Internet on the Road
Are we there yet?

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Increasing Mobile Data Rate is Creating New Market Opportunities

The Only WiFi Hotspot Designed for your Car.

BMW

iComera
The QoS Challenge in Vehicular Environment
User experience with multimedia may become a key factor

- Multimedia, e.g., audio and video streaming, will be very popular in vehicular environment (entertainment factor)
- Unfortunately, quality of experience with multimedia is very sensitive to network problems
- High-speed motion leads to very dynamic networking environment
  - User changes her location many times within a network session
  - Frequent bandwidth changes or disconnections not uncommon

Research Efforts

- Lot of interesting work (not an exhaustive list)
  - IETF’s Network Mobility (NEMO) WG
    - Standardizing the multi-homed mobile router paradigm
  - MAR (Rodriguez, Banerjee, et. al, Mobisys 2004)
    - Exploiting provider/technology diversity in a multi-homed mobile router
  - Drive-Thru Internet (Ott et al., INFOCOM 2004)
    - Hot-spot Internet access on highways
  - Cartel (Bychovsky, Mobisys 2007) & DieselNet (Levine, et al.)
    - Vehicular Internet access using open WiFi in urban areas
  - ViFi (Balasubramaniam, et al, Sigcomm 2008)
    - Exploiting AP diversity for WiFi vehicular Internet access
Our Work

- Characterize location-bandwidth dependency in vehicular mobility
- Investigate applications of location-bandwidth dependency for improving QoS in vehicular Internet

Presentation Overview

- Background on geographical influence on bandwidth
- Data collection on the roads of Sydney
- Location-bandwidth dependency analysis
  - WAN bandwidth varies significantly at many scales
  - Past tells more than present (a case for bandwidth map)
- Experiments with bandwidth map
  - Video streaming (in conventional setting)
  - Audio streaming (in NEMO setting)
- Conclusion and future direction
WAN Bandwidth and Geography
It seems that location determines your luck with bandwidth

- Wired.com’s iPhone 3G survey in 2008 (www.wired.com)

3G bandwidth varied significantly at country and region level

HSDPA Data Rate Variation in 1-Hour Driving

- HSDPA performance and evolution, Derksen et al., Ericsson, 2006

“The HSDPA bit rate adapted quickly to the different radio conditions”
Our Experience in Sydney

- We have found that 3G and some pre-Wimax bandwidth vary drastically while driving.
- Bandwidth variation is too severe causing significant damage to quality of user experience for audio and video streaming applications.
- We will show how the situation (QoS) can be improved by creating bandwidth maps for the roads.

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Measurement Architecture

Probe Server @ UNSW

Provider A (HSDPA)
Provider B (HSDPA)
Provider C (pre-wimax)

Internet

Probe Client

Downlink Probe (Packet Train)
Probe Trigger (every 200m)

Measurement Hardware/Software

- Off-the-shelf Hardware (Soekris)
- Totally user-driven (no support from service provider)
Routes Taken
- Two routes (inbound: 7Km & outbound: 16.5Km)
- Typical driving speed ~70-80Kmh
- 75 repeated trips spread over 8 months (Aug’07 – Apr’08)

Bandwidth Estimation Using Probes
- We used 10-pk trains, 1KB pks for every 200 meters
- 180MB worth of downlink probes per provider for the 75 trips (~0.5GB in total)
- A `saturated' measurement would cost ~65GB of downloads (130 times more than probing)

\[ C = \frac{(N - 1) \times L}{\sum_{k=1}^{k=N-1} t_k} \]

- N: the total number of packets in a train (10)
- L: packet size (1KB)
- \( t_k \): inter-arrival time between the \((k+1)\)th and \(k\)th packets.
  (Dovrolis04)

Measurements are geo-tagged
- Each probe yields one tuple \(<\text{bandwidth, location, time}>\) every 200m
- Approx. 115 tuples in the bandwidth database for each trip (23Km)
- Produce bandwidth samples for different resolutions by averaging multiple tuples (e.g., avg(5 tuples) \(\rightarrow\) avg. bandwidth for 1Km)
How Accurate is the probe-based Estimation?

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### Bandwidth Varies Significantly at Many Geographical Scales (individual trip data)

**Loc (500m granularity)**

<table>
<thead>
<tr>
<th>Trip</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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<td>1</td>
<td>333</td>
<td>93</td>
<td>252</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>94</td>
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<td>436</td>
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<tr>
<td>3</td>
<td>384</td>
<td>163</td>
<td>119</td>
<td>198</td>
<td>187</td>
<td>544</td>
<td>68</td>
<td>256</td>
<td>20</td>
<td>11</td>
<td>0</td>
<td>128</td>
<td>121</td>
<td>169</td>
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**Loc (1000m granularity)**

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<td>313</td>
<td>346</td>
<td>276</td>
<td>30</td>
<td>97</td>
<td>225</td>
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<tr>
<td>2</td>
<td>284</td>
<td>245</td>
<td>300</td>
<td>268</td>
<td>50</td>
<td>94</td>
<td>276</td>
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<tr>
<td>3</td>
<td>306</td>
<td>145</td>
<td>445</td>
<td>227</td>
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<td>64</td>
<td>145</td>
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**Loc (1500m granularity)**

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<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>1</td>
<td>217</td>
<td>356</td>
<td>262</td>
<td>65</td>
<td>173</td>
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<td>2</td>
<td>246</td>
<td>315</td>
<td>265</td>
<td>94</td>
<td>211</td>
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<tr>
<td>3</td>
<td>257</td>
<td>409</td>
<td>208</td>
<td>99</td>
<td>140</td>
</tr>
</tbody>
</table>

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### Bandwidth Varies Significantly at Many Geographical Scales (average bandwidth from 75 trips)

**Loc (500m granularity)**

<table>
<thead>
<tr>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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<tbody>
<tr>
<td>mean</td>
<td>320</td>
<td>255</td>
<td>308</td>
<td>408</td>
<td>271</td>
<td>352</td>
<td>211</td>
<td>296</td>
<td>89</td>
<td>8</td>
<td>32</td>
<td>180</td>
<td>304</td>
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</tbody>
</table>

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<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>304</td>
<td>355</td>
<td>337</td>
<td>281</td>
<td>87</td>
<td>101</td>
</tr>
</tbody>
</table>

**Loc (1500m granularity)**

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<td>358</td>
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<td>98</td>
</tr>
</tbody>
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Past Tells More Than Present
A case for bandwidth maps

Past: Average bandwidth at location #7 from last 2 trips is 133 Kbps
133 - 68 = 65 Kbps

Present: bandwidth at previous location during current trip is 544 Kbps
544 - 68 = 476 Kbps

RMSE comparison for Past and Present (averaged over all 75 trips)

Error with Present (previous location in current trip)
Error with Past (bandwidth average from past trips in the same location)
How Bandwidth Map Can Help (assume it stores average bandwidth observed in a given location from the previous trips)

At the entry to location #7, bandwidth map would give 133 kbps, but a link monitor agent would give 544. Convergence to 68 would be faster and smoother if started from 133 instead of 544.

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Adaptive Video Streaming in Vehicular Environment

- Applications: Video Conferencing, Video on Demand, etc.
- Popular Codec: H.264, MPEG-4
- Encoding quality: Controlled by Quantizer Scale (Q, smaller - better - more bandwidth thirsty)
- Bandwidth Adaptation: change Q to adapt to the current bandwidth
- Current bandwidth is continuously monitored and feedback

Mobile Video Adaptation

- TCP-Friendly Rate Control (TFRC) for delivering Real-time Adaptive Video
  \[ TFRC(p, R) = \frac{8}{R \sqrt{\frac{2p}{3}} + t_{RTO} \sqrt{\frac{27p}{8}} p(1 + 32p^2)} \]
- TCP-like AIMD congestion control can be affected by WWAN bandwidth fluctuation
  - From low to high bandwidth: slow ramp up - waste bandwidth
  - From high to low: slow response - cause packet loss
- End-Results: Lower video quality
Geo-TFRC (TFRC with access to bandwidth map)

- **Goal:** To help TFRC adapt to sudden bandwidth variations at location crossings

```
Plain Vanilla TFRC
(sending rate = TFRC_rate)

LOC_CHANGED

Location Changed
(sending rate = BW_MAP)

TFRC_rate(t) ≤ TFRC_rate(t-1) && TFRC_rate(t) < BW_MAP

2RTT Elapsed

TFRC_rate(t) > TFRC_rate(t-1)

Restoring
(sending rate = BW_MAP)

Cur_time - Last_changed < 2RTT
```

Simulation: MPEG-4 VBR Video

- Provider B for inbound route
- Raw source video file: foreman.qcif (resolution: 176x144)
- Foreman.qcif is self-concatenated multiple times to create a 30min-long raw video to last the entire trip
Video Rate Adaptation Evaluation in ns-2

Based on Evalvid-RA (Lei et al. ’07), Evalvid (Ke et al. ’08)

Video quality measurement (video quality is affected by packet loss from buffer overflow at cellular tower)

- The PSNR metric

\[
PSNR(n)_{dB} = 20 \log_{10} \left( \frac{V_{peak}}{\sqrt{\frac{1}{N_{col} N_{row}} \sum_{i=0}^{N_{col}} \sum_{j=0}^{N_{row}} [V_s(n,i,j) - V_D(n,i,j)]^2}} \right)
\]

- For acceptable video quality: PSNR >= 31
Throughput Comparison

PSNR Comparison
PSNR Comparison (cont.)

Fraction of Time With Poor Streaming Quality (PSNR < 31)
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NEMO

Downlink load balancing at MR Home Agent (HA)

Sudden change in bandwidth at the entry to a new location may overload a link causing buffer overflow at the cellular tower
Load Balancing

- Balance load using Proportional Fair Scheduler (assign load to a link proportional to its bandwidth capacity)
- **No bandwidth map**: estimate bandwidth every 2 sec and reshuffle loads if necessary
- **Bandwidth map**: continue as before, but upon entering a new location, fetch bandwidth data from the map and reshuffle load if necessary (much like the geo-TFRC)

Simulation Setup

- **Training Set**: 35 trips, **Evaluation Set**: 40 trips
- **Trace-driven** (Varied WWAN bandwidth)

- **Application**
  - 64Kbps Audio steaming (G771 Codec)
  - Poisson streaming session arrival
  - Exponential session duration (mean 2 minutes)
Measuring User Perceived QoS

- We use Mean Opinion Score (MOS)

<table>
<thead>
<tr>
<th>MOS</th>
<th>Quality</th>
<th>Impairment</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Excellent</td>
<td>Imperceptible</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>Perceptible</td>
</tr>
<tr>
<td>3</td>
<td>Fair</td>
<td>Slightly Annoying</td>
</tr>
<tr>
<td>2</td>
<td>Poor</td>
<td>Annoying</td>
</tr>
<tr>
<td>1</td>
<td>Bad</td>
<td>Very Annoying</td>
</tr>
</tbody>
</table>

- Packet loss statistics (loss rate, burst size, etc.) are converted to MOS using ITU E-model
- If MOS drops below 3, we will call it a `glitch' (because it will 'annoy' the user)

ITU E-Model

R factor:

\[ R = R_o - I_s - I_d - I_{e-eff} f + A \]

- \( R_o \): Basic signal-to-noise ratio, \( R_o = 93.2 \) for G711.
- \( I_s \): impairments which occur with the voice signal, set to 0.
- \( I_d \): impairments caused by delay and the effective equipment impairment factor, set to 0
- \( I_{e-eff} \): impairments due to packet-losses of random distribution.
E-Model (cont.)

\[ I_{e-ef} = I_0 + (95 - I_0) \cdot \frac{P_{pl}}{P_{bl}} \cdot \frac{P_{pl}}{B_{urstR}} + B_{pl} \]

Ppl: Packet-loss Probability
Packet-loss Robustness Factor \( B_{pl} = 25.1 \) for G.711.A (with PLC)
BurstR: Average Burst Length of Burst Lost Packets

E-Model (cont.)

Converting R factor to MOS:

For \( R < 0 \):

\[ \text{MOS} = 1 \]

For \( 0 < R < 100 \):

\[ \text{MOS} = 1 + 0.035R + R(R - 60)(100 - R)7 \cdot 10^{-6} \]

For \( R > 100 \):

\[ \text{MOS} = 4.5 \]
Number of Glitches per Trip
(as a Function of distance from the entry to a new location)

Usefulness of bandwidth map is more pronounced at the entry to a new location

Number of Glitches per Trip
(as a Function of location ids)

Statistics are for the first 50m from location entry

100-300% more glitches if bandwidth map not used
Probability of a Session Suffering Glitches
(as a Function of location ids)

Statistics are for the first 50m from location entry

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Conclusion

- Location, even at 500m scale, seems to influence WAN bandwidth
- Bandwidth variation due to location change is severe enough to cause significant damage to multimedia experience on the road
- Location dependent bandwidth history (bandwidth map) seems to be very useful in combating bandwidth variation on the road

Future Direction

- Do the bandwidth properties discovered on Sydney roads hold for other cities?
- Better maps?
  - Store more than first-order (mean) of past observation
  - Sort according to other contexts (time, weather, …)
- How can users contribute to build bandwidth maps for the whole city/nation?
  - Can cars contribute to build bandwidth maps?
- What else we can use a bandwidth map for?
  - Policy-driven navigation (select the route with higher bandwidth)?
Publications
http://www.cse.unsw.edu.au/~vnet