BreadCrumbs: Forecasting Mobile Connectivity

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Outline

1. INTRODUCTION
2. Connectivity Forecasting
   1. Mobility model
   2. Prediction
3. USING COLLIE FOR LINK ADAPTATION
4. CONCLUSION
Introduction

• We observe that people are creatures of habit.

• The aim of BreadCrumb is to improve the application-level for mobile device by connectivity forecasts.
Introduction

Predicted bandwidth: ?! KB/s
Introduction

Pre-Fetch

Don’t pre-fetch
CONNECTIVITY FORECASTING

1. Mobility model
2. Quality of connect
3. Forecast
4. Prediction
Mobility model

• Evaluation found a second-order Markov model

\[ x^{(0)} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad P = \begin{bmatrix} 0.9 & 0.1 \\ 0.5 & 0.5 \end{bmatrix} \]

\[ x^{(1)} = x^{(0)} P = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0.9 & 0.1 \\ 0.5 & 0.5 \end{bmatrix} = \begin{bmatrix} 0.9 \\ 0.1 \end{bmatrix} \]

Sum=1

Example:
nth-order Markov Example

1st-order matrix

<table>
<thead>
<tr>
<th>Note</th>
<th>A</th>
<th>C#</th>
<th>Eb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>C#</td>
<td>0.25</td>
<td>0.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Eb</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
</tr>
</tbody>
</table>

2nd-order matrix

<table>
<thead>
<tr>
<th>Note</th>
<th>A</th>
<th>D</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>0.18</td>
<td>0.6</td>
<td>0.22</td>
</tr>
<tr>
<td>AD</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>AG</td>
<td>0.15</td>
<td>0.75</td>
<td>0.1</td>
</tr>
<tr>
<td>DD</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DA</td>
<td>0.25</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>DG</td>
<td>0.9</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>GG</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>GA</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>GD</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Diagram:

- $X_0$: 174.91 KB/s
- $X_1$: 45.07 KB/s
- $X_2$: 0.00 KB/s
- $X_3$: 21.82 KB/s

Transition probabilities:

- $X_0$ to $X_1$: 0.12
- $X_1$ to $X_0$: 0.18
- $X_0$ to $X_2$: 0.70
- $X_2$ to $X_1$: 0.27
- $X_1$ to $X_3$: 1.00
Define state

- Building fundamental block by geographic coordinates.
- A $0.001\degree \times 0.001\degree$ grid square is $110\,m \times 80\,m$.
- Markov chain where a state transition fires every $\tau$ seconds.

Example:
Define state

A $0.001^\circ \times 0.001^\circ$ grid square is $110 \text{ m} \times 80 \text{ m}$.

These transitions occur every $\tau$ seconds.

<table>
<thead>
<tr>
<th>State</th>
<th>Last GPS</th>
<th>Current GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$(80.275,-80.747)$</td>
<td>$(80.275,-80.747)$</td>
</tr>
<tr>
<td>3</td>
<td>$(80.276,-80.747)$</td>
<td>$(80.276,-80.747)$</td>
</tr>
<tr>
<td>4</td>
<td>$(80.277,-80.746)$</td>
<td>$(80.277,-80.746)$</td>
</tr>
<tr>
<td>5</td>
<td>$(80.277,-80.746)$</td>
<td>$(80.277,-80.745)$</td>
</tr>
</tbody>
</table>
Forecasting Future Conditions

• How to combine data with the predictions of the mobility model.

• Build an AP quality database by Virgil.
Internet

- Downstream bandwidth
- Upstream bandwidth
- Latency to remote Internet hosts
- DHCP
Example – one step

the model transition period $\tau$
State of best bandwidth

- This model considers what network quality is to be forecast

```
BBW (state x)
    best ← 0.00
    foreach ap ∈ {APs previously seen at state x}
        if ap.bandwidth > best
            best ← ap.bandwidth
    return best
```

(a) Best bandwidth algorithm

x_3
21.82 KB/s
Connectivity forecasts

\[ \text{CF (state } x_i, \text{ int steps)} \]

\[
\begin{align*}
\text{if } \text{steps} & \leq 1 \\
\text{return } & \sum_{\forall j} \{ p_{ij} \cdot \text{BBW}(x_j) \} \\
\text{else} & \\
\text{return } & \sum_{\forall j} \{ p_{ij} \cdot \text{CF}(x_j, \text{steps} - 1) \}
\end{align*}
\]

(b) Connectivity forecast algorithm

Example:
\[ CF(x_0, 1) = \sum_{\forall j} p_{0j} \cdot BBW(x_j) \]

\[
CF(x_0, 1) = p_{00} \cdot BBW(x_0) + p_{01} \cdot BBW(x_1) + p_{02} \cdot BBW(x_2) \\
= 0.12 \cdot 174.91 + 0.70 \cdot 45.07 + 0.18 \cdot 0.00 \\
= 52.54 \text{ KB/s}
\]

\[
CF(x_0, 2) = \sum_{\forall j} p_{0j} \cdot CF(x_j, 1) \\
= p_{00} \cdot CF(x_0, 1) + p_{01} \cdot CF(x_1, 1) + p_{02} \cdot CF(x_2, 1)
\]
Connectivity forecasts

• Bread-Crumbs calculates this forecast as the weighted sum of the best bandwidth.

• If steps is greater than one, connectivity forecasts are calculated recursively.
Implementation

Scan thread
- Scan for AP
- Probe connection quality

Application interface
- Application request for forecasts
Implementation

Time: train 1 week and evaluation 1 week
Period: 10s

Omitting those locations where no encountered AP had a probed bandwidth greater than zero
Implementation
% steps in trace

bandwidth (KB/s)

10 KB/s over 50%
50 KB/s over 80%
# Overhead

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>states in model</td>
<td>652</td>
</tr>
<tr>
<td>model size</td>
<td>27984 bytes (42.92 B/state)</td>
</tr>
<tr>
<td>test results</td>
<td>1335</td>
</tr>
<tr>
<td>test DB size</td>
<td>92132 bytes (69.01 B/entry)</td>
</tr>
</tbody>
</table>
Overhead

![Bar chart showing overhead times for different values of k.](chart.png)

<table>
<thead>
<tr>
<th>k</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>75</td>
</tr>
</tbody>
</table>
Conclusion

• Focus on how connectivity changes over time.
• BreadCrumbs maintains a personalized mobility history.
• It also probe the application-level quality.
• It could apply to more application.