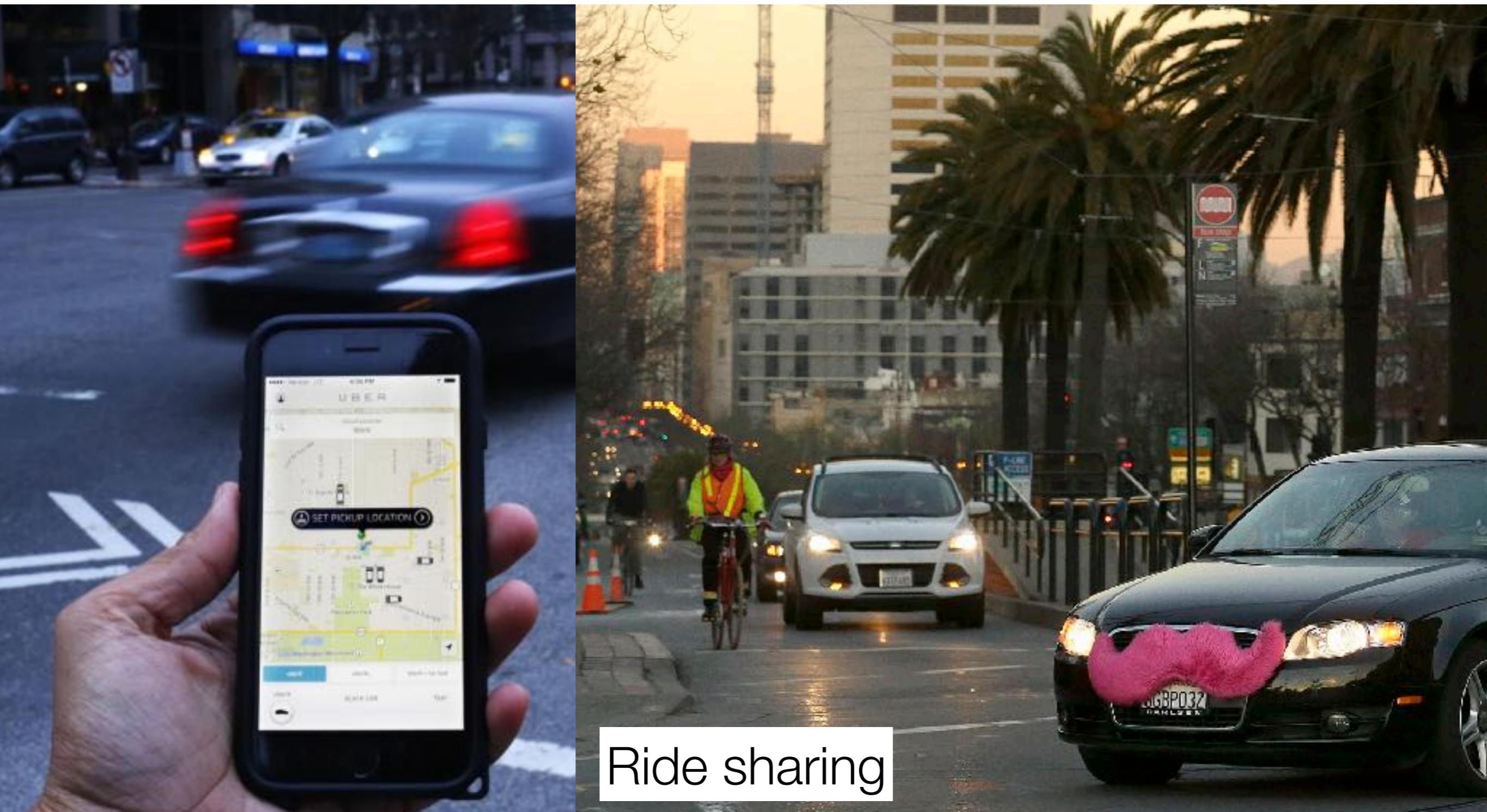




Trading Off Accuracy, Timeliness, and Uplink Usage in Online GPS Tracking

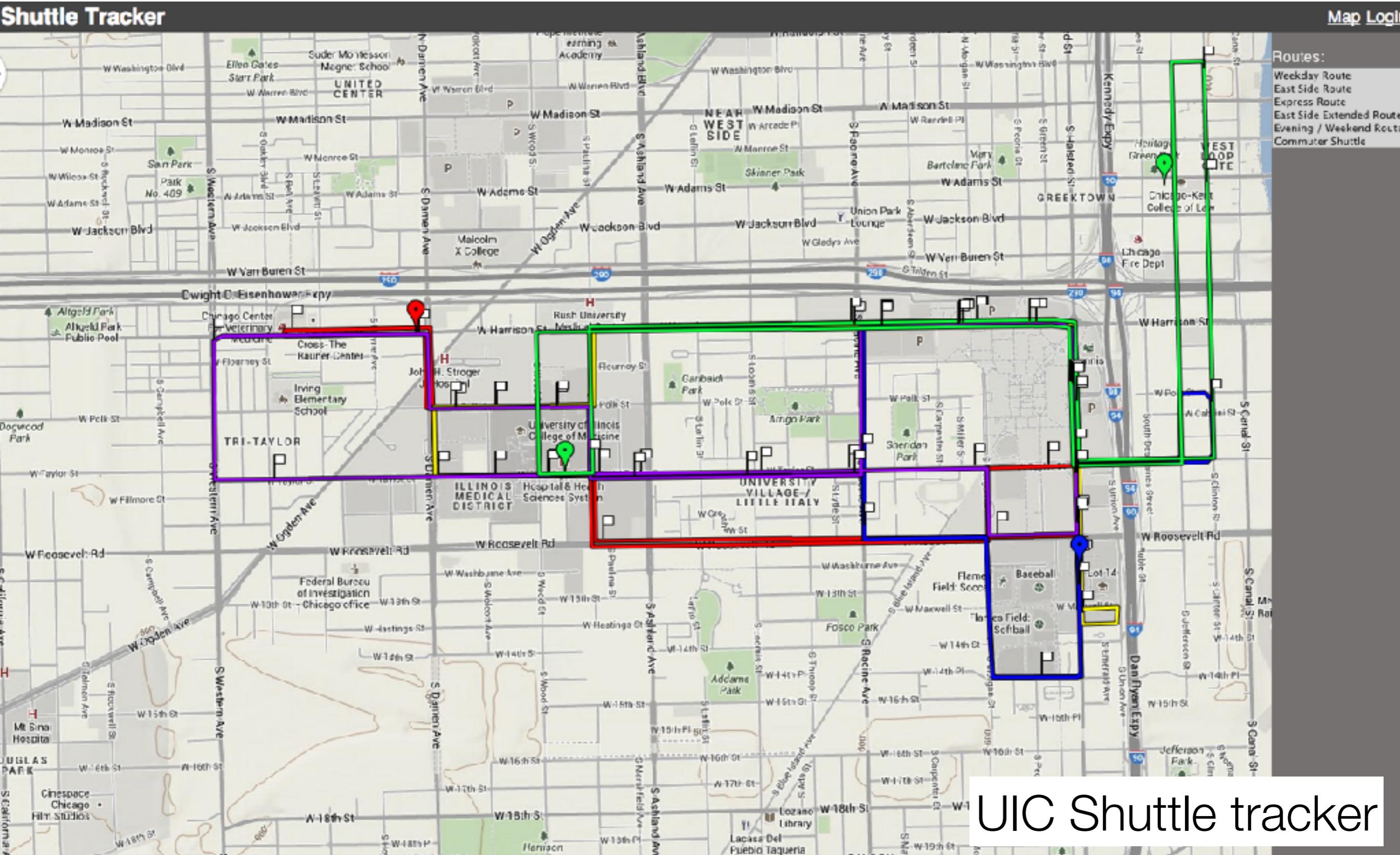
ABM Musa, James Biagioni, Jakob Eriksson

GPS tracking applications

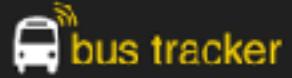


Ride sharing

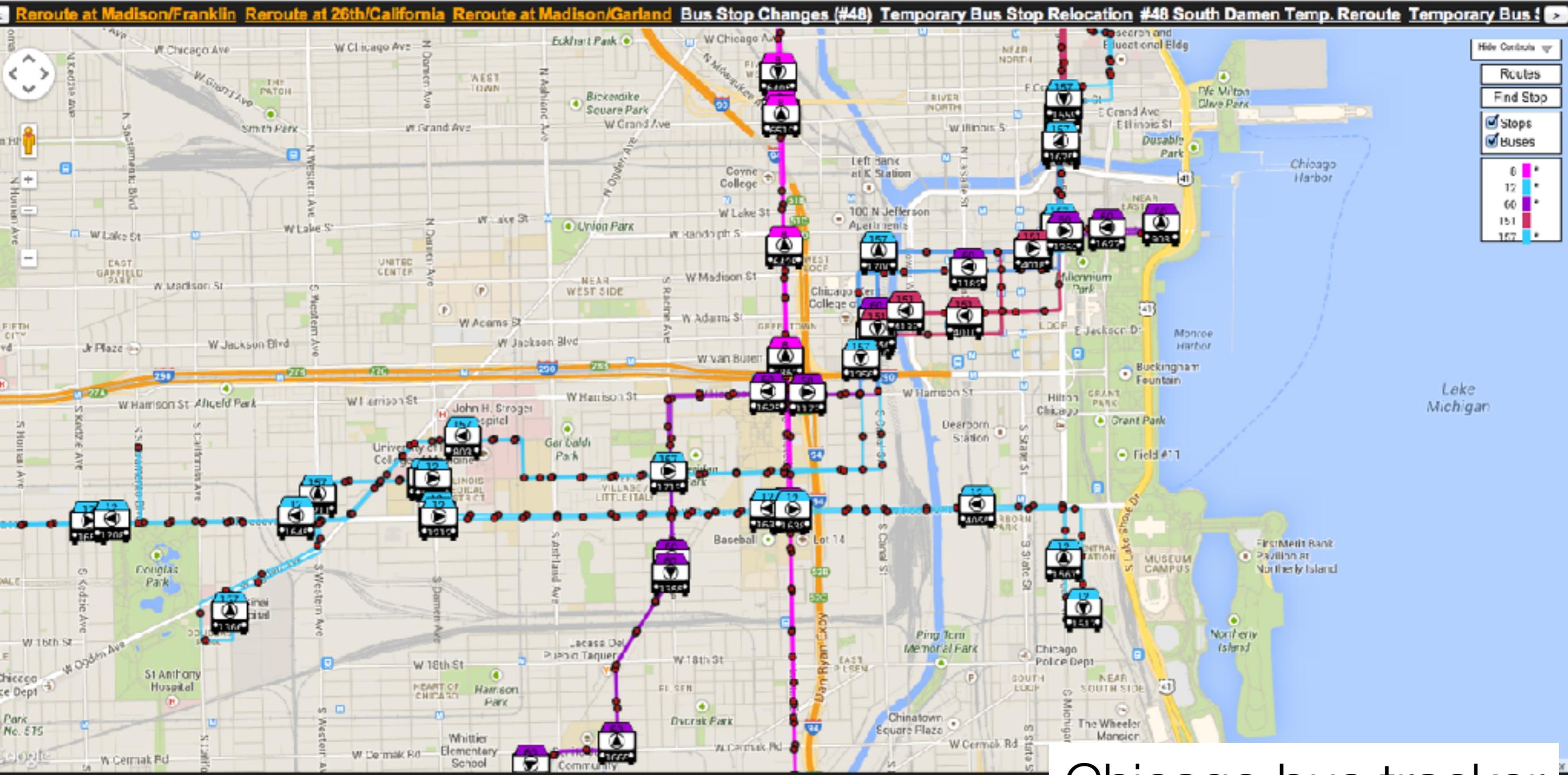
GPS tracking applications



GPS tracking applications

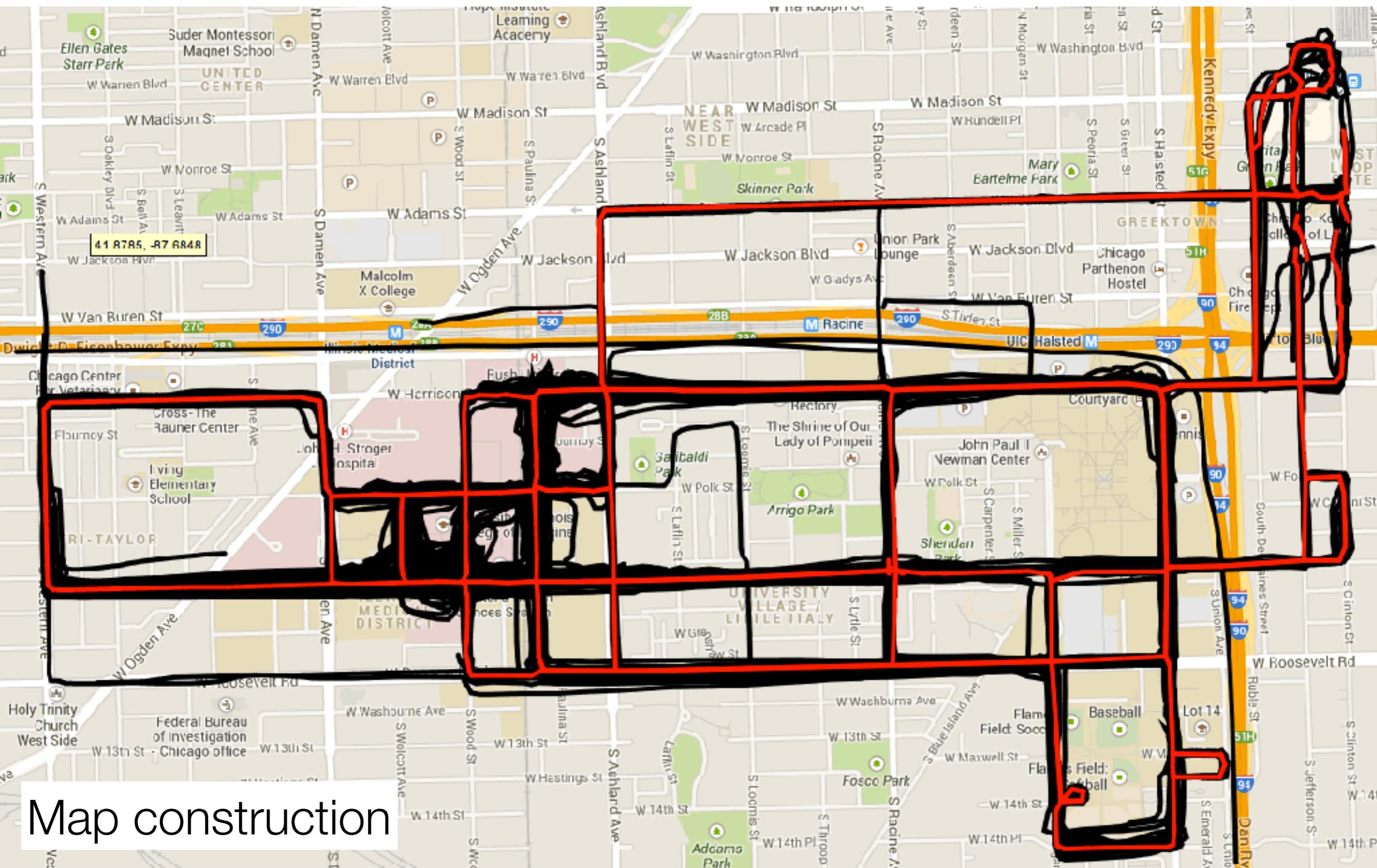


4:12 PM 77°F Arrivals



Chicago bus tracker

GPS tracking applications



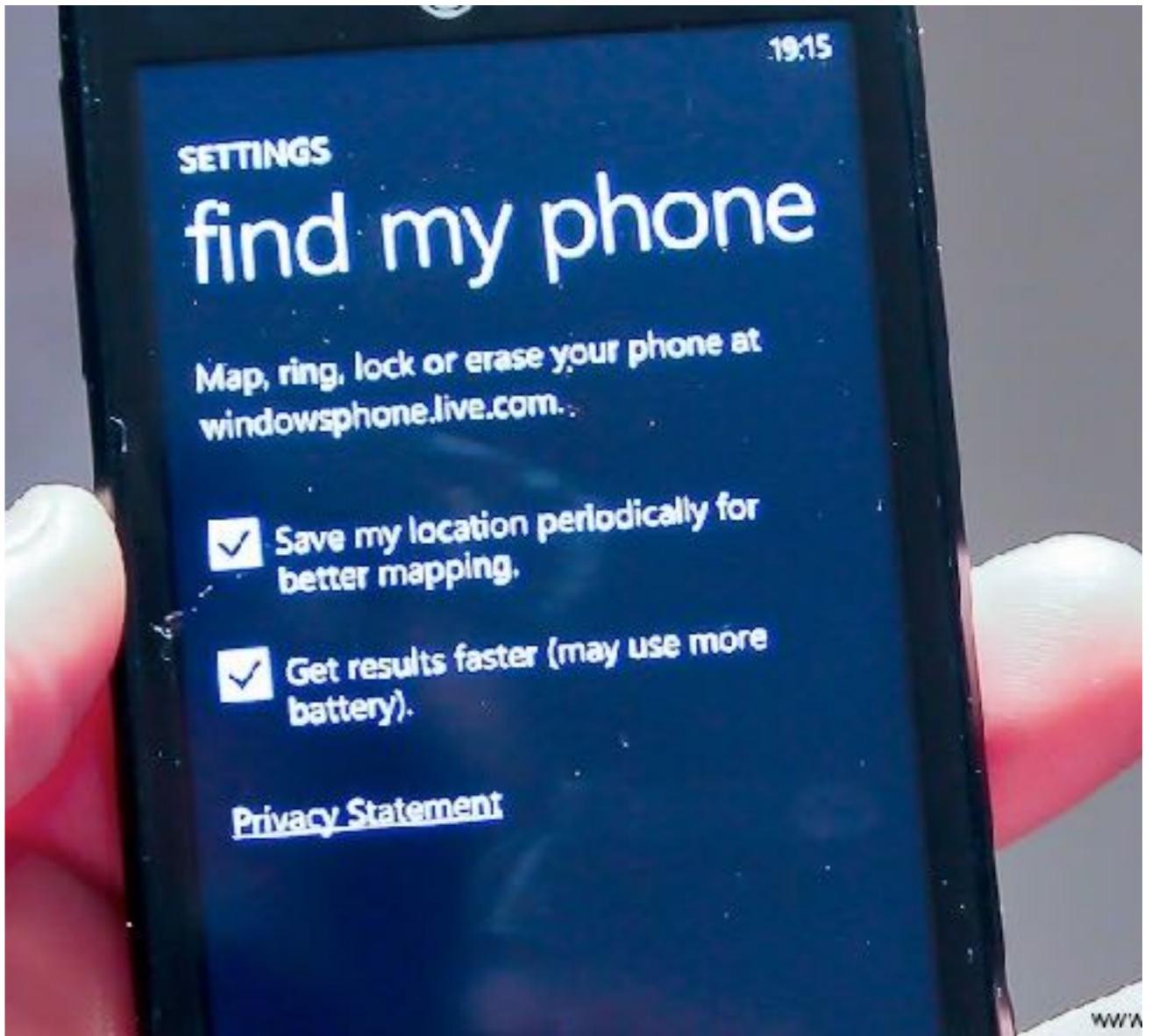
Map construction

GPS tracking applications



Fleet tracking

GPS tracking applications



Pet and gadget tracking

GPS tracking

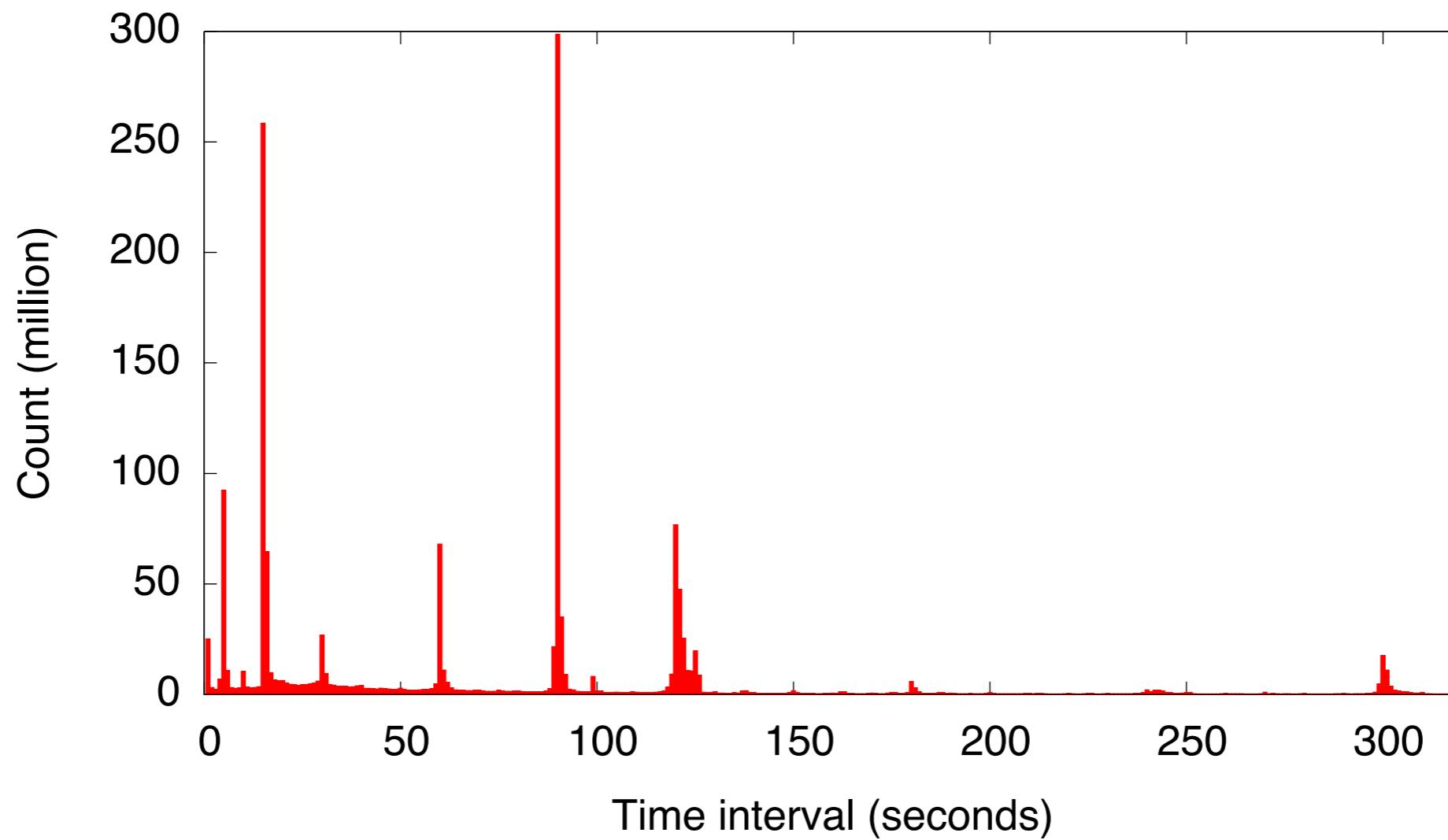


cellular uplink



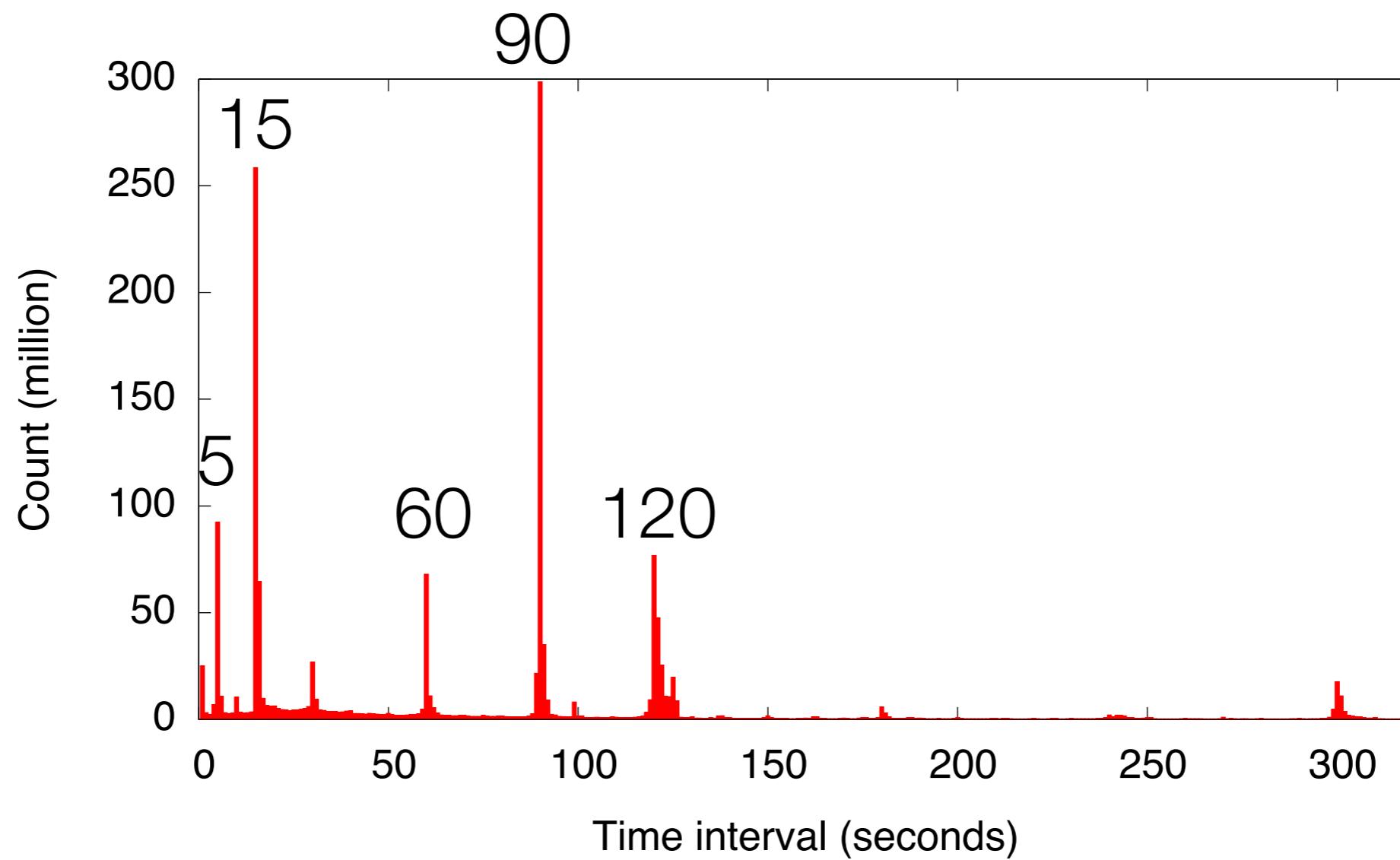
Status quo

Observation from 1.6 billion GPS points



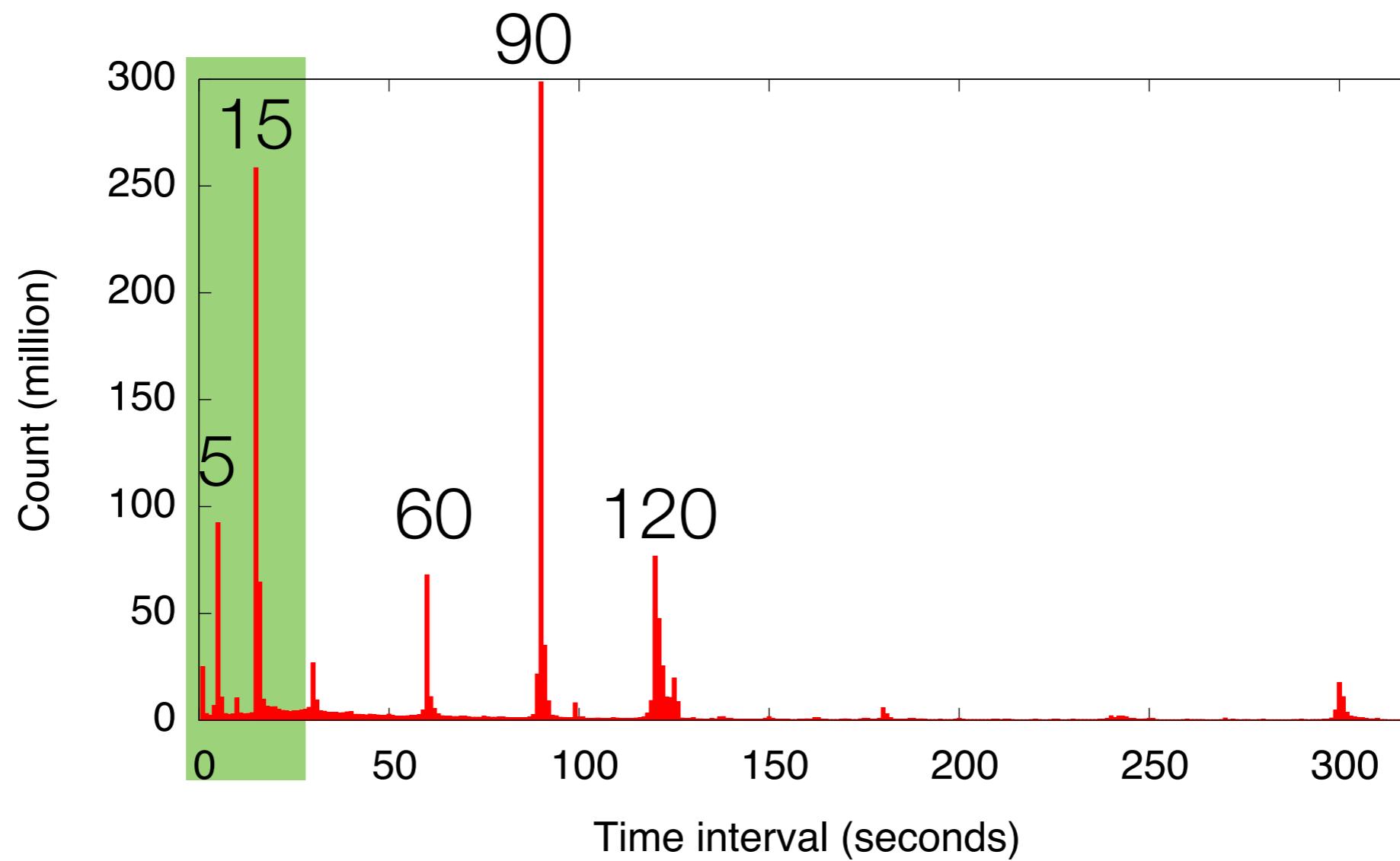
Status quo

Observation from 1.6 billion GPS points



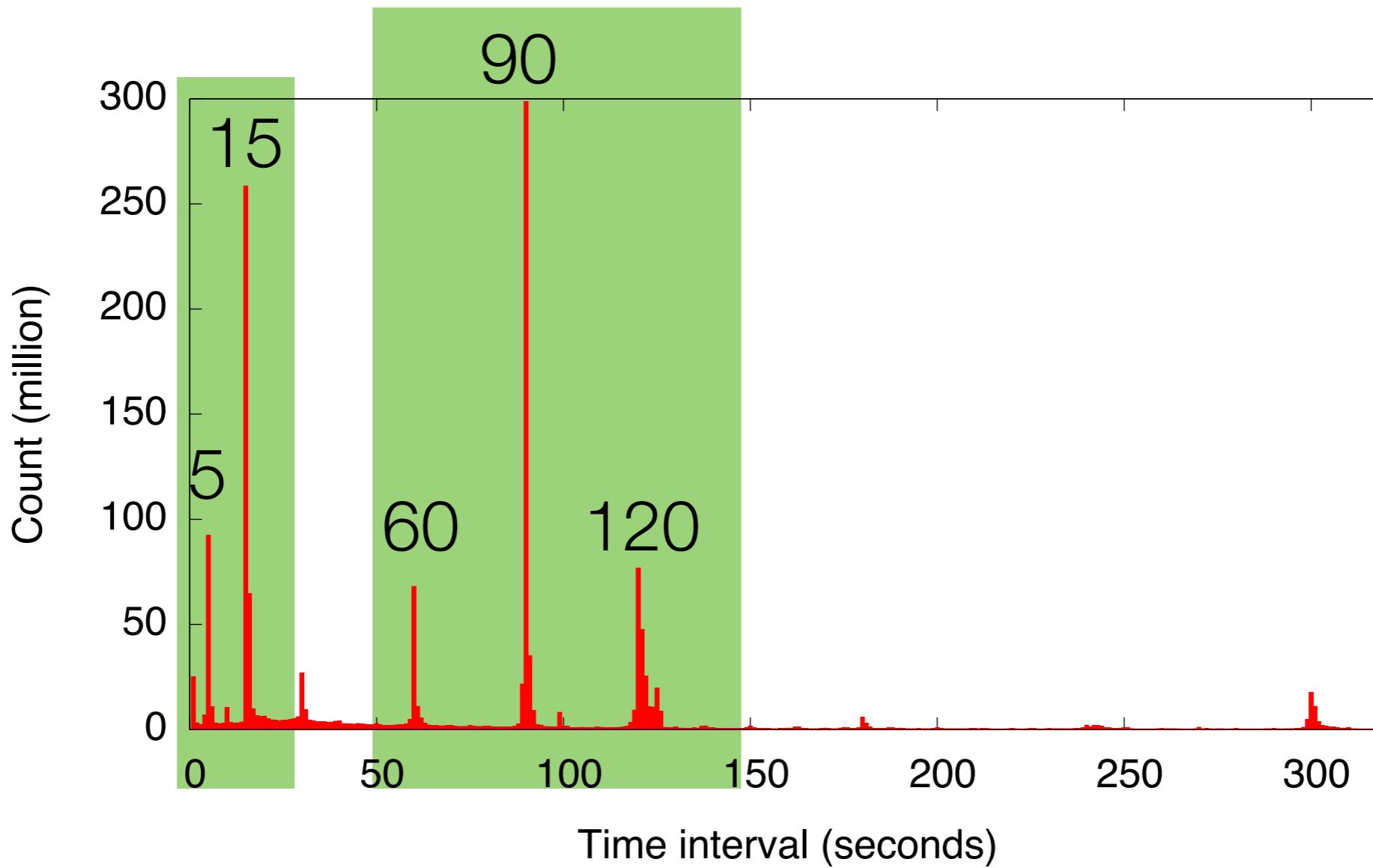
Status quo

Observation from 1.6 billion GPS points



Status quo

Observation from 1.6 billion GPS points

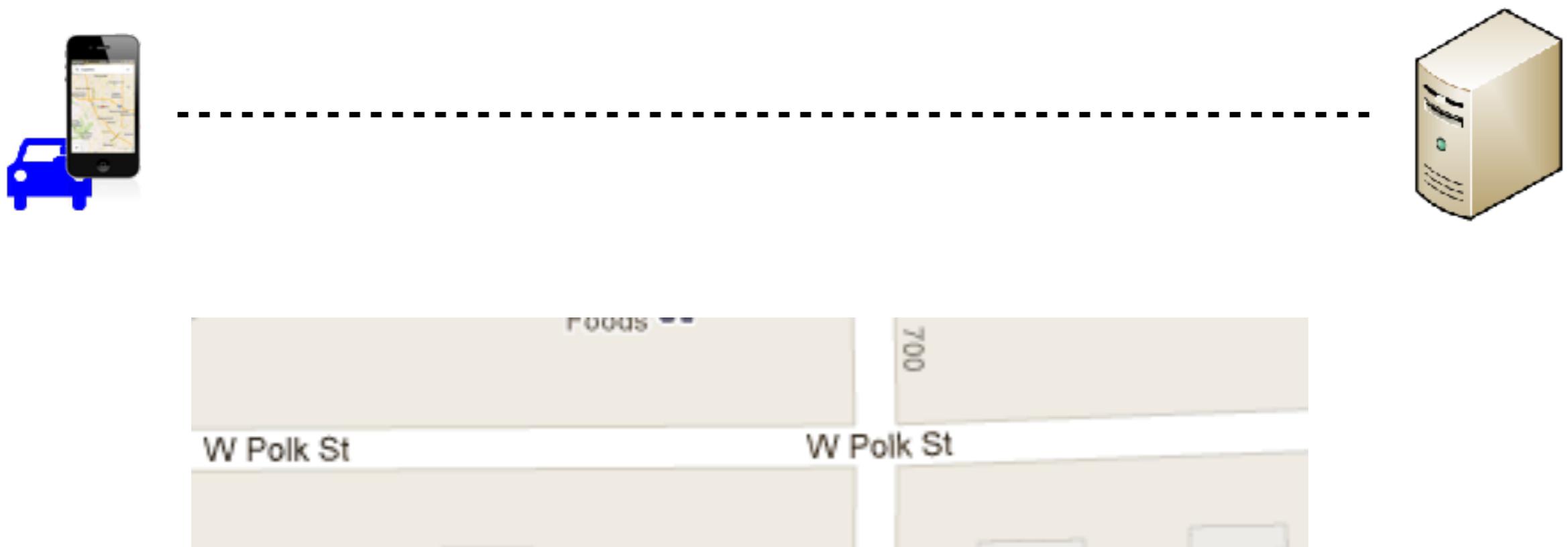


Cellular data usage



Protocol	Data Usage per Update	Data Usage per Day
UDP	84 bytes	7 MB
TCP	168 bytes	14 MB
HTTP/REST	1218 bytes	100 MB

Key problem



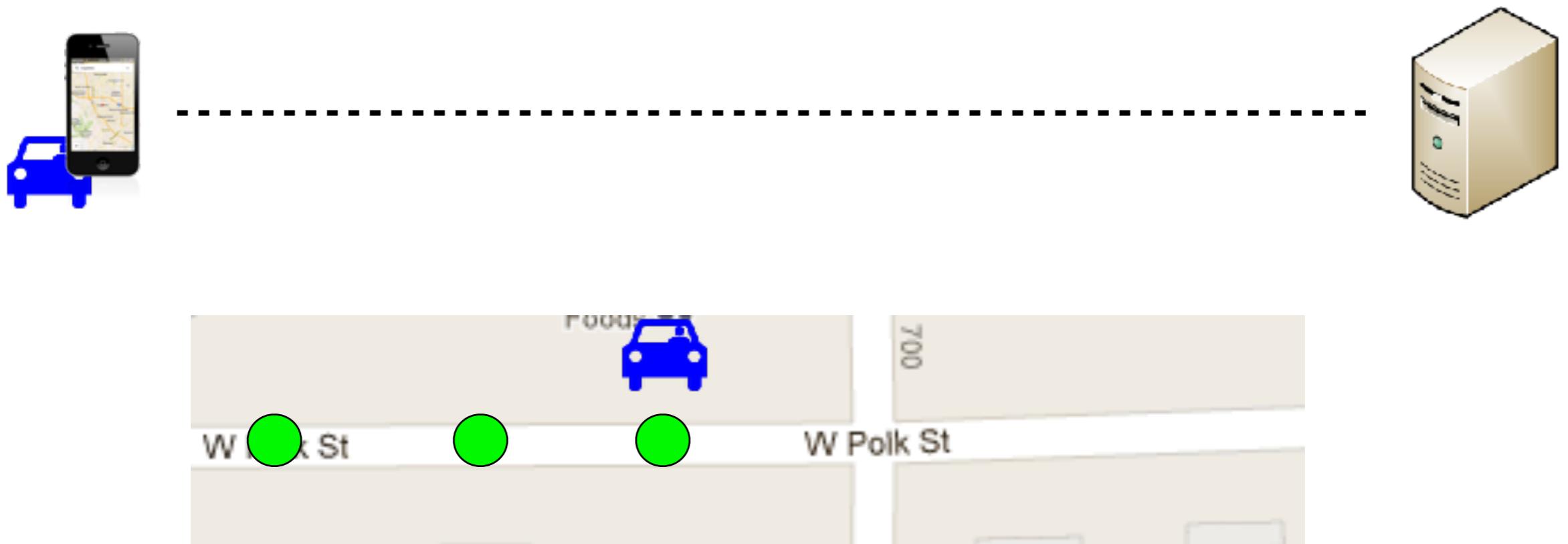
Key problem



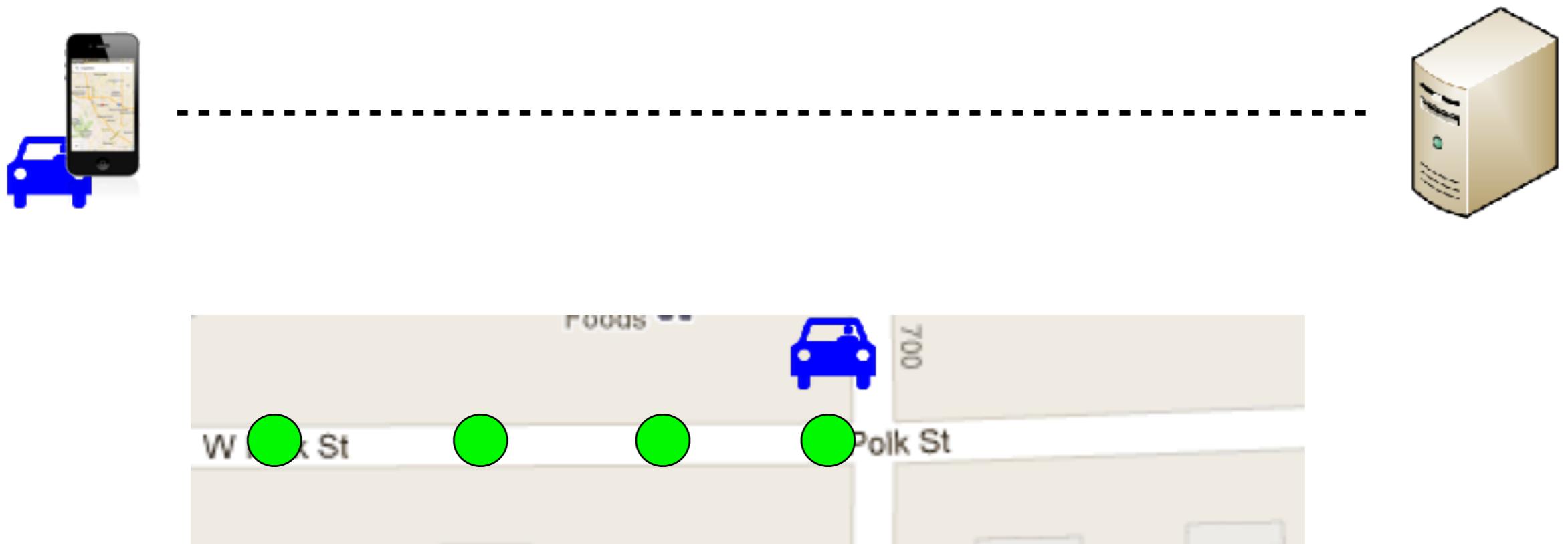
Key problem



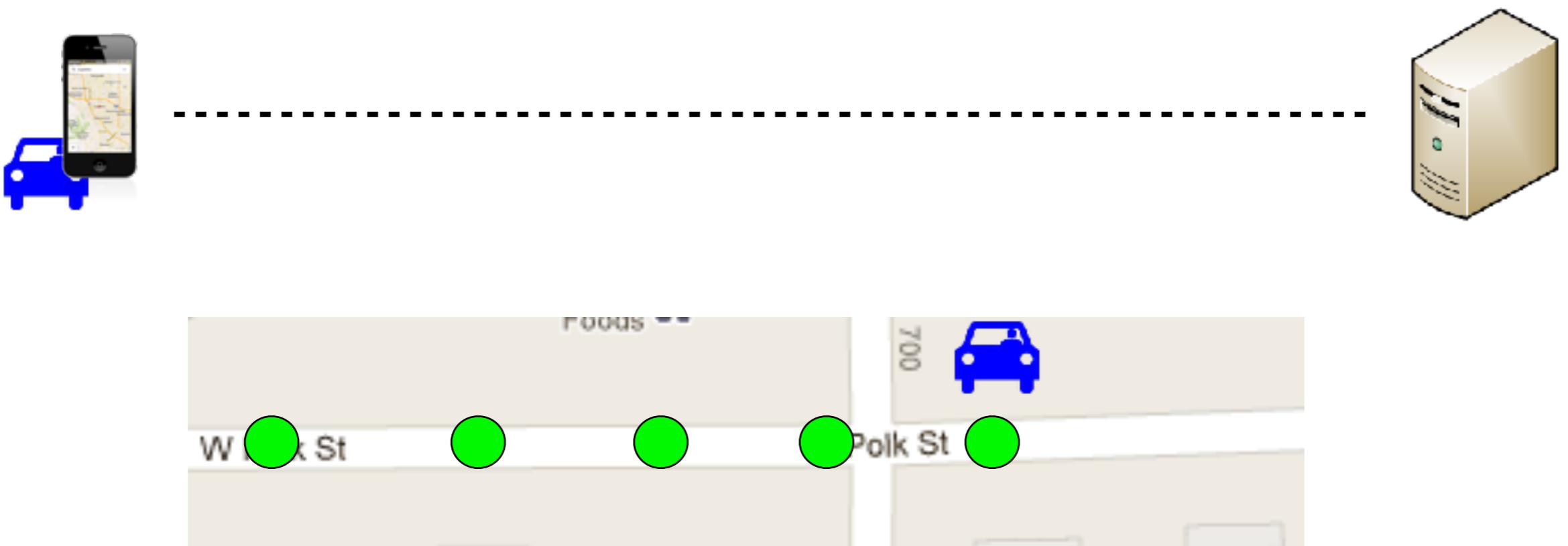
Key problem



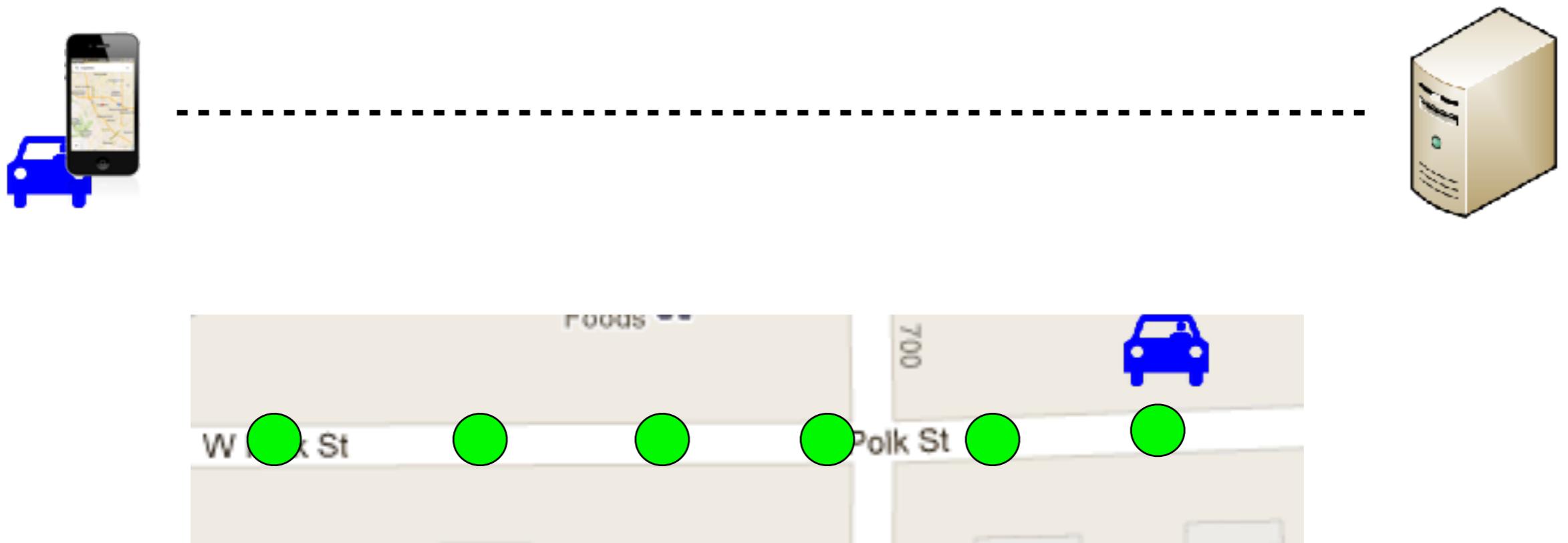
Key problem



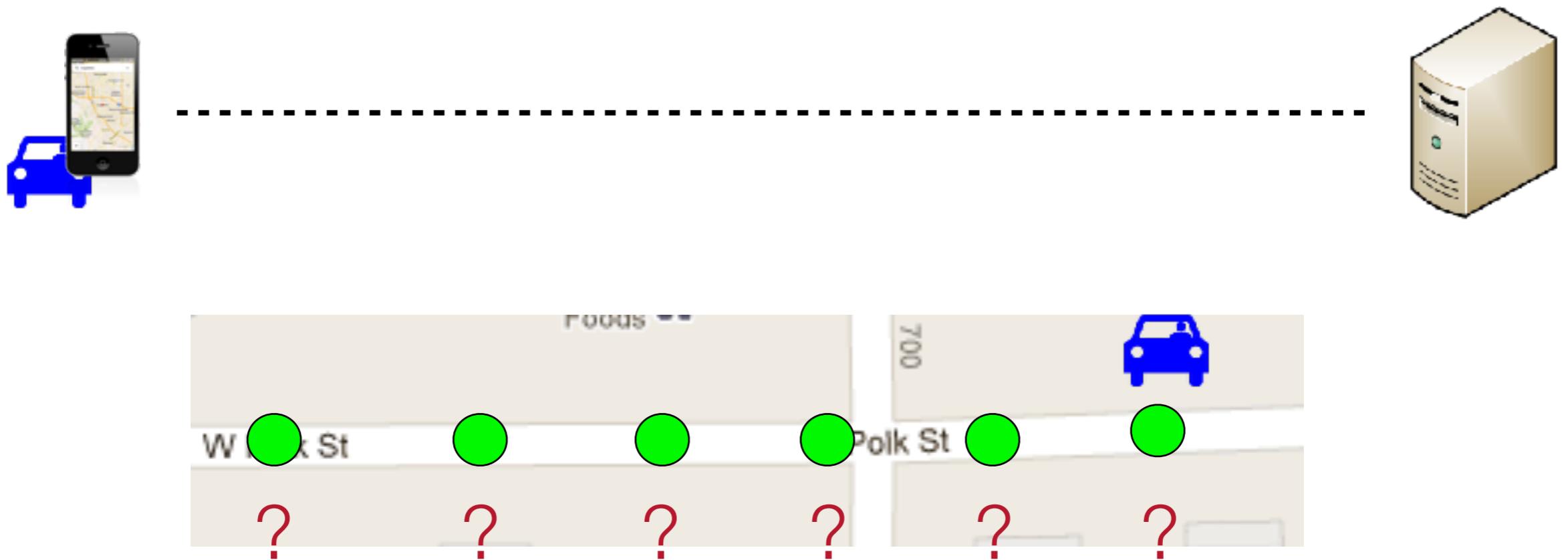
Key problem



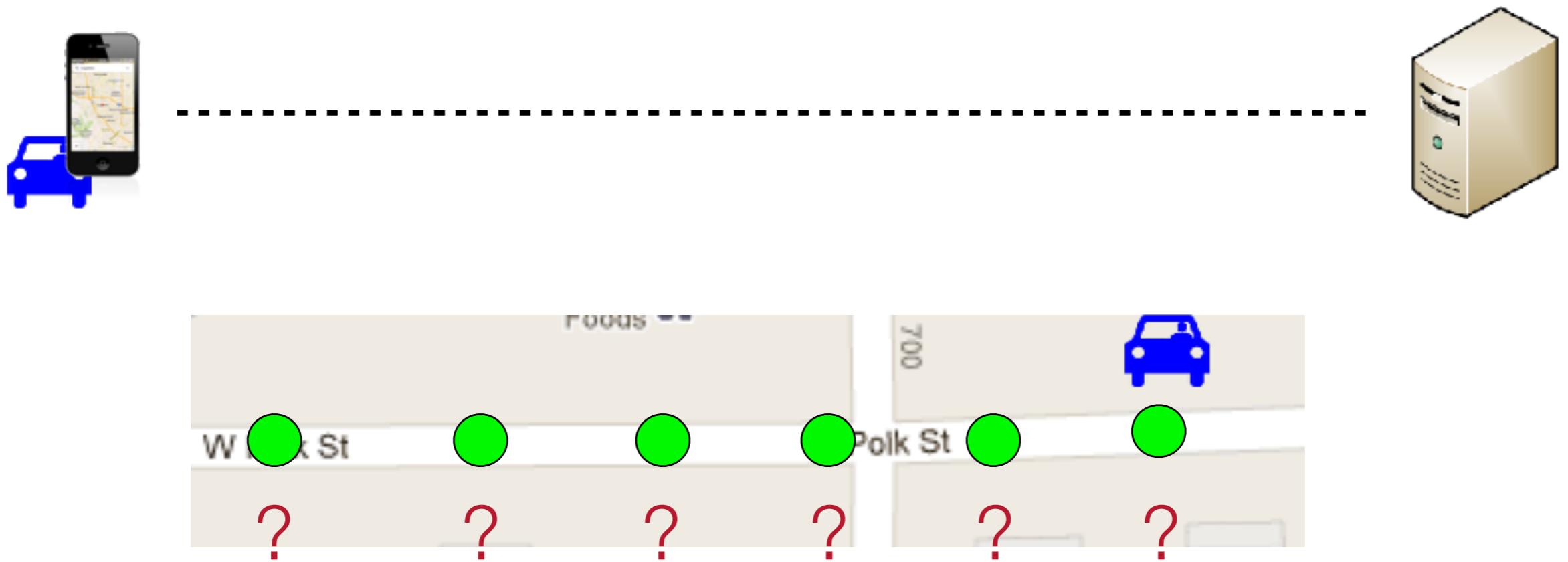
Key problem



Key problem

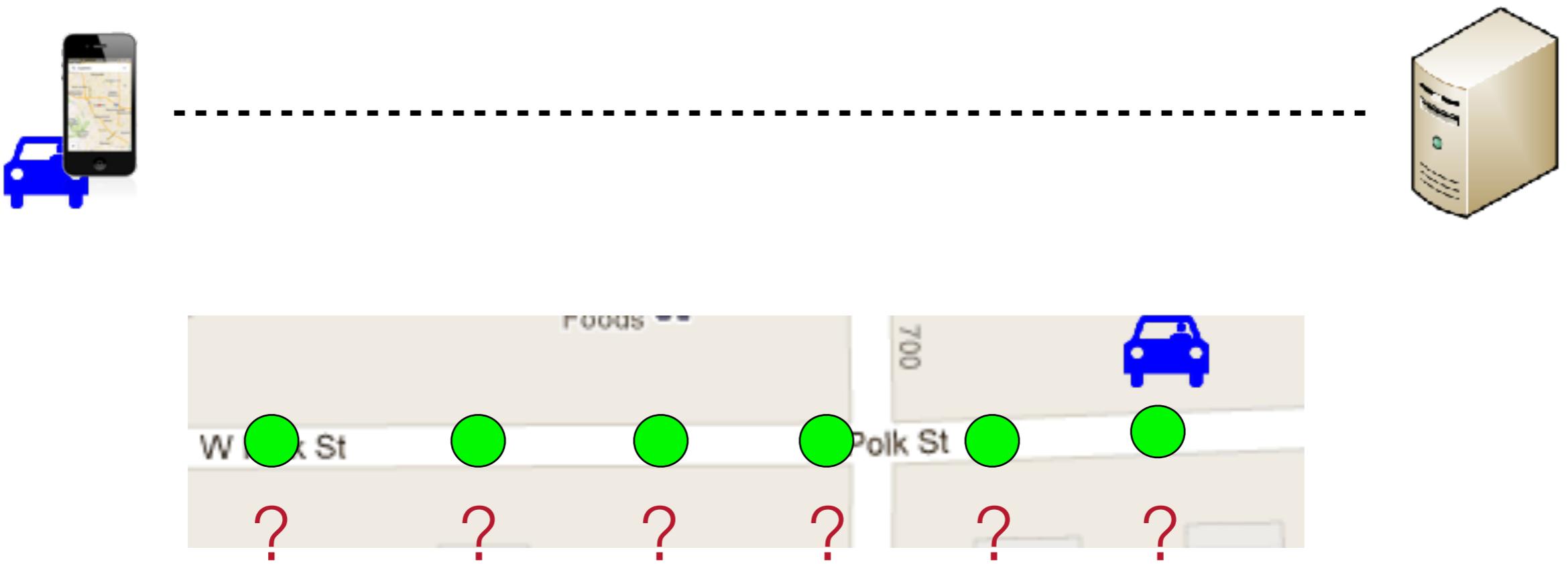


Key problem



Which coordinates to transmit?

Key problem



Which coordinates to transmit?

Sampler

Naive samplers

- ▶ Periodic sampling
 - Predictable **data-usage**
 - No guarantee on **error**
- ▶ Sampling at uniform distance
 - Predictable **error**
 - No guarantee on **data-usage** and **timeliness**

Adaptive Sampling

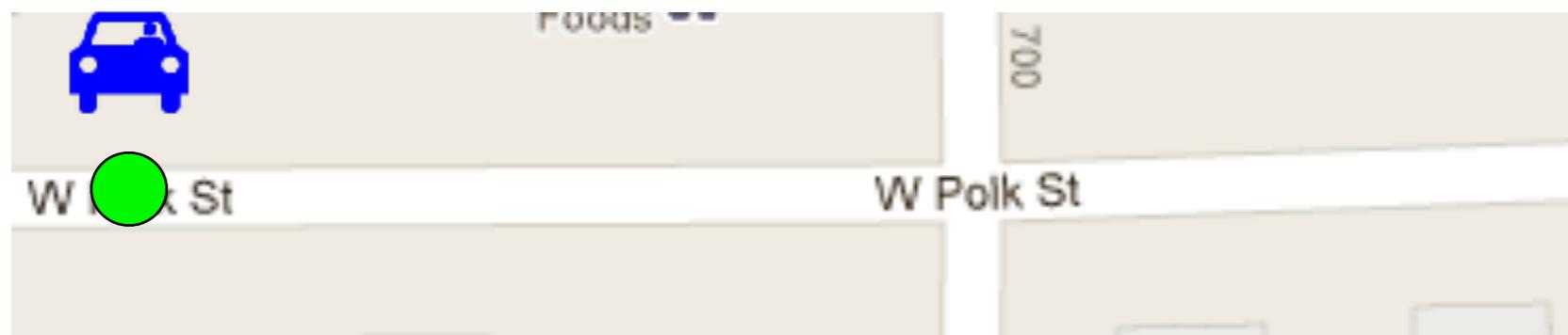
GPS Extrapolation

- ▶ Predicts the future locations



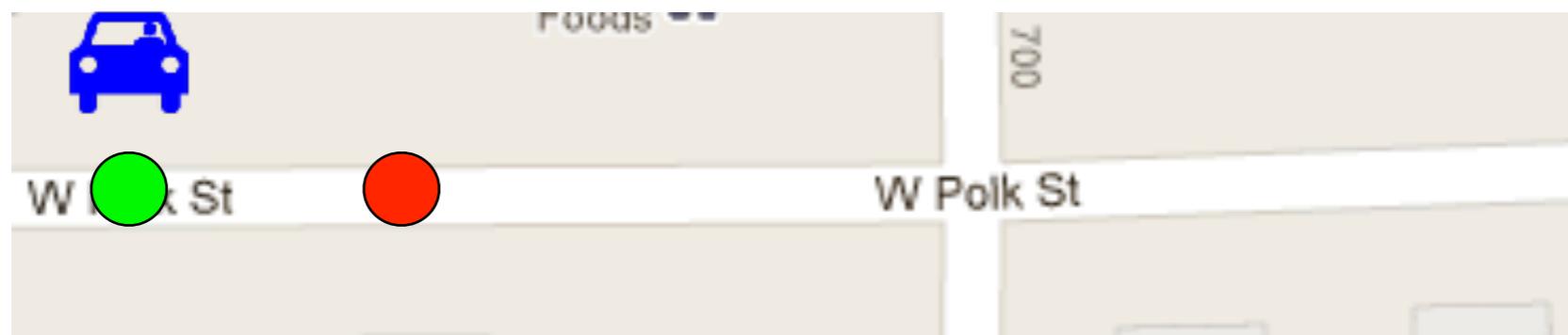
GPS Extrapolation

- ▶ Predicts the future locations



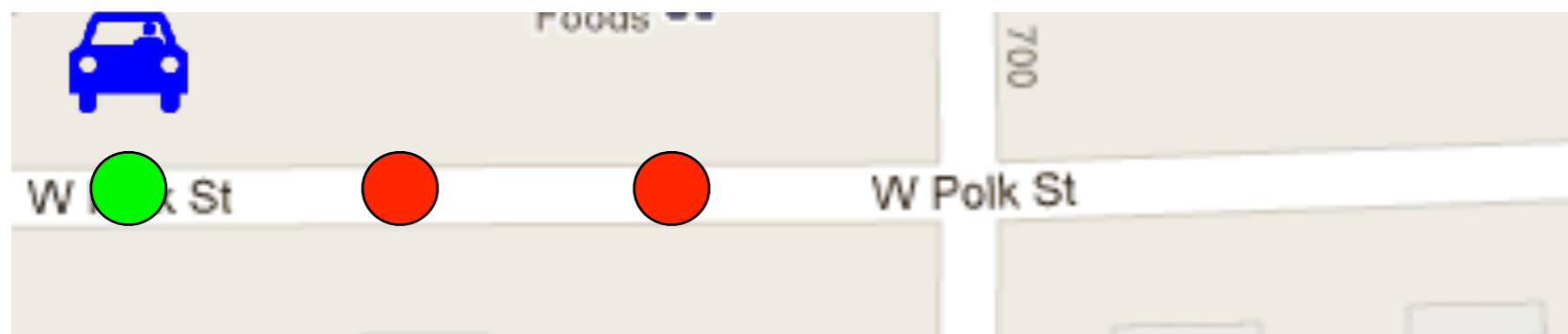
GPS Extrapolation

- ▶ Predicts the future locations



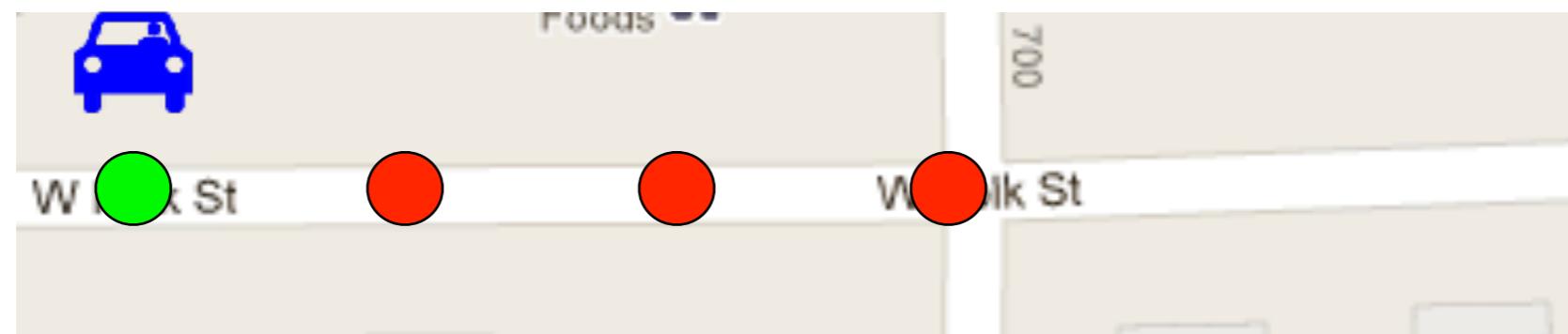
GPS Extrapolation

- ▶ Predicts the future locations



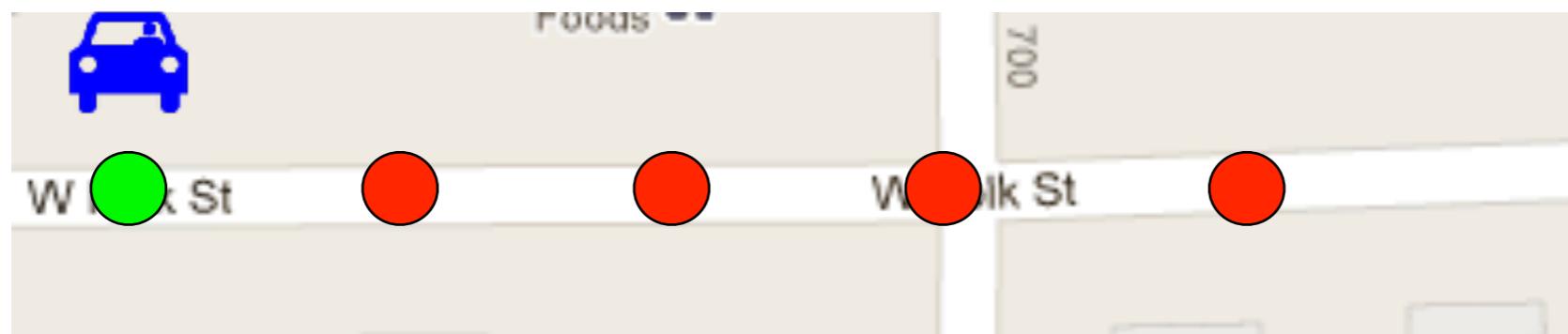
GPS Extrapolation

- ▶ Predicts the future locations



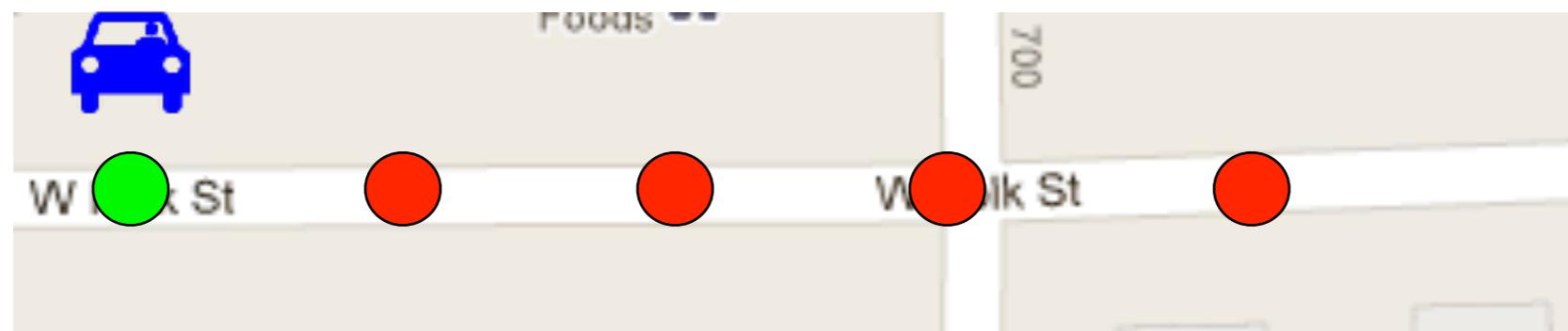
GPS Extrapolation

- ▶ Predicts the future locations



GPS Extrapolation

- ▶ Predicts the future locations



Actual GPS location



Extrapolated location

GPS Extrapolation

- ▶ Constant Location
- ▶ Constant Velocity
- ▶ Constant Acceleration
- ▶ Constant Deceleration
- ▶ Map based

GPS Extrapolation

- ▶ Constant Location
- ▶ Constant Velocity
- ▶ Constant Acceleration
- ▶ Constant Deceleration
- ▶ Map based

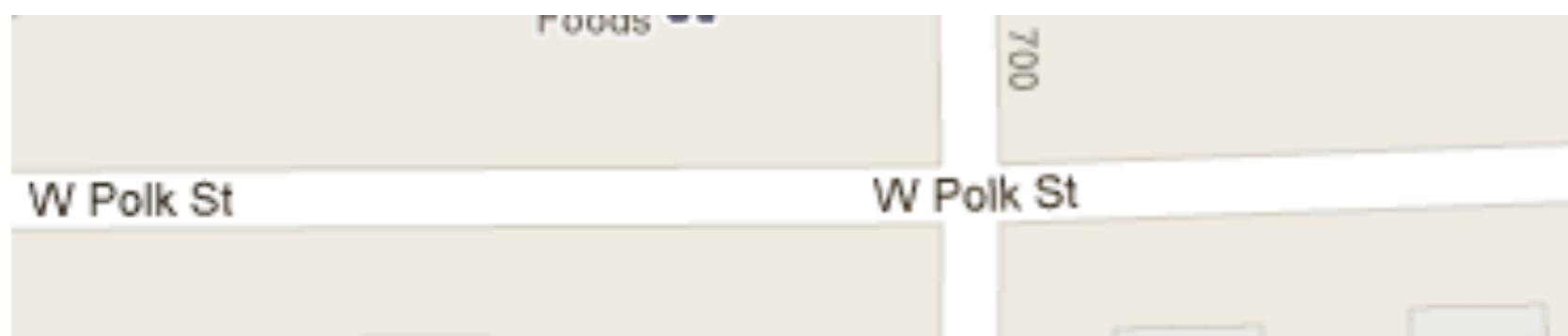
Automatic Switching

GPS Extrapolation

- ▶ Constant Location
- ▶ Constant Velocity
- ▶ Constant Acceleration
- ▶ Constant Deceleration
- ▶ Map based
- ▶ Unified

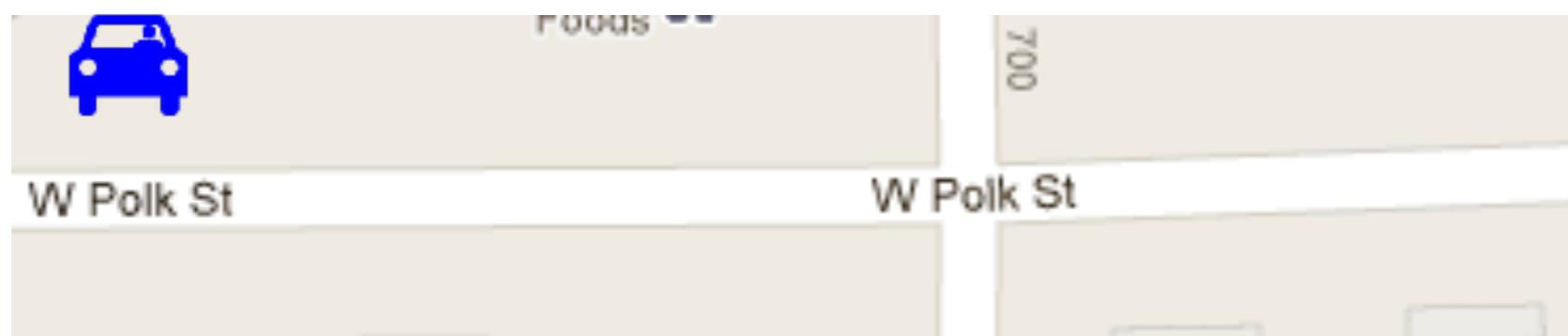
Automatic Switching

Fixed delay in reporting



Actual GPS location

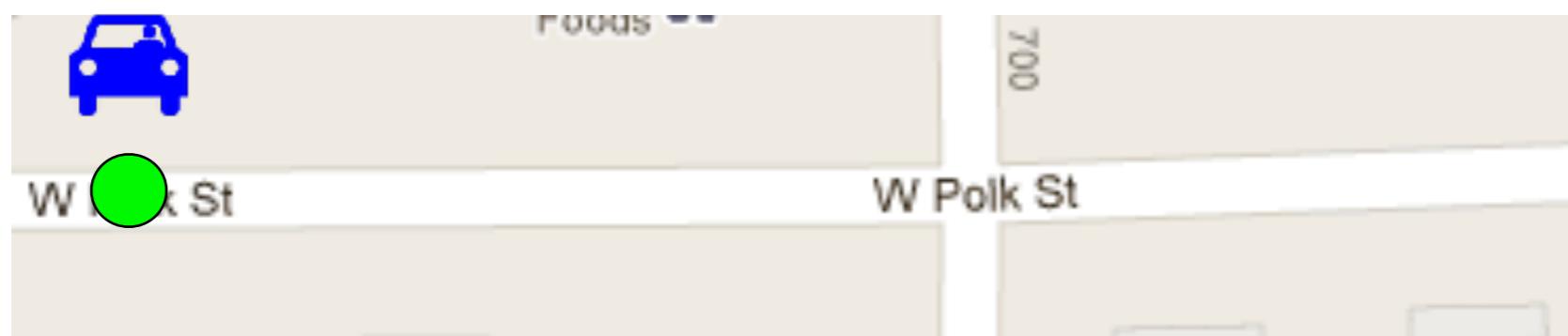
Fixed delay in reporting



5 seconds delay

● Actual GPS location

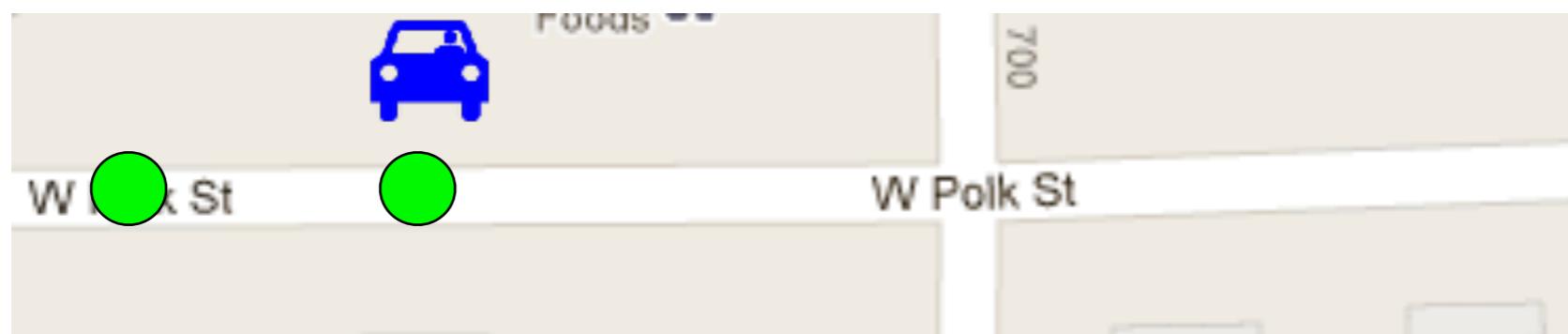
Fixed delay in reporting



5 seconds delay

Actual GPS location

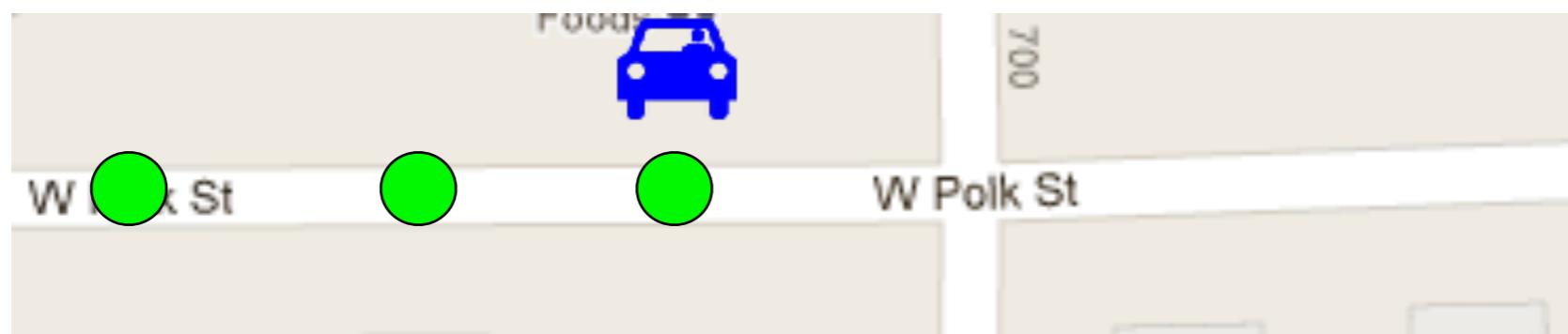
Fixed delay in reporting



5 seconds delay

Actual GPS location

Fixed delay in reporting



5 seconds delay

● Actual GPS location

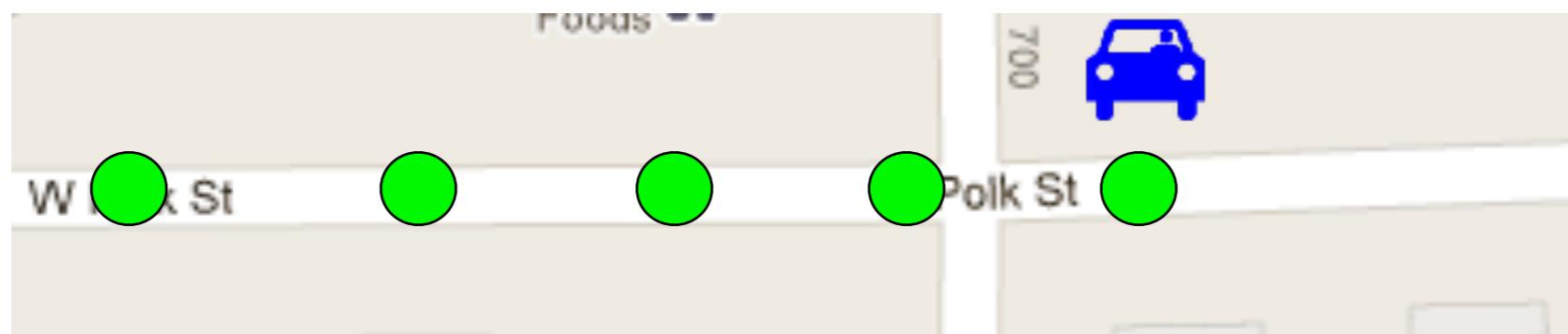
Fixed delay in reporting



5 seconds delay

Actual GPS location

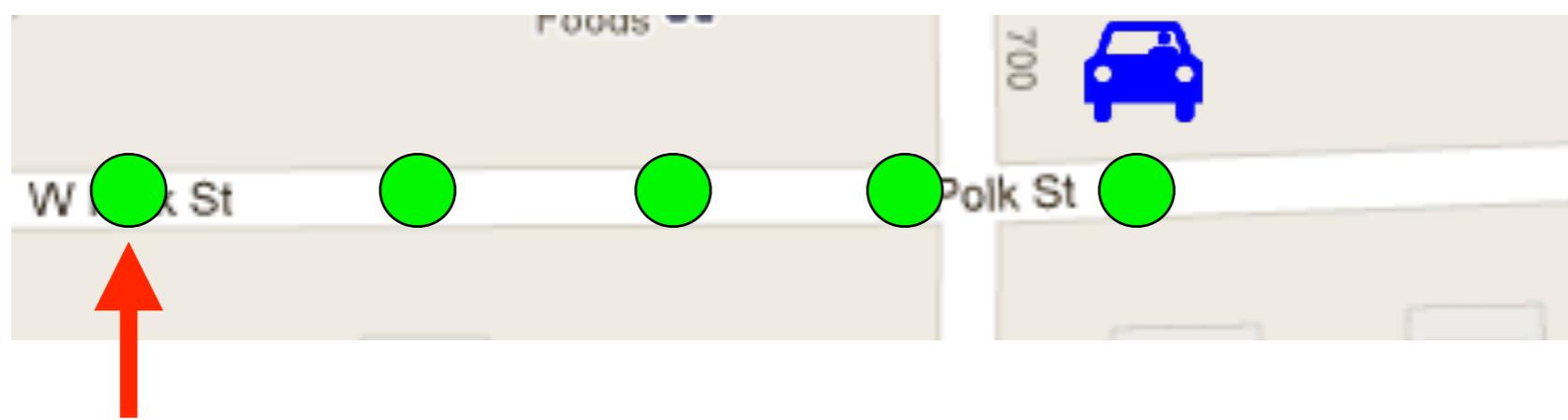
Fixed delay in reporting



5 seconds delay

● Actual GPS location

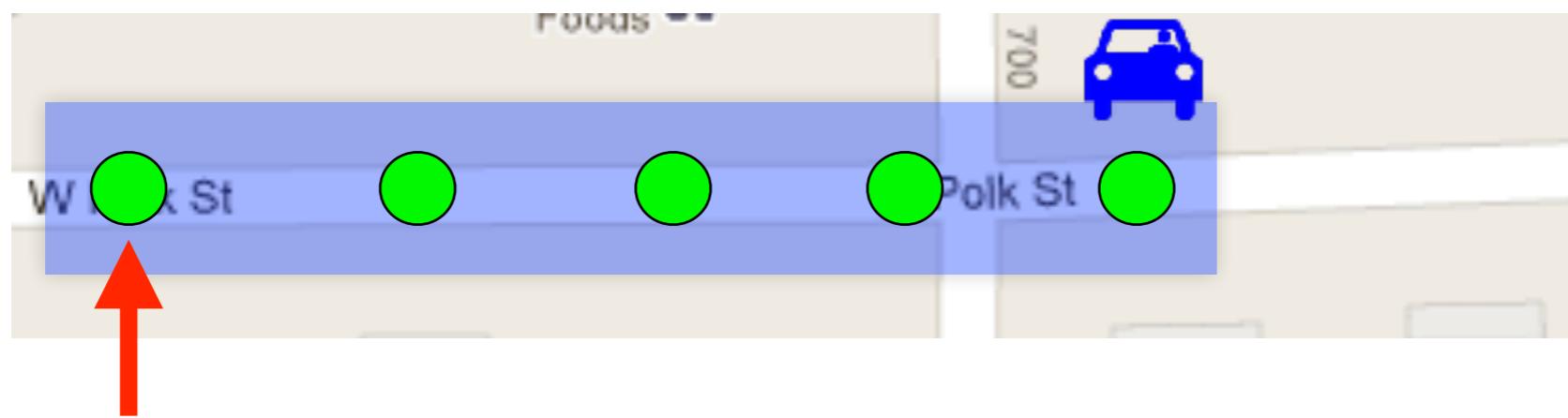
Fixed delay in reporting



5 seconds delay

Actual GPS location

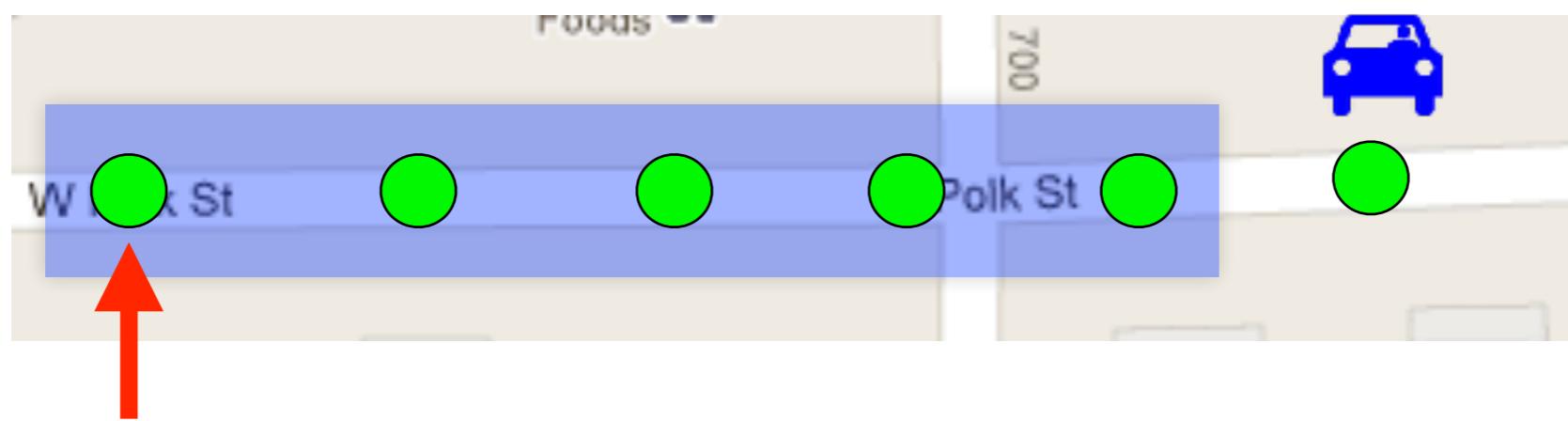
Fixed delay in reporting



5 seconds delay

● Actual GPS location

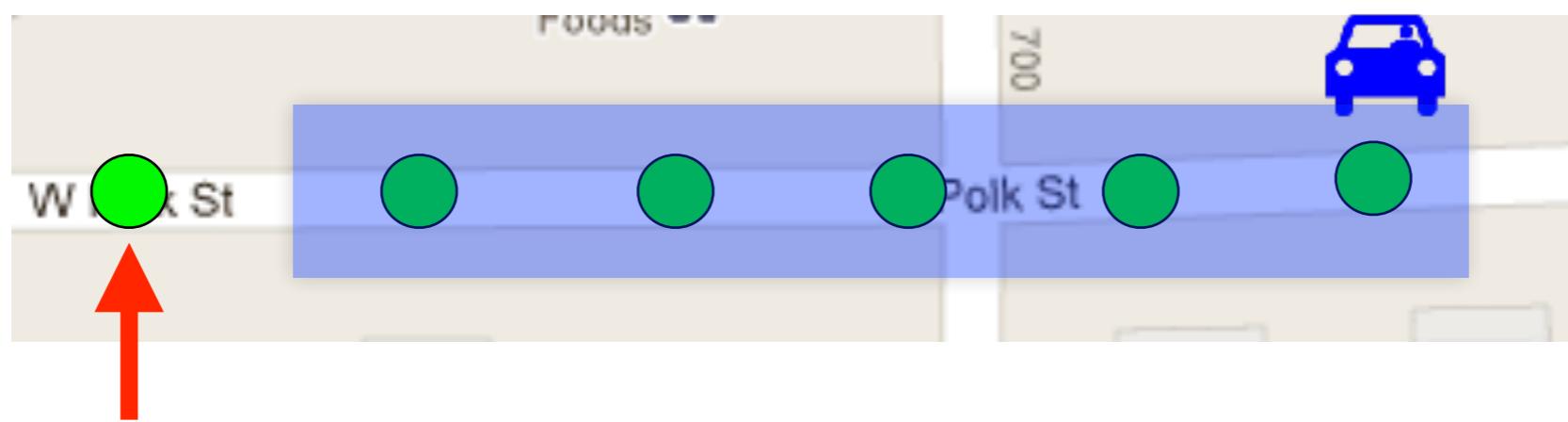
Fixed delay in reporting



5 seconds delay

Actual GPS location

Fixed delay in reporting



5 seconds delay

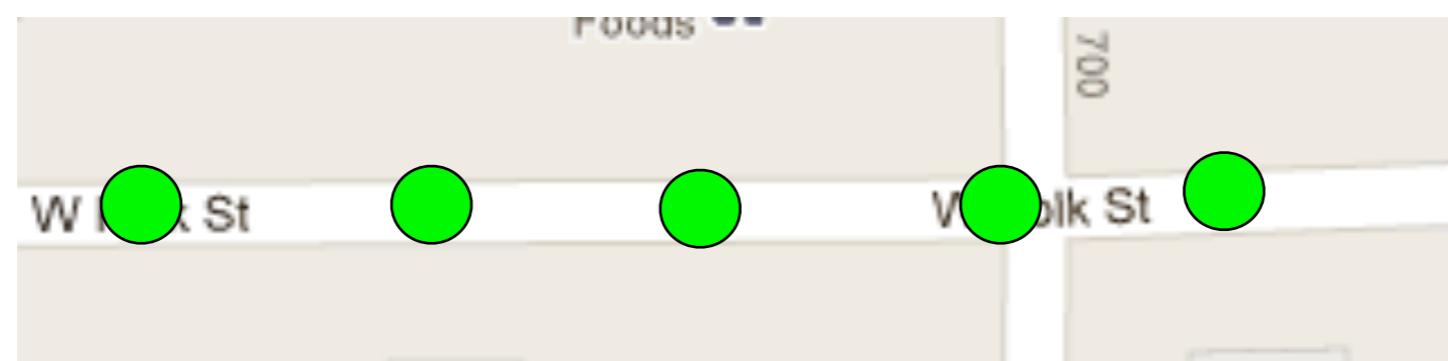
Actual GPS location

GPS compression/decompression



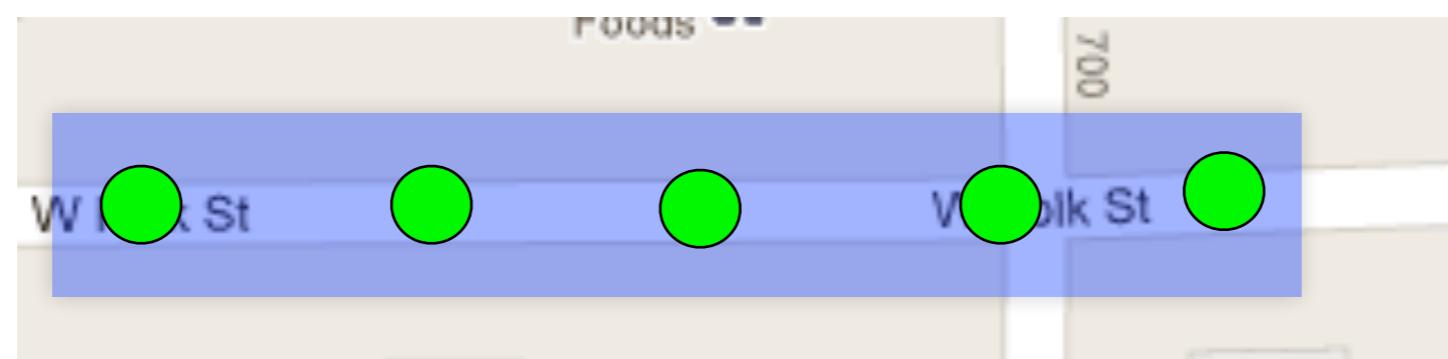
Actual GPS location

GPS compression/decompression



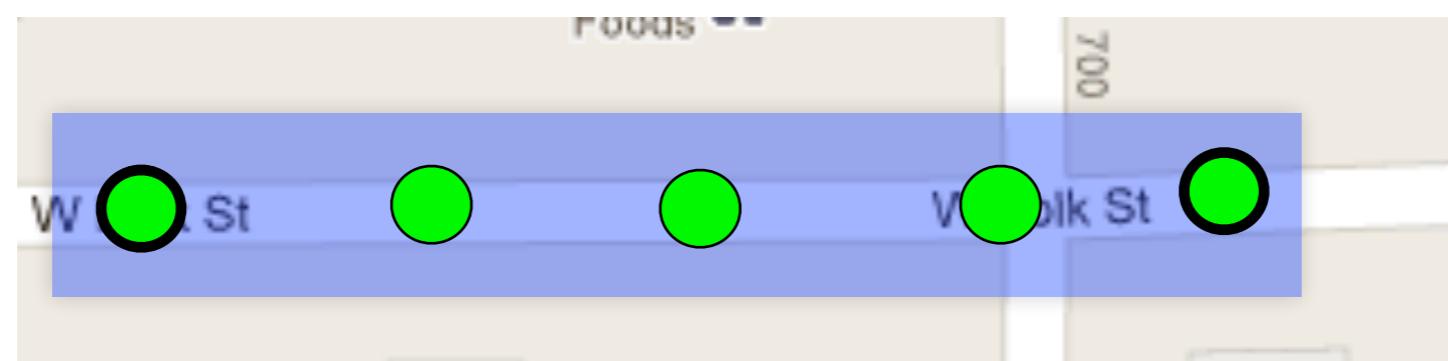
Actual GPS location

GPS compression/decompression



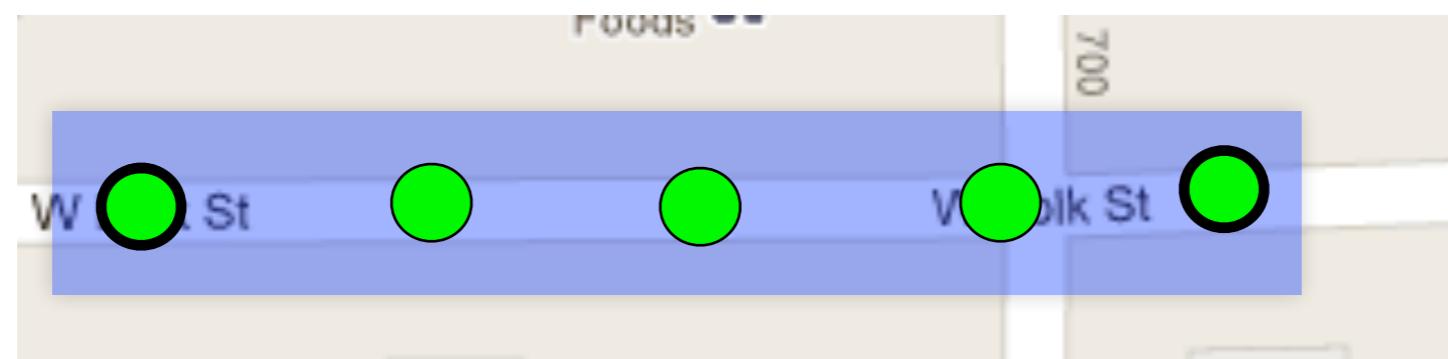
Actual GPS location

GPS compression/decompression



Actual GPS location

GPS compression/decompression



- Actual GPS location
- Actual GPS location transmitted to the server

GPS compression/decompression



Interpolation

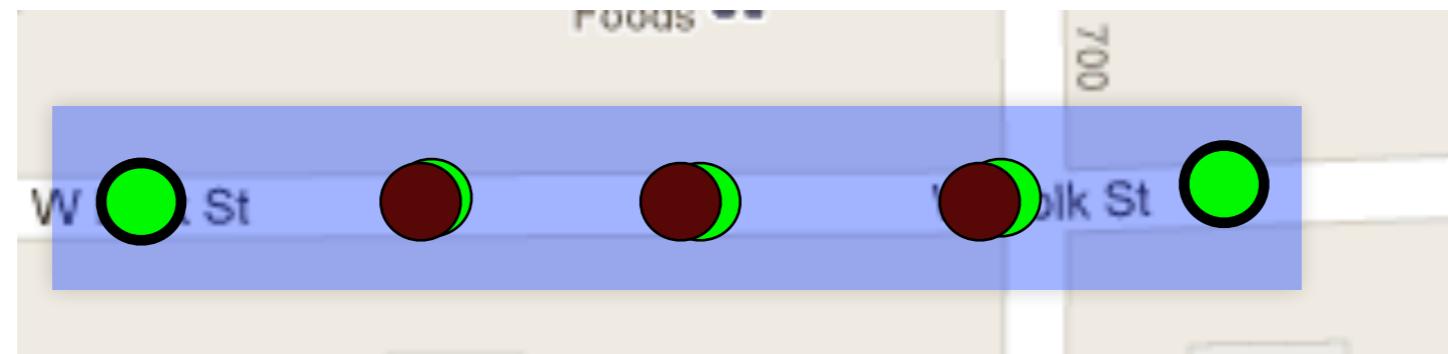


- Actual GPS location
- Actual GPS location transmitted to the server

GPS compression/decompression



Interpolation

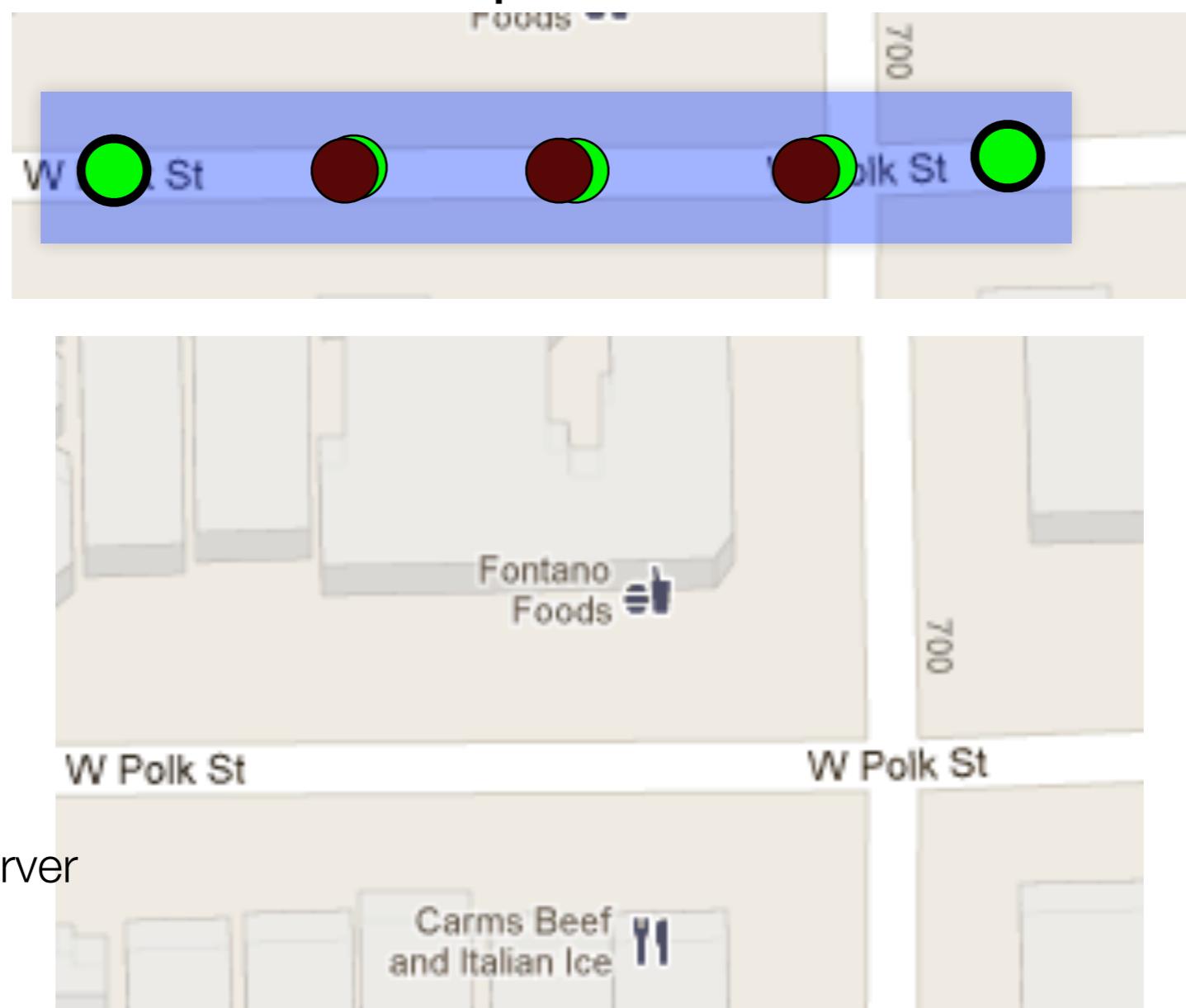


- Actual GPS location
- Actual GPS location transmitted to the server

GPS compression/decompression



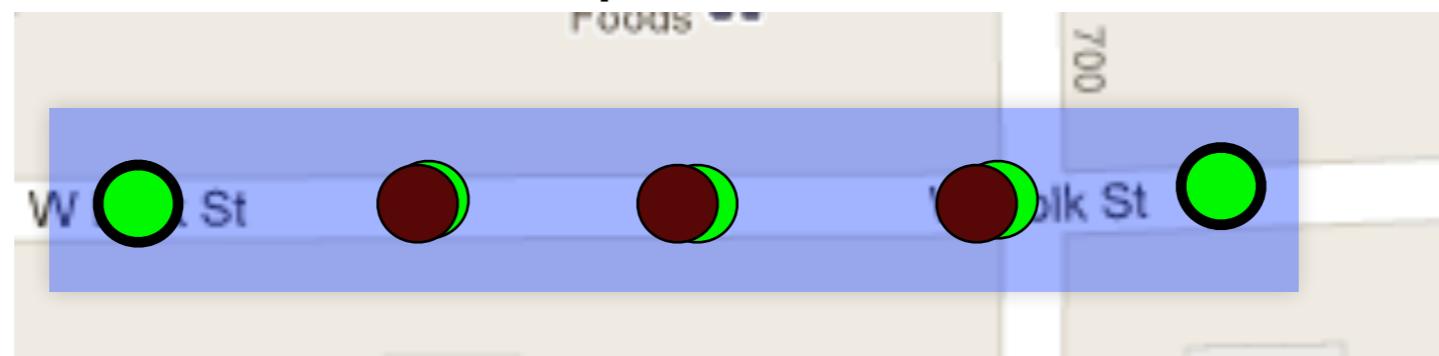
Interpolation



GPS compression/decompression



Interpolation



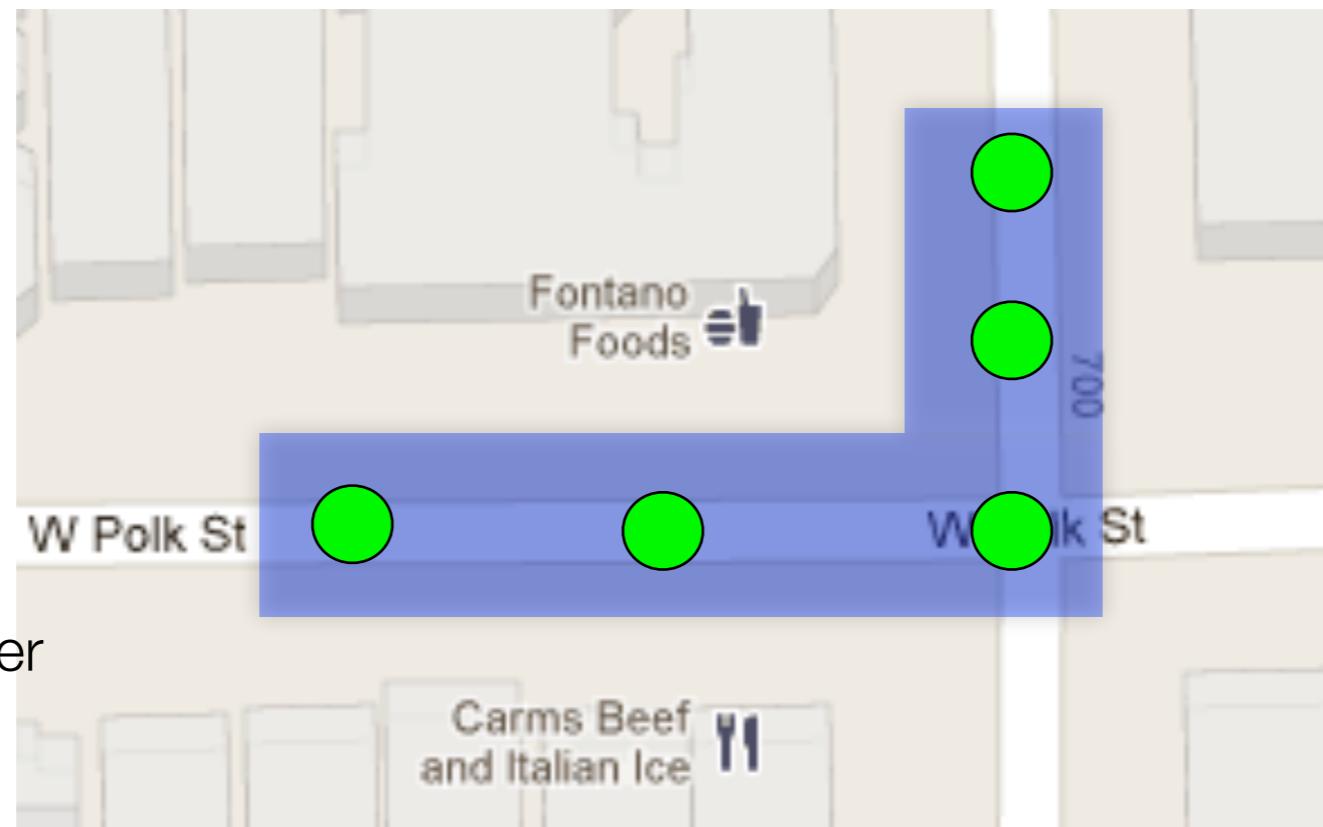
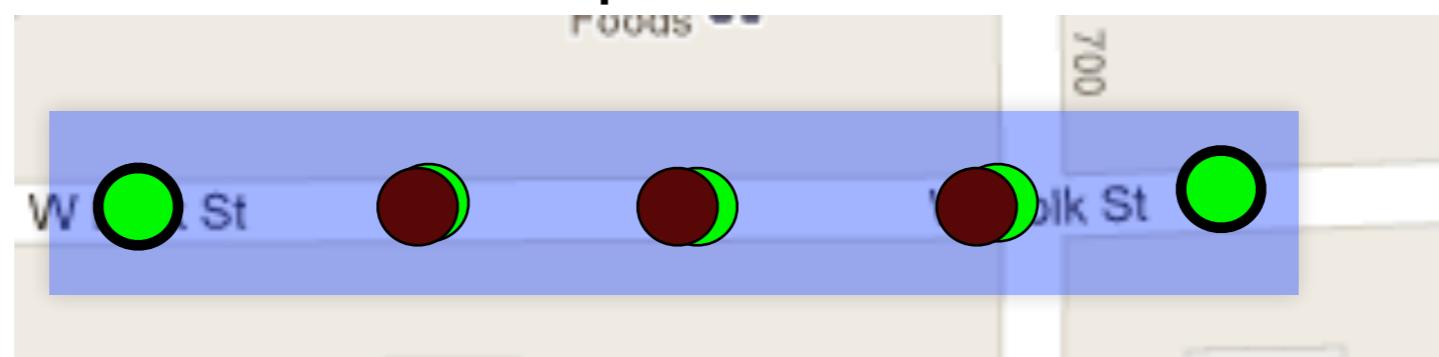
● Actual GPS location

● Actual GPS location
transmitted to the server

GPS compression/decompression



Interpolation



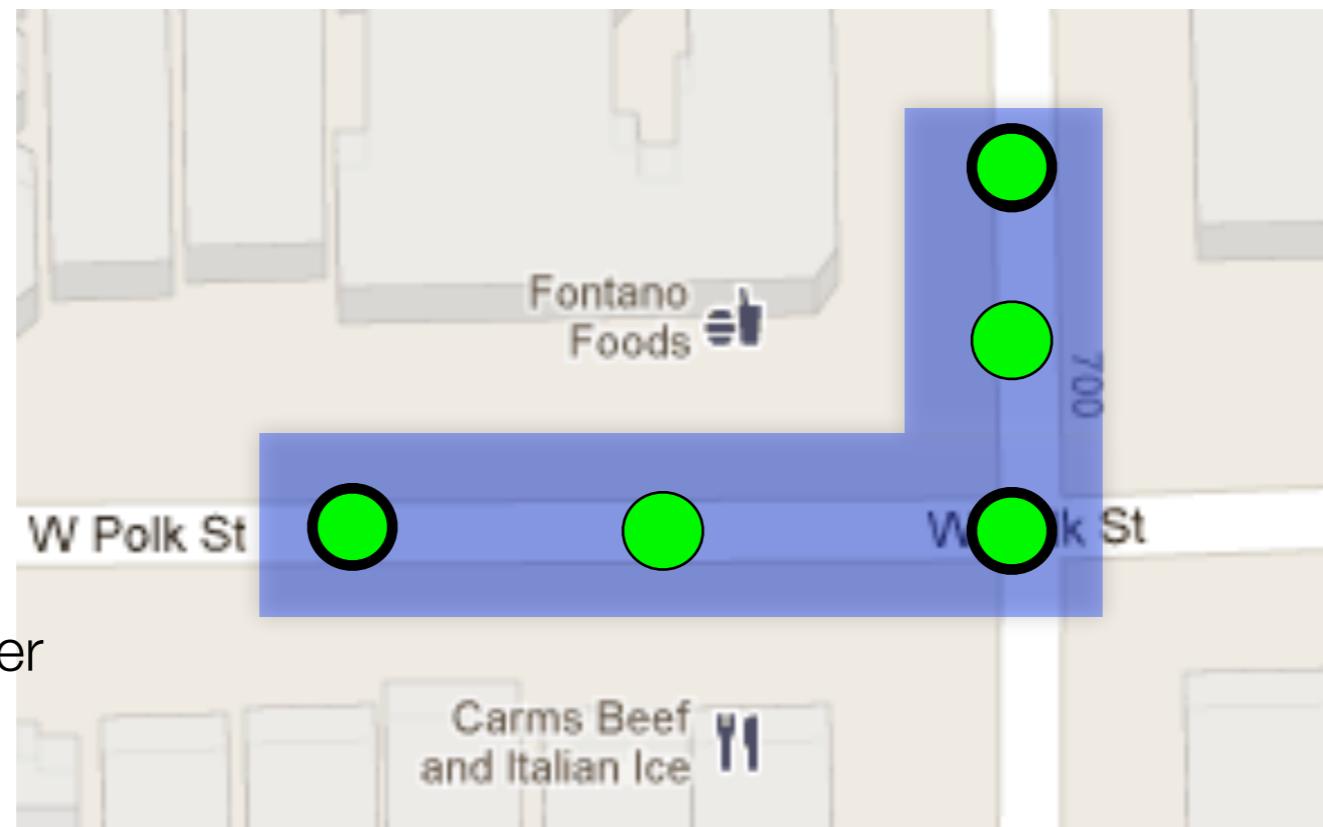
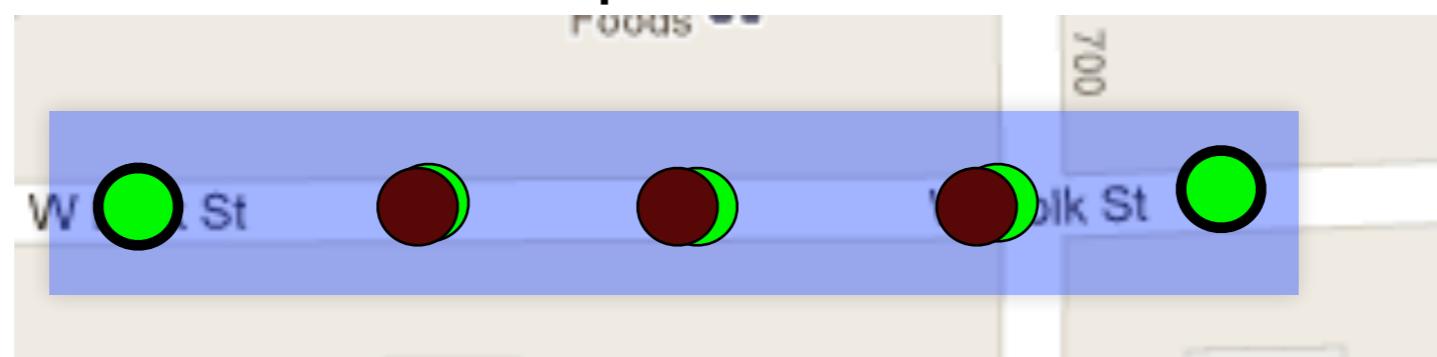
● Actual GPS location

● Actual GPS location
transmitted to the server

GPS compression/decompression



Interpolation



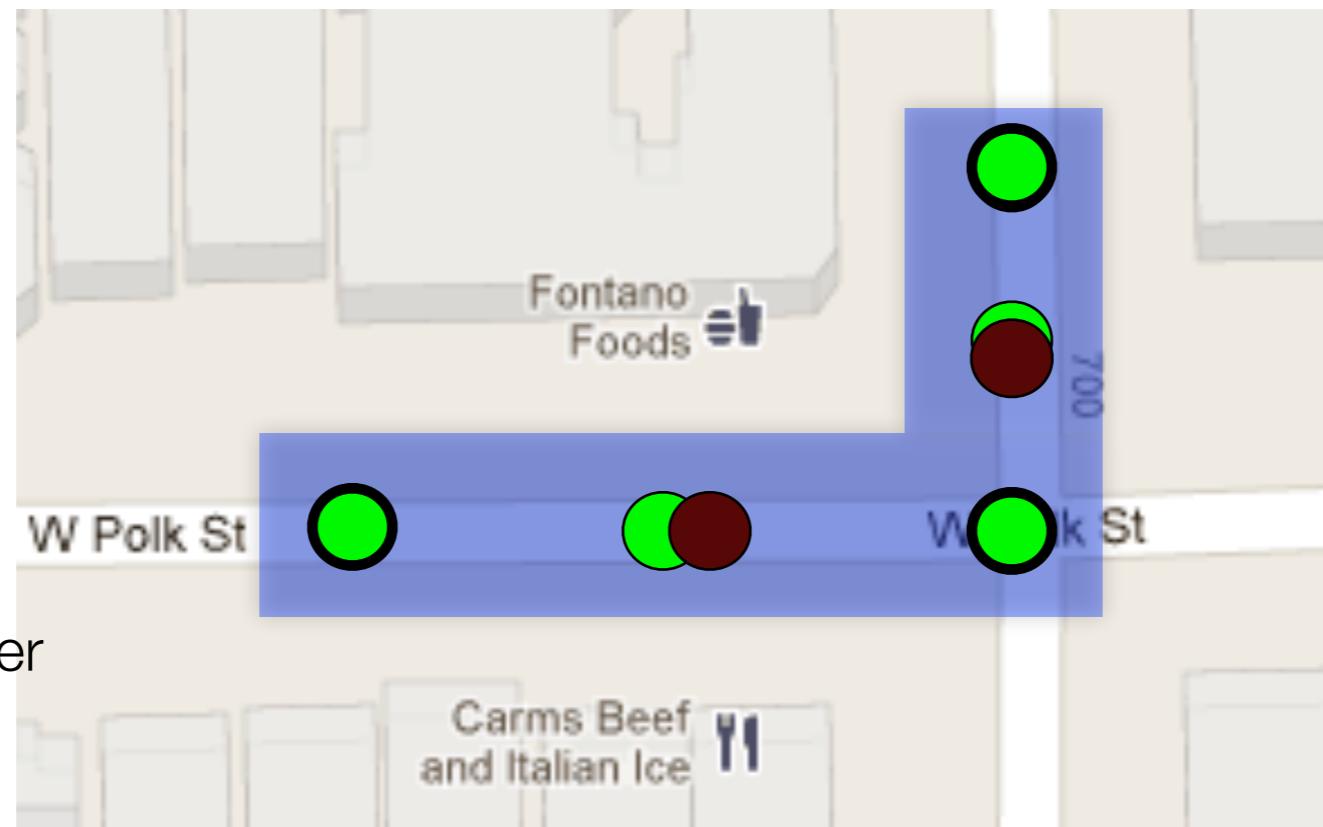
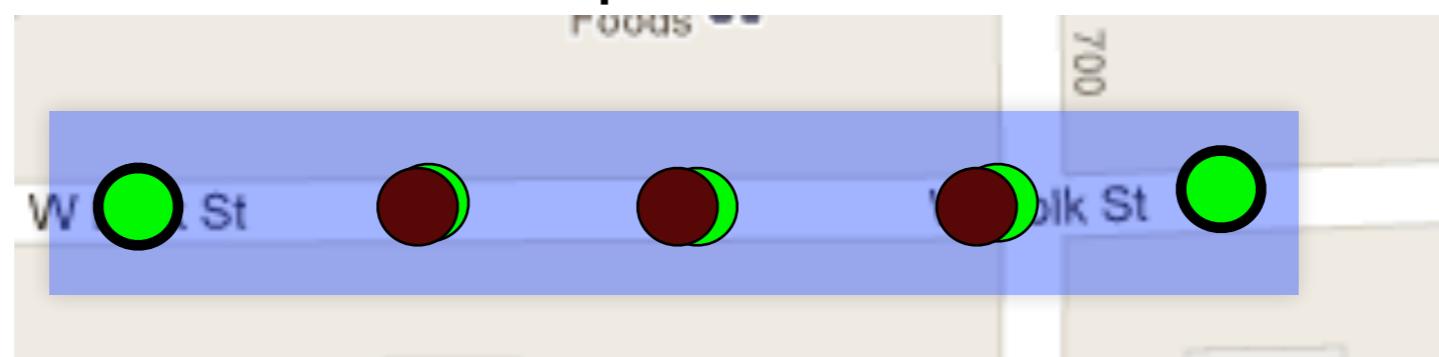
● Actual GPS location

● Actual GPS location
transmitted to the server

GPS compression/decompression



Interpolation



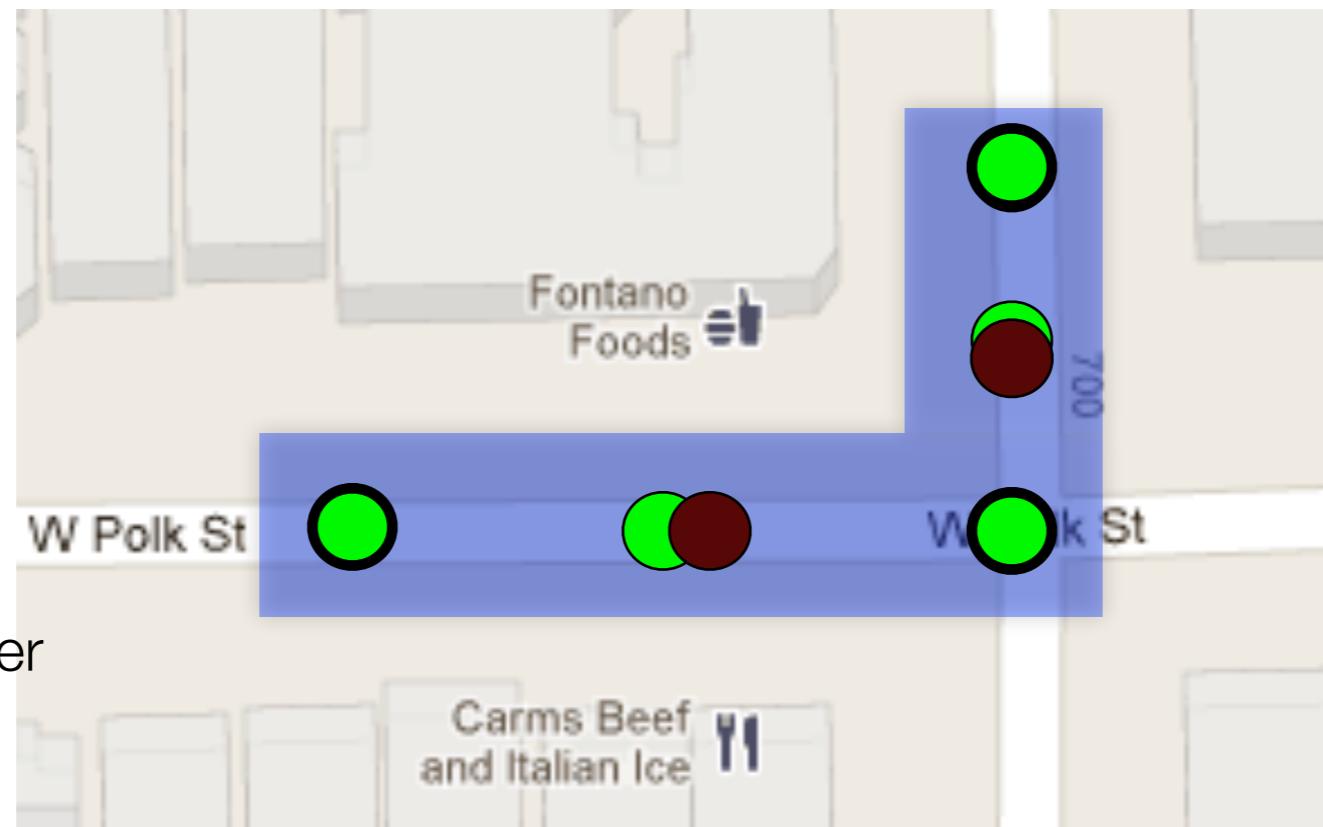
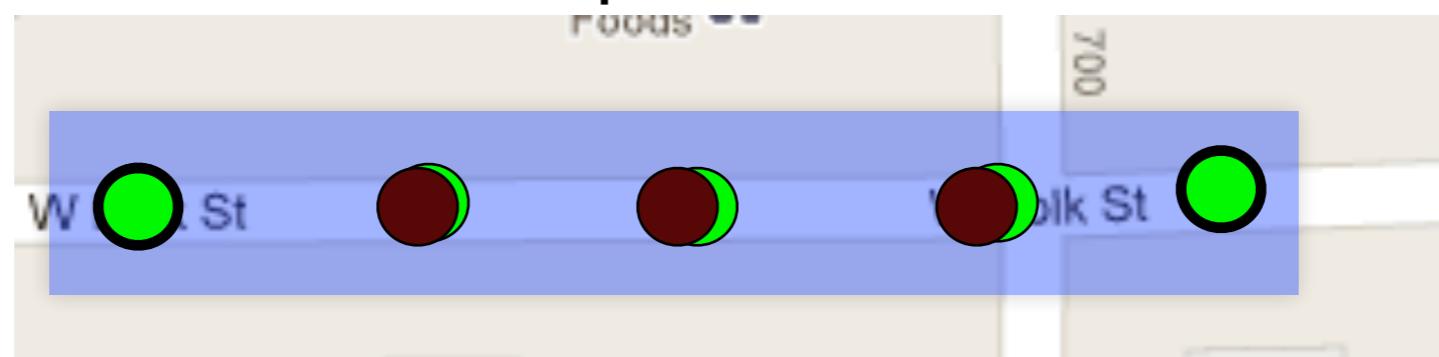
● Actual GPS location

● Actual GPS location
transmitted to the server

GPS compression/decompression



Interpolation



● Actual GPS location

● Actual GPS location
transmitted to the server

● Interpolated location

Adaptive Sampling

Adaptive Sampling

Data-usage

Adaptive Sampling

Data-usage

Error

Adaptive Sampling

Data-usage

Error

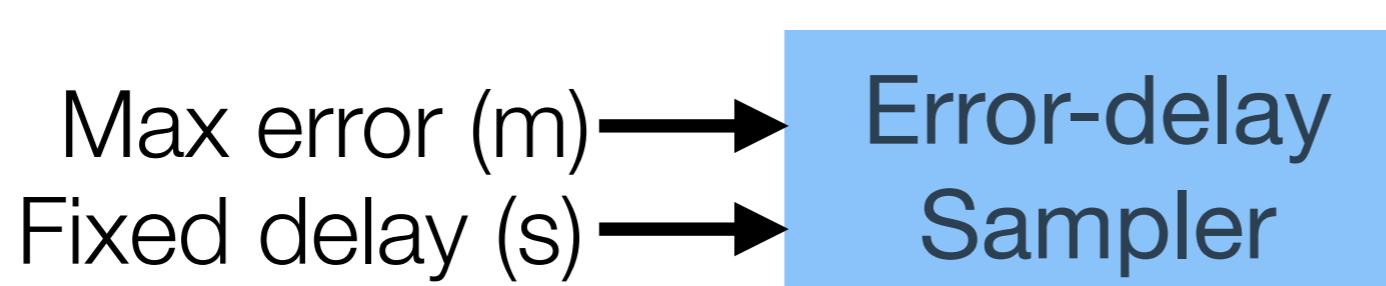
Delay

Adaptive Sampling

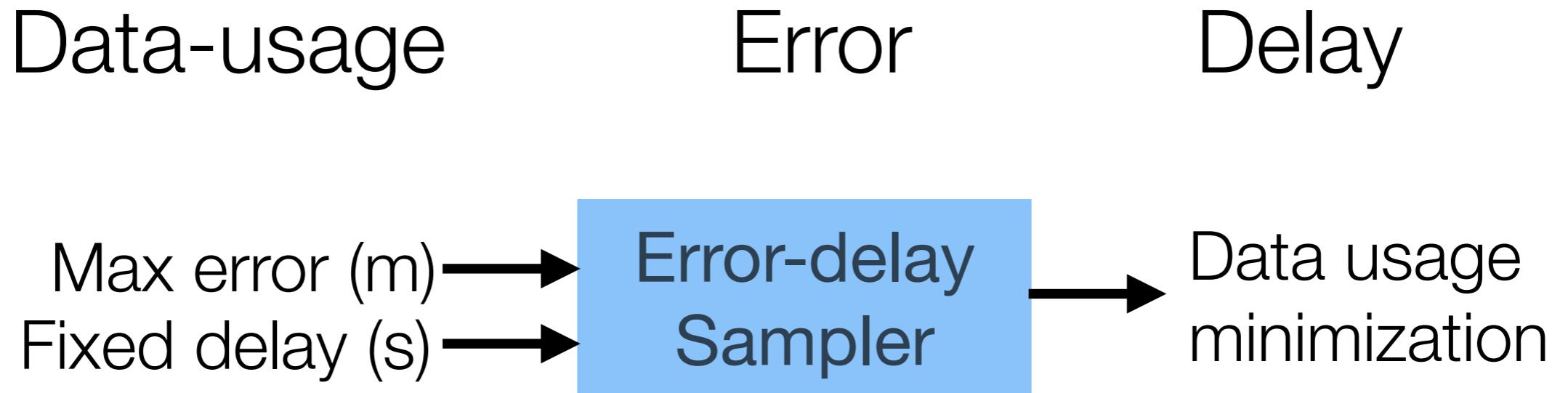
Data-usage

Error

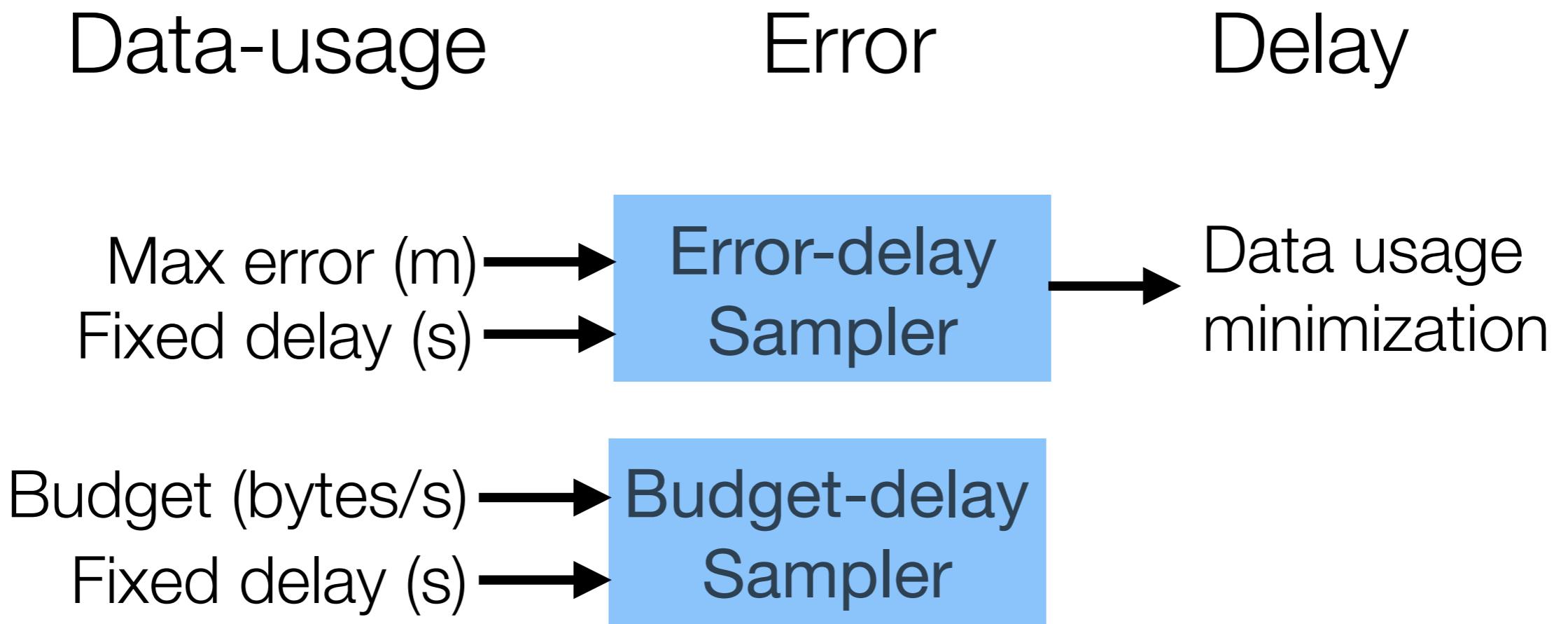
Delay



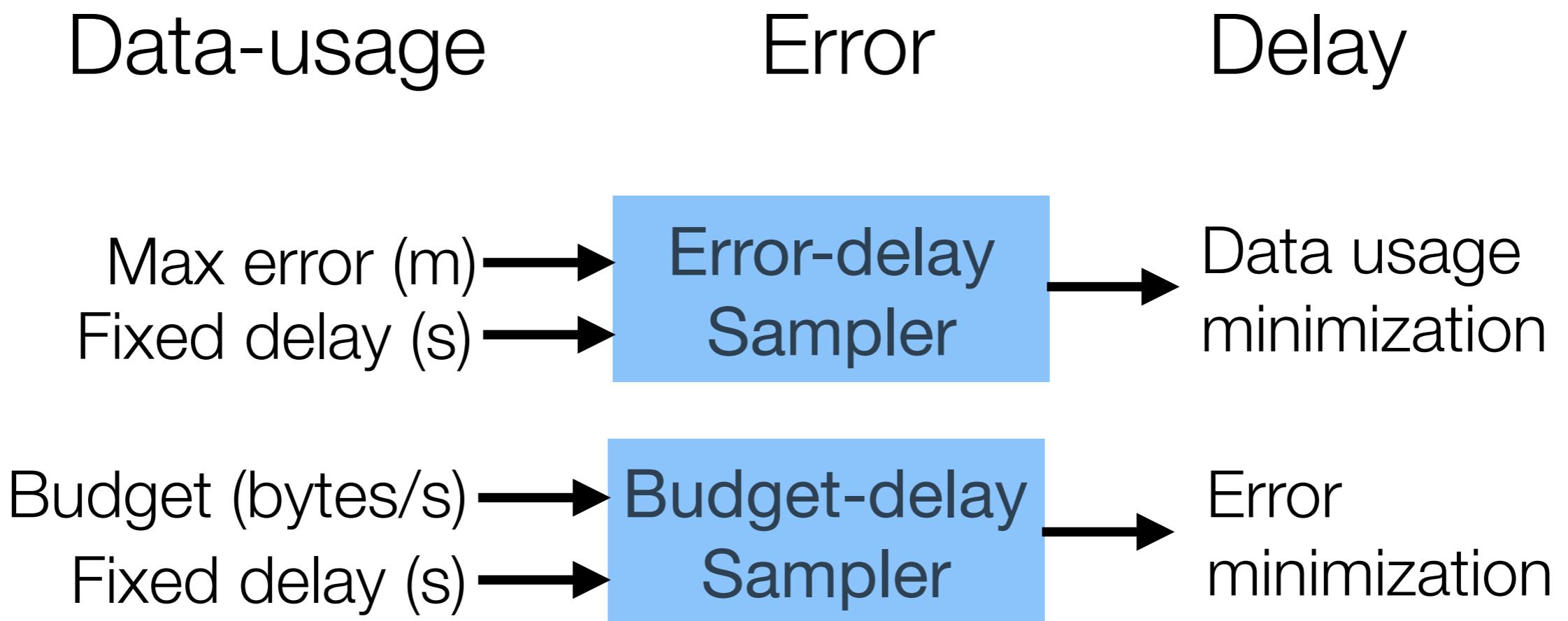
Adaptive Sampling



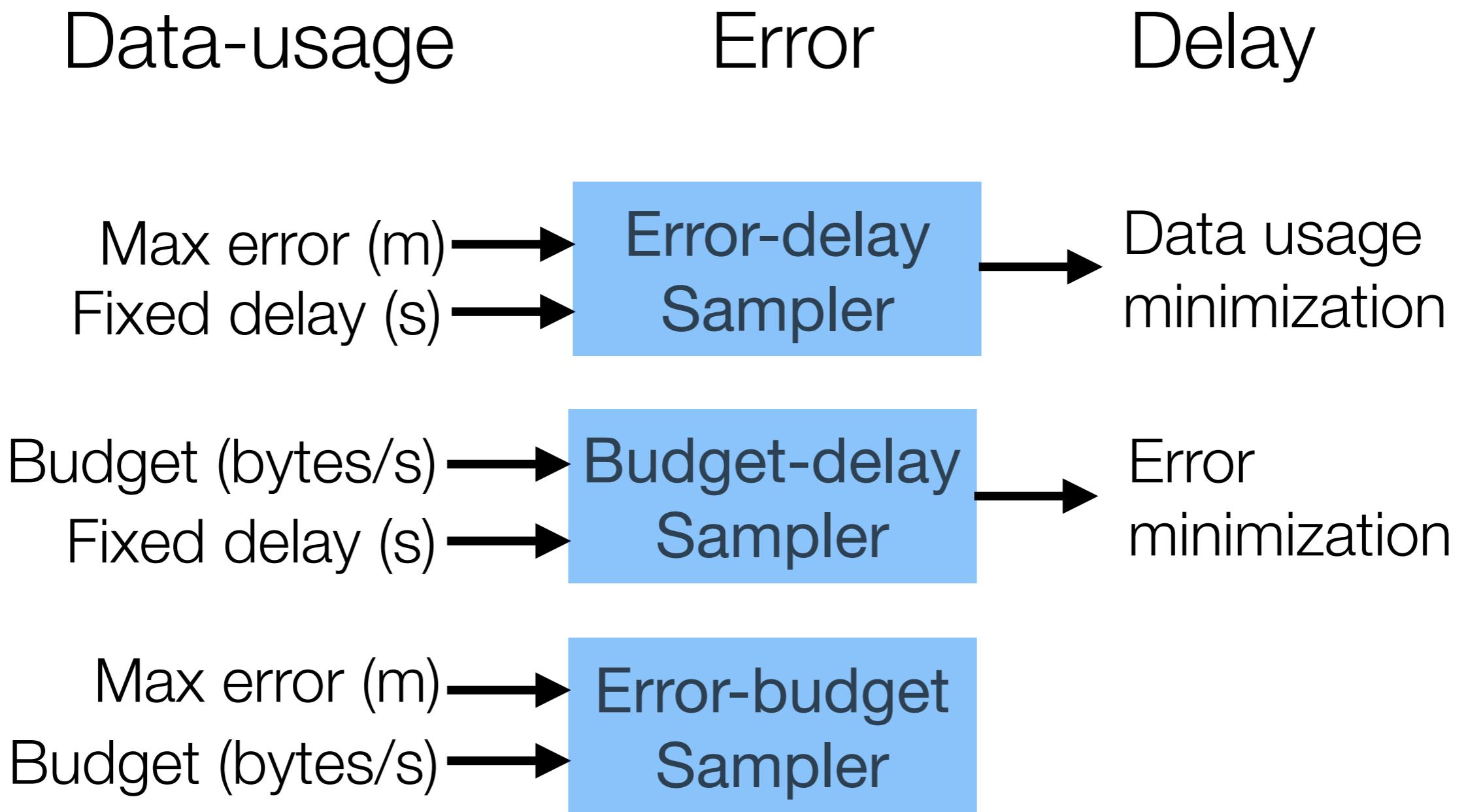
Adaptive Sampling



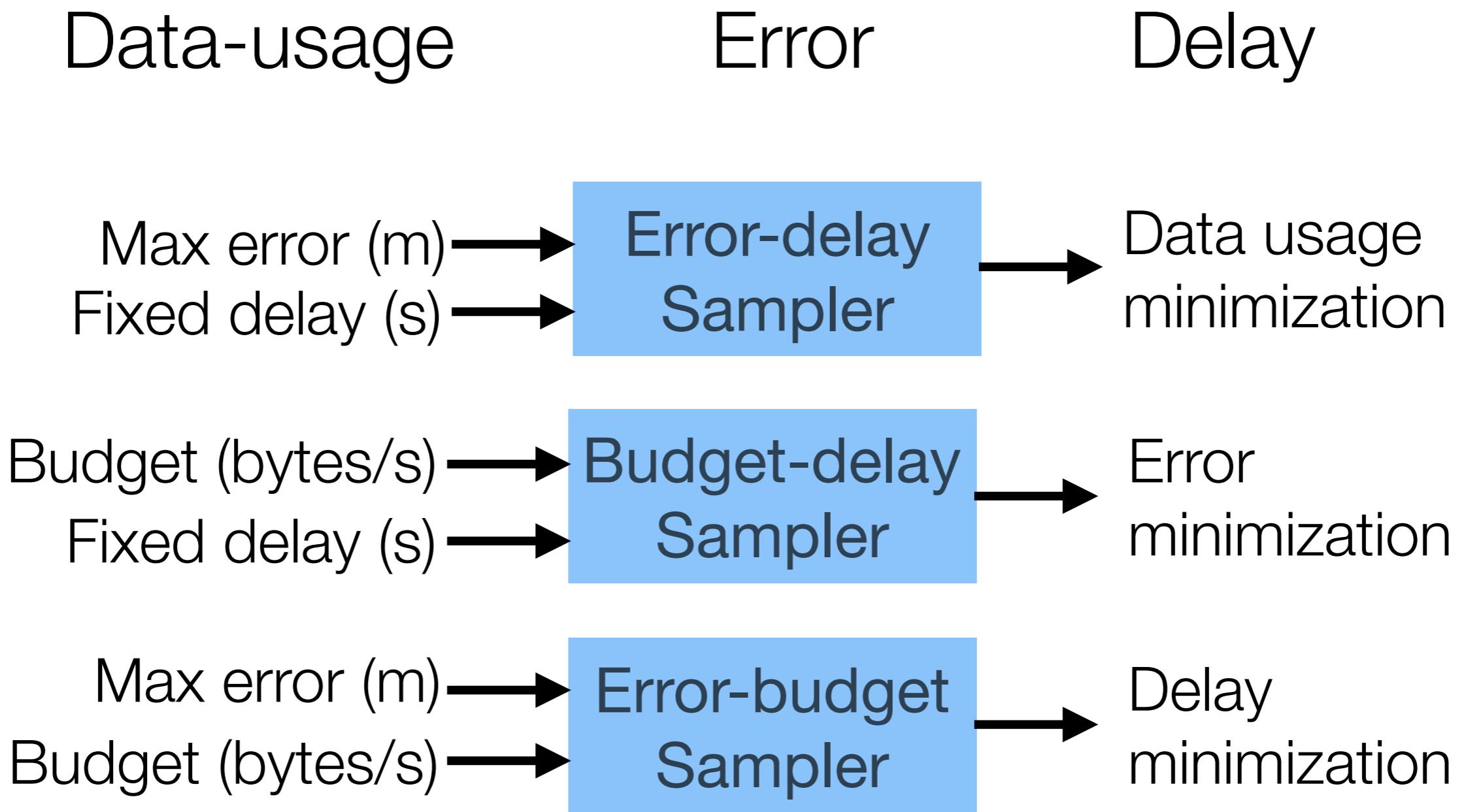
Adaptive Sampling



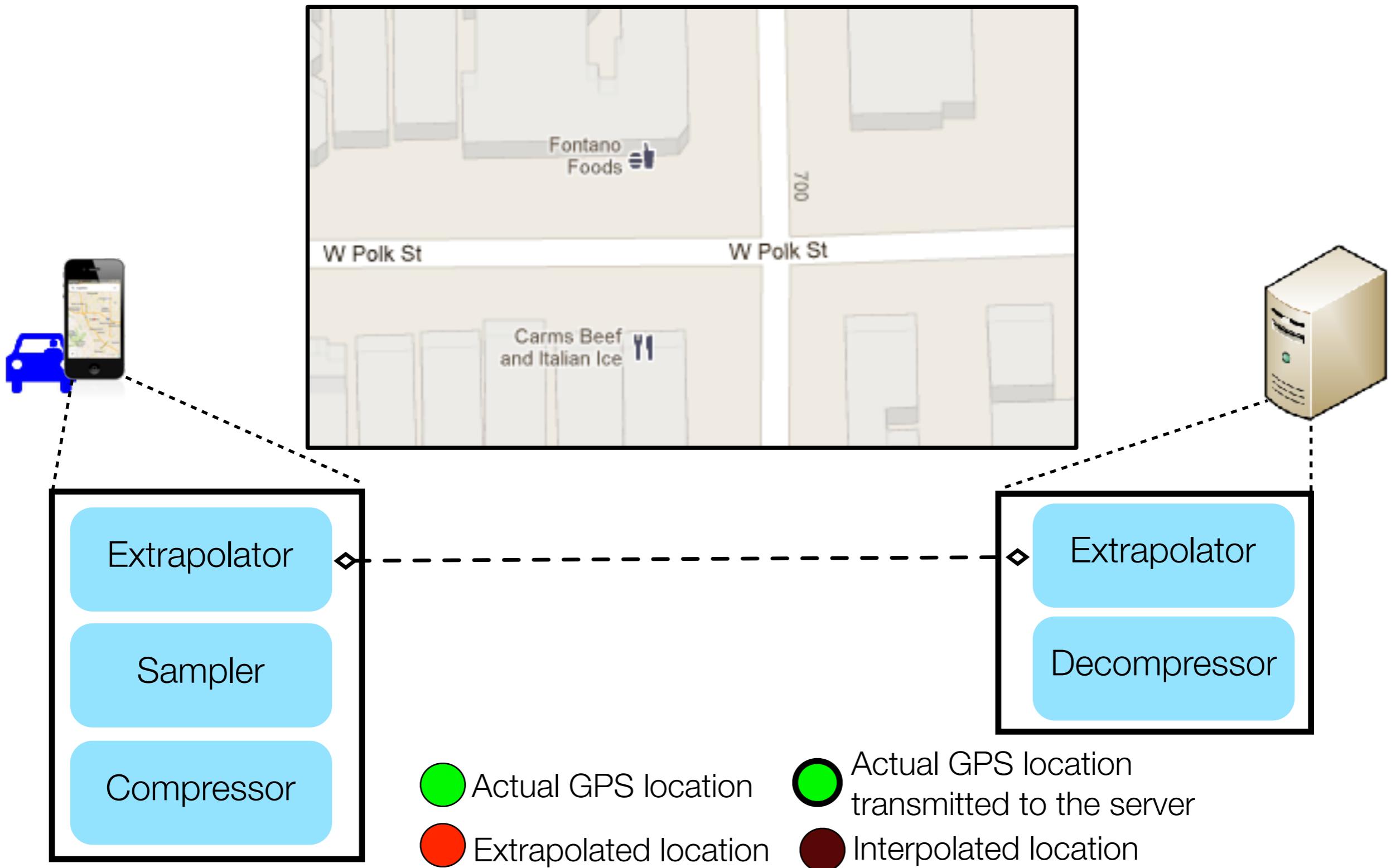
Adaptive Sampling



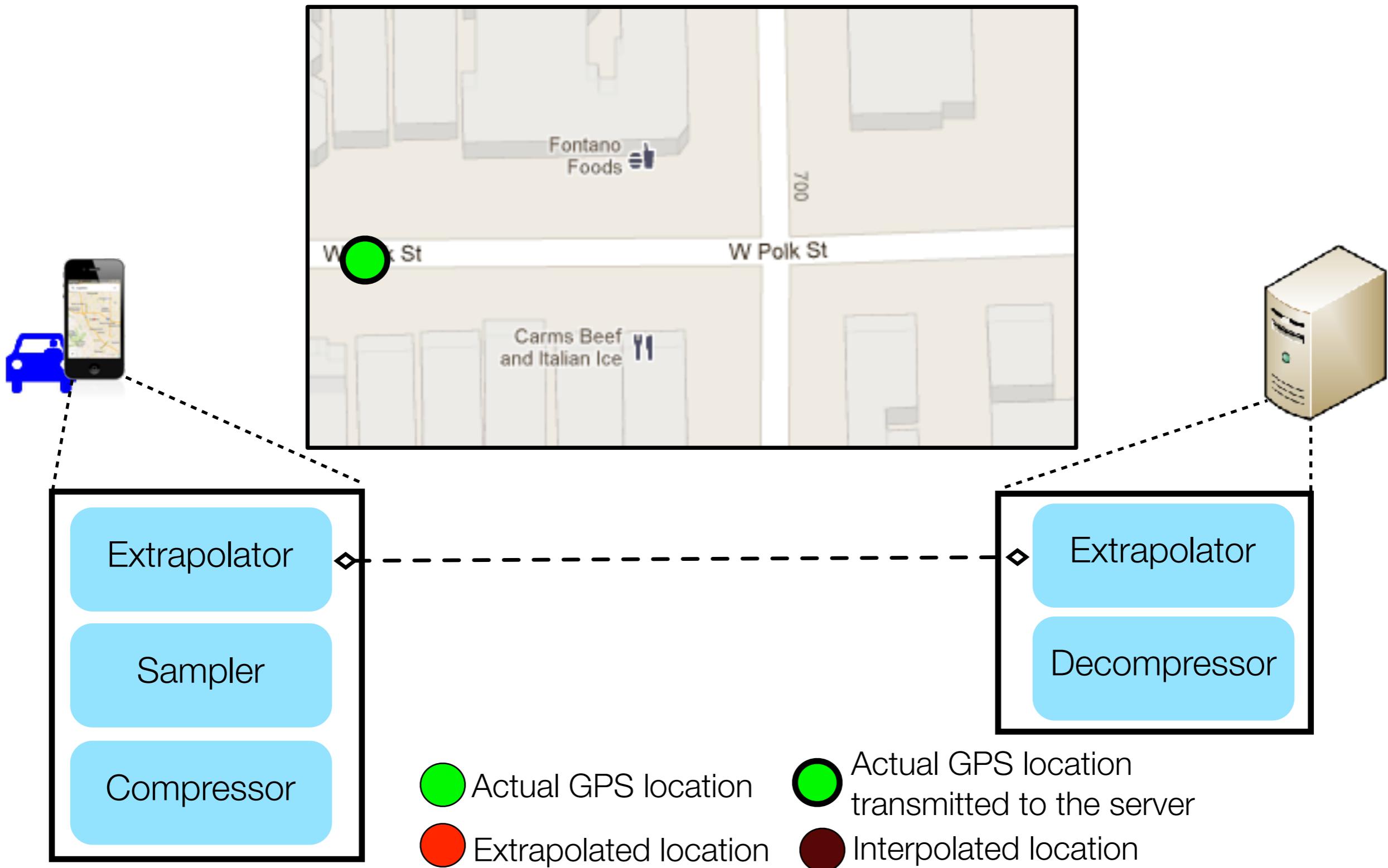
Adaptive Sampling



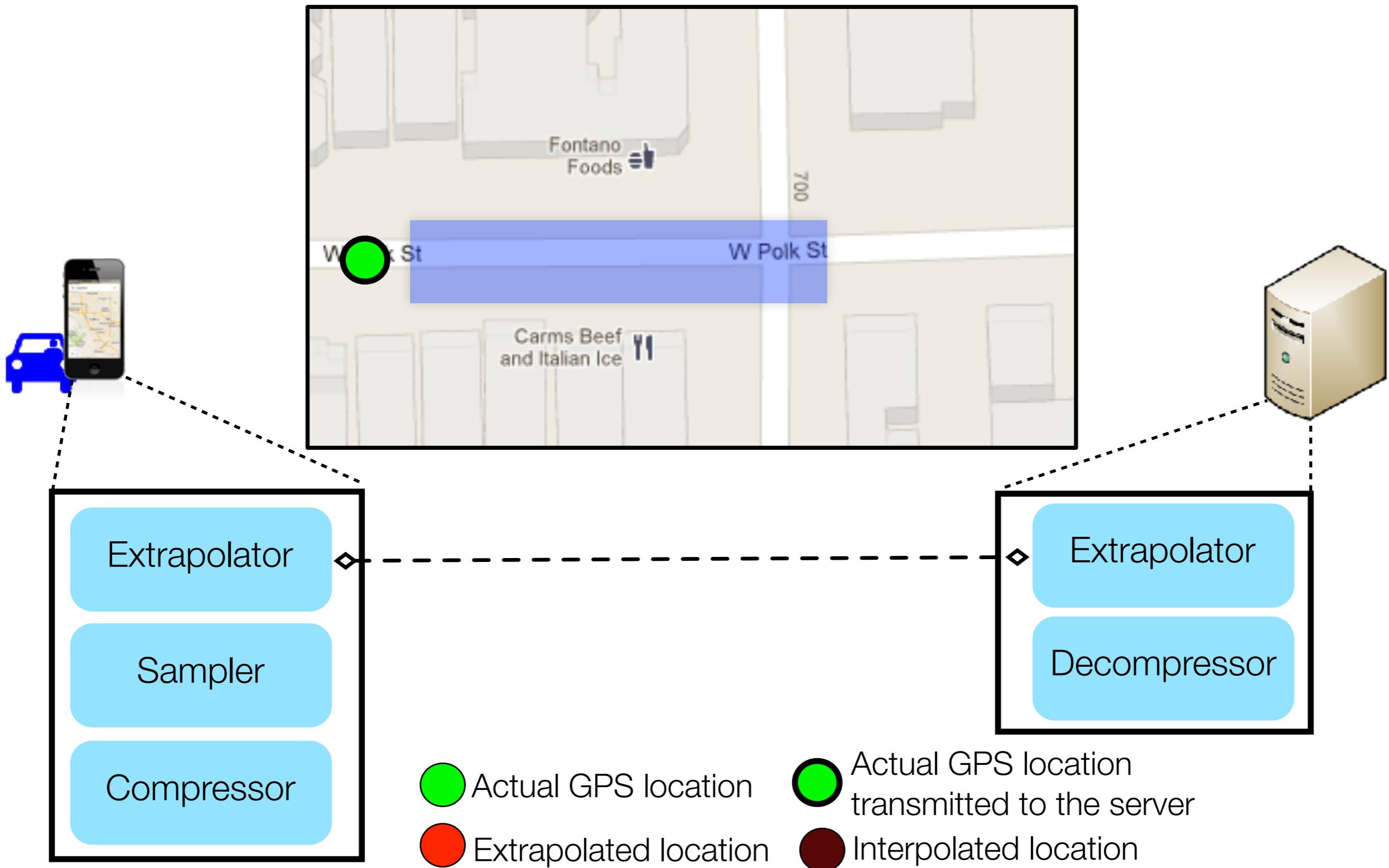
System overview



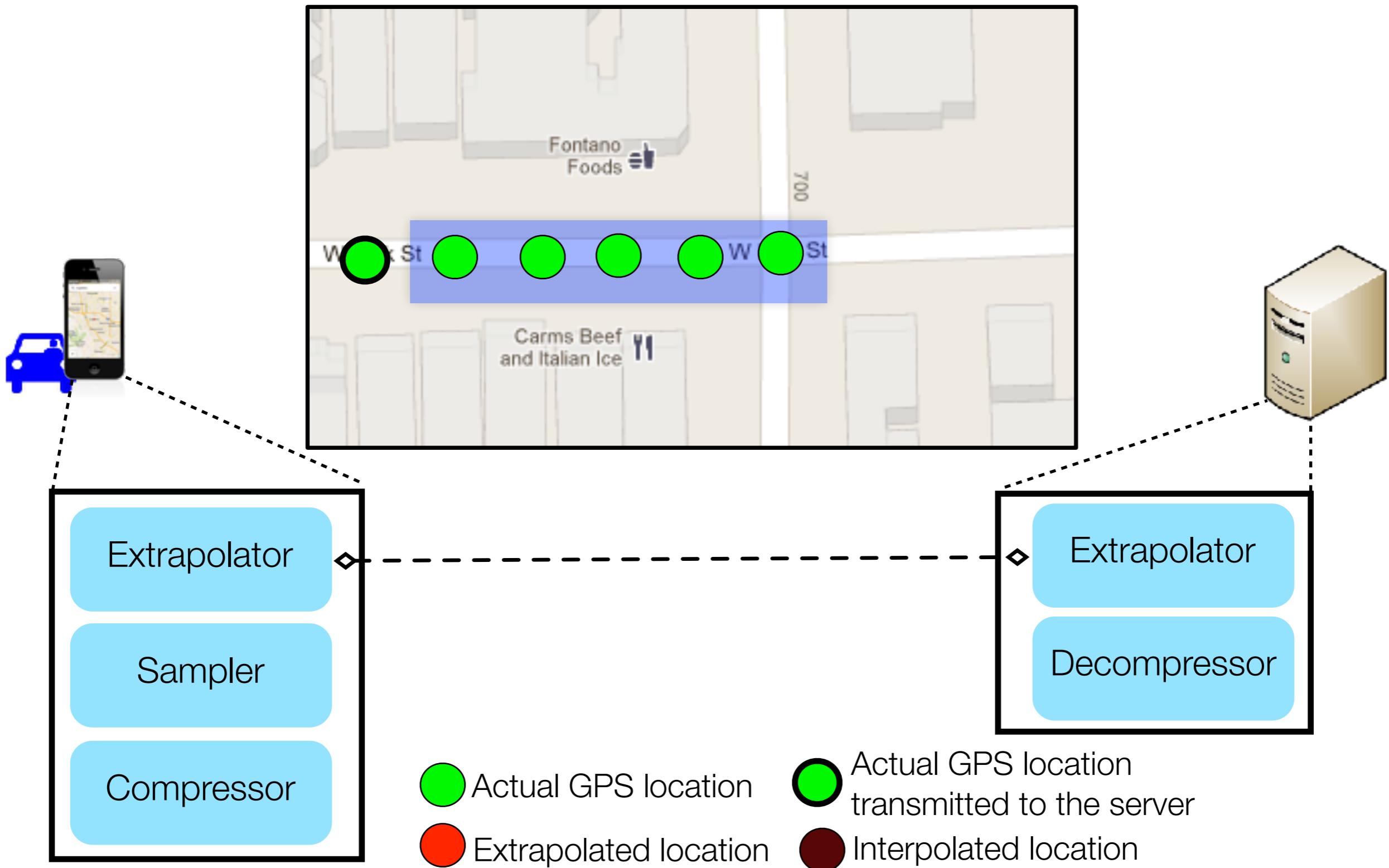
System overview



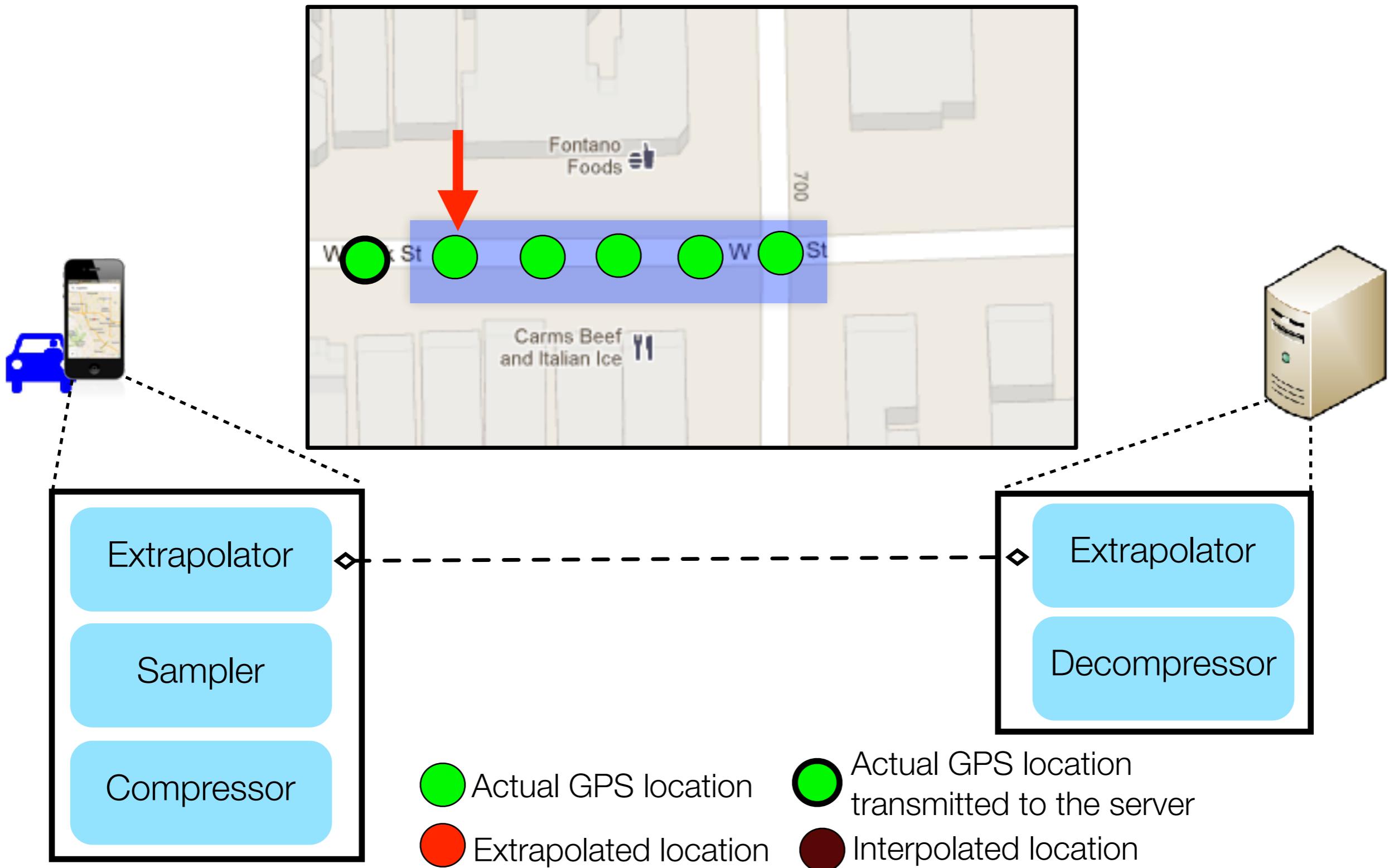
System overview



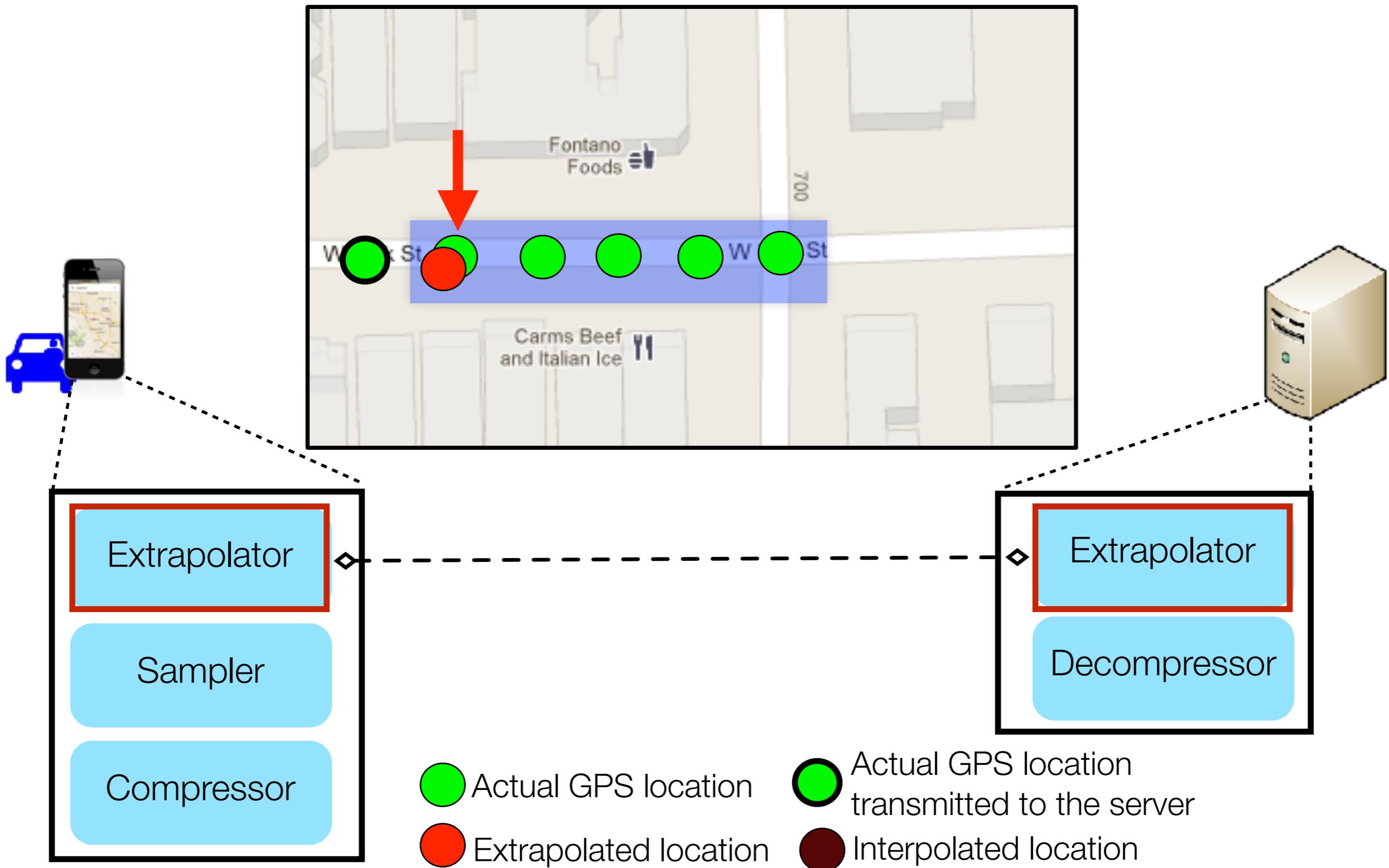
System overview



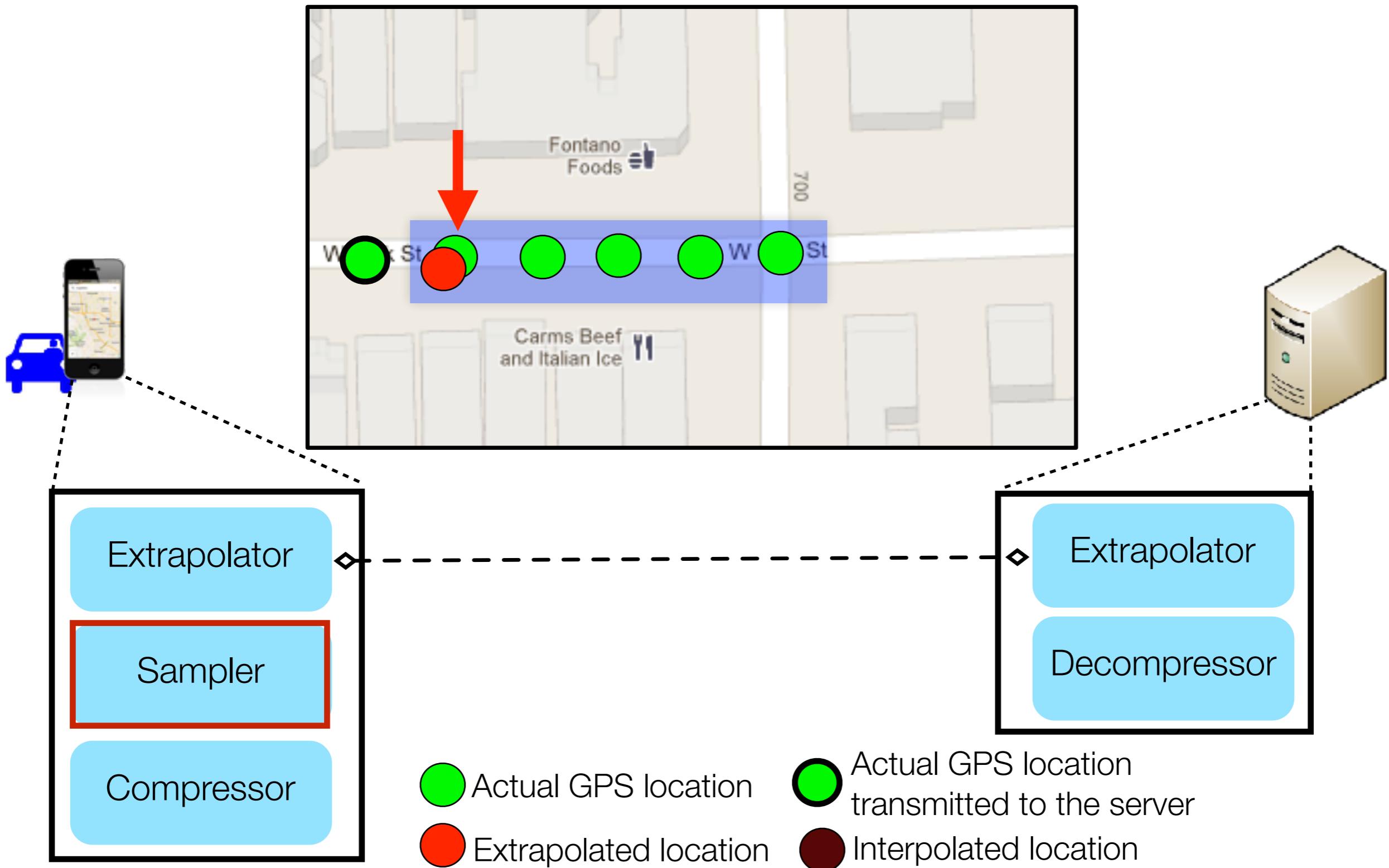
System overview



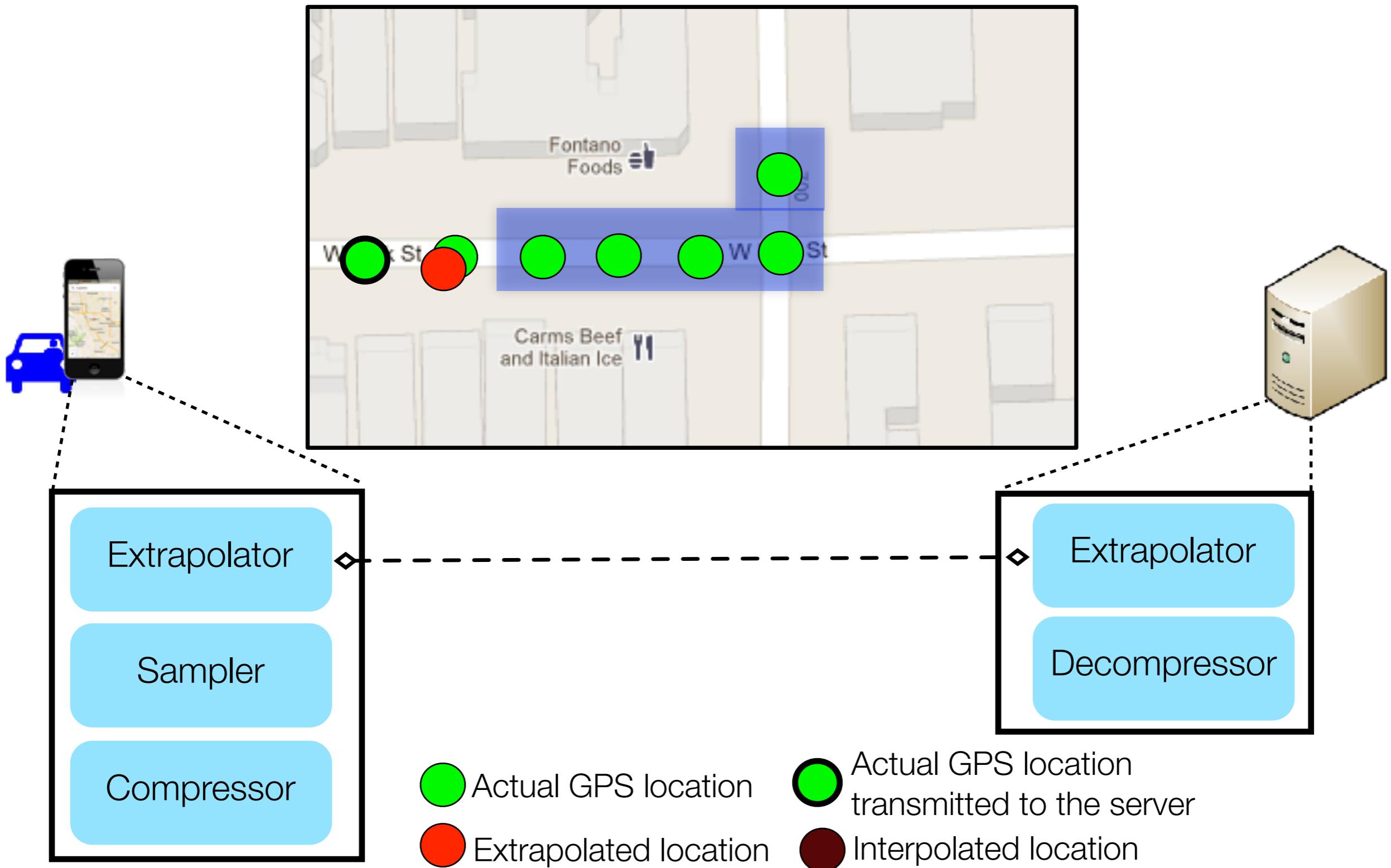
System overview



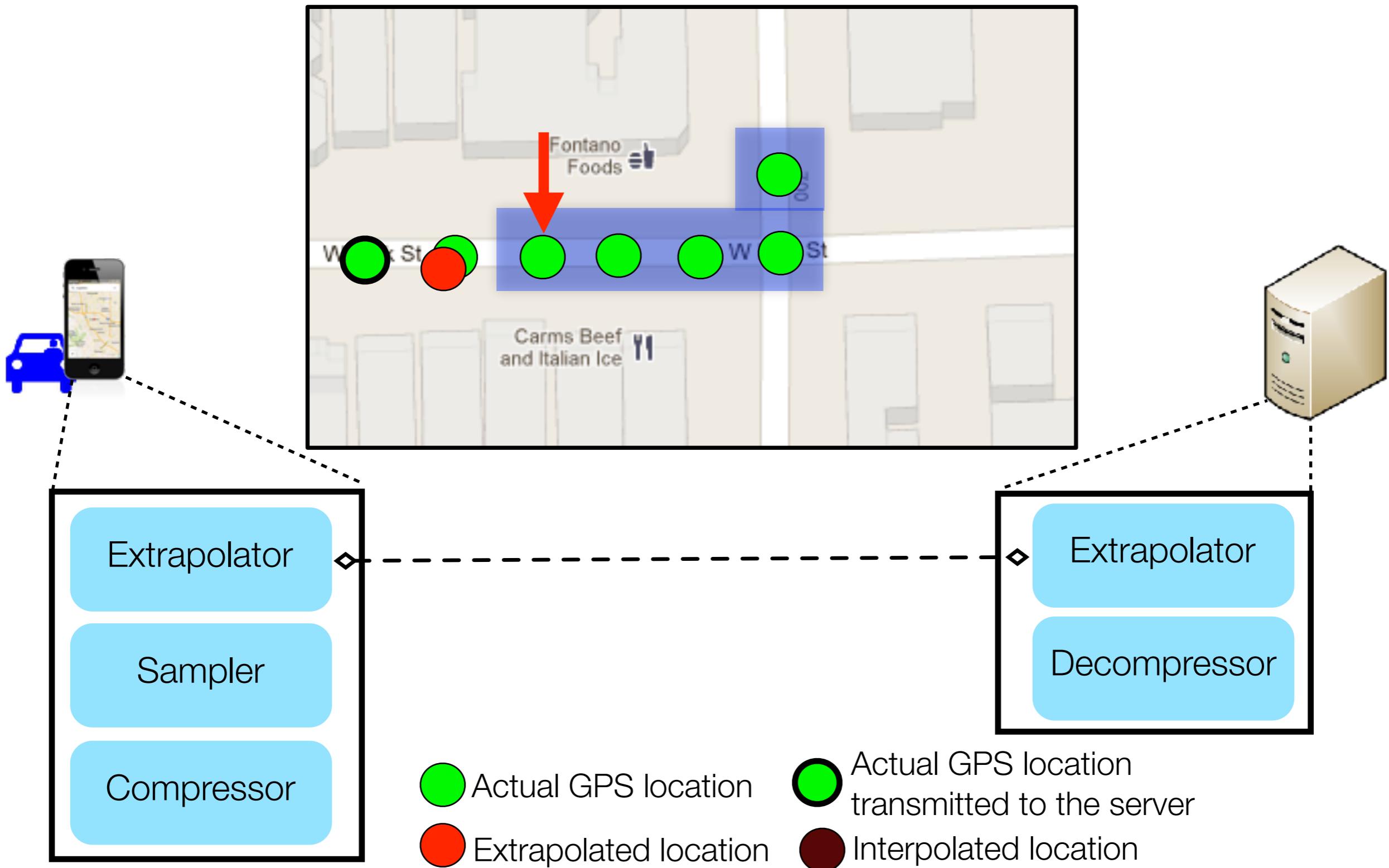
System overview



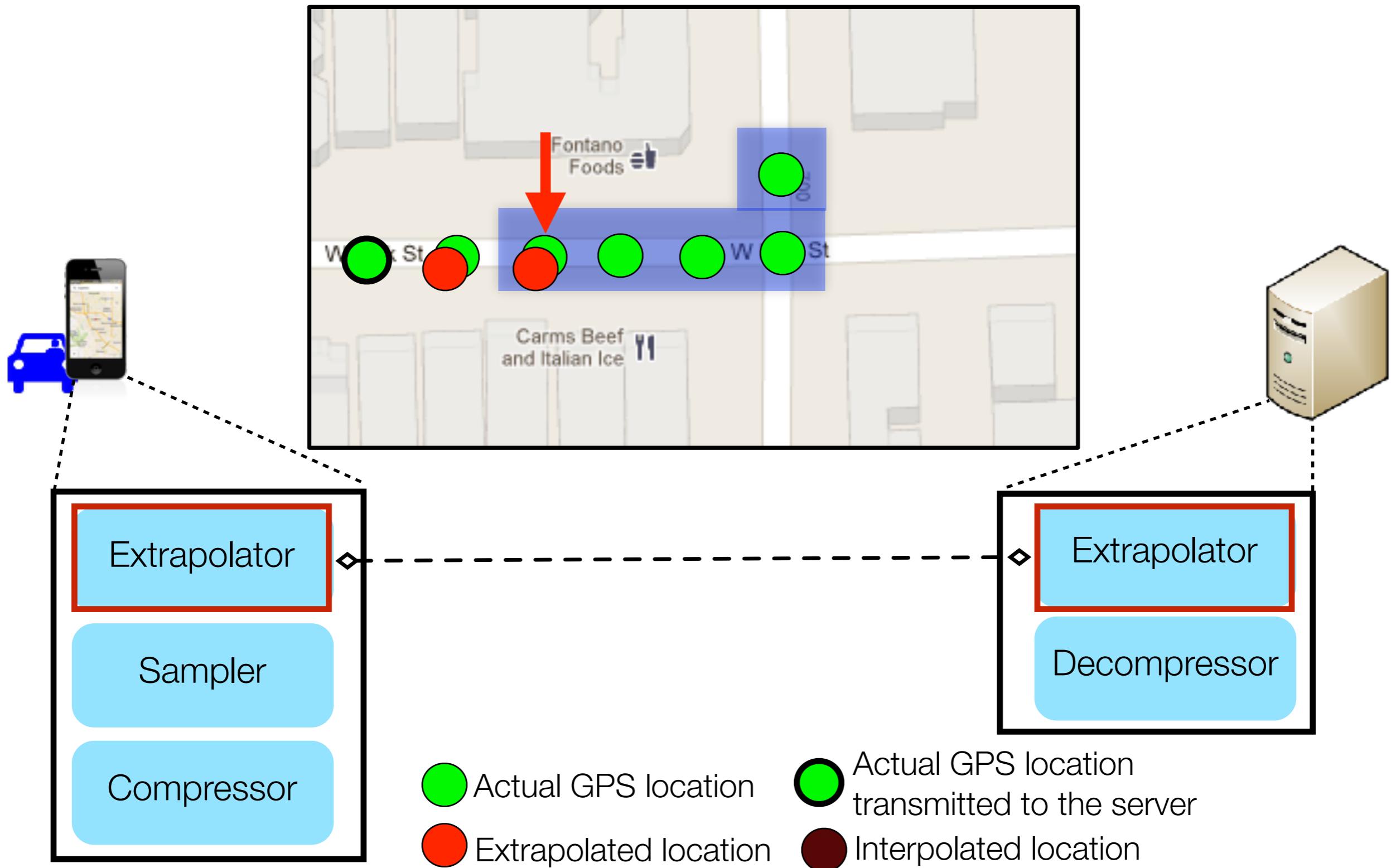
System overview



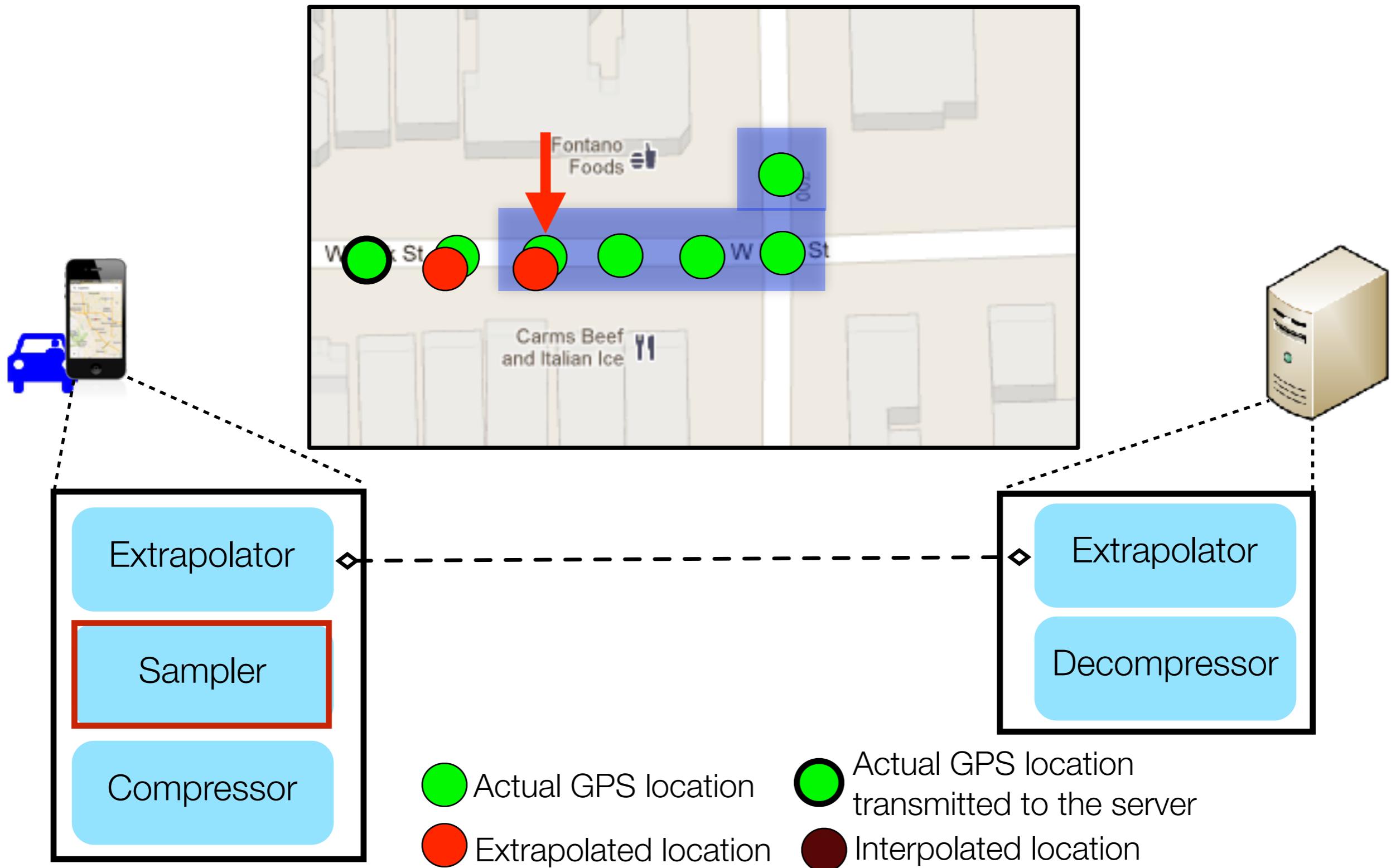
System overview



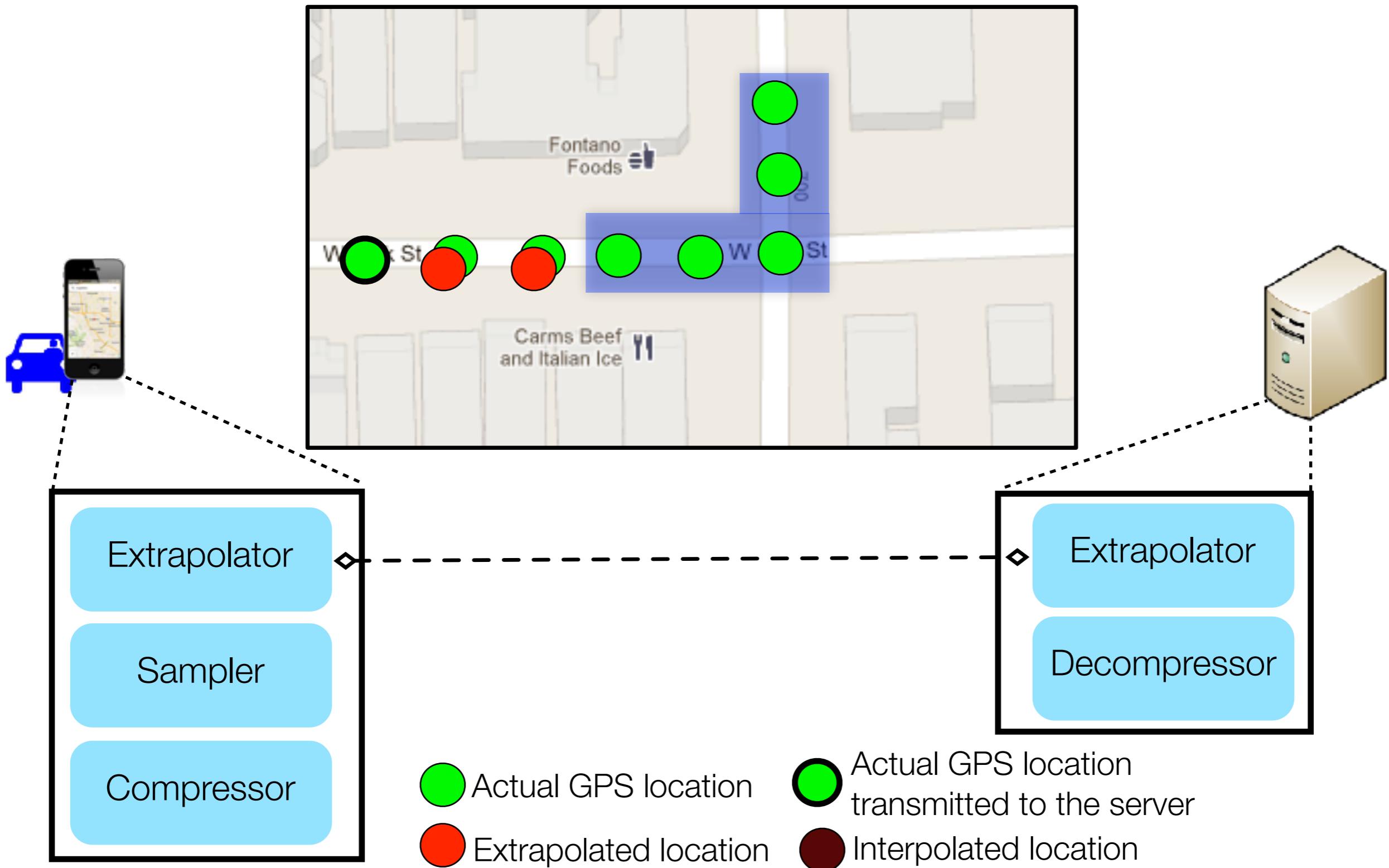
System overview



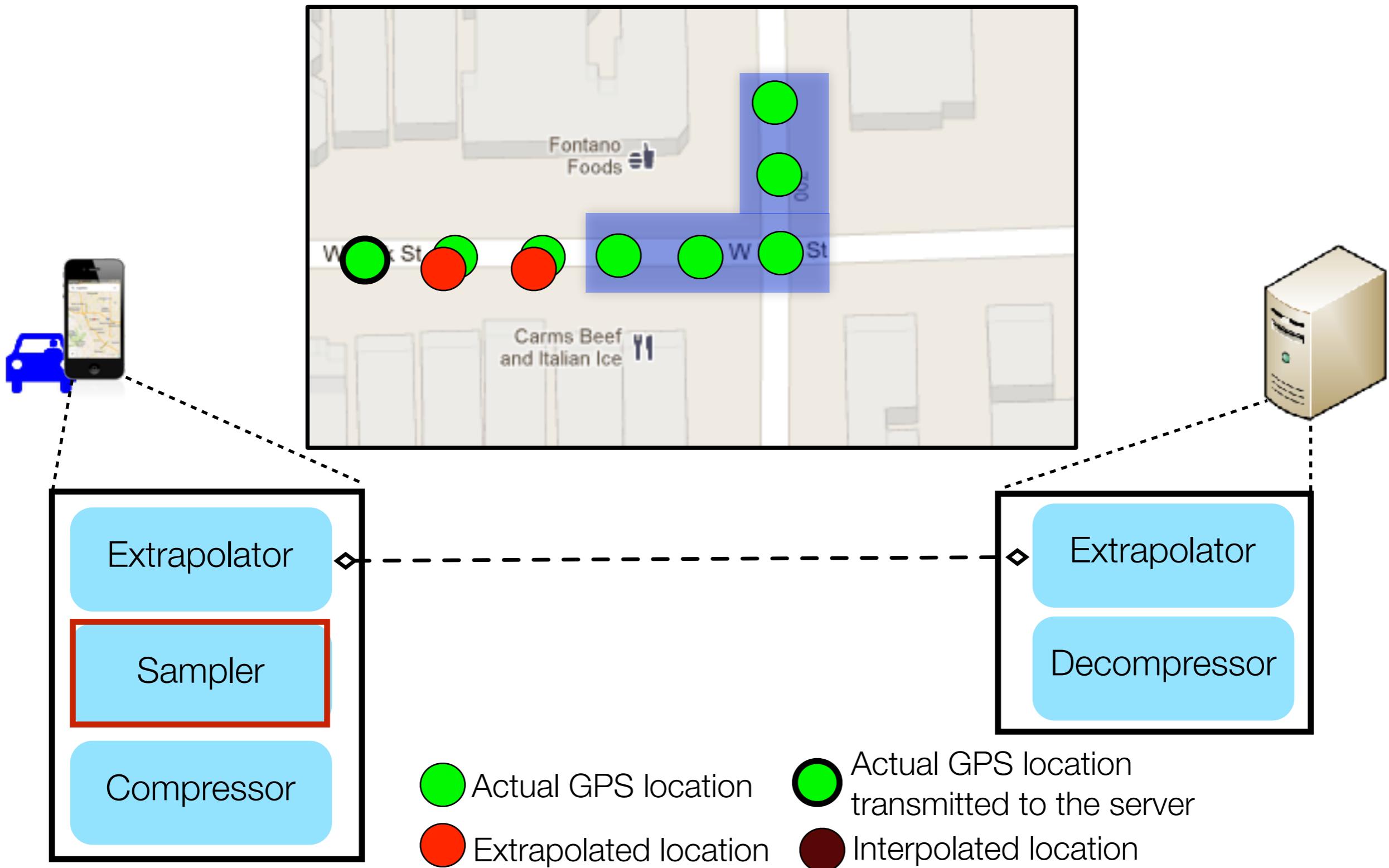
System overview



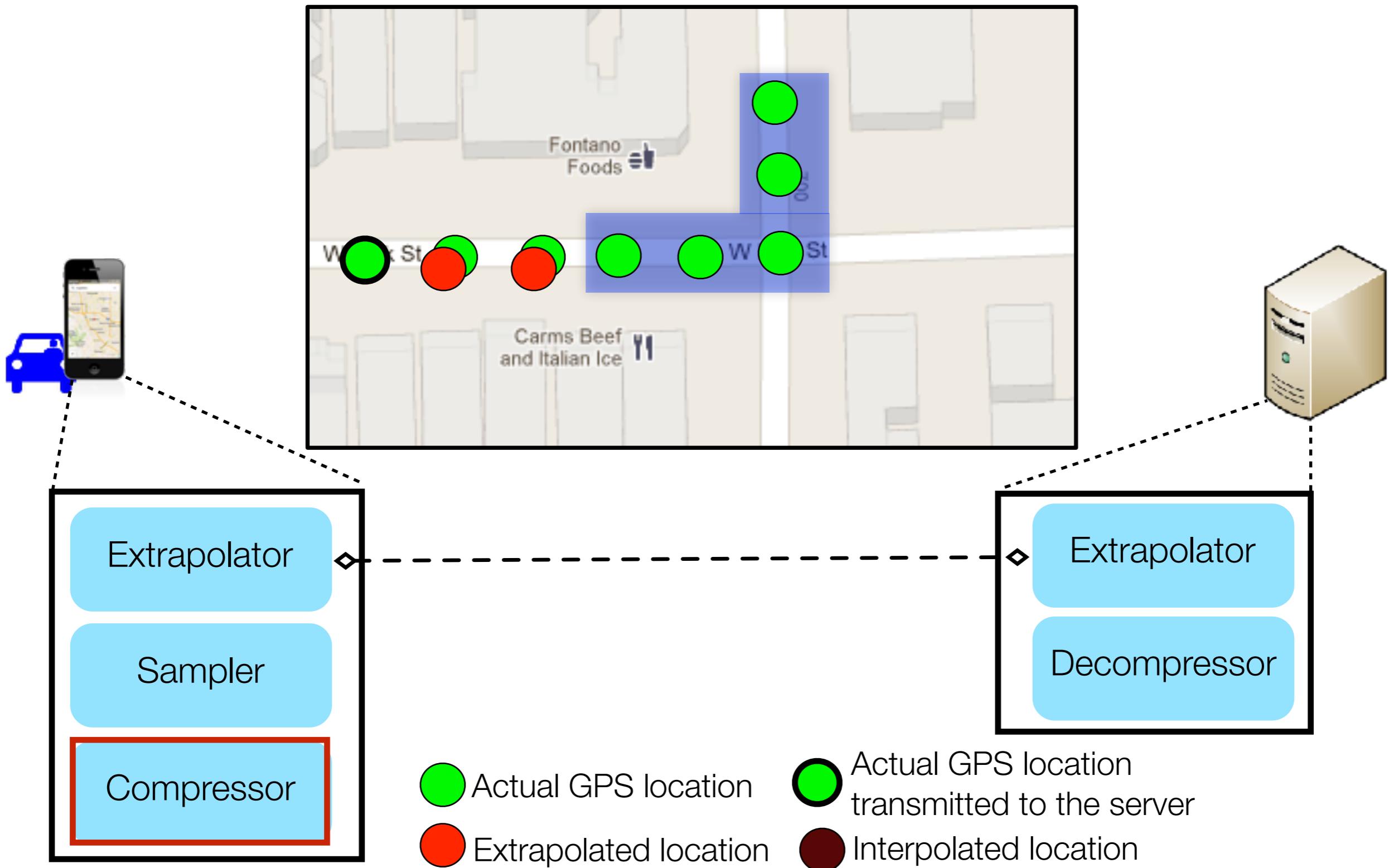
System overview



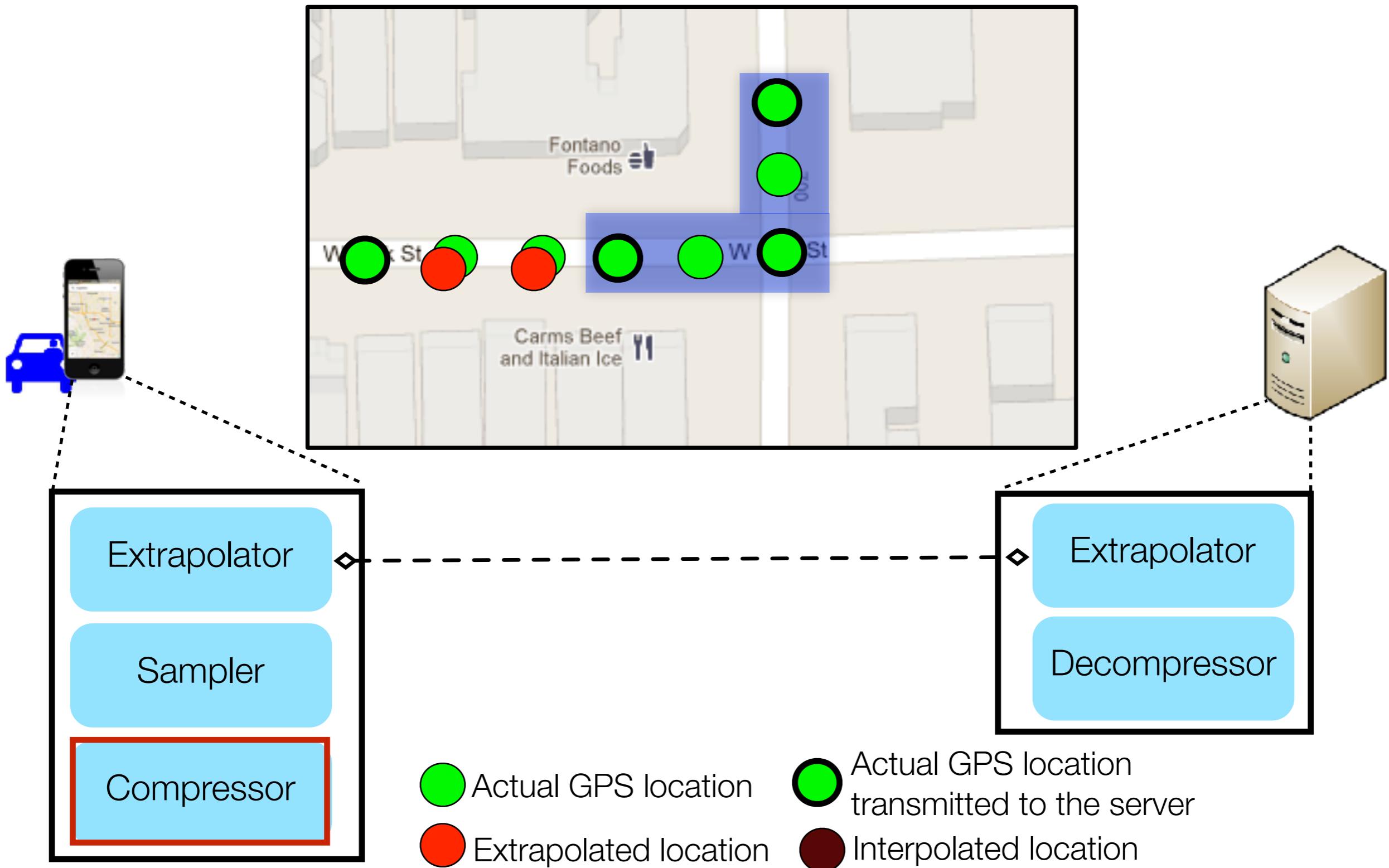
System overview



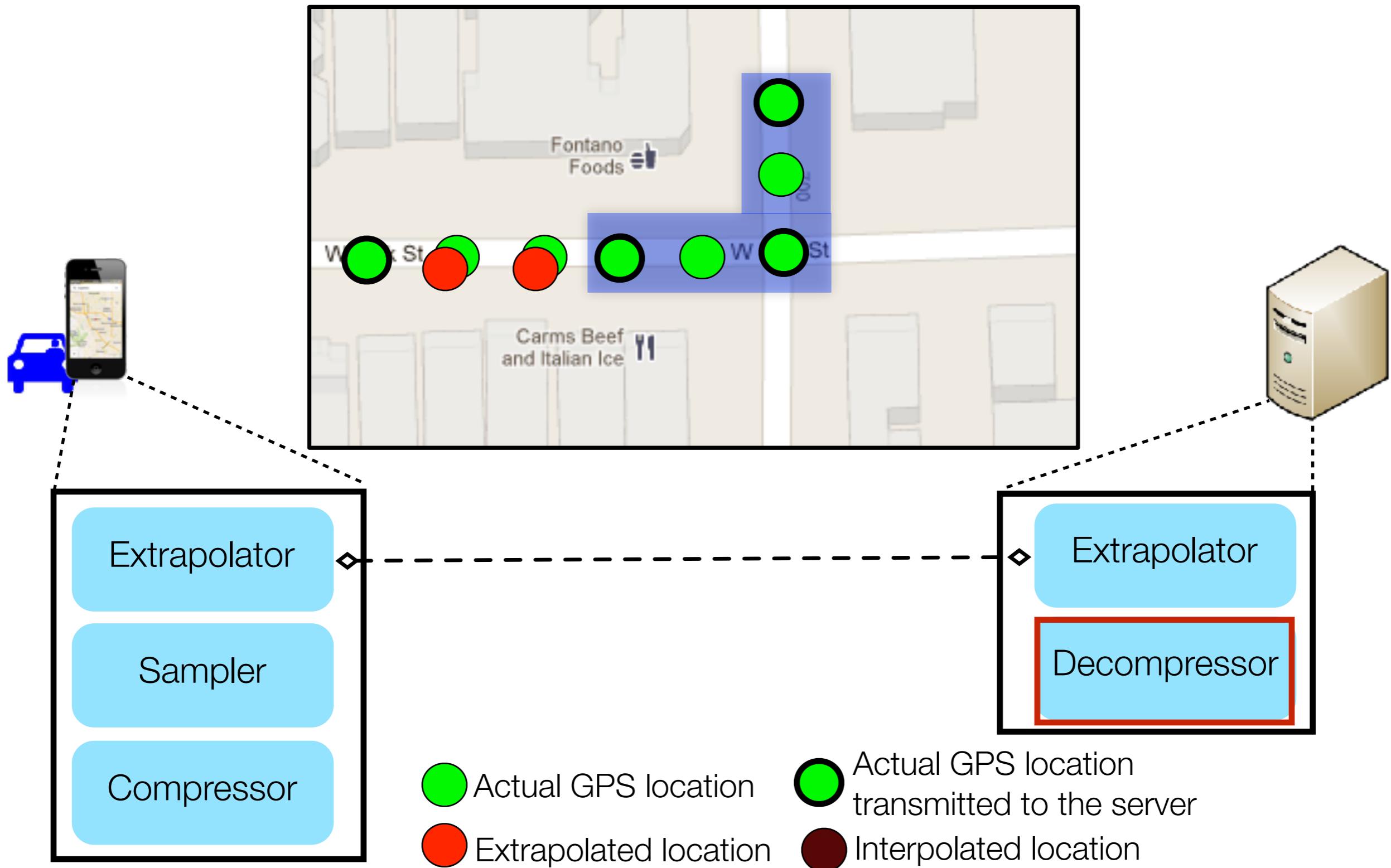
System overview



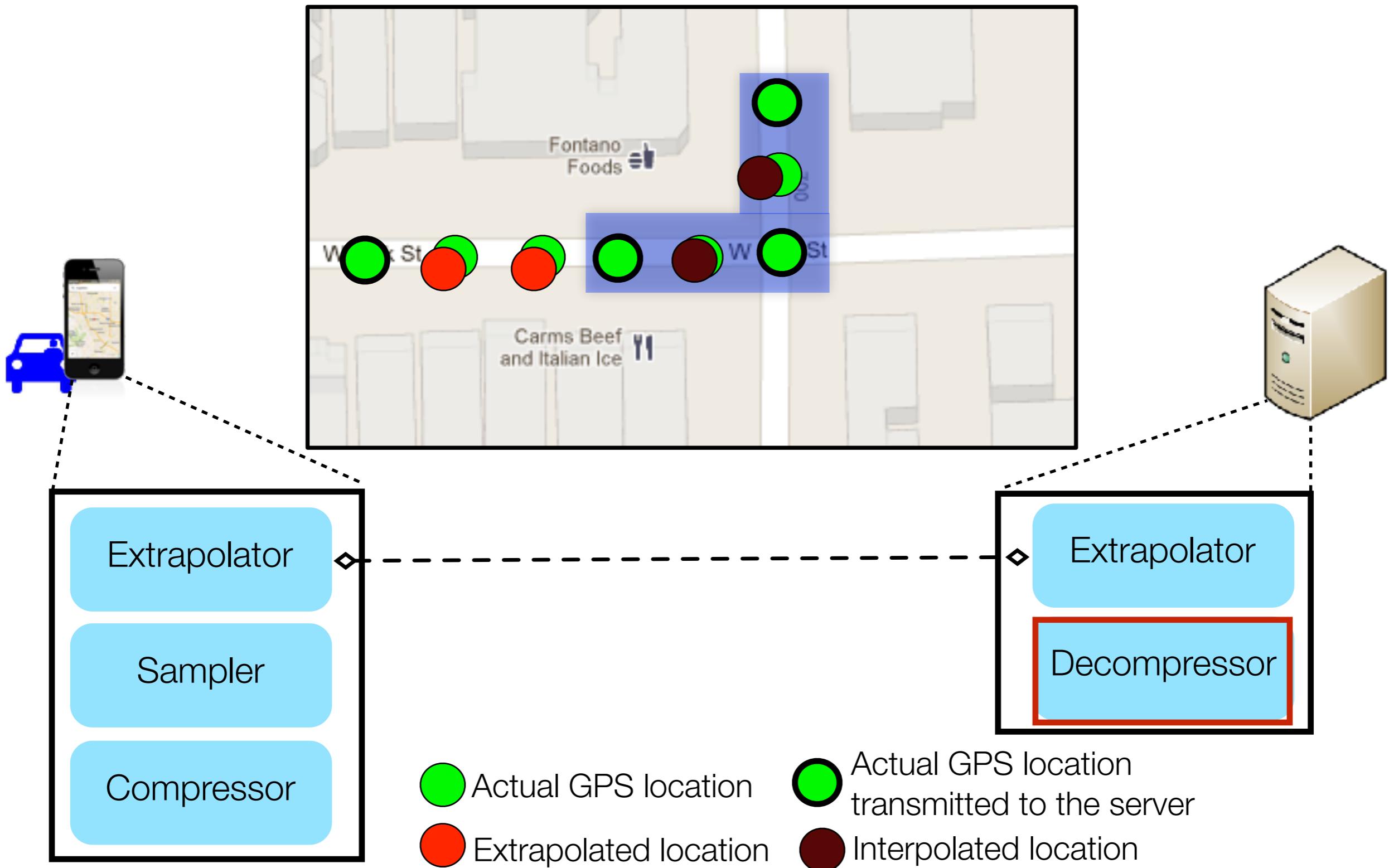
System overview



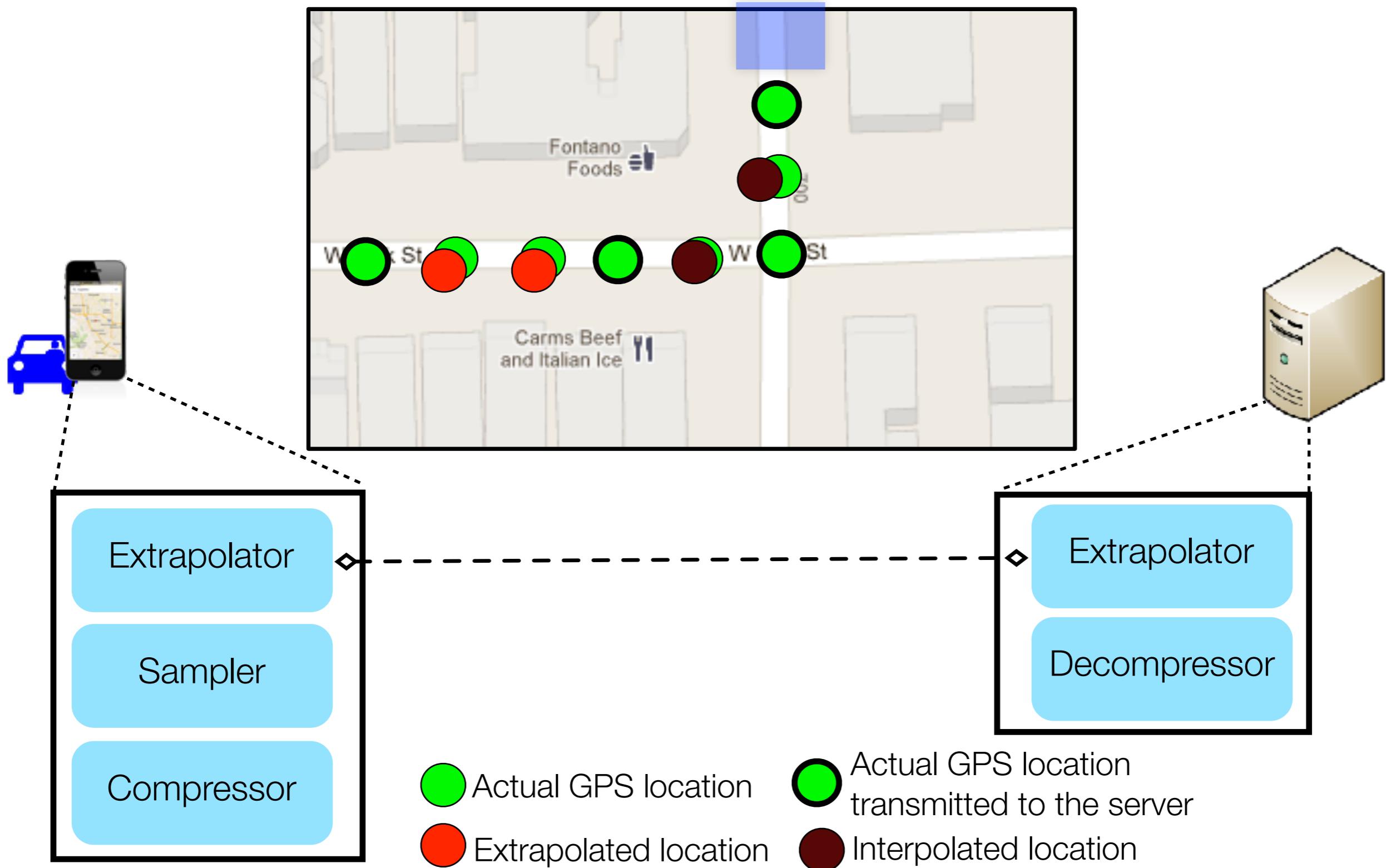
System overview



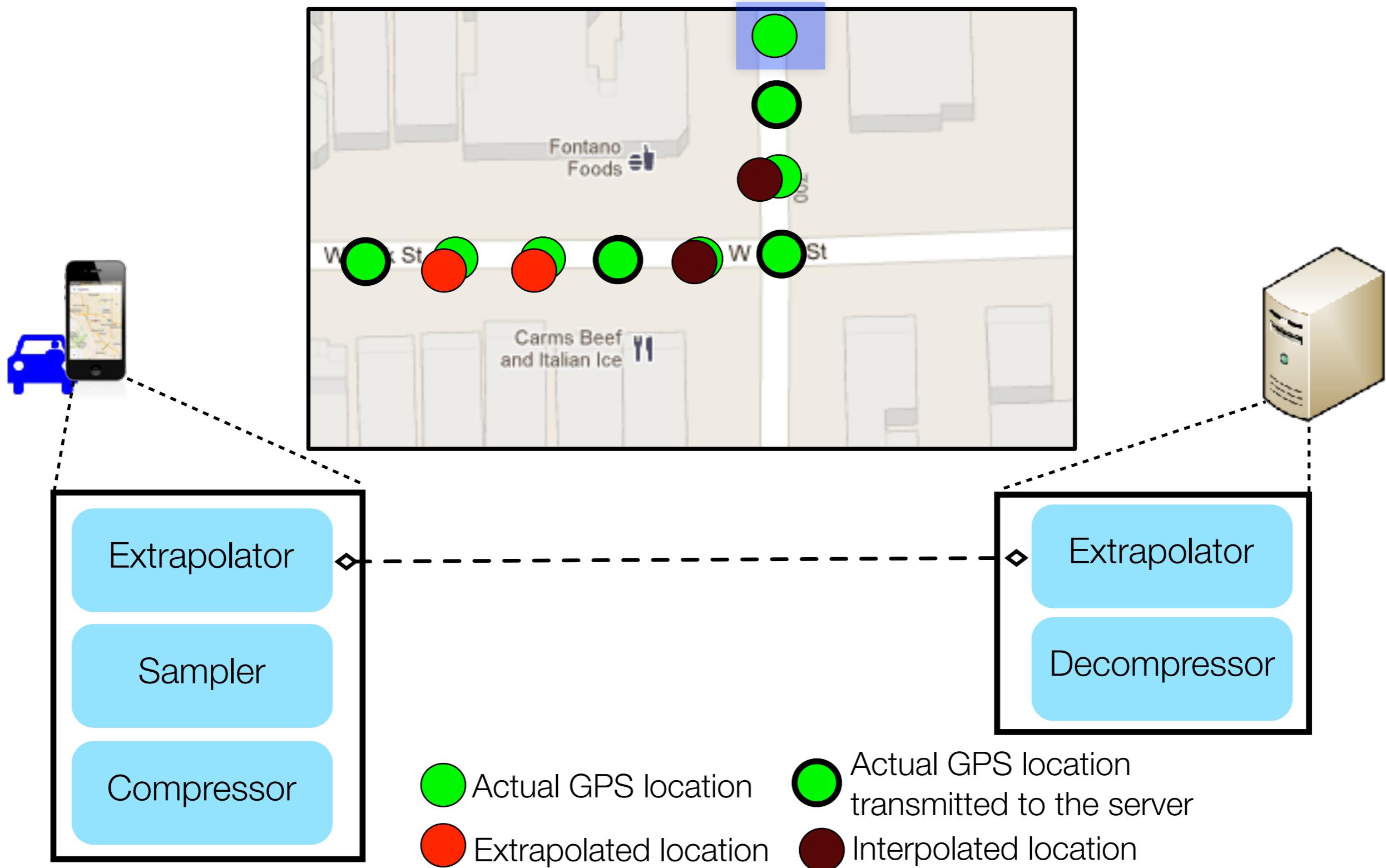
System overview



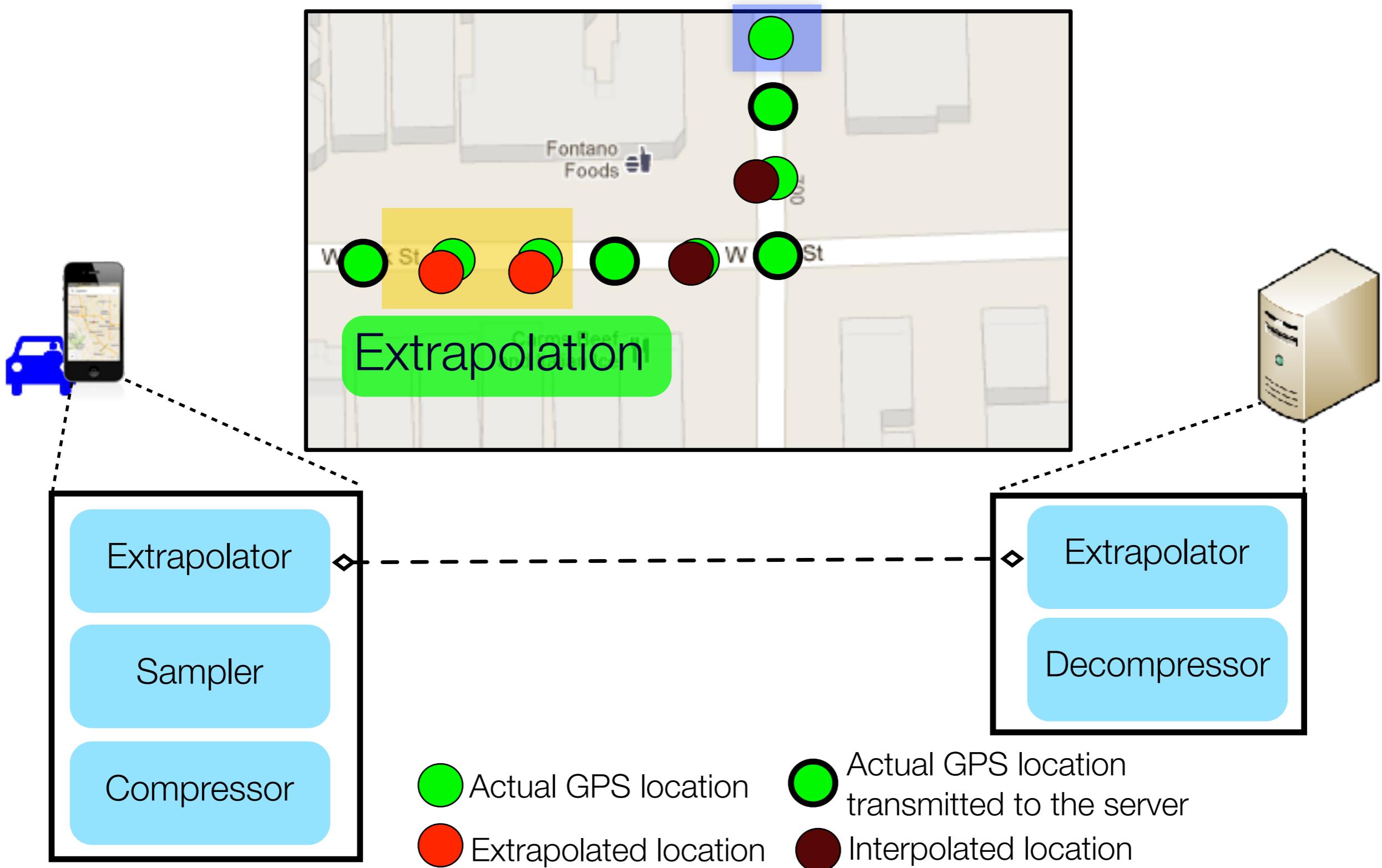
System overview



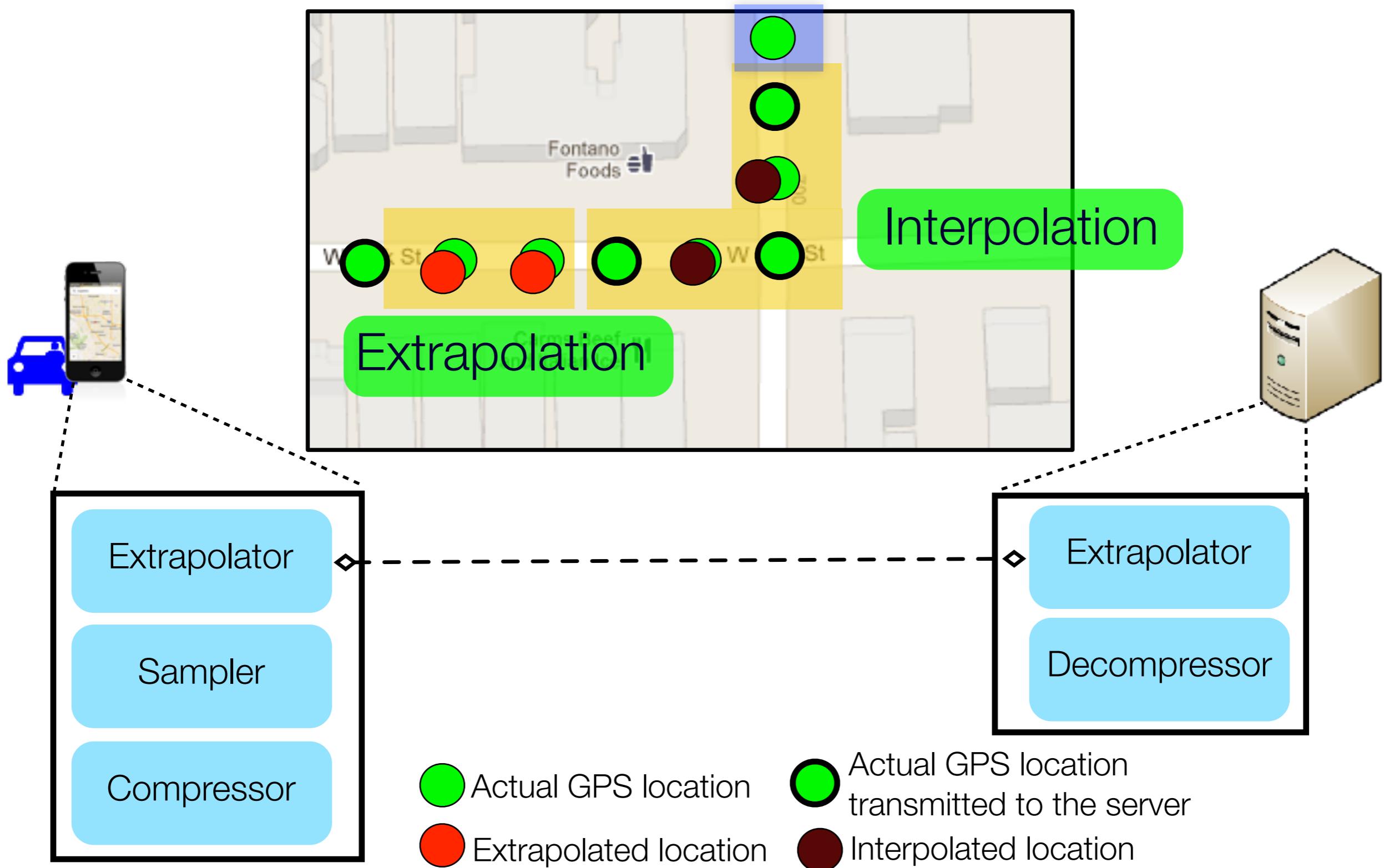
System overview



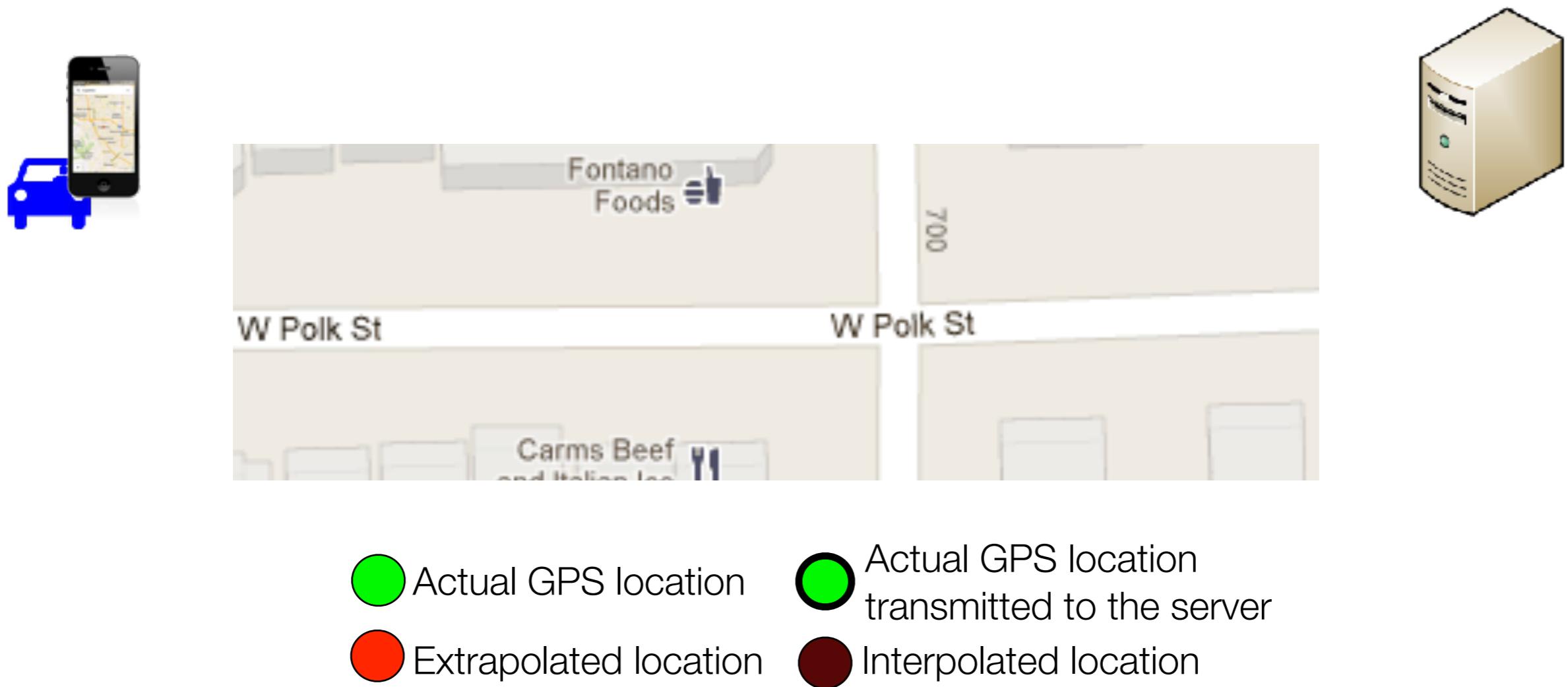
System overview



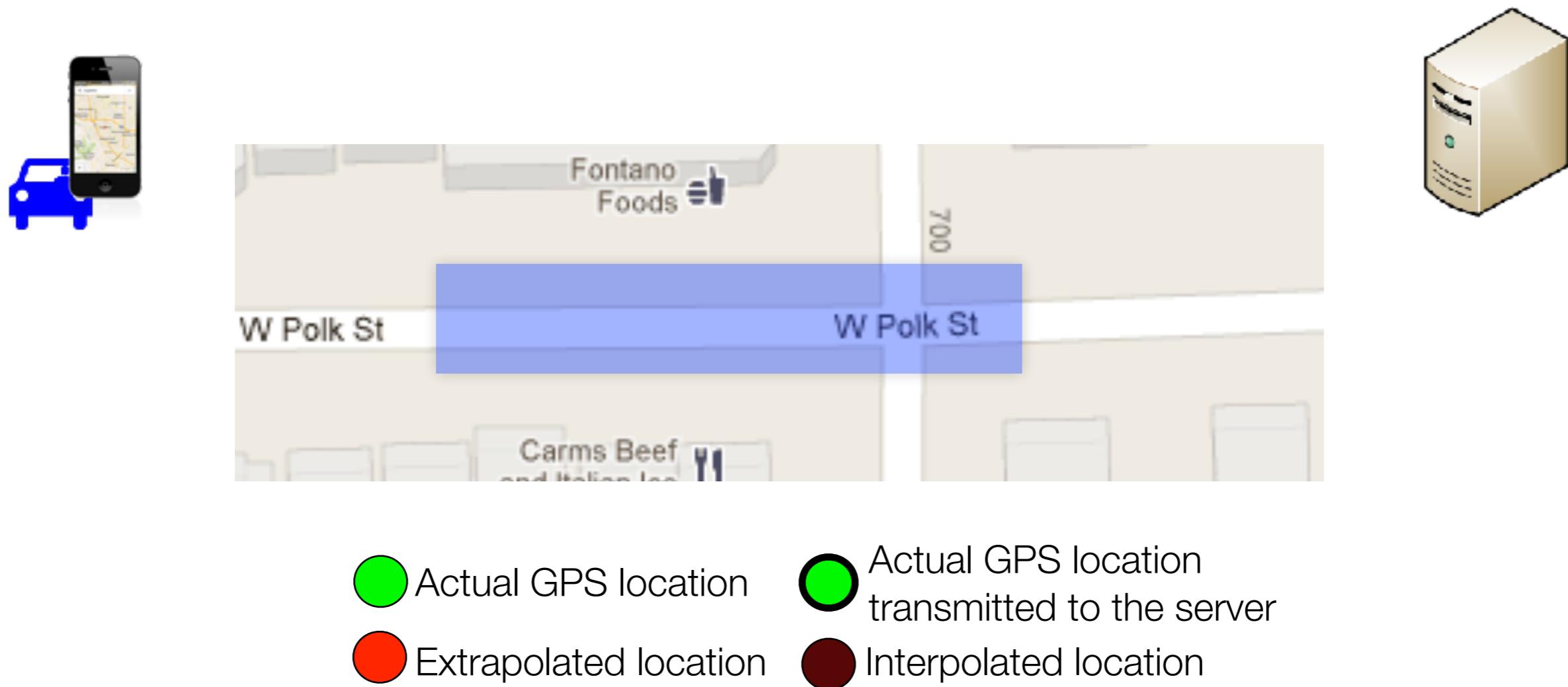
System overview



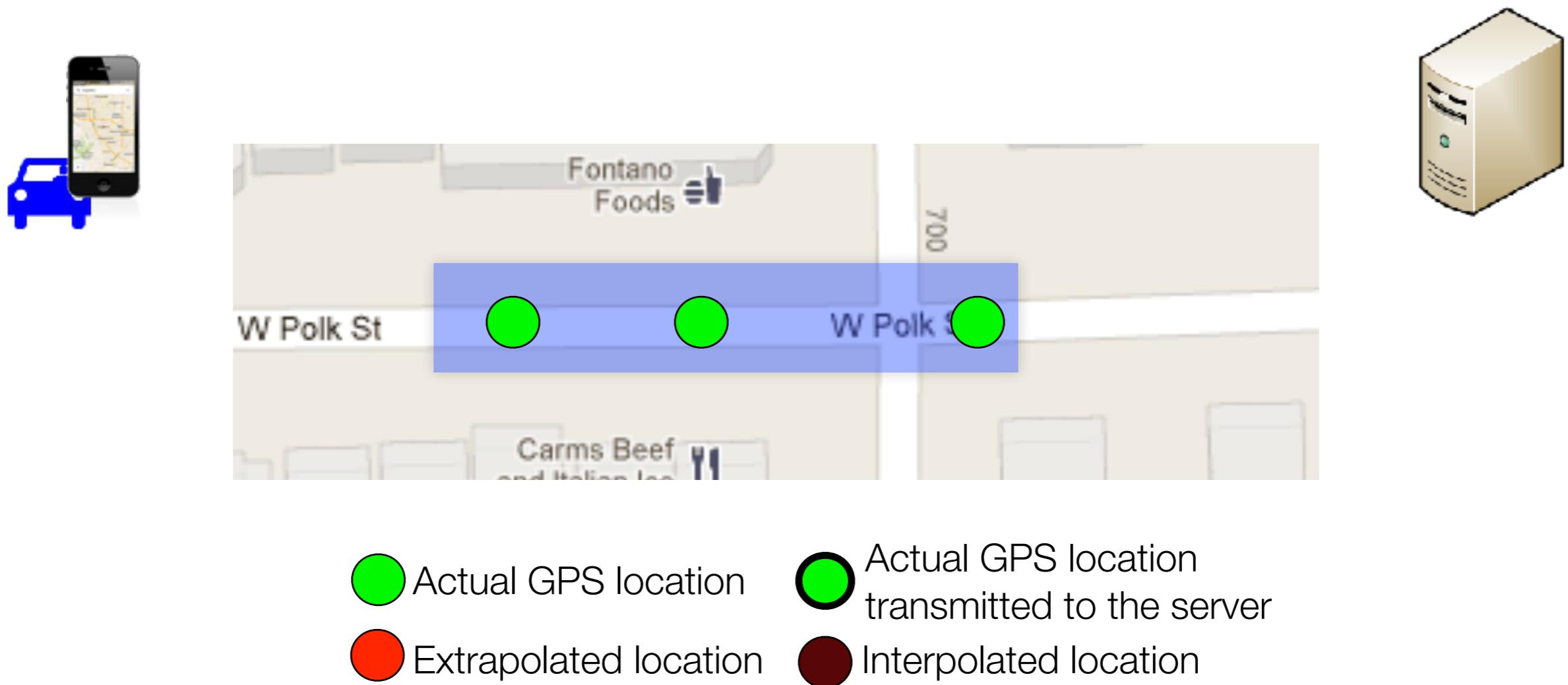
Error-delay sampler



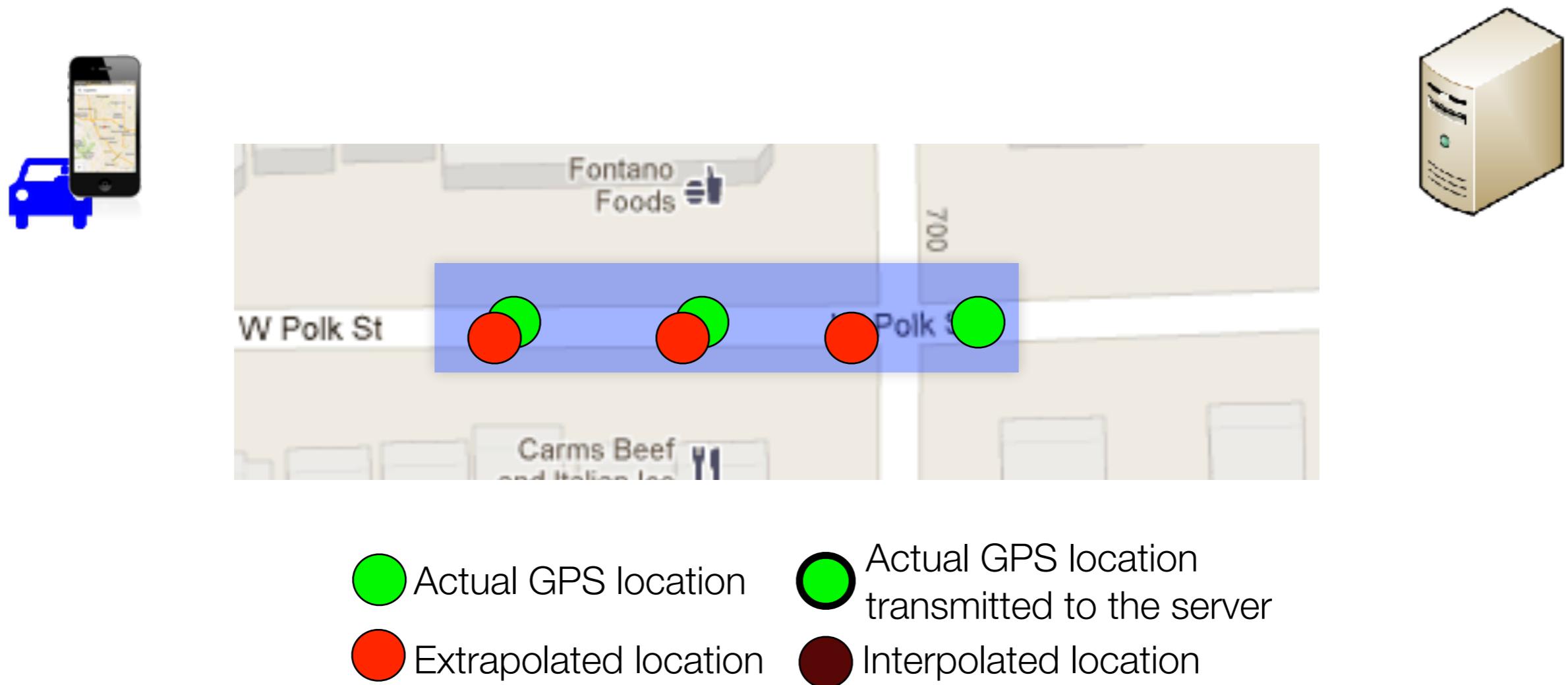
Error-delay sampler



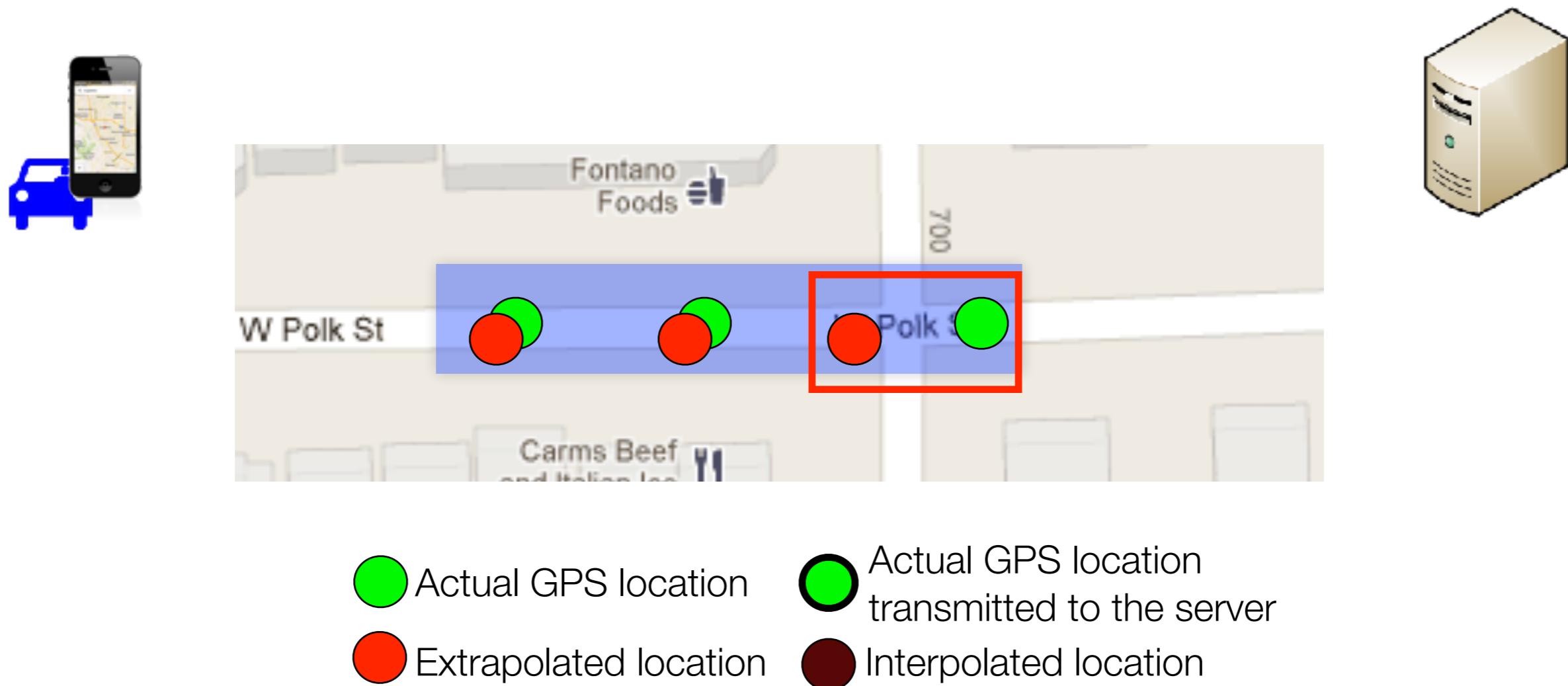
Error-delay sampler



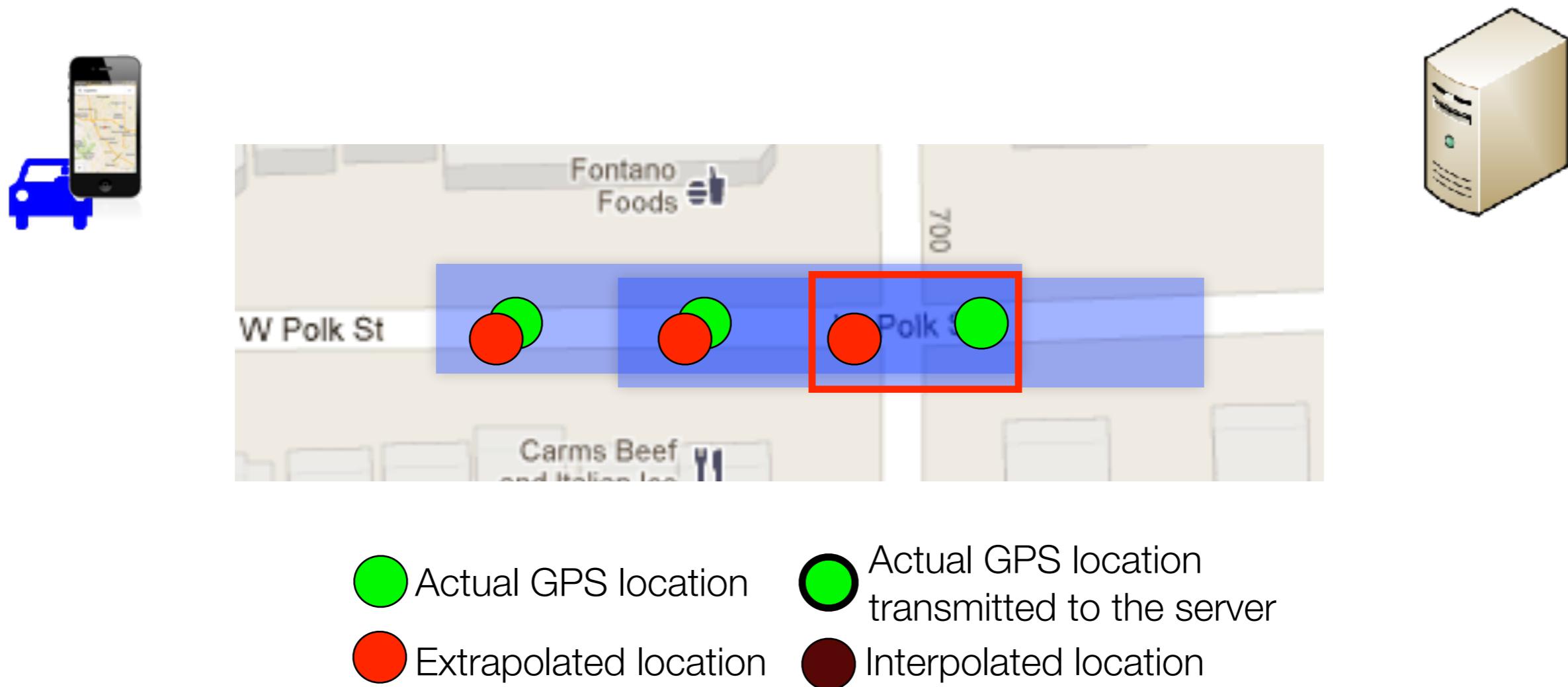
Error-delay sampler



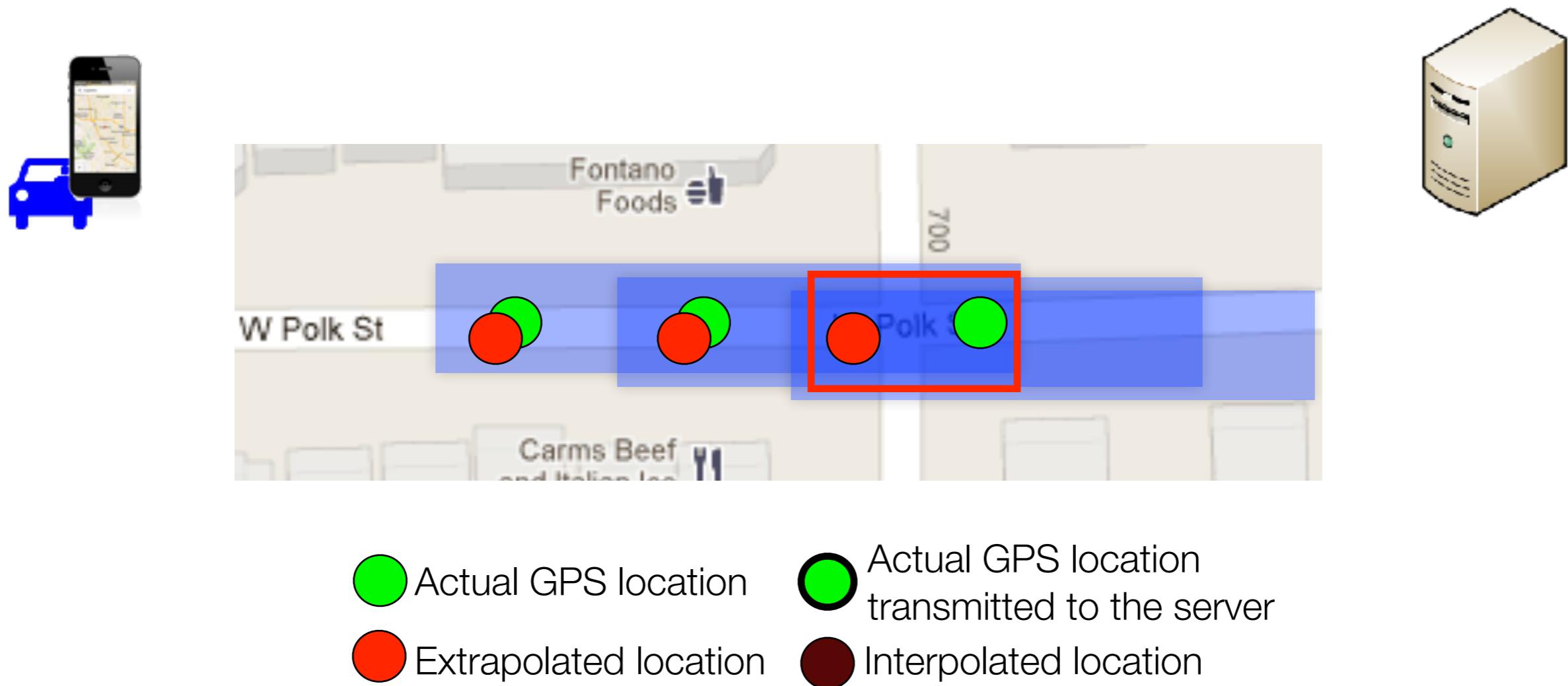
Error-delay sampler



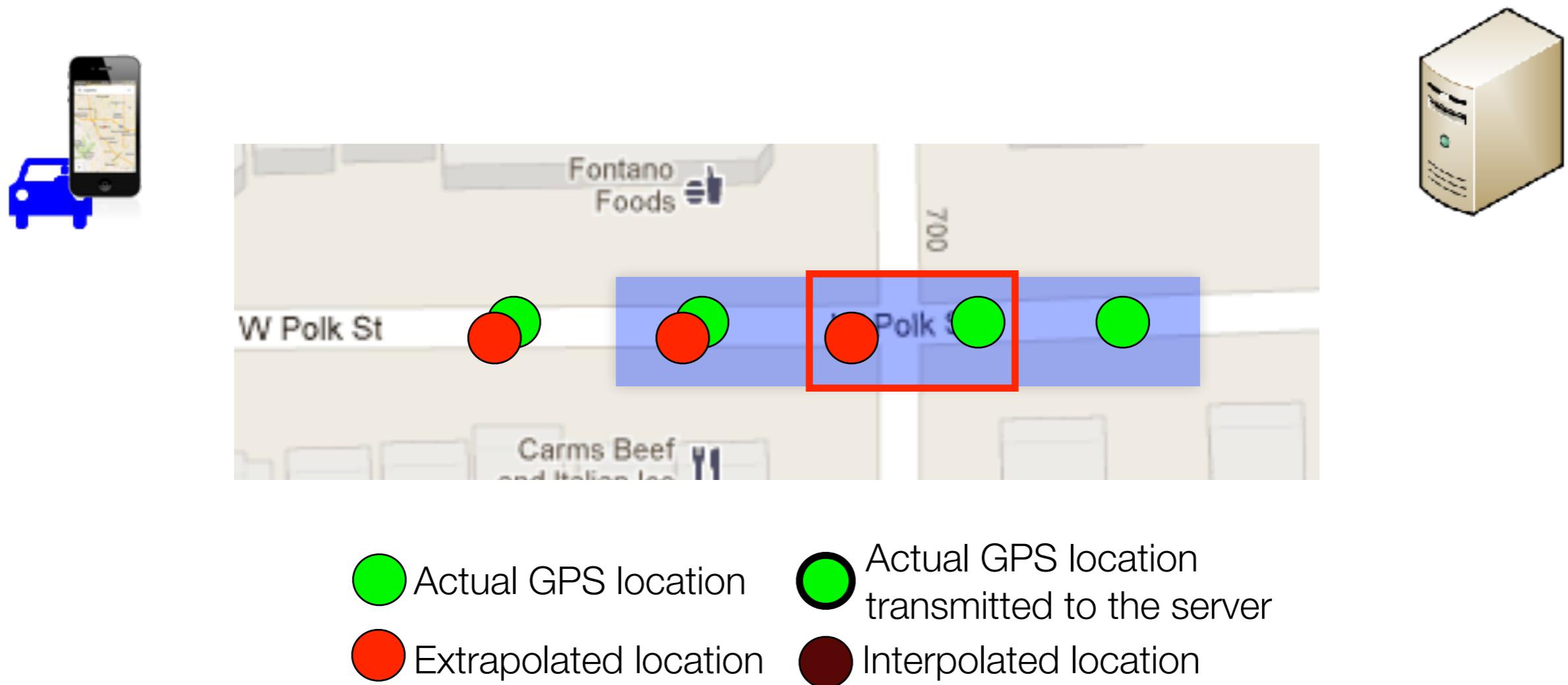
Error-delay sampler



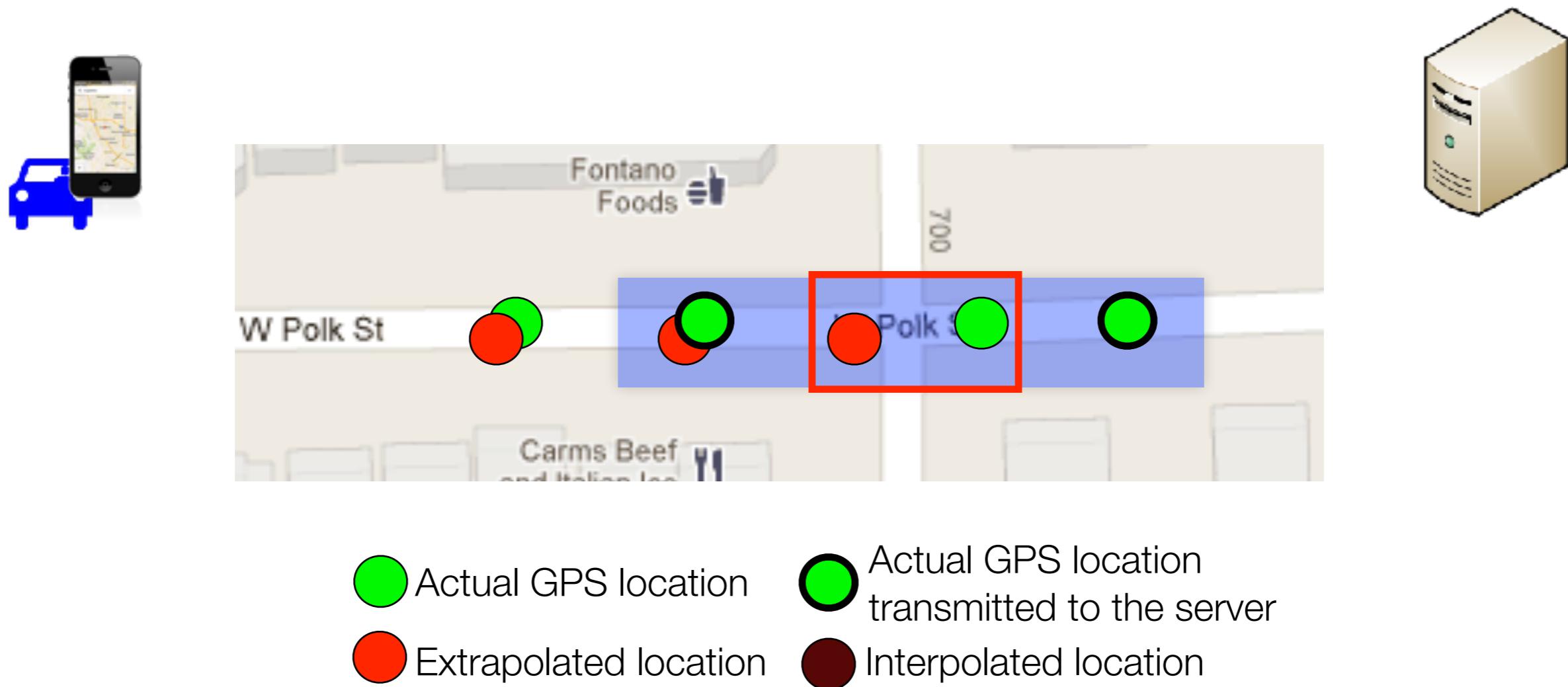
Error-delay sampler



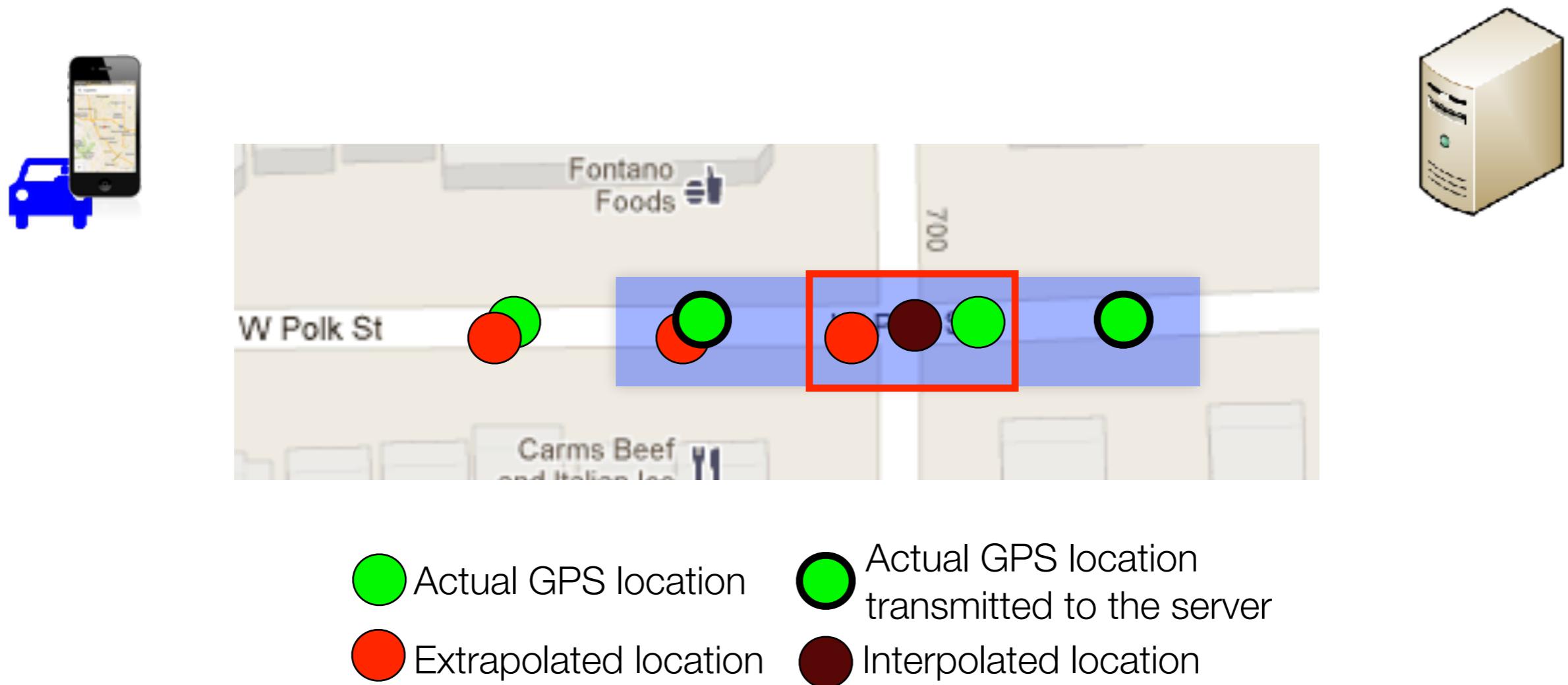
Error-delay sampler



Error-delay sampler



Error-delay sampler



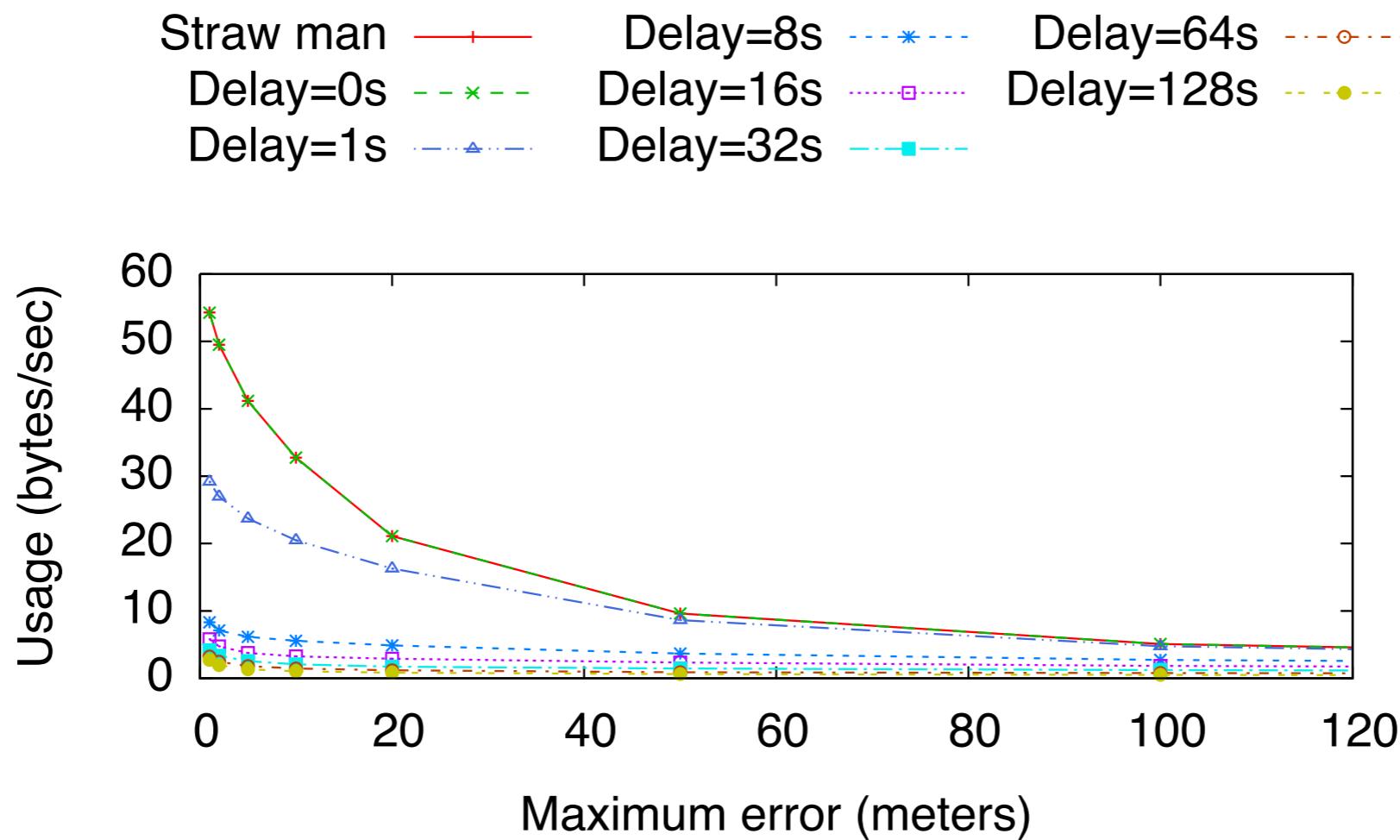
Datasets

OpenStreetMap: 12.4 million

UIC shuttle: 1.9 million

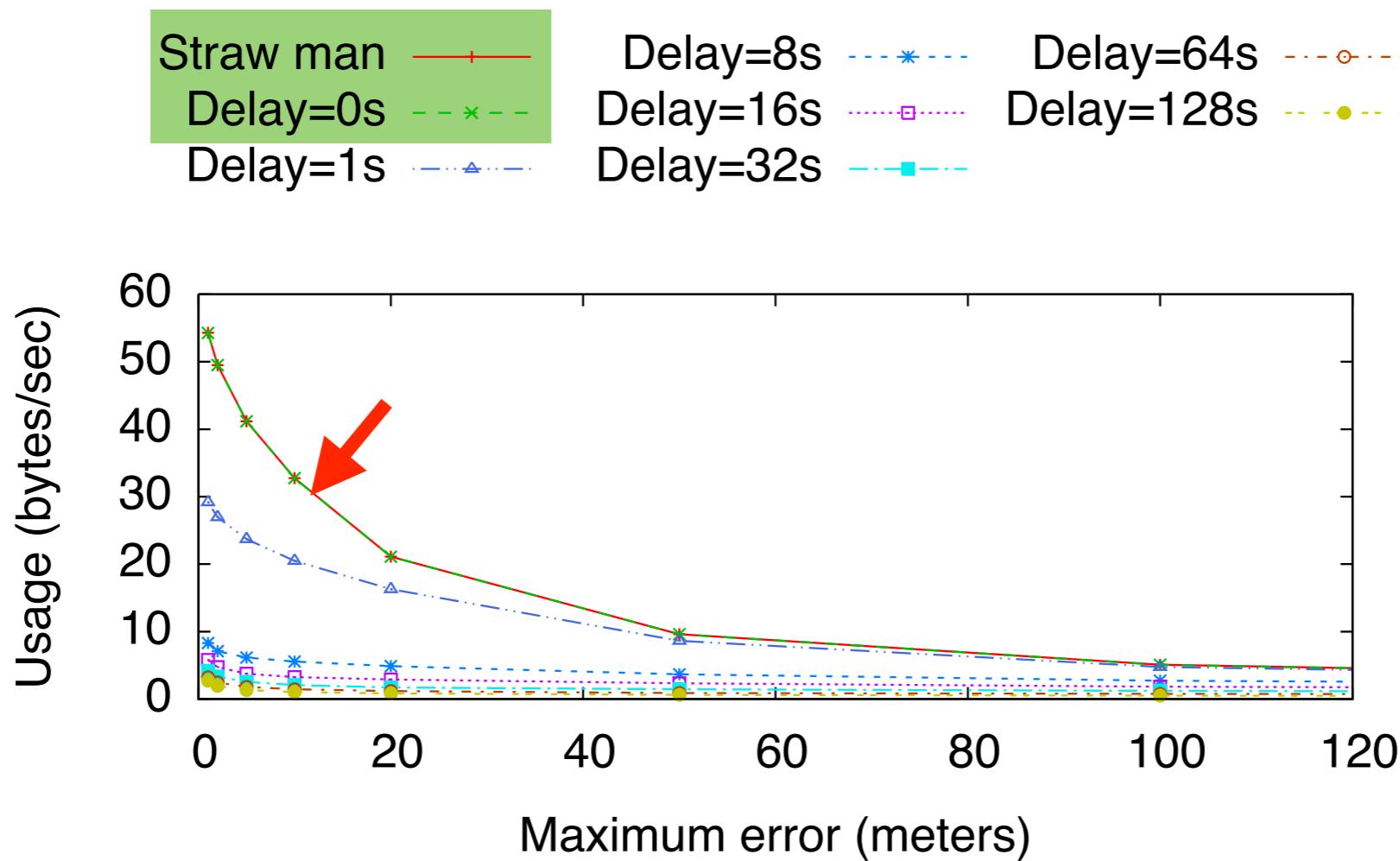
Microsoft: 500 thousands

Error-delay sampler with constant-location extrapolator



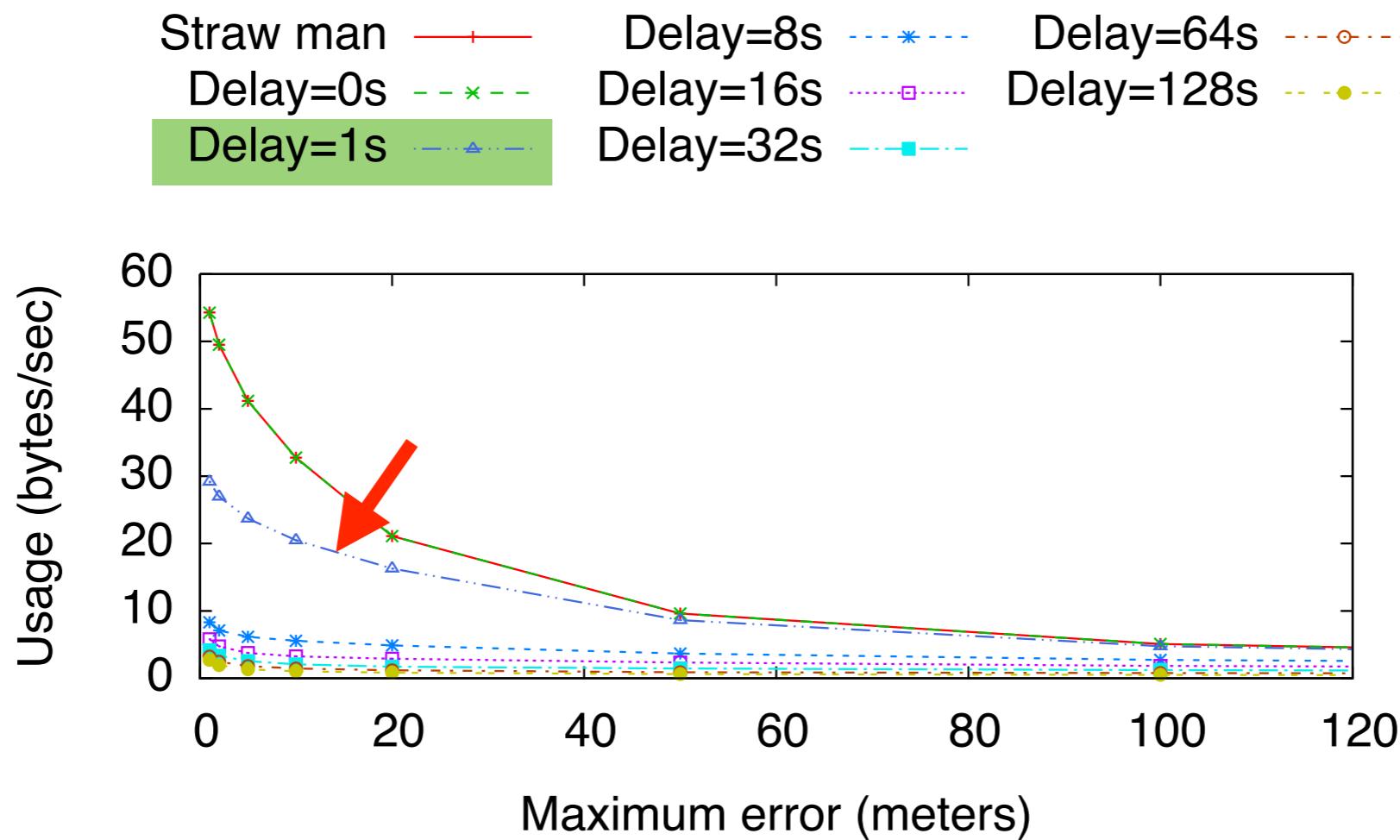
Straw-man: Transmits at every error-bound meter

Error-delay sampler with constant-location extrapolator



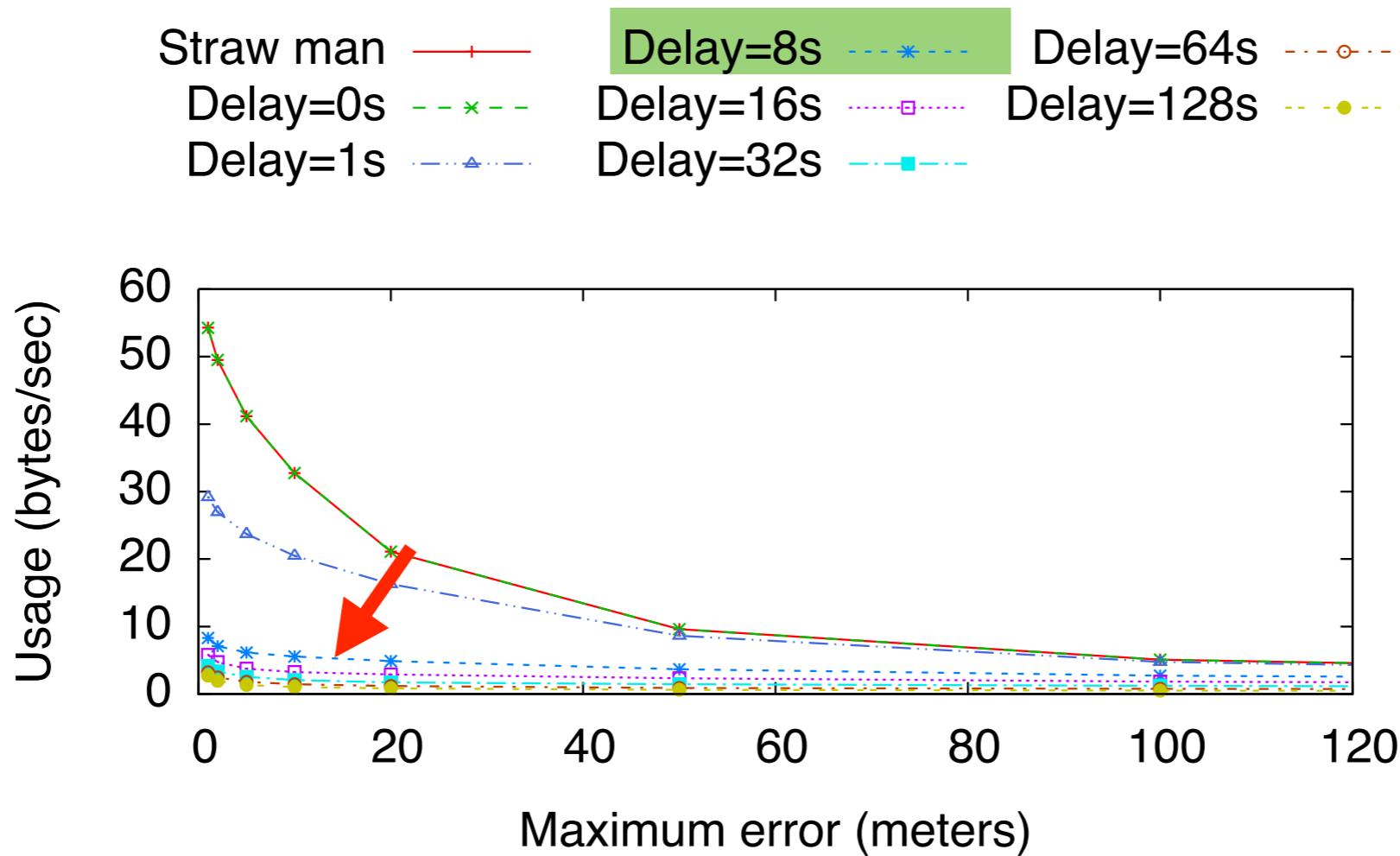
Straw-man: Transmits at every error-bound meter

Error-delay sampler with constant-location extrapolator



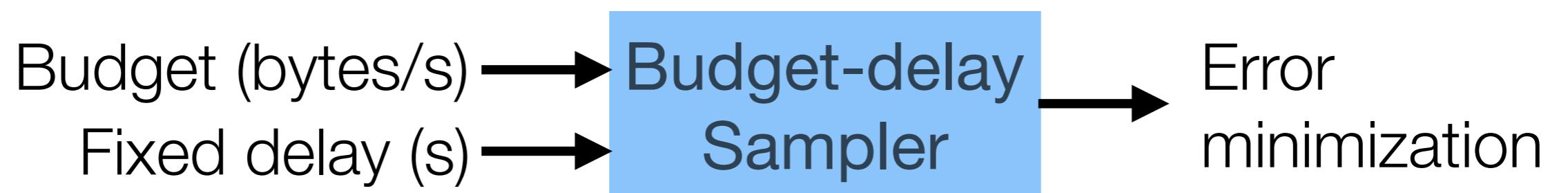
Straw-man: Transmits at every error-bound meter

Error-delay sampler with constant-location extrapolator



Straw-man: Transmits at every error-bound meter

Budget-delay sampler



Budget-delay sampler



Budget-delay sampler



$$\text{extrapolation_error} = \beta * \text{expected_error}$$

Budget-delay sampler



$$\text{extrapolation_error} = \beta * \text{expected_error}$$

long-term
(based on historical statistics)

Budget-delay sampler



$$\text{extrapolation_error} = \beta * \text{expected_error}$$

short-term
(based on current balance)

long-term
(based on historical statistics)

Budget-delay sampler



$$\text{extrapolation_error} = \beta * \text{expected_error}$$

short-term
(based on current balance)

long-term
(based on historical statistics)

balance accumulation: Budget bytes every sec

Budget-delay sampler



$$\text{extrapolation_error} = \beta * \text{expected_error}$$

short-term
(based on current balance)

long-term
(based on historical statistics)

balance accumulation: Budget bytes every sec

balance expenditure: cost of transmission

Budget-delay sampler



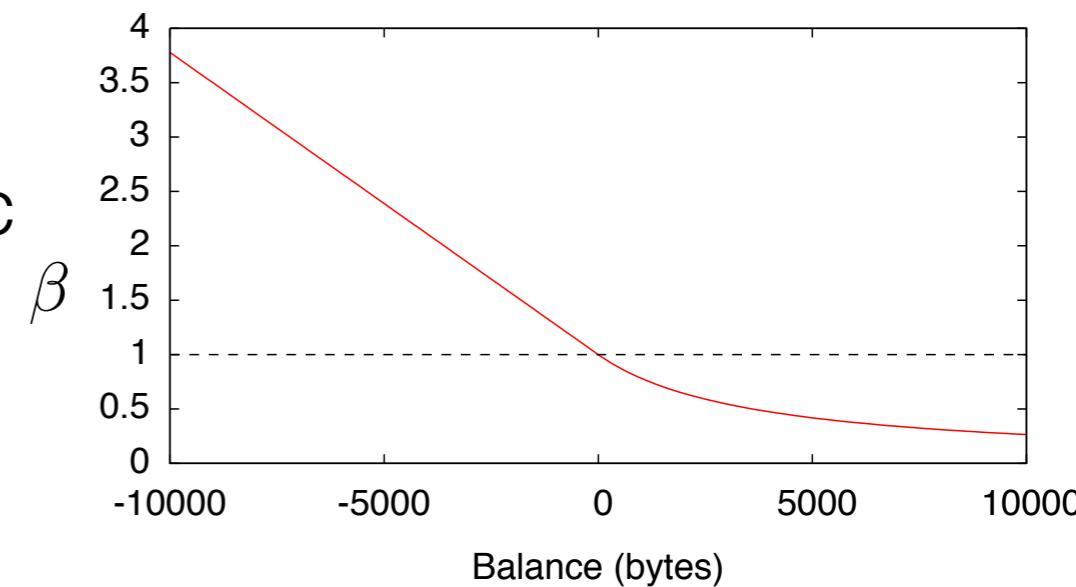
$$\text{extrapolation_error} = \beta * \text{expected_error}$$

short-term
(based on current balance)

long-term
(based on historical statistics)

balance accumulation: Budget bytes every sec

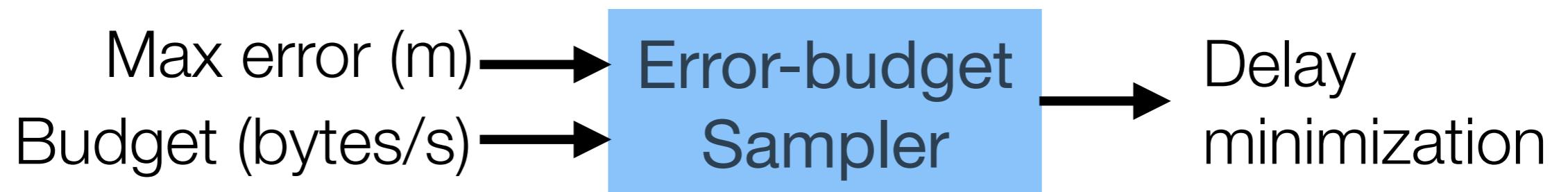
balance expenditure: cost of transmission



Error-budget sampler

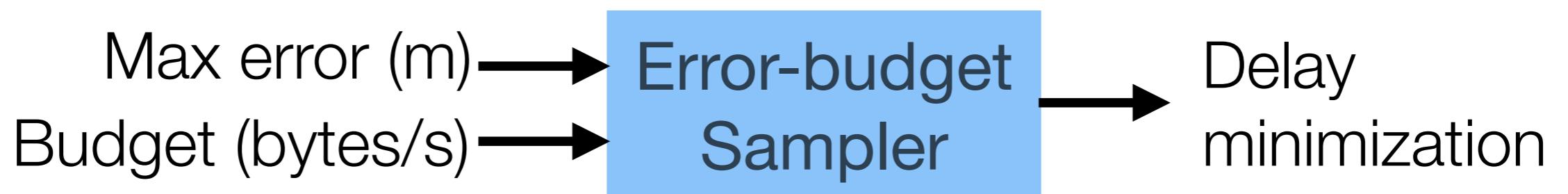


Error-budget sampler



Mean budget (bytes/sec): long-term goal
Max error bound (meters): every step

Error-budget sampler



Mean budget (bytes/sec): long-term goal
Max error bound (meters): every step

Combination of budget-delay and
error-delay samplers

End-to-end Results

Error-delay sampler

With unified extrapolator

Data usage reduction

10m error bound, 0s delay: **77%**

10m error bound, 8s delay: **88%**

10m error bound, 64s delay: **96%**

Budget-delay sampler

With unified extrapolator

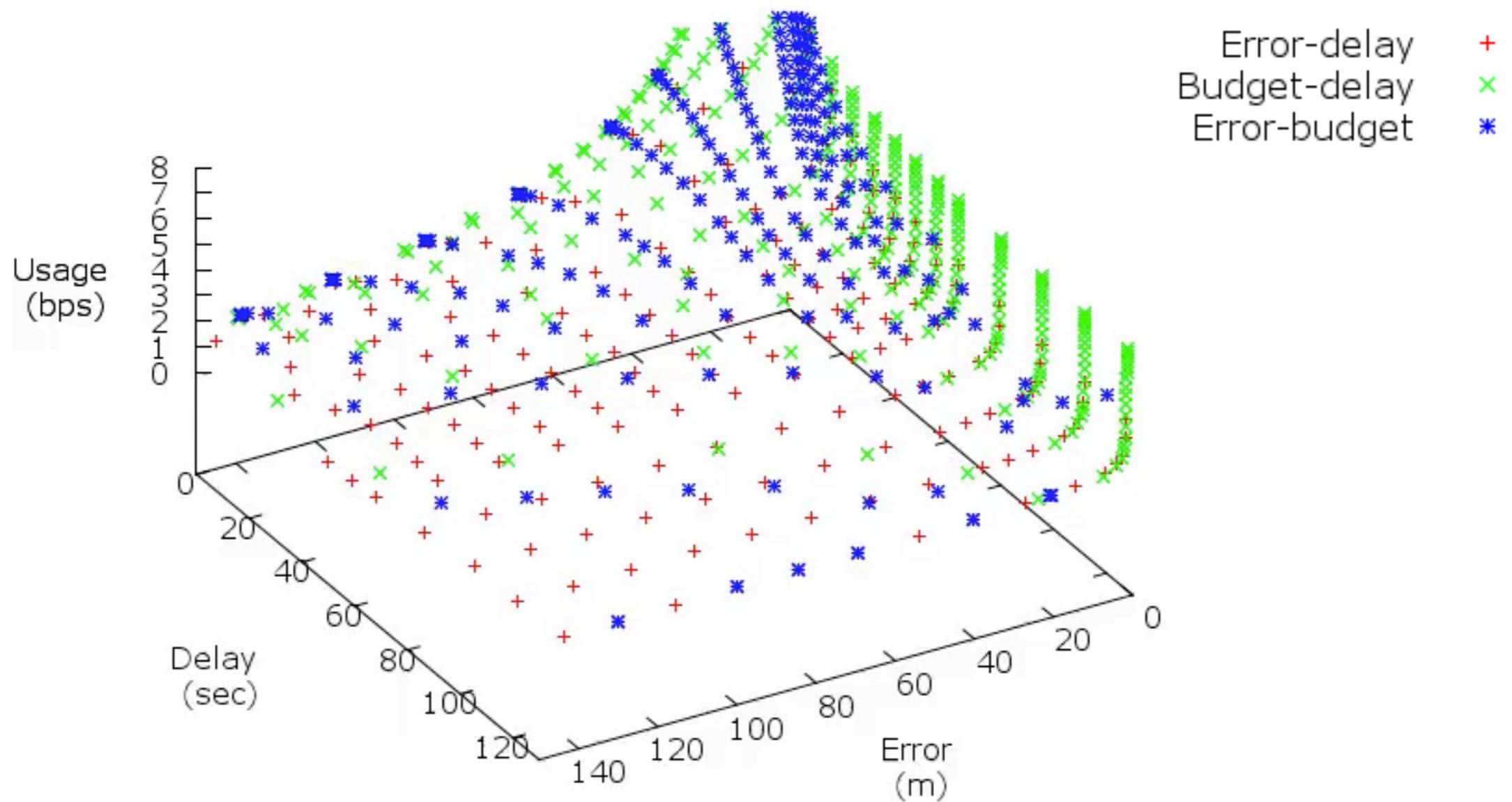
Error reduction

2 bytes/sec budget, 0s delay: **81%**

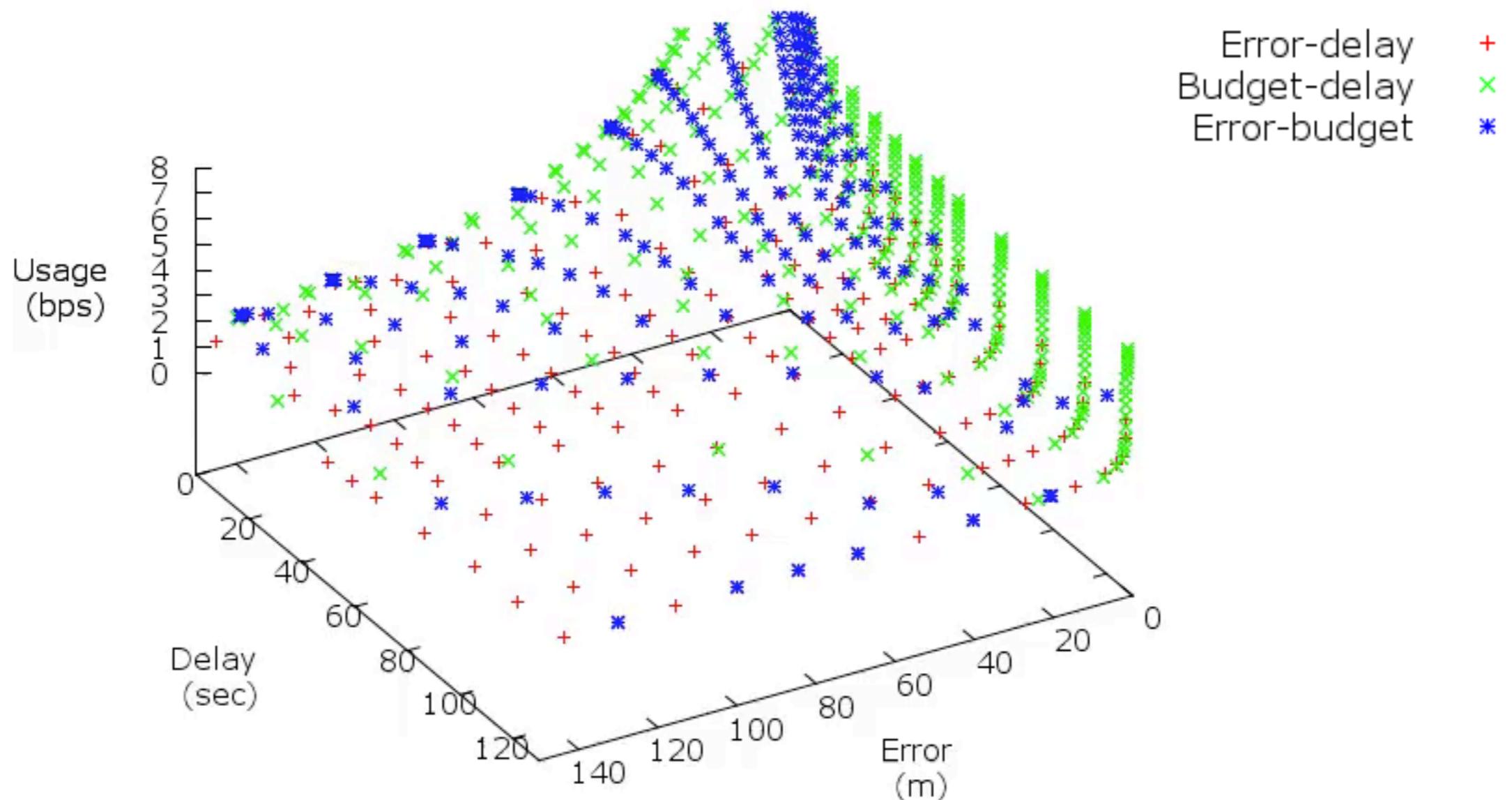
2 bytes/sec budget, 8s delay: **91%**

2 bytes/sec budget, 64s delay: **99%**

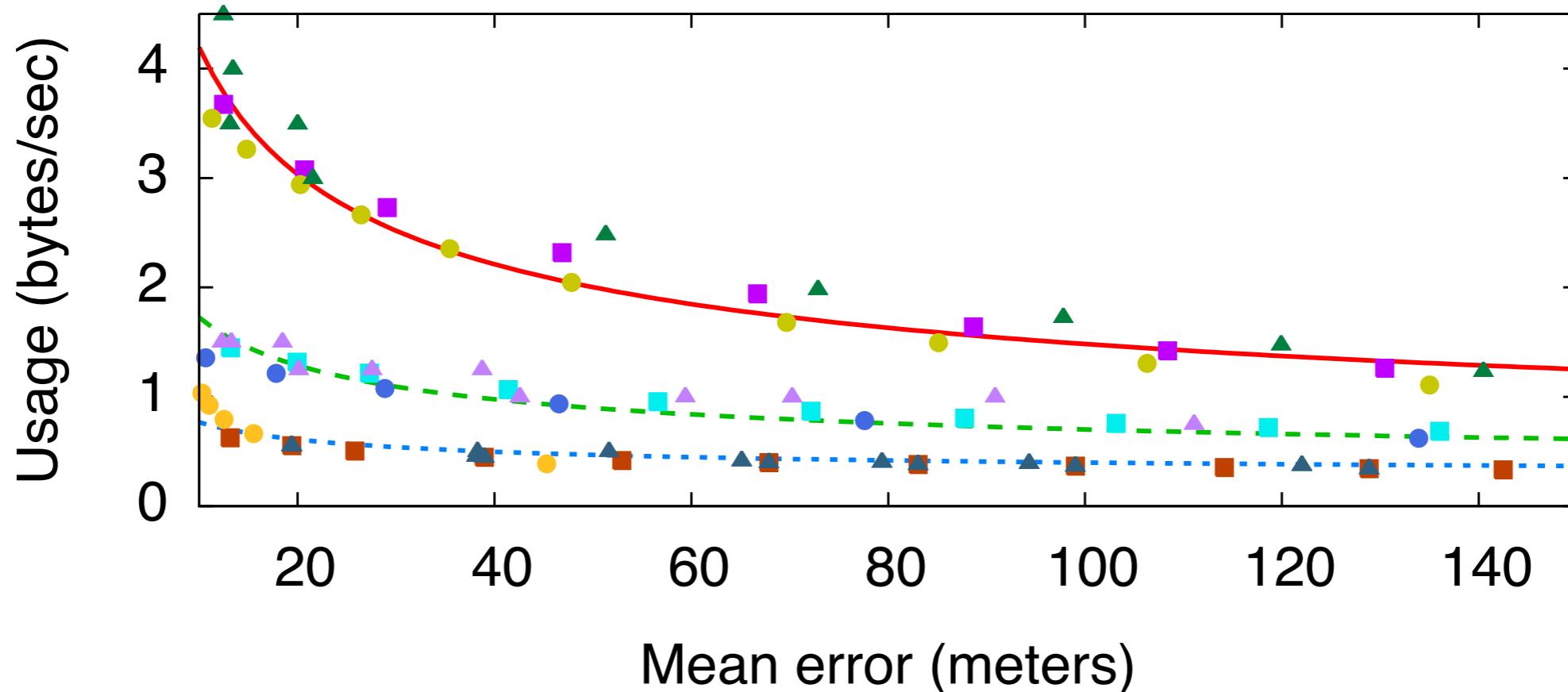
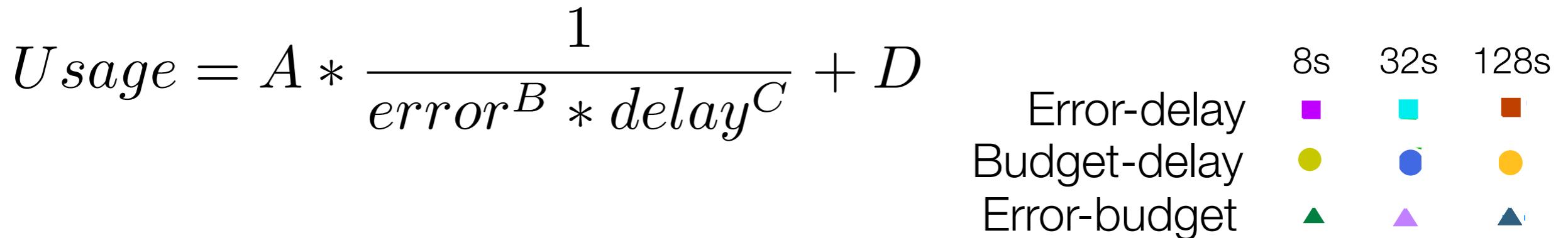
Unification of Samplers



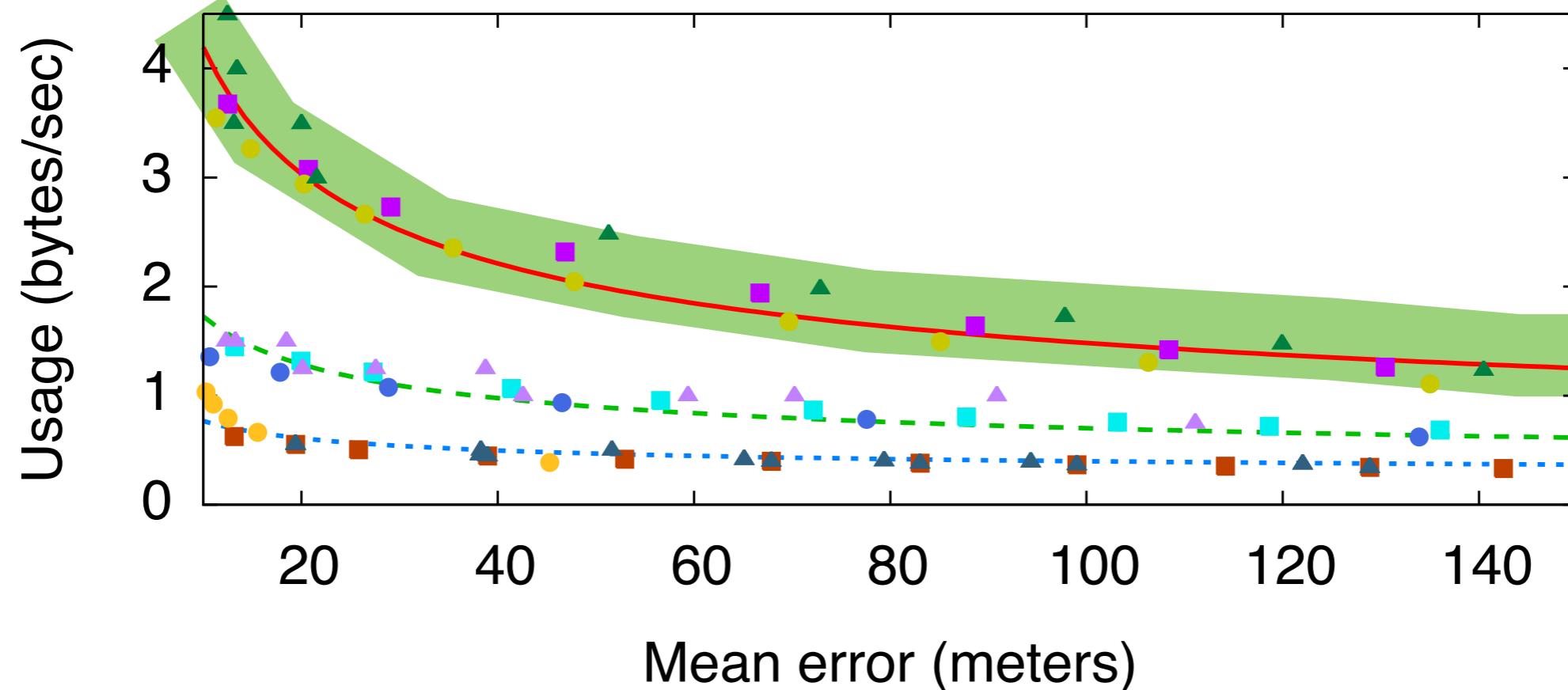
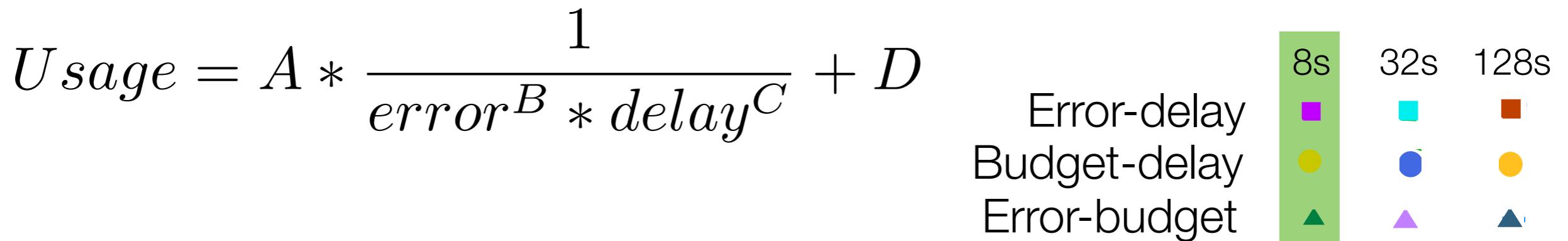
Unification of Samplers



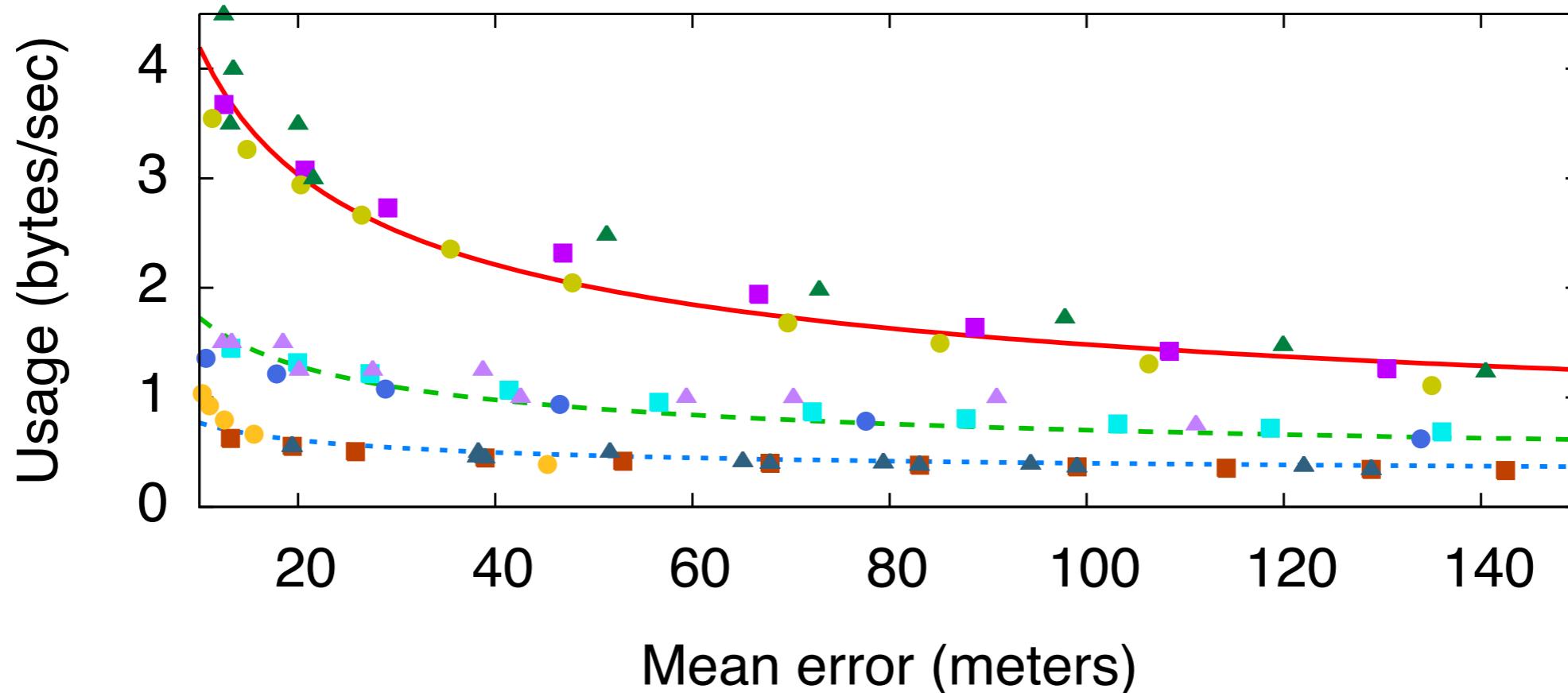
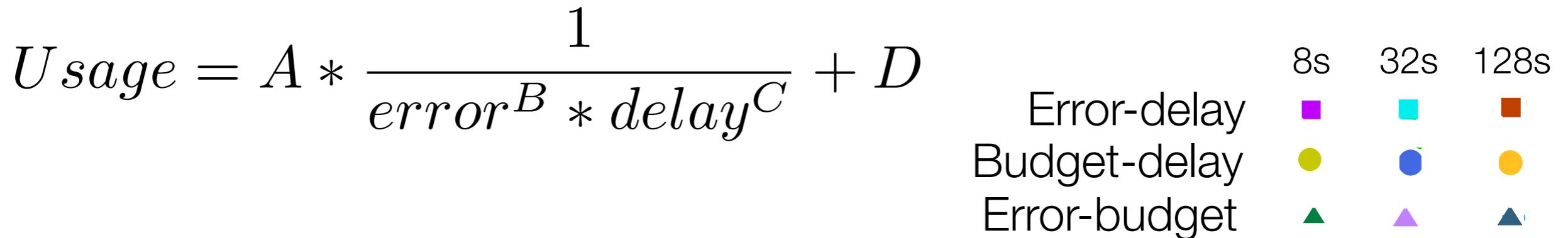
Unification of Samplers



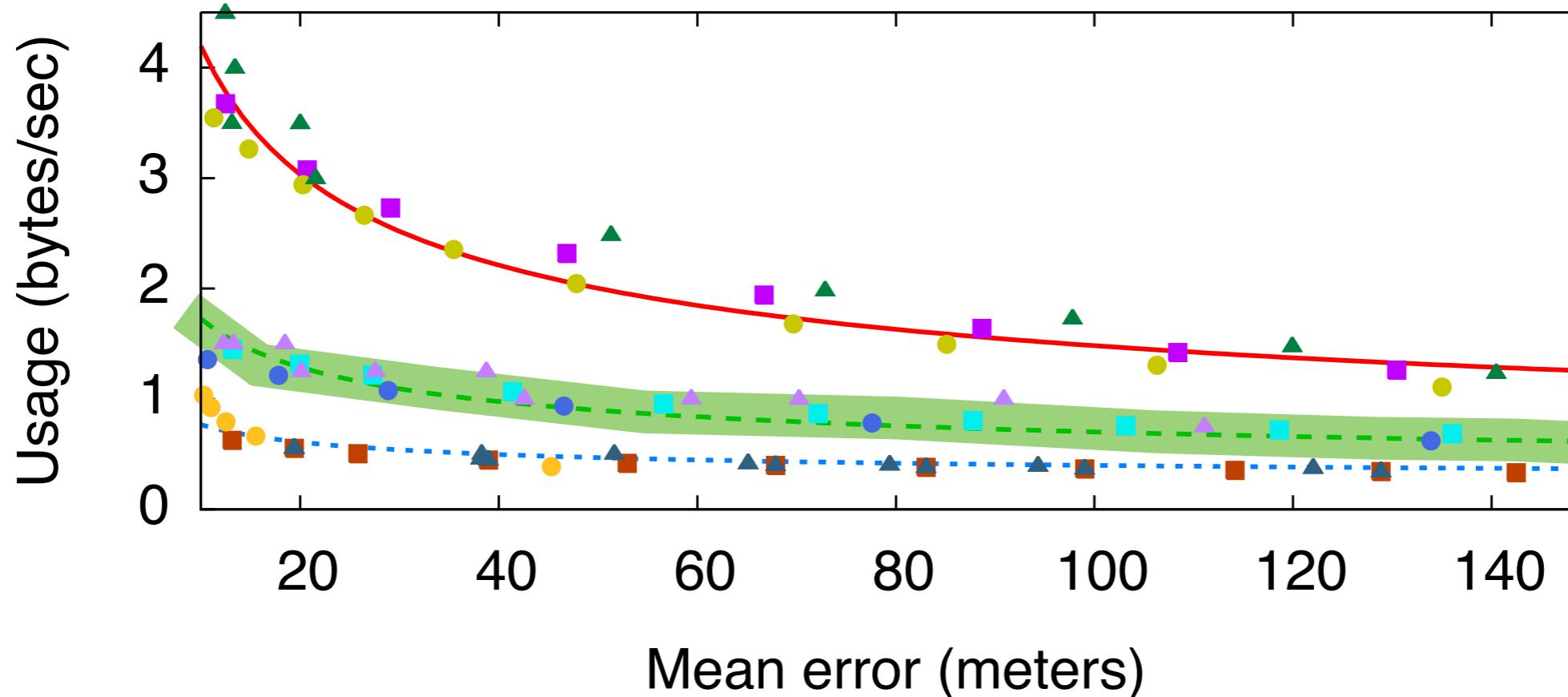
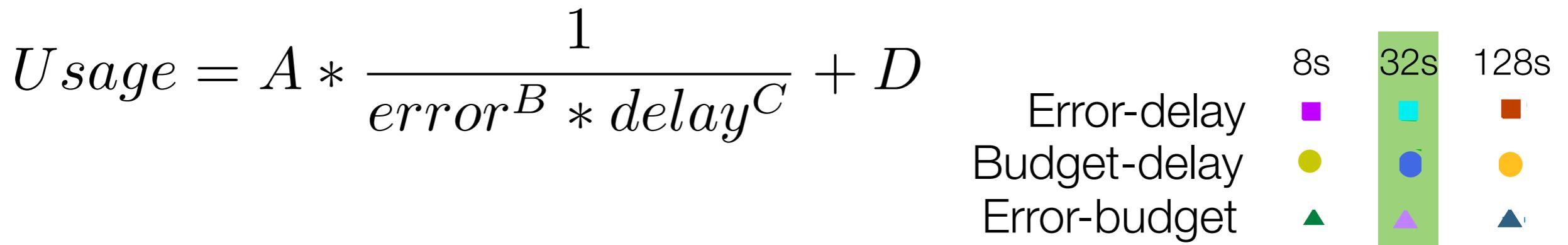
Unification of Samplers



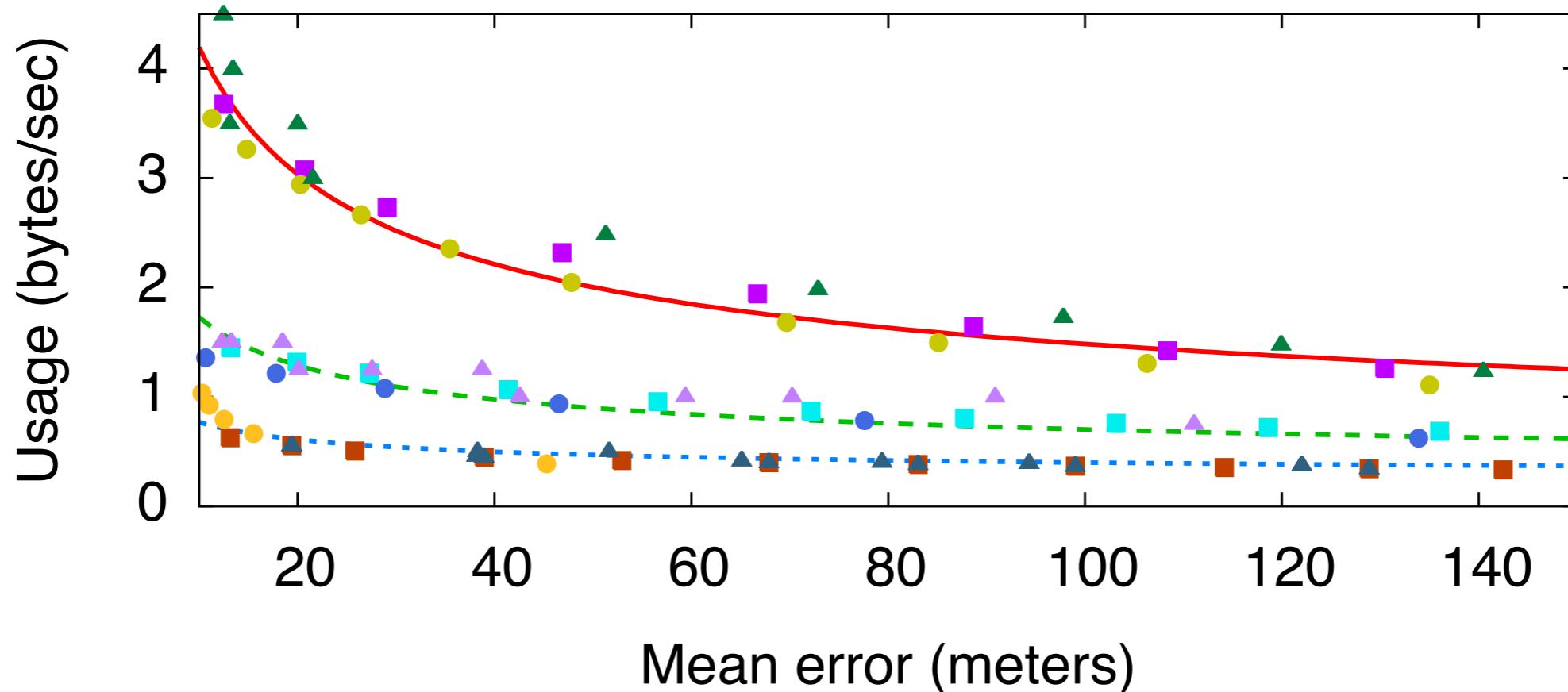
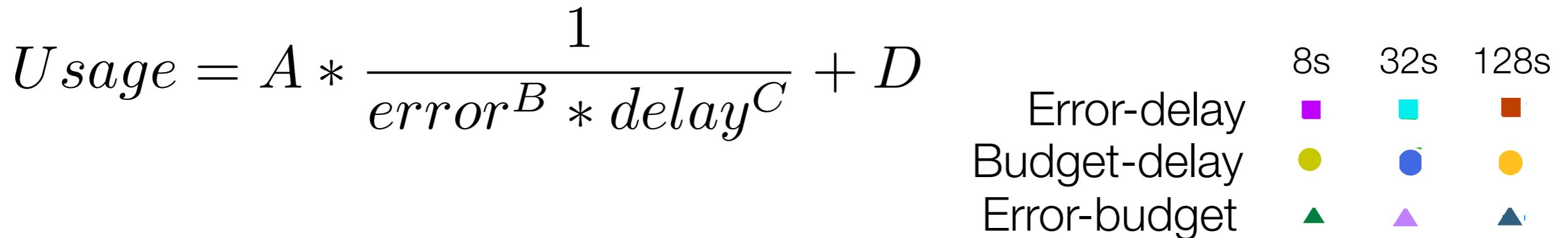
Unification of Samplers



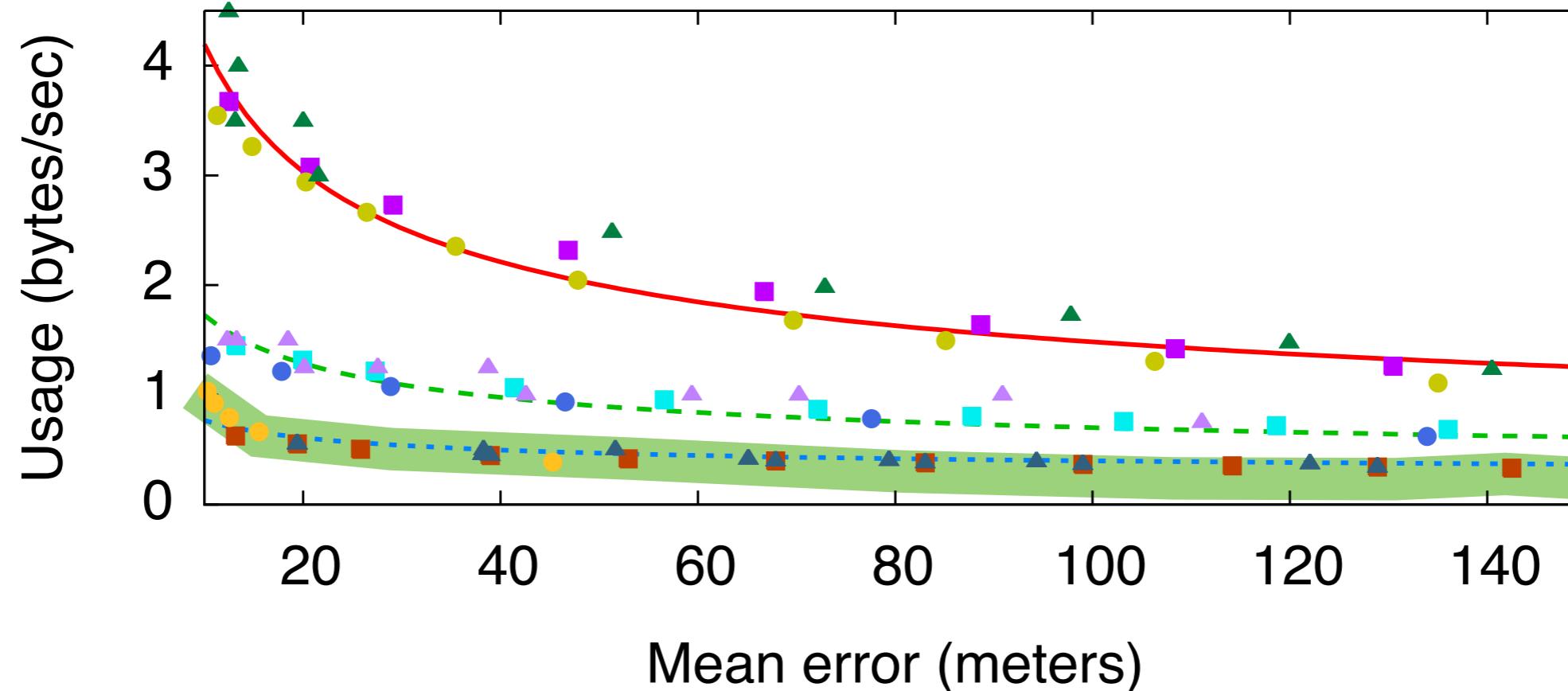
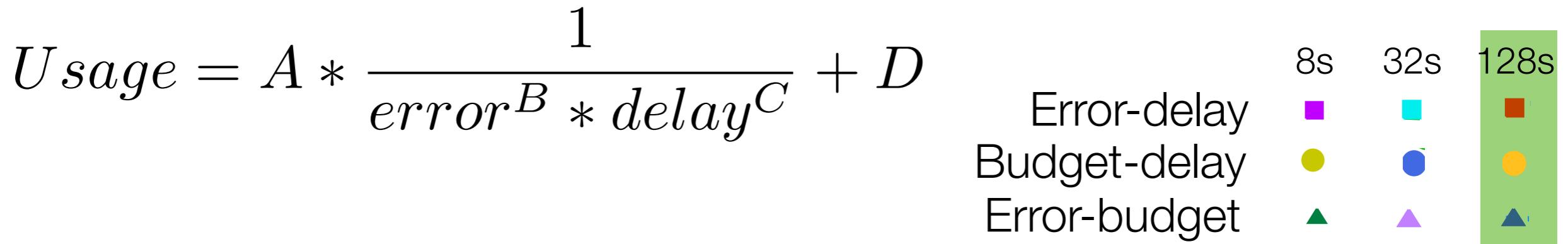
Unification of Samplers



Unification of Samplers



Unification of Samplers



Thank you!

Questions?