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Location Privacy Protection with a Semi-honest Anonymizer in Information Centric Networking

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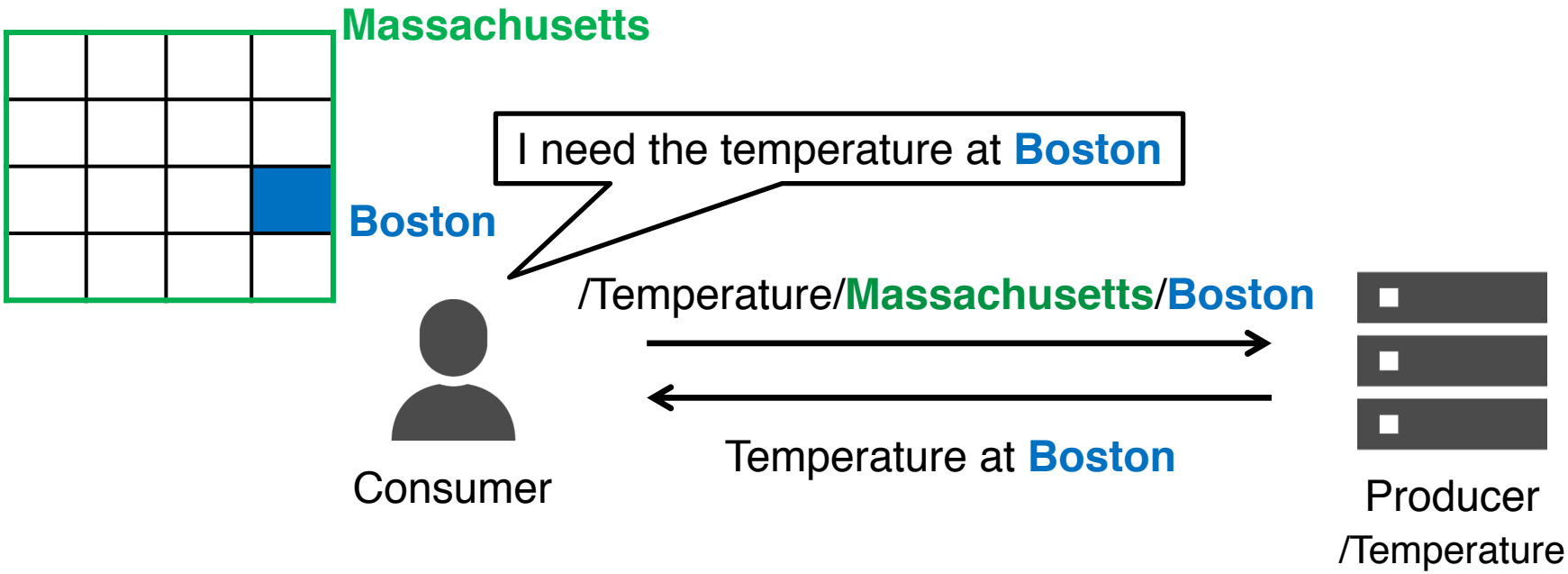
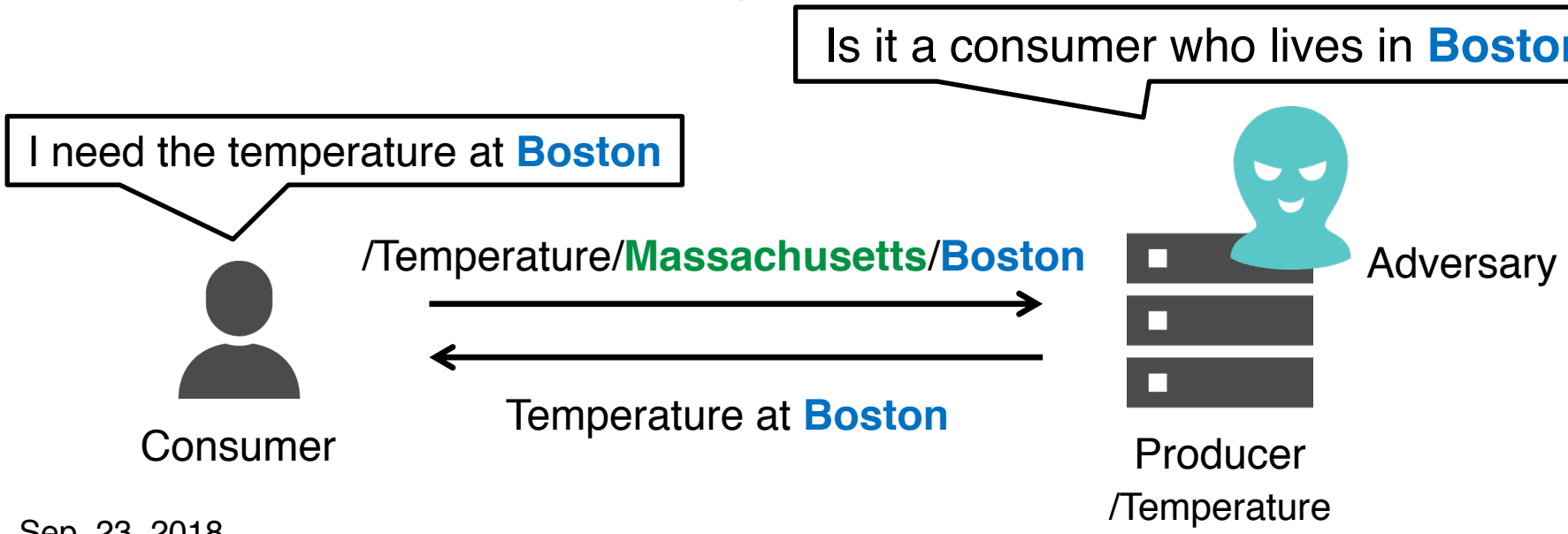
Location-Based Services

- System model of LBSs
  - Consumers choose locations of their interests (target locations) from a set of locations where producers offers its services (service area) and send names of the locations to the producers
  - Producers return data based on the locations



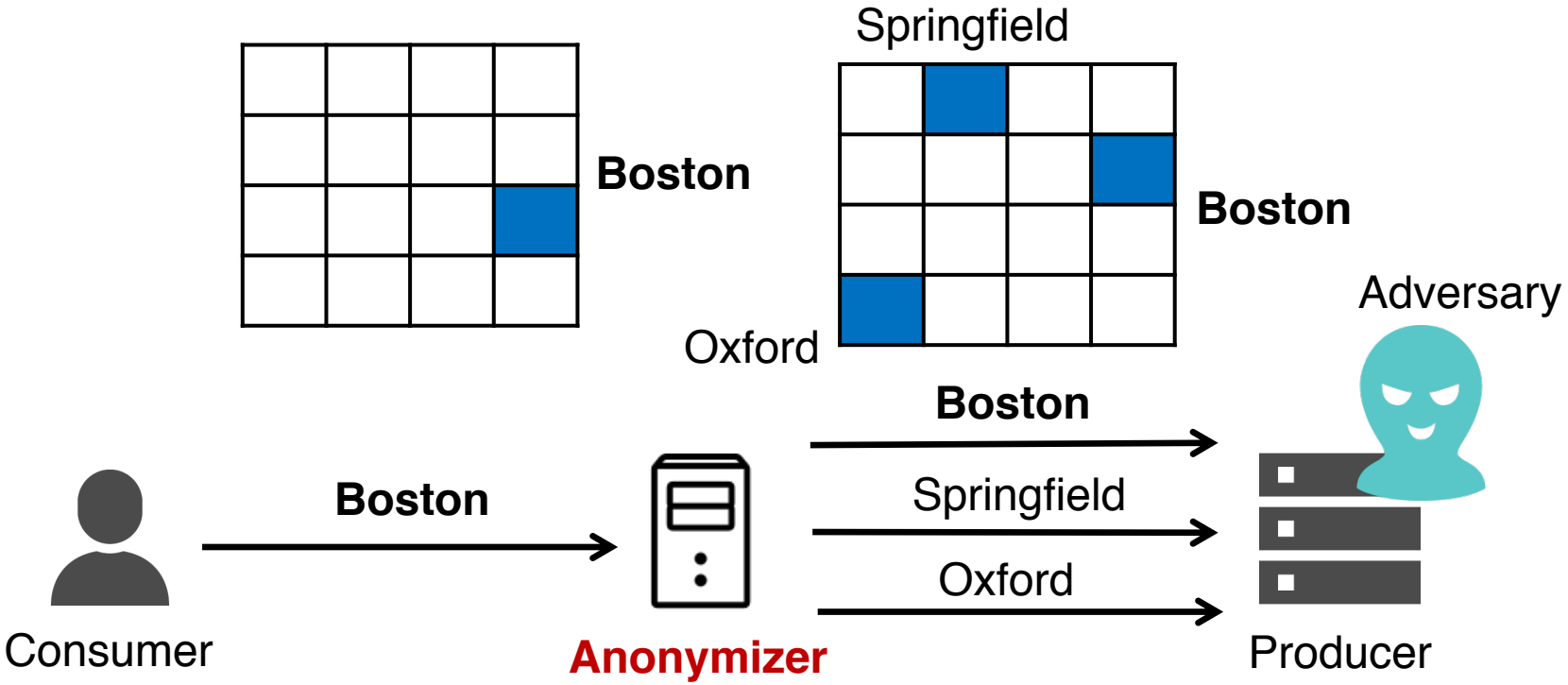
Privacy in LBSs

- Goal : **Location Privacy**
  - Hiding consumers' target locations from adversaries (including producers) in LBSs
- Privacy Problem in LBSs
  - Consumers' target locations can easily be linked to their sensitive information
    - home locations, life styles



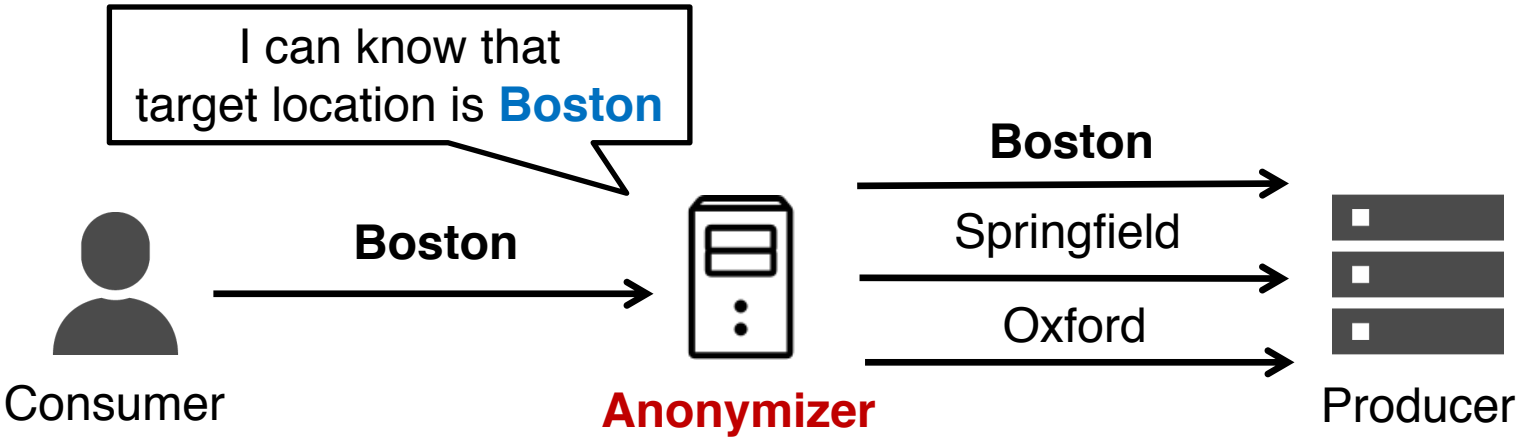
Existing Approaches

- Honest anonymizer to achieve location anonymity
  - Hiding each consumer's target location into other $k-1$ dummy locations to achieve k-anonymity of locations
    - Anonymous location set : a set of k locations which includes a consumer's target location
  - An anonymizer generates anonymous location sets from consumers' requests about their target locations



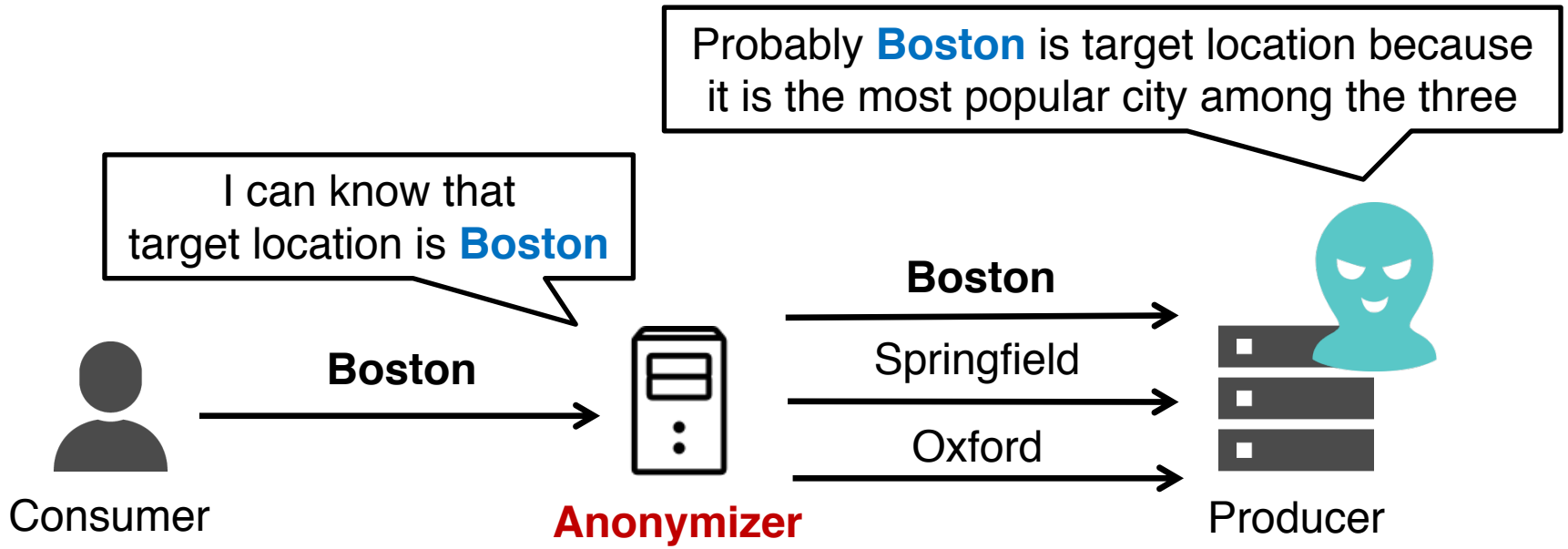
Problems #1 in Existing Approaches

1. The anonymizer can identify consumers' target locations
   - Hence, the anonymizer must be honest (trusted third party)



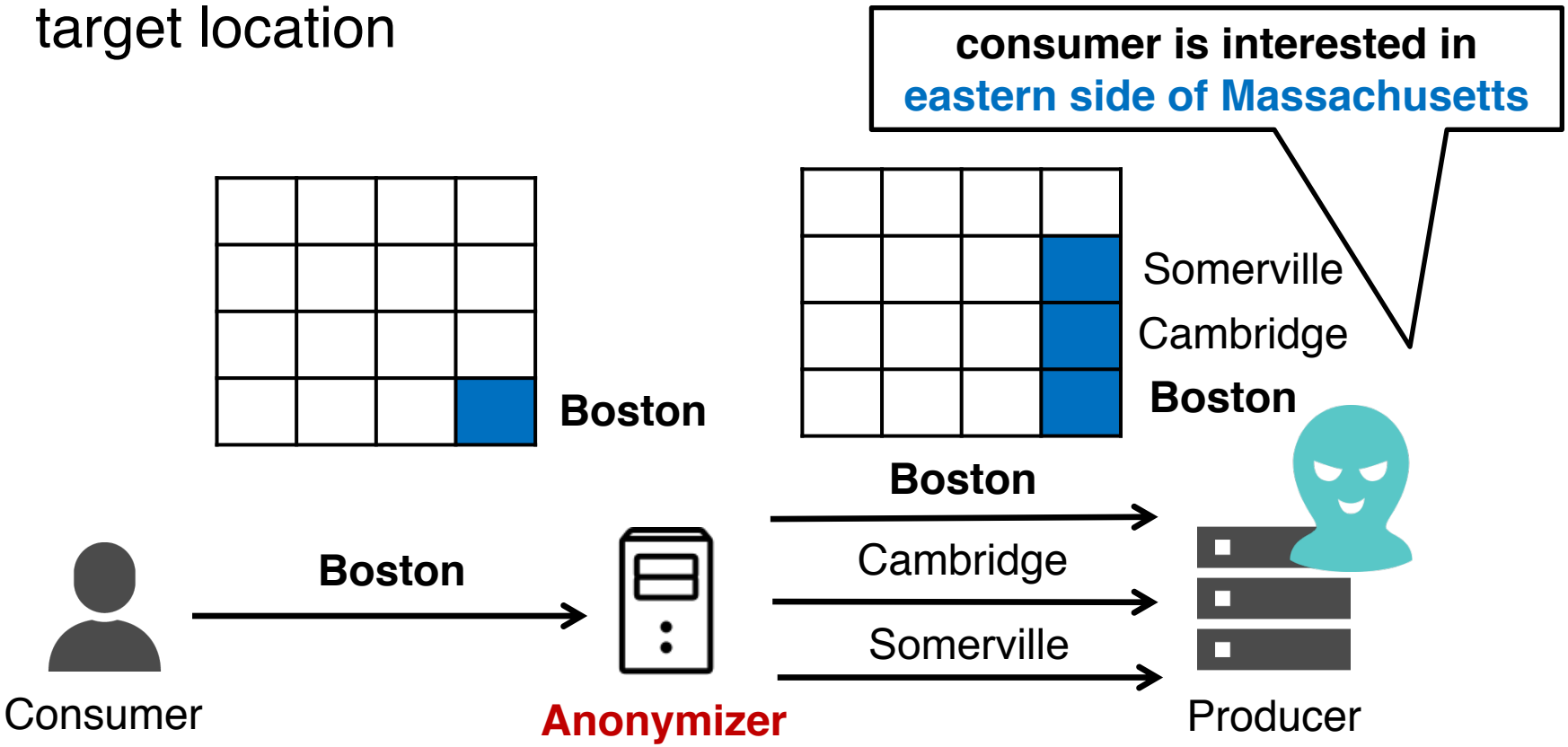
Problems #2 in Existing Approaches

1. The anonymizer can identify consumers' target locations
   - Hence, the anonymizer must be honest (trusted third party)
2. Adversaries can infer target locations from anonymous location sets by leveraging popularities of locations



Problems #2 in Existing Approaches

1. The anonymizer can identify consumers' target locations
   - Hence, the anonymizer must be honest (trusted third party)
2. Adversaries can narrow target location to a region with a certain degree of accuracy even if they cannot infer target location



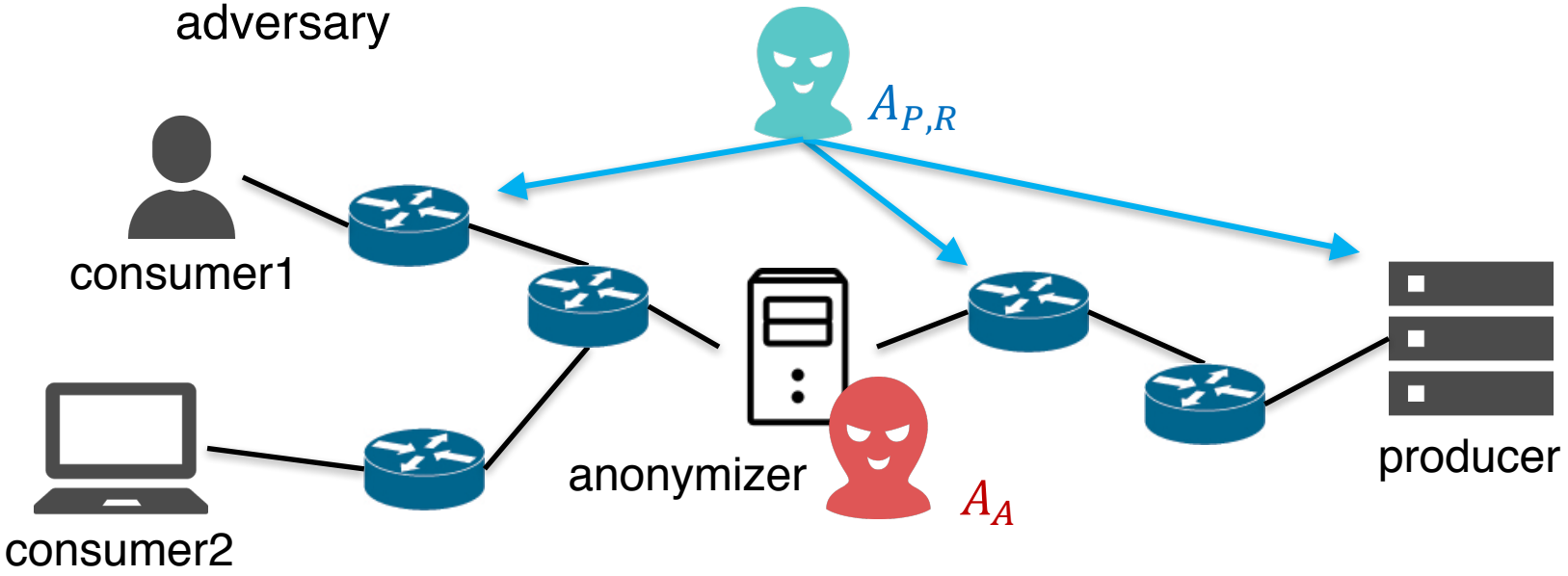
Challenges

1. Semi-honest anonymizer
   - Designing a semi-honest anonymizer in NDN
     - An semi-honest entity **follows prescribed protocols** but attempts to gain more information than allowed from the protocols, and **does not collude** with others to launch attacks

2. Dummy locations selection
   - Rigorously defining location anonymity satisfying the following two requirements
     1. Preventing adversaries from **probabilistically inferring** target locations
     2. Minimizing **geographical information** of target locations leaked to adversaries

Adversarial Model

- Two semi-honest adversaries who attempt to infer target locations from received/eavesdropped packets
  - $A_{P,R}$: An adversary on some producers and networks
    - An adversary on producers as well as on routers should be considered
  - A_A : An adversary on the anonymizer
    - Unlike existing studies, we assume that the anonymizer is also an adversary



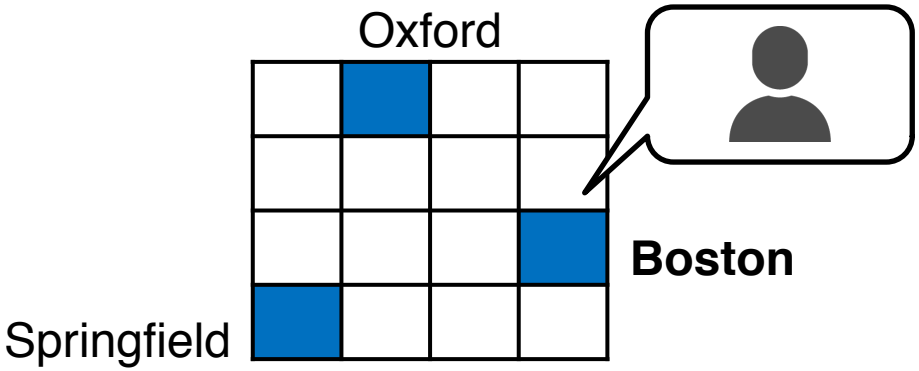
Location Privacy

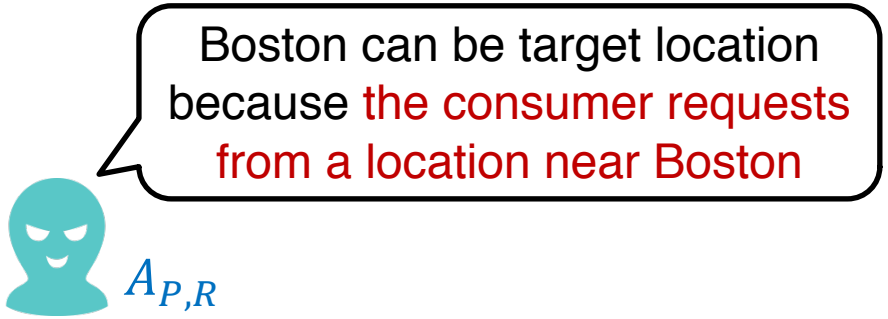
- Is it sufficient to achieve location anonymity to protect location privacy as in existing approaches?

- Location Privacy
  = location anonymity + session anonymity
  - Session anonymity ensures indistinguishability of consumers
    - Adversaries cannot gain information about consumers
      - Who is the consumers
      - Whether two requests are from the same consumer or not

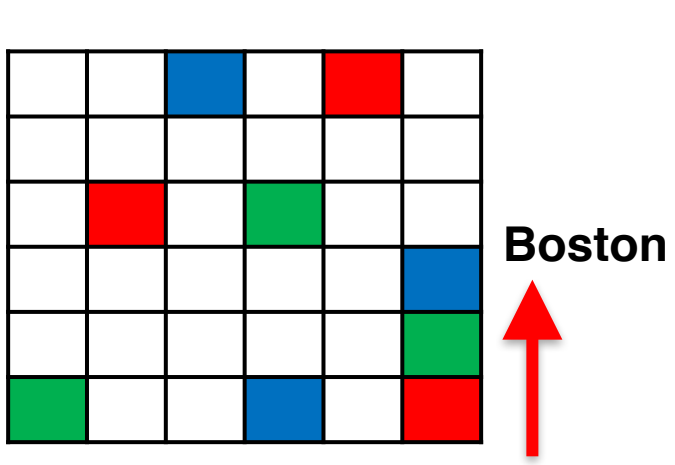
Necessity to Achieve Session Anonymity

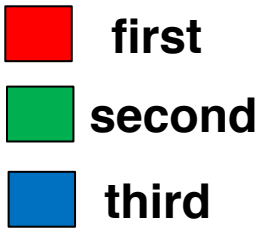
- Auxiliary information about consumers breaks k-anonymity
  - Adversaries can Infer target location based on the possibility that the consumer chooses each location as target location

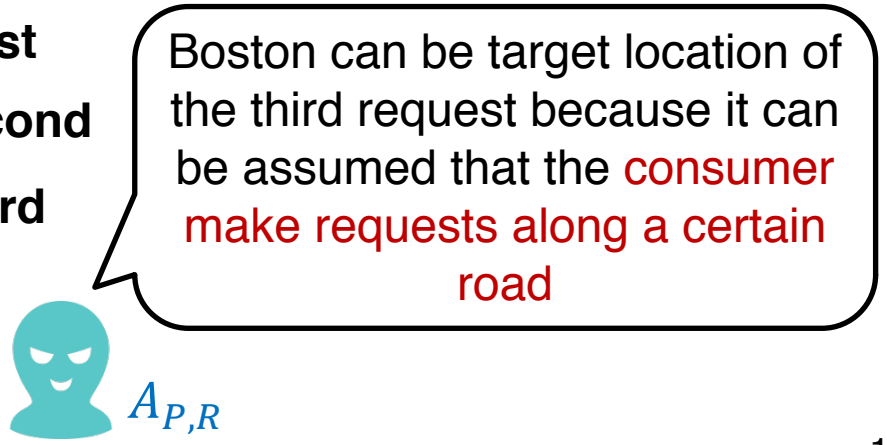




  - Adversaries can Infer target location based on the past anonymous location sets of the consumer







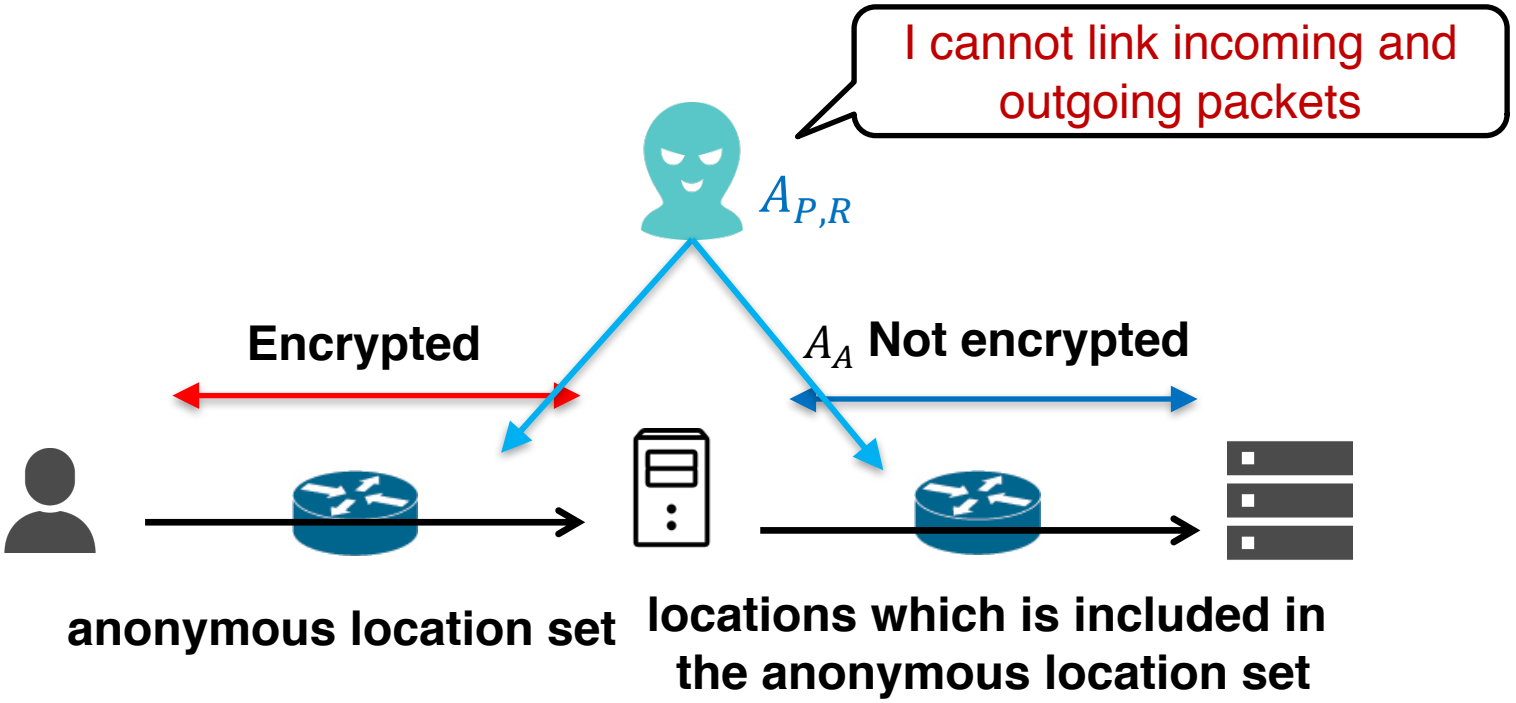
Design Rationale of Architecture

- Solution to achieve location anonymity
  - Each consumer makes request specifying an anonymous location set to the anonymizer instead of target location
    - The anonymizer generates a map of anonymous location sets for all the locations and distribute it to consumers

- Solution to achieve session anonymity
  - We leverage lack of source/destination addresses on packets in NDN (against A_A)
    - Interest and Data packets do not convey any information about consumer.
  - The anonymizer also works as a mix-router (against $A_{P,R}$)

Anonymizer as a mix-router

- Session anonymity against $A_{P,R}$
  - The Anonymizer acts as a Chum's mix router to prevent $A_{P,R}$ from link incoming and outgoing packets at the anonymizer
    - Encryption/decryption at the anonymizer
    - Batching N incoming packets
    - Sometimes make dummy requests



Requirements to Location Anonymity

1. Preventing adversaries from **probabilistically inferring** target locations
   - Location k-anonymity
     - Adversaries cannot infer a consumer's target location l_T from her/his anonymous location set $\mathcal{L}$

       $$P[l_T = l_i \mid \mathcal{L}] = P\left[l_T = l_j \mid \mathcal{L}\right] (\forall l_i, l_j \in \mathcal{L})$$

2. Minimizing **geographical information** of target locations leaked to adversaries
   - Location t-closeness
     - Each anonymous location set $\mathcal{L}$ is scattered uniformly throughout the service area S

       $$D[\mathcal{L}, S] \leq t$$

       ,where $D[\cdot,\cdot]$ is the difference between two geographical distributions

Requirement #1 to Location Anonymity

- Location k-anonymity
  - Adversaries cannot infer a consumer's target location l_T from her/his anonymous location set $\mathcal{L}$

$$P[l_T = l_i \mid \mathcal{L}] = P\left[l_T = l_j \mid \mathcal{L}\right] (\forall l_i, l_j \in \mathcal{L})$$

  - $P[l \mid \mathcal{L}] = P[\mathcal{L} \mid l]P[l]/P[\mathcal{L}]$ (Bayes' theorem)

The probability that $\mathcal{L}$ is used under the condition that target location is l

the probability that l is selected as a target location (popularity)

  - We should take these two factors into account to generate anonymous location sets

Solution #1 to Location Anonymity

- Making disjoint anonymous location set
  - If we divide the service area into disjoint anonymous location sets, the anonymous location set for each target location is deterministically determined
    - $\forall l \in \mathcal{L},\ P[\mathcal{L}|l] = 1$ and $\forall l \notin \mathcal{L},\ P[\mathcal{L}|l] = 0$

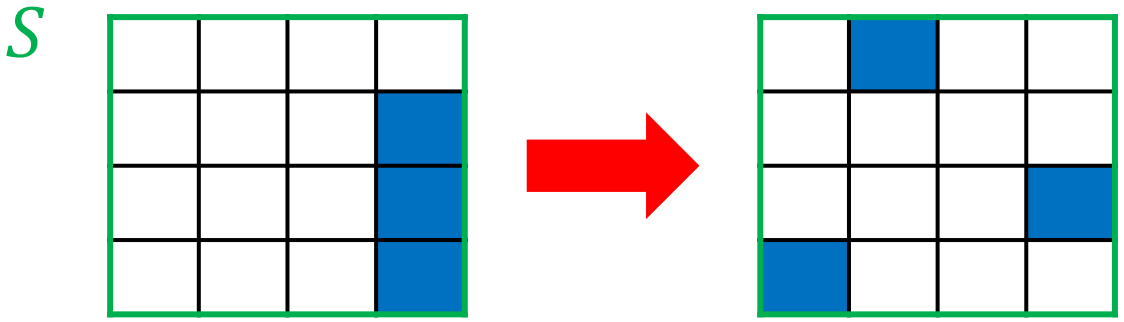
  $\rightarrow P[l \mid \mathcal{L}] = P[\mathcal{L} \mid l]P[l]/P[\mathcal{L}] = P[l]/P[\mathcal{L}]$
- Maximizing entropy of popularities of locations
  - $H_{\mathcal{L}} = -\sum_{l \in \mathcal{L}} p_{l,\mathcal{L}} * \log_2 p_{l,\mathcal{L}}$
    - where $p_{l,\mathcal{L}} = P[l]/\sum_{l_i \in \mathcal{L}} P[l_i]$ (normalized popularity)
  - Selecting k locations so that their popularities $P[l]$ are as close as possible
    - We evaluate later

Requirement #2 to Location Anonymity

- Location t-closeness
  - Each anonymous location set $\mathcal{L}$ is scattered uniformly throughout the service area S

    $$D[\mathcal{L}, S] \leq t$$

    where $D[\cdot,\cdot]$ is the difference between two distributions
  - Motivation to achieve location t-closeness
    - If all the locations in an anonymous location set is close, adversaries can narrow target location to a region with a certain degree of accuracy even if they cannot infer target location



  - Solution
    - Combining sufficiently scattered locations to generate anonymous location sets

Anonymous Location Sets Generation

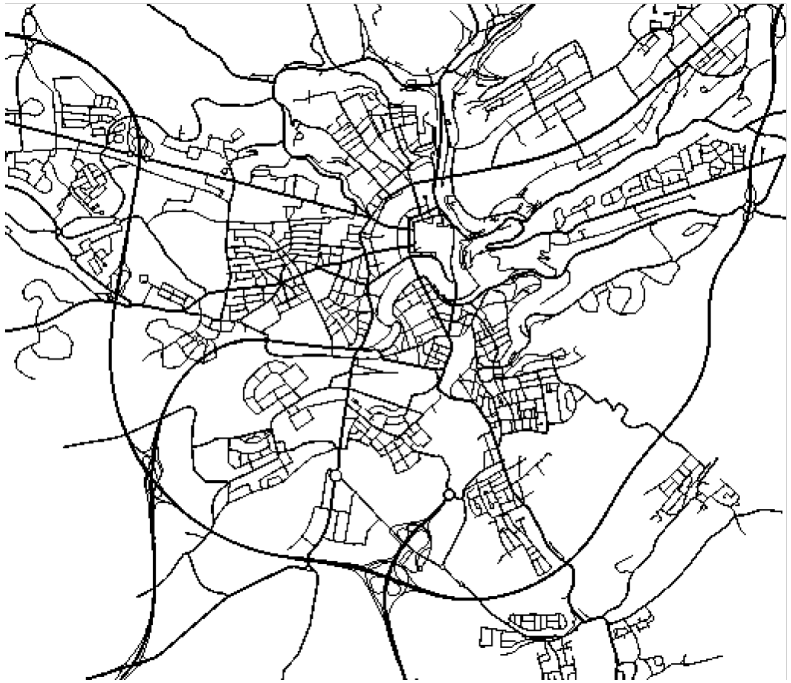
- Overview of our algorithm to generate anonymous location sets
  1. Dividing the service area into k segments
     - k is degree of k-anonymity
     - Each segment consists of neighboring locations
  2. Selecting a location from each segment according to the popularities and combine those k locations
     - Locations with similar popularities that are located far enough can be combined.
     - Anonymous location sets become disjoint

Evaluation of Anonymous Location Sets

- Measurements
  - Entropy of popularities of locations in each anonymous location set
  - Ratio of size of the range covered by each anonymous location set with respect to that of a service area
- Conditions
  - An LBS which collect speed of vehicles in each location
  - Use SUMO simulator to obtain vehicle movements
  - The service area is approximately 60 km^2 and is divided into 1024 locations
  - anonymity degree $k = 15$

Generated Anonymous Location Sets

- Examples of anonymous location sets
  - A set of locations painted with the same color is one anonymous location set.



Service are

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16	48	-1	-1	-1	-1	35	37	-1	-1	-1	-1	2	-1	42	-1	-1	-1	23	16	32	49	47	43	-1	15	36	41	10	37	46	4
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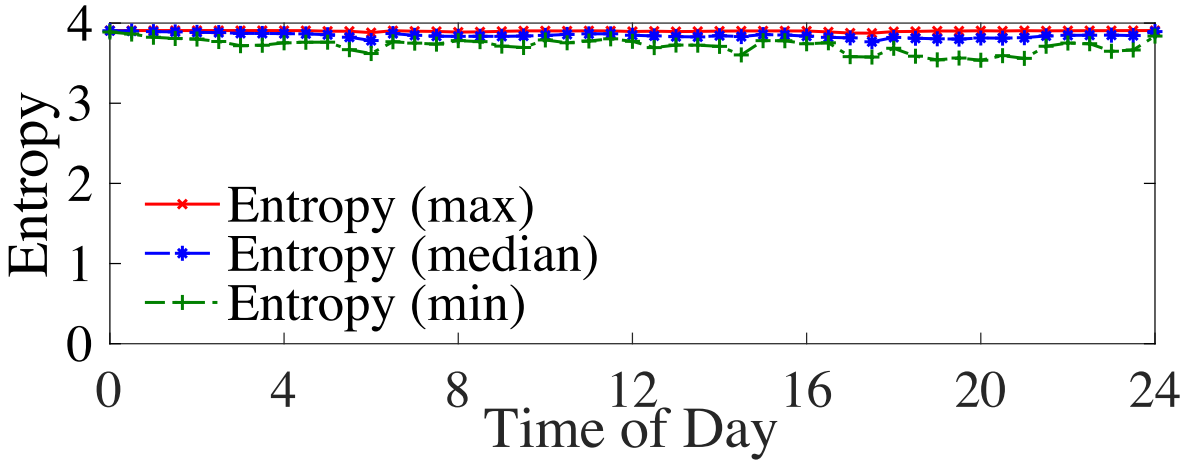
Anonymous location sets

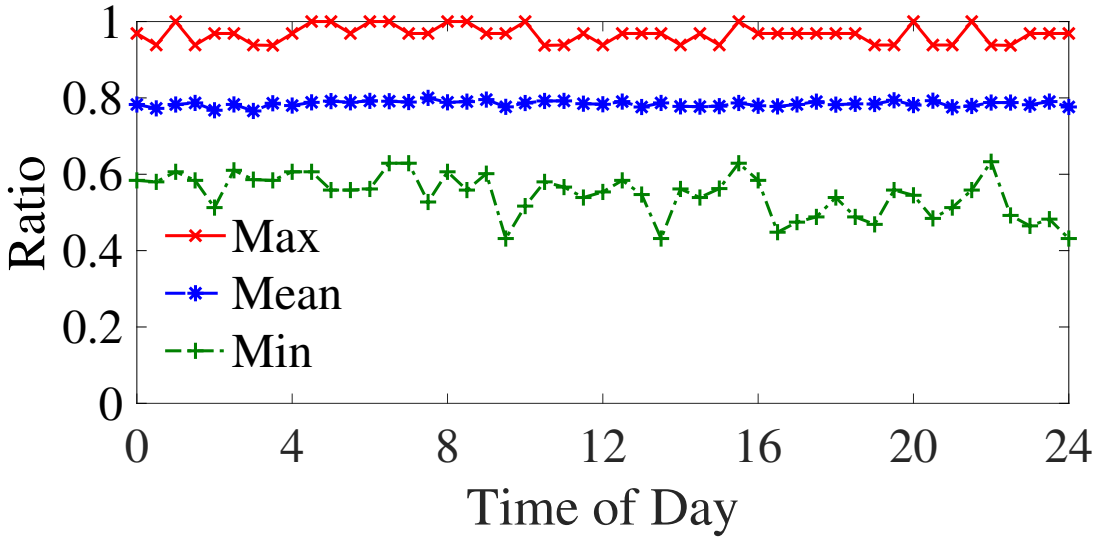
Result #1

- Location k-anonymity : Location Entropy of the popularities of locations
  - The larger the entropy, the smaller the differences in popularities of locations and adversaries cannot infer target locations.
    - optimal value is $H_{\mathcal{L}} = -\log_2\left(\frac{1}{k}\right)$ =3.91
  - Observation
    - Our algorithm generates good anonymous location sets because the entropy is sufficiently close to the optimal value



Result #2

- Location t-closeness : Ratio of size of the range covered by each anonymous location set with respect to that of the service area
  - The greater the ratio is, the more adversaries cannot gain geographical information of target locations
  - Observation
    - Even the worst anonymous location set covers a sufficiently large area of the service area.



Conclusions

- Conclusions
  - We define location privacy as a combination of location anonymity and session anonymity
  - We propose an architecture to achieve session anonymity under the adversarial model that none of the anonymizer, producers, and networks are honest
  - We propose an anonymous location sets generation algorithm to achieve location anonymity which is defined using k-anonymity and t-closeness