Optimizing Roadside Unit (RSU) Placement in Vehicular CPS

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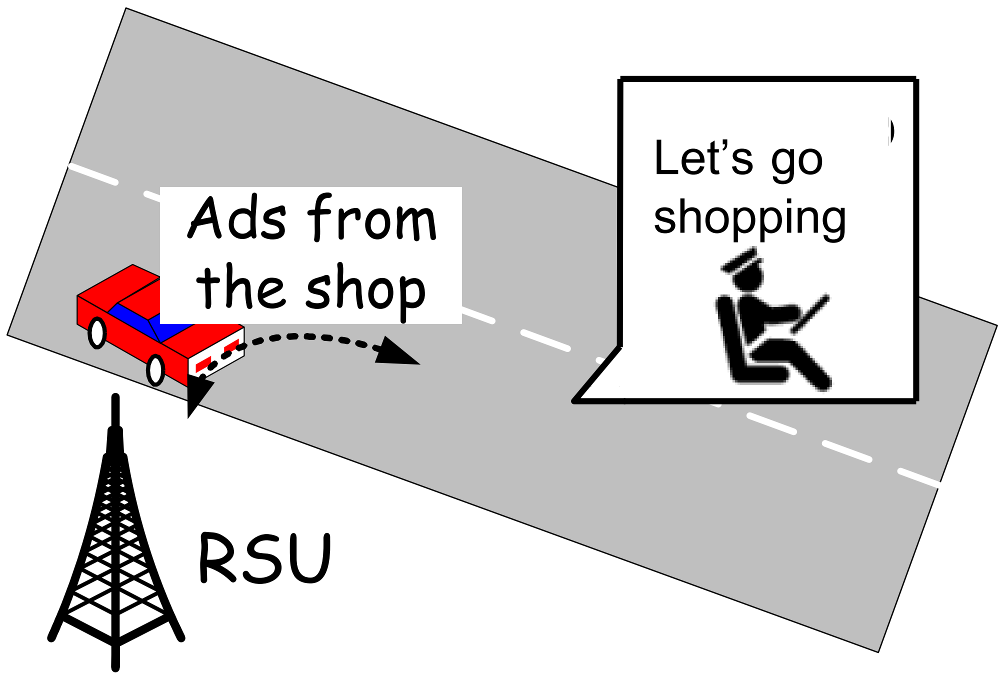
RSU Placement

- Roadside advertisement
  - Attracting shoppers
  - Variation of maximum coverage problem
- Traffic flow monitoring
  - Tracking traffic flow
  - Variation of set cover problem

Roadside Advertisement

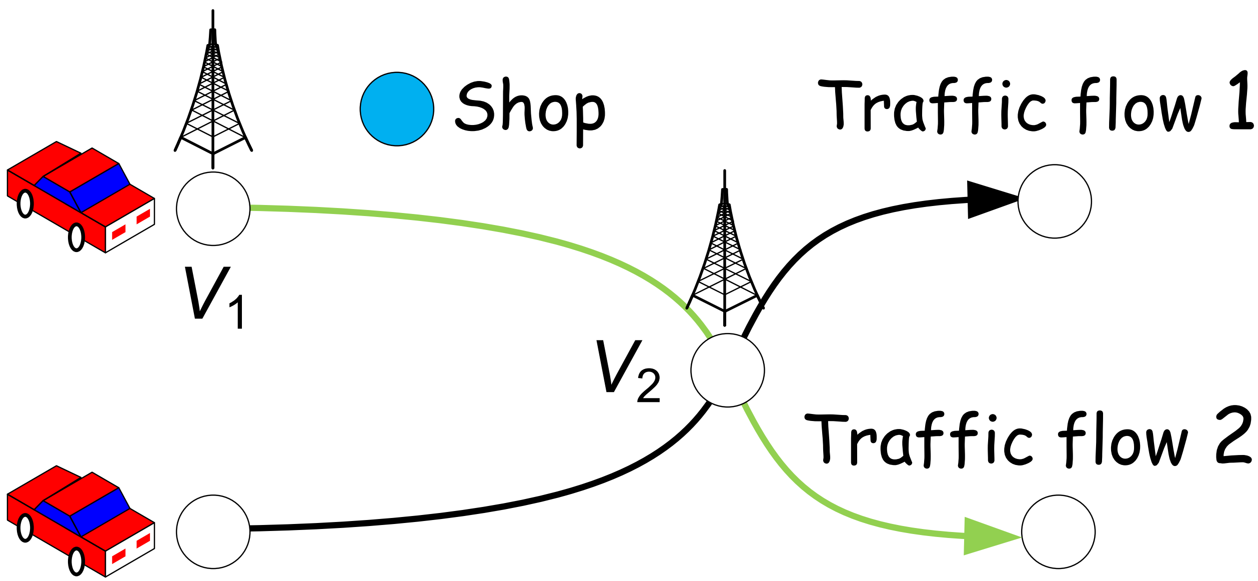
- Passengers, shopkeeper, and roadside unit (RSU)
- Shopkeeper disseminates ads to passing vehicles through RSUs
- Passengers may go shopping, depending on detour distance



Roadside Advertisement

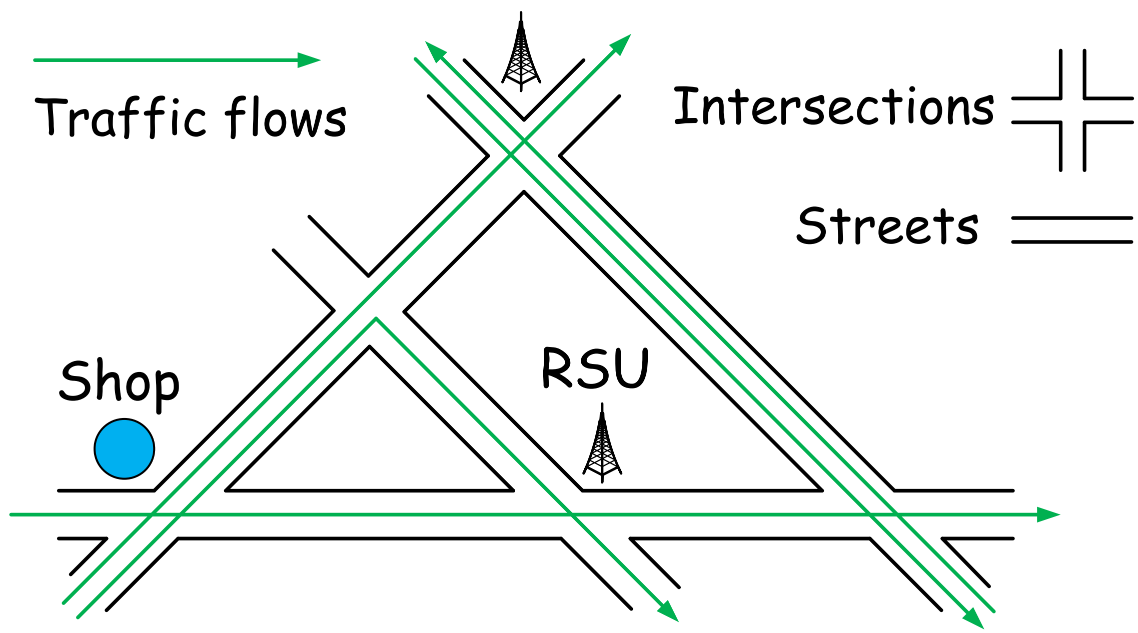
RSUs placement optimization

- Given a fixed number of RSUs and (traffic) flows, maximally attract passengers to the shop
- Tradeoff between traffic density and detour probability



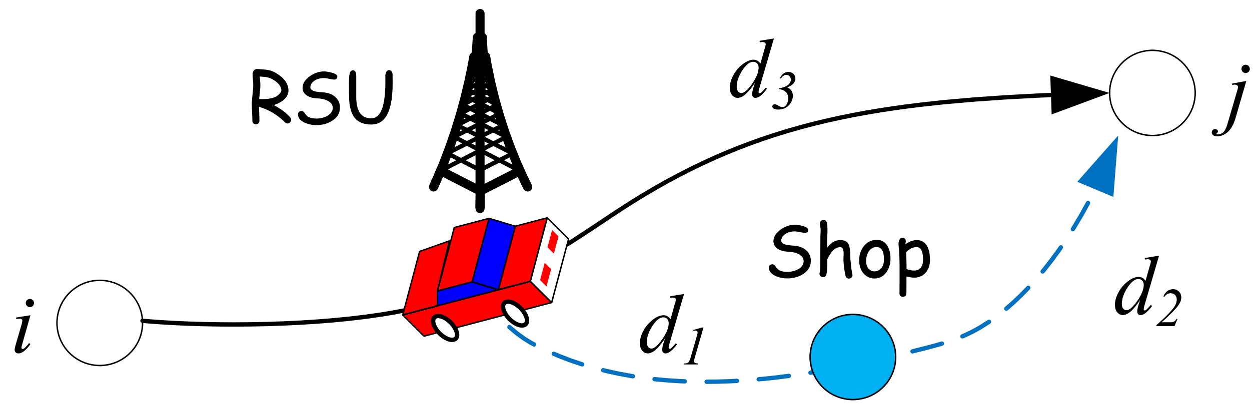
Graph Model: G = (V, E)

- V: a set of street intersections (vertices)
  - One shop and RSUs located at street intersections
- E: streets (directed edges)
- Traveling path is the shortest path



Detour Model

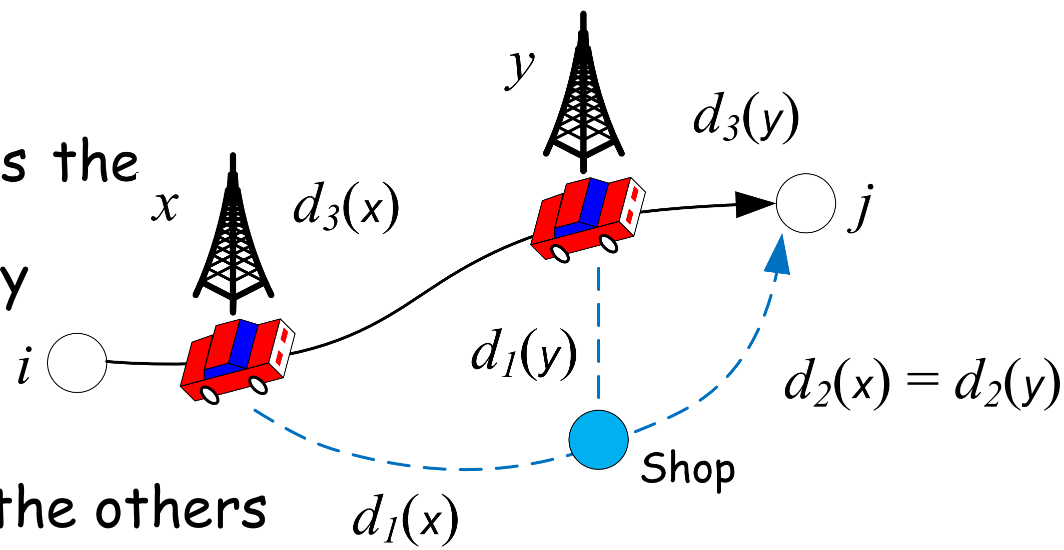
- Shopkeeper disseminates ads to passengers through RSUs
- Passengers in a flow may detour to the shop
- Detour probability depends on detour distance: $d_1 + d_2 - d_3$



Property

For a given flow, the first RSU on its path always provides the best detour option (compared to all other RSU locations on the path)

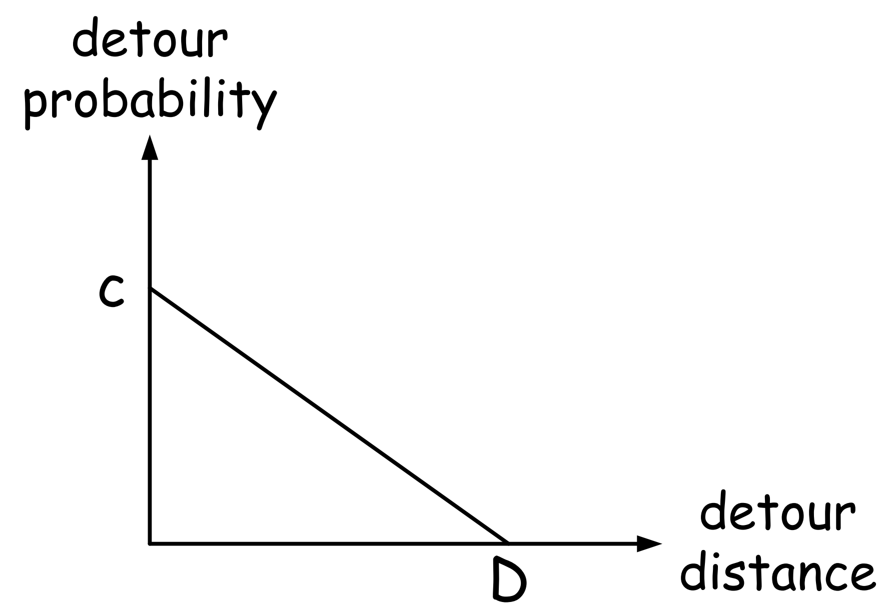
- Insight: first RSU provides the highest traveling flexibility
- The first RSU dominates the others
  - Redundant ads do not provide extra attraction



Detour probability

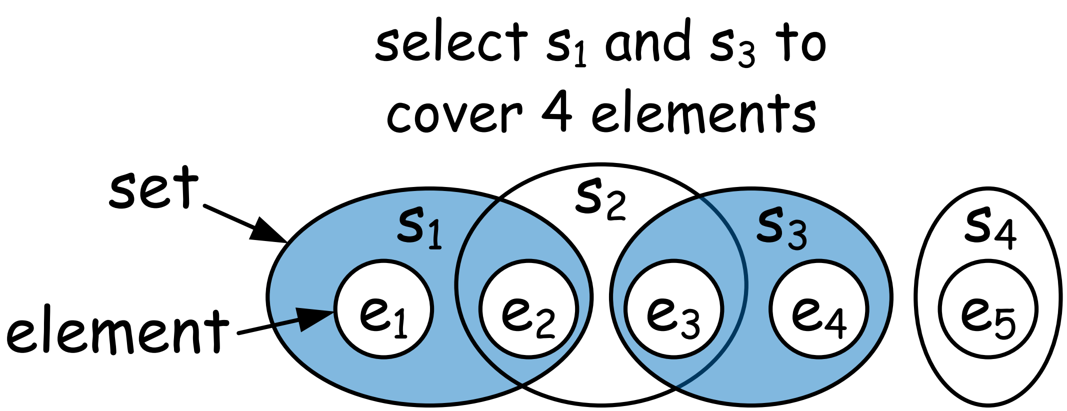
- For a traffic flow, *f*, with a detour distance, *d*
  - *p(d)*: the detour probability, decreasing utility function
  - An expectation of *|f| p(d)* passengers detour to the shop

$$p(d) = \begin{cases} c \times (1 - d / D) & d \leq D \\ 0 & otherwise \end{cases}$$



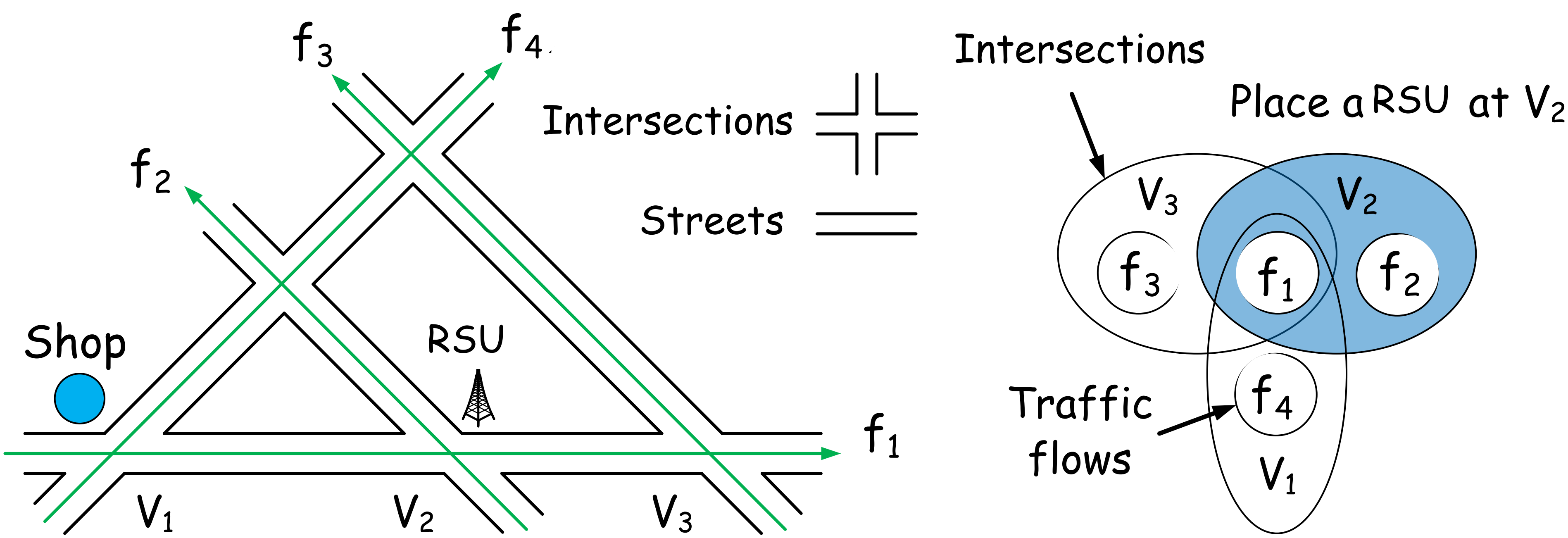
Related Work: Maximum Coverage

- Use a given # of sets (s) to maximally cover elements (e)
- Greedy algorithm with max marginal coverage has an approximation ratio of *1-1/e*
- Inapproximability result: best polynomial time approximation algorithm
- Weighted version: elements have benefits, sets costs



Our Problem

- Place RSUs on intersections to cover flows
- Different RSUs bring different detour probabilities



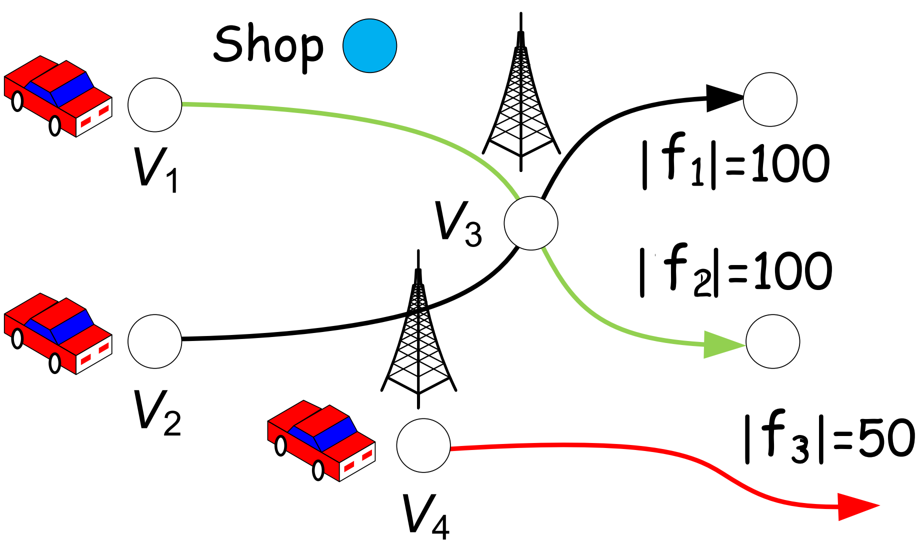
RSU Placement

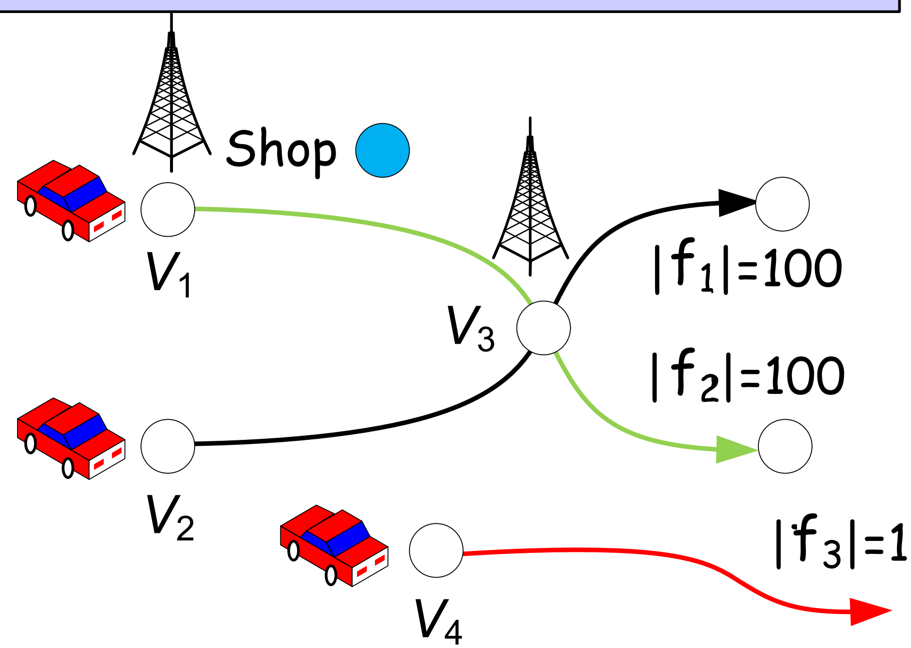
Composite Greedy Solution (CGS)

Iteratively find an intersection that can attract the maximum:

- Candidate i: passengers from the uncovered flows;
- Candidate ii: passenger from the covered flows, providing smaller detour distances;

Select i or ii that can attract more passengers to the shop





RSU Placement

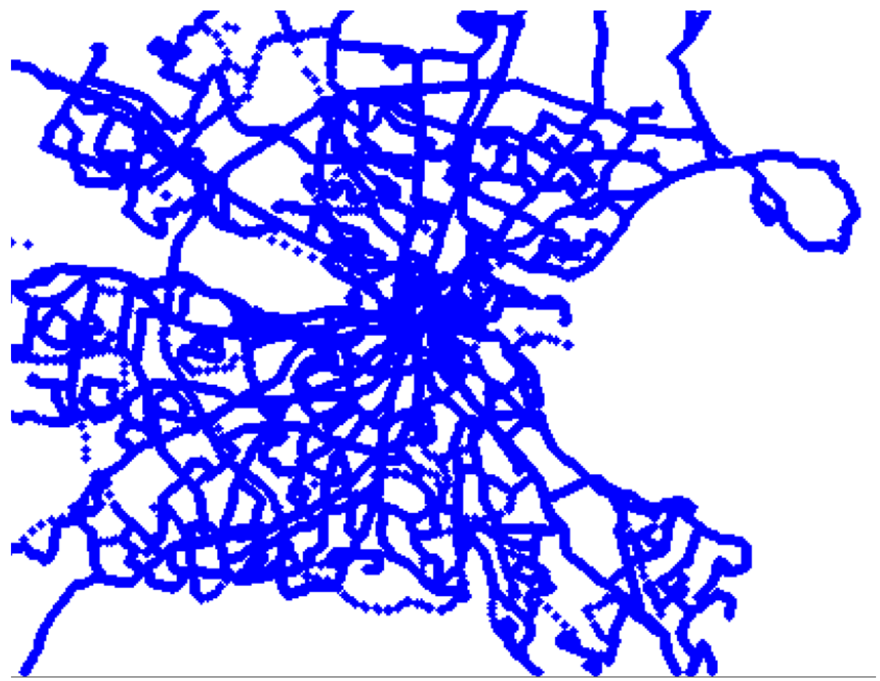
Theorem 1 [a]: The composite greedy solution has an approximation ratio of $1-1/\sqrt{e}$ to the optimal solution

Time complexity: $O(|V|^3+kn|V|)$

- $|V|$: # of intersections, k: # of RSUs, and n: # of flows
- Computing the detour distance takes $|V|^3$ (shortest paths of all pairs using the Floyd algorithm)
- Greedy algorithm has k steps; in each step, it visits each intersection to check traffic flows for coverage: $n|V|$

Experiments

- Dataset: Dublin bus trace
  - Includes bus ID, longitude, latitude, and vehicle journey ID
  - A vehicle journey represents a traffic flow
  - 80,000 * 80,000 square feet, c is set to be 0.001

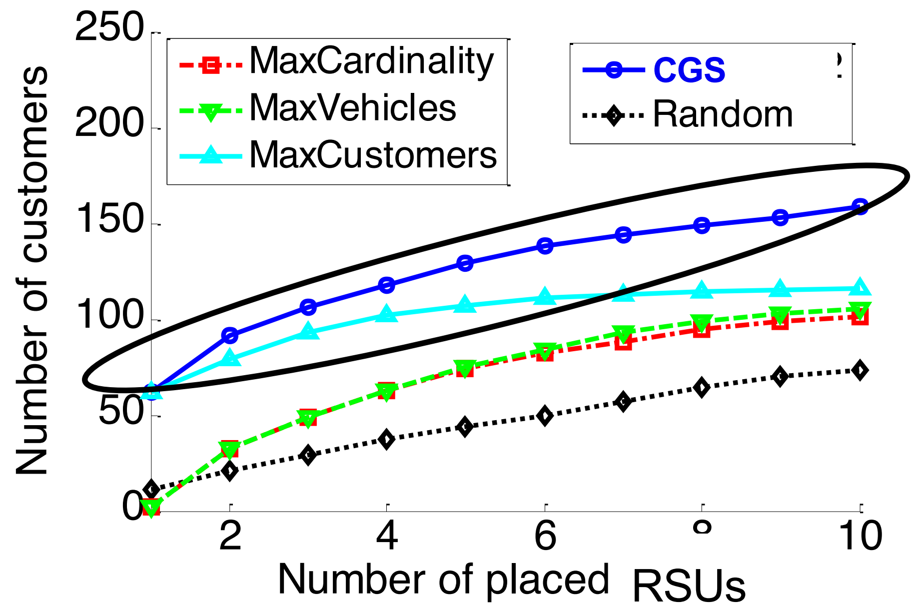


Experiments

- Other algorithms in comparison
  - MaxCardinality: ranks intersections by # of bus routes and places RSUs at the top-*k* intersections
  - MaxVehicles: ranks intersections by # of passing buses and places RSUs at the top-*k* intersections
  - MaxCustomers: ranks the intersections by the # of attracted passengers (flows) and places RSUs at the top-*k* intersections.
  - Random: places RSUs uniform-randomly among all the intersections

Experiments

- The impact of utility function (Dublin trace)
  - Shop in the city with *D*=20,000



$$f(d) = \begin{cases} 0.001 \times (1 - d / D) & d \le D \\ 0 & otheriwse \end{cases}$$

Traffic flow monitoring

Coverage

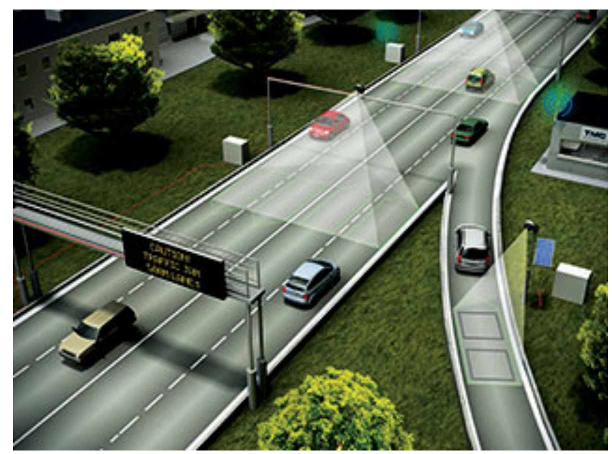
Each traffic flow goes through at least one RSU

Distinguishability

RSUs used to cover each flow is unique

Objective

Minimize the number of placed RSUs



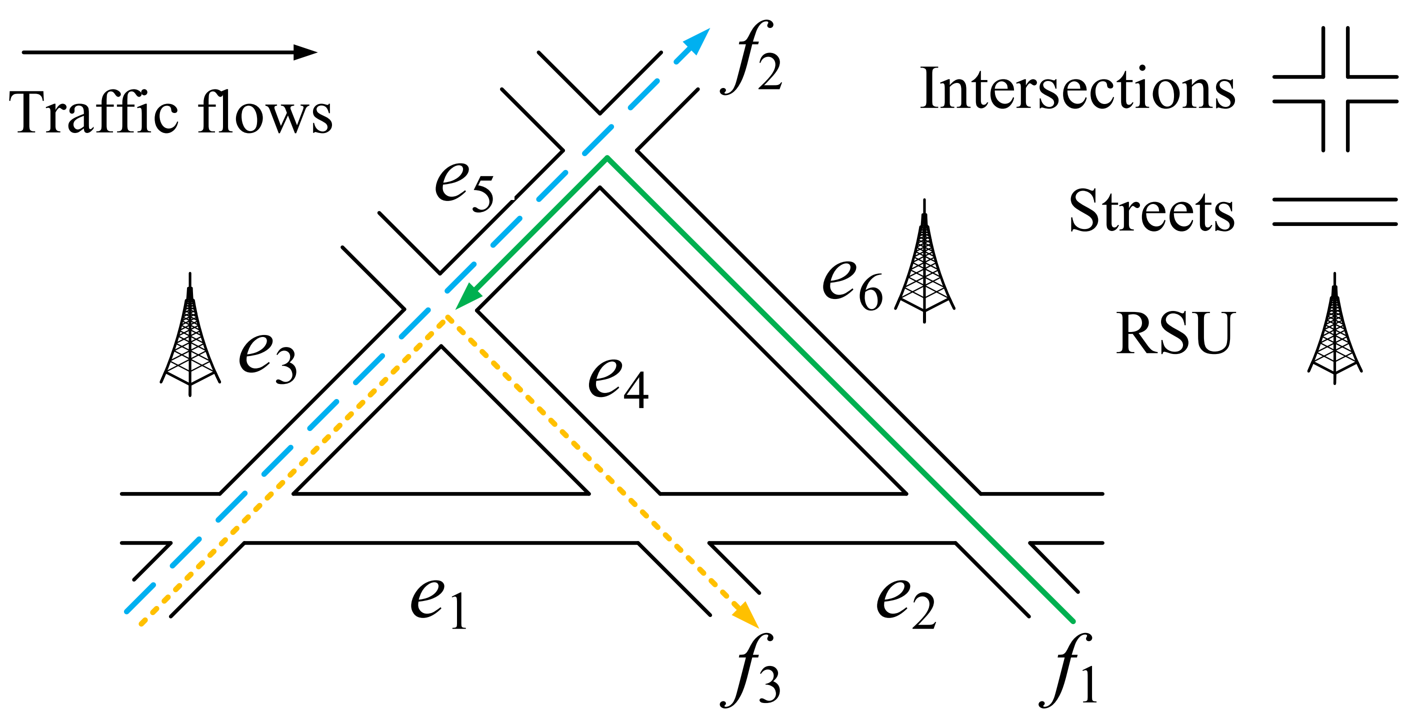
Examples

Case 1: f_2 and f_3 are covered, but not distinguishable

$f_1 : \{e_5, e_6\}$ $f_2 : \{e_3, e_5\}$ $f_3 : \{e_3, e_4\}$

Case 2: f_1, f_2 and f_3 are distinguishable, but f_1 is uncovered

$f_1 : \{e_5, e_6\}$ $f_2 : \{e_3, e_5\}$ $f_3 : \{e_3, e_4\}$



Model and Formulation

Graph G = (V, E)

V: street intersections, and E: streets

$F = \{f_1, f_2, \ldots, f_n\}$ is a set of *n* known flows on G

S is a subset of E on which RSUs are placed

S(f) is a subset of S that covers f

Formulation

Objective: minimizing the number of RSUs

minimize $|S|$ (# of RSUs)

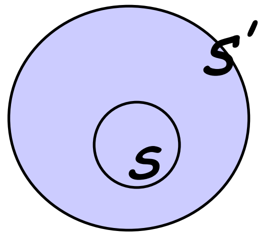
s.t. $S(f) \neq \emptyset$ for $\forall f \in F$ (coverage)

$S(f) \neq S(f')$ for $f \neq f'$ (distinguishability)

Related Work: Submodularity

N(S): # of covered and distinguishable flows under S

Monotonicity: $N(S) \leq N(S')$ for $\forall S \subseteq S', S' \subseteq E$



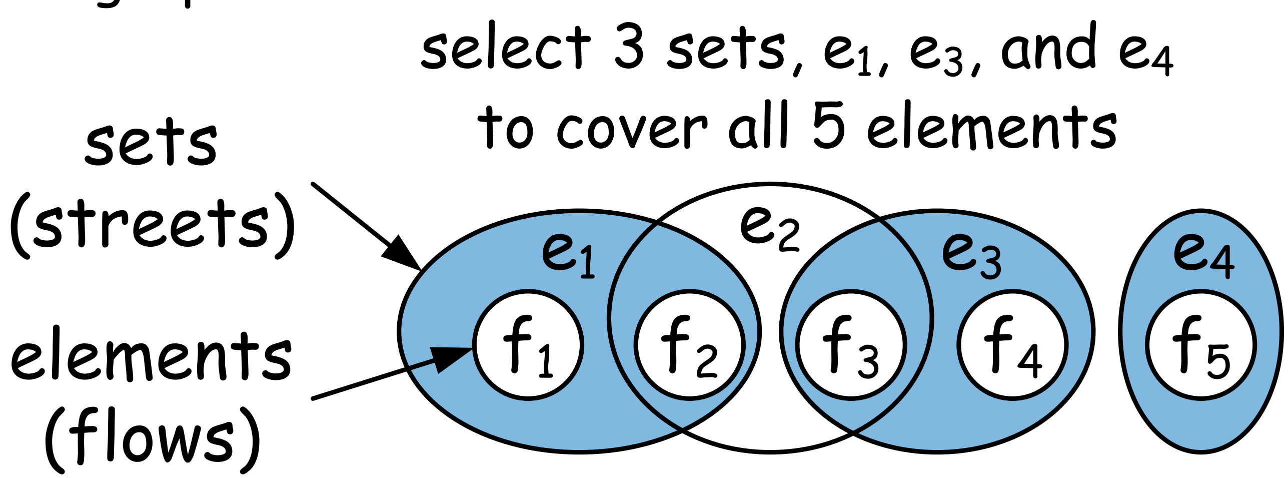
(Monotonicity enables greedy approaches)

Submodularity: $N(S \cup \{e\}) - N(S) \geq N(S' \cup \{e\}) - N(S')$ for $\forall e \in E$

(Submodularity ensures bounds)

Related Work: Set Cover

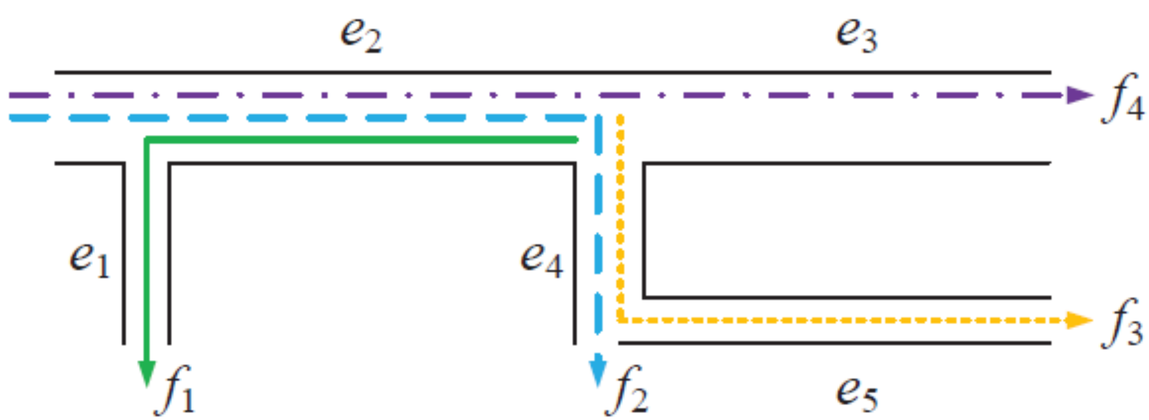
- Use minimum number of sets to cover all elements
- Greedy algorithm with max marginal coverage has a ratio of O(log n) due to submodularity
- Inapproximability result: best polynomial time approx. algo.
- Hitting set problem: right-vertices cover left-vertices in a bipartite graph



Problem Analysis

NP-hard: reduction from the set cover problem

Non-submodularity: traditional coverage



$S = \{e_1\}$ and $S' = \{e_1, e_4\}$

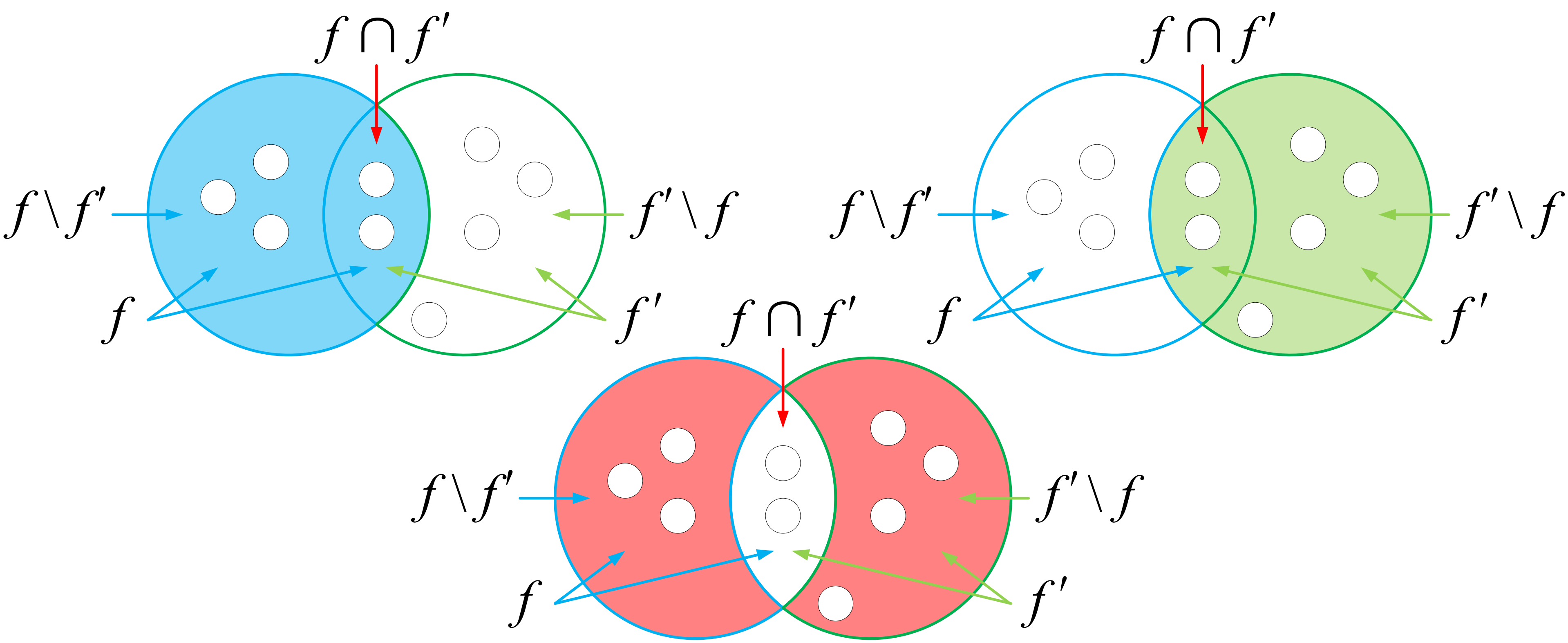
$N(S) = N(S') = 1$, only f_1 is covered/distinguishable

$N(S \cup \{e_2\}) = 1$, no change

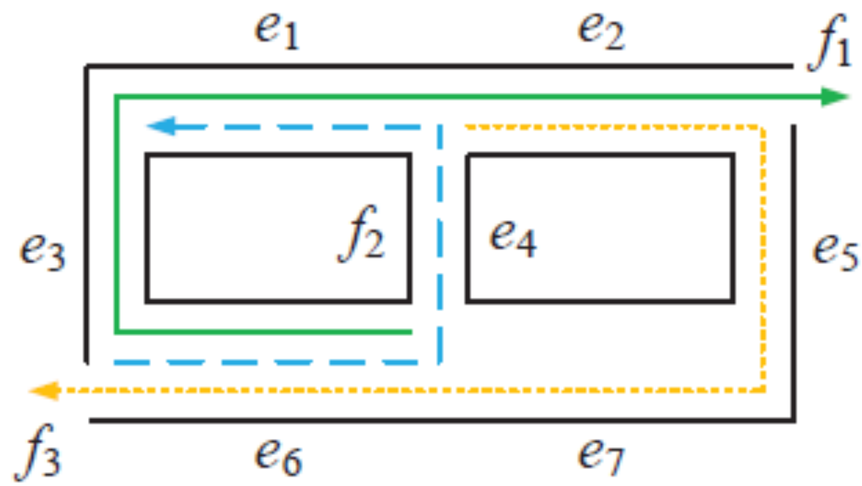
$N(S' \cup \{e_2\}) = 4$, all flows are covered/distinguishable

3-out-of-3 Principle

To cover and distinguish an arbitrary pair of traffic flows (f and f'), each of f, f', and $f \triangle f' = (f \setminus f') \cup (f' \setminus f)$ should include a street with a RSU placement



Example



subsets	f_1	f_2	f_3
streets	e_1, e_2, e_3, e_6	e_1, e_4, e_6	e_2, e_5, e_6, e_7

subsets	$f_1 \triangle f_2$	$f_1 \triangle f_3$	$f_2 \triangle f_3$
streets	e_2, e_3, e_4	e_1, e_3, e_5, e_7	e_1, e_2, e_4, e_5, e_7

1st iteration, e_1 is added to S (appears in 4 subsets)

2nd iteration, e_2 is added to S, and terminated

S = {e1, e2}, with $S(f_1) = \{e_1, e_2\}$, $S(f_2) = \{e_1\}$, and $S(f_3) = \{e_2\}$

Improved Subset-Based Greedy (ISBG)

Idea: in each greedy iteration, place an RSU that is in maximum number of subsets of f, f', and f △ f'

Initialize S = ∅
for each pair of traffic flows (say f and f') **do**
    Generate subsets of f, f', and f △ f'
while there exists a subset **do**
    Update S to place an RSU that is in maximal number of subsets, remove corresponding subsets
return S

ISBG Performance

Theorem 2 [b]: ISBG has an approximation ratio $\ln [n(n+1)/2] = O(\ln n)$ to the optimal solution, where n is the number of traffic flows

Prove by converting to set cover with a ratio of ln [n(n+1)/2], where n(n+1)/2 is the number of subsets

Time complexity: $O(n^2|E|^2)$

Each greedy iteration visits |E| RSUs for n(n-1)/2 pairs of traffic flows, with |E| iterations

Experiments

Real data-driven: Seattle

- 10,000 × 10,000 square foot area
- 135 given traffic flows on 2,283 streets

(a) The Seattle map.

(b) The bus trace.

Comparison Algorithms

Coverage-Oriented Greedy (COG): greedily covers all traffic flows, and then uniform-randomly place RSUs to distinguish them. $O(n^2|E|^2)$

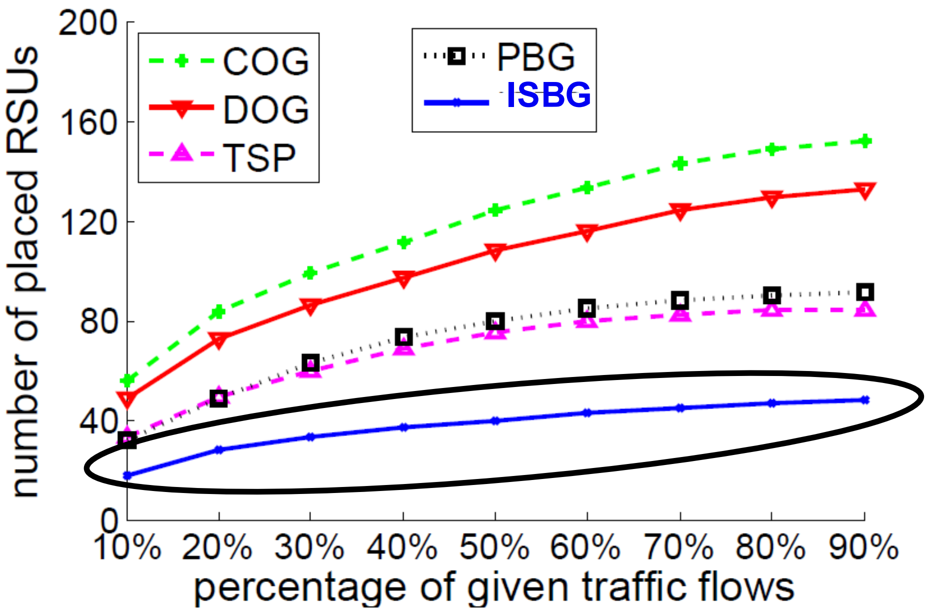
Two Stage Placement (TSP): greedily covers all traffic flows in the 1st stage, and then, greedily distinguishes all traffic flows in the 2nd stage. $O(n^2|E|^2)$

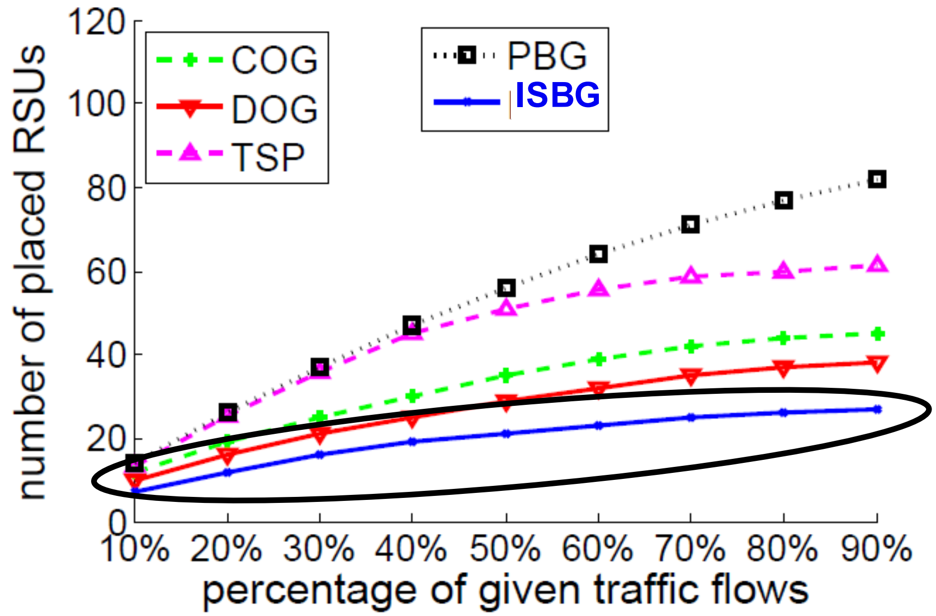
Distinguishability-Oriented Greedy (DOG): greedily distinguishes pairs of traffic flows by placing an RSU at $f \triangle f'$ until all flows are distinguishable. $O(n^2|E|^2)$

2-out-of-3 (PBG): To cover and distinguish an arbitrary pair of traffic flows (f and f'), two RSUs should be placed on streets from two different subsets from $f \backslash f'$, $f' \backslash f$, and $f \cap f'$. $O(n^2|E|^3)$

Experiments

Dublin (left) and Seattle (right)





Different flow patterns in Dublin and Seattle

Conclusion

Maximum and minimum coverage using RSUs

- Variation of max coverage to maximally attract passengers
- Variation of min set cover to ensure coverage and distinguishability

Future works

- Extensions: Effect of multiple RSUs, multiple shops, …
- Applications: Flow monitoring/calculation in SDN networks, …

Q & A

[a] H. Zheng and J. Wu, "Optimizing Roadside Advertisement Dissemination in Vehicular Cyber-Physical Systems," *Proc. of IEEE ICDCS* 2015.

[b] H. Zheng, W. Chang, and J. Wu, "Coverage and Distinguishability Requirements for Traffic Flow Monitoring Systems," *Proc. of IEEE/ACM IWQoS* 2016 (Best Paper Award).