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: 09:06:17
Distance: 3.52 miles
Vehicle: 

Sensor Data Overlays

Avg. Speed: 33.62 mph
Max. Speed: 56.06 mph

* To zoom in on the map, use the +/button, or press Z to define the zoom region and X to zoom out.

Embedded Linux: Pentium-class, 128MB Ram, 1GB storage
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
  
  ```sql
  SELECT oil_temp
  FROM obd
  BUFFER IN engine
  PRIORITY 1
  ```

- **CafNet**: CarTel’s network stack
  - Handles variable and intermittent connectivity

This talk: study properties of network, using CarTel itself to do this (MobiCom ‘06)
What are the performance properties of these organically grown networks?
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
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)
Coverage Region

Coverage = diameter of set of points that could successfully communicate with AP
Median coverage about 80 meters, tail surprisingly long
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
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”
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
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:**
- **Avg. Speed:** 65.37 mph
- **Max. Speed:** 99.84 mph

*To zoom in on the map, use the +/− buttons, or press z to define the zoom region and x to zoom out.*
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?
CarTel Software Architecture

**CarTel Portal**
- Web server
- Data visualization
- App 1
- App 2
- App 3
- DBMS
- IceDB Server
- CQ
- CafNet

**CarTel Remote Nodes**
- Sensor
- DBMS
- CQ
- Output Buffers
- CafNet

Queries & Results

Queries ➔ Results

IceDB Remote

CafNet
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

Wi-Fi association succeeds

End-to-end ping

Successful AP ping

Unsuccessful AP ping

End-to-end ping
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”
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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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
```

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