Sensor and actuator placement for contaminant containment in water distribution networks

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Introduction

- Public water distribution networks are vulnerable to contamination, particularly from bio-terrorism [1, 2]
- Solution: use sensors to detect contaminants, and valves (actuators) to stop further contamination.
- Review of containment strategies, using optimization [3].
- Formulated as multi-objective linear program on a graph theoretic abstraction of network to simultaneously get optimum placement in terms of number of sensors, actuators used.

Legend and definitions

- Node is a point in the abstract graph of the distribution network. Total number: **N**
- Vulnerable nodes are the only attack-able nodes. i^{th} node is vulnerable: $\mathbf{y_i = 0}$
- Demand nodes are points of exit from the network. i^{th} node is demand: $\mathbf{y_i = 1}$
- Sensors, assumed capable of instantly and accurately detecting contamination of that node, placed at i^{th} node: $\mathbf{x_i = 1}$
- Actuators cut off flow from one end to the other. Placed on i^{th} edge $\mathbf{z_i = 1}$
- Goal: No demands node must stay contaminated, with minimum total number of sensors + actuators (cardinality). $min \sum \mathbf{x_i} + \sum \mathbf{y_i}$

Sensor Placement

- Given the specification of a network, vulnerable nodes and demand nodes, we can come up with a sensor placement strategy to detect any contaminant

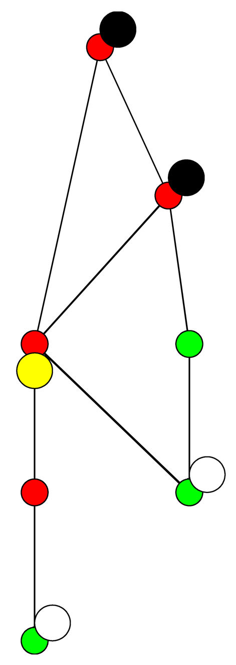

Fig. 1: Example network; basic sensor placement

Constraints: $\mathbf{Ax} \leq [\mathbf{0}]$ where $A_i = 1$ if i^{th} node is affected by the vulnerable node.

- We can also add constraints to make sure contaminant is detected before any demand is compromised.
- Once we detect contaminants, we can shut off source (partition the network) to prevent further contamination.

Actuator Placement

- This actuator placement is independent of sensor placement - global optima at optima of sub-problems.

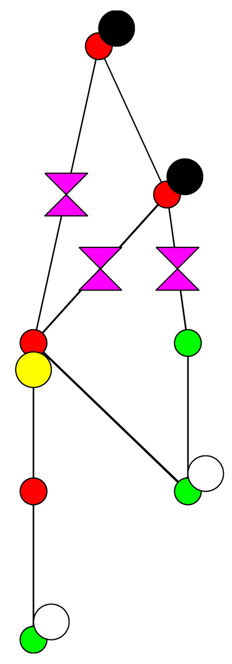

Fig. 2: Independent sensor and actuator placement on example

- Adding the requirement of detection before contamination of any vulnerable node

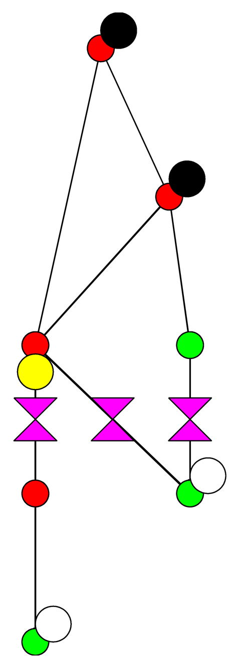

Fig. 3: Trying to solve for containment after sensor placement

- We can extend this and later descriptions to identifiability – knowing which set of sensors were attacked.

Simultaneous Placement

- The globally optimal solution can only be obtained by iterating through the process, a non-linear optimization problem.
- A simultaneous linear program formulation for both sensor and actuator placement makes this problem tractable.
- Within the linear program, we store the minimum distance to sensing for each vulnerable node, and require that each actuator be beyond that distance:

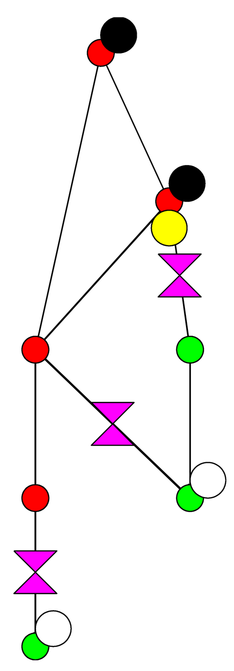

Fig. 4: Result of simultaneous optimization on example network

Results

- The formulation was applied to solving the case study used in [4]. Cardinality of 26 was obtained, for allowing no compromised demands:

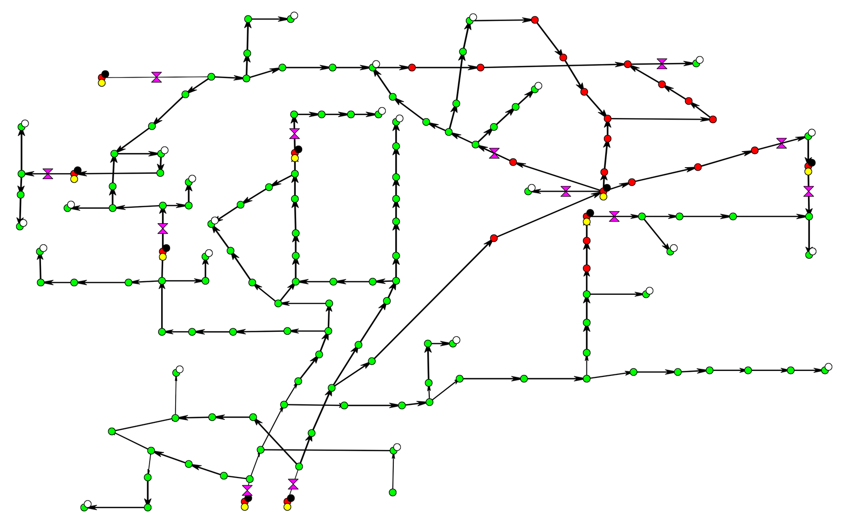

Fig. 5: Results on Bangalore network, with vulnerable nodes [1 2 3 19 32 37 39 53 66]

- The results for allowing initial contamination of demand nodes from the work was reproduced (cardinality of 21):

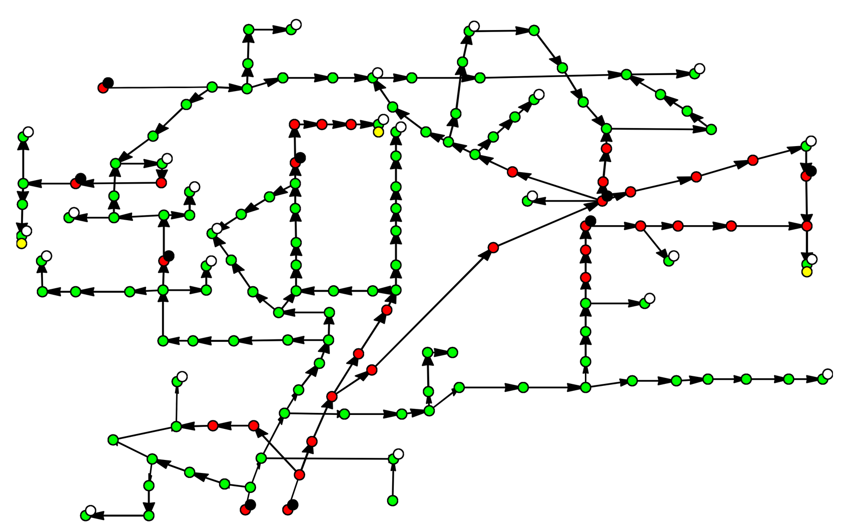

Fig. 6: Reproduction of results from [4]

Acknowledgements

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References

[1] Kessler, A.; Ostfeld, A.; Sinai, G. Detecting Accidental Contaminations in Municipal Water Networks. Journal of Water Resources Planning and Management 1998, 124, 192–198.

[2] Ostfeld, A. et al. The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms. Journal of Water Resources Planning and Management 2008, 134,

[3] Review of Sensor Placement Strategies for Contamination Warning Systems in Drinking Water Distribution Systems

[4] Venkata Reddy Palleti, Varghese, Shankar Narasimhan and Raghunathan Rengasamy: Actuator network design to mitigate contamination effects in water distribution networks