Cost-Effective Outbreak Detection in Networks
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Motivation
Goals
Evaluating Sensor Placement
Alternative Formulation
Penalty Functions
Optimization
   Greedy Algorithm
      Constant Cost
      Non-Constant Cost
   Cost Effective Forward (CEF) Selection
  “Online” Bound Computation
Performance Optimizations
   Observations
   Cost-Effective Lazy Forward (CELF) Selection
Experimental Results
   Case Study: Blog Networks
   Results
   Water Networks
   Results
Motivation

Detecting contamination in municipal water distribution network
Selecting blogs to monitor for influential trends
Goals

- Early detection
- Guaranteeing detection
- “Sensor” cost
- Incident impact
Evaluating Sensor Placement

Definition

Penalty:

- Time before incident is detected by sensor
- Number of nodes exposed to incident before detection
Evaluating Sensor Placement

Minimize penalty over all possible incidents

\[ \pi(A) = \sum_i P(i) \pi(T(i, A)) \]

- \( \pi \) is the penalty
- \( A \) is the set of sensors in the a placement
- \( P \) is the incident probability distribution
- \( T(i, A) \) is the best detection time across all sensors in the placement \( A \)
An Alternative Evaluation Function

Reduction in penalty for a specific incident:

\[ R_i = \pi(\infty) - \pi_i(T(i, A)) \]

Reduction in penalty across all incidents:

\[ R = \sum_i P(i)R_i(A) = \pi(\emptyset) - \pi(A) \]
A Reminder...

Definition
Submodularity: the benefit of adding an element to a smaller set is guaranteed to be equal or greater than the benefit of adding that element to any larger set.
Defining Penalty

- Detection likelihood
- Detection time
- Population affected
Multicriterion Optimization

\[ \vec{R} = (R_i(A), R_2(A), \ldots, R_m(A)) \]

**Definition**

*Pareto-optimal*: a solution such that no other solution exists which is at least as good in all criteria and strictly better in one

**Definition**

*Scalarization*: pick positive weights for all criteria and sum over the products
Unit-Cost Greedy Algorithm

All nodes have equal cost, maximize the marginal benefit at each step
If the cost is actually equal, this algorithm is within 63% of optimal
Variable Cost Greedy Algorithm

Maximize benefit-cost ratio at each step
No longer guaranteed bound against the optimal solution
Cost Effective Forward (CEF) Selection

Compute greedy benefit-cost and greedy unit cost
Select the solution with the better score
Guaranteed bound against the optimal
$O(B|V|)$
“Online” Bound Computation
Assume outbreaks are “sparse”
Allows for powerful optimizations in conjunction with penalty-reduction formulation
Index reduction in penalty by sensor index, $s$

$$R(A) = \sum_{i \text{ s.t. } i \text{ detected by } A} P(i) \max_{s \in A} R_i \{s\}$$
Submodularity!
Reduce the number of marginal-benefit calculations
Store marginal benefits calculated in a priority queue
Evaluate invalidated nodes in decreasing order. More often than not, the highest benefit node stays on the top after re-evaluation
Blog Networks

Dataset drawn from blogs with at least 3 incoming links in the first 6 months of 2006

- 45,000 blogs
- 10.5 million posts
- 16.2 million links, 1 million “internal” links
- 30 GB of data
- 17,589 cascades
Objectives: Detection Likelihood, Detection Time, Population Affected
Unit-cost model selects big blogs with many posts
Cost-model + number of posts ⇒ aggregators
Comparison with Heuristics Friday is the best day to read blogs
Shortcomings

CELF overfit present data
Prevent CELF from selecting particularly small blogs
Degraded results but better generalization
Watere Sensor Networks

Data from Battle of Water Sensor Networks (BWSN)

- 21k nodes
- 25k pipes
- 3.6 million contamination scenarios
Setup

- Detection Likelihood
- Detection Time
- Population Affected

Population affected increases very quickly (sparsity) Detection Likelihood, Detection Time: grow with more sensors
Results

Concentrate in areas with high population density to decrease population affected. Spread sensors out to increase detection likelihood and detection time.