Resolving Policy Conflicts in Multi-Carrier Cellular Access

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† UCLA ‡ Purdue University
What is multi-carrier cellular access?

One SIM card, access to *multiple* carriers

- Phone automatically switches to a carrier with good service

Google Project Fi: industry’s leading effort; device-side solution

Animation source: fi.google.com
What are the benefits?

**Better** carrier access, **without** additional deployments from single carrier
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How it works?
How it works?

1. Select a carrier by inter-carrier policy

T-Mobile 3G

Sprint LTE

T-Mobile LTE

Sprint 3G
How it works?

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How it works?

1. Select a carrier by inter-carrier policy
2. Select a cell by intra-carrier policy

Two-tiered selection
Two policies involved

**Inter-carrier** policy: operated by multi-carrier service providers (i.e. Google)
- i.e. “Choose an appropriate carrier which has 4G”

**Intra-carrier** policy: configured & kept in each carrier
- i.e. “Connect to a cell with strongest signal strength”
- Example: cell handoff priority
Two policies involved

**Inter-carrier** policy: operated by multi-carrier service providers

- i.e. “Choose an appropriate **carrier** which has 4G”

**Intra-carrier** policy: configured & kept in each carrier

- i.e. “Connect to a **cell** with strongest signal strength”
- Example: cell handoff priority
Why policy-based inter-carrier switching

Project Fi’s *de facto* practice

Seen in most real operational networks
  - i.e., cell handoff, BGP routing ...

Benefits: Flexible + Scalable

Non-technical issues
Conflicts between inter- & intra-carrier policy
Conflicts between inter- & intra-carrier policy

T-Mobile
3G
inter-carrier policy: prefers LTE

Sprint
LTE

Sprint
3G

UCLA
Conflicts between inter- & intra-carrier policy

**Inter-carrier policy:** prefers LTE

**Intra-carrier policy:** enterprise small cell
Conflicts between inter- & intra-carrier policy

- **Inter-carrier policy:** prefers LTE
- **Intra-carrier policy:** prefers LTE
- **Intra-carrier policy:** enterprise small cell
Conflicts between inter- & intra-carrier policy

- **T-Mobile 3G**: intra-carrier policy: stronger RSS
- **T-Mobile LTE**: inter-carrier policy: prefers LTE
- **Sprint LTE**: prefers LTE
- **Sprint 3G**: intra-carrier policy: enterprise small cell
Policy conflicts lead to persistent loop!

Persistent carrier switching loops under static case

- No mobility
- Invariant network conditions
- Unchanged, deterministic policies

Persistent loops are bad:

- Negative impact (disruption, battery, ...) x Frequent occurrence
- Design issue
In this work

Q1: what are the carrier switching loops?
   1. Identify loop incurred by policy conflicts (similar to BGP)
   2. Theoretical analysis on loop condition
   3. Validation via operational Google Project Fi

Q2: how to resolve loops by policy conflict?
   4. Proposed practical guidelines
   5. Experiment validation on the effectiveness
Roadmap to our analytical framework

Common Policies - Loop Condition - Project Fi Validation - Practical Guidelines - Experiment Results
Policies, loops & validations

Q1: what are the carrier switching loops?
### Inter-carrier policies

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Policy form:

- Preferences on (carrier, RAT, e.g. 3G/4G) pair
- Switching to a carrier w/ higher preference

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• Inter-carrier policy prefers LTE
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Intuition: Preference set by inter-carrier policy conflicts with that in intra-carrier policies

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Loop condition

THM 6.1 INTER/INTRA-CARRIER PREFERENCE CONFLICT

A persistent N-carrier loop happens iff.
(a) every carrier has RAT_H assigned with same highest preference; and
(b) every carrier’s intra-carrier policy prefers a different RAT_L over RAT_H.
How Project Fi works: big picture
How Project Fi works: big picture

Step 1. Inter-Carrier Policy Config

Intra-Carrier Policy (Handoff)
How Project Fi works: big picture

1. Inter-Carrier Policy Config

2. Intra-Carrier Policy (Handoff)

User Space

Hardware

Fi SIM card

Google Project Fi Server

LTE

3G

Fi

T

Project Fi
How Project Fi works: big picture

Step 1. Inter-Carrier Policy Config

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Step 3. Reconfiﬁg SIM
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1. Inter-Carrier Policy Config
2. Intra-Carrier Policy (Handoff)
3. Reconfig SIM
4. Reconnect
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Step 1. Inter-Carrier Policy Config
Step 2. Intra-Carrier Policy (Handoff)
Step 3. Reconfig SIM
Step 4. Reconnect
Step 5: Crowdsourcing report

Google Project Fi Server

LTE

3G

Project Fi

User Space Hardware

Fi SIM card

Project Fi

Inter-Carrier Policy (Handoff)
How Project Fi works: inside the phone

Monitor: NetworkType
Decision
Policy 1
Conditions

Monitor: GeoLocation
Decision
Policy 2
Conditions

Monitor: ML-based
Decision
Policy 3
Conditions

Switch or not? Target Carrier?

Other Monitors (Roaming etc.)
Validation in Project Fi

Project Fi: Network Type Monitor

- T-Mobile <-> Sprint loop every 10 mins

---

Trace 2 Persistent loop by RAT-aware preference

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Google’s remedies

Trace 2 Persistent loop by RAT-aware preference

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Validation in Project Fi

Project Fi: Network Type Monitor

- T-Mobile <-> Sprint loop every 10 mins

Google’s remedies

- Lockdown timer

---

**Trace 2 Persistent loop by RAT-aware preference**


14:19:47 New lock request to Sprint is approved. Requester: PoorNetwork.

14:20:48 Switch T-Mobile LTE -> Sprint 1xRTT done. result:Success.
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- Lockdown timer
- Getting stuck, losing flexibility

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- Lock Timer
- Stuck in no service state
Validation in Project Fi

Project Fi: Network Type Monitor
- T-Mobile <-> Sprint loop every 10 mins

Google’s remedies
- Lockdown timer
- Getting stuck, losing flexibility
- Cannot fundamentally eliminate loops

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Trace 2 Persistent loop by RAT-aware preference

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Threshold-based policy

Inter-carrier policy:
  • i.e., current cell’s latency > 120ms && the optimal latency in other carrier < 100ms

Intra-carrier policies:
  • i.e., stronger RSS && higher inner priority
Threshold-based policy

Inter-carrier policy:
  
  • i.e., current cell’s latency > 120ms && the optimal latency in other carrier < 100ms

Intra-carrier policies:
  
  • i.e., stronger RSS && higher inner priority

Intuition: Different measures used by inter-carrier policy could conflict with that used by intra-carrier policies
THM 7.2 MINIMUM-MEASURE RULE

Assume inter-carrier policy’s measure $M$ and intra-carrier policy’s measure $Q$ are independent. The stability is violated if and only if $M(C_i) - M_{\min}(C_i) \leq g(F^*)$ cannot always hold, no matter how per-cell measures change, where $g(F^*)$ is defined as:

$$g(F^*) = \begin{cases} 
\phi - \theta, & F^* = F_2, \\
\delta, & F^* = F_3 \text{ or } F_4.
\end{cases}$$
Validation in Project Fi

Project Fi: ML-based monitor

- T-Mobile <-> Sprint loop

Observation:

- Crowdsourced score (latency, throughput, etc.) is independent to intra-carrier’s
- Cannot guarantee conflict-free!

Google’s remedy:

- memorize & limit switching count

---

**Trace 4 Persistent loops caused by inconsistent measures**

1. 19:57:00 K2so sorted carriers: T-Mobile, USCC, Sprint.
2. 19:57:00 Switch request to T-Mobile is approved. Requester: K2so.
3. **19:59:02 Switch Sprint 1xRTT->T-Mobile Unknown done** result: TimeOut.
   
   srcSignalStrength:-103. destSignalStrength:-200.
4. 20:04:20 K2so sorted carriers: T-Mobile, Sprint, USCC.
5. 20:04:21 Switch request to Sprint is approved. Reason: signal loss.
6. **20:05:11 Switch T-Mobile Unknown->Sprint 1xRTT done** result: Success.
   
   srcSignalStrength:-200. destSignalStrength:-119.
7. 20:04:20 K2so sorted carriers: T-Mobile, Sprint, USCC.
8. 20:05:12 Switch request to T-Mobile is approved. Requester: K2so
9. 20:07:13 Switch Sprint 1xRTT->T-Mobile Unknown done. result: TimeOut.
   
   srcSignalStrength:-119. destSignalStrength:-200.
10. 20:07:14 Wait for 05:00 before attempting another switch.
11. 20:12:17 Switch request to Sprint is approved. Reason: signal loss.
12. 20:12:45 Switch T-Mobile Unknown->Sprint 1xRTT done.
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Guidelines & experiments

Q2: how to resolve loops by policy conflict?
Yes, we can

**Goal:** stability (break the loop!)

**Constraint:** cannot change intra-carrier policies

**Intuition:** revise inter-carrier preferences (inspired by BGP [Rexford-Gao])

- How to revise w/o intra-carrier policy details?
- Can the revision be **flexible**?
Yes, we can

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Sprint-LTE >= T-Mobile-LTE > T-Mobile-3G > Sprint-3G
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- Can the revision be *flexible*?

**Guideline 1. Coordination via priority aggregation**

Coordinate inter-carrier policy with aggregated intra-carrier priorities to achieve monotonicity in carriers’ preferences.
Threshold policy: how to fix it?

Follow the same principle for guideline

- Do not use loop-prone comparison criteria
- Consider the worst-case measure in target carrier
Threshold policy: how to fix it?

Follow the same principle for guideline

- Do not use loop-prone comparison criteria
- Consider the worst-case measure in target carrier

Guideline 4. Relaxed Minimum Measure

Intuition: Consider the minimum measure in the target carrier; rule out some cells if necessary
Hybrid policy: results still apply!

Combines preference + threshold policy

All previous analytical results apply
Practical stability guidelines

<table>
<thead>
<tr>
<th>Policy</th>
<th>Sub-category</th>
<th>Stability Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preference-based</td>
<td>Assigned to RAT</td>
<td>Guideline 1: Coordinating preferences of inter-policy</td>
</tr>
<tr>
<td></td>
<td>Assigned to carrier</td>
<td>Guideline 2: Avoid preference-unavailability conflicts</td>
</tr>
<tr>
<td></td>
<td>Inconsistent measures</td>
<td>Guideline 3: Consider the worst case of target carriers</td>
</tr>
<tr>
<td>Threshold-based</td>
<td>Inconsistent config</td>
<td>Guideline 4: Coordination via aggregate internal thresholds</td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
<td>Guidelines 4, 5, 6</td>
</tr>
</tbody>
</table>
Experimental validation

Inter-carrier policy: crawled from Project Fi’s real coverage data

Intra-carrier policy: extracted from MobileInsight dataset, 50GB [1]

- Preference-policy: enumerate all 75 possible orderings of preference
- Threshold-policy: enumerate possible values of thresholds

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Results

All loops in static case are eliminated

<table>
<thead>
<tr>
<th>Preference Setting</th>
<th>Spatial Loop Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only 3G has highest pref</td>
<td>6.160%</td>
</tr>
<tr>
<td>One carrier’s LTE has highest pref</td>
<td>0.088%</td>
</tr>
<tr>
<td>Both carriers’ LTE have highest pref</td>
<td>0.003%</td>
</tr>
</tbody>
</table>

![Diagram showing loop frequency vs. threshold for different scenarios](Diagram.png)
Related works

Policy-based network config: BGP, SDN, ...
  • different problem/mechanism/methodology

5G and new standards: HetNet, network slicing, ...
  • device-side approach vs. infrastructure-based approach
  • policy may still apply
Conclusion

Multi-carrier cellular access is promising

• Project Fi: great effort from Google; device-side solution; policy-based switching

Problem: carrier switching loop!

• Caused by conflicts between inter-carrier policy and intra-carrier policy

This work: analytical framework on inter-carrier policies

• Loops eliminate by regulating inter-carrier policy (practical guidelines)

Still applicable to 5G/dual-SIM context
Q & A