Communication-constrained $p$-Center Problem for Event Coverage in Theme Parks

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Introduction

- Theme parks are crowded regions and have security vulnerabilities.

- *Events*: incidents such as violence, robbery or emergency.

- The aim is to cover events by deploying a WSN with mobile sinks:
  - Sensors collect information regarding the events and relay to mobile sinks.
  - Mobile sinks: Limited number of electric safety vehicles controlled by humans.

- Crowdsensing via smart phones can also be applied to collect information.
Introduction: Problem

- The problem reduces to the effective placement of mobile sinks
- Each event should be covered in the minimal time by sending the closest sink
- The problem is modeled as a vertex $p$-center problem (on a weighted graph)
- Original $p$-center problem: minimizing the maximum travel time for each sink
- We have additional constraint for communication among the mobile sinks
- The new variant: communication-constrained $p$-center problem
Preliminaries: Background on \( p \)-center problem

- \( p \)-center problem consists of \( p \) facilities and clients (i.e., vertices)
- Each client is assigned to a facility
- The problem is to minimize maximum distance between a client and the facility assigned to it
- Two variants: absolute and vertex \( p \)-center
  - Facilities can be located anywhere in absolute \( p \)-center
  - Facilities must be on vertices in vertex \( p \)-center
- In weighted \( p \)-center, weights represent demands of the clients
- \( p \)-median problem is minimizing sum of the shortest distances
Preliminaries: WSN model

- **Static sensor nodes**
  - are deployed throughout the theme park
  - detect events in their vicinity
  - transmit their observations via hop-by-top transmission
  - stay idle or sense environmental data for regular monitoring if no event occurs

- **Mobile sinks**
  - patrol inside the attractions for data collection and event coverage
  - have ability to move fast and share data with each other
  - are responsible for moving to the event region if they are chosen
We use a graph model for attractions (vertices) and roads (edges).
Vertex weights are event probabilities of attractions.
Edge weights are estimated travel times along the roads.
Weights of edges and vertices change throughout the operation due to crowd flows.
Event coverage: Motivation

- Mobile sink placement can be solved by one of the existing heuristics of $p$-center problem
- However, mobile sinks should be directly connected and take collaborative actions
- Mobile sinks always preserve a connected topology as illustrated below
Event coverage: Motivation

- We face with a new variant due to the additional constraint
- We call the new variant *communication-constrained p-center problem*
- Communication paths are different than physical paths
- Therefore, the solution uses two distinct graphs
Event coverage: Problem formulation

- Given: Theme park graph $G$ (with set of vertices $V$), connectivity graph $G^c$
- Each vertex $v_i$ has a weight value $w(v_i)$ and $w(v_i) > 0, \forall v_i \in V$ (demand of client)
- The objective is to find the subset of vertices $F = \{f_1, f_2, \ldots, f_p\}$
- $F \subset V$, $|F| = p$ and we locate the facilities with the following goal:

  \[
  \text{Min } \eta(F) \text{ s.t. } F \text{ is connected on } G^c
  \]

  \[
  \text{, where }
  \]

  \[
  \eta(F) = \max_{1 \leq i \leq n} \left\{ \min_{1 \leq j \leq p} \{ (w(v_i) \cdot d(f_j, v_i)) \} \right\}. \quad (1)
  \]

- The minimum value of $\eta(F)$ gives the optimal subset $F$ for facility locations
Event coverage: Proposed approach

- We propose an exact algorithm for solving the new variant

- The algorithm has two steps: (see Algorithm 1)
  - Step 1: Compute the connected subgraphs with $p$ vertices using $G^c$
  - Step 2: Place the facilities to the subgraph which minimizes the maximum distance

- We implemented two strategies
  - $P$-center positioning (PcP): Minimize the maximum distance from an attraction to the closest sink
  - $P$-median positioning (PmP): Minimize the sum of distances from attractions to the closest sinks
Event coverage: Proposed approach

- $G^c$ is a static graph since attraction locations are static while $G$ is dynamic
- $G^c$ is initially provided to mobile sinks
- Mobile sinks have discrete location update times because of weight changes in $G$
- At each update time, weight values are shared with a chosen mobile sink (master)
- Master runs Algorithm 1 ($p$-center alg.) and assigns new positions to other sinks (slaves)
Difference between PcP and PmP is illustrated for one mobile sink

Assume the distances are relative and attractions’ event probabilities are equal

PcP minimizes the max distance, PmP minimizes sum of all distances
# Simulation study: Simulation setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>simulation time ($T$)</td>
<td>10 hours</td>
</tr>
<tr>
<td>terrain size</td>
<td>$500 \times 500$ m</td>
</tr>
<tr>
<td>number of attractions ($n$)</td>
<td>15</td>
</tr>
<tr>
<td>min distance among attractions</td>
<td>50 m</td>
</tr>
<tr>
<td>max distance among attractions</td>
<td>250 m</td>
</tr>
<tr>
<td>node degree of $G$</td>
<td>4</td>
</tr>
<tr>
<td>sink update time $t$</td>
<td>30 min</td>
</tr>
<tr>
<td>sink transmission range</td>
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</tr>
<tr>
<td>event probability change rate</td>
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</tr>
<tr>
<td>expected number of events</td>
<td>100</td>
</tr>
<tr>
<td>min active time of events</td>
<td>200 sec</td>
</tr>
<tr>
<td>max active time of events</td>
<td>600 sec</td>
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<tr>
<td>edge weight change rate</td>
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</tr>
<tr>
<td>max edge weight difference</td>
<td>400%</td>
</tr>
<tr>
<td>max mobile sink speed</td>
<td>1.00 m/sec</td>
</tr>
</tbody>
</table>
Simulation study: Baselines and performance metrics

- Four strategies are compared PcP, PmP, WP, RP
  - WP: Weighted positioning according to vertex weights
  - RP: Random mobile sink positioning on vertices

- We simulated scenarios in which communication constraint does (w/ CC) or does not (w/o CC) exist

- w/o CC assumes no need for communication (global knowledge), relaxes the problem but it is not practical

- Two metrics:
  - Average event handling time: travel time to reach the events on average
  - Success ratio: ratio of successfully reaching events before they expire
Simulation study: Performance results

Events are generated based on attraction weights

- PcP and PmP are the winners while WP is slightly better than RP
- PmP performs slightly better than PcP, since we observe average handling time (not the maximum time)
Simulation study: Performance results

Events are randomly generated on attractions
Compared to the previous case, the gap between PcP and PmP is almost negligible
Placing based on attraction weights (WP, PmP) is not good for random scenario
Simulation study: Performance results

c) 1 to 14 sinks, random event distribution

Better results with the increasing number of mobile sinks
Performance gap between PmP and PcP decreases as the number of sinks increases
As the network becomes saturated with more sinks, the gap between w/ CC and w/o CC diminishes
Conclusion

- We focused on the event coverage in theme parks
- We proposed a new variant of p-center problem
- We proposed PcP and PmP approaches for sink positioning
- The evaluation indicated significant success compared to WP and RP

Future work:
- Developing a heuristic algorithm with reduced complexity
- Heuristic is needed for theme parks with large number of attractions