A First Look at Unstable Mobility Management in Cellular Networks

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HotMobile’16
Ubiquitous Cellular Network Access

Cellular Networks

7.9+ billion in 2015
Mobility Management (MM) via Handoff

Cellular Networks

- Seamless connectivity (via switching the serving cell)
  - Each cell: limited radio coverage
Desirable Handoff: Stability

Why desirable?
- Handoff comes at a cost
  - Multi-round signaling exchange
  - Service disruption/degradation

- Converge to certain cell given an invariant setting
Desirable Handoff

- Stability
  - Converge to certain cell

Problematic Handoff

- Instability (persistent loop):
  - C1->C2->C3->C1->C2->C3…
This Work: Instability in Mobility Management

- Q1: Does it exist in real networks?
- Q2: Why unstable?
- Q3: How to identify such risk?

Caused by fundamental (persistent) conflicts in policy not by transient factors (radio dynamics etc)
Q1: Does unstable MM exist in reality?

- Unfortunately, Yes!
3-Cell Loop Example

- Static, 40hr-loop

Cell1: 4G
Cell2: Femtocell (3G)
Cell3: 3G

Loop every few mins (90% loops in 200s)
Negative Impacts in Real-world

- Hurt both carriers and users
- Excessive signaling overhead (2-8x)
- Performance degradation (10+ fold slowdown)

![Graph showing num. msgs per hour](image)

- [Bar chart with num. msgs per hour]

  - 1 loop: 1K
  - 2 loop: 2K, 3.5x
  - 3 loop: 8K, 8.5x

![Graph showing web loadtime](image)

- [Line graph with web loadtime]

  - cnn 5MB file:
    - 3s
    - 76s

- [Line graph with downloading time]

  - 5MB file:
    - 12s
    - 180s
Q2: Why is MM unstable?
Distributed Nature of Handoff

- Each handoff: trigger-decision-execution phases
- Sequence of handoffs

Cell 1

Handoff decision@C1

Handoff decision@C2

…

Cell 2
Handoff for Versatile Demands

- Seamless connectivity
- Voice/data support
- Performance

Each individual handoff: OK

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The interplay among multiples: OK
3-Cell Loop Example

Rule/preference configuration@C1 (4G)
- C2 (Femto) > C1 (4G) for offloading
- C1 (4G) > C3 (3G) for higher-speed

C1: C1 → C2

@C2 (3G Femto)
- Best radio strength with same preferences for all cells

C2: C2 → C3

@C3 (3G)
- C1 (4G) > C3 (3G) for higher-speed

C3: C3 → C1
From Example to Generalization

- Each handoff decision: \( t = F_s(s, C) \)
  - \( s \): serving cell
  - \( C \): set of candidate cells
  - \( F_s \): decision function for serving cell \( s \)
  - \( t \): target cell

- The sequence of handoff decisions
  \( s \rightarrow F_s(s) \rightarrow \cdots c_i \rightarrow [c_{i+1} = F_{c_i}(c_i)] \rightarrow \cdots, c_i \in C. \)
From Example to Generalization

- Instability = No convergence
  - e.g., persistent loop: \( c \rightarrow \cdots c_i \rightarrow c_{i+1} \rightarrow \cdots c \).

- **[Necessary stability condition]** there exists at least one \( t \), s.t. \( \exists t \in C, t = Ft(t, C) \)

- **[Necessary and sufficient condition]** (1) \( \exists t \in C, t = Ft(t, C) \); (2) there exists a handoff path from the initial cell \( s \) to the desirable \( t \)
Q3: How to detect possible instability?
MMDIAG

- In-device diagnosis
  - Carriers: reluctant to provide network-side MM info
- Two-phase: analyzer and validation
MMDIAG

- Model based on 3GPP spec
- Decision logic, configuration parameters and runtime observation (scenario)
MMDIAG

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§ Model based on 3GPP spec
§ Decision logic, configuration parameters and runtime observation (scenario)
§ Violation check

- Config. Collector
- Scenario Emulator
- MM Automata
- Instability Analyzer
- Counter examples
- Empirical Validation
MMDIAG

- Scenario reconstruction and experiments
  - Configurations and observations in counterexample
  - Trace collection and comparison
Real-World Findings

- One top-tier US carrier
- Los Angeles and Columbus
  63 locations (outdoor)
  50 spots (indoor)
Preliminary Results

- 17 loops (idle)
- 1 loop (active)
Four Classes (Root Causes)

- **#1:** uncoordinated handoff goals
  - 8 variants, 4G-Femto-3G
    - c1 (4G, band 17)
    - c2 (4G, band 2)
    - c3 (4G, band 4)
    - c4 (Femtocell)
    - c5 (3G, band 850)
    - c6 (3G, band 1900)
    - c7 (2G)
Four Classes

- #2: device-side misconfiguration
  - 8 variants, 4G-Femto-2G-3G

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Diagram:
- L1: 4G-Femtoell-3G
- L2: 4G-Femtoell-2G-3G
- L3: 4G-4G
- c1 (4G, band 17)
- c2 (4G, band 2)
- c3 (4G, band 4)
- c4 (Femtocell)
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- c6 (3G, band 1900)
- c7 (2G)
Four Classes

- **#3: Imprudent 4G upgrade**
  - One 4G-only loop

- **#4: uncoordinated load balancing**
  - One 4G-only loop (active)
Takeaway

- Largely stable in practice
  - Instability mainly caused by Femtocells or incompatible upgrades

- But in principle, instability likely exists
  - Distributed nature
  - Diversity and external (non-carrier) factors in case of heterogeneous networks (femtocells, small cells, WiFi, etc)
Open Issues

- Non-stability properties
  - Handoff converges to an undesirable choice (3G/2G when 4G available)

- Cooperate with network-side efforts

- From detection to fix
  - Report identified problems to carriers
  - Assist end-devices to intervene the loop
Summary

- A first look at instability in mobility management over cellular network

- Disclose real-world persistent loops caused by misconfigurations and policy conflicts

- Propose MMDIAG to detect unstable MM

- Call for more attention and efforts
Thank you! Questions?