iCellular: Device-Customized Cellular Network Access on Commodity Smartphones

Yuanjie Li\textsuperscript{1}, Haotian Deng\textsuperscript{2}, Chunyi Peng\textsuperscript{2}, Zengwen Yuan\textsuperscript{1}, Guan-Hua Tu\textsuperscript{1}, Jiayao Li\textsuperscript{1}, Songwu Lu\textsuperscript{1}

\textsuperscript{1} University of California, Los Angeles
\textsuperscript{2} The Ohio State University
User Demands for High-Quality Cellular Access

• “We want high-quality cellular network service anytime, anywhere”
• No single carrier network can always satisfy these demands
• Let the end devices access multiple carriers and choose the best one
• Emerging efforts: Google Project Fi, Apple SIM, Samsung e-SIM, etc.
An Alternative Approach: Multi-Carrier Access

• Let the end devices access multiple carriers and choose the best one
• Emerging efforts: Google Project Fi, Apple SIM, Samsung e-SIM, etc.

Report: Apple and Samsung in talks to adopt e-SIM technology
Desired Features for Multi-Carrier Access

#1: Switch when expected
Example: Will my phone switch to T-Mobile when it is better than Sprint?

#2: Make a wise decision
Example: Will my phone select T-Mobile 4G or Sprint 3G?

#3: Fast and seamless switch
Example: Will my phone quickly switch to Sprint 4G with minimal data disruption?
• Multi-carrier access today: three issues
  • Root cause analysis

• iCellular design

• Evaluation
Multi-Carrier Access Primer

- Rich coverage at each location (3G/4G, multi-carriers)
- Inter-carrier switch: monitoring → selection → switch
Issue 1: Passive Monitor Misses Better Network

#1: Switch when expected

#2: Make a wise decision

#3: Fast and seamless switch
Issue 1: Passive Monitor Misses Better Network

- Monitoring is triggered when the serving carrier network fails
- Optimized for single-carrier access: roaming to other carriers was not preferred

#1: Switch when expected
#2: Make a wise decision
#3: Fast and seamless switch
Issue 2: Unwise Network Selection

#1: Switch when expected

#2: Make a wise decision

#3: Fast and seamless switch
• Intra-carrier handoff is still preferred, although other carriers are better
  • Serving carrier network affects the mobility decision

#1: Switch when expected

#2: Make a wise decision

#3: Fast and seamless switch
to Sprint 3G
Issue 3: Long Switch Time and Service Disruption

#1: Switch when expected

#2: Make a wise decision

#3: Fast and seamless switch
Issue 3: Long Switch Time and Service Disruption

- Exhaustive search for all possible carrier networks

**#1: Switch when expected**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:19:57.414</td>
<td>Out-of-service. Start network search</td>
</tr>
<tr>
<td>11:19:57.628</td>
<td>Scanning AT&amp;T 4G cell 1, unavailable</td>
</tr>
<tr>
<td>11:19:57.748</td>
<td>Scanning AT&amp;T 4G cell 2, unavailable</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11:20:11.788</td>
<td>Scanning Verizon 4G cell 1, unavailable</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11:20:12.188</td>
<td>Scanning T-Mobile 4G cell 1, available</td>
</tr>
<tr>
<td>11:20:12.771</td>
<td>Attach request (to T-Mobile 4G)</td>
</tr>
<tr>
<td>11:20:14.788</td>
<td>Attach accept</td>
</tr>
</tbody>
</table>

**#2: Make a wise decision**

- RF band scanning: 14.7s
- Network registration: 2.6s

**#3: Fast and seamless switch**

Monitoring networks...
Reality of Multi-Carrier Access

#1: Switch when expected

#2: Make a wise decision

#3: Fast and seamless switch
Reality of Multi-Carrier Access

P1: Passive monitor

P2: Unwise selection

P3: Long switch and disruption

Can we solve these problems without changing 3G/4G design?

Empower the end device with low-level cellular info!
iCellular Overview

- **P1:** Passive monitor
- **P2:** Unwise selection
- **P3:** Long switch and disruption

Active monitor → Intelligent selection → Direct switch
iCellular Architecture

• A in-phone software service
• Leverage low-level mechanism and info
  • Runtime cellular info (knowing more for a wiser decision)
  • Ability for adaptation in existing mechanisms (action ready now)
• **Goal**: proactively detect other available carrier networks
• **Mechanism**: manual network search
• **Challenge**: searching other carriers may disrupt data service!
• **Key insight**: data reception is regulated by paging cycle

• Schedule the manual network search with low-level cellular feedback
• Without registration, data performance cannot be measured ...

• Better signal strength ≠ Faster speed!
  • Heterogeneous carrier networks

<table>
<thead>
<tr>
<th></th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-4G</td>
<td>-95dBm</td>
</tr>
<tr>
<td>S-4G</td>
<td>-100dBm</td>
</tr>
</tbody>
</table>
Intelligent Selection with Prediction

• Collect each carrier network’s profile: QoS + radio parameters

• Predict carrier performance with radio measurements + cellular profile

<table>
<thead>
<tr>
<th>RSS</th>
<th>QoS class</th>
</tr>
</thead>
<tbody>
<tr>
<td>-95dBm</td>
<td>Background</td>
</tr>
<tr>
<td>-100dBm</td>
<td>Interactive</td>
</tr>
</tbody>
</table>

Downlink Speed (Mbps)

Active monitor → Intelligent selection → Direct switch

Sprint → T-Mobile

Is T-Mobile 4G faster?
• Conflicts with network-side mobility rules
Decision Faults Prevention

- Conflicts with network-side mobility rules
- Safeguard device selection by predicting decision faults

### Intra-carrier handoff profile

| T-4G     | Handoff to 3G if \( \text{RSS}_{T-4G} \leq -120\,\text{dBm} \), and \( \text{RSS}_{T-3G} > -90\,\text{dBm} \) |

<table>
<thead>
<tr>
<th>RSS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T-4G</td>
<td>-123dBm</td>
</tr>
<tr>
<td>T-3G</td>
<td>-85dBm</td>
</tr>
</tbody>
</table>

T-4G→T-3G handoff would be triggered!
Adaptive Direct Switch

- **Goal**: minimize switch time and service disruption
- **Key insight**: most switch time is spent on exhaustive search
- **Solution**: cross-layer adaptation for PLMN preference

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:19:57.414</td>
<td>Out-of-service. Start network search</td>
</tr>
<tr>
<td>11:19:57.628</td>
<td>Scanning AT&amp;T 4G cell 1, unavailable</td>
</tr>
<tr>
<td>11:19:57.748</td>
<td>Scanning AT&amp;T 4G cell 2, unavailable</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11:20:11.788</td>
<td>Scanning Verizon 4G cell 1, unavailable</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11:20:12.188</td>
<td>Scanning T-Mobile 4G cell 1, available</td>
</tr>
<tr>
<td>11:20:12.771</td>
<td>Attach request (to T-Mobile 4G)</td>
</tr>
<tr>
<td>11:20:14.788</td>
<td>Attach accept</td>
</tr>
</tbody>
</table>

RF band scanning: 14.7s
Network registration: 2.6s
Implementation

• In-phone daemon service on Nexus 6/6P
• Leverage Project Fi SIM card for multi-carrier access
• Built-in strategies for better usability
Evaluation Setup

• Comparison between iCellular and Project Fi

• Pedestrian mobility and static experiments at campus

• Four representative applications:
  • **Bulk file transfer**: SpeedTest
  • **Web**: Firefox
  • **Video streaming**: Youtube
  • **VoIP**: Skype
- Downlink speed increment: 23.8% on average, 3.74x at maximum
- Video suspension reduction: 37% on average, 6.9x at maximum
- VoIP latency reduction: 60.4% on average, 1.9x at maximum
- Web loading time reduction: 7.3% on average, 46.5% at maximum
Inter-carrier Switch Time Reduction

- Average saving: **37.7s → 8.8s (76% reduction)**
- Further improvement is possible with better SIM implementation

![Graph Showing Switch Time Reduction](#)

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:40:36.756</td>
<td>Deregister from Sprint 4G</td>
<td></td>
</tr>
<tr>
<td>16:40:36.890</td>
<td>Invalidate SIM data request</td>
<td></td>
</tr>
<tr>
<td>16:40:36.892</td>
<td>Reconfiguring SIM card...</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>16:40:43.100</td>
<td>SIM card configuration done</td>
<td></td>
</tr>
<tr>
<td>16:40:44.501</td>
<td>Scanning T-Mobile 4G cell 1, available</td>
<td></td>
</tr>
<tr>
<td>16:40:44.709</td>
<td>Attach request (to T-Mobile 4G)</td>
<td></td>
</tr>
<tr>
<td>16:40:45.471</td>
<td>Attach accept</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Network registration:</strong> <strong>2.3s</strong></td>
<td></td>
</tr>
</tbody>
</table>
iCellular’s Overhead

• **Signaling overhead**: 32 msg/s at maximum

• **CPU/Memory**: below 2%/16.5MB

• **Energy consumption**: 4.75% battery usage in 24-hr normal usage test
  • Comparable to normal mobile apps: e.g., 4.54% for Skype in same test

![Graph showing CPU usage and signaling traffic](image_url)
Conclusion

• Multi-carrier access is promising, but its full benefits are constrained
  • Legacy 3G/4G was designed for single-carrier access

• The end device can take a more active role in multi-carrier access

• Leveraging runtime cellular information is an alternative dimension to enhance device-side inter-carrier switch
Thank you!