# Modeling and Performance Analysis of a Public Safety Broadband Network

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# Acknowledgement


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# Background

- PSCR developed detailed nationwide modeling and analysis tools to evaluate the performance of LTE in support of public safety communications and the deployment of a nationwide broadband network.
- Modeling results are used to inform the public safety stakeholders, including FirstNet, on the expected network performance, important parameters to consider, and resources needed for the future nationwide build-out.

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# Motivations

- Given a site plan designed and built to support public safety traffic:
  - How sensitive is the network to varying configurations and parameters?
  - How sensitive is the network to varying traffic loads?
  - How is the network affected by large scale incidents?
  - How resilient is the network in the case of equipment failures or infrastructure loss?
  - What it the user experience in case of a large scale-incident?

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# Outline

- Network modeling overview
  - Inputs and assumptions
  - Traffic models
  - Performance metrics
- Parameter sensitivity analysis
  - Nationwide scenarios
  - Outdoor coverage, reliability, high power UE, traffic growth
- Network resiliency analysis
  - Modeling methodology and metrics
  - Performance results
- Large scale incident modeling
  - Modeling methodology
  - Performance results
- Characterizing the user experience

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# NETWORK MODELING OVERVIEW

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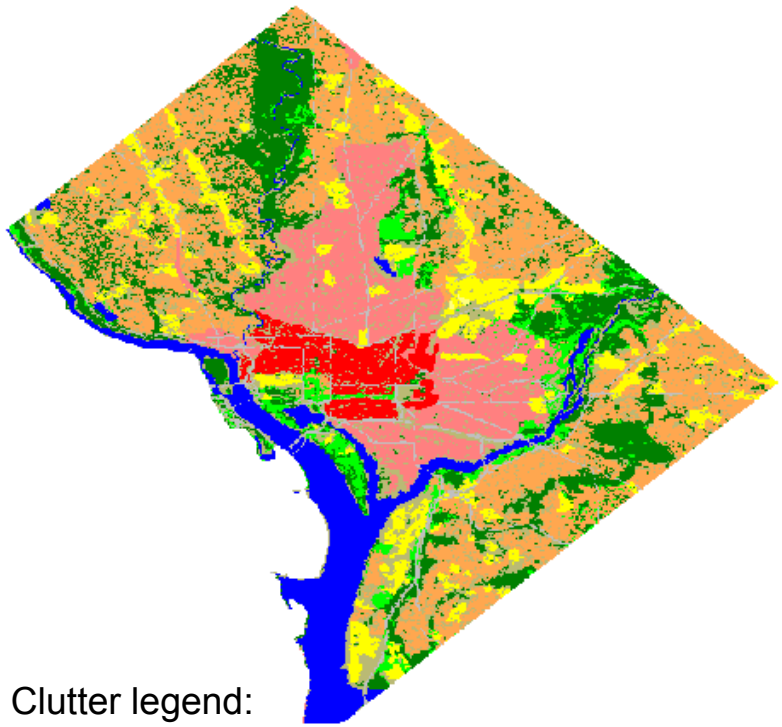
# Inputs and Assumptions

Example: Washington DC



Clutter legend:

- Airport
- Commercial Industrial
- Core Urban
- Forested Dense Vegetation
- Grassland Agriculture
- High Density Urban
- Inland Water
- Marsh Wetland
- Open
- Open in Urban
- Residential with few Trees
- Residential with Trees
- Rural
- Seawater
- Transportation
- Urban

- Area
  - Boundaries
  - Geodata (elevation, clutter)
- User distribution
  - How many and where
- Traffic model
  - Application types
  - Usage scenarios
- Propagation model
  - CRC Predict, Universal Model
  - Model tuning
- Site placement

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# Inputs and Assumptions

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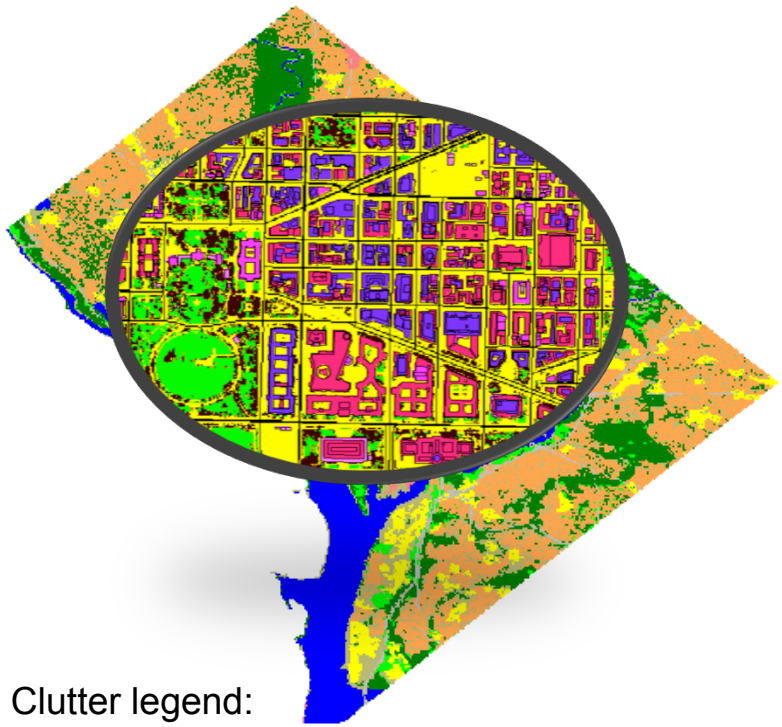

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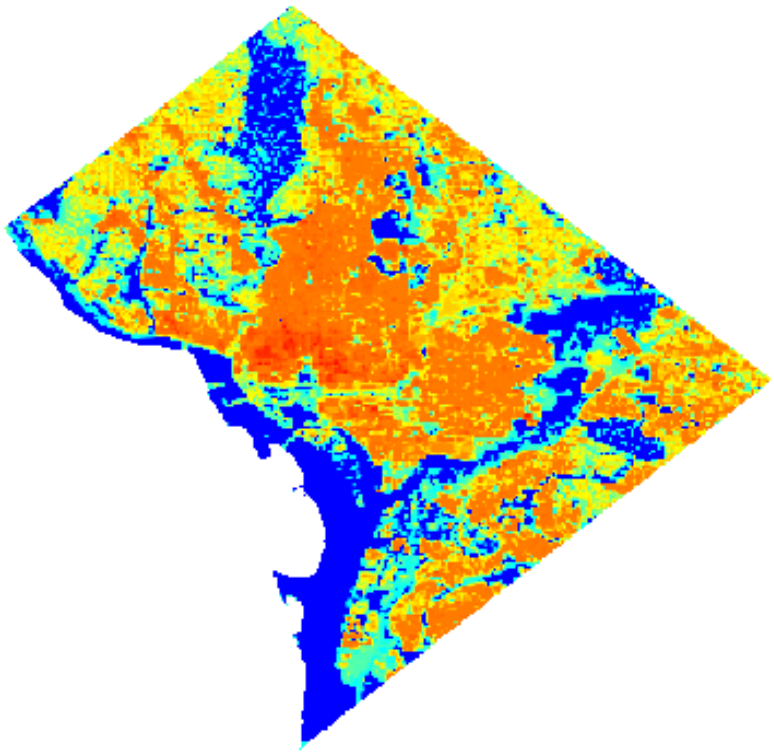

Total user count ~ 28,500

User density ( user/km$^2$):

- 0
- 13
- 83
- 210
- 4600

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  - Boundaries
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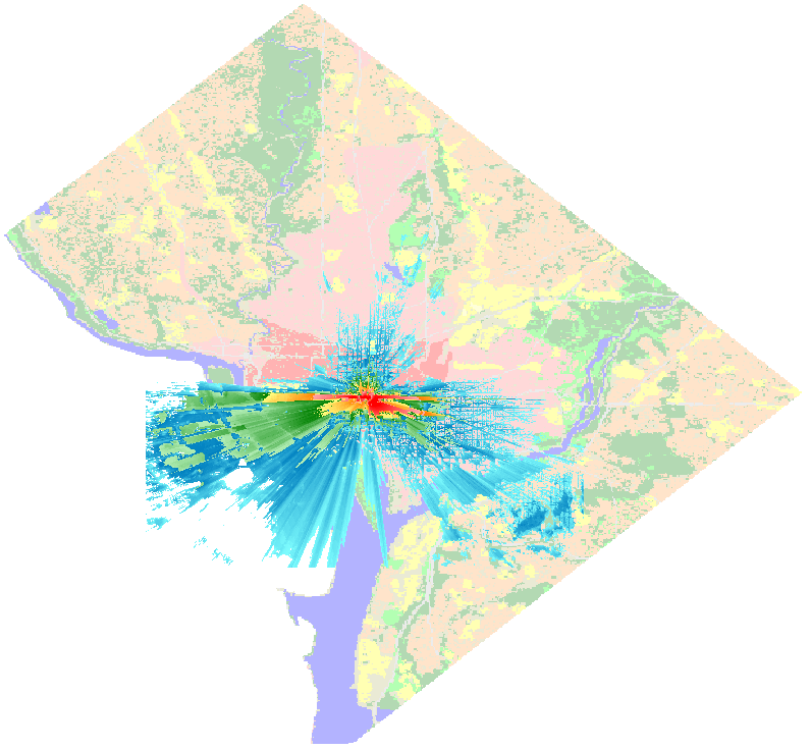

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# Incident Traffic and Statistics

- Public safety traffic is incident-based:
  - Small scale, day-to-day activities
    - Motor vehicle accidents (10M in 2009)
    - Traffic stops (17.7M in 2008)
    - Violent and property crimes (5.5M and 18M respectively annual average 2004-2008)
    - Fires (1.375M in 2012)
  - Large scale, infrequent incidents
    - Natural disasters (95 in 2013, including 5 emergency declarations)
    - Active Shooters (15 in 2012)
- Traffic models are needed to characterize small and large scale incidents.

Statistics sources: http://www.census.gov/compendia/statab/cats/transportation/motor_vehicle_accidents_and_fatalities.html, http://www.bjs.gov/index.cfm?ty=tp&tid=44, http://www.nfpa.org/research/reports-and-statistics/fires-in-the-us, http://www.fema.gov/disasters/grid/year/2013, http://leb.fbi.gov/2014/january/active-shooter-events-from-2000-to-2012

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# Traffic Model Examples

## Small scale

- Based on Minneapolis bridge collapse* with a reduction of 50% of the activity factors and no command unit videos.
- Average data rates per users: 7.7 kb/s uplink and 9.1 kb/s downlink

| | Uplink (MB) | Downlink (MB) | Total (MB) |
|---|---|---|---|
| Daily usage – 8-hr shift | 27 | 32 | 59 |
| Monthly – 160-hr | 540 | 644 | 1184 |

- Used for nationwide site planning

## Large scale incidents

- Number of users, applications used and incident size are scenario based
- Scenarios drawn from the National Public Safety Telecommunications Council (NPSTC) and Minnesota Department of Public Safety reports

*"The Public Safety Nationwide Interoperable Broadband Network: A New Model for Capacity, Performance and Cost," FCC White Paper, June 2010, Exhibit 9, p. 26.

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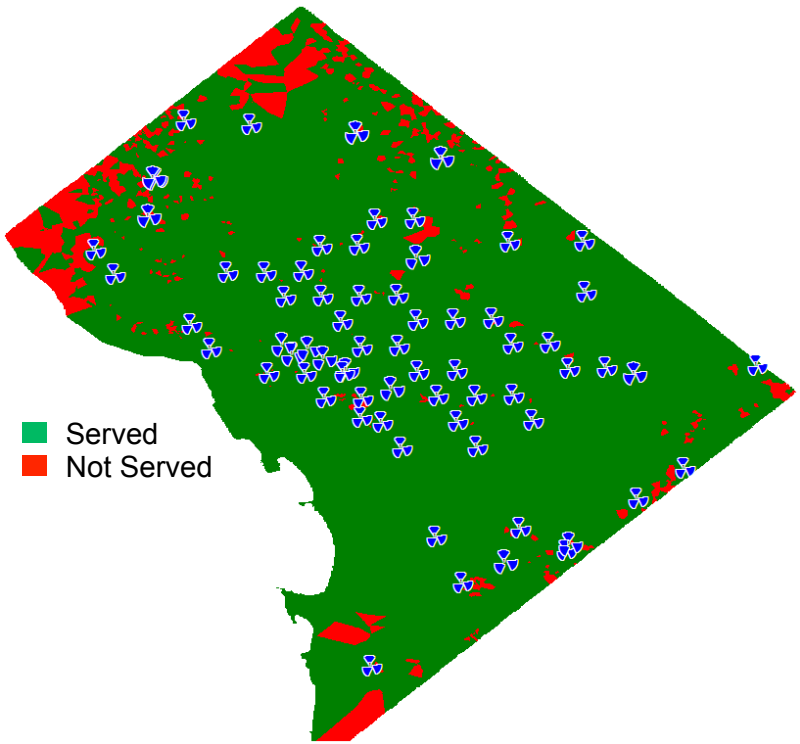
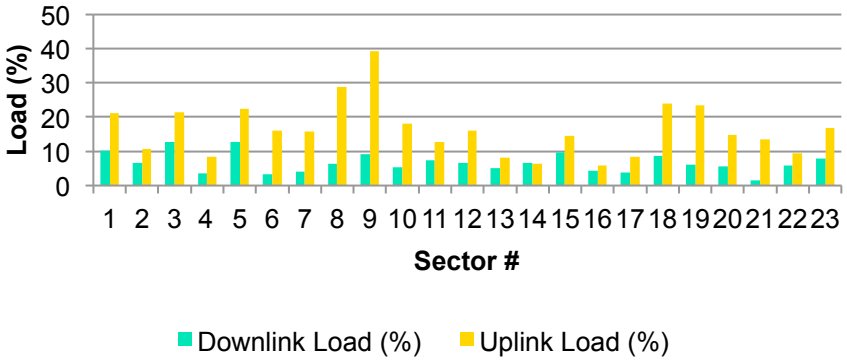
# Performance Metrics




- User coverage
  - Number of users deployed and served within the area
- Area coverage
  - Uplink, downlink, and combined coverage
  - Based on achievable data rate
- Population coverage
  - Uses the population distribution within the area covered
- Network throughput
- Sector loads

- Number of sites: 70
- User coverage: 95.7 %
- Area coverage: 92 %
- Population coverage: 96.2 %

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# PARAMETER SENSITIVITY ANALYSIS FOR THE NATIONWIDE PUBLIC SAFETY NETWORK

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# Parameter Sensitivity Analysis

- Gain insights on performance trends and trade-offs.
- Inform rollout scenarios
- Identify key input parameters such as reliability, operation environment, UE power, and traffic growth and assess their effects on the user coverage and site count.

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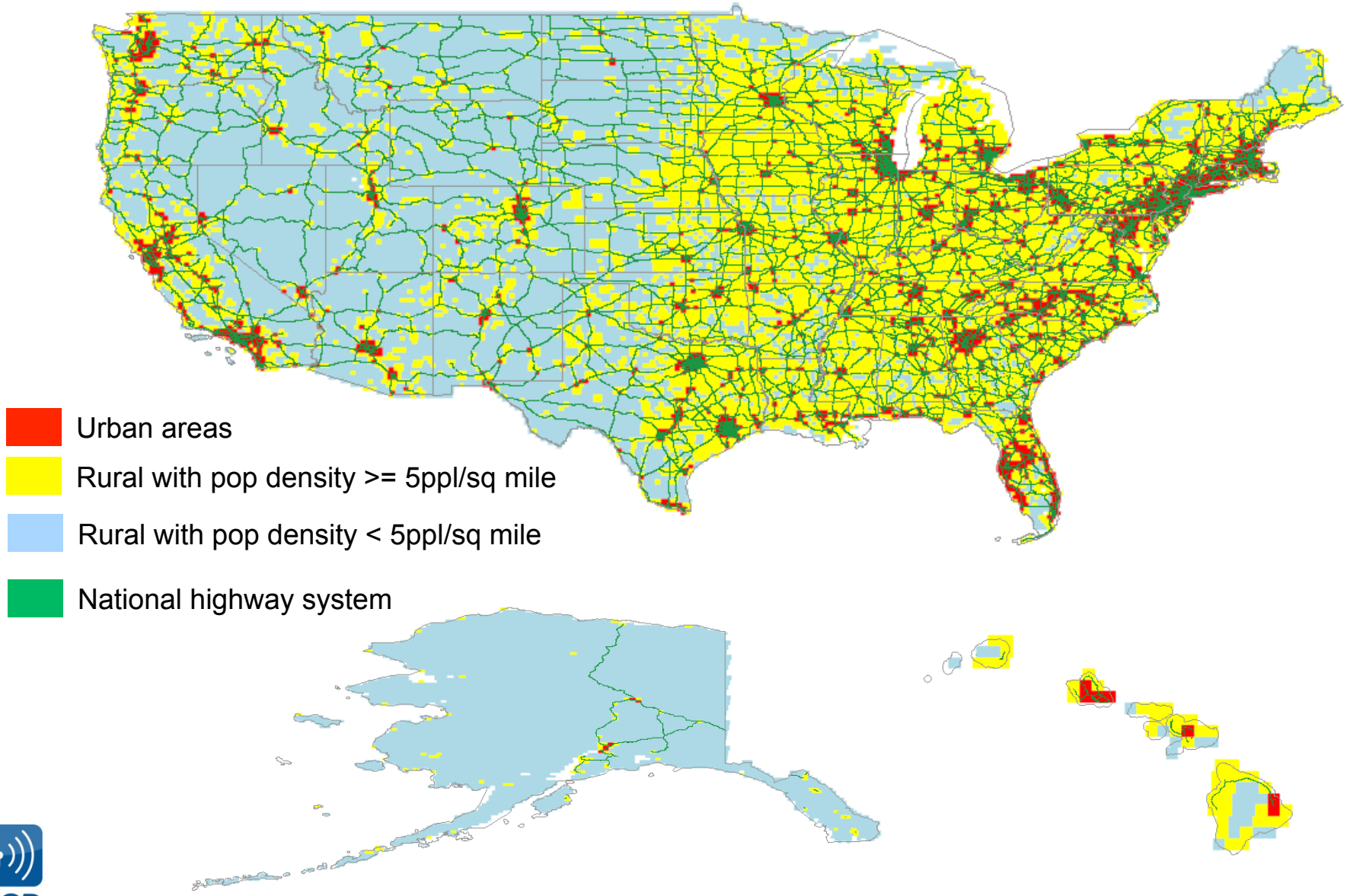
# Area Definitions

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# Target Criteria and Parameter Changes

| Scenario | Urban areas | Rural areas with pop. density ≥ 5 per sq. mile | Rural areas with pop. density < 5 per sq. mile | National Highway System |
|---|---|---|---|---|
| *Baseline* | **95 % reliability Indoor environment 23 dBm UE power** | **95 % reliability Outdoor environment 23 dBm UE power** | **85 % reliability Outdoor environment 31 dBm UE power** | **95 % reliability Outdoor environment 23 dBm UE power** |
| *Urban outdoor* | **Outdoor environment** | | | |
| *85 % rural reliability* | | **85 % reliability 31 dBm UE power** | | **85 % reliability 31 dBm UE power** |
| *Urban outdoor and 85 % rural reliability* | **Outdoor environment** | **85 % reliability 31 dBm UE power** | | **85 % reliability 31 dBm UE power** |
| *High power* | **31 dBm UE power** | **31 dBm UE power** | | **31 dBm UE power** |

- The target user and population coverage is 95 %.

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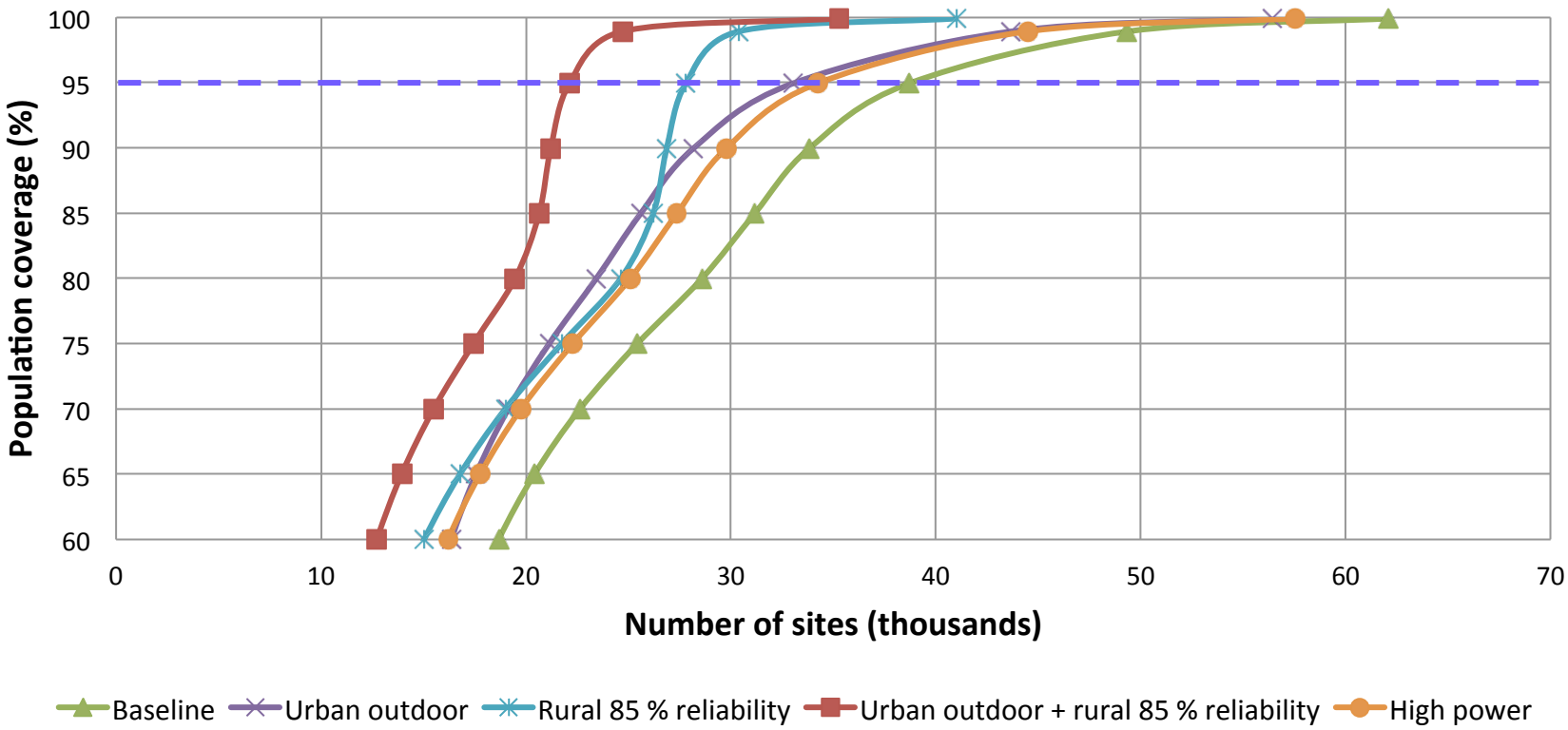
# Impact on Population Coverage




Results provided have an estimated error of ±10% with a 85 % confidence interval

For 95% population coverage:

- No indoor coverage decreases the site count by 14.1%
- Reducing the reliability to 85% decreases the site count by 28.2%
  - 42% when combining with no indoor coverage
- The use of high power UEs decreases the site count by 11.5%

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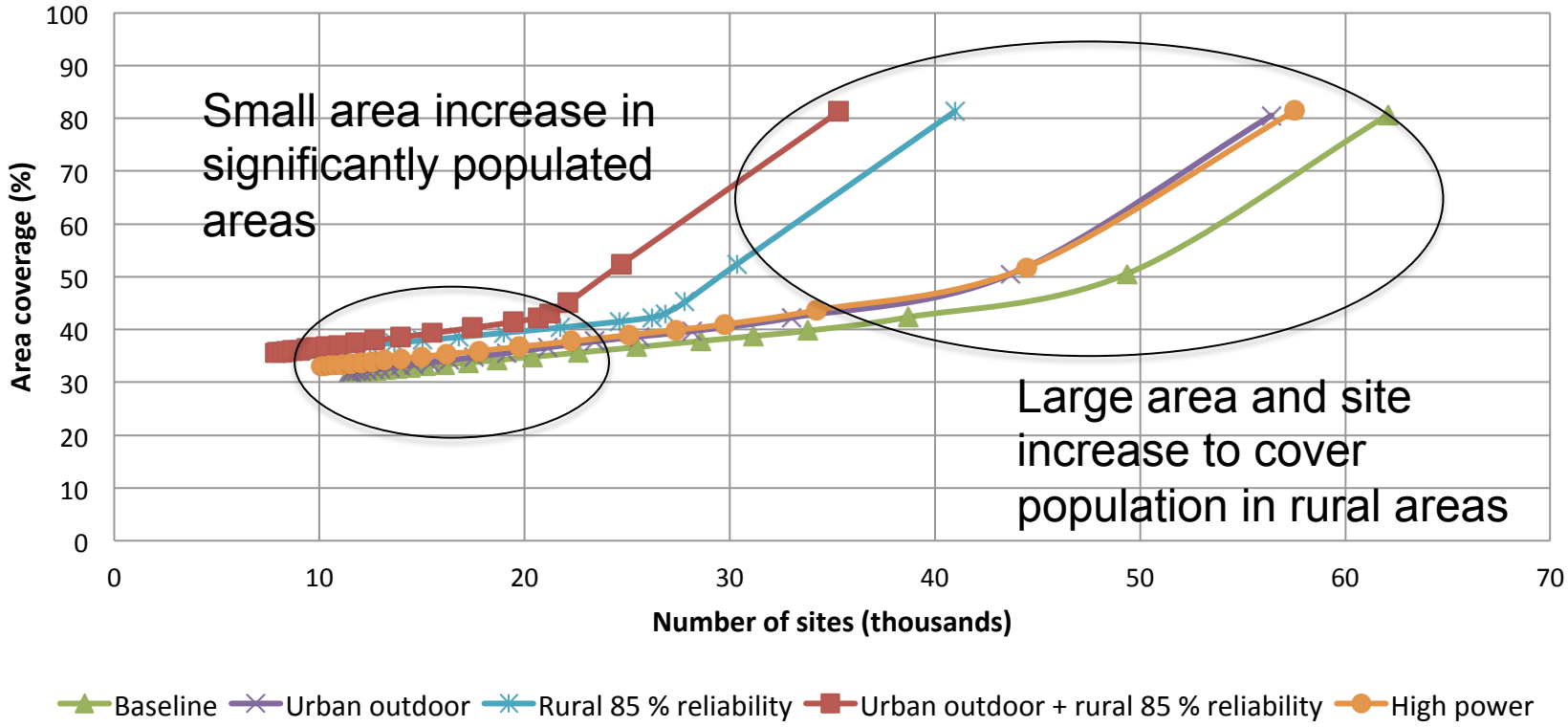
# Impact on Area Coverage




Each data point represents an increase of 5% in population coverage:

- Initially, very small area increase because densely populated areas are selected first
- Significant area coverage increase as population coverage reaches rural areas

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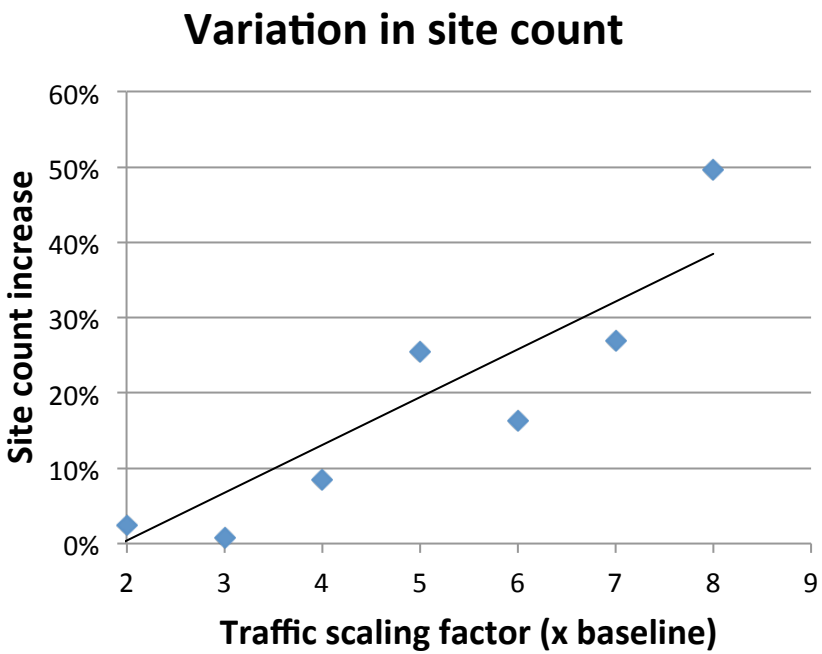
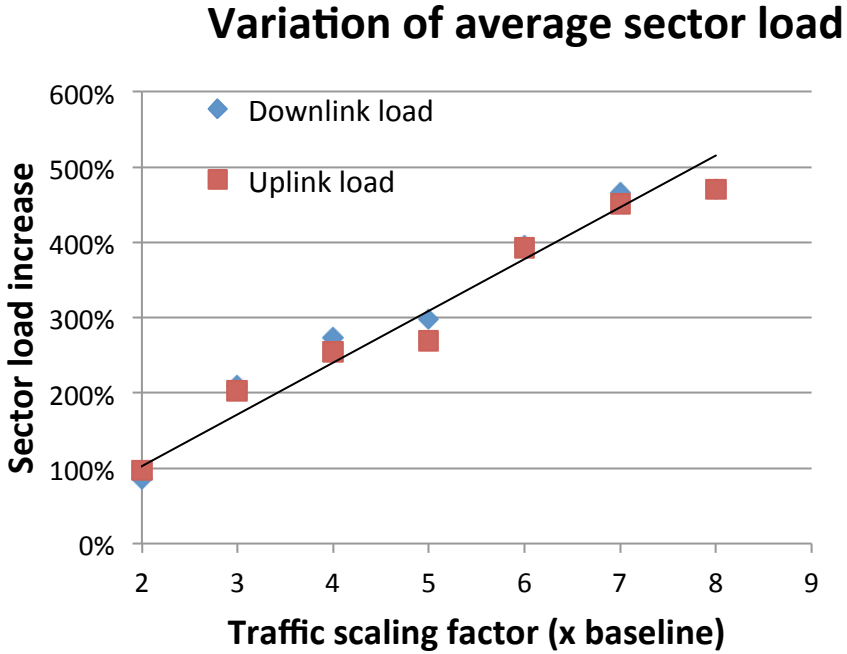
# Impact of Traffic Growth




Results shown for rural areas with population densities greater than 5 per square miles.

- The initial network is coverage limited and capacity is available due to the high level of reliability.
- The site count increase is slower than the traffic increase.

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# RESILIENCY ANALYSIS

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# Network Resiliency: Why is it Important?

- NPSTC has identified resiliency as an important design metric that will be used in the construction of the National Public Safety Broadband Network (NPSBN)*.
- Network planning cannot be based solely on providing a minimum service for day to day operations; unplanned situations that will stress the network *will* happen.
- Examine the effects on performance when part of the network infrastructure is not operational (for example, due to maintenance operations or a natural disaster) by:
  - Modeling various combinations of site failures and measuring performance.
  - Defining metrics to characterize the network's ability to provide minimum service when failures have occurred.

* *Defining Public Safety Grade Systems & Facilities*, National Public Safety Telecommunications Council, Littleton, CO, May 22, 2014

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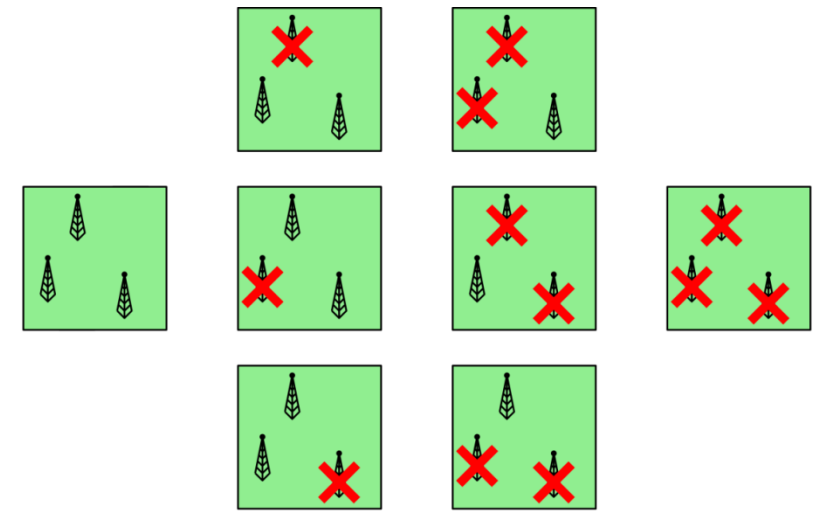
# Resiliency Methodology




- Simulate and measure performance with all sites working (0 failures)
- Examine all possible combinations of site failures
  - Failures are indicated by red x's in the figure
  - Each combination of failed sites is called a "failure scenario"
  - Simulate and collect performance metrics for each scenario
- *N* sites produce $2^N$ scenarios (over 1 billion scenarios for 30 sites).
  - A heuristic algorithm allows the reduction of the number of simulations while still obtaining accurate measurements for the minimum, maximum, and average coverage performance for a given number of site failures.

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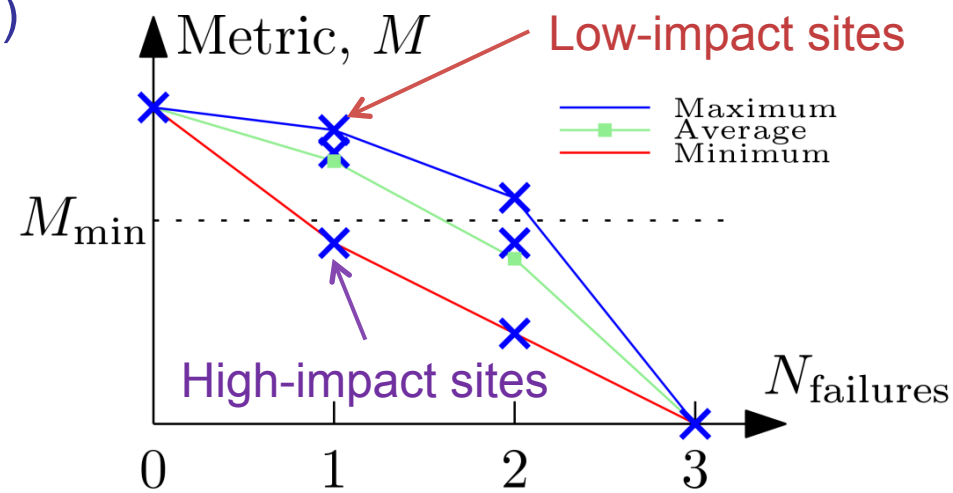
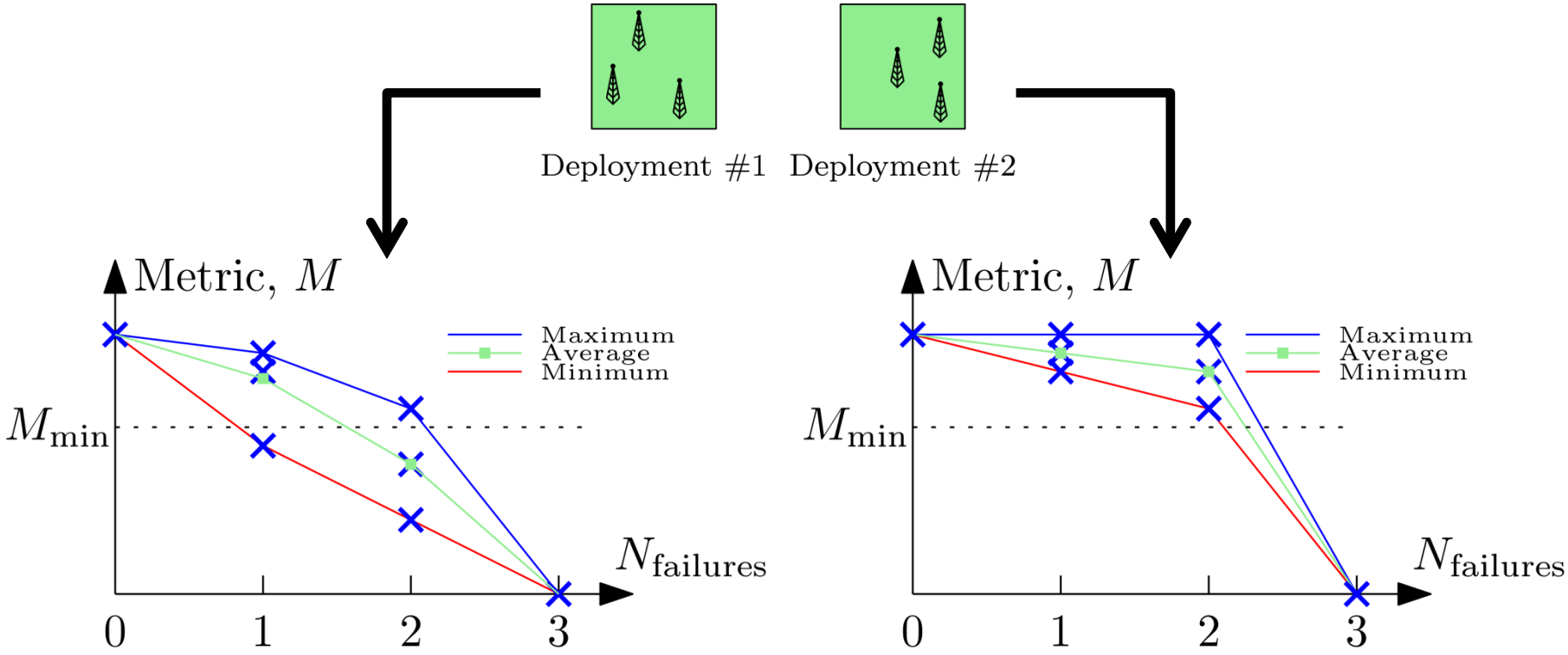
# Measuring Resiliency

- NPSTC defines resiliency as "the ability of the NPSBN to withstand a disruption to the network that would result in loss of coverage…"
- Network performance metrics include:
  - Load and throughput
  - User service rates
  - Coverage (uplink, downlink, population)
- The resiliency with respect to a metric is measured by the number of sites that can fail while still maintaining at least the target performance level ($M_{min}$)
- The analysis helps identify high-impact sites that are candidates for additional hardening or redundancy and low-impact sites already providing resiliency.



# Comparing Deployment Options Using Resiliency




- Min: 0-site resiliency
- Mean: 1-site resiliency

- Min: 2-site resiliency
- Mean: 2-site resiliency

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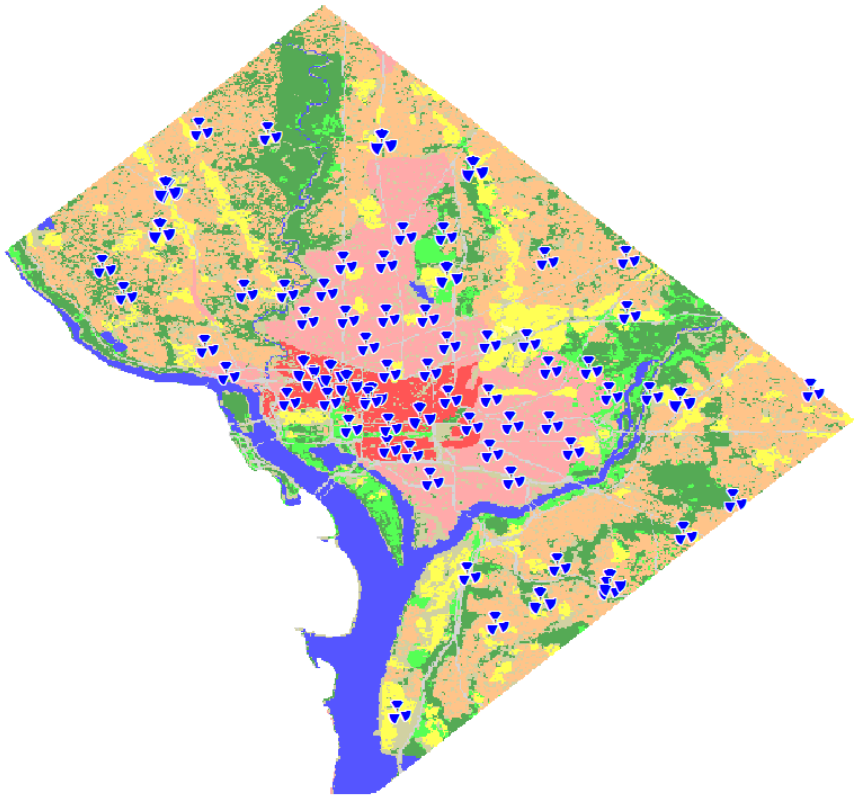
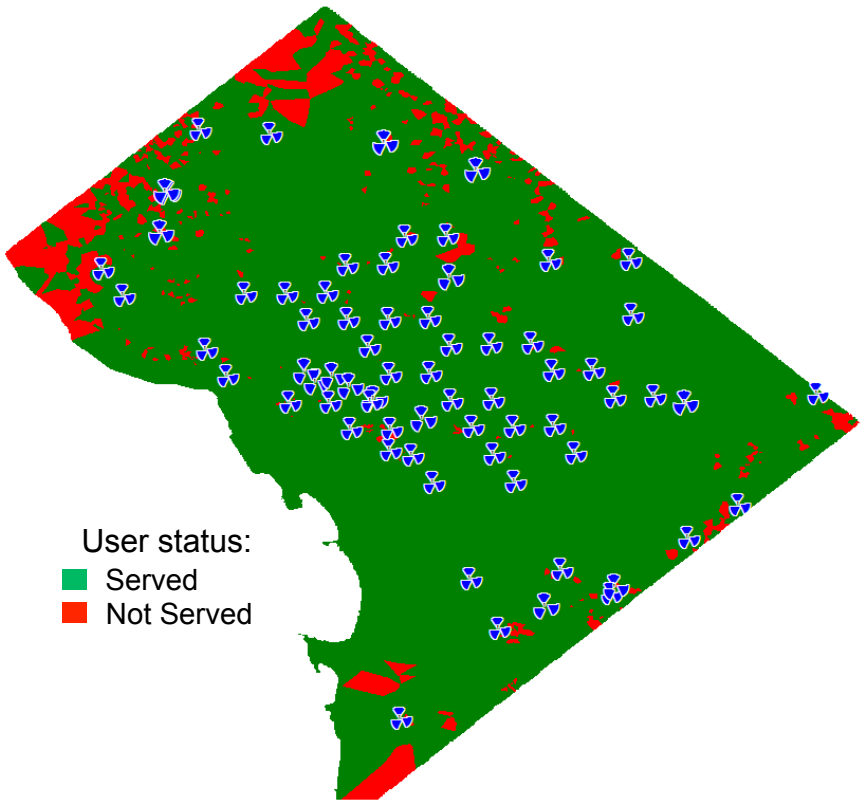
# Site Placement Example: Washington DC



Number of sites: 70




User coverage: 95.7 %

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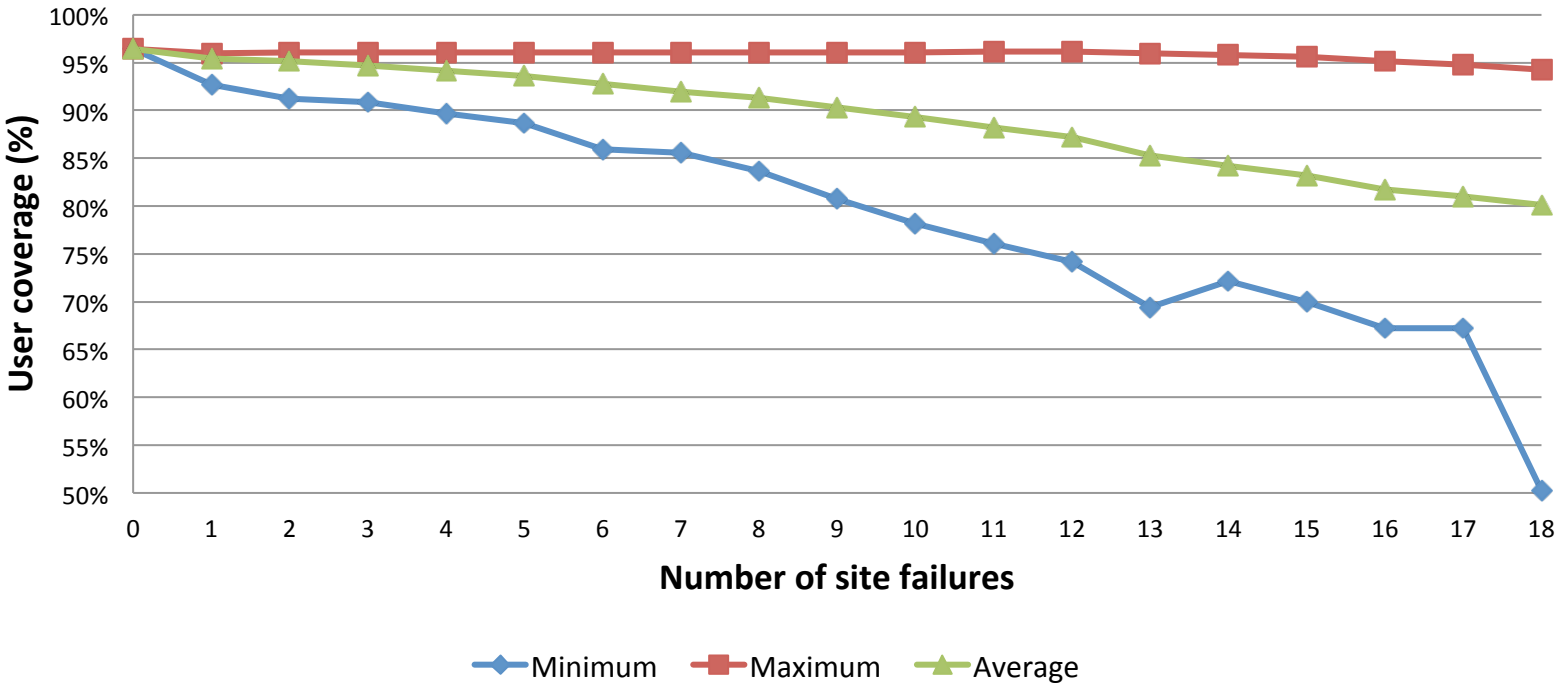
# Impact of Site Failures on User Coverage




- The minimum path shows the presence of a critical site that drives the user coverage below 95 % with a single failure (0-site resiliency).
- On average, the network can sustain 2 simultaneous failures while still maintaining 95 % user coverage, and about ½ of scenarios with 2 failures give coverage above 95 %
- At least one combination of 54 sites provides 95 % user coverage, but beyond 16 failures there is no scenario with more than 95 % coverage

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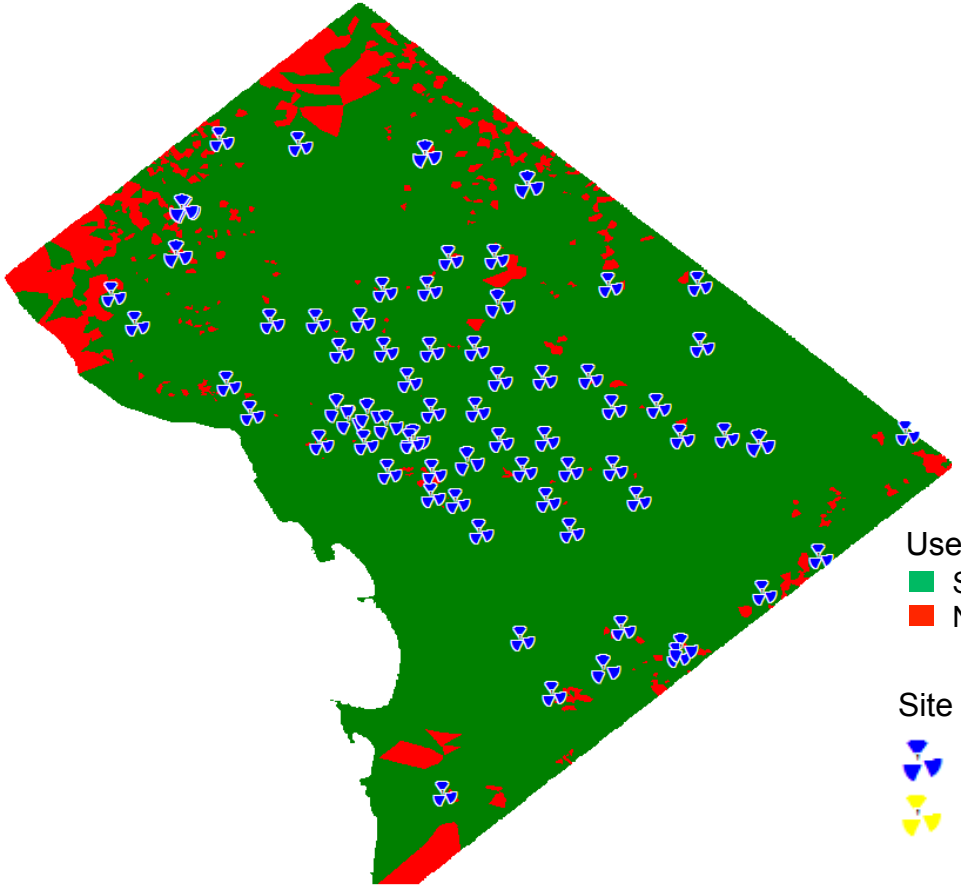
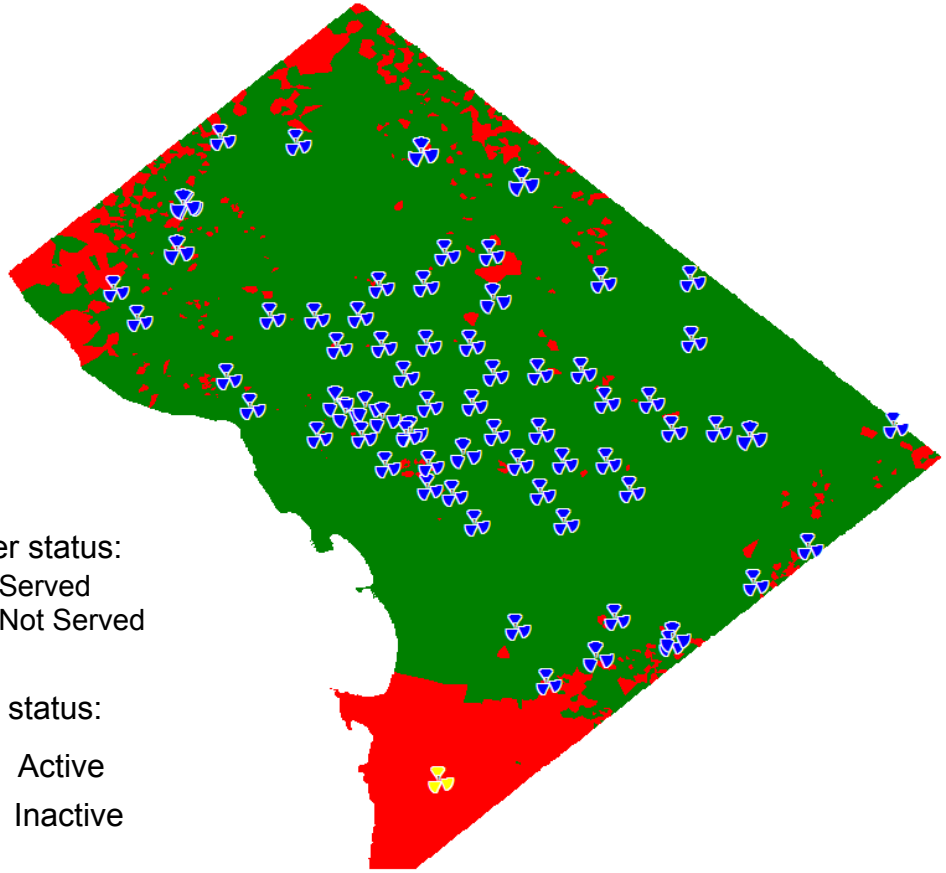
# High-Impact Sites

Coverage with no failed sites



Coverage with failed highest impact site



User status:
- Served
- Not Served

Site status:
- Active
- Inactive

Losing a single site reduces coverage from 95.7 % to 92.7 %

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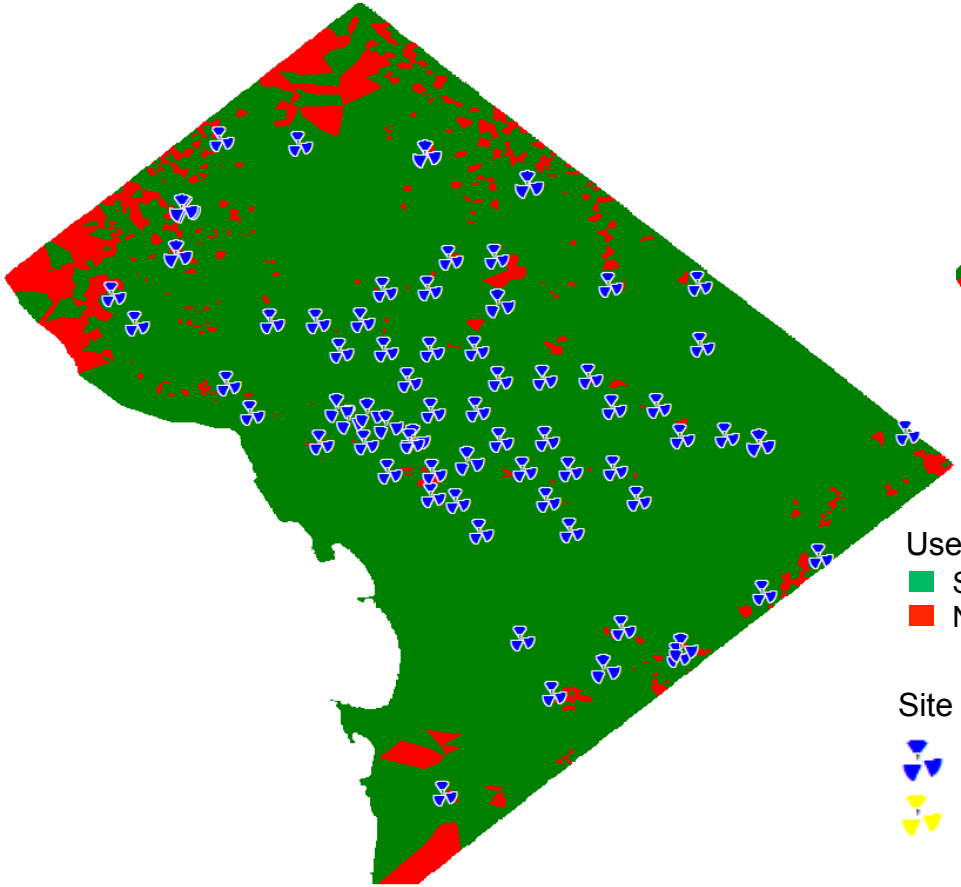
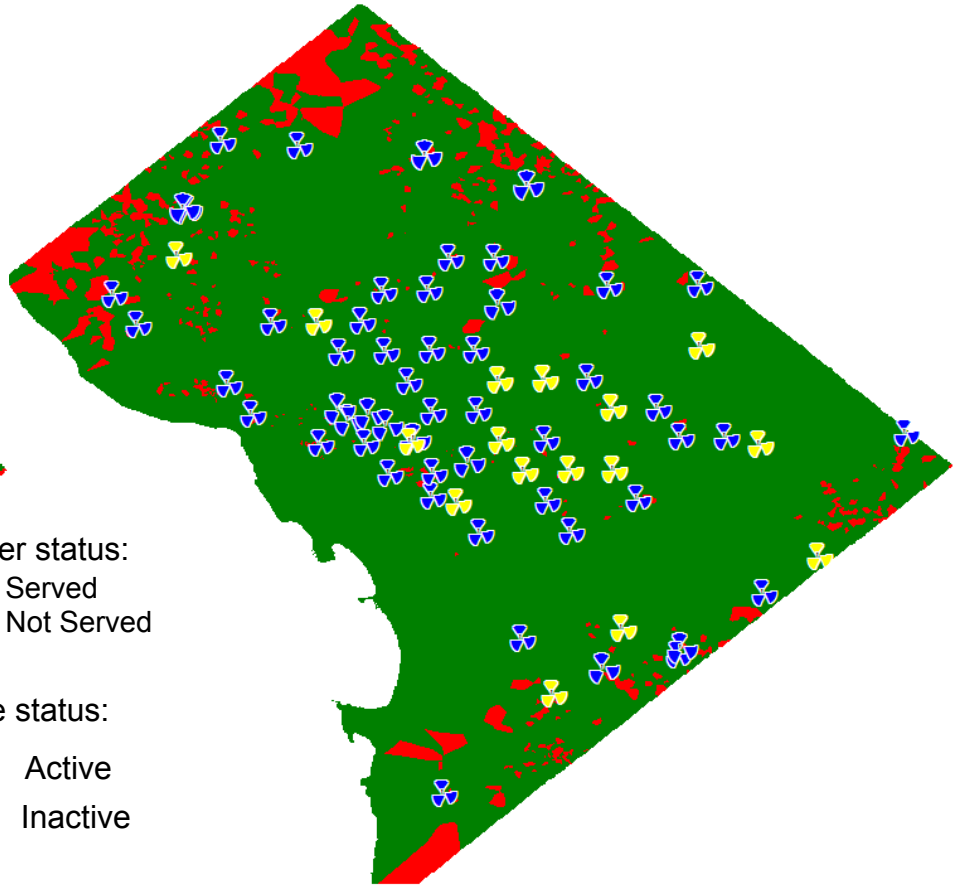
# Low-Impact Sites

Coverage with no failed sites



Coverage with failed lowest impact



User status:
- Served
- Not Served

Site status:
- Active
- Inactive

Losing these 16 sites has low effect on performance providing a 95.1 % user coverage.

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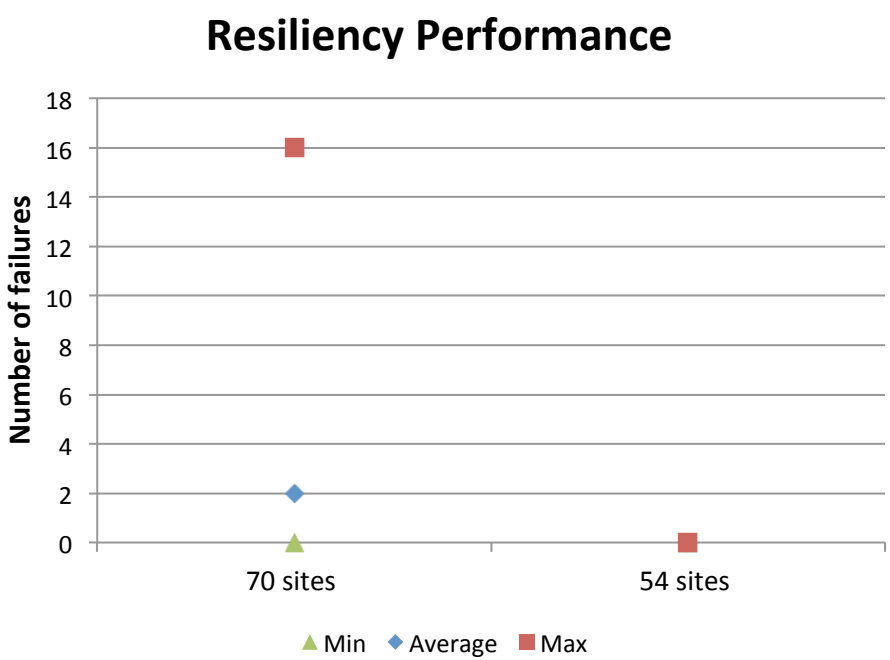
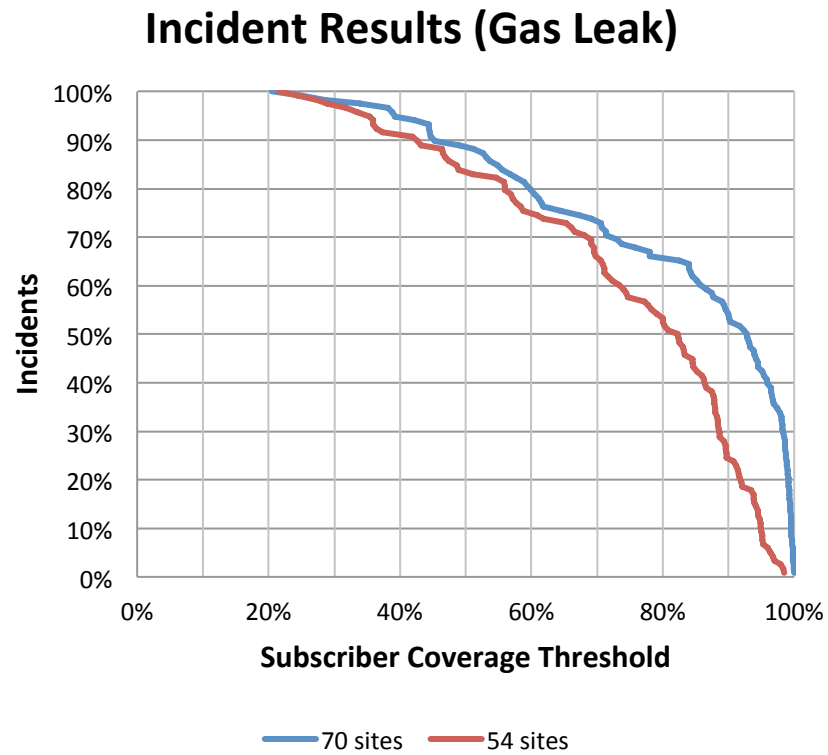
# Any Benefits to Low Impact Sites?




Increased resiliency: Without low impact sites, the network does not maintain minimum coverage with even one failure

Increased capacity: Only in 4 % of the incidents, 95 % of the users are served compared to 48 % with 70 sites.

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# Key Observations

- Resiliency analysis provides the network operator with an important tool to assess the robustness of a given deployment
  - Identify high-impact sites that are candidates for hardening using some of the best practices identified by NPSTC
  - Determine the probability of below-threshold performance
- Low-impact sites may not need to be hardened or supported with backups, but:
  - Reducing site count reduces resiliency margin
  - Excessive pare-back of sites can leave the network vulnerable to even a single failure
  - Overall network capacity is reduced with fewer sites
- A comparative resiliency analysis will identify site deployments for the NPSBN that “bake in” resiliency, and will allow scarce resources to be spent on the sites whose impact on performance is the greatest.

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# LARGE SCALE INCIDENT ANALYSIS

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# Network Response to Large Scale Incidents

- During a large scale incident, traffic loads and user counts increase significantly with respect to day-to-day operations
- Different incidents types vary in size, location and the number of responders involved.
- It is important to test the robustness of the network within a geographical region (e.g. city, county) where different incident types occur.

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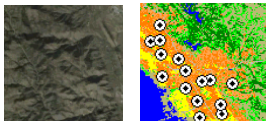
# Incident Analysis Methodology

Incident scenario

- Incident area size
- Number of responders
- Applications used

Incident area morphology

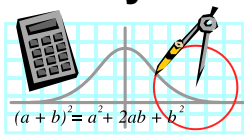


- Terrain
- Clutter
- Population

**Incident Placement**

Incident locations

**Incident Analysis**




Statistics:

- Number of subscribers served, failure status
- Sector load and throughput

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# Example Incident Scenarios

- Scenario 1: Toxic **Gas Leak**
  - Source: "Public Safety Communications Assessment 2012-2022: Technology, Operations, & Spectrum Roadmap," NPSTC Public Safety Communications Report, June 5, 2012 (http://www.npstc.org/download.jsp?tableId=37&column=217&id=2446&file=AFST_NPSTC_Report_06232012.pdf)
  - "report of a toxic gas leak in a large public assembly building near the National Mall in Washington, DC."
- Scenario 2: **Shooter** Inside High School (Urban)
  - Source: "Minnesota Department of Public Safety Public Safety Wireless Data Network Requirements Project Needs Assessment Report" (https://dps.mn.gov/divisions/ecn/programs/armer/Documents/Minnesota_Needs_Assessment_Report_FINAL.pdf)
  - Active shooter / hostage scenario at a large high school and involving casualties
- Scenario 3: Barricaded **Hostage**
  - Source: "East Bay Regional Communications System Authority (EBRCSA). Project Cornerstone Network LTE Testing", Andrew M. Seybold and Robert O'Hara.
  - "A gunman holds one or more hostages in a building."
  - Uses peak traffic.

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# Incident Traffic Summary

| Area / User Distribution | User Type | Uplink Data Rate (kb/s) | Downlink Data Rate (kb/s) |
|---|---|---|---|
| Outer Perimeter is 1.6 km x 1.6 km. Incident Command personnel are concentrated in a small area. Remainder of the 327 responders and 127 vehicles are deployed uniformly in the incident area. | Responders Subtotal | 7,154 kb/s | 2,568 kb/s |
| | Unified Command Subtotal | 280 kb/s | 8,477 kb/s |
| | **Gas Leak scenario TOTAL** | **7,433 kb/s** | **11,046 kb/s** |
| Outer Perimeter is 1 km x 1 km, with around 100 responders. Most responders are grouped in the Incident Command or the Staging Area. | Strike Team Subtotal | 2,667 kb/s | 303 kb/s |
| | Incident Command Subtotal | 427 kb/s | 6,524 kb/s |
| | Staging Area Subtotal | 947 kb/s | 513 kb/s |
| | Perimeter Subtotal | 257 kb/s | 256 kb/s |
| | **Shooter scenario TOTAL** | **4,298 kb/s** | **7,596 kb/s** |
| Assumes same perimeter as scenario 2 due to the similar nature of the scenarios. | Sniper 1 (high resolution) | 3,100 kb/s | 0 kb/s |
| | Sniper 2 (low resolution) | 1,200 kb/s | 0 kb/s |
| | Police car camera Subtotal | 1,900 kb/s | 3,800 kb/s |
| | Police commander Subtotal | 0 | 7,400 kb/s |
| | SWAT commander Subtotal | 0 | 7,400 kb/s |
| | **Hostage scenario TOTAL** | **6,200 kb/s** | **18,600 kb/s** |

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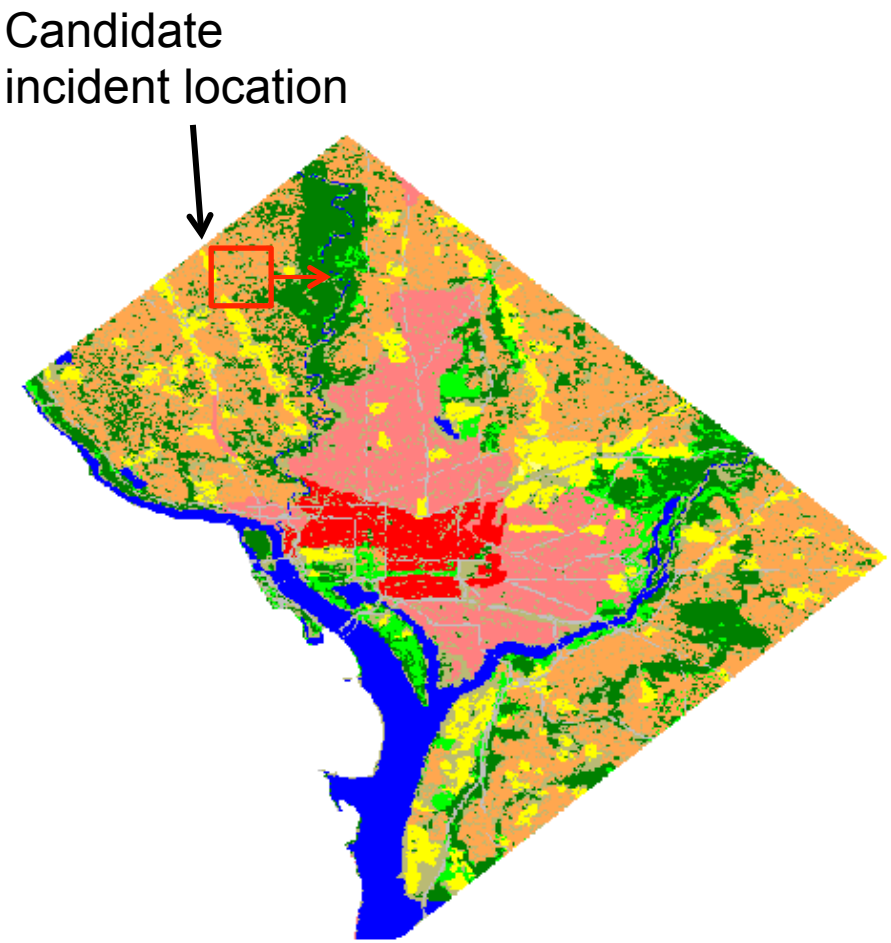
# Incident Location Placement




- Given the incident area size (e.g. 2.56 $km^2$)
- Scan the entire region
  - For each candidate location, check if its morphology matches the incident area morphology
  - Move the candidate location by a fixed increment (e.g. 500 m)
- Remove overlapping areas

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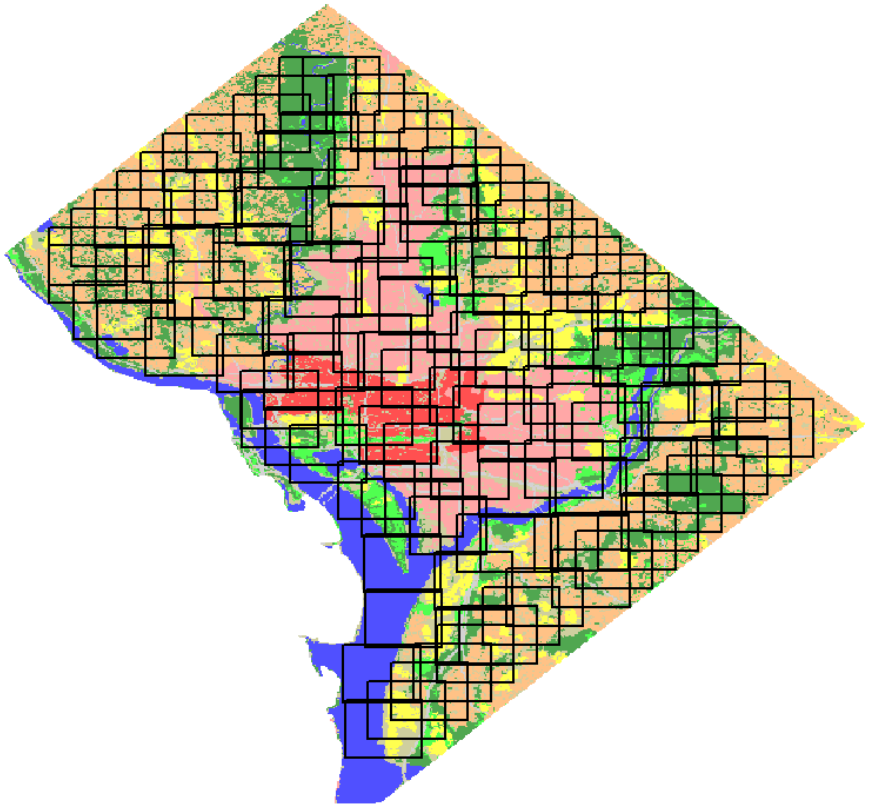
# Incident Location Placement



118 incident locations

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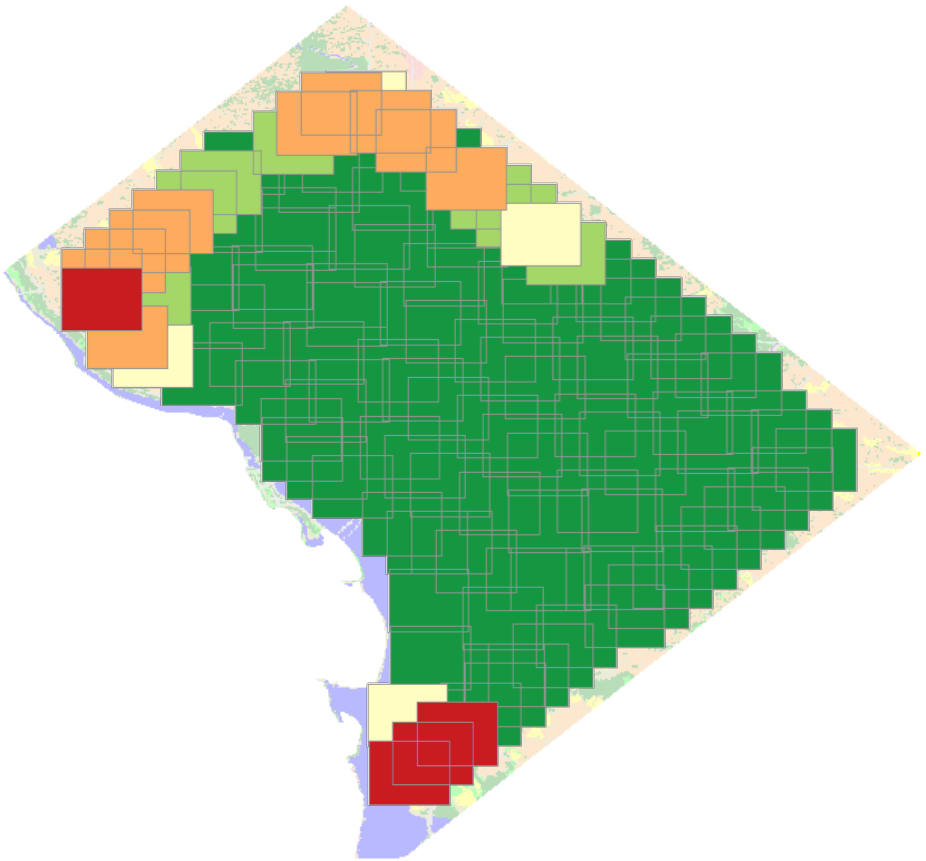
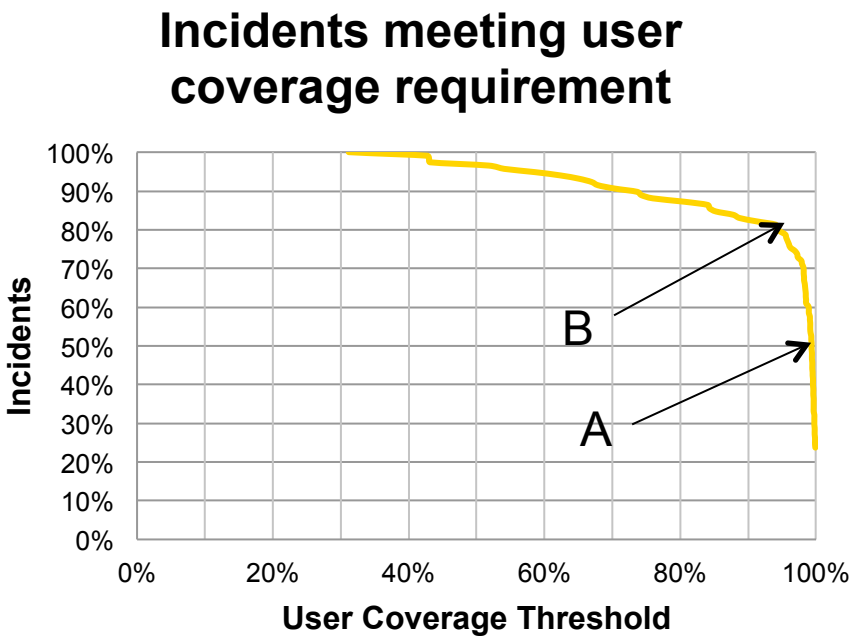
# Gas Leak Incident






A. In 50 % of the incidents, 99 % of the users were served
B. In 79 % of the incidents, at least 95 % of the users were served

User coverage at 95 % reliability (%)

- 0 – 50
- 50 – 75
- 75 – 85
- 85 – 95
- 95 - 100

Most of the areas where coverage is not met are located at the edge of the network. This is due to the lack of overlap from neighboring sites

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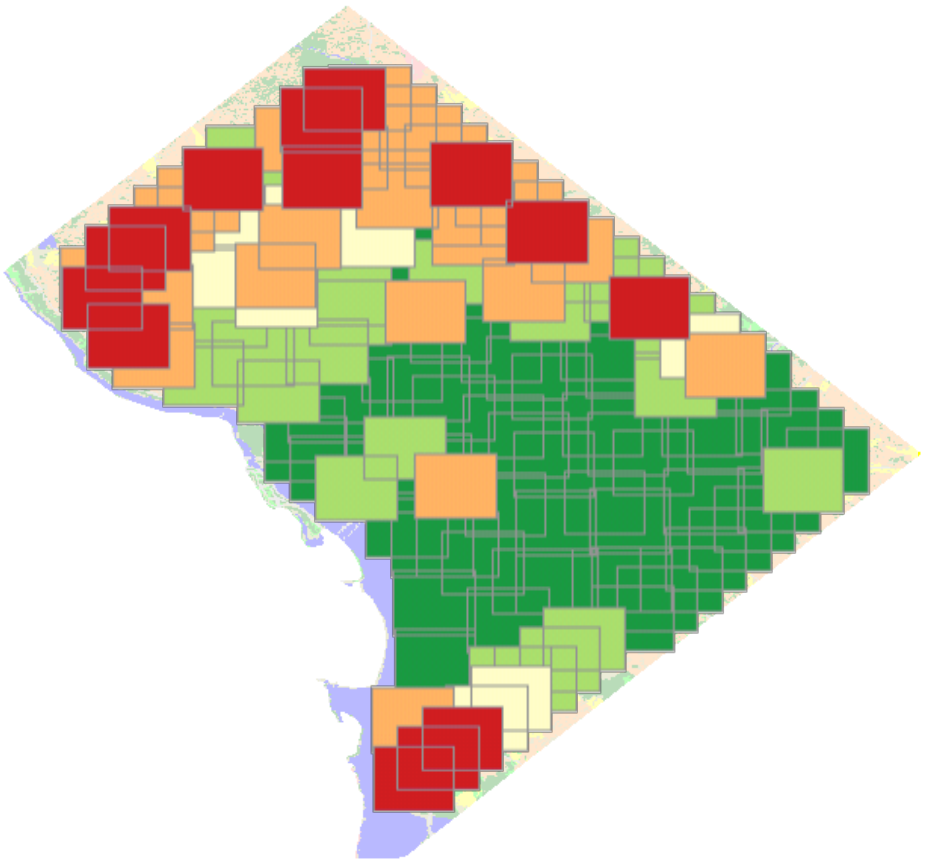
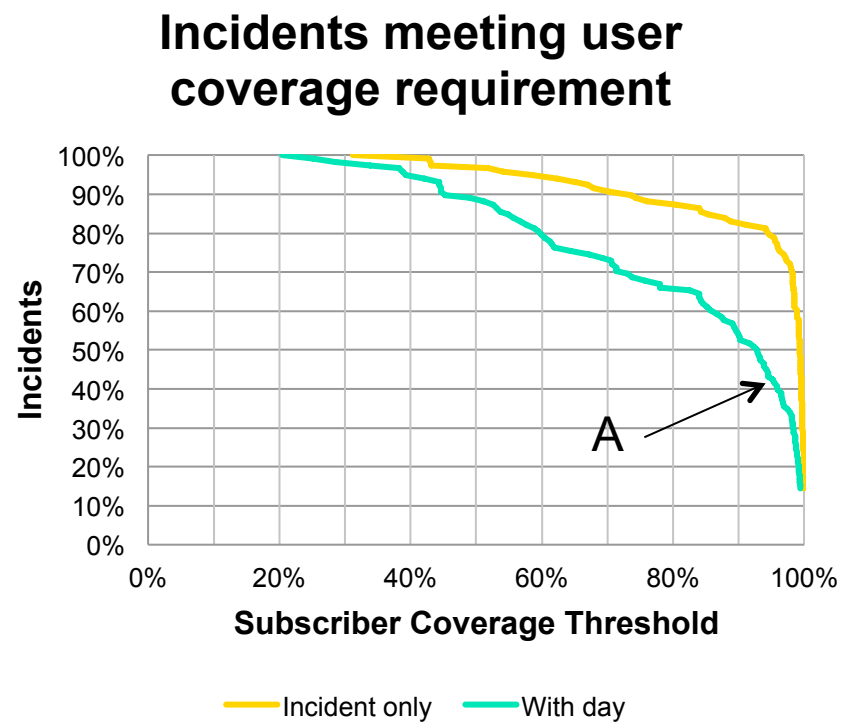
# Gas Leak Incident + Day-to-day Traffic



User coverage at
95 % reliability (%)

- 0 – 50
- 50 – 75
- 75 – 85
- 85 – 95
- 95 - 100




A. In 43 % of the incidents, at least 95 % of the users were served when day-to-day traffic is included compared to 79 % with only the incident traffic

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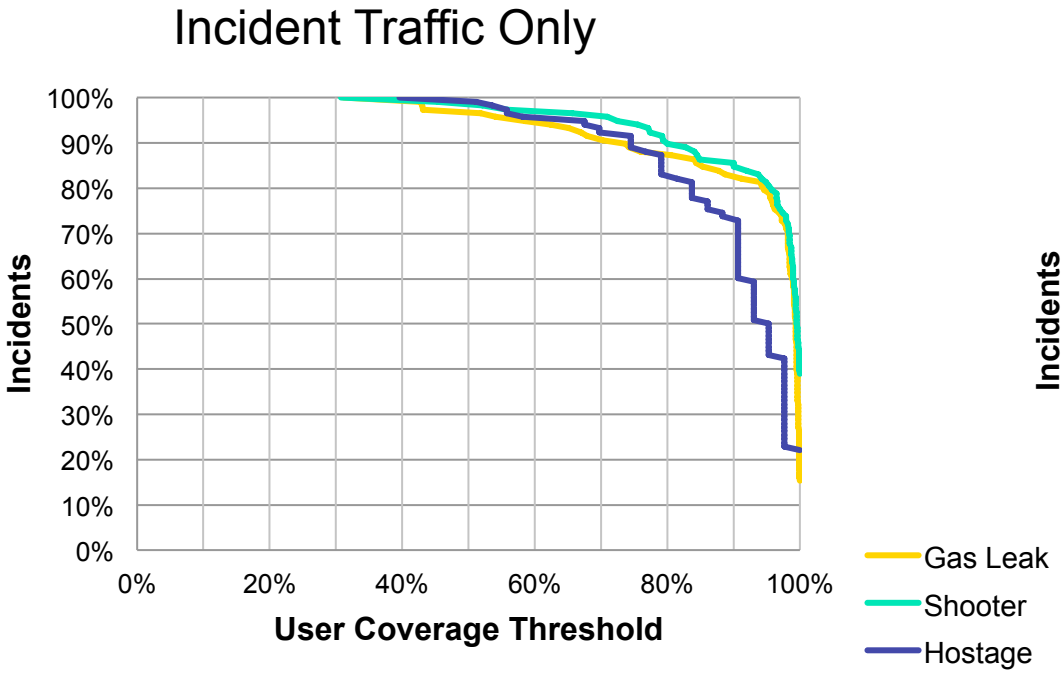
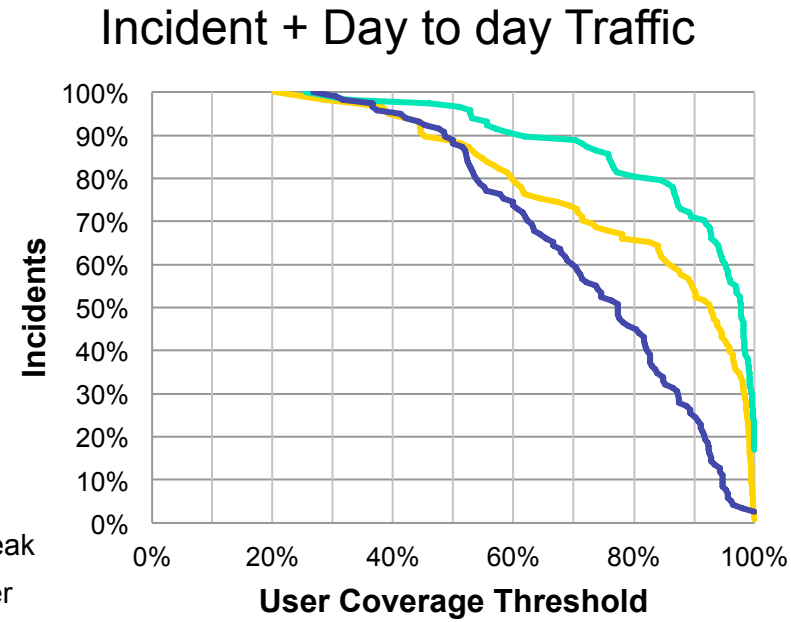
# Summary Results for All Incident Scenarios




- The capability of the network to sustain an incident is directly linked to the amount of traffic to carry
  =>The network is not able to sustain as many Hostage incident scenarios because of the higher data rate requirements
- Coverage decreases for all scenarios when day to day traffic is included

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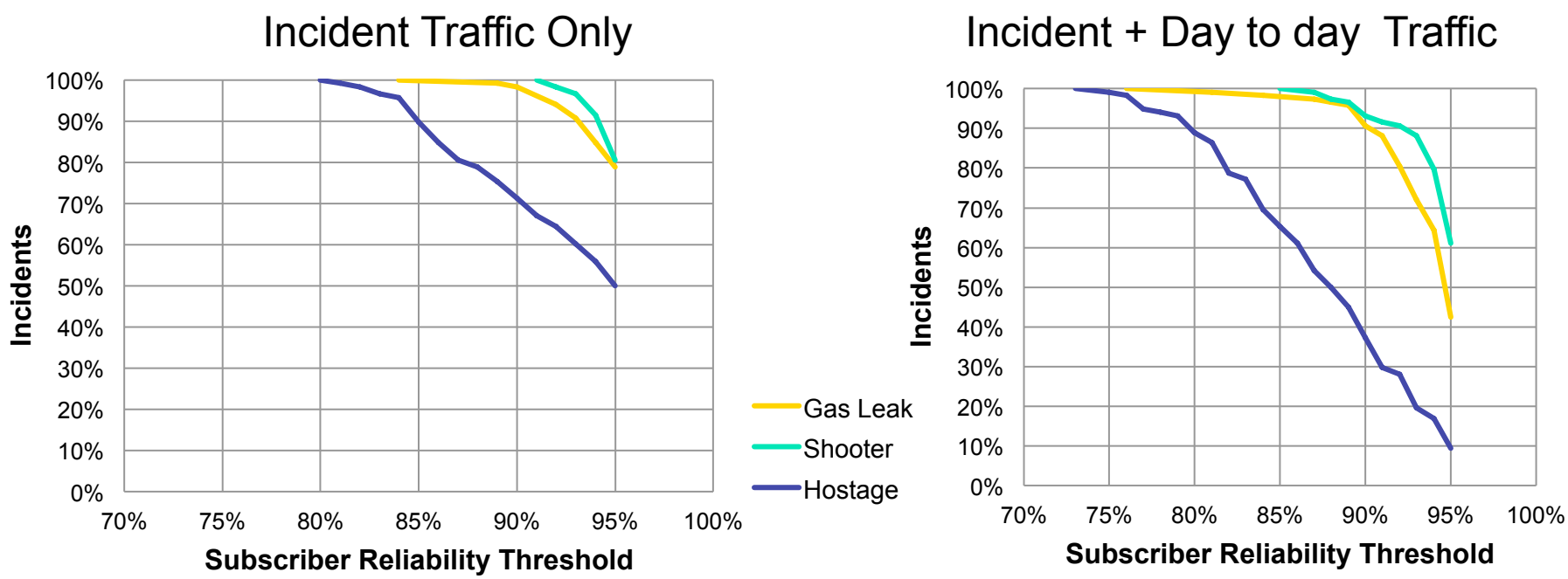
# Effective User Reliability




- The users not served at 95 % reliability can still be served at a lower reliability
  - In more than 98 % of the Gas Leak and Shooter incidents, the users were served with at least 90 % reliability.
- The presence of day to day traffic lowers the reliability of the users responding to the large incidents.

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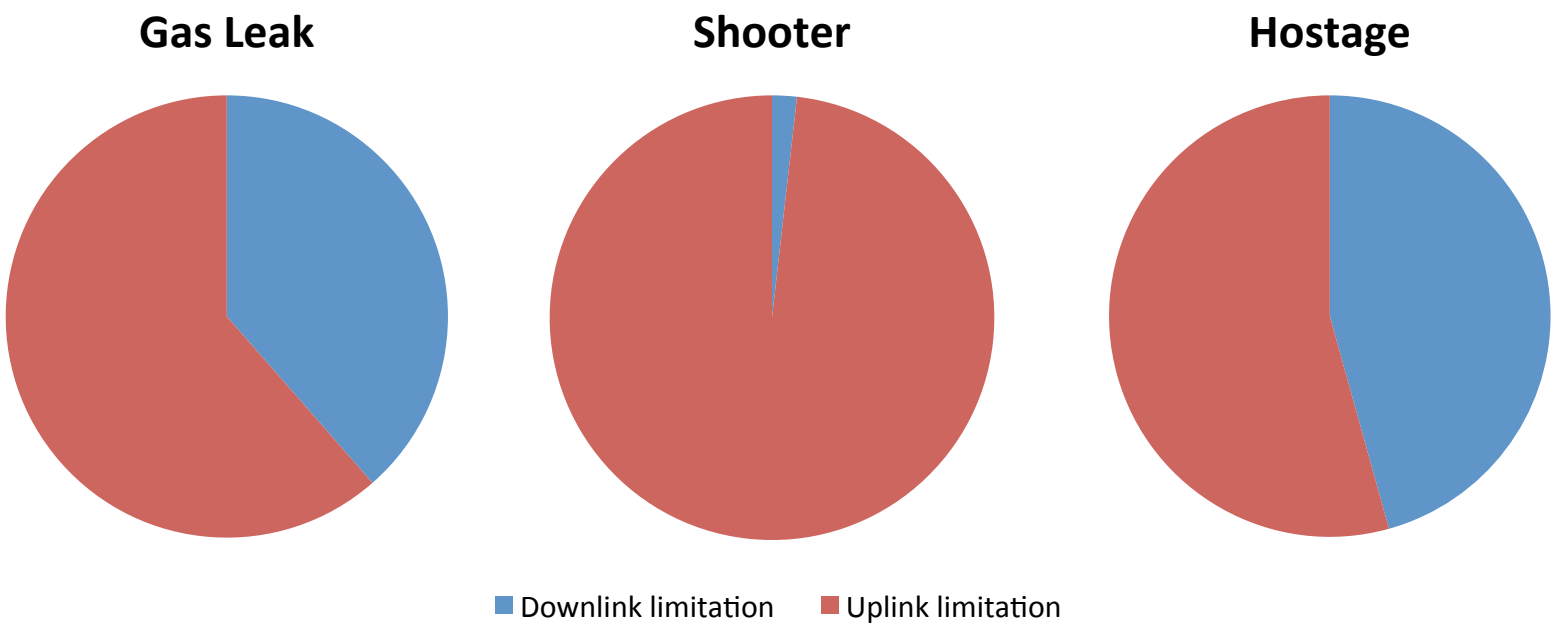
# Reasons for Users Not Served

- Each incident scenario has a different set of requirements (number of users, data rates, area) that can lead to different reasons for users to not be served or served with a lower reliability.




- While all the scenarios are uplink limited, some scenarios still show limitations in the downlink.

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# Key Observations

- Presented a methodology to test the performance of a network deployment for various incident assumptions
- Considered user coverage, reliability, and failure status to analyze the network performance.
- The network performance is dependent on the type of incident scenario considered:
  - Size of the affected area, number of responders, and type of applications
  - Not all areas can sustain higher traffic demands
- The user reliability varies during an incident
  - It is likely to decrease and may be location dependent
- There is a significant performance decrease when large incidents are added to the day-to-day traffic.

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# CHARACTERIZING THE USER EXPERIENCE

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# Characterizing the User Experience

- The results presented so far were mainly about assessing the network performance:
  - Using statistical averages
  - Limited to the radio access network
- It is important to consider the application performance end-to-end and assess the user experience
  - Consider a video application during an incident

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# Example Incident Scenario

- The scenario is based on the NPSTC Public Safety Communications Report, similar to the 'Toxic Gas Leak' incident.
- The incident involves Police, Fire and EMS responders, along with a Command Center:
  - 327 responders and 127 vehicles.
- Use a wide range of applications: live video streaming of varying quality, location tracking, bio-telemetry, file transfer, sensor reading, weather tracking and voice calls.
- 11 sites providing service to the area, 7 of which are actively used.
- First responders are located within 1 sq. mile of the incident area and heavily concentrated near the incident location.

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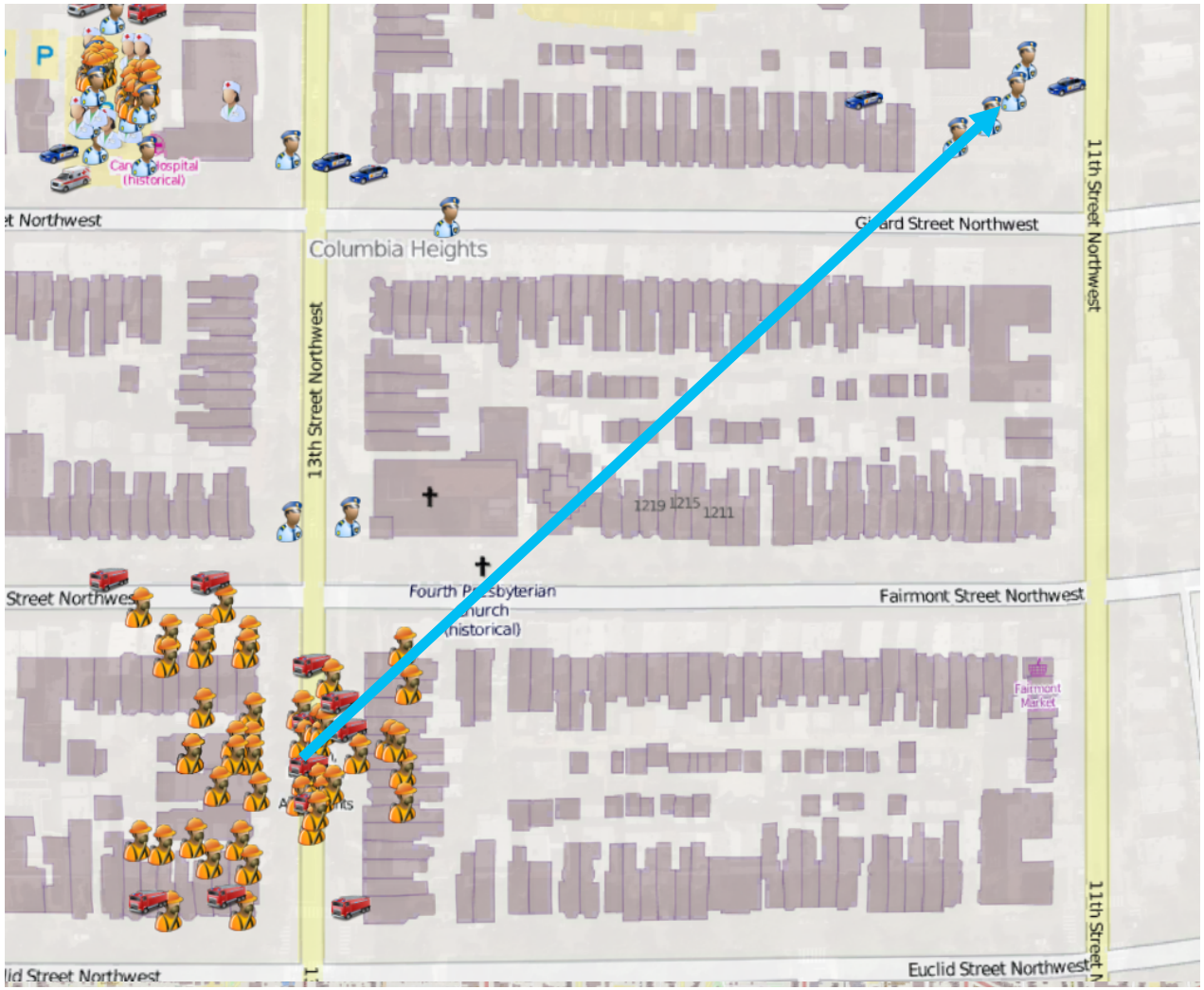
# Incident Scene




- Consider the video stream sent from one of the responders to the command center.

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# Play Responder to Command Video Stream

- Reference video (no loss)
- Video stream during incident
  - No priority management
  - Priority management

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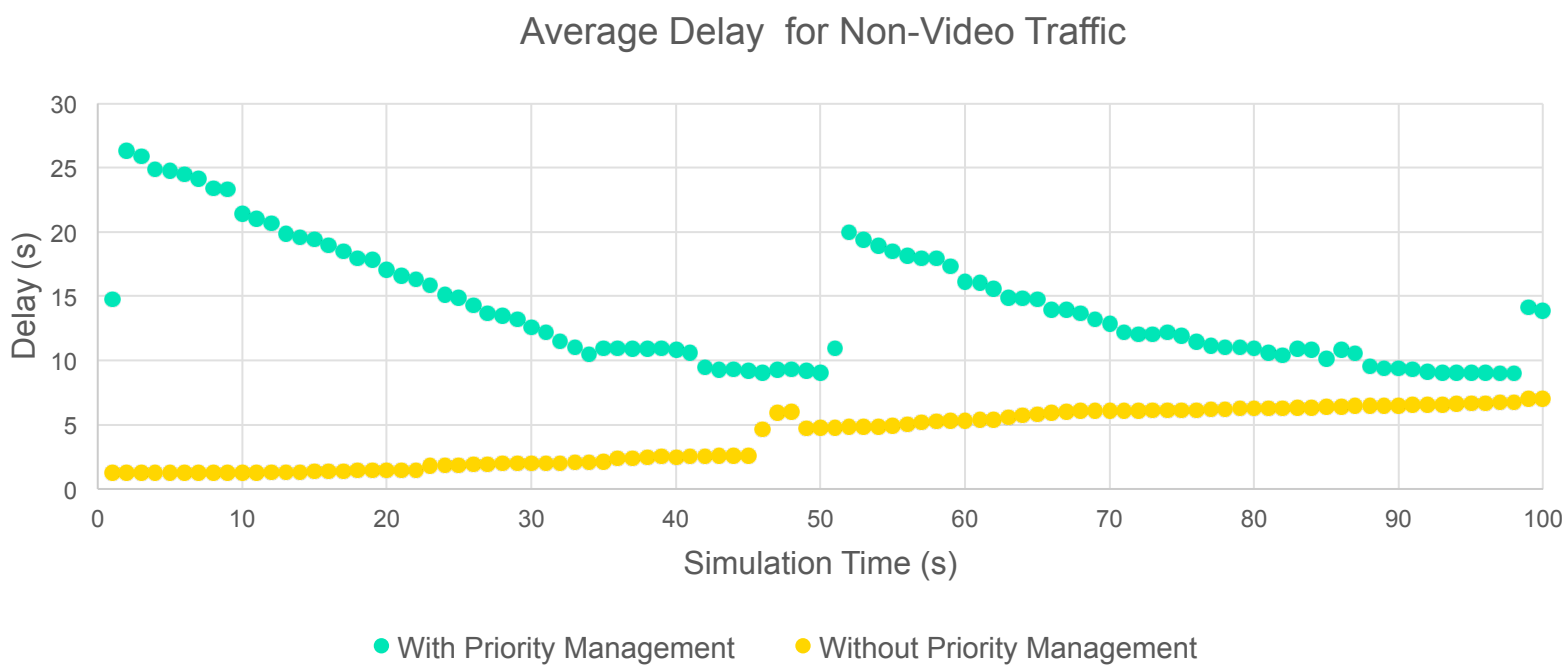
# Impact of Video Prioritization on Other Traffic




- Without priority management, all the applications are treated the same and the video quality was poor.
- When the video stream is sent over a dedicated bearer, the loss is reduced and we observe higher transmission delays on the other traffic.

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# CONCLUSIONS

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# Key Take-Aways (1)

- Discussed parameter sensitivity analyses to evaluate the impact of parameter and configuration changes on the number of sites required and the coverage performance obtained nationwide:
  - Reducing the reliability requirement from 95% to 85% in rural areas reduces the site count by about a third for 95 % population coverage.
  - A five fold increase in the traffic leads to a 25% increase in the site count.
- Quantified a resiliency metric and provided tools to identify low and high-impact sites.
- Evaluated the impact of large scale incidents on the network coverage and reliability.
  - Incidents with higher data rates will cause a more significant drop in coverage and reliability.
  - Managing day to day traffic during large scale incidents can be used to improve the network performance.

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# Key Take-Aways (2)

- Priority management is necessary, especially when considering the user experience
  - Studied a video application performance during an incident
  - Preliminary results show that priority management is needed in order to keep an acceptable video quality
- Future work to focus on end-to-end network performance modeling
  - Modeling the user experience (voice, video)
  - Priority management
  - Quality of service support

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