A Nationwide Study on Cellular Reliability: Measurement, Analysis, and Enhancements

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Outline

1. Background
2. Methodology
3. Key Findings
4. Enhancements
5. Summary
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1.1 Cellular Network Today

- Cellular Network Empowers Modern Mobile Ecosystem
- 5G Networks Drive Our Grand Vision of AI and IoT
  - 10 Gbps bandwidth: 100× faster than 4G
  - 1 millisecond latency: 50× faster than 4G
  - 1 million devices/km² connection density: 100× more than 4G

Performance ↑ Availability ↑
1.2 What Have We Missed?

How Reliable Is Today’s Cellular Data Network?

Performance Is Meaningless when *Cellular Data Connections Fail to Work*
1.3 Current Knowledge of Cellular Reliability

- **For A Device, Cellular Data Connections Can Fail Mostly in 3 Ways**

<table>
<thead>
<tr>
<th>Failure Types</th>
<th>Signal</th>
<th>Connection</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data_Setup_Error</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Out_of_Service</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Data_Stall</td>
<td>✓</td>
<td>✓</td>
<td>✓, but the connection abnormally stalls</td>
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</table>

- **Unfortunately, Cellular Reliability Is Rarely Studied**

  - Insufficient Infrastructures
  - Large-scale Study Is Challenging
  - In-lab Study Lacks Representativeness

**Cellular Reliability Constantly Acts as an X-factor in Discussion**
Outline

1. Background
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2.1 Collaborative Study

Collaboration & Objectives

- In collaboration with Xiaomi, a phone vendor with ~250M users
- To conduct a large-scale study on cellular reliability problems

Our goal is to understand

- Prevalence
- Severity
- Root Causes

Xiaomi’s business interests

- A Major Source of Complaints
- Elusive Problems for Its Engineers

Well Aligned
2.2 Understanding Vanilla Android

- Vanilla Android’s Cellular Management Facilities
  - Life cycle of a cellular connection is modeled by a state machine
  - As state changes, failure-related problems are monitored

![State Machine Diagram]
2.3 Limitations of Vanilla Android

For concerned problems, Android provides

- notification interfaces for system services
- simple event logging, typically only for occurrences

Major limitations & challenges

- Partial availability of user-space interfaces
- False-positive events
- Lacking in-situ information
- Cannot simply build an app to capture failures
- Invalid basis of analysis
- Hindering in-depth understanding
2.4 Continuous Monitoring Infrastructure

- **Android-MOD: Customized Android for Cellular Failure Capturing**
  - System service instrumentation
  - Fine-grained system-level tracing
  - Failure recovery monitoring

- **Service Instrumentation & Fine-Grained Tracing**

```
Cellular Connection Management Service
  Event Notifiers  Interfaces

TelephonyManager Service
  Interfaces

ServiceState Service
  Interfaces

Android-MOD Cellular Failure Monitoring Service
```

- Event listener
- ... Protocol error logger
- BS/radio info logger
2.5 Failure Recovery Monitoring

- Data_Stall: 10 outbound TCP segments but no inbound in 1 min
  - Fixed 1-min detection time
  - Lacking network stack information
  - Up to 1 min of error
  - Contain false positives

- Our approach: active and lightweight network-state probing
  - At most 5 seconds of detection time
  - Cross validation for ruling out false positives
2.6 Large-Scale Deployment

- **Crowdsourcing Measurement**
  - Invited all the 250M Xiaomi’s users to participate, **70M opted in**
  - OS upgraded to Android-MOD
  - Duration: **Jan.- Aug. 2020 (8 months)**
  - Involved **34 device models**
  - Captured **2 billion** cellular failures, involving **16 million** user devices, **3 mobile ISPs** and **5 million** base stations

<table>
<thead>
<tr>
<th>Model</th>
<th>CPU</th>
<th>Memory</th>
<th>Storage</th>
<th>5G</th>
<th>Android</th>
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</tr>
</tbody>
</table>
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3.1 Prevalence & Duration

- As many as **33 cellular failures** occur to a phone on average
- 77% report no failures; a device can experience up to 198K failures
- Average failure duration is **3.1 minutes**
3.2 Hardware Configuration

- Failures occur prevalently on all the 34 studied phone models
- Prevalence varies from 0.15% to 45% and averages at 23%
- Prevalence and frequency tend to increase with better hardware!
3.3 5G Capability

- Prevalence and frequency are higher on 5G devices
- 5G modules inflict high workload on the network stack of Android
- Today’s production state of 5G modules is still immature
3.4 Android Version

- The 34 models run Android 9 and Android 10
- Despite quite a few improvements, Android 10 suffers more failures
- Android 10’s **blindly prioritizing 5G** impairs connection stability
- The situation of Android 11 is similar to that of Android 10
3.5 Data_Stall Recovery

- **Data_Stall**: 10 outbound TCP segments but no inbound in 1 min

- **Three-Stage Progressive Recovery**
  - **Lightweight**
    - Connection Cleanup & Restart
  - **Heavyweight**
    - Network Re-registration
    - Radio Restart

- **Effective but inefficient**
  - 60% Data_Stall failures are automatically fixed in just 10 seconds
  - Victim users would manually reset the data connection within ~30 seconds

![Graph showing CDF of Data_Stall Auto-Recovery Time]

- Min=0
- Median=3
- Mean=176
- Max=70,860
3.6 ISP & Base Station

- Failure distribution is quite skewed on BSes
- BSes with the most failures are mainly located in urban areas
- Failures are more prevalent on the users of ISP-B (China Telecom)

\[
\log(y) = -0.82 \log(x) + 17.12
\]
3.7 RAT & RSS

- Radio Access Technology (RAT): 3G BSes manifest fewer failures

- Received Signal Strength (RSS): excellent signal ≠ reliable connection!

- Excellent-RSS failures: densely-deployed BSes around public transport hubs, which increase LTE mobility management overhead
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4.1 Guidelines in Principle

- **General Guidelines**

- Failures are severer on 5G devices
- Android 10 is subject to more failures
- 3G BSes encounter fewer failures
- More failures under excellent (level-5) RSS
- Vendors should carefully validate 5G modules
- Sufficient testing should be conducted for new OS features
- Better utilization of the relatively “idle” infrastructures
- Coordinated BS deployment, e.g., cross-ISP infrastructure sharing
4.2 Real-World Practice (1)

- **Stability-Compatible RAT Transition**
  - Android 10’s *blindly prioritizing 5G* impairs connection stability
  - Taking the likelihood of cellular failures into account
  - Better reliability without sacrificing data rate
  - 4G/5G dual connectivity: smoother transition

![Diagram of cellular network connections](image)

Increase of normalized prevalence of cellular failures. **Deeper color represents larger increase**
4.3 Real-World Practice (2)

- Data_Stall: 10 outbound TCP segments but no inbound in 1 min
- Android’s Data_Stall Recovery: effective but inefficient

Key insight: the conceptual three-stage recovery is essentially a state transition process. We can formalize the overall recovery time with a Markov model.
4.3 Real-World Practice (2)

- **TIMP-based Flexible Data Stall Recovery**

Traditional Markov process

- Transition Probability Is Constant

Real-world scenario

- State Transition Depends on Elapsed Time

**Time-inhomogeneous Markov process (TIMP)** models transition in a **time-sensitive** manner

- Optimizing overall recovery time modeled by TIMP with our data to acquire more appropriate triggers

\[ \min T_{\text{recovery}}, \quad s.t. \ T_0 = T_{\text{recovery}}, \]

\[ T_i = \int_{\sigma P_{0 \rightarrow i} \rightarrow (t) dt} + \sigma P_{i \rightarrow i+1} \cdot T_{i+1} + O_i, \quad i = 0, 1, 2, 3. \]
4.4 Real-world Deployment and Evaluation

- **Patching the Two Enhancements in Android-MOD**
  - 40% of the 70M opt-in users upgraded, evaluated for two months
  - Failures occur **40.3% less frequently** on the 5G phones
  - **38% reduction** on the Data_Stall duration on average
5 Conclusion

- We conduct the first large-scale measurement of cellular reliability in the wild with more than 70M phones. We present our continuous monitoring infrastructure for capturing cellular failures on end devices.

- We identify critical factors affecting cellular reliability. In particular, we pinpoint that software reliability defects are among the main root causes of cellular data connection failures.

- We provide actionable insights for improving cellular reliability at scale. Most importantly, we have built on our insights to develop enhancements that yield remarkable real-world impact.

- Source code released at https://CellularReliability.github.io