Resilient design and operation of urban water infrastructure networks

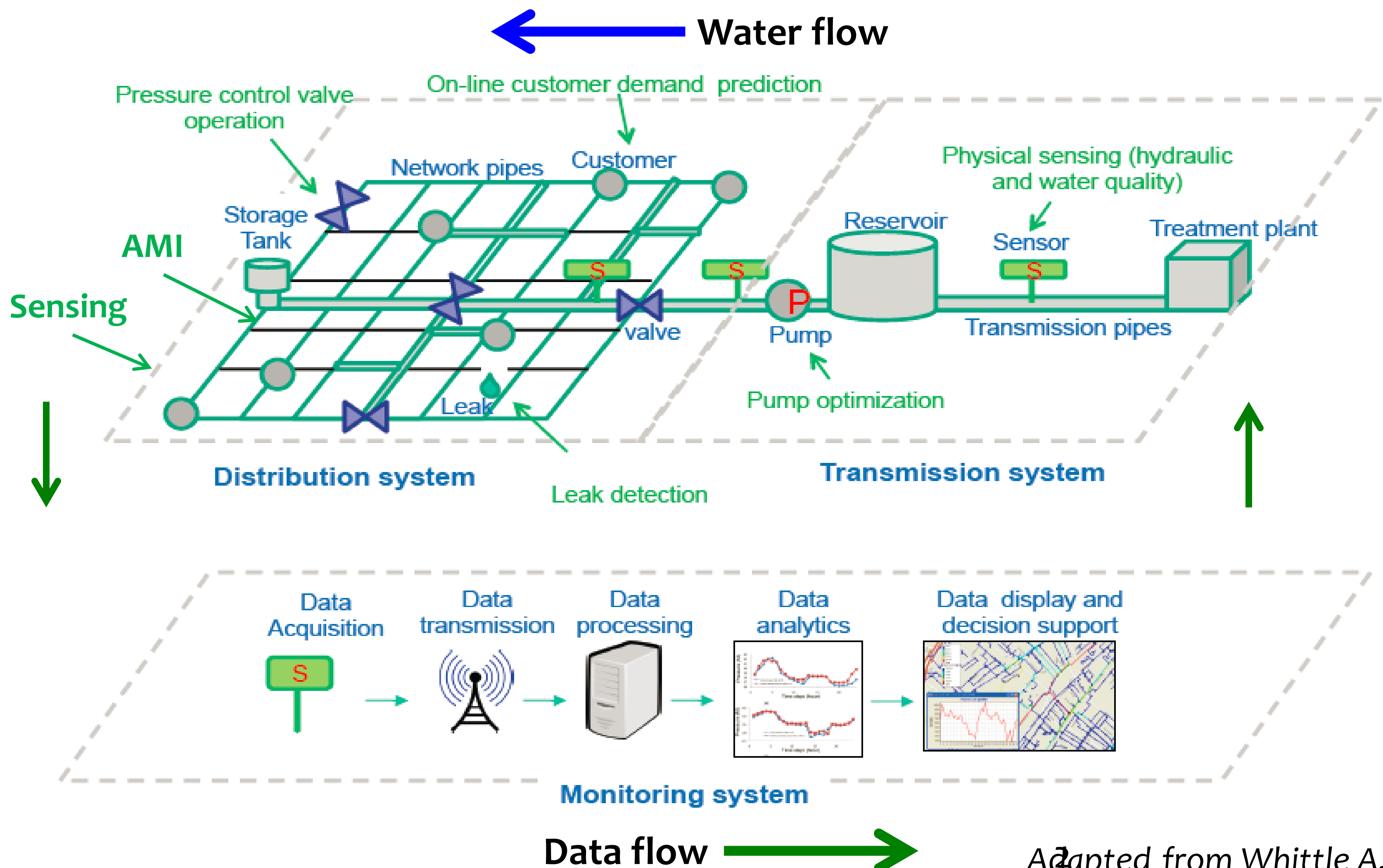
Lina Sela and Saurbh Amin, MIT

Challenge: How to ensure water security in the urban sector through resilient water networks aided by sensing and real-time data analytics?

May 28, 2015

Motivation: Smart water networks

- Sensing Modeling Analytics and Real-time Technology (SMART)



Adapted from Whittle A. 2012

Smart water networks

Objective

- How to ensure water security in the urban sector through resilient water networks?

Challenges

- Infrastructure deterioration and risk of disruptions
- Demand-supply uncertainty
- Cyber-physical systems interdependency

Approach

- Strategic design of network of sensors
- Real-time data acquisition and analytics for fault diagnosis
- Active network control and demand management

Smart water networks

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Joint work with Waseem Abbas and Xenofon Koutsoukos
Vanderbilt University

Water losses

Challenges

- Aging infrastructure
- Leaks & bursts

Impacts

- Service disruption
- Public health risk
- Waste of water and energy resources

Active leakage control

Network of sensor nodes

- What to sense?
- When to sense?
- Where to place the sensors?

US:

- No regulations for auditing & reporting water losses from public water systems
- ~250K reported;
  > 500K estimated breaks/year

Where to place the sensors?

Objective

- Sensor placement for detection and **location identification** of bursts

Challenges

- Uncertainty in pipe failure events
- Uncertainty in sensing quality
- Budget constraints

Impacts

- Early detection of reported losses (visible)
- Detection of unreported losses (not visible)
- Improved localization

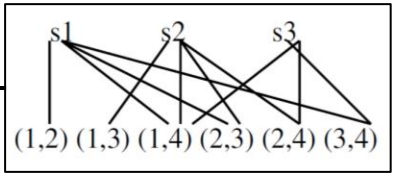
Approach

Event and sensing modeling

1. Network model
2. Transient flow model
3. Sensing model

Combinatorial optimization

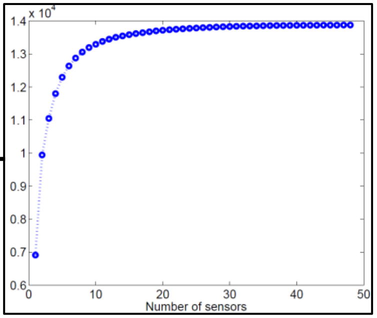
1. Minimum test cover
2. Test cover to set cover
3. Greedy optimization

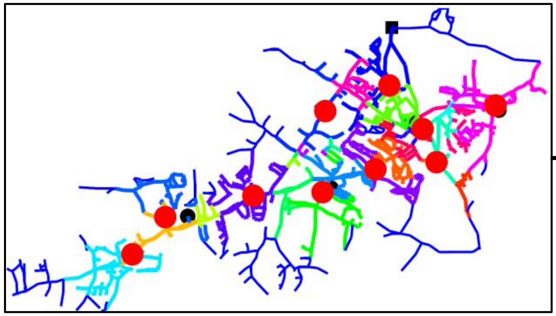


	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
ℓ_1	1	1	1	0	1	0	0	0
ℓ_2	1	1	1	1	0	1	0	0
ℓ_3	1	1	0	1	1	0	0	1
ℓ_4	1	0	1	1	1	1	1	0
ℓ_5	1	0	1	1	0	1	1	0
ℓ_6	0	1	1	1	1	0	1	1
ℓ_7	0	0	1	1	1	1	1	1
ℓ_8	0	1	0	1	1	0	1	1
ℓ_9	0	0	1	1	0	1	1	1
ℓ_{10}	0	0	0	1	1	1	1	1

Performance evaluation

1. Detection
2. Identification
3. Localization





Problem formulation

Find the subset of sensor locations $S \subseteq \mathcal{S}$ such that sensor network performance function, f, is maximized:

$$\max_{S \subseteq \mathcal{S}} \left\{ f\left(\mathrm{S}; \mathcal{L}\right), \left|S\right| \leq M \right\}$$

$\mathcal{S} = \left\{S_1, \ldots, \mathrm{S}_m\right\}$: set of sensors $\mathcal{L} = \left\{\ell_1, \ldots, \ell_n\right\}$: set of failure events

- Detection:

  $f_D\left(\mathrm{S}; \mathcal{L}\right)$ - the number of events ℓ that are detected by the set of sensors S

- Identification:

  $f_I\left(\mathrm{S}; \mathcal{L}\right)$ - the number of pair-wise events $\left(\ell_i, \ell_j\right)$ that are distinguishable by the set of sensors S

Network dynamics

- Influence matrix represents events and sensors states:

$$\mathcal{M}(\mathcal{L},\mathcal{S}) = \begin{bmatrix} \boldsymbol{y}_{\mathcal{S}}(\ell_1) \\ \vdots \\ \boldsymbol{y}_{\mathcal{S}}(\ell_n) \end{bmatrix}$$

$\mathcal{S} = \{S_1, \ldots, S_m\}$ - set of sensors

$\mathcal{L} = \{\ell_1, \ldots, \ell_n\}$ - set of failure events

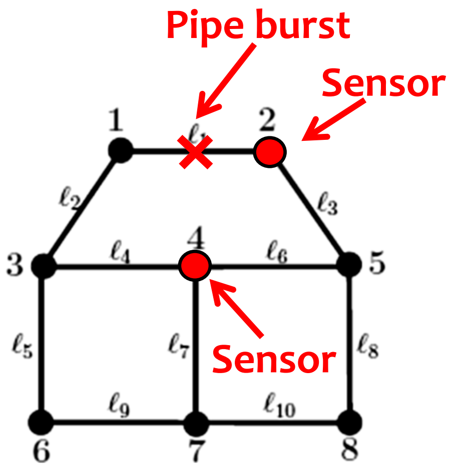
$\boldsymbol{y}_{\mathcal{S}}(\ell_j)$ - output of sensors in response to event ℓ_j

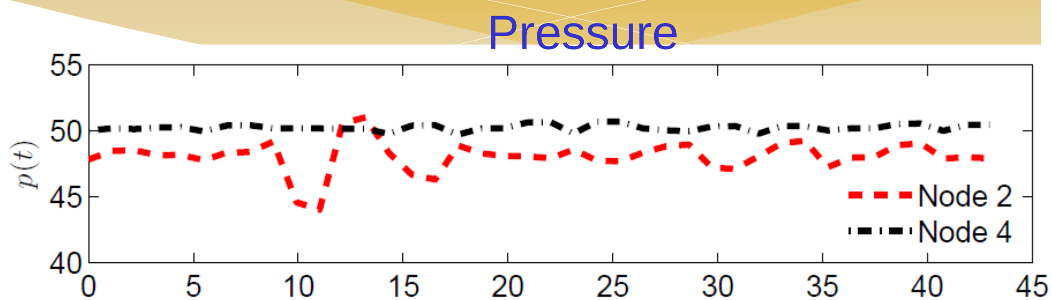
$C_i \subseteq \mathcal{L}$ - is a set of link failures detected by S_i

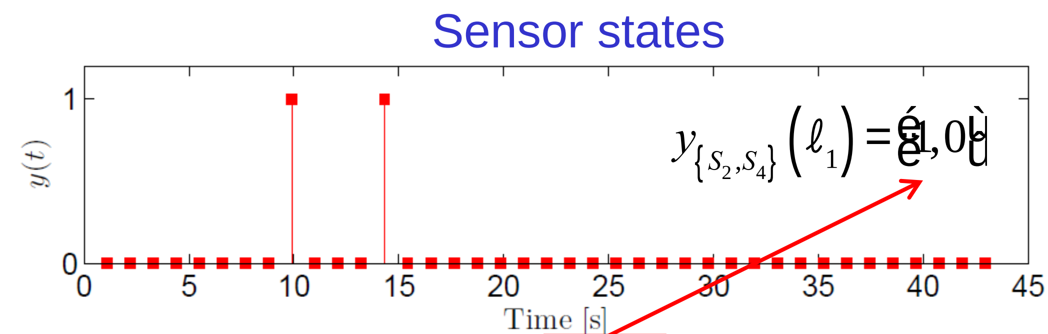
$\mathcal{M}_{ij} = 1$ - if sensor S_i detects event ℓ_j; 0 otherwise

Network dynamics

- Example: event ℓ_1







- Consider:

$y_S(\ell_j)$: sensors' response to event ℓ_j

C_i : events detected by sensor i

$$\mathcal{M}(\mathcal{L},\mathcal{S}) = \begin{array}{c} \ell_1 \\ \ell_2 \\ \ell_3 \\ \ell_4 \\ \ell_5 \\ \ell_6 \\ \ell_7 \\ \ell_8 \\ \ell_9 \\ \ell_{10} \end{array} \begin{pmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

Detection as minimum set cover

Detection:

- Find the minimum number of sensors and their locations such that every link failure can be detected by at least one sensor

Minimum set cover (MSC) problem:

- Find the smallest number of sets in a family of sets that cover the family, i.e., their union is equal to the union of all sets in the family
- Submodular: $f\left(A \cup \{C\}\right) - f\left(A\right) \geq f\left(B \cup \{C\}\right) - f\left(B\right)$ $\quad A \subseteq B \subseteq \boldsymbol{C}$ and $C \in \boldsymbol{C} \setminus B$
- Greedy solution with the best approximation ratio: $O\left(\ln k\right)$

Proposition 1: Detection of failures in the network is comparable to the set cover problem

Identification as minimum test cover

Identification:

- Find the minimum number of sensors and their locations so that every link failure can be uniquely identified, i.e., distinguished from any other link failure

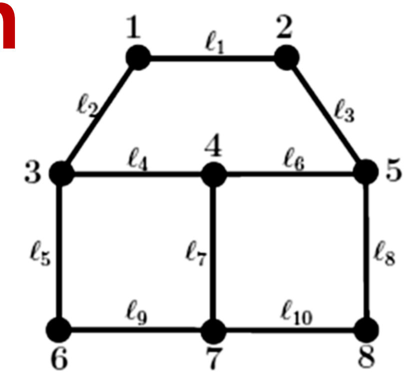
Minimum test cover (MTC) problem:

- Unknown a fault must be classified in one of the given categories based on the outcome of the set of tests

Proposition 2: Identification of failures in the network is comparable to the test cover problem

Pipe burst	→	Fault
Sensors' states	→	Set of tests
Location identification	→	Classification

Detection and identification



- Example (cont.):

$$S_A = \{S_1, S_7\}$$

Output		Localization-set
1	0	$\{\ell_1, \ell_2, \ell_3\}$
0	1	$\{\ell_6, \cdots, \ell_{10}\}$
1	1	$\{\ell_4, \ell_5\}$

$$\mathcal{M} = \begin{array}{c} \\ \ell_1 \\ \ell_2 \\ \ell_3 \\ \ell_4 \\ \ell_5 \\ \ell_6 \\ \ell_7 \\ \ell_8 \\ \ell_9 \\ \ell_{10} \end{array} \begin{array}{cccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{array}$$

$$S_B = \{S_1, S_2, S_3, S_5\}$$

$$\mathcal{M} = \begin{array}{c} \\ \ell_1 \\ \ell_2 \\ \ell_3 \\ \ell_4 \\ \ell_5 \\ \ell_6 \\ \ell_7 \\ \ell_8 \\ \ell_9 \\ \ell_{10} \end{array} \begin{array}{cccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{array}$$

- **All** events are detected
- Only **three** sets of events are identified

- **All** events are detected
- **All** events are uniquely identified

Solving the MTC problem

1. **Input:** given a set of sensors and a set of events

   $\mathcal{S} = \{S_1, \ldots, S_m\}, \mathcal{L} = \{\ell_1, \ldots, \ell_n\}$

2. **Transform:** MTC to MSC $\mathcal{L}, \mathcal{C} \rightarrow \mathcal{L}^t, \mathcal{C}^t$

   - obtain a new matrix $\mathcal{M}^t(\mathcal{L}^t, \mathcal{S})$ of dimension $\binom{n}{2} \times m$ such that $\mathcal{M}^t(e_{ij}, k) = 1$ if sensor k detects and distinguishes between events $\{\ell_i, \ell_j\}$; 0 otherwise

4. **Solve:** the counterpart MSC using greedy algorithm

   1. Start with an empty set: $S^* \leftarrow \varnothing$
   2. Find the sensor that covers the most uncovered elements:
   3. Add to current set: $S^* \leftarrow S^* \cup S_i$
   4. Repeat steps 2-3 until no more elements are covered

$$S_i = \arg\max_{S_i \subseteq \mathcal{S}} \left\{ f_D\left(S^* \cup S_i; \mathcal{L}^t\right) \right\}$$

$$f_I(\mathrm{S}; \mathcal{L}) = f_D\left(\mathrm{S}; \mathcal{L}^t\right)$$

5. **Output:** $S^* \subseteq \mathcal{S}$

Performance measures

Detection score

- The number of events detected by the sensor set

$$I_D(\mathrm{S};\mathcal{L}) = \left| \bigcup_{C_j \in \mathcal{C}_S} C_j \right|$$

Identification score

- The number of uniquely identified pairs of failure events

$$I_I(\mathrm{S};\mathcal{L}) = \left| \bigcup_{C_j^t \in \mathcal{C}_S^t} C_j^t \right| = I_D\left(\mathrm{S};\mathcal{L}^t\right)$$

Localization score

- The number of unique sensors' states I_S or the number of localization sets, i.e. unique rows in $\mathcal{M}(\mathcal{L},\mathrm{S})$

$$I_L(\mathrm{S};\mathcal{L}) = |I_S|$$

Application

$|\mathcal{S}| = 959$ - number of potential sensor locations

$|\mathcal{L}| = 1156$ - number of failure events

Example: Consider

$$S = \{S_1, S_2, S_3\}$$

No. of detected events

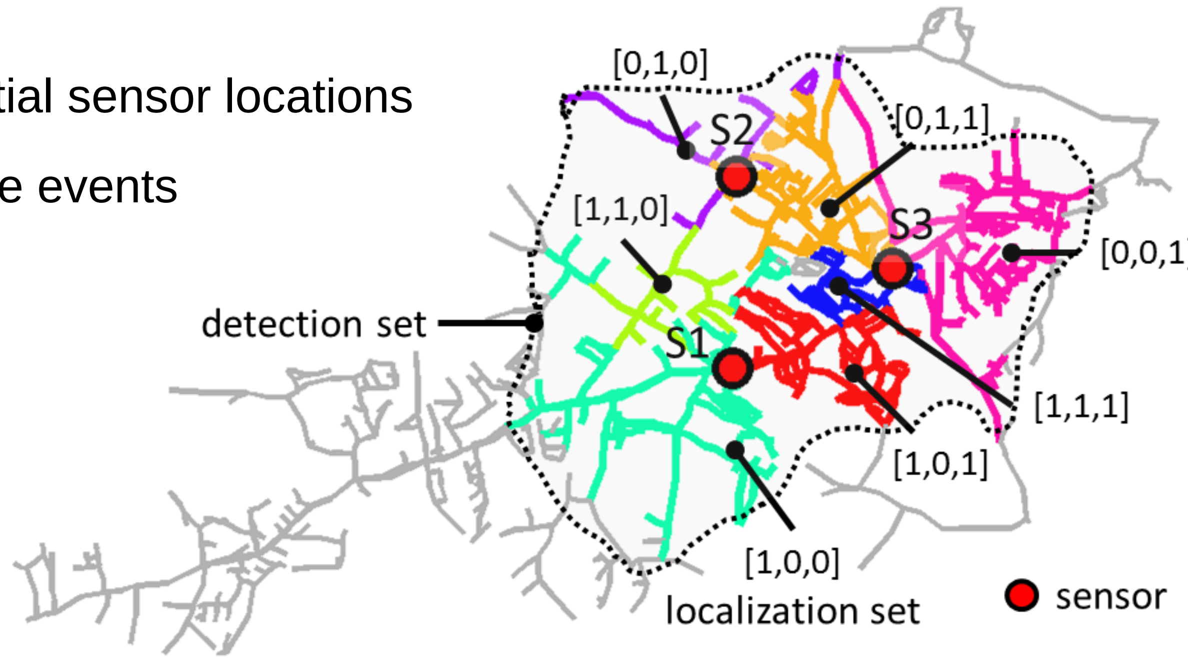
$$I_D(\mathrm{S}; \mathcal{L}) = 586$$

No. of unique pair-wise events

$$I_I(\mathrm{S}; \mathcal{L}) = 474{,}581 \quad \text{out of: } |\mathcal{L}^t| = \binom{1156}{2}$$

No. of localization sets

$$I_L(\mathrm{S}; \mathcal{L}) = |I_S| = 7 \quad \text{out of: } |\mathcal{L}| = 1156$$

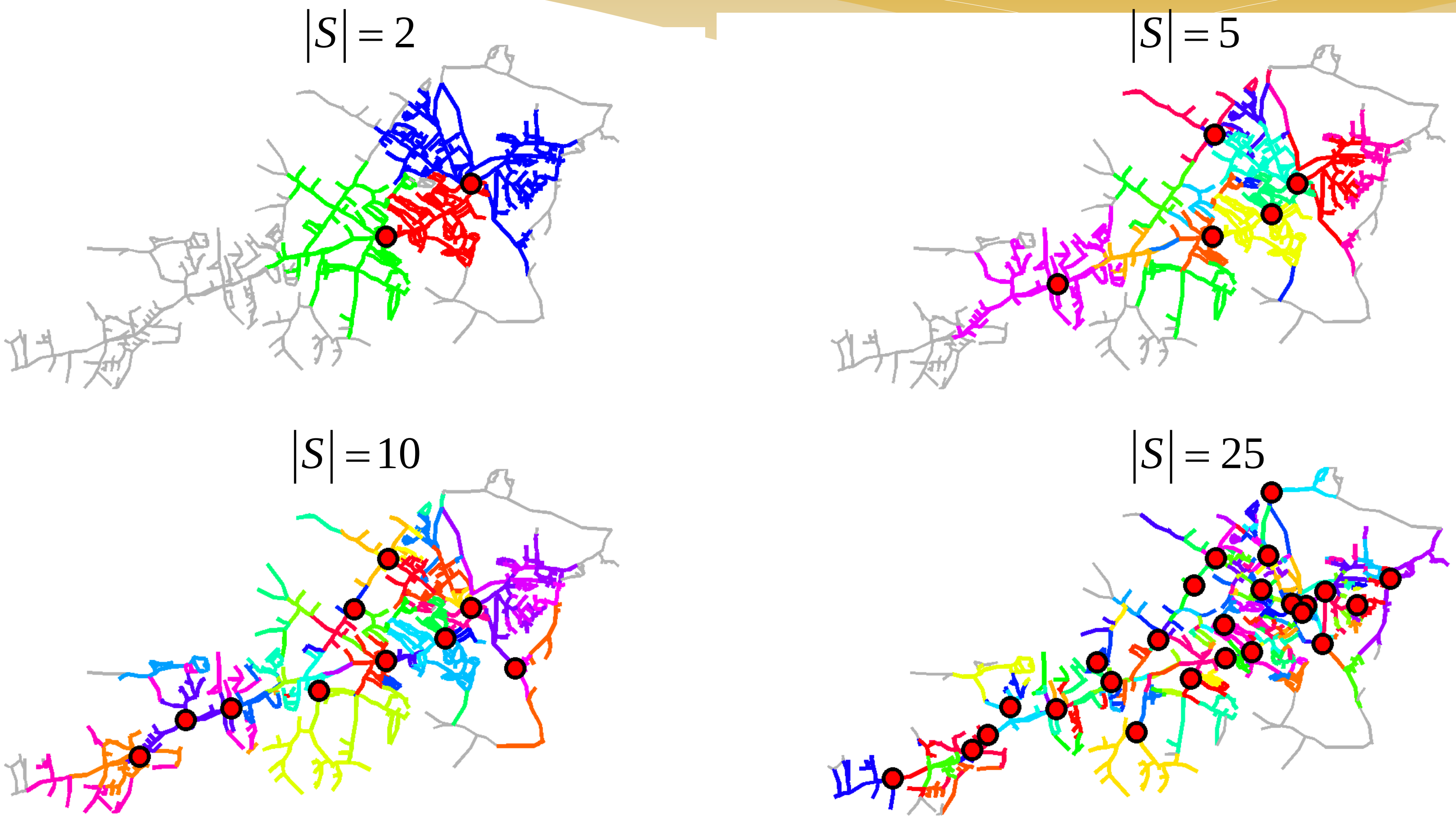


Kentucky network

Adopted from Jolly et al 2014

- 260 km of total pipe length
- Daily supply ~ 1.5M gal/day
- 1 reservoirs; 4 storage tanks
- 959 nodes; 1156 pipes;

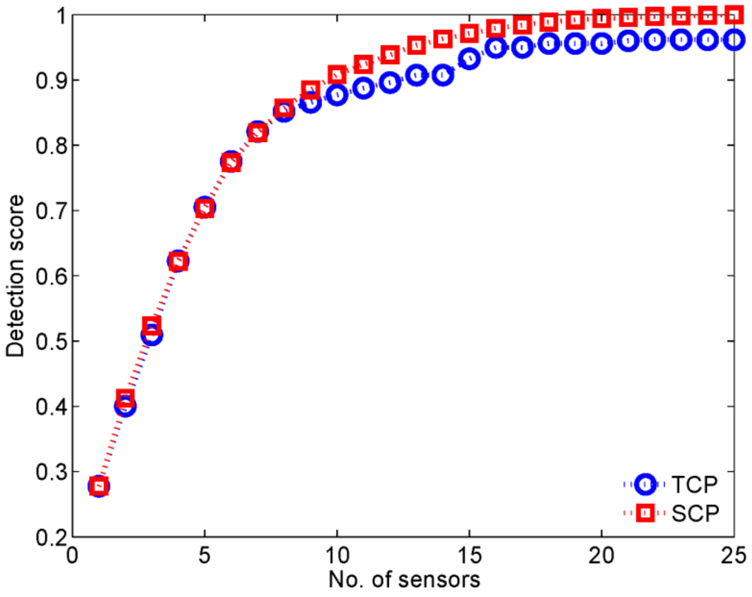
Application



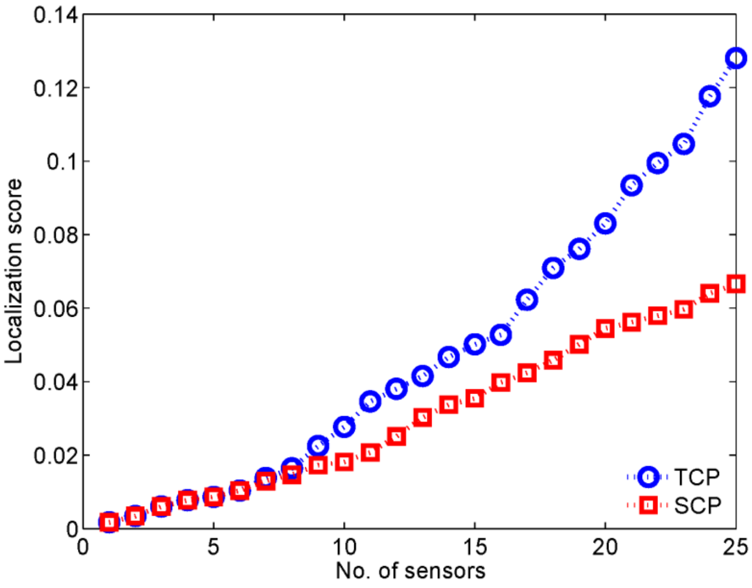
- Everything that is colored is detected
- Different colors represent unique localization sets, i.e. we can distinguish between events in different colored sets and cannot distinguish within same color set

Detection vs. Identification

Detection score



Localization score



- TCP – solution obtained solving the MTC problem
- SCP – solution obtained solving the MSC problem

Smart water networks

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Challenges

- Infrastructure deterioration and risk of disruptions
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Approach

- Strategic design of network of sensors
- Real-time data acquisition and analytics for fault diagnosis
- Active network supply-demand control

Control of water networks

Objective

- Strategic supply-demand control

Challenges

- Nonlinear network flow
- Collective vs. individual demand shedding

Approach

- Nonlinear network flow and demand modeling
- Convex approximation using geometric programming (GP)
- Standard convex solver (CVX + Mosek)

Geometric programming (GP) approach

Geometric programming

A class of structured convex optimization problems with special form objective and constraints:

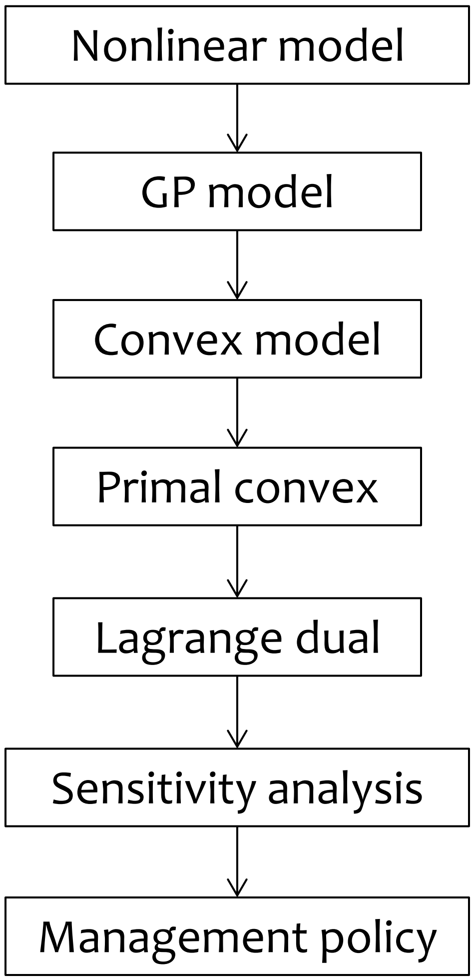
$$
\begin{aligned}
\underset{x}{\text{minimize}} \quad & f_0(x) \\
\text{subject to} \quad & f_0(x) < 1 \quad i = 1, \ldots, m \\
& h_i(x) = 1 \quad i = 1, \ldots, l \\
& x > 0
\end{aligned}
$$

Where:

monomials: $h(x) = c x_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}$

posynomials: $f(x) = \sum_{j=1}^{k} c_j x_1^{a_{1j}} x_2^{a_{2j}} \cdots x_n^{a_{nj}}$

Approach



Network flow

- Flow conservation at nodes: $\forall i \in N$

k - link
i - start node
j - end node

$$\sum_{k\in E_{out(i)}} q_k + d_i = \sum_{k\in E_{in(i)}} q_k \longrightarrow \sum_{k\in E_{out(i)}} q_k + s_i d_i \le \sum_{k\in E_{in(i)}} q_k \quad (1)$$

demand shedding (s_i)

inequality ($\le$)

- Energy conservation over links: $\forall k \in E$

R - resistance
α - power

$$R_k q_k^{\alpha} + H_j = H_i \longrightarrow R_k q_k^{\alpha} + H_j \le H_i \quad (2)$$

inequality ($\le$)

- Operating pumps: $H_j = \beta_k H_i$ (3) $\quad 1 \le \beta_k \le \bar{\beta}_k$ (4) - adding head
- Control valves: $H_j = \gamma_k H_i$ (5) $\quad 0 \le \gamma_k \le 1$ (6) - decreasing head
- Operating range: $\underline{H}_i \le H_i \le \bar{H}_i$ (7)

q - flow
H - head

Network supply-demand control

$$\underset{H,q,\beta,\gamma,s}{\text{minimize}} \quad \sum_{k\in E_{pump}} c_{1k} q_k \beta_k^{m_{1k}} + \sum_{i\in N_{demand}} c_{4i} d_i s_i^{-m_{4i}} + \sum_{i\in E_{valve}} c_{2i} \gamma_i^{-m_{2i}} + \sum_{i\in N} c_{3i} H_i^{-m_{3i}}$$

$$\text{subject to} \quad \text{eq.}(1)-(7)$$

$$q_k \beta_k \le \overline{Power}$$

$$\underline{s}_i \le s_i \le 1$$

Energy cost

Demand shedding penalty

Relaxation penalty

available resources

demand shedding

$s_i = 1$ zero demand shedding;

$s_i = 0$ full demand shedding;

- This problem formulation has a special structure conforming with geometric programming modeling constraints
- Current formulation is suitable for tree network topology

Application

Controls:

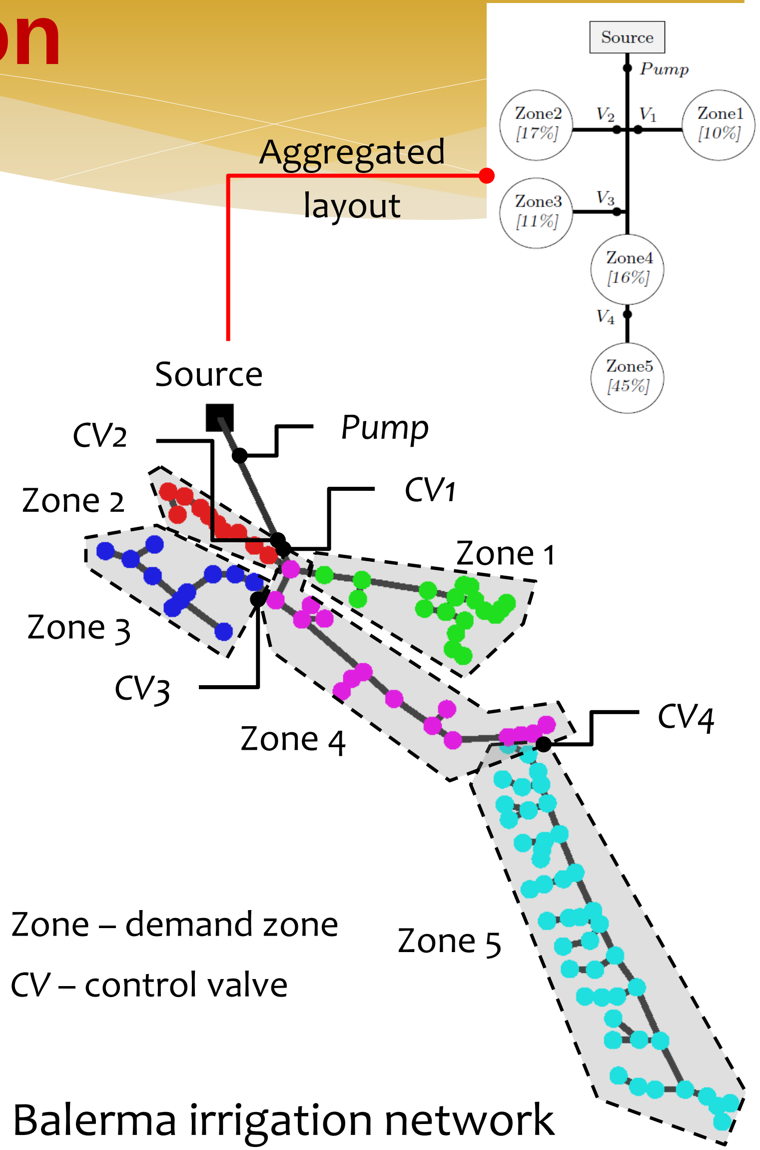
- Pumps – adding power to the system
- Control valves – decreasing pressure
- Demand shedding for each demand zone

Costs:

- Energy cost for operating the pump
- Penalty cost for demand shedding
- Penalty cost for relaxing equality constraints

Constraints:

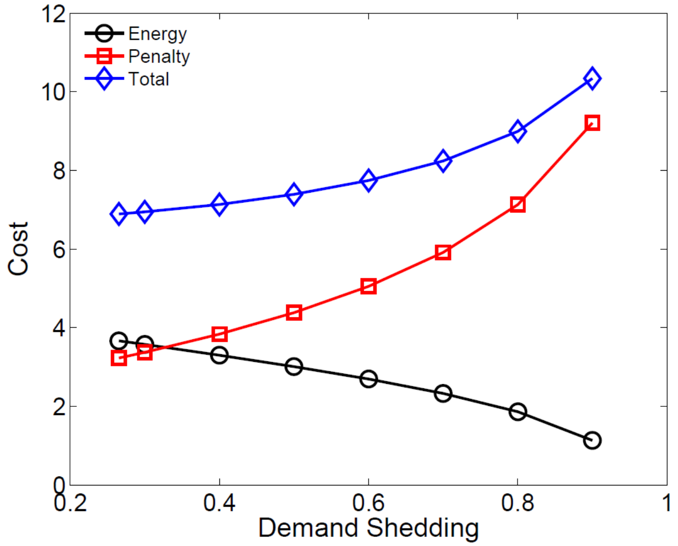
- Physical constraints
- Maximum available resources
- Maximum allowed demand shedding



Balerma irrigation network
Adopted from Reca and Martinez, 2006

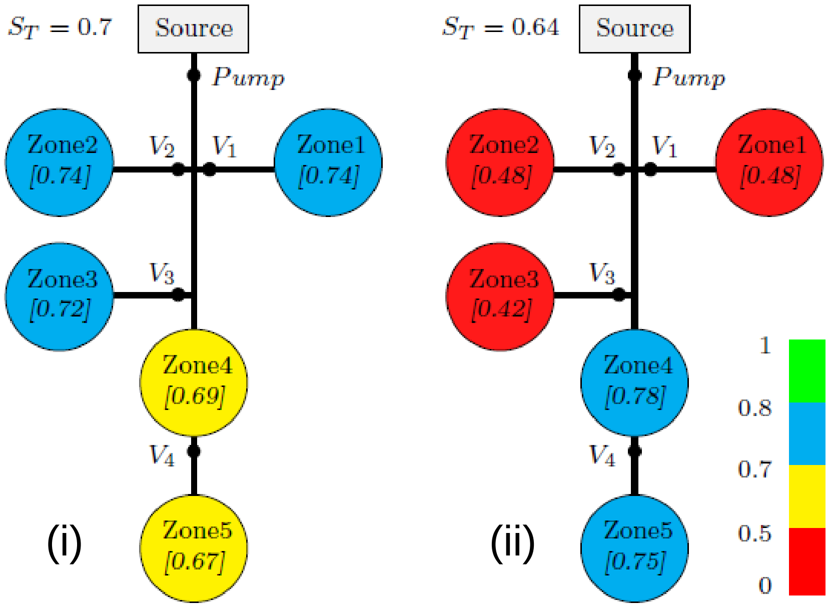
Controlled demand shedding

Energy cost and supply deficiency penalty



- Trade-off between cost of energy and water resources and penalty for supply shortage

Individual demand shedding



(i) Equal penalty – downstream consumers suffer more

(ii) Mixed penalties – variable allocation

Future work

Sensor placement

- Better approximation of the physical disturbance model
- Robustness to sensor failures
- Heterogeneous sensors

Network control

- Extension to looped topologies
- Supply-demand management for different operational regimes
- Demand response through water pricing schemes

Thank you!