Coverage and Distinguishability in Traffic Flow Monitoring

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Road Map

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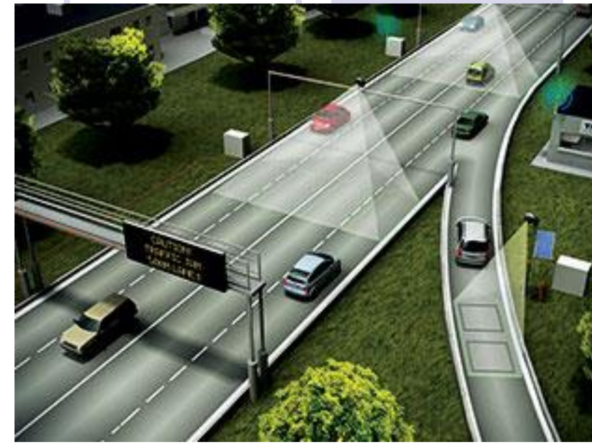
- 2. Model and Formulation
- 3. Related Work
- 4. Problem Analysis and Algorithms
- 5. Experiments
- 6. Conclusion

1. Introduction



Traffic flow monitoring system

- Camera and WiFi based monitor
- Roadside Unit (RSU) deployment

Multiple applications

- Outdoor flow rate with flow trajectory
- Indoor tracking with beacon messages
- General network (SDN) monitoring

RSU placement

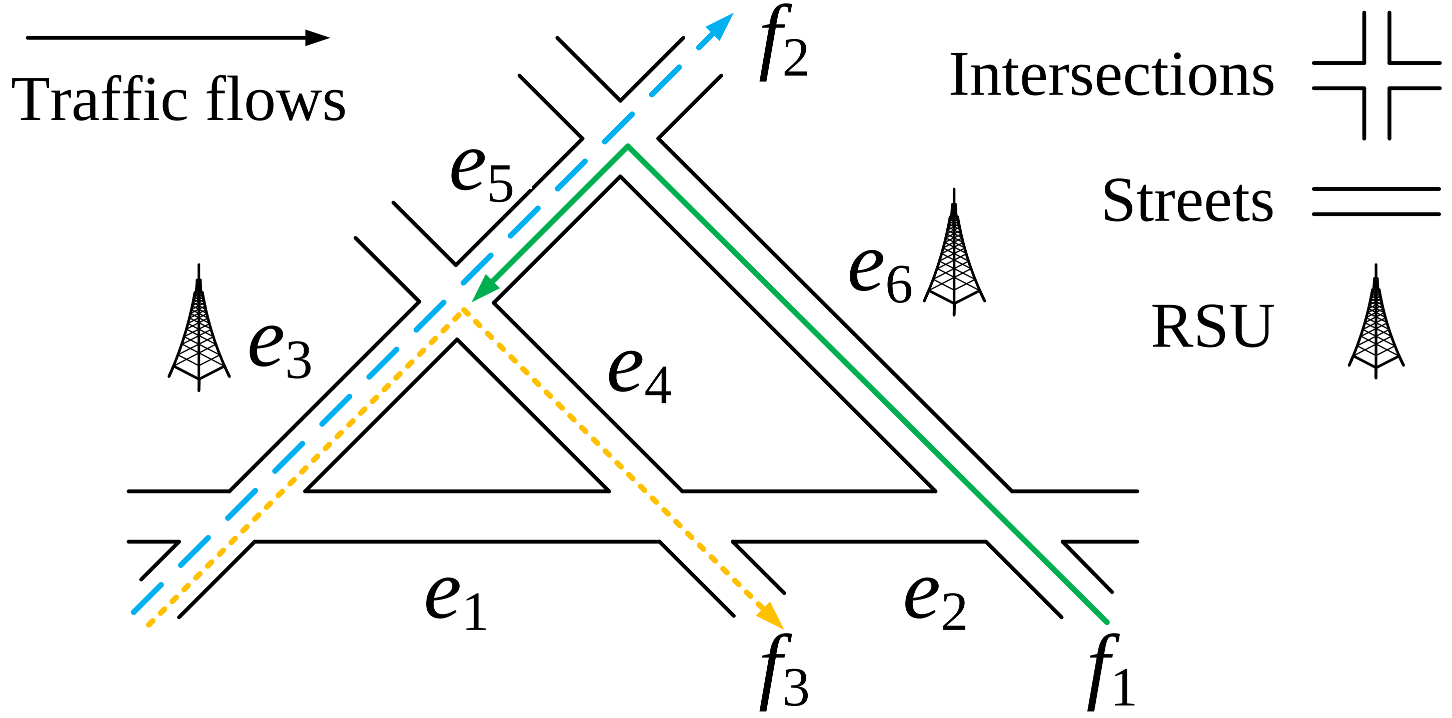
RSU placement problem (given traffic flows)

- Coverage
  - Each traffic flow goes through at least one RSU
- Distinguishability
  - The set of bypassed RSUs is unique for each flow
- Objective
  - Minimize the number of placed RSUs

Example 1

f_2 and f_3 are covered, but not distinguishable

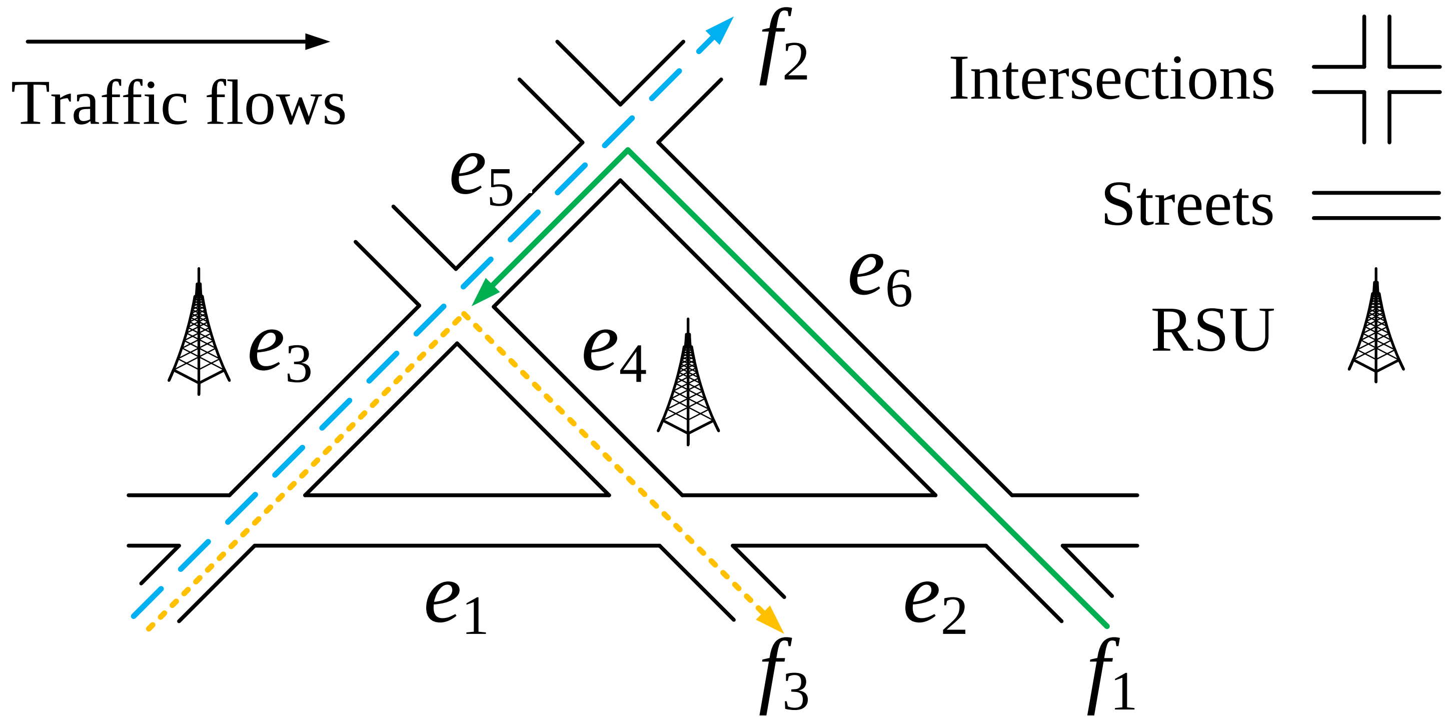
$f_1 : \{e_5, e_6\}$ $f_2 : \{e_3, e_5\}$ $f_3 : \{e_3, e_4\}$



Example 2

f_1, f_2 and f_3 are distinguishable, but f_1 is uncovered

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



2. 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 traffic flows on G

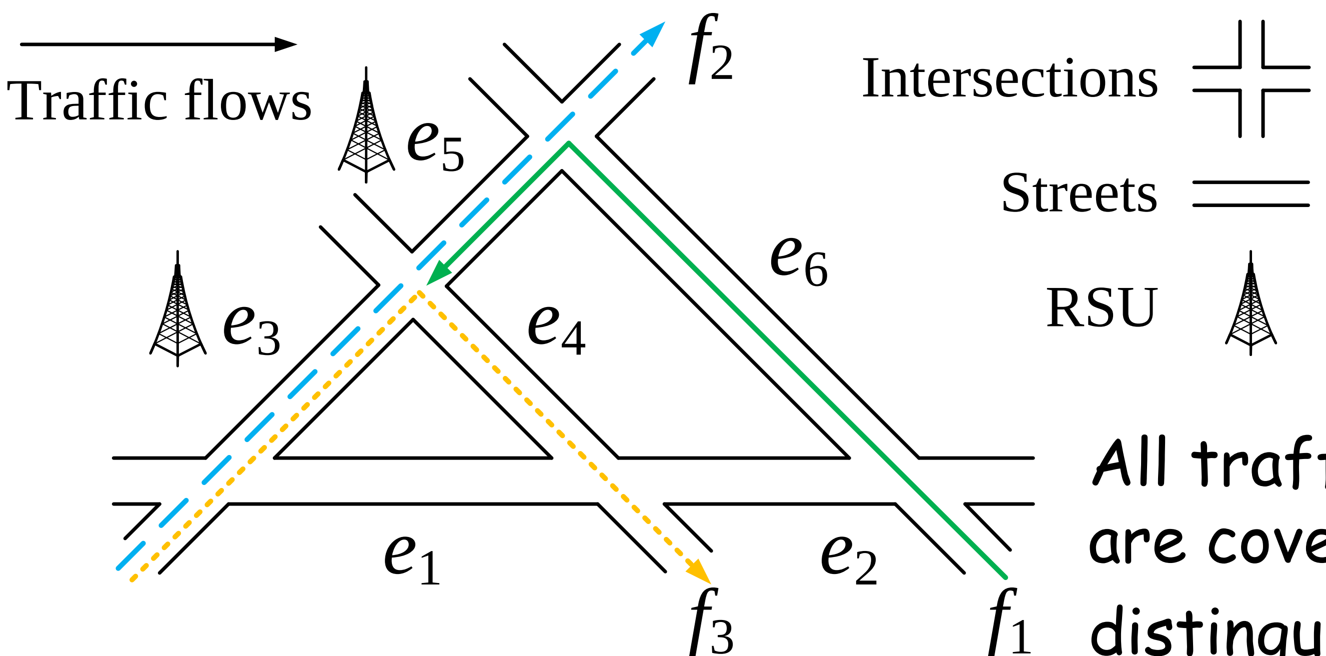
S is a subset of E on which RSUs are placed

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

Another Example

$S = \{e_3, e_5\}$ with $F = \{f_1, f_2, f_3\}$

f_1: $\{e_5, e_6\}$ $S(f_1) = \{e_5\}$	f_2: $\{e_3, e_5\}$ $S(f_2) = \{e_3, e_5\}$	f_3: $\{e_3, e_4\}$ $S(f_3) = \{e_3\}$



All traffic flows are covered and distinguishable

Formulation

Objective is minimizing the number of RSUs

- Coverage
  - Each traffic flow goes through at least one RSU
- Distinguishability
  - The set of bypassed RSUs is unique for each flow

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)

3. Related Work: Set Cover Problem

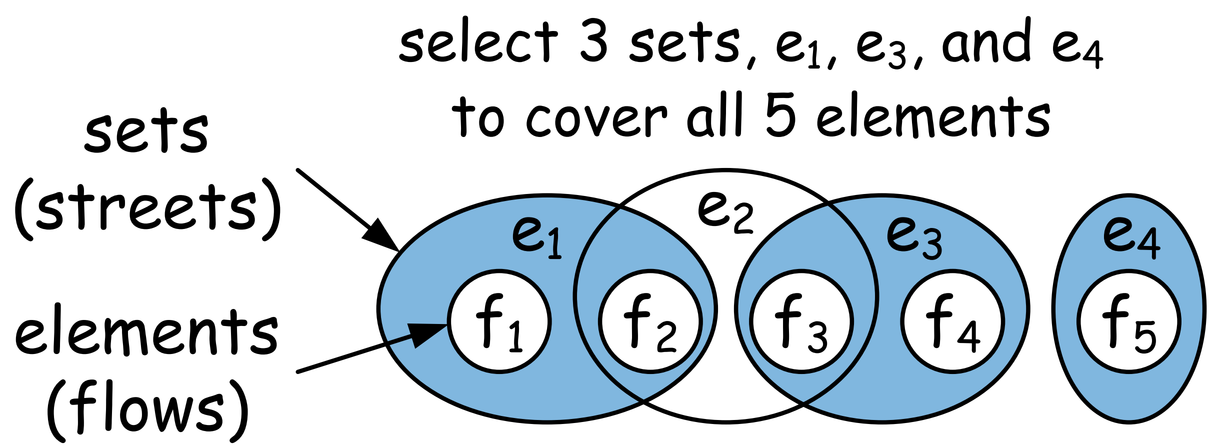
Use minimal sets to cover all elements

Greedy algorithm with max marginal coverage has a ratio of log n due to submodularity

Complexity: $O(p^2q)$

p: # of sets

q: # of elements



Submodularity

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

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

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

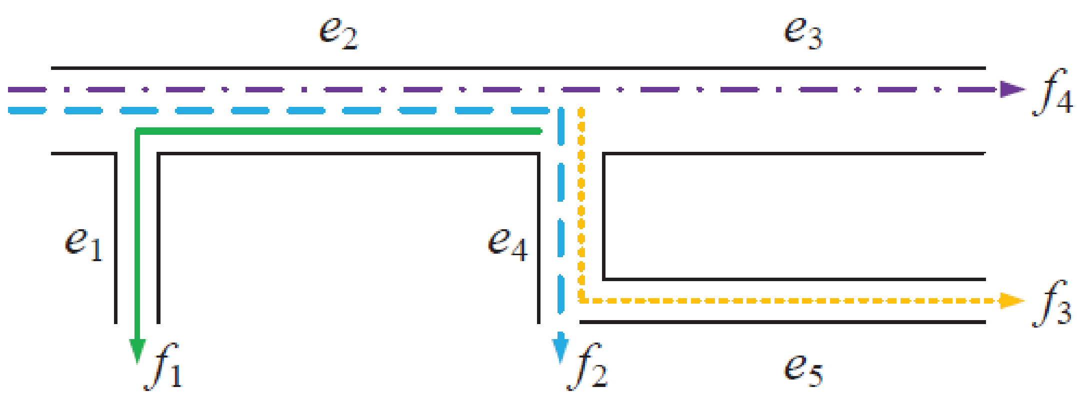
Monotonicity enables greedy approaches

Submodularity ensures bounds

4. Problem Analysis and Algorithms

NP-hard: reduction from the set cover problem

Counter-example of submodularity using traditional coverage



Existence case: $S = \{e_1\}$ and $S' = \{e_1, e_4\}$

$N(S) = N(S \cup \{e_2\}) = N(S') = 1$, only f_1 is covered

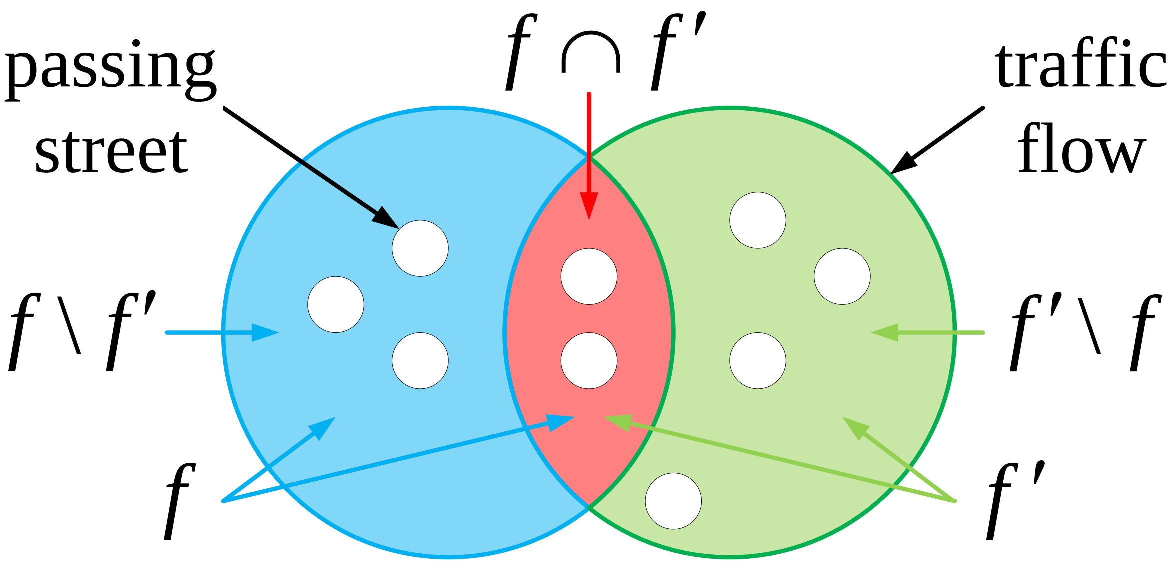
$N(S' \cup \{e_2\}) = 4$, all flows are covered/distinguishable

$N(S \cup \{e_2\}) - N(S) = 0 < N(S' \cup \{e_2\}) - N(S') = 3$

2-out-of-3 principle

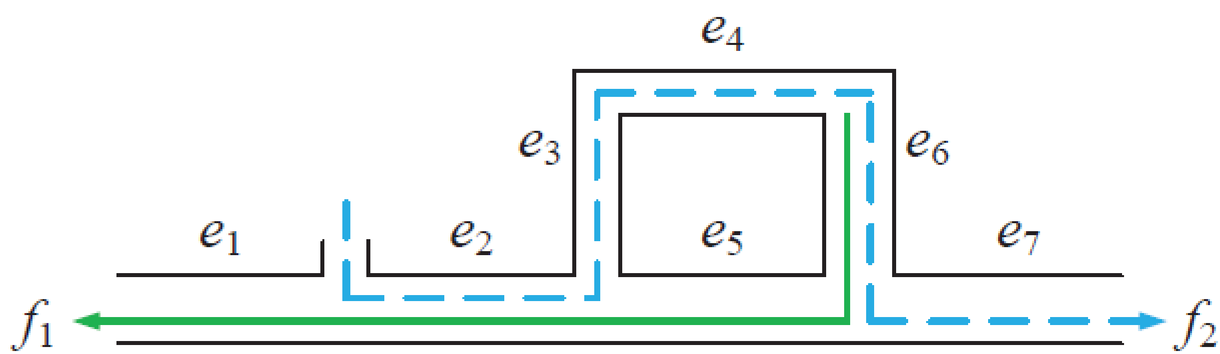
Key idea: place pairwise distinguishability in coverage

To cover and distinguish an arbitrary pair of traffic flows (f and f'), two RSUs should be placed on streets from two different subsets of f\f', f'\f, and f ∩ f'.



2-out-of-3 Example

Subsets



three disjoint subsets for $f_1 \cup f_2$	$f_1 \backslash f_2$	$f_2 \backslash f_1$	$f_1 \cap f_2$
corresponding streets (edges)	e_1, e_5	e_3, e_4, e_7	e_2, e_6

To satisfy $S(f_1) \neq \emptyset$, $S(f_2) \neq \emptyset$, and $S(f_1) \neq S(f_2)$

S can have $\{e_1, e_3\}$, $\{e_2, e_4\}$, or $\{e_5, e_6\}$

cannot have $\{e_1, e_5\}$, $\{e_3, e_4\}$, or $\{e_2, e_6\}$

Simple Algorithm

Pair-Based Greedy (PBG)

Idea: place a pair of RSUs in each greedy iteration

Initialize S = ∅

while there exists a pair of traffic flows **do**

    Update S to place a pair of RSUs that cover and distinguish maximum pairs of traffic flows

    Remove corresponding pairs of traffic flows

return S

Element in submodular coverage: a pair of RSUs

PBG Performance

Approximation ratio: $n * \ln [n(n-1)/2]$

- n is the number of traffic flows

Prove by converting to set cover problems

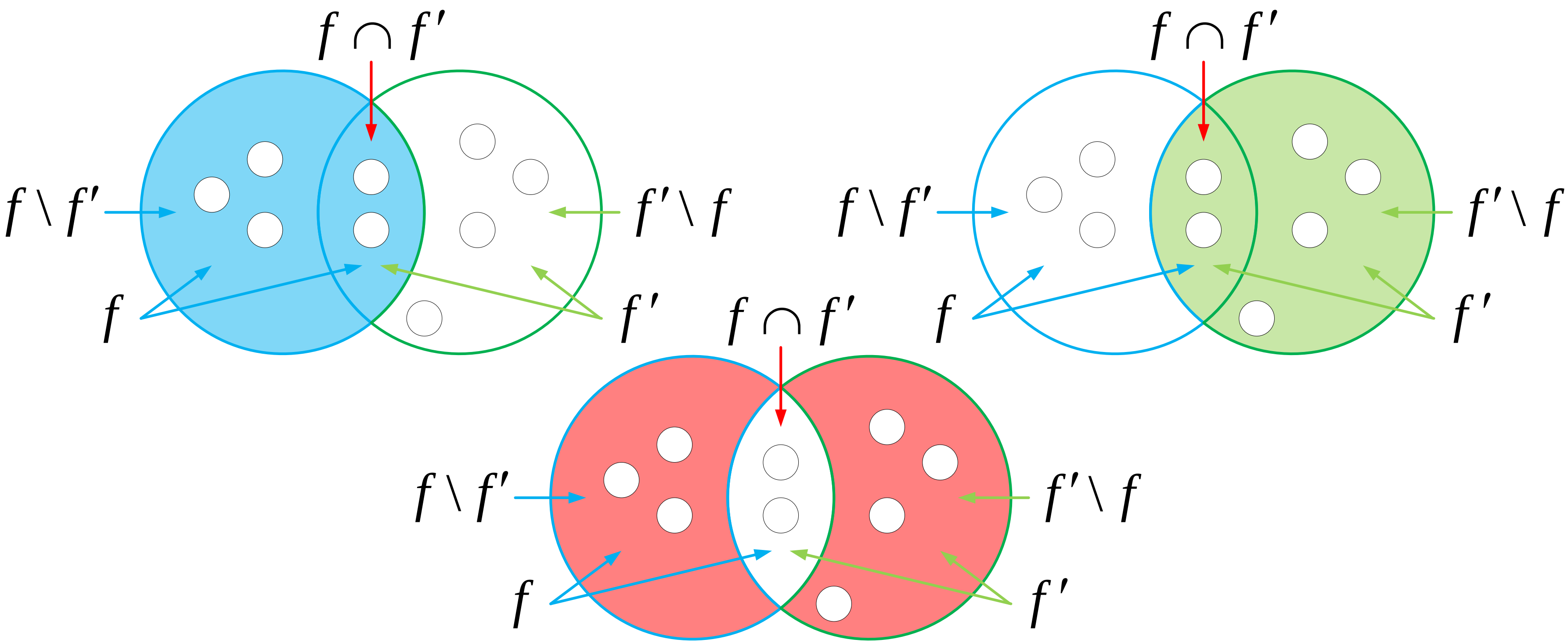
- Pair conversion brings a loss ratio of n, and set cover has a ratio of $\ln [n(n-1)/2]$ with $n(n-1)/2$ sets

Time complexity: $O(n^2|E|^3)$

- Each greedy iteration visits $|E|^2$ pairs of RSUs for n^2 pairs of traffic flows, with $|E|$ iterations.

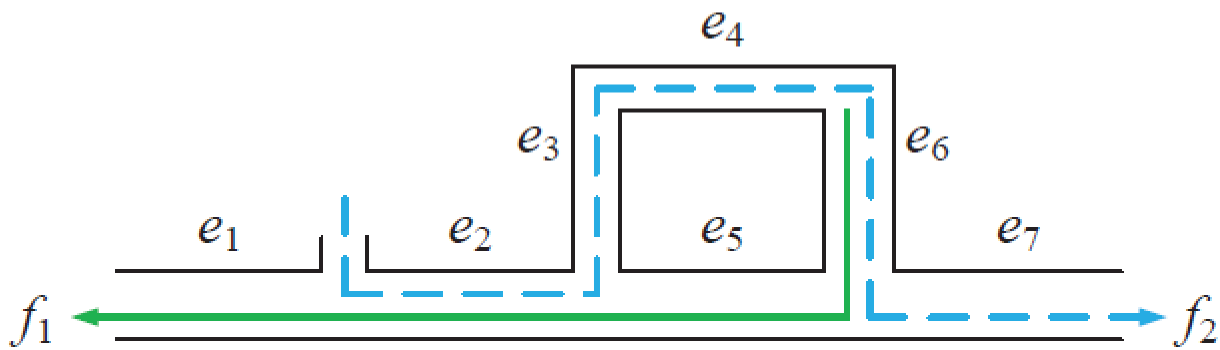
3-out-of-3 Principle

To cover and distinguish an arbitrary pair of traffic flows (f and f′), each of f, f′, and f∆f′ = (f\f′)∪(f′\f) should include a street with a placed RSU.



3-out-of-3 Example

Subsets



subsets	f_1	f_2	$f_1 \triangle f_2$
streets (edges)	e_1, e_2, e_5, e_6	e_2, e_3, e_4, e_6, e_7	e_1, e_3, e_4, e_5, e_7

To satisfy $S(f_1) \neq \emptyset$, $S(f_2) \neq \emptyset$, and $S(f_1) \neq S(f_2)$

S can have $\{e_1, e_3\}$, $\{e_2, e_4\}$, or $\{e_5, e_6\}$

cannot have $\{e_1, e_5\}$, $\{e_3, e_4\}$, or $\{e_2, e_6\}$

Improved Algorithm

Improved Subset-Based Greedy (ISBG)

Idea: in each greedy iteration, place an RSU that is in maximal 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 subsets, remove corresponding subsets
return S

Elements in submodular coverage: each RSU

ISBG Performance

Approximation ratio: $\ln [n(n+1)/2]$

n is the number of traffic flows

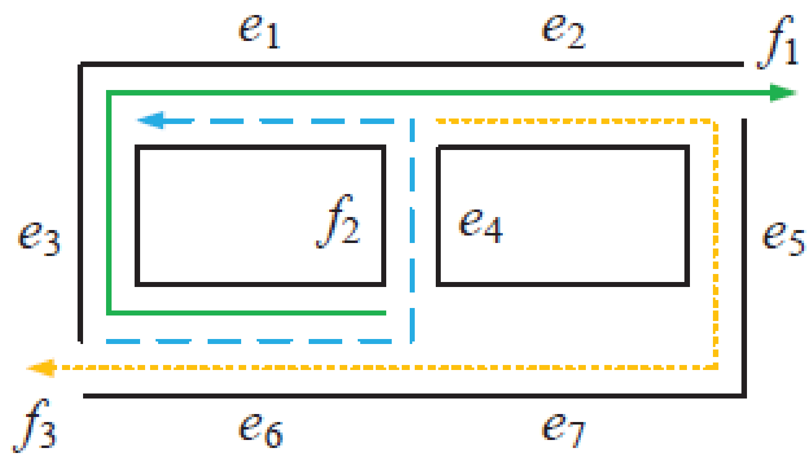
Prove by converting to set cover problems

Perfect conversion, and set cover has a ratio of $\ln [n(n+1)/2]$ with $n(n+1)/2$ sets

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

Each greedy iteration visits $|E|$ RSUs for n^2 pairs of traffic flows, with $|E|$ iterations

ISBG 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

Terminate when S = {e1, e2}

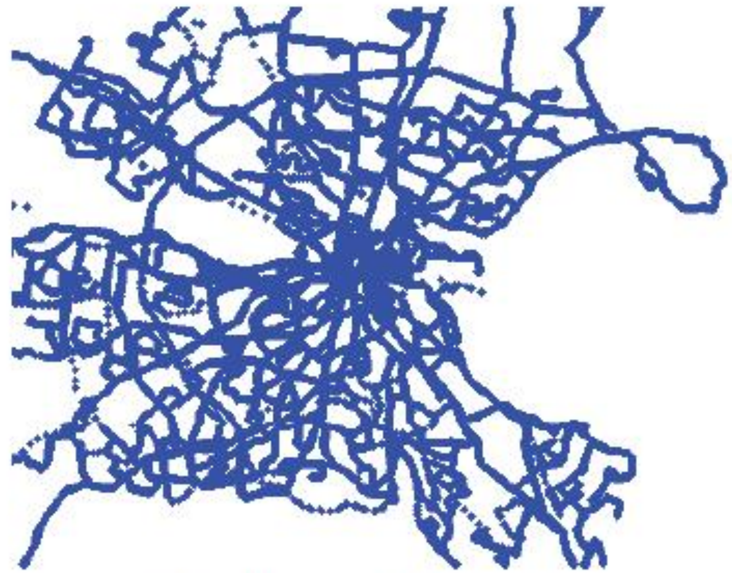
$S(f_1) = \{e_1, e_2\}$, $S(f_2) = \{e_1\}$, and $S(f_3) = \{e_2\}$

5. Experiments

Real data-driven: Dublin

- 80,000 × 80,000 square foot area
- 628 given traffic flows on 3,657 streets

(a) The Dublin map.



(b) The vehicle trace.

Experiments (con't)

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

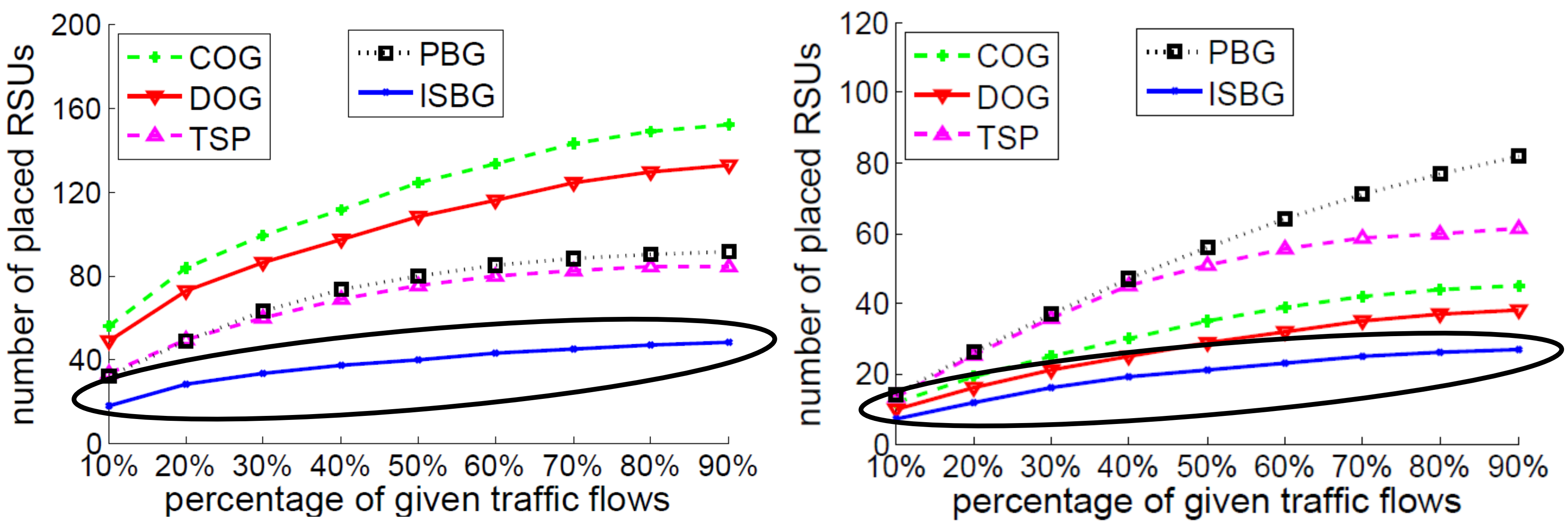
Coverage-Oriented Greedy (COG): greedily covers all traffic flows, and then uniform-randomly place RSUs to distinguish them. $O(n^2|E|^2)$

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. $O(n^2|E|^2)$

5. Experiments

Dublin (left) and Seattle (right)



Smaller is the better

Different flow patterns in Dublin and Seattle

6. Conclusion

- Minimize the number of RSUs
  - Under coverage and distinguishability requirements
- NP-hard, monotonicity, but non-submodularity
  - Different from classic submodular set cover problems
- Approximation algorithms
  - Different intuitions and time complexities