Mobile Macroscopes: The CarTel Project

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What is CarTel?

- Distributed software system that makes it easy to:
  - collect,
  - process,
  - deliver,
  - visualize & analyze

  data from mobile sensors (cars, phones, etc)

- Goals + Challenges:
  - Heterogeneous data
  - Lots of data (“media-rich” sensors)
  - Intermittent network connectivity + mobility
  - Programmability

Portal

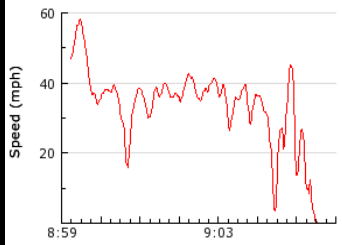
Trace Detail: Fri,03/10/06 - 8:59 PM

Duration:	00:06:17
Distance:	3.52 miles
Vehicle:	[redacted]

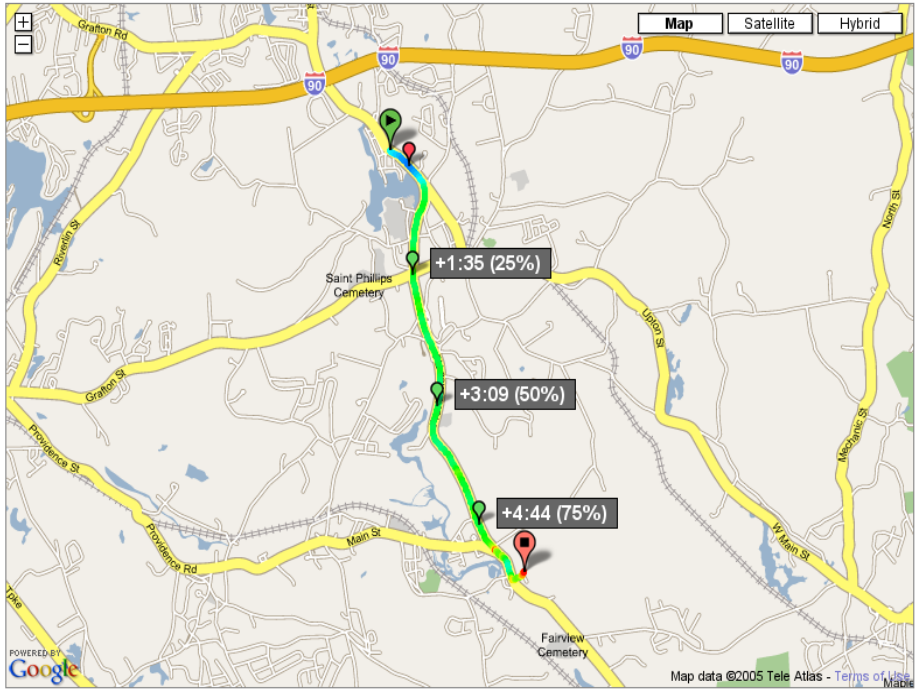
Sensor Data Overlays:

speed

Avg. Speed:	33.62 mph
Max. Speed:	58.06 mph



* To zoom in on the map, use the +/- buttons, or press **z** to define the zoom region and **x** to zoom out.



Embedded Linux: Pentium-class, 128MB Ram, 1GB storage

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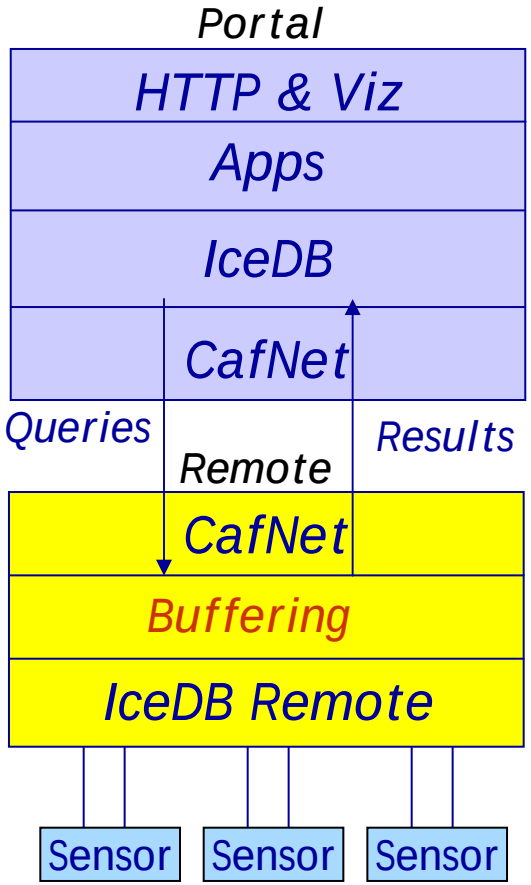
CarTel Software Components

- *CarTel Portal*: Centralized, visual user interface
- *IceDB*: Intermittently connected DB
  - Centralized declarative queries
  - Executed in distributed fashion by mobile nodes
  - *Delay-tolerant continuous query processing*

```
SELECT oil_temp
FROM obd
BUFFER IN engine
PRIORITY 1
```

- *CafNet*: CarTel's network stack
  - H
    c



This talk: study properties of network, using CarTel itself to do this (MobiCom '06)

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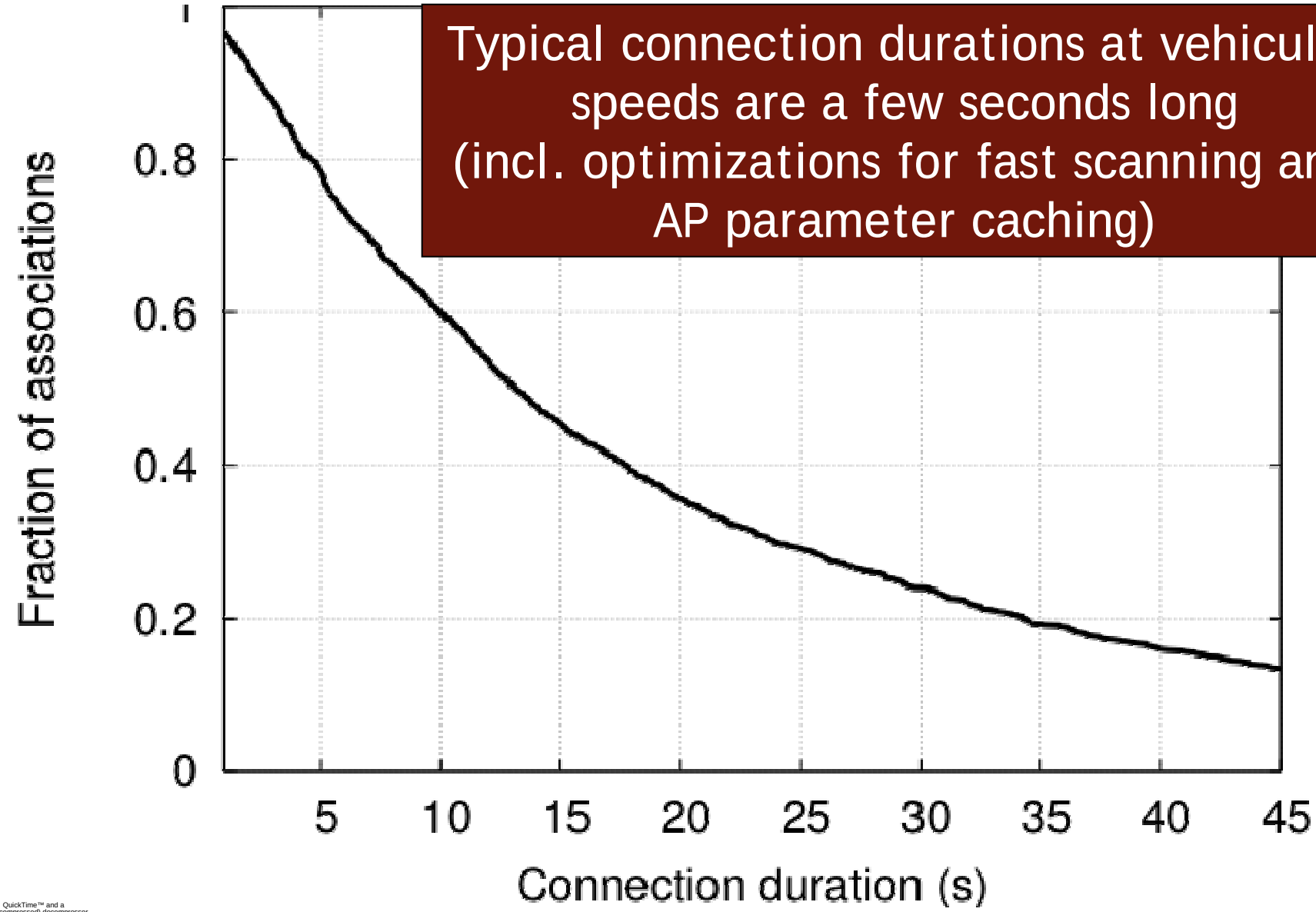
Experimental Setup

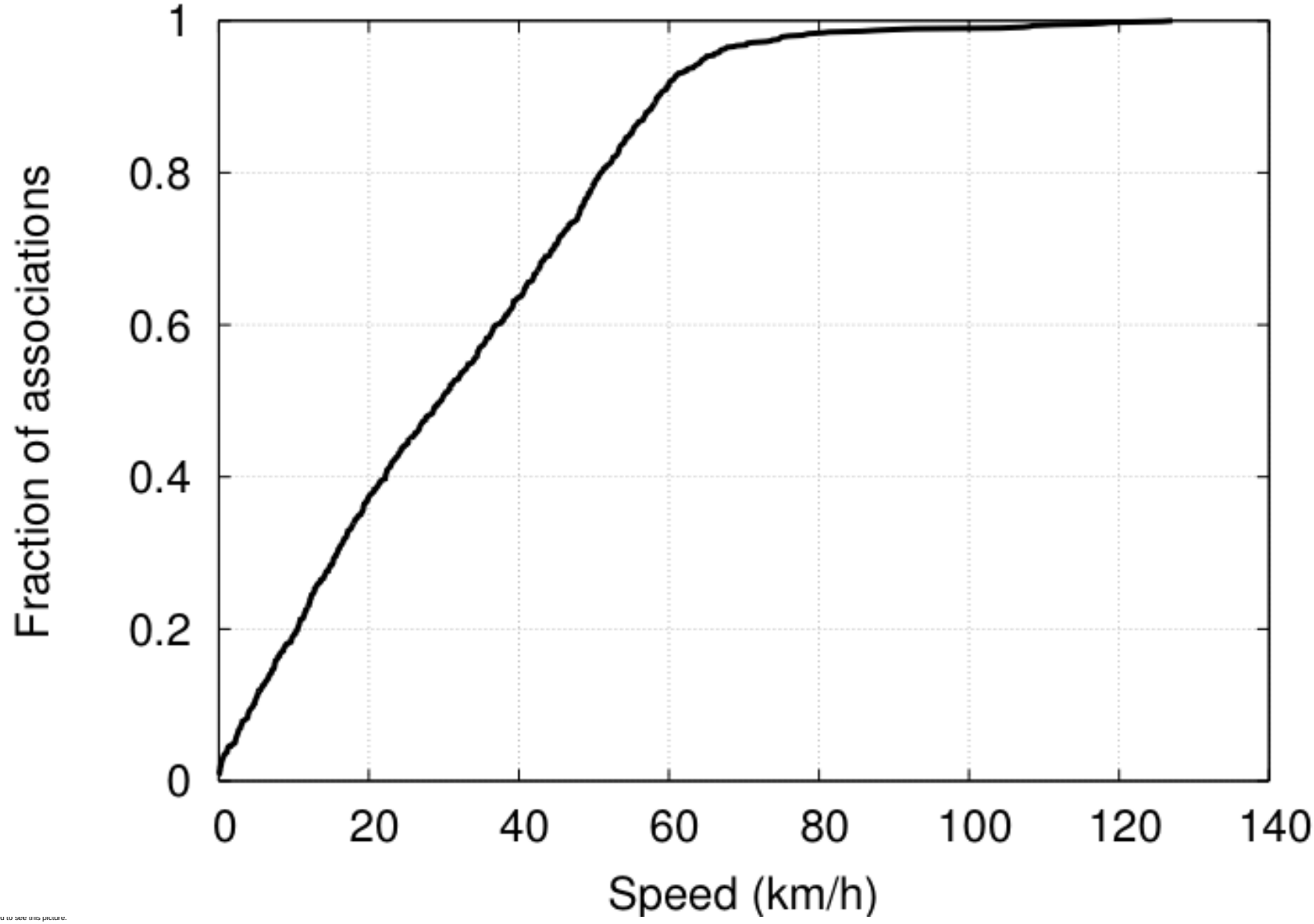
- 6 cars equipped with CarTel box and software
  - Driving normally in parts of the Boston area
  - ~32K access points (APs) mapped in all on a relatively small number of distinct routes
  - ~300 drive hours
- Fast scanning of WiFi access points, caching of AP parameters to speed up connection establishment
- Careful (small and unobtrusive) TCP data transfers to measure throughput, latency, loss rates
- Track performance statistics: connection durations, throughput distributions, etc.

Connection Duration Distribution



Typical connection durations at vehicular speeds are a few seconds long (incl. optimizations for fast scanning and AP parameter caching)

Impact of Car's Speed



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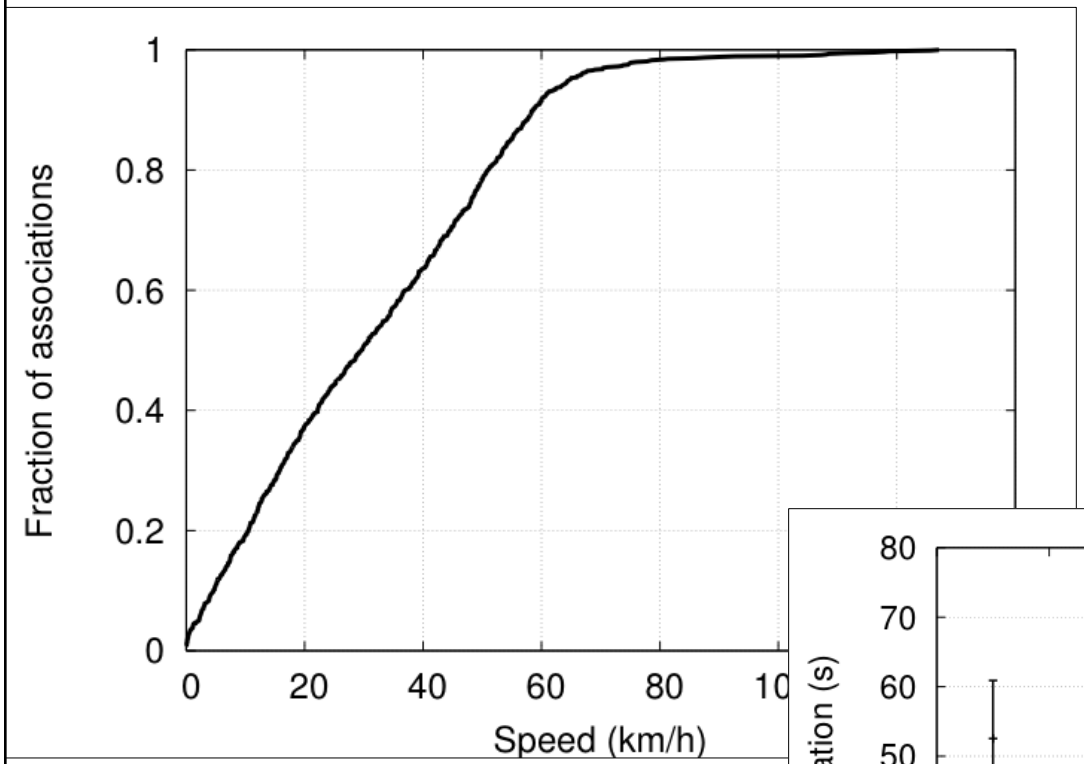
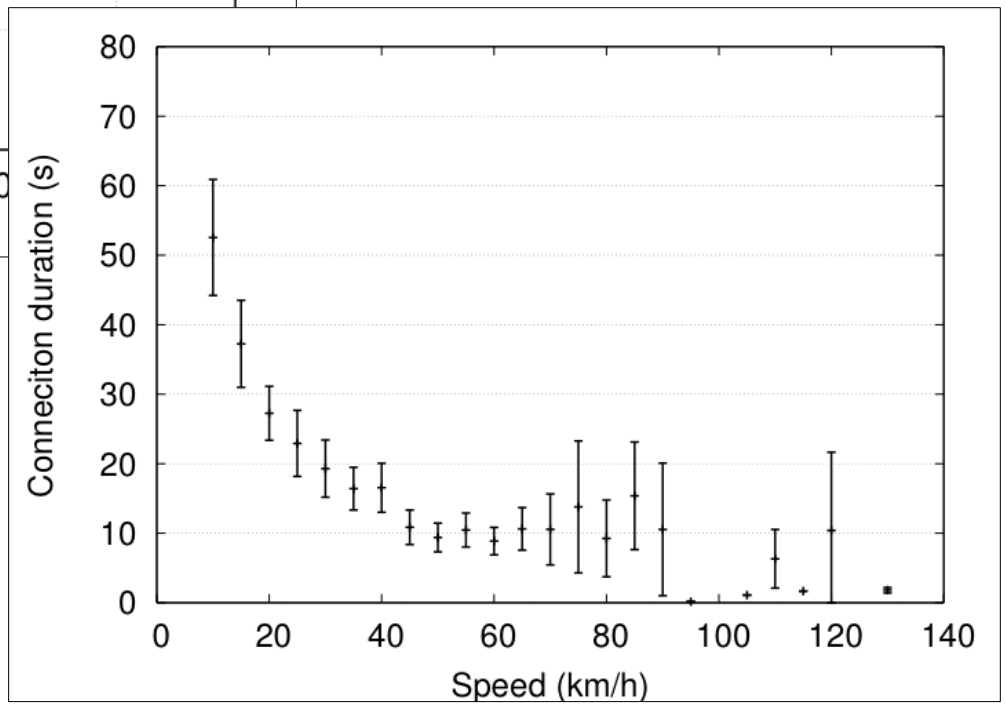
Impact of Car's Speed



Connections establish at range of speeds

Very little data at higher speeds (system isn't optimized for subsecond connections yet)



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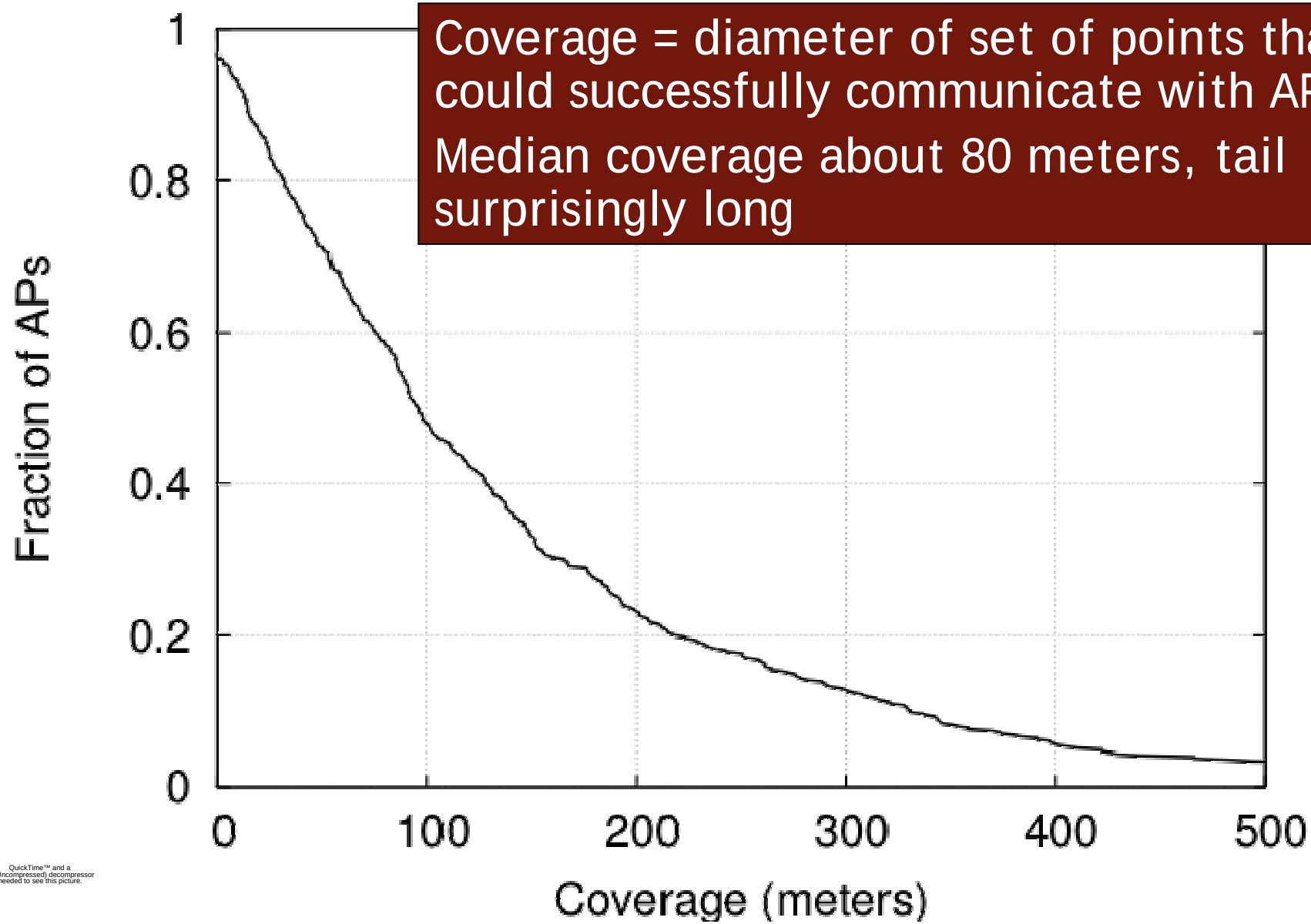
Coverage Region

Coverage = diameter of set of points that could successfully communicate with AP

Median coverage about 80 meters, tail surprisingly long



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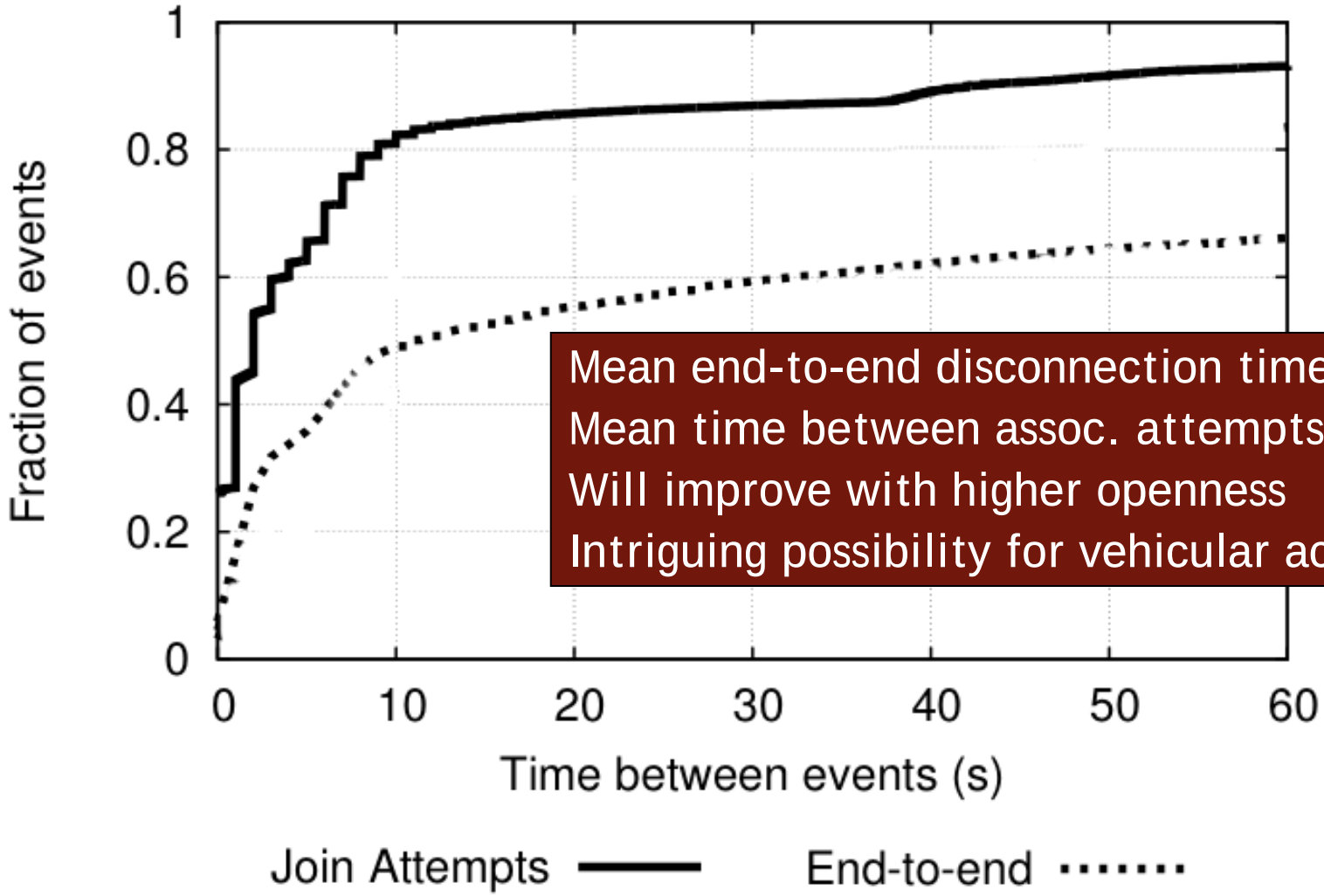
Disconnection Duration Distribution



Mean end-to-end disconnection time 260 s
Mean time between assoc. attempts 23 s
Will improve with higher openness
Intriguing possibility for vehicular access

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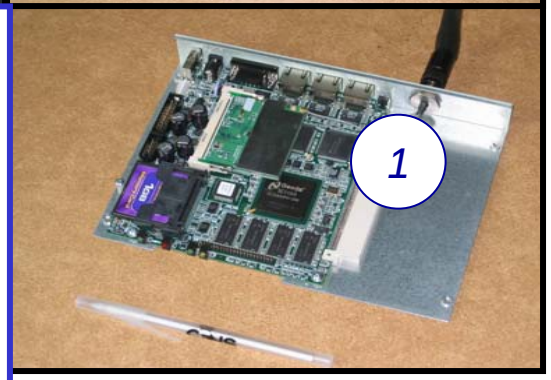
Other Vehicle-based Applications

- Smart route finding & congestion mgmt
  - Past + current data
- Fleet management
  - E.g., trucks, taxis, buses
- "Geo-logging" for road warriors, teenagers, etc.
- Visual mapping (images, video) of regions
- Civil and environmental monitoring
- Wireless network monitoring
  - "can you hear me now"

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Current Status

- Various components built and being evaluated
- Small deployment and experiments with 6 cars
- “Alpha” deployment underway (20 cars)



1. **Embedded Computer**
2. **WiFi Antenna**
3. **GPS Receiver (Seattle)**
4. **OBD-II Adapter**

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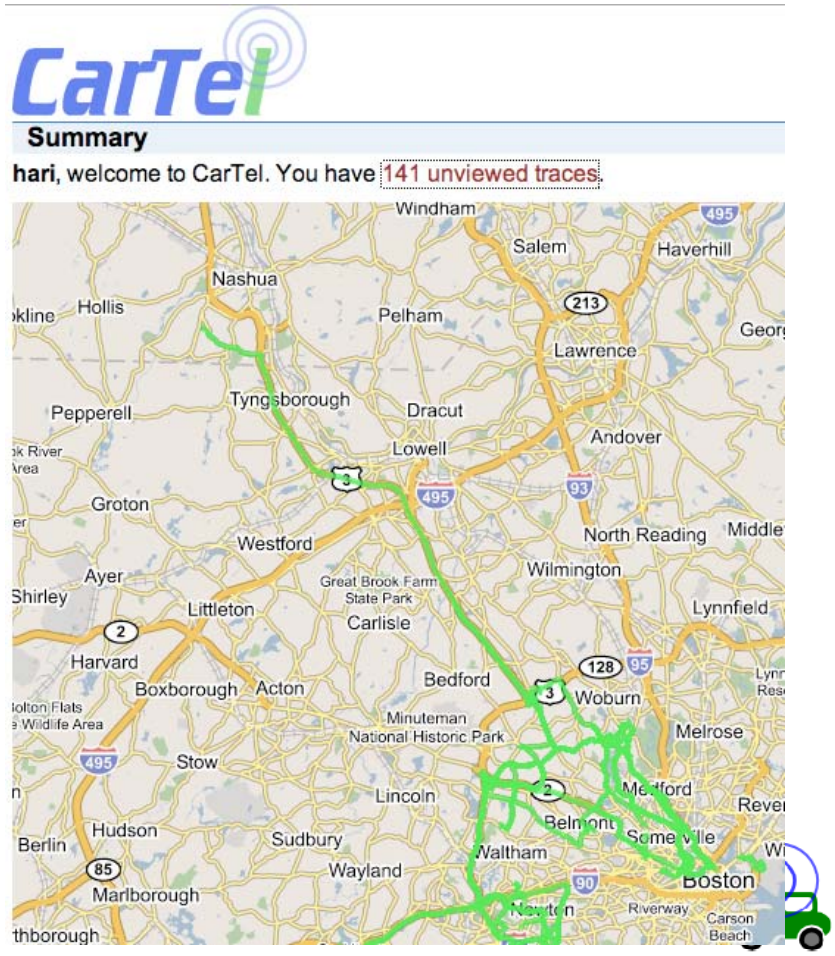


Current Status

CarTel AutoPortal

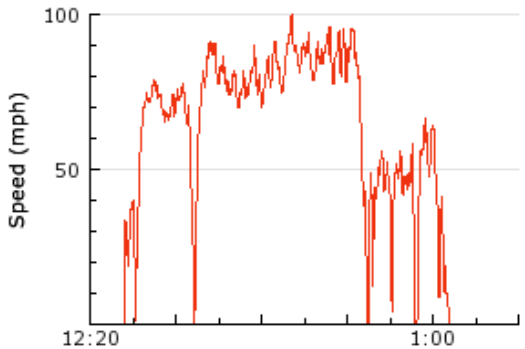
Trace Detail: Sat,03/04/06 - 12:23 AM

Duration:	00:38:21
Distance:	41.78 miles
Vehicle:	cartel7

Sensor Data Overlays:

speed

Avg. Speed:	65.37 mph
Max. Speed:	99.84 mph



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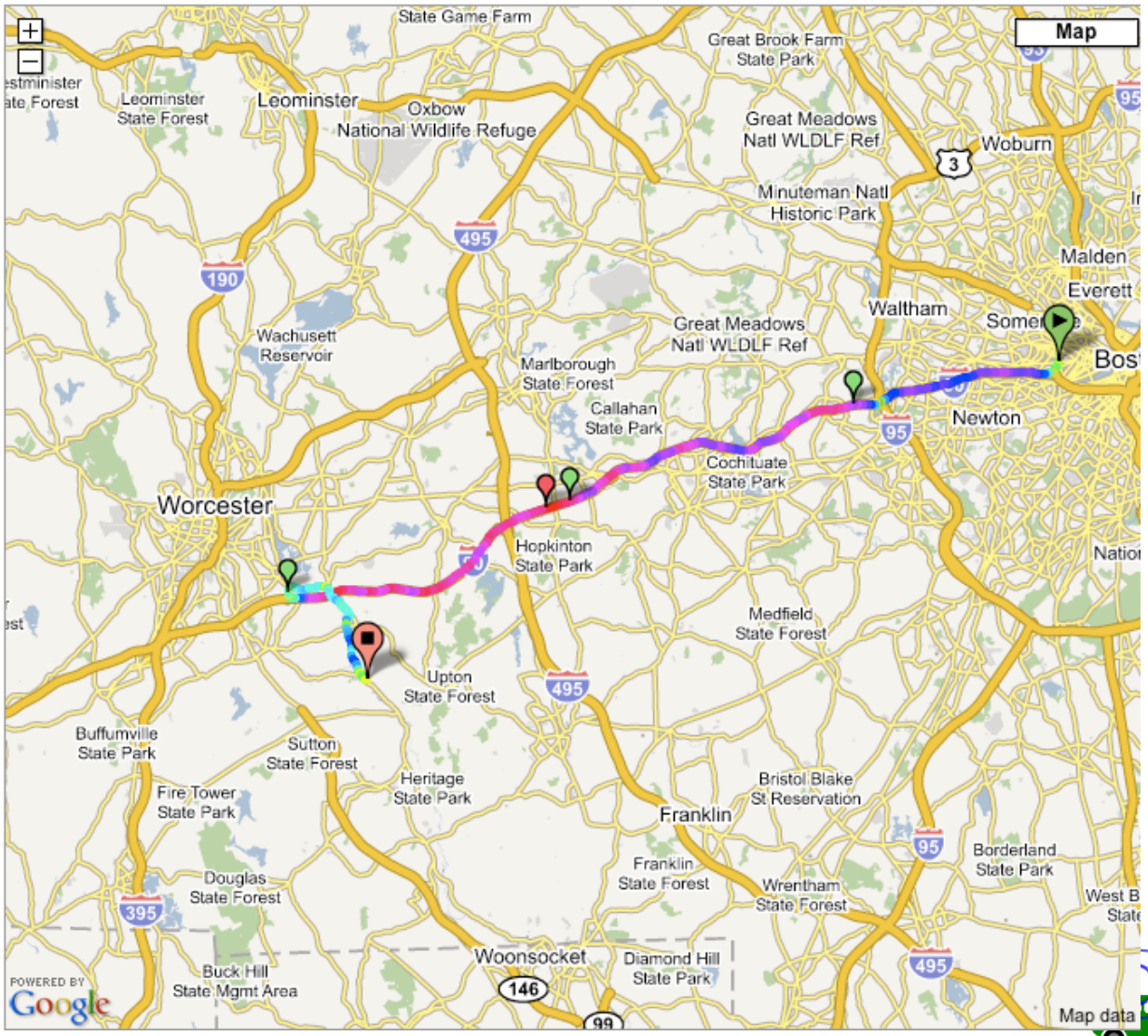

Lessons & Challenges

- Disconnectivity
- Prioritization
- Live, real-time, visualizations
- Lack of ubiquitous networking infrastructure
- Good environmental sensing hardware
- Performance of Postgres on low-end embedded hardware

Conclusion

- Mobile sensor networks can sense at much higher scale over large areas than static networks
- Several applications: traffic, fleet management, automotive diagnostics, **wireless network monitoring**, civil/environmental monitoring, …
- Key challenges: heterogeneous data, intermittent connectivity, programmability, privacy
- In urban areas, Wi-Fi is a viable uplink technology
- For more info: http://cartel.csail.mit.edu

Questions?

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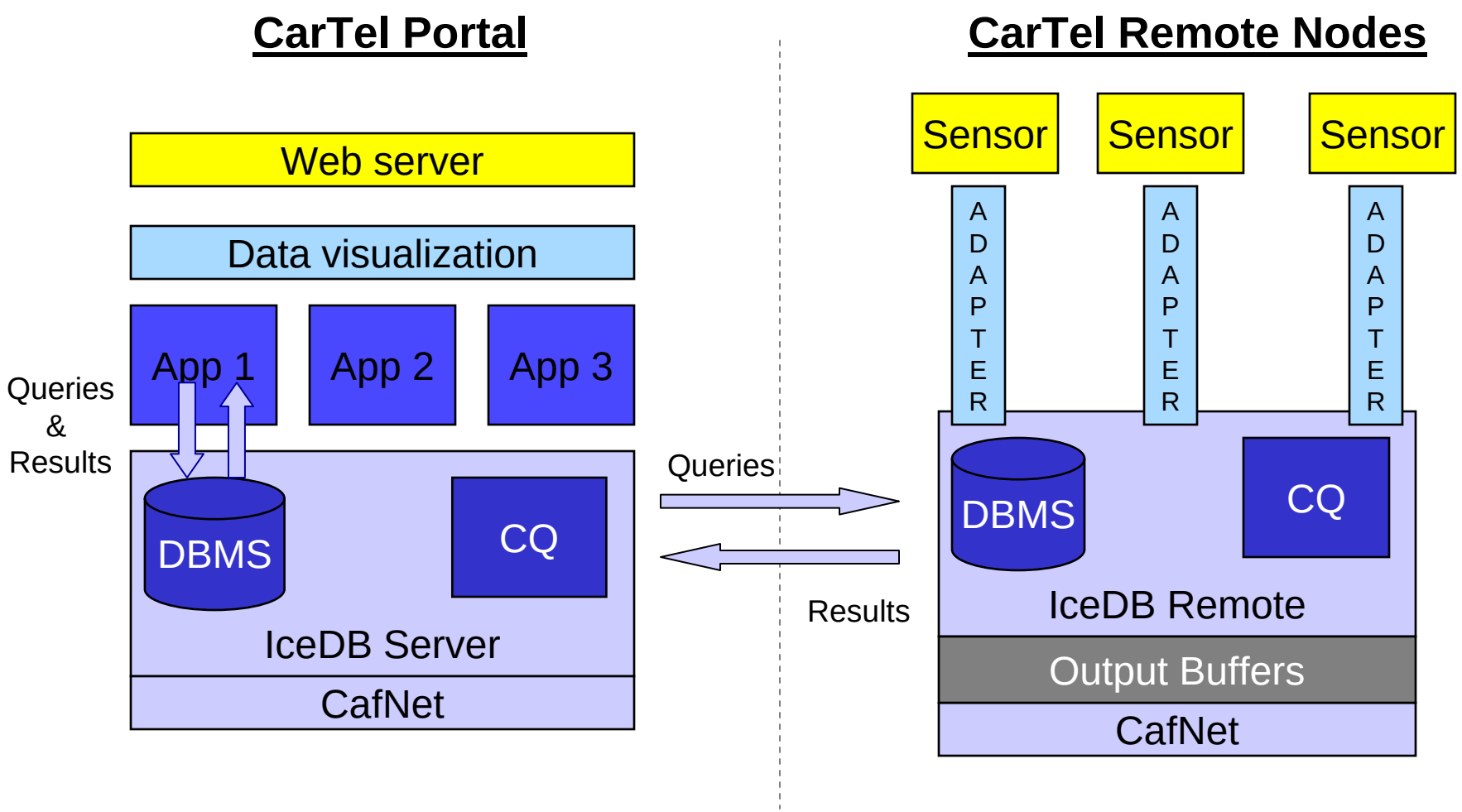
CarTel Software Architecture



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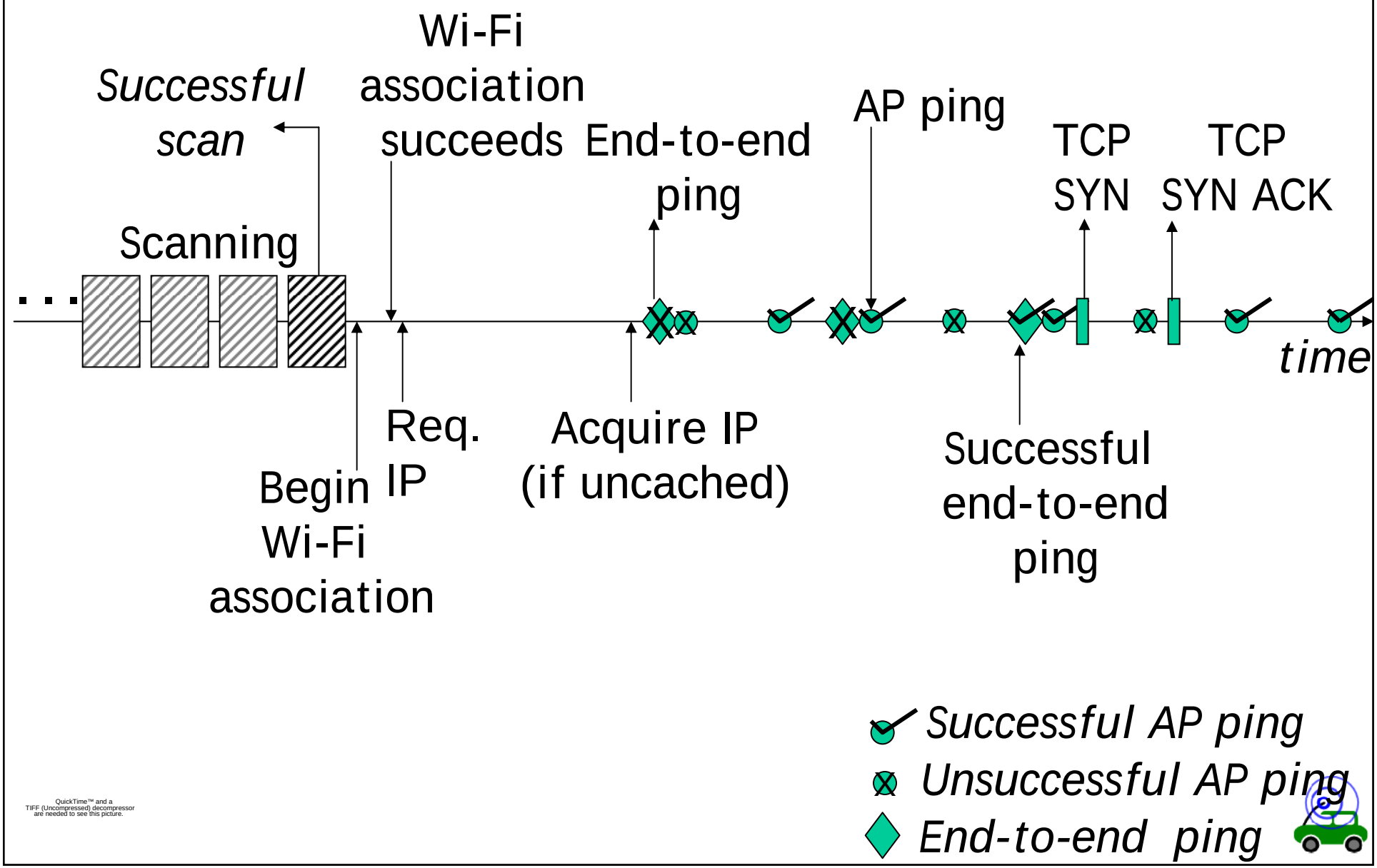
Related Work

- Mobility in sensornets [Princeton/Zebranet,UCLA/NIMS,MIT/Underwater]
- DTN protocols: primarily focused on routing, but cf. [Rutgers/infostations,Intel/DTN-stack,Toronto/DTN-stack,CMU/DOT]
- Dist. query & stream processing: much work, but little when connectivity is intermittent [TinyDB,Cougar,Olston,Borealis]
- Back-end DBMS (geo-spatial, moving object databases)
- Traffic monitoring [JamBayes,traffic.com,smartraveler.com,inrix, Rutgers/TrafficLab,Umass/Diesel]
  - Focused on sensors on roads and/or real-time
  - CarTel instruments cars, mostly historic modeling
- Wireless / Wi-Fi monitoring
  - Very few previous studies of vehicular Wi-Fi

Timeline of Events

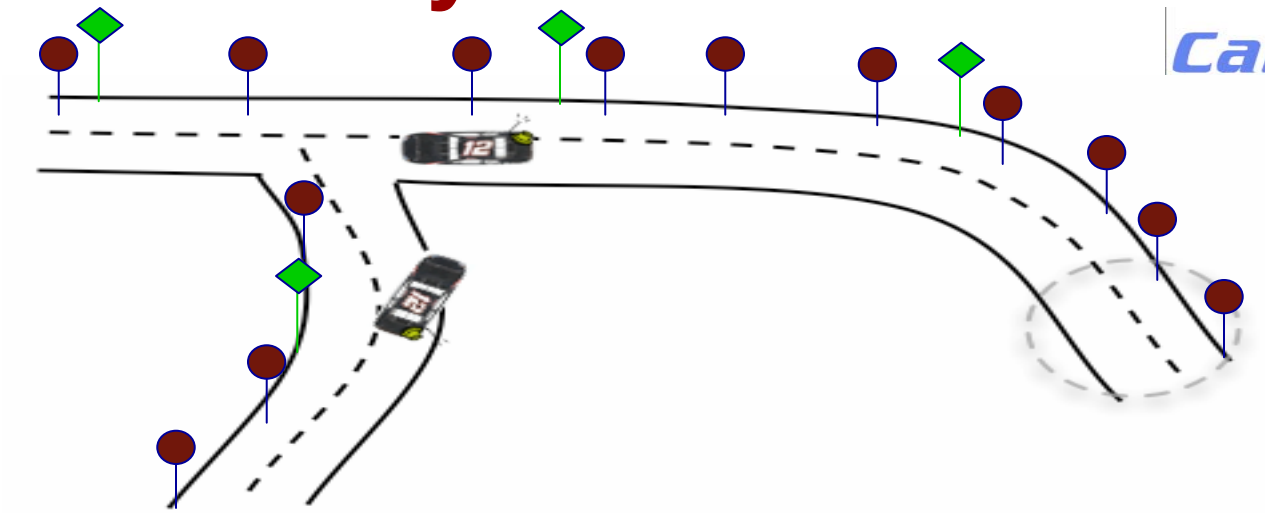


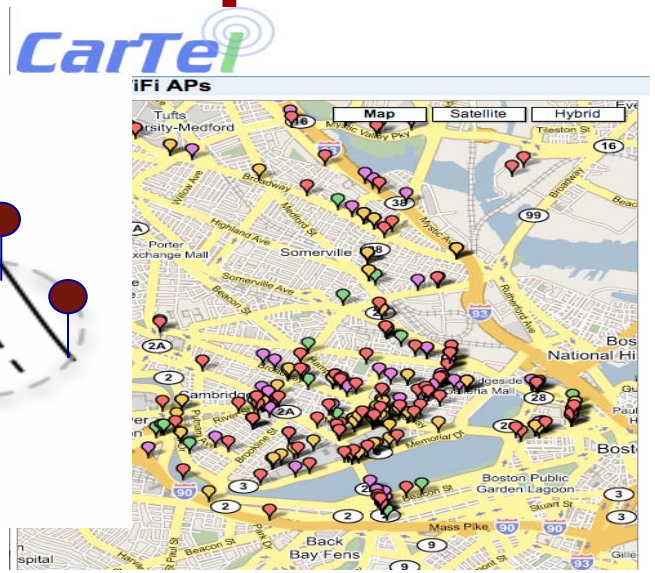
Determining Priorities and Delivery Order

- Q: In what order should data be sent to server?
- A: Utility = f(loc, time, sensor_type, sensor_value)

- Examples: Consider a car with GPS, camera taking pictures once per second
  - In what order should data be sent?
  - Maximal spacing between pictures?
  - Prioritize hot-spots?
  - Take into account what other cars there are?

Utility Maximization Example





- Suppose data gathered at $P = \{P_1, P_2, \ldots P_n\}$
  - Can be sent at locations $C_1, C_2, \ldots C_m$
- User query for random position *x* at time *t*
- Want: data as current as possible, as near x as possible
  - Minimize: $E = \text{dist}(x, Q(t'))$, where $Q(t')$ is in P, subject to $t - t' < \delta$
  - A "delay-tolerant query"

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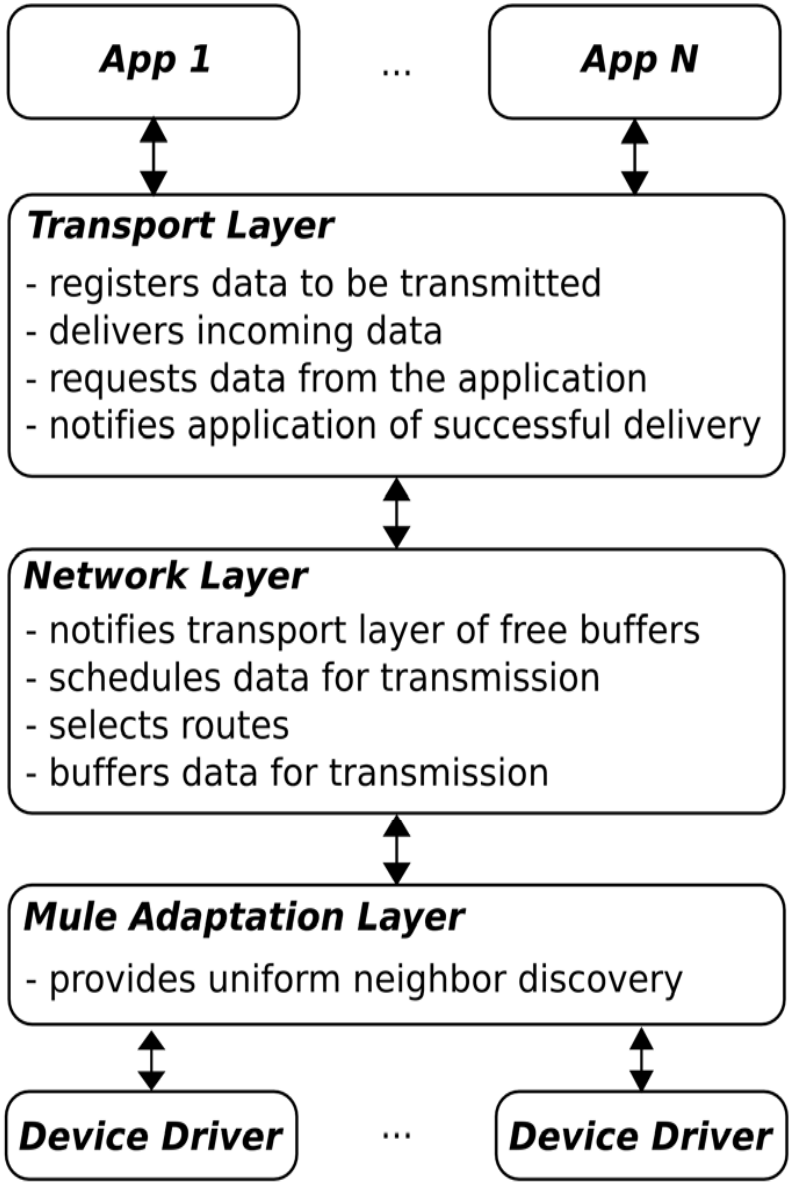
CafNet: A Delay-Tolerant Network Stack

- Data moves through regions of highly variable connectivity
- "Mule" = element that stores data to be relayed toward the destination when "the time is right"
  - I.e., a delay-tolerant network (DTN)
- CafNet delivers results to portal and queries to nodes



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CarTel Software Components

- *CarTel Portal*: Centralized, visual user interface
- *IceDB*: Intermittently connected DB
  - Centralized declarative queries
  - Executed in distributed fashion by mobile nodes
  - Delay-tolerant continuous query processing
- *CafNet*: CarTel's network stack
  - Handles variable and intermittent connectivity

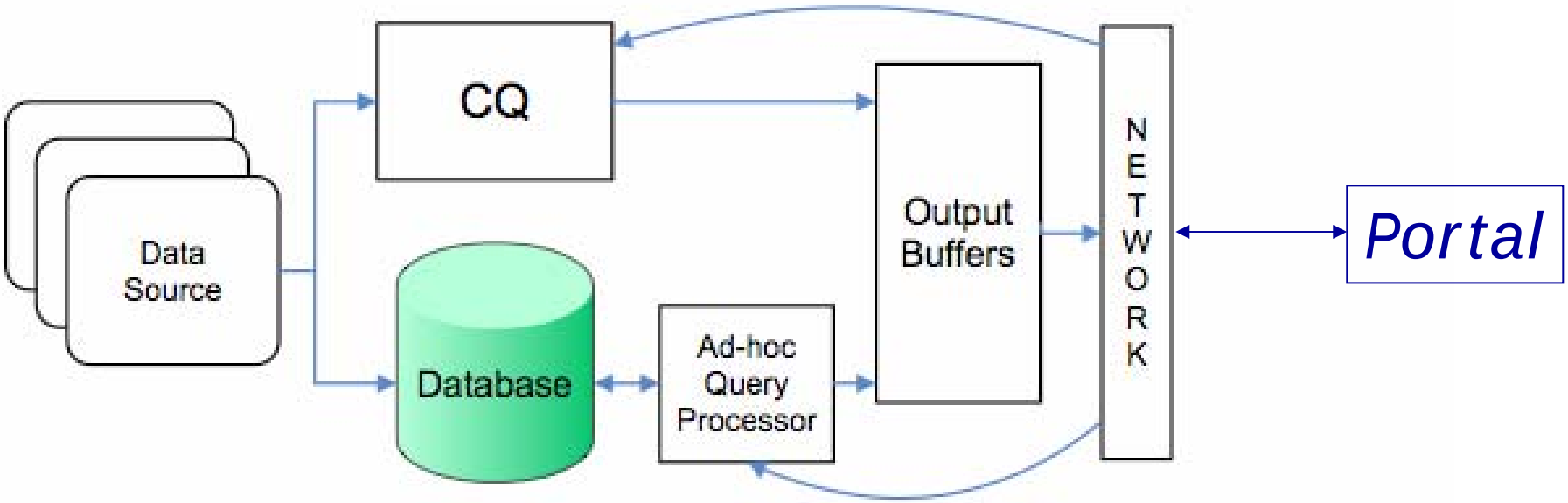
IceDB: Intermittently Connected DB

- Delay tolerant, distributed continuous query engine
  - Highly variable connectivity & bandwidth
- SQL extensions to handle intermittent connectivity
  - To prioritize results
- Adapters for managing heterogeneous data types
  - Meta-data package describing attributes of sensor
  - *Create* local tables for sensor readings
  - *Acquire* tuples from sensor
  - *Parse* sensor readings

Continuous Queries

- Current model for stream processing
  - Process data streams via long-running queries
  - Windowed aggregates, filters, windowed joins, merges, etc.
- Network is assumed to be “always on”
  - Disconnection is a fault to be masked (or a failure occurs)

Delay-Tolerant Continuous Queries



- IceDB stages data into output buffers to hide variable connectivity
- Key idea: Data in output buffers get re-evaluated dynamically, each time a new item arrives into it

Result Prioritization

- Limited BW necessitates deliberate ordering
- Three simple SQL extensions
  - For local (per-box) ordering:
    - `PRIORITY`
    - `DELIVERY ORDER BY`
  - For global ordering:
    - `SUMMARIZE AS`

PRIORITY

- *Idea*
  - Some queries are more important than others
- *Details*
  - Add **PRIORITY** clause to SQL
  - Drain output buffers in priority order

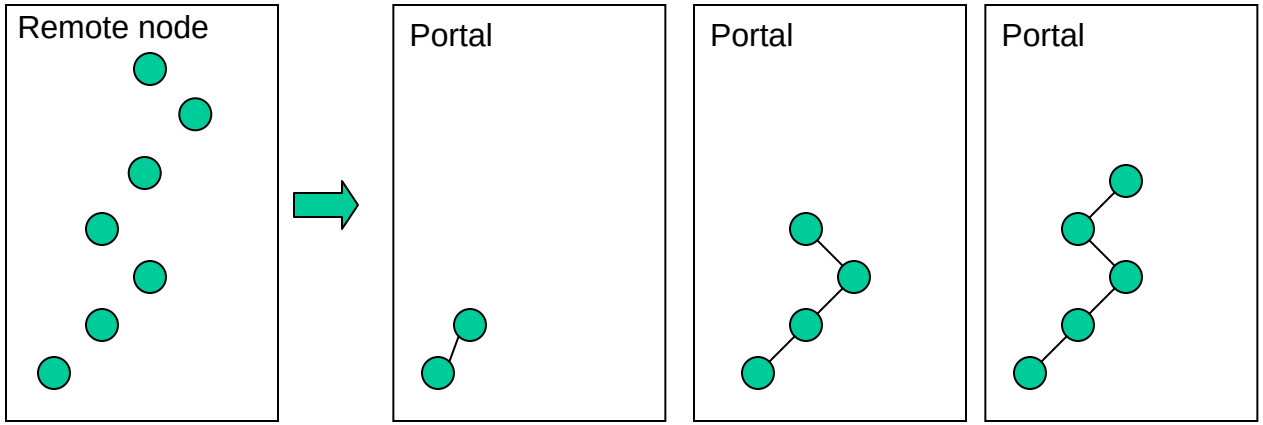
```
SELECT lat, lon, mph
FROM gps
WHERE mph > roads.mph_limit
BUFFER IN driver
PRIORITY 10
```

```
SELECT oil_temp
FROM obd
BUFFER IN engine
PRIORITY 1
```

DELIVERY ORDER BY

- *Idea*
  - Prioritize tuples to maximize incremental marginal utility
- *Details*
  - Query specifies transmission order via **`DELIVERY ORDER BY`** clause
  - User-defined ordering function (e.g. `bisect`)
  - Operates over entire query output buffer

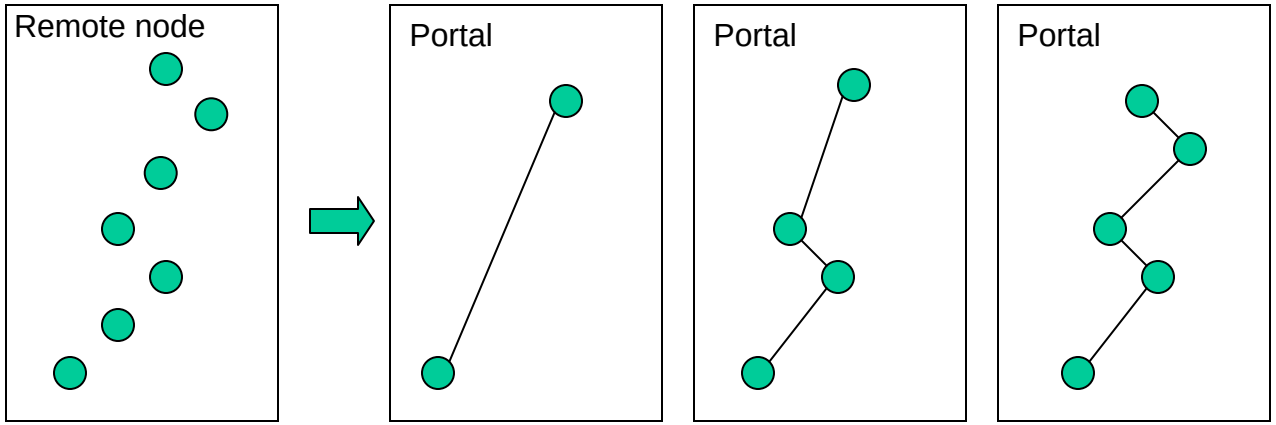
DELIVERY ORDER Example




```
SELECT lat, lon
FROM gps
WHERE insert_time
          > cqtime – 5
EVERY 5 seconds
BUFFER IN gpsbuf
DELIVERY ORDER BY fifo
```

FIFO

t=1 t=2 t=3




```
SELECT lat, lon
FROM gps
WHERE insert_time
          > cqtime – 5
EVERY 5 seconds
BUFFER IN gpsbuf
DELIVERY ORDER BY bisect
```

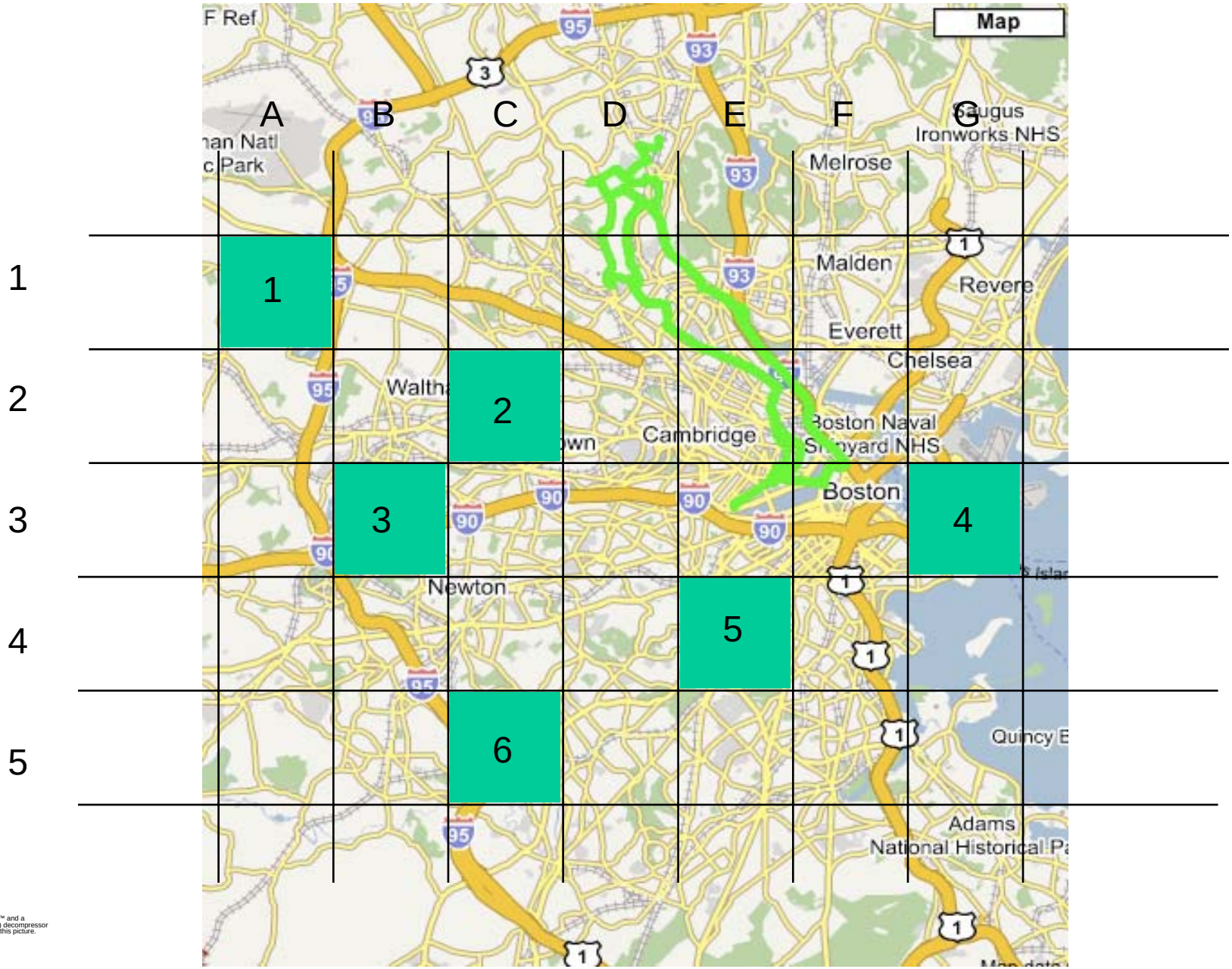
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

BISECT

SUMMARIZE

- *Idea*
  - Nodes send server low-resolution summary of output buffer contents
  - Server sends back transmission ordering
- *Details*
  - Users specify “summarization query” alongside main query
  - Summary defines “summary segments”
  - Server ranks segments using app-defined metric
  - Ranking pushed to nodes to set output ordering

SUMMARIZE Example



QuickTime™ and a
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are needed to see this picture.

SUMMARIZE Example

```
SELECT lat, lon, image
FROM camera
WHERE insert_time > cqtime – 5
EVERY 5 seconds
BUFFER IN cambuf
SUMMARIZE AS
      SELECT floor(lat/100), floor(lon/100)
      FROM cambuf
      GROUP BY floor(lat/100), floor(lon/100)
```