Security of GPS/INS based On-road Location Tracking Systems

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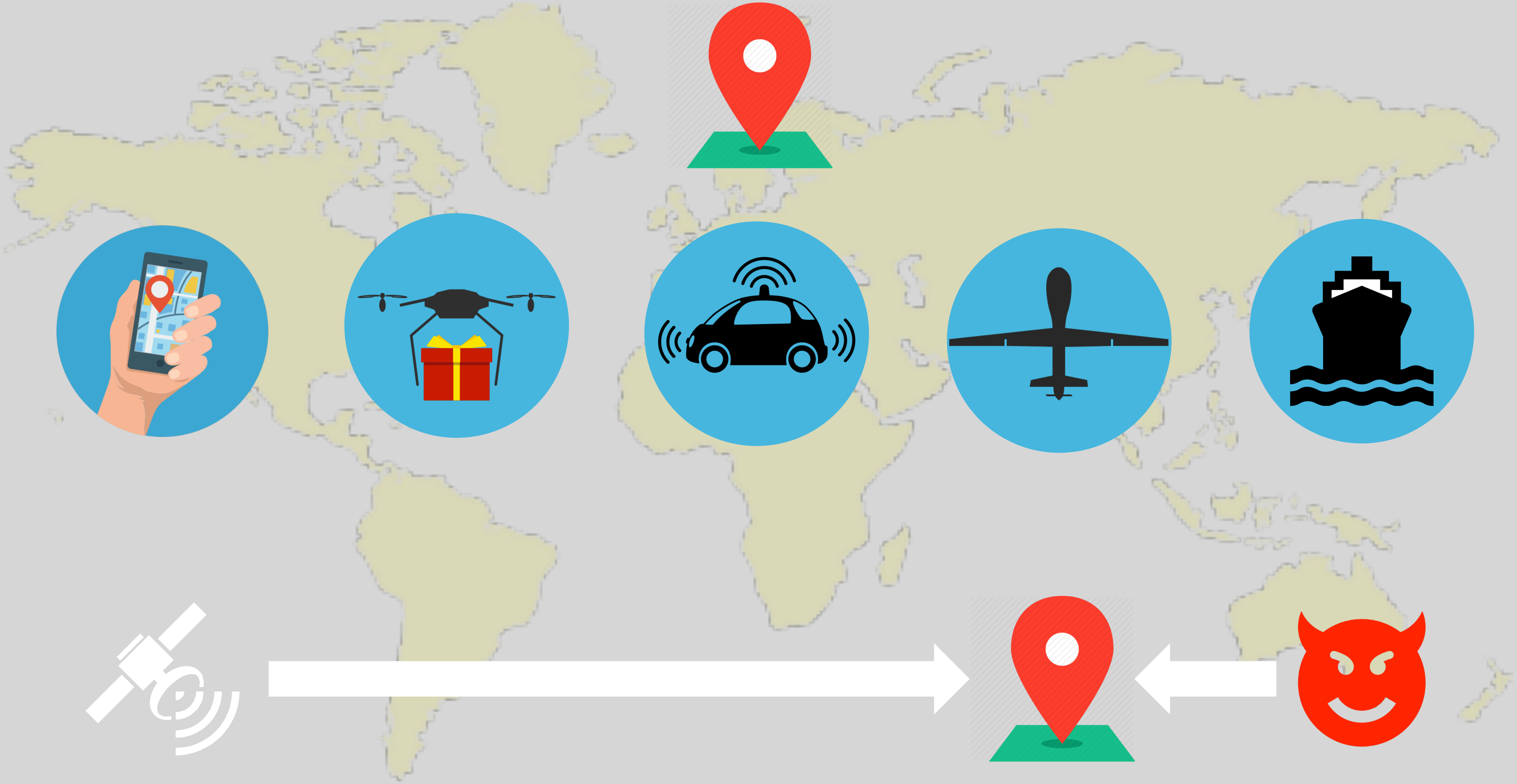

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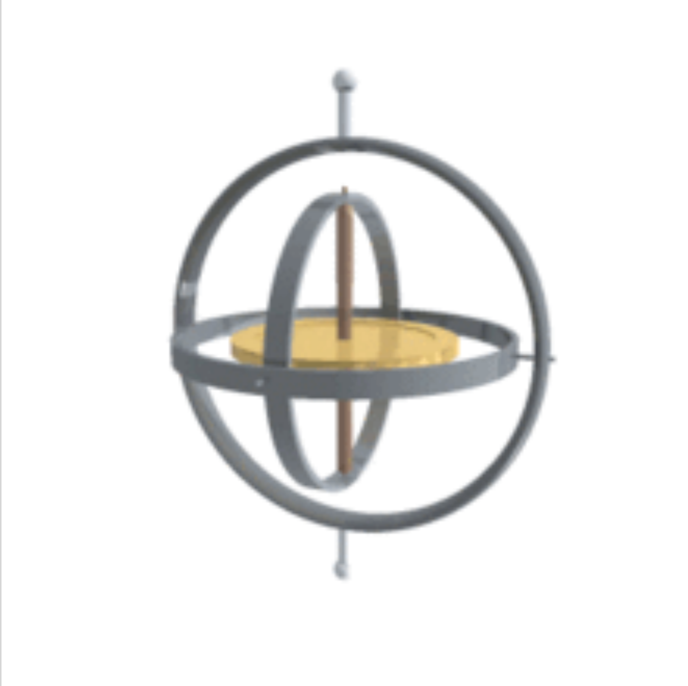
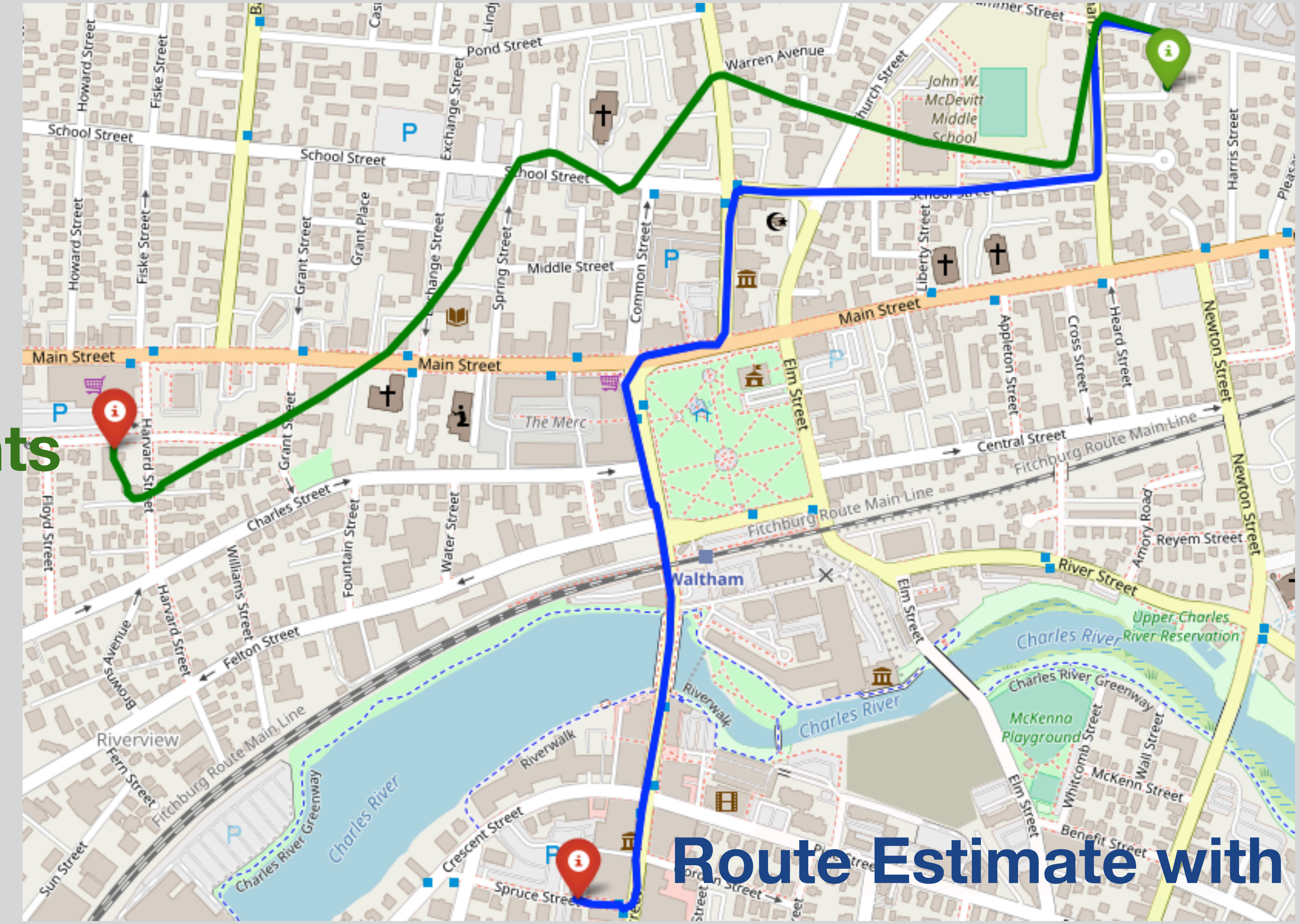




No constraints

Route Estimate with Road Constraints

Given a roadmap and
assuming inertial sensor data is monitored
(in addition to GPS)

Is it possible for an attacker to spoof their navigation path / final destination?

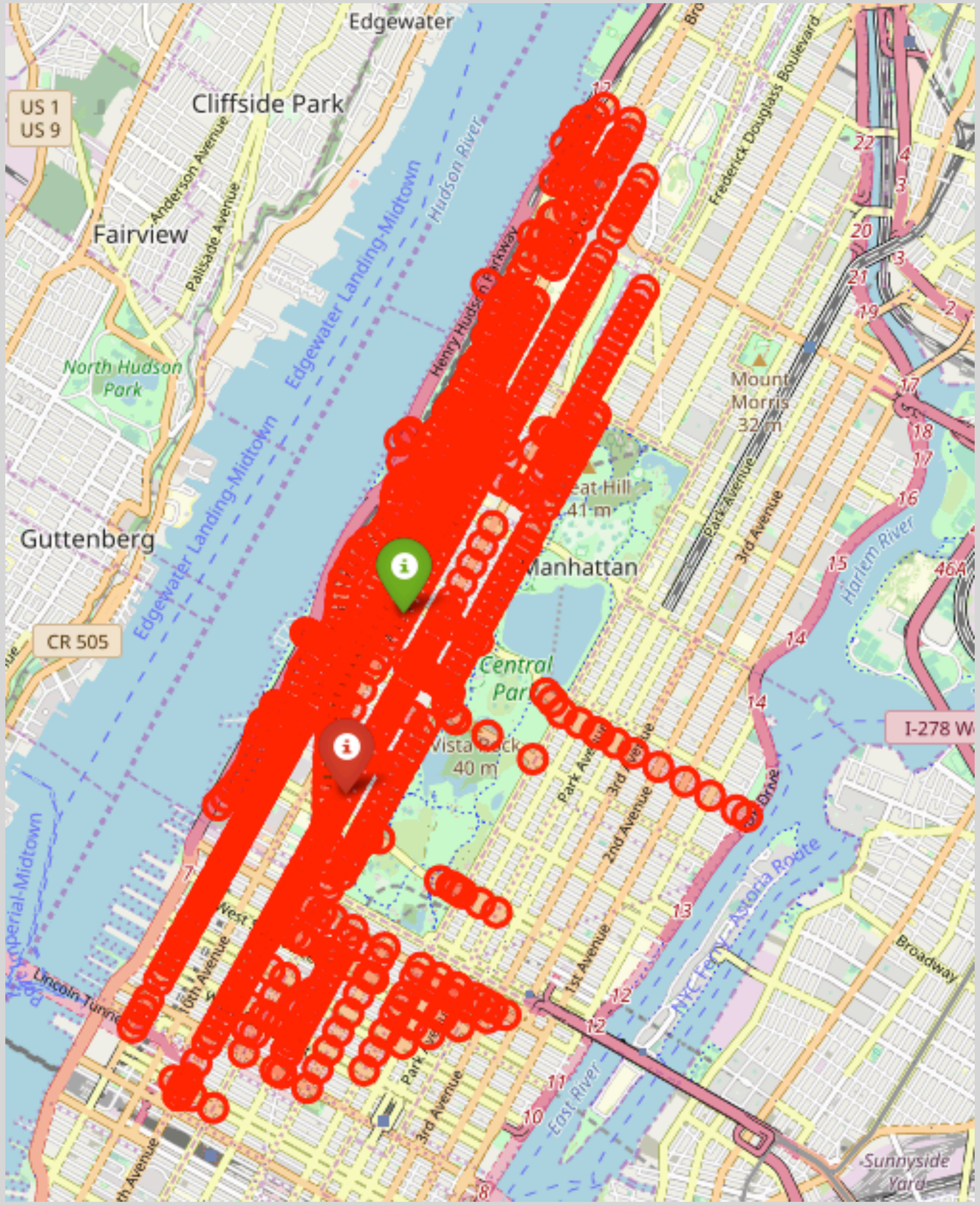
Contributions

- **Developed algorithms that derive potential destinations** reachable without raising an alarm
  - Leveraging regular patterns that exist in urban road networks
  - Rendering any GPS/INS based monitoring system useless
- **First real-time integrated GPS/INS spoofer** that accounts for traffic fluidity, lights and stop signs
  - Dynamically generates GPS spoofing signals
  - And it works in the real world!

High-level Attack Overview

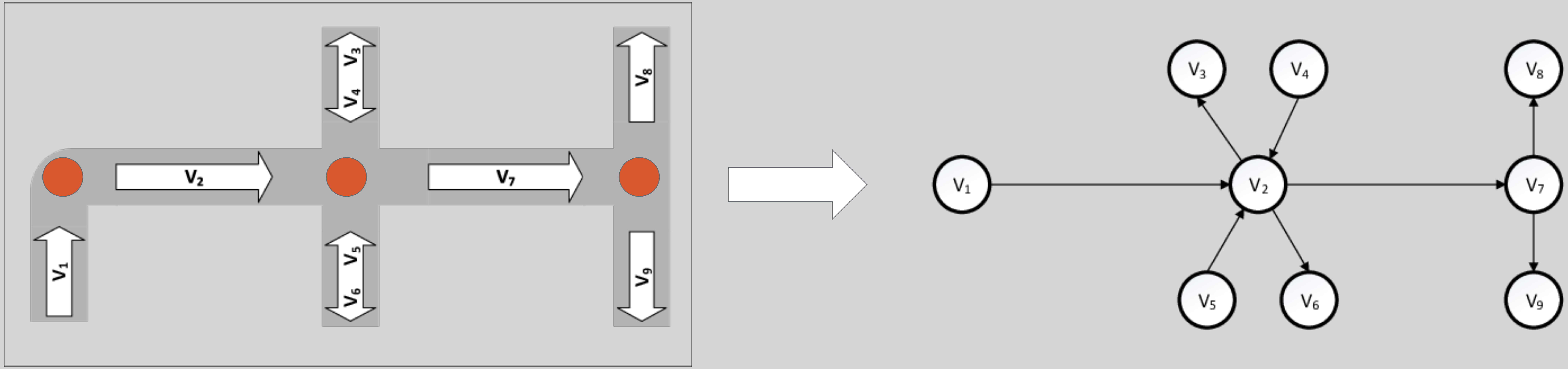
A Visual Representation

Attack Algorithm



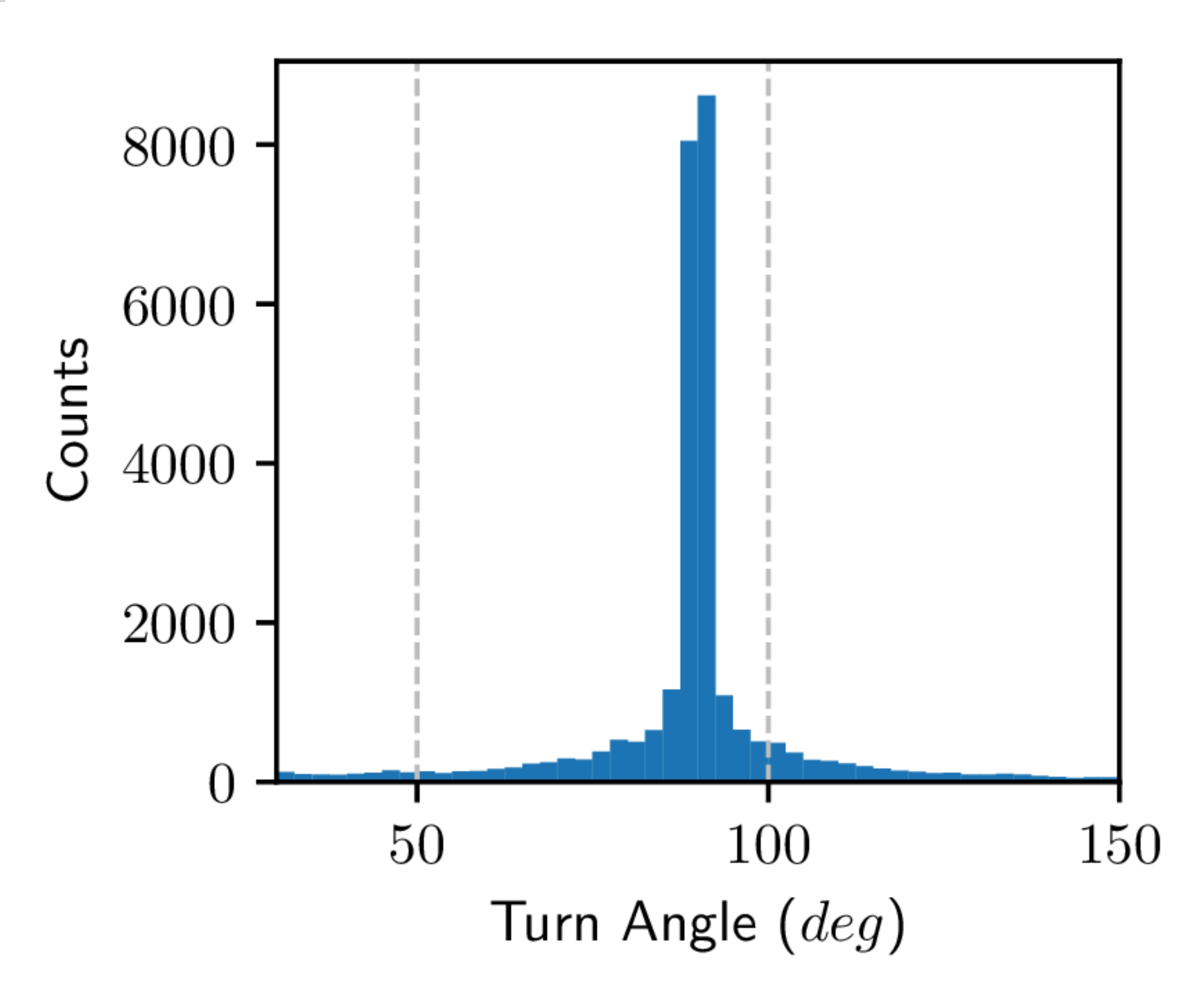
Graph Construction

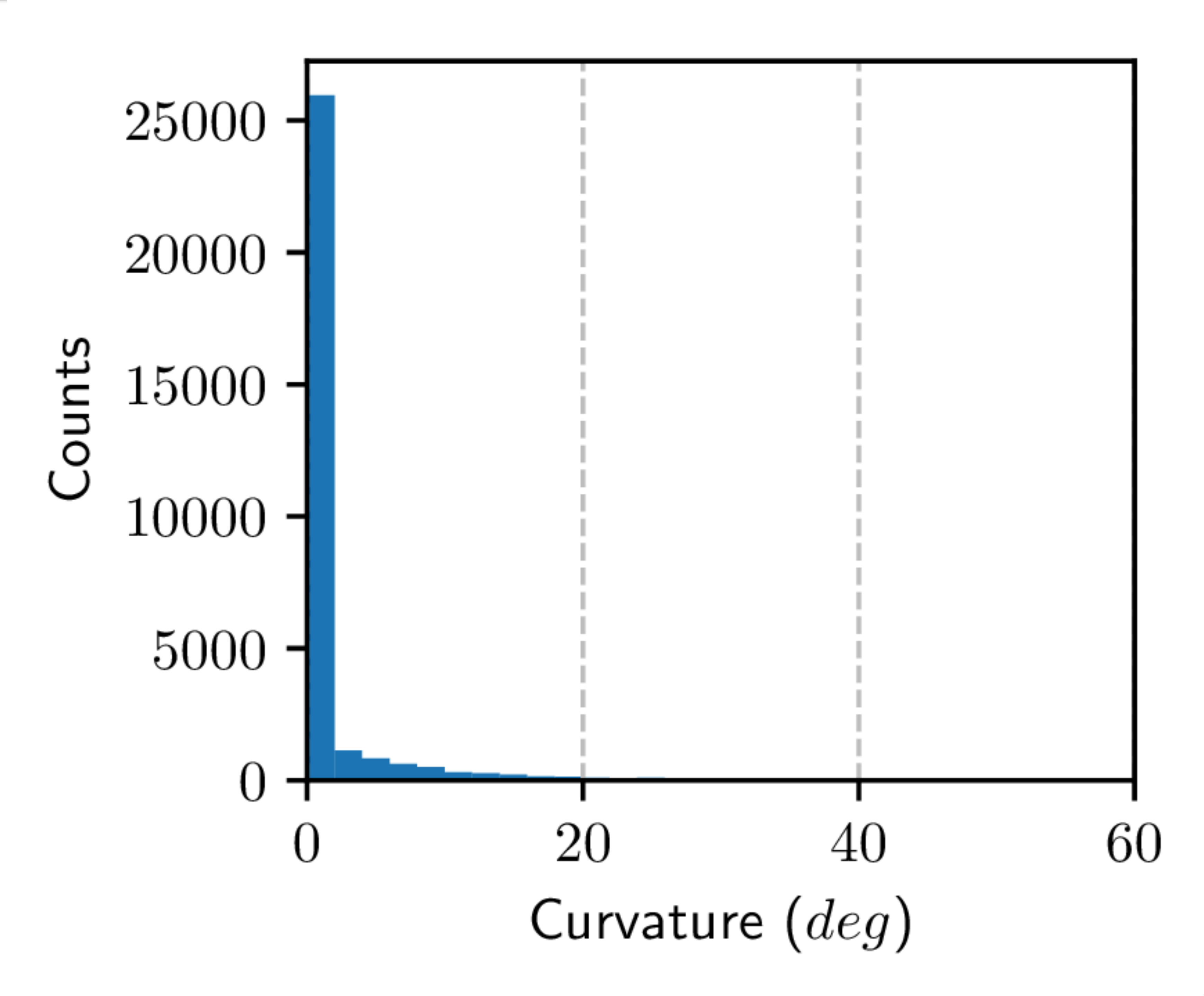
- **Edges** → Intersections
  - Contains turn angle
- **Vertices** → Road between Intersections
  - Contains curvature + travel time



Intuition for Spoof Routes Generation

- **Maximize Probability of Spoofing**
  - Use curves + turns common in the road network





Distribution for Manhattan

Spoof Routes Generation Algorithm

- **Extended Depth First Search**
  - **Filter routes** unlikely to reach destination
    - Define constraints for likely routes
    - Direct routes towards destination
  - **Score routes** that reach destination
    - Using turn angles and road curvature
    - Compound probability of all vertices in path
  - Select the top scoring paths

Input: $G = (V, E)$, $Loc(s)$, $Loc(d)$, N_P
Output: $\mathcal{S} = \{p_1, \ldots, p_{N_P}\}$

$Initialization: \mathcal{S} \leftarrow \emptyset;\ p \leftarrow [\,];\ v \leftarrow \emptyset$
$s \leftarrow getSourceVertex(Loc(s))$
$d \leftarrow getDestinationVertex(Loc(d))$
`GenerateSpoofedPaths` (s, d)
$\boxed{\mathcal{S} \leftarrow selectTopPaths(\mathcal{S}, N_P)}$

function `GenerateSpoofedPaths` (s, d):
    $p \leftarrow p + [s]$
    $v \leftarrow v \cup \{s\}$
    if $s = d$ **then**
        $\mathcal{S} \leftarrow \mathcal{S} \cup \{p\}$
    else
        for $e \in V$ *such that* $(s, e) \in E$ **do**
            $\boxed{\textbf{if } e \notin v \textbf{ and } Filter(s, e, p)\ passed}$ **then**
                $\boxed{p.score \leftarrow p.score * Score(s, e, p)}$
                `GenerateSpoofedPaths` (e, d)
        end
    $p \leftarrow p - [s]$
    $v \leftarrow v - \{s\}$

Intuition for Escape Routes Generation

- **Exploit noise sensitivity of sensors**
    - Accelerometers sensitive to road irregularities
    - Magnetometer sensitive to vehicle magnets
    - Gyroscopes can have significant drift

Escape Routes Generation Algorithm

- **Extended Depth First Search**
  - Ensures **spoof routes and escape routes are topologically similar**
    - Accounting for varying road curvatures and lengths
    - **Renders any sensor monitoring useless**
  - **Filter paths** dissimilar to spoof routes
    - Exceeded the turn count
    - Turn, Curvature or Distance is outside noise threshold

Input: $G = (V, E)$, $\mathcal{S}_I$
Output: N_P, $\mathcal{E} = \{p_1, \ldots, p_{N_P}\}$

$Initialization : \mathcal{E} \leftarrow \emptyset;\ N_P \leftarrow 0;\ p \leftarrow [\,];\ v \leftarrow \emptyset$
$s \leftarrow getSourceVertex(\mathcal{S}_I)$
$t \leftarrow getTurnsCount(\mathcal{S}_I)$
`GenerateEscapePaths(`s, t`)`

function `GenerateEscapePaths(`s, t`):`
  $p \leftarrow p + [s]$
  $v \leftarrow v \cup \{s\}$

  if $len(p.turns) > t$ **then**
    return

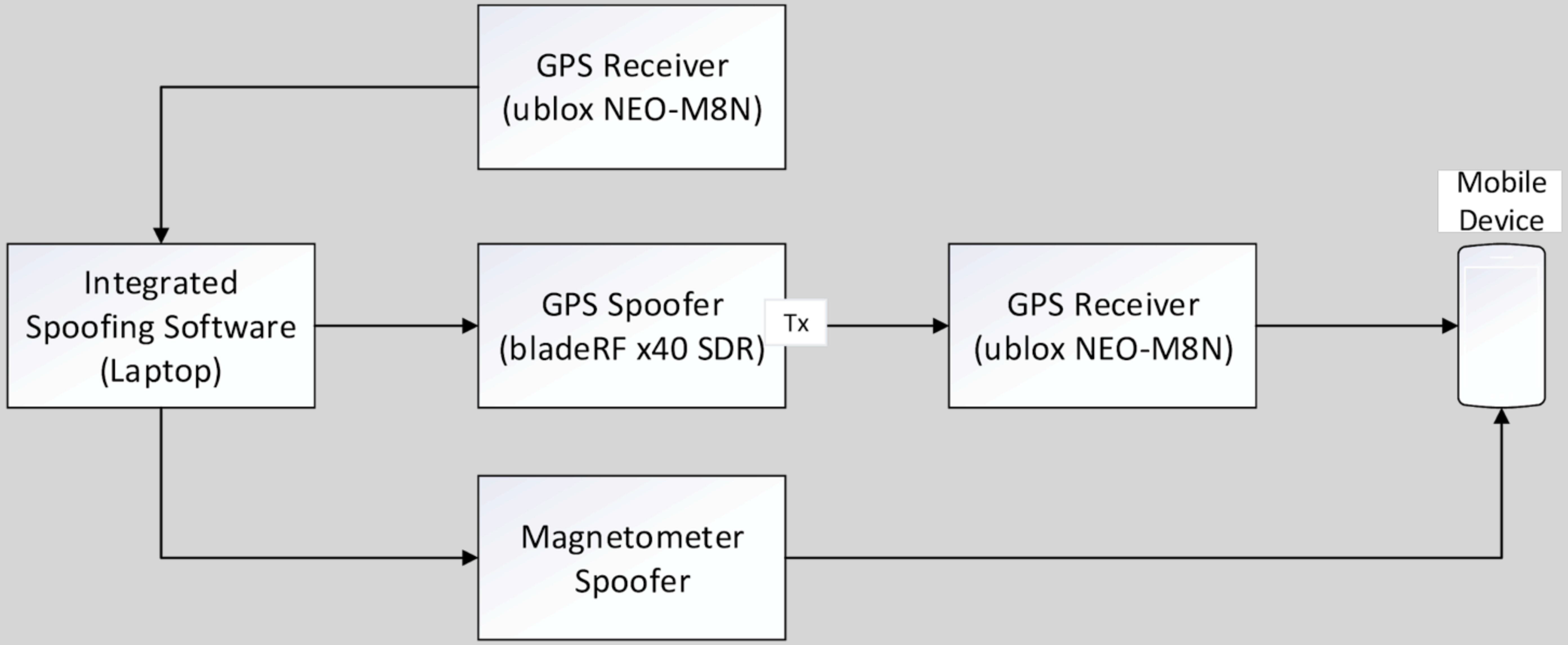
  if $len(p.turns) = t$ **then**
    $\mathcal{E} \leftarrow \mathcal{E} \cup \{p\}$
    $N_P \leftarrow N_P + 1$

  for $e \in V$ *such that* $(s, e) \in E$ **do**
    if $e \notin v$ **and** $Filter(s, e, p, \mathcal{S}_I)$ *passed* **then**
      $p.curve \leftarrow updateCurvature(s, e, p)$
      $p.turns \leftarrow updateTurns(s, e, p)$
      $p.score \leftarrow p.score * Score(s, e, p, \mathcal{S}_I)$
      `GenerateEscapePaths` (c, t)
  end

  $p \leftarrow p - [s]$
  $v \leftarrow v - \{s\}$

Real-World Spoofer

- **Generic system** usable in many different attack scenarios
- In case of Road Networks -
  - First implementation to account for **traffic fluidity**, **traffic lights** and **stop signs**
  - On receipt of driver's real (spoof) location -
    - Calculates a escape location and bearing **efficiently within ~5 ms**
    - **GPS spoofer generates NMEA packets** for escape location
    - **Magnetometer Spoofer generates magnetic field** for escape bearing



True location

Real-World Spoofer Evaluation

- **GPS lock never lost during 10 routes**
- **Maximum delay of 60 ms** between spoof and escape location
- **All sensor errors within range** of error threshold

Evaluation Methodology

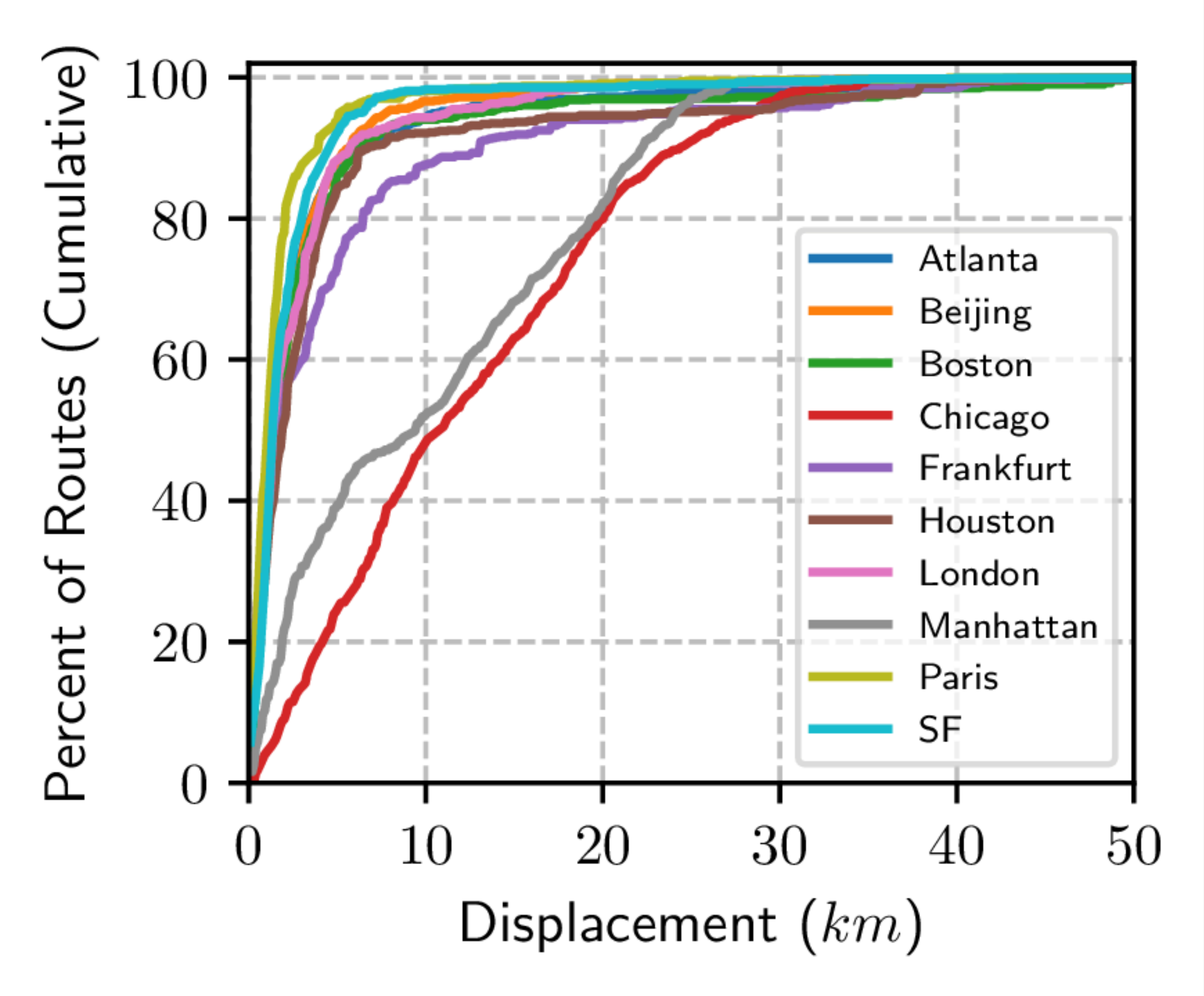
- **Perform simulations for 10 global cities**
  - Major transportation and logistic hubs
  - With **diverse road networks**
    - Structured & Grid-like -> E.g., Manhattan and Chicago
    - High variability -> E.g., London and Paris
    - Somewhere in between -> E.g., Boston and San Francisco

- **Simulate 1000 routes in each chosen city**
  - “Residence” to “Office” using OpenStreetMap
  - Measure -
    - **Maximum Displacement from Intended Destination**
    - **Estimated Coverage Area of Escape Routes**

Atlanta
Beijing
Boston
Chicago
Frankfurt
Houston
London
Manhattan
Paris
San Francisco

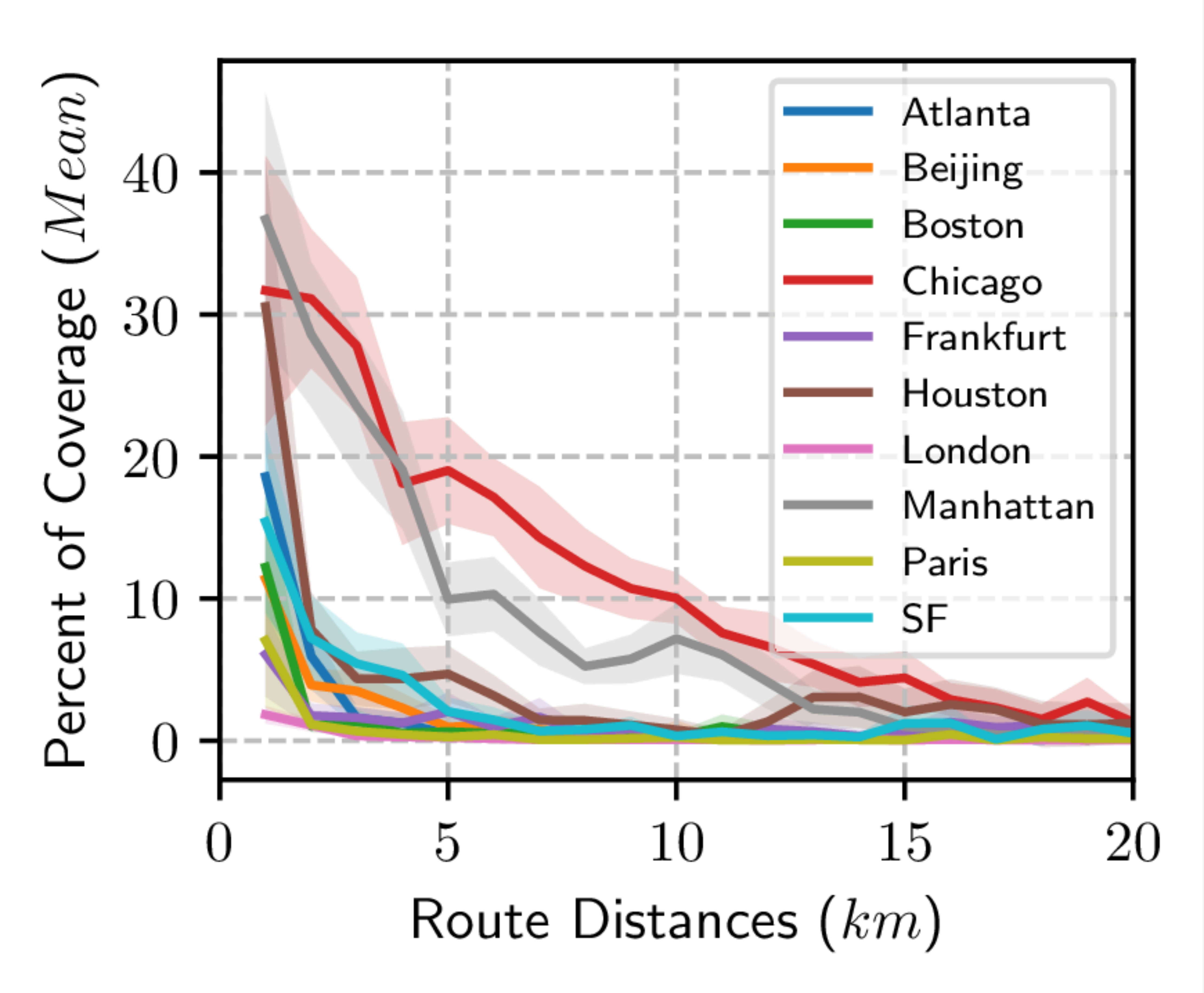
Maximum Displacement from Intended Destination

- **Significant Deviation possible**
  - In **grid-like** cities
    - **> 10 km for 50% routes**
    - **> 20 km for 20% routes**
  - In other cities
    - **> 10 km for 10% routes**
    - **Several routes with 30-40 km deviation**



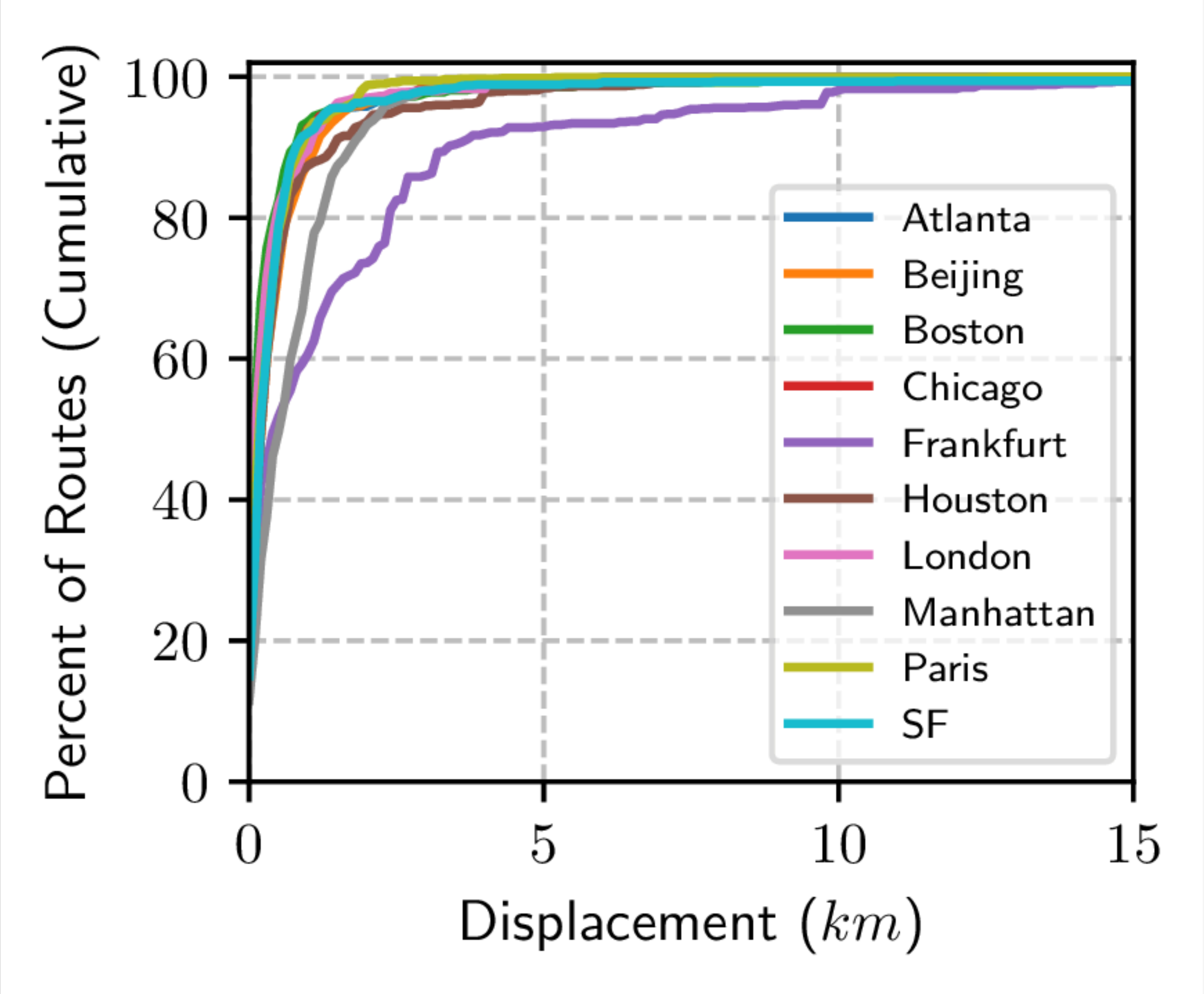
Estimated Coverage Area of Escape Routes

- **Monte-Carlo Simulations**
  - **Define a circle** with
    - Source as center
    - Distance from destination as radius
  - **Calculate area** of escape destinations
    - Within the circle
    - Assuming user walks 50m around parking
- **Possible to Cover**
  - **> 30% area in grid-like cities**
  - **> 8% area for long routes (~10 kms)**



Countermeasure - "Secure Paths" Algorithm

- **Generate routes with low probability of spoofing**
  - **Reverse the spoof routes generation** algorithm
  - Run escape routes generation algorithms
  - Choose spoof route with least escape routes



Summary & Questions?

- **Developed algorithms that derive potential destinations** reachable without raising alarms on GPS/INS tracking systems
    - **Possible to deviate > 10 km (> 20 km) for 50% (20%) routes** in grid-like cities
    - **Possible to deviate 30-40 km for many routes** in all cities
- **First real-time integrated GPS/INS spoofer** that accounts for traffic fluidity, lights and stop signs
    - **GPS lock never lost** during 10 routes
    - **All sensor errors within range of threshold**