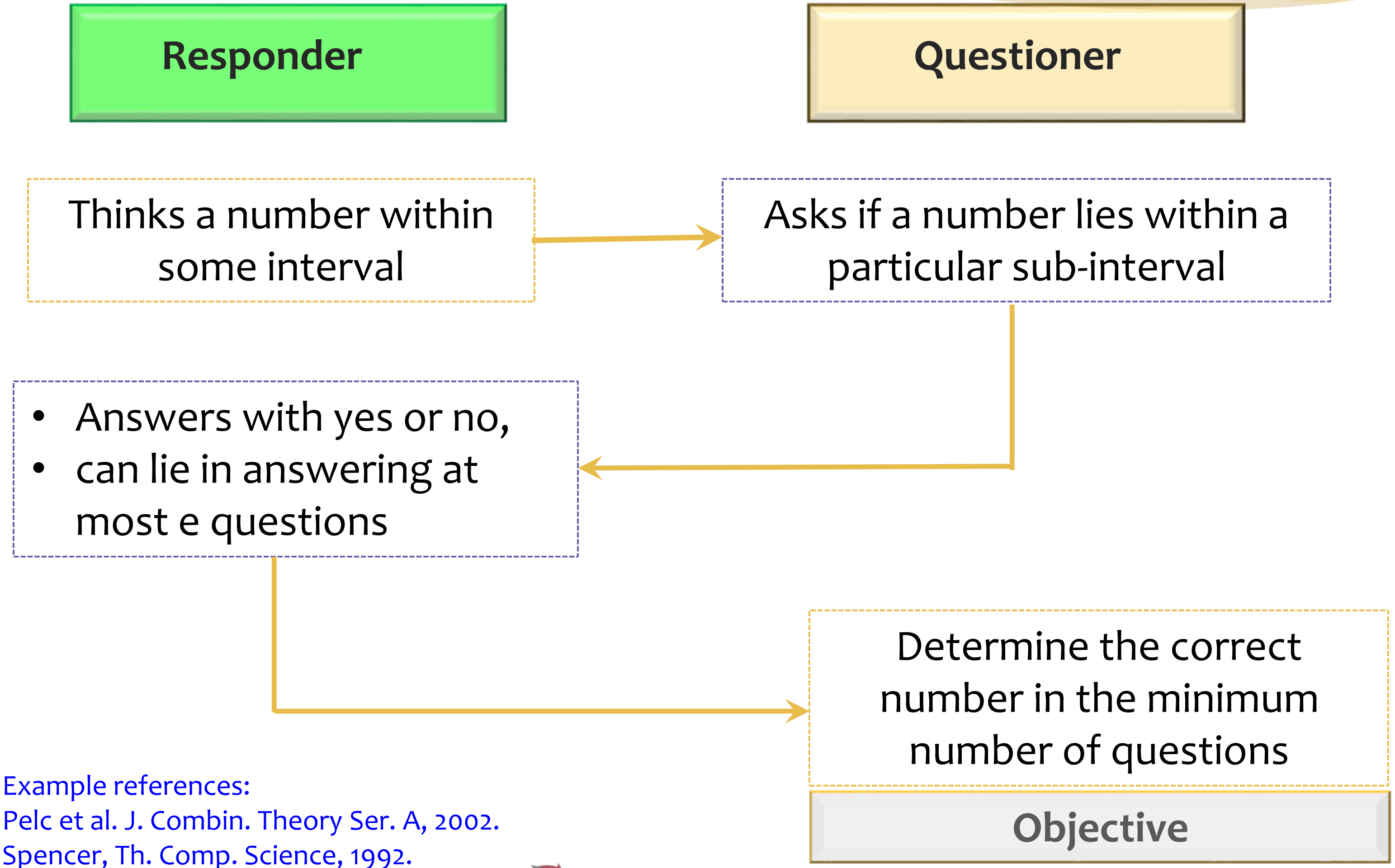
Ulam Games



Responder

Questioner

Thinks a number within some interval

Asks if a number lies within a particular sub-interval

- Answers with yes or no,
- can lie in answering at most e questions

Determine the correct number in the minimum number of questions

Objective

Example references:
Pelc et al. J. Combin. Theory Ser. A, 2002.
Spencer, Th. Comp. Science, 1992.

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Localization with Sensor Errors

$$\begin{array}{c|cccc} & S_1 & S_2 & & S_{m'} \\ \text{event 1} & 1 & 1 & \dots & 0 \\ \text{event 2} & 0 & 1 & \dots & 1 \\ \vdots & & & & \\ \text{event n} & & & & \end{array}$$

Influence matrix

$$\begin{array}{c|cccc} & S_1 & S_2 & & S_{m'} \\ \text{Pair-wise event (1,2)} & 1 & 0 & \dots & 0 \\ \text{Pair-wise event (1,3)} & & & & \\ \vdots & & & & \\ \text{Pair-wise event (n-1,n)} & & & & \end{array}$$

Pair-wise influence matrix

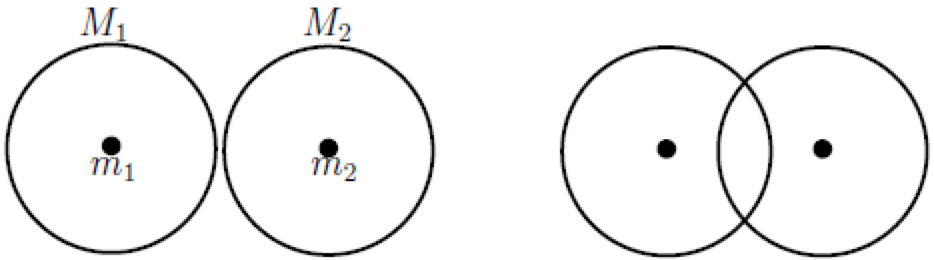
Two events can be distinguished in the presence of at most **e sensor errors** as long as the hamming distance between their signatures is at least **(2e + 1).**

Example:

$m_1 = 0\ 0\ 0\ 1$

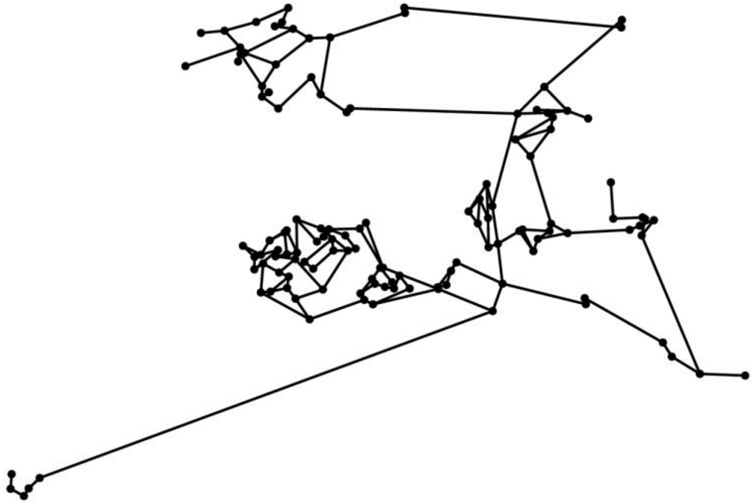
$m_2 = 1\ 1\ 0\ 0$

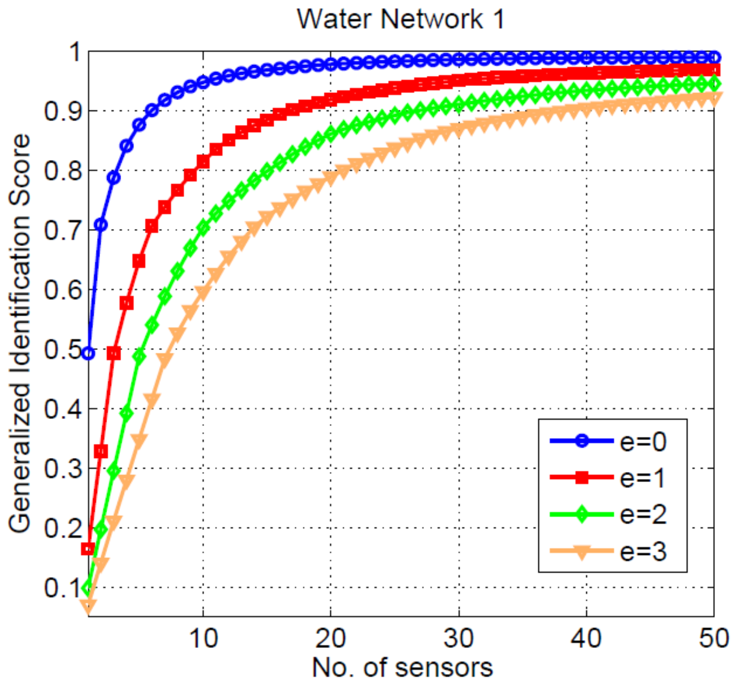
$e = 1$



(a) (b)

Simulations





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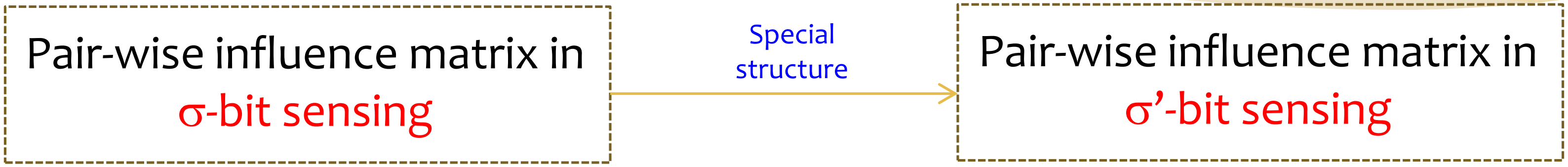
Errors in High versus Low Level Sensing



Pair-wise influence matrix in σ-bit sensing

Special structure

Pair-wise influence matrix in σ'-bit sensing

select m columns that maximally K-cover its rows

select m columns that maximally K'-cover its rows

What is the maximum K' such that K'-coverage achieved with m sensors in σ'-bit pair-wise influence matrix is at least as good as K-coverage achieved in σ-bit pair-wise influence matrix ?

$$T_{\sigma} = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

2-coverage yields 0.833 localization score

$$T_{\sigma'} = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \end{bmatrix}$$

3-coverage yields 0.833 localization score