Control-Plane Protocol Interactions in Cellular Networks

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* The first two authors contribute equally to this work.

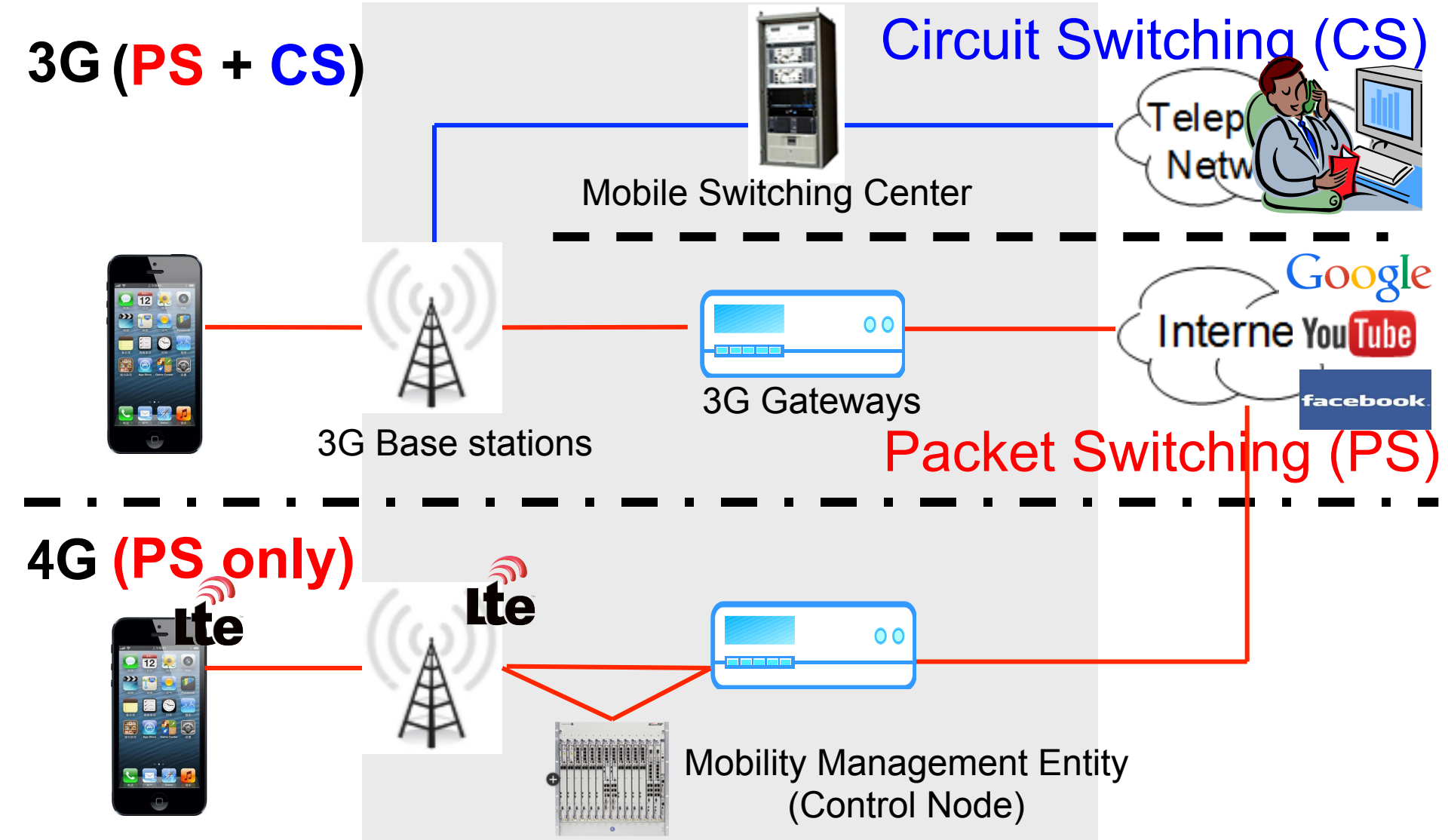
Cellular Services are Ubiquitous

- Large-scale wireless infrastructure
- Offer data and voice services to *anyone, anywhere, anytime*

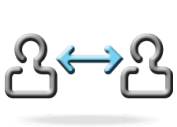
6.8+ billion

Source: http://www.4gamericas.org/

Cellular Network Architecture



Control Plane in Cellular Network

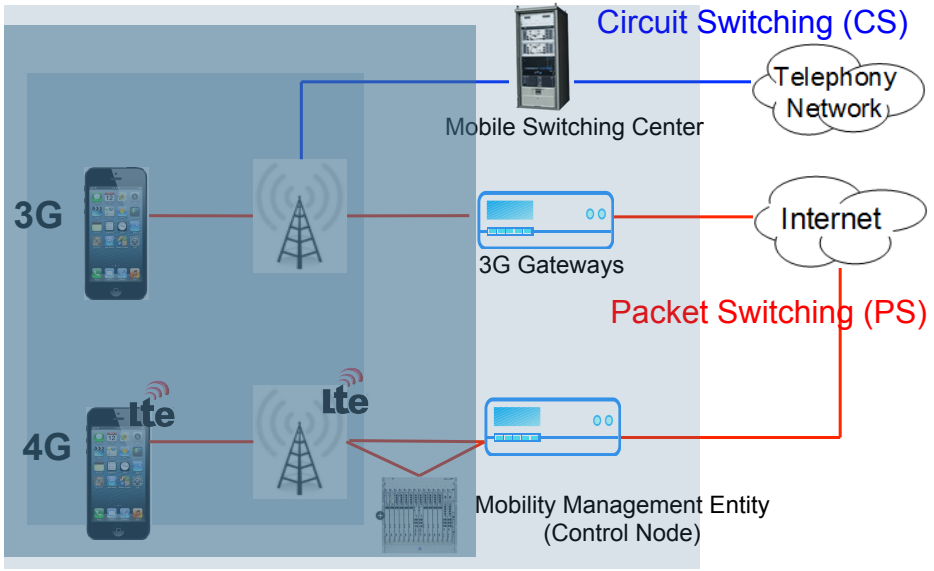


Connectivity Management (CM)

Mobility Management (MM)

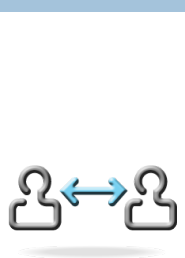
Radio Resource Control (RRC)

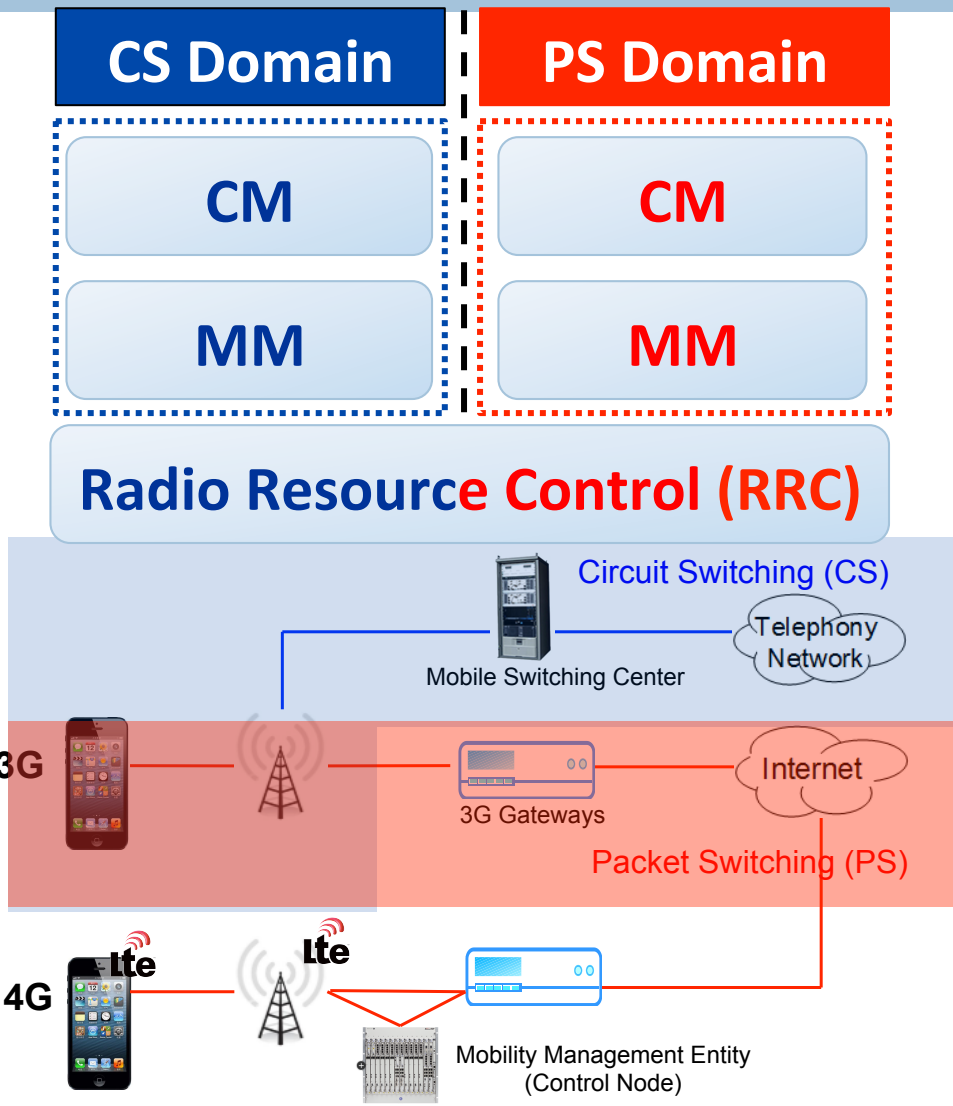
- Layered protocol stack



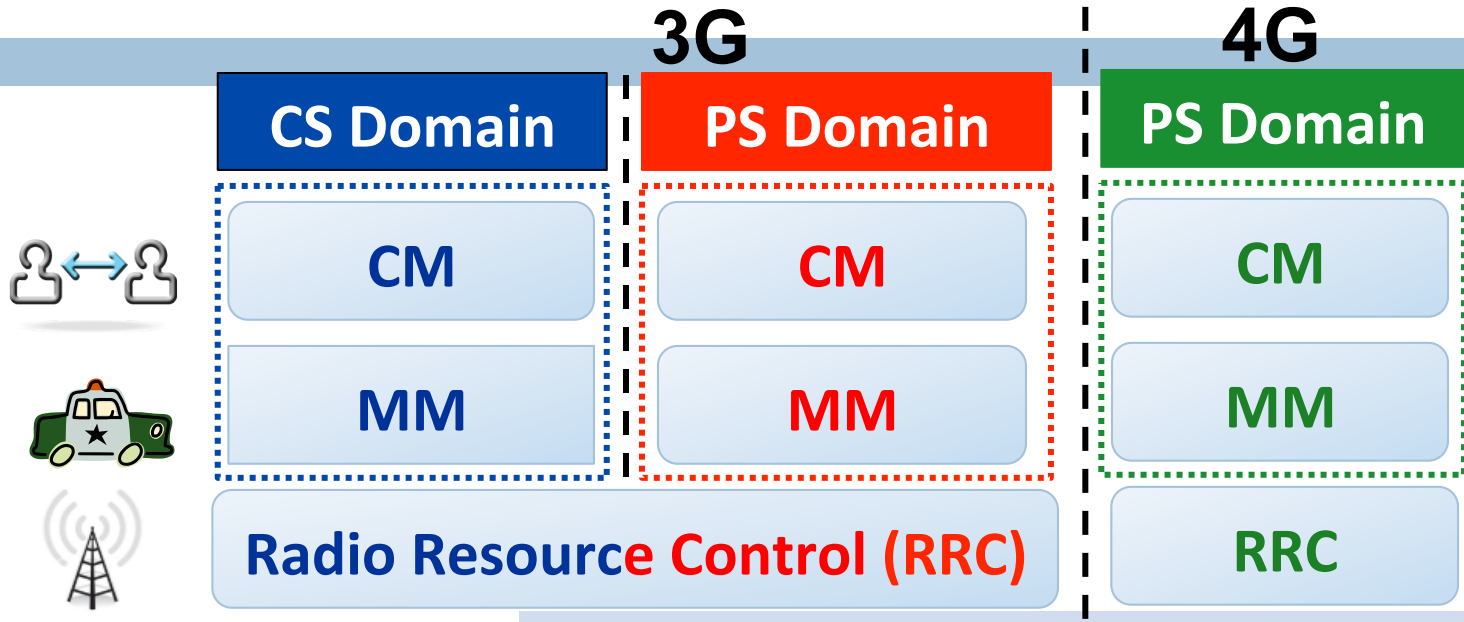
Control Plane in Cellular Network

- Layered protocol stack
- Domains separated for voice (CS) and data (PS)

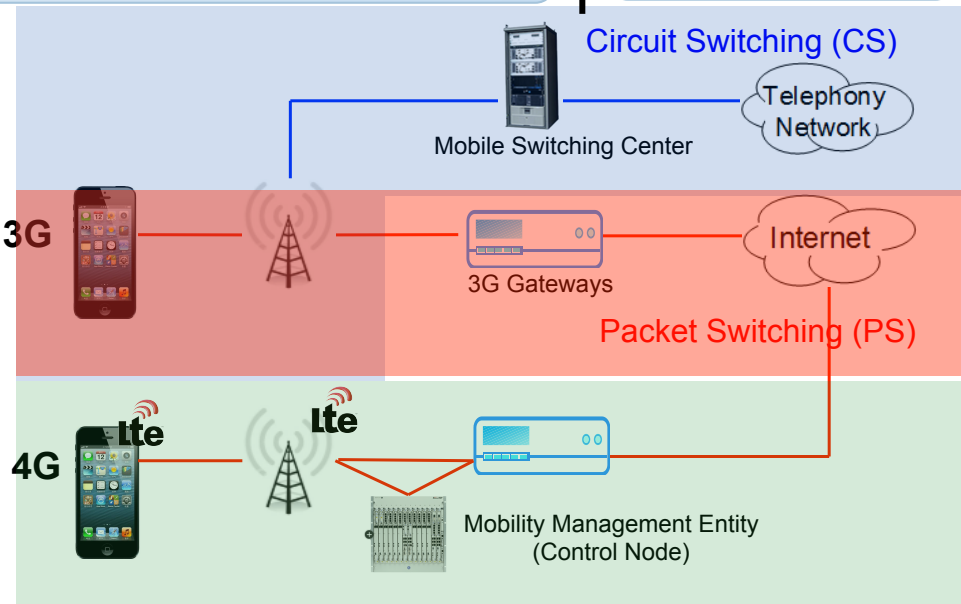




Control Plane in Cellular Network

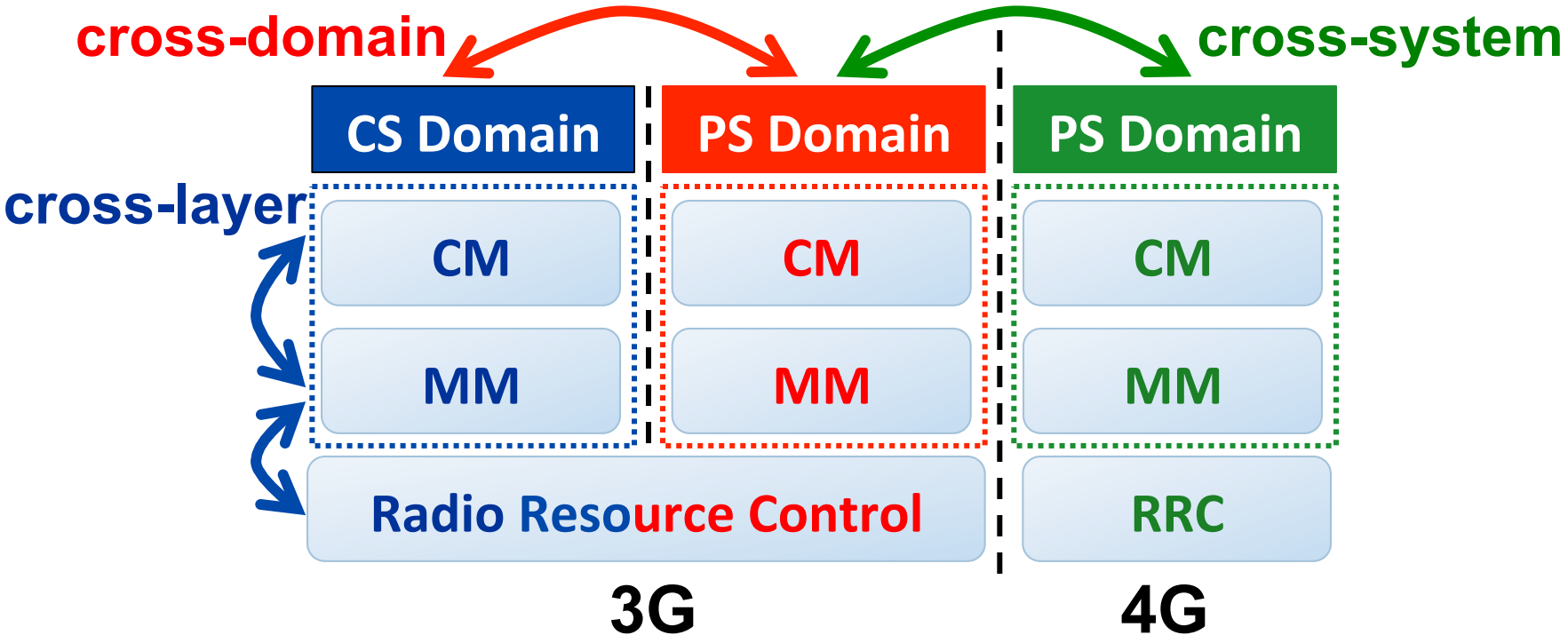


- Layered protocol stack
- Domains separated for voice (CS) and data (PS)
- Hybrid 3G/4G systems



Complex Interactions

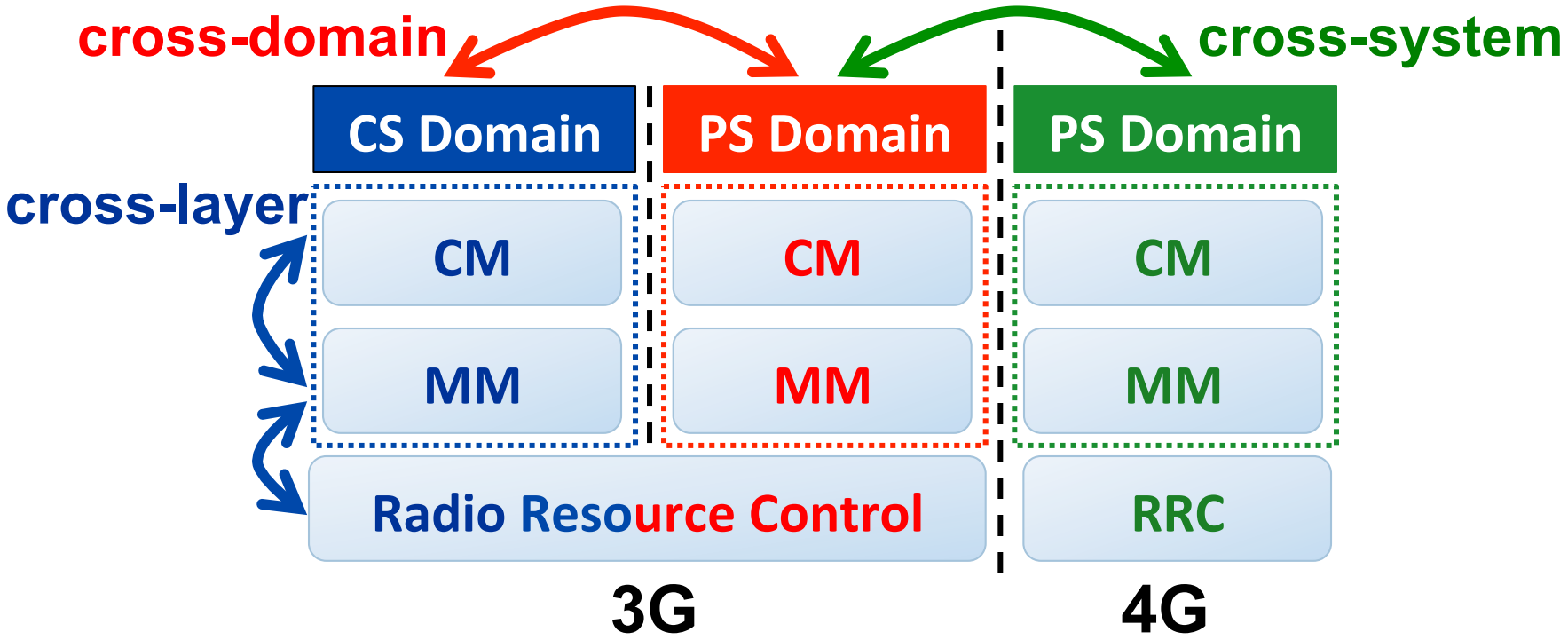
- Protocols **work together** to offer vital 3G/4G utilities
- Rich patterns along three dimensions



Problem:

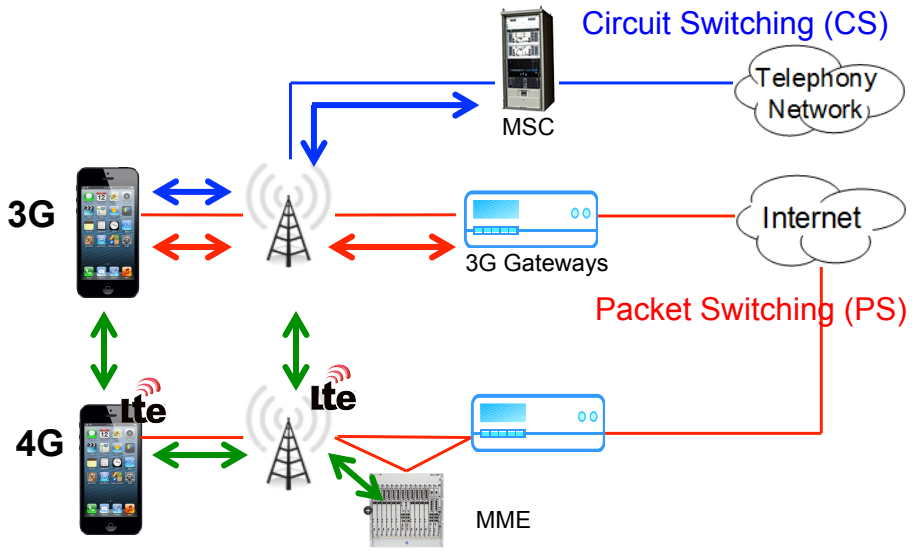
Each individual protocol may be well designed.

How about protocol interactions?



Rich Protocol Interactions

- Complex interactions in common scenarios
  - Inevitable interplay between radio, mobility, data/voice
  - Concurrent voice and data use
  - 3G/4G switch due to hybrid deployment, mobility, voice
- Two causes of problematic interactions
  - Design defects
  - Operation/Implementation slips



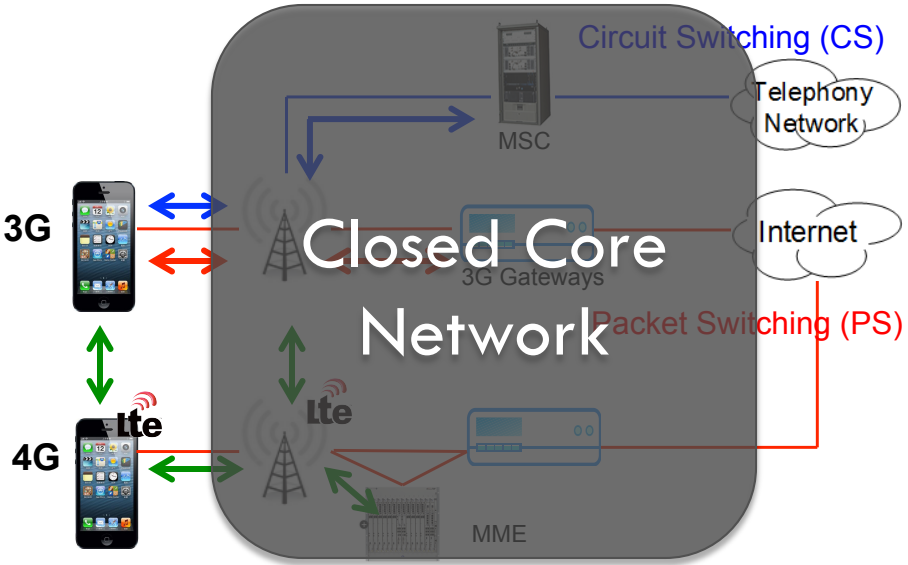
Rich Protocol Interactions

- Complex interactions in common scenarios

Diagnosis over one layer/domain/system is insufficient

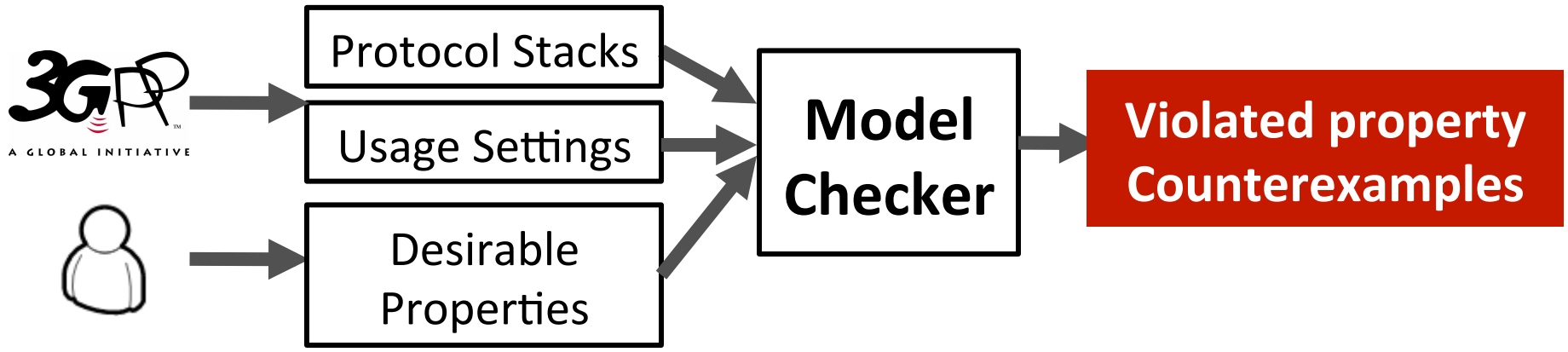
- Two causes of problematic interactions

Single-type test fails to unveil both issues



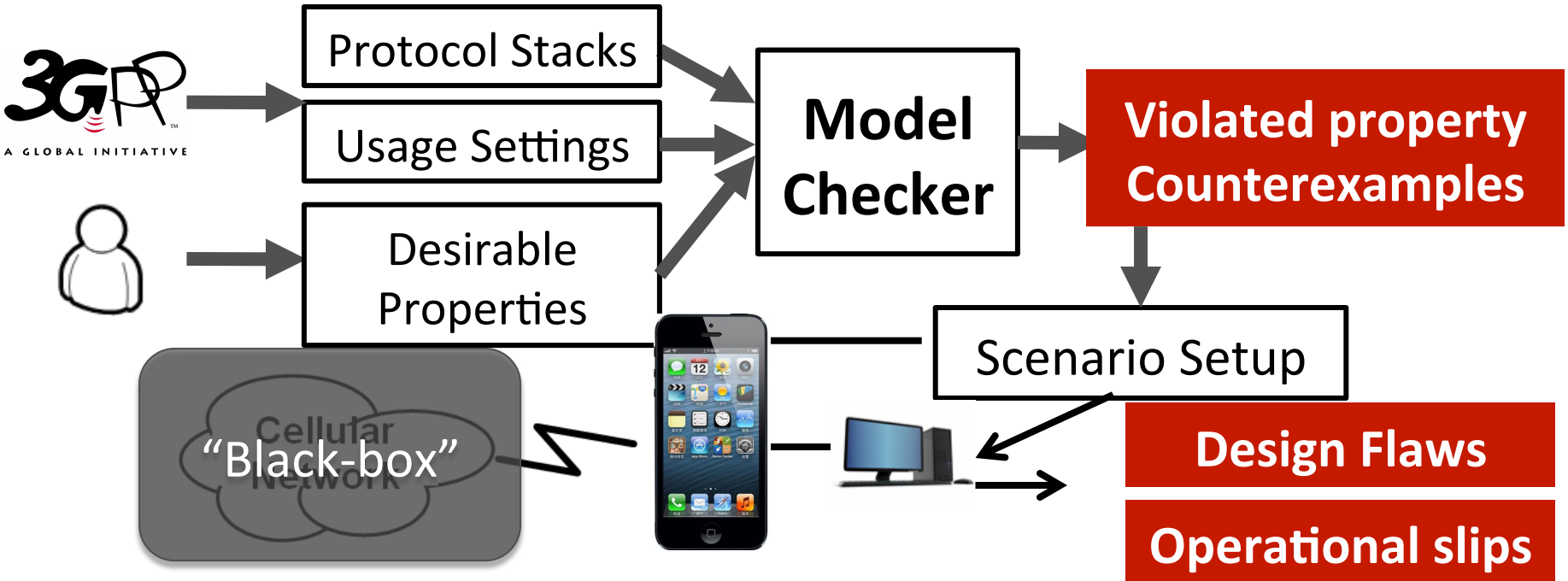
Our Solution: CNetVerifier

- Cellular-specific model checking
  - Extract full-stack cellular model from 3GPP standards
  - Create a variety of usage scenarios
  - Define desirable user-perspective properties
  - Discover counterexamples for possible design defects



Our Solution: CNetVerifier

- Cellular-specific model checking
- Phone-based experimental validation
  - Instrument end devices to collect traces for verification
  - Discover operational slips in real networks

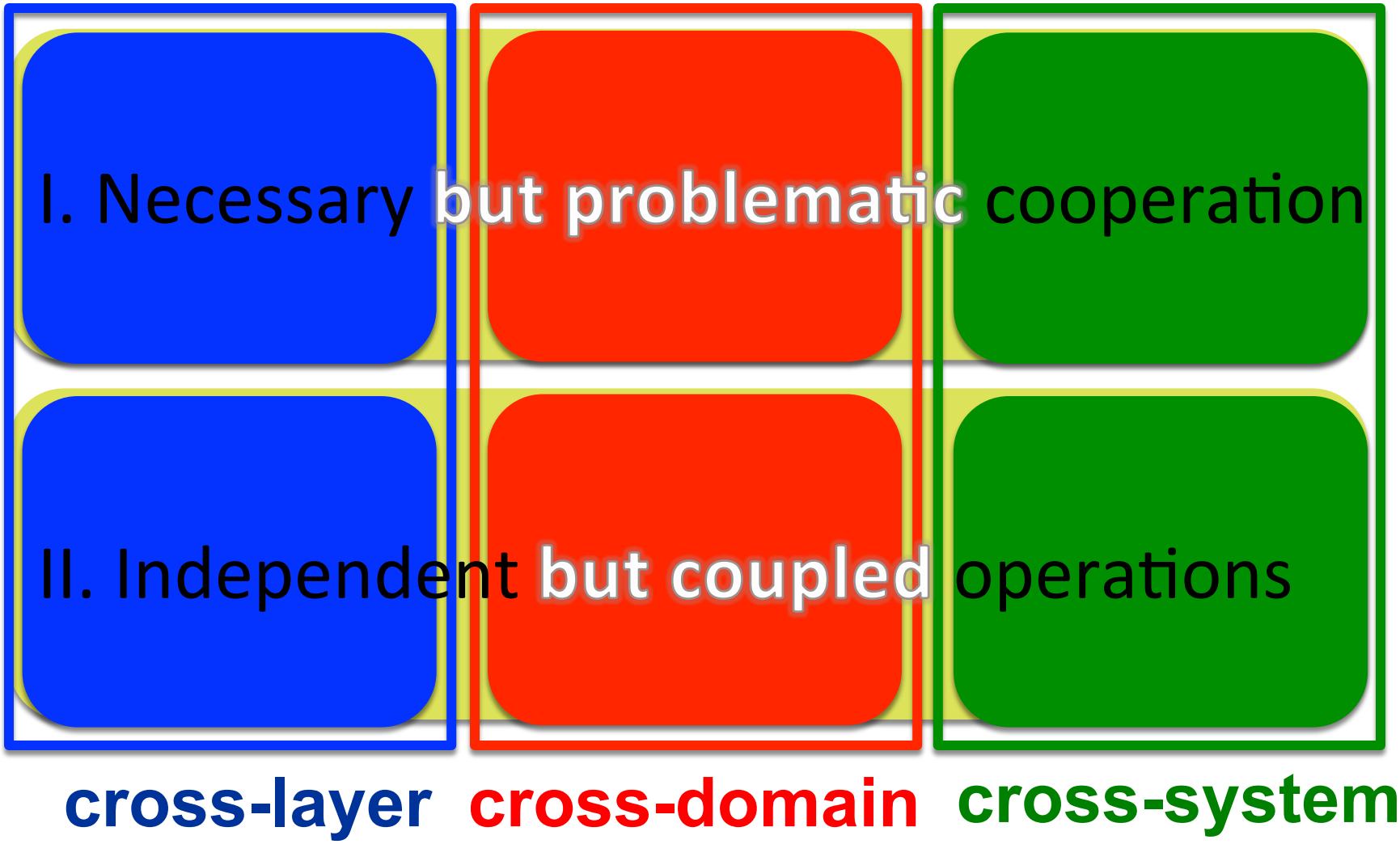


Finding Overview

I. Necessary but problematic cooperation

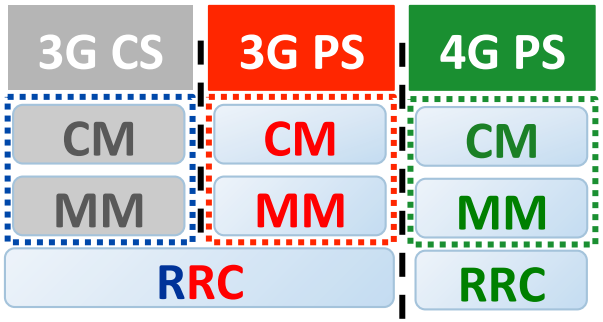
II. Independent but coupled operations

Finding Overview

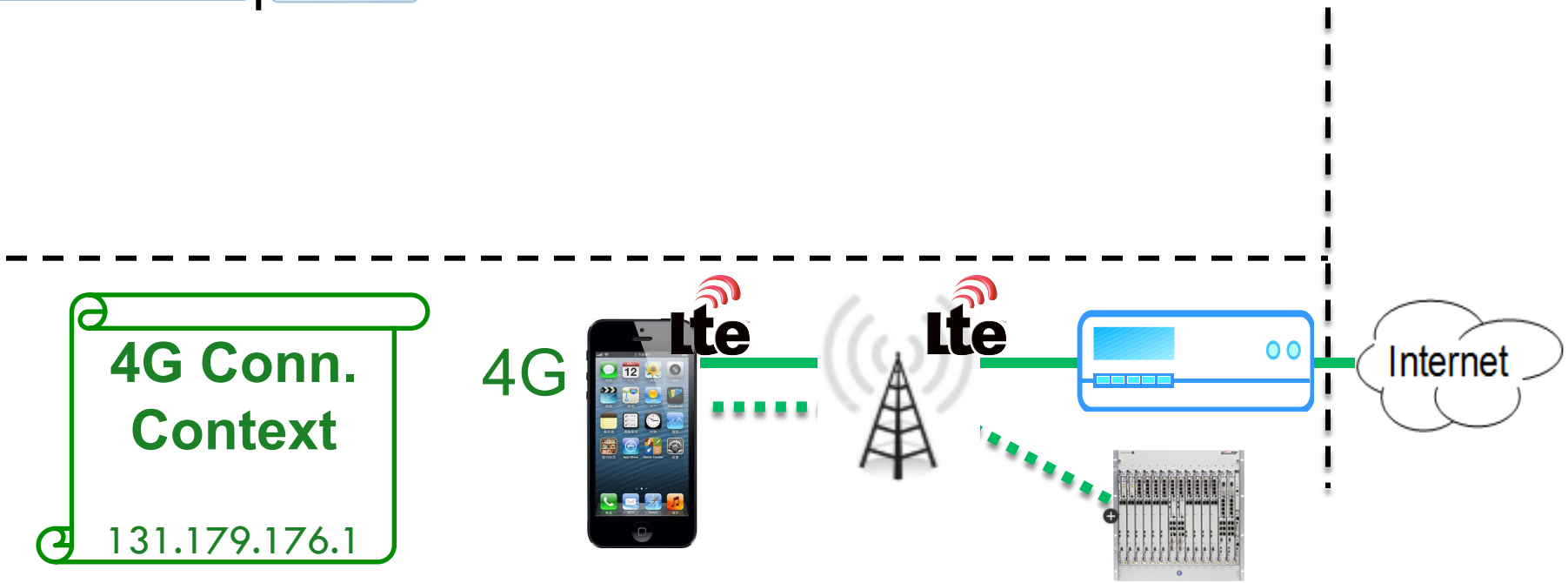


Improper cooperation: Cross-System

- Scenario: run data services during 4G→3G→4G



1. Setup 4G connectivity to access internet



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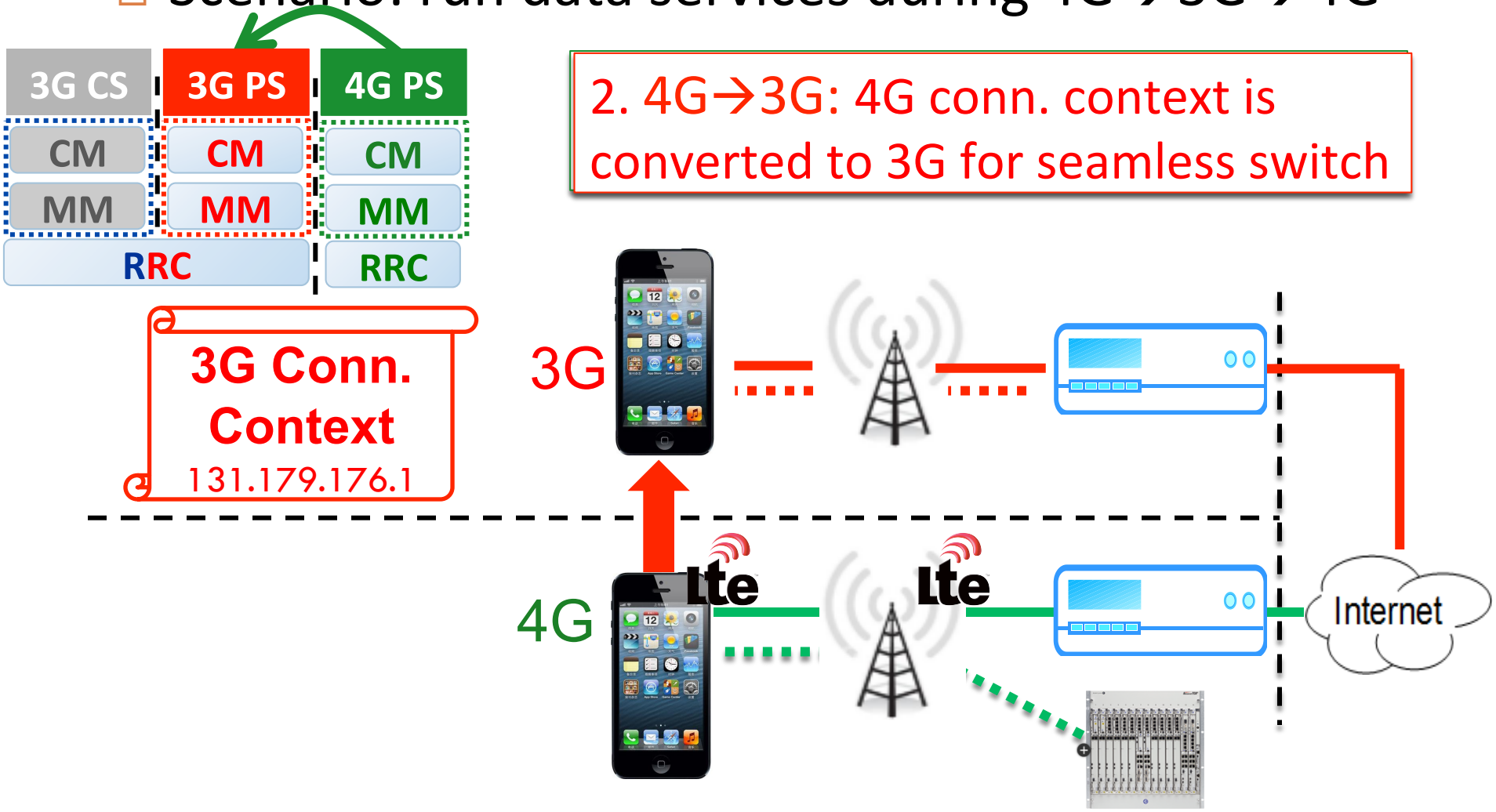

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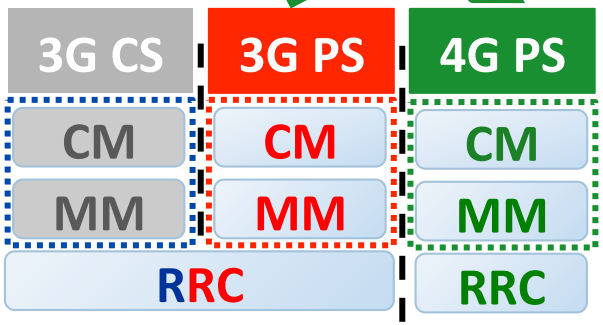
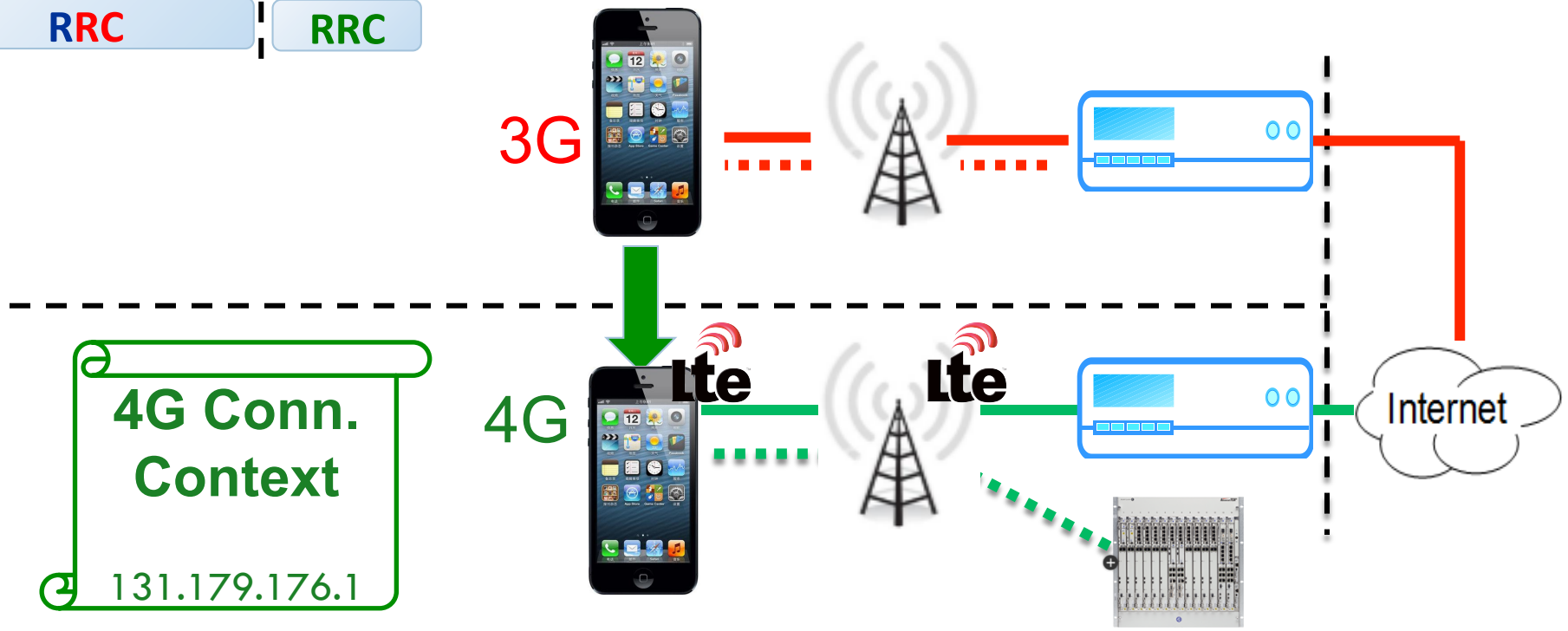
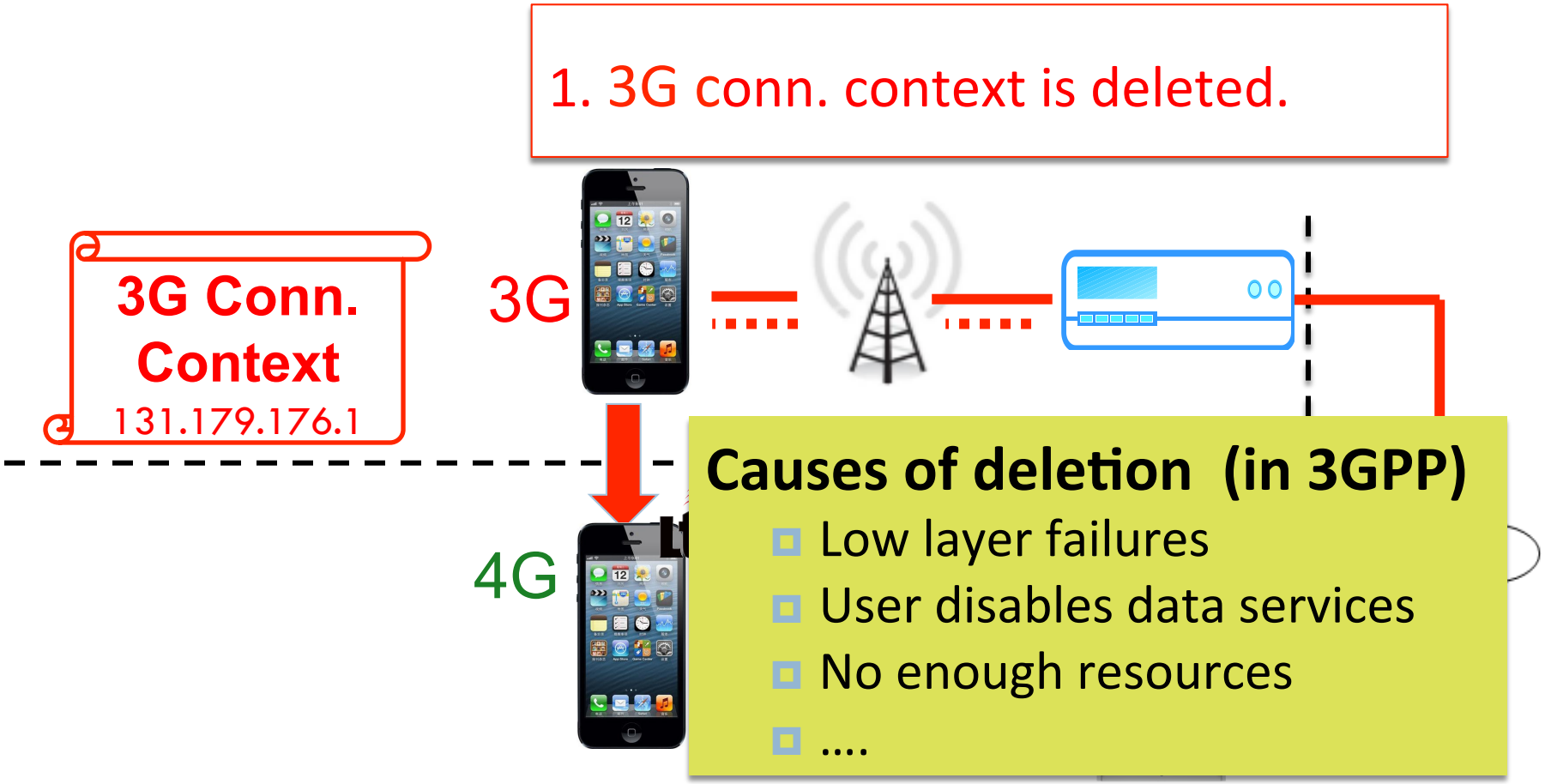


3. 3G→4G: 3G conn. context is converted back to 4G



Improper cooperation: Cross-System
How and why?

- Problematic scenario: **3G context is deleted** before returning to 4G



Improper cooperation: Cross-System
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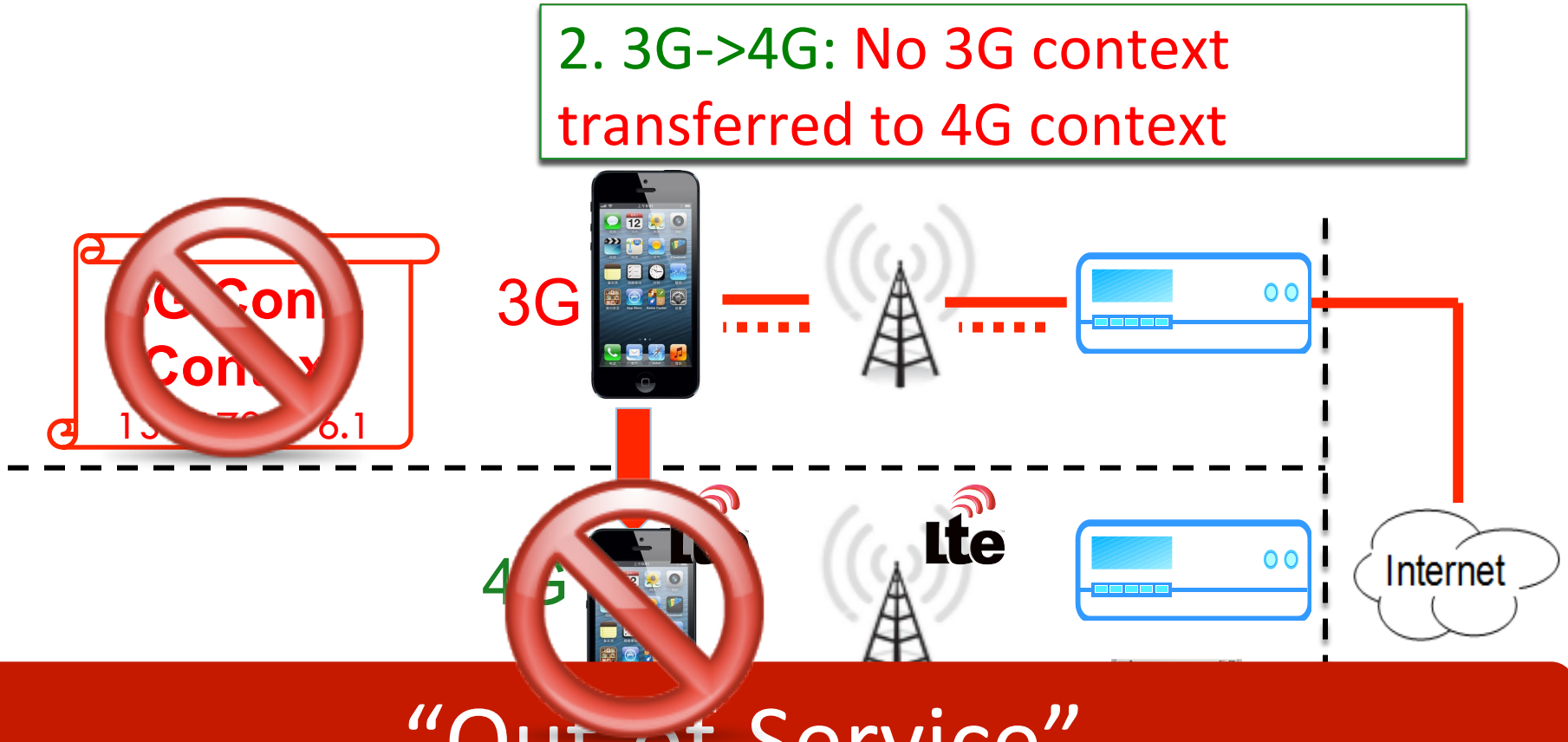


Improper cooperation: Cross-System

How and why?

- Problematic scenario: **3G context is deleted** before returning to 4G

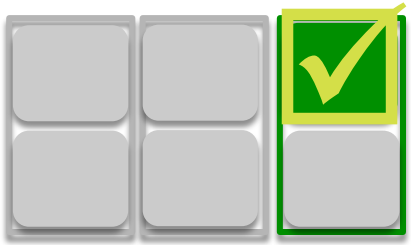
2. 3G->4G: No 3G context

*PS conn context is **not mandatory in 3G** **(PS+CS)**,*

*but **mandatory in 4G** **(PS only)***

Shared context** **for 4G and 3G** **is not well protected** **in 3G

"Out-of-Service"

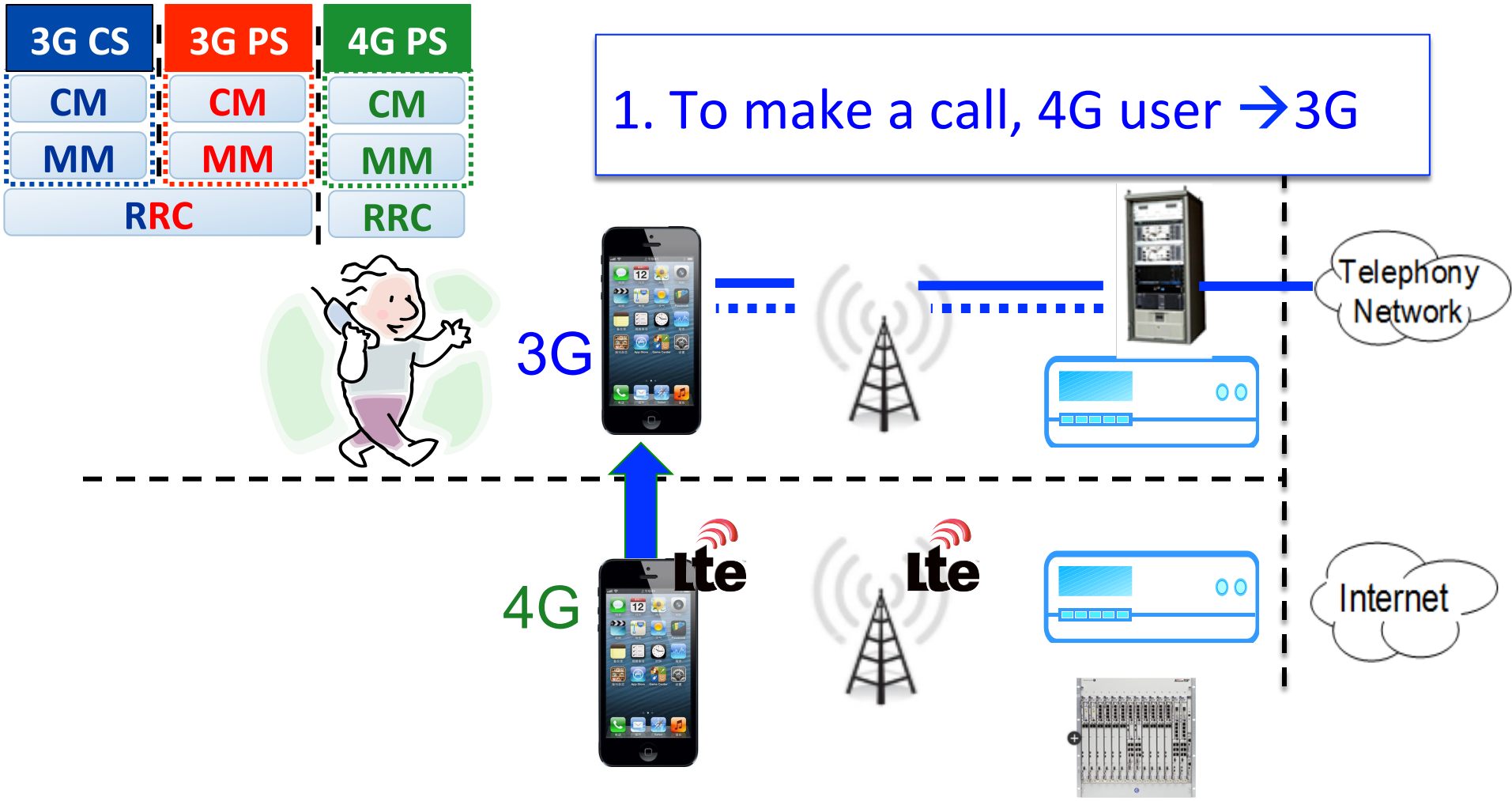


Improper cooperation: Cross-System

- **Real-world impact**
  - Occurs 3.1% in user study
  - "out-of-service" for up to 25s
- **Lessons: a design defect**
  - Different demands of packet switching in 3G & 4G
  - Desirable but not enforced: shared context should be consistently protected in 4G & 3G
- **Proposed remedies**
  - Avoid unnecessary 3G PS context deactivation
  - Immediately enable 4G PS context reactivation

Improper cooperation: cross-domain+system

- Scenario: 4G users make calls via 3G CS Fallback



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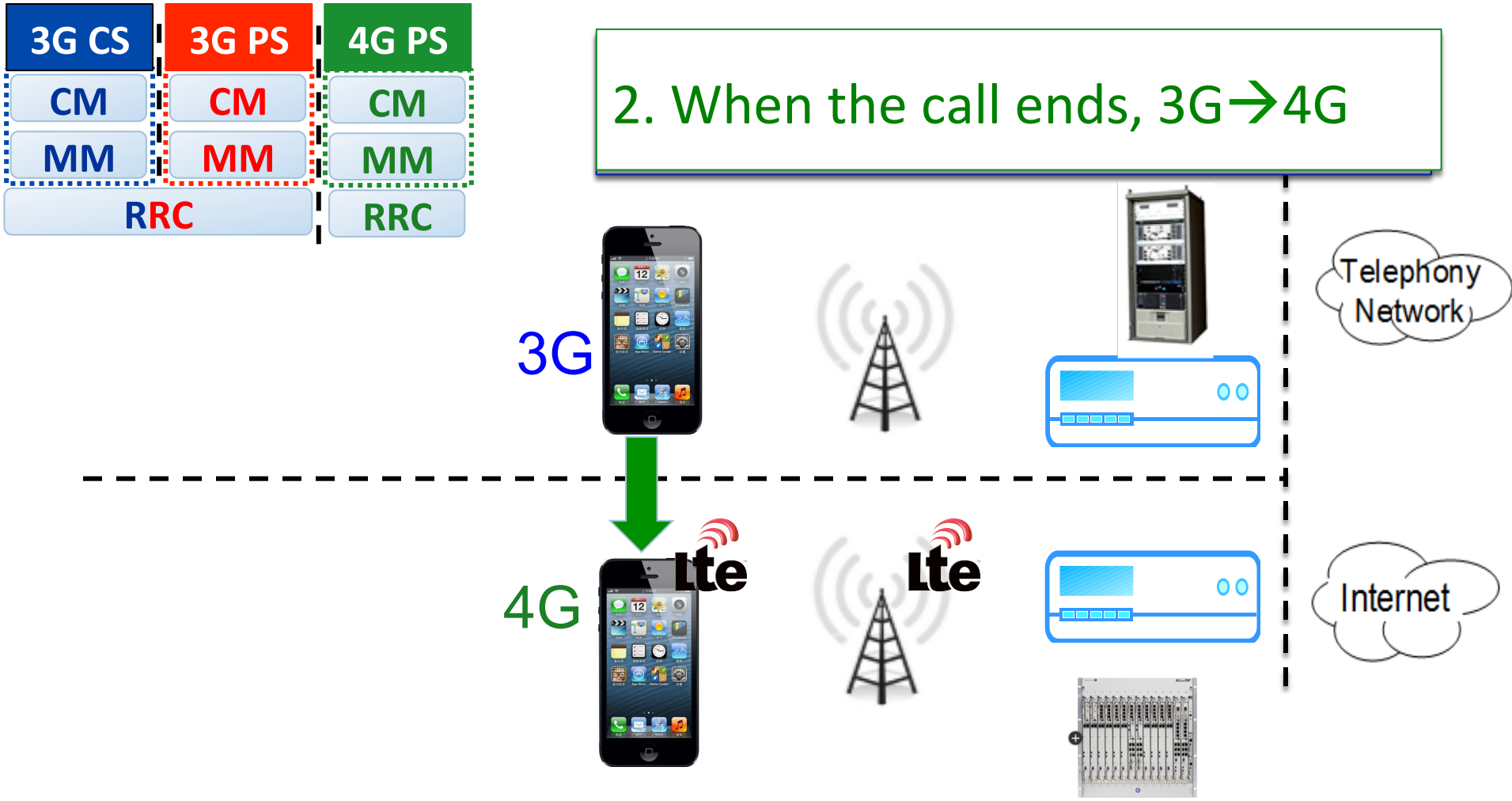
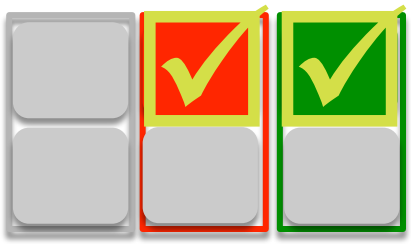
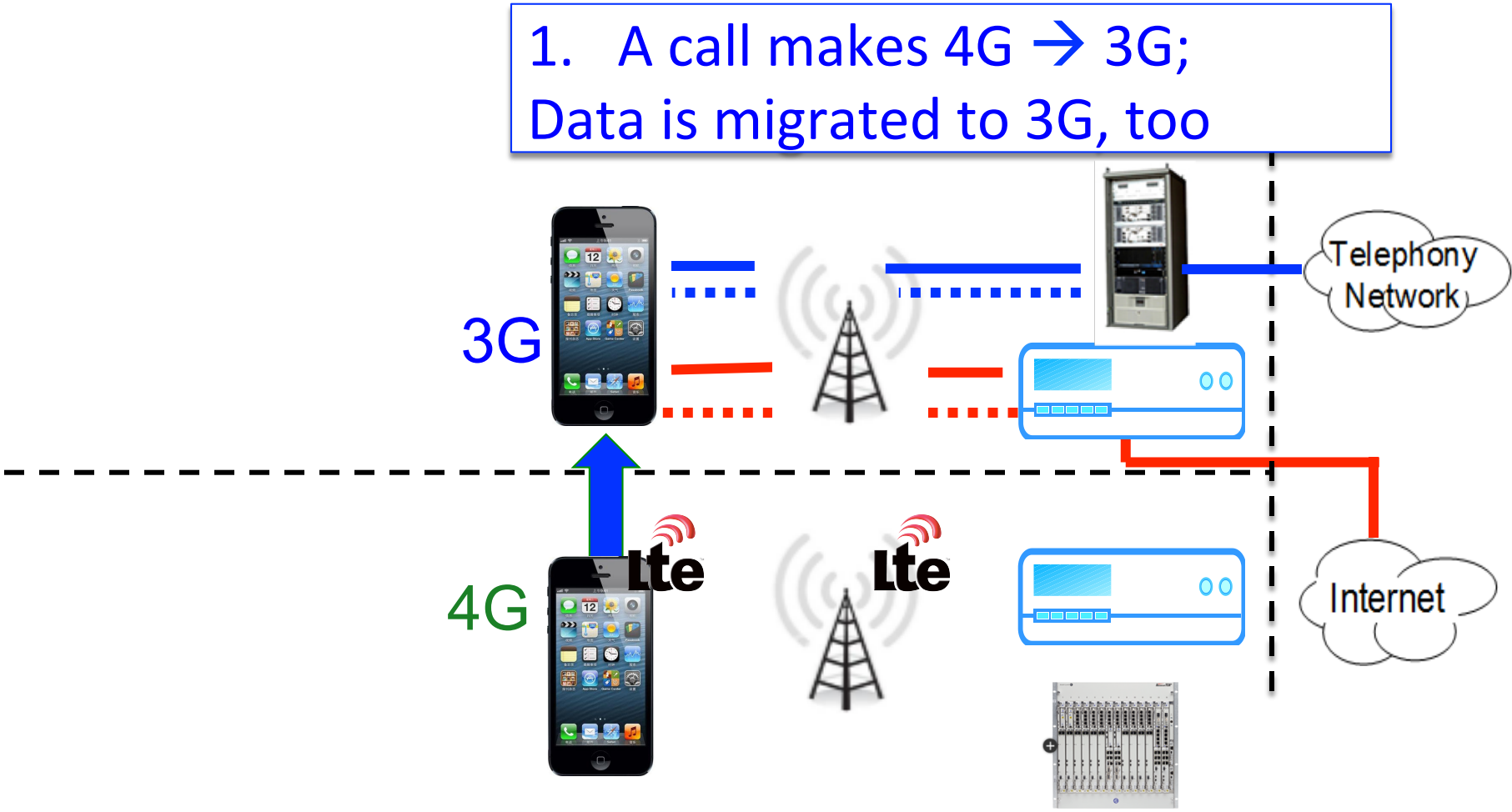


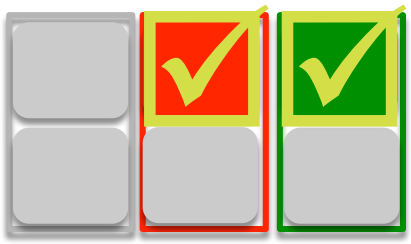


Improper cooperation: cross-domain+system

How and Why?

- Problematic Scenario: Call with background data





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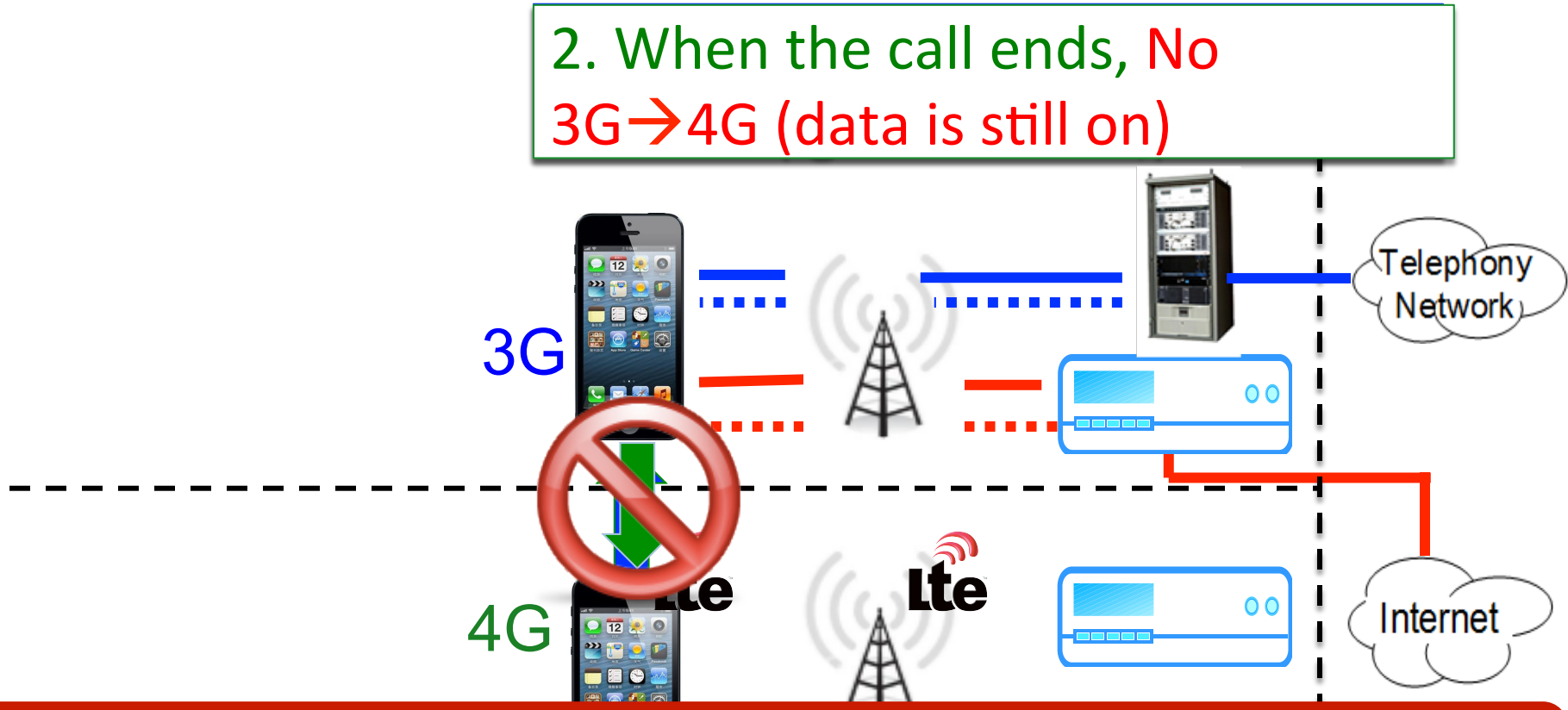
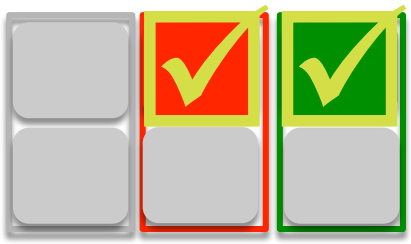


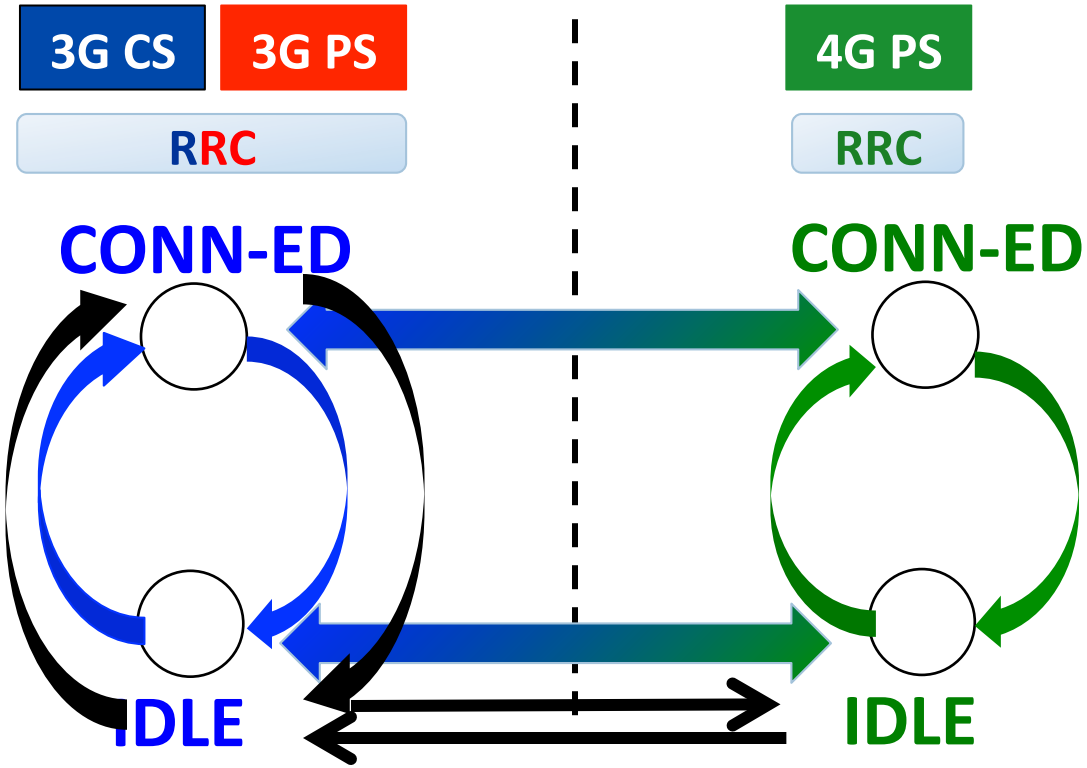
User gets stuck in 3G, losing 4G.

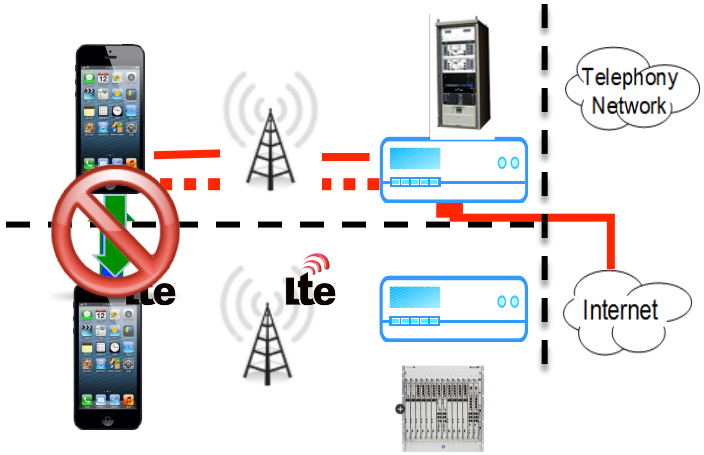


Improper cooperation: cross-domain+system

How and Why?

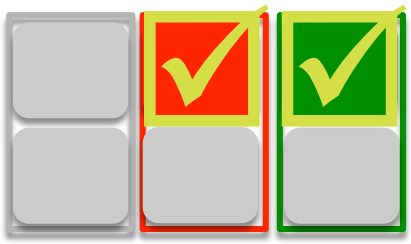
- Unexpected loop in RRC state machine





Voice only

User gets stuck in 3G, losing 4G.



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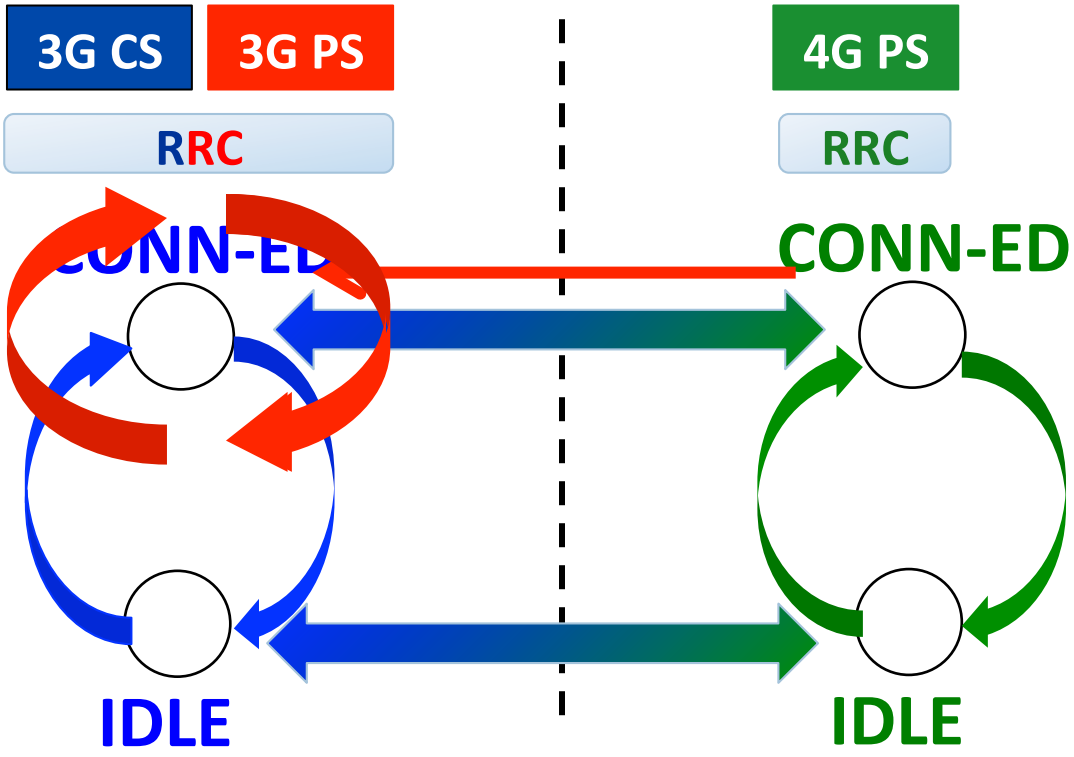
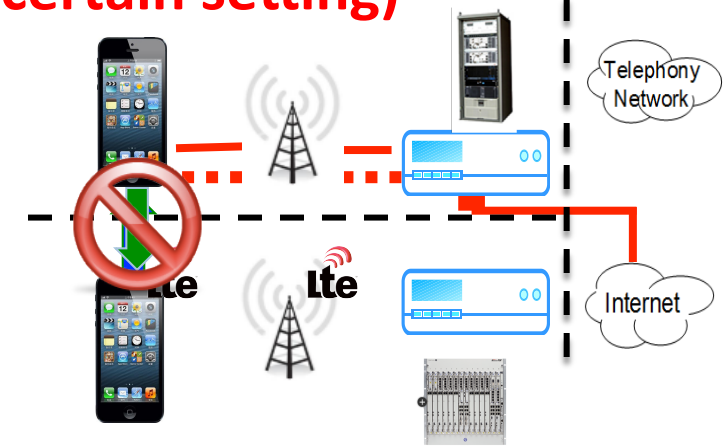


Voice + Data

(certain setting)



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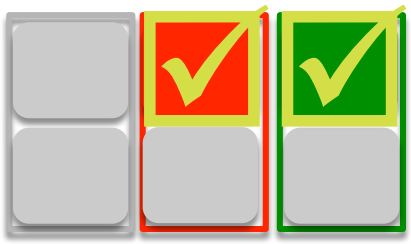

Improper cooperation: cross-domain+system

How and Why?

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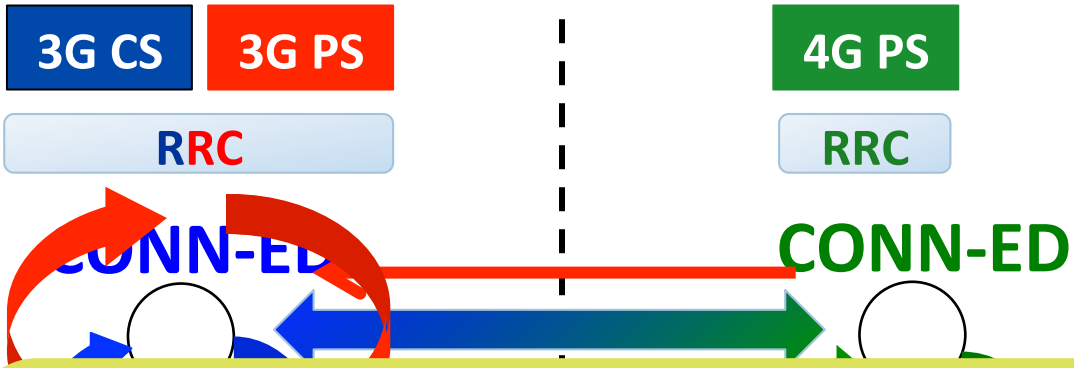
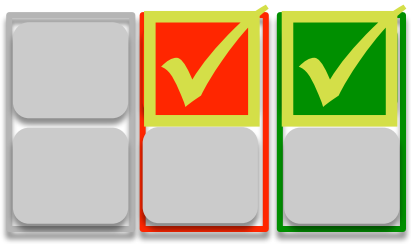


Voice + Data

(certain setting)

RRC state transition is inconsistent with dual-domain, inter-system settings

User gets stuck in 3G, losing 4G.



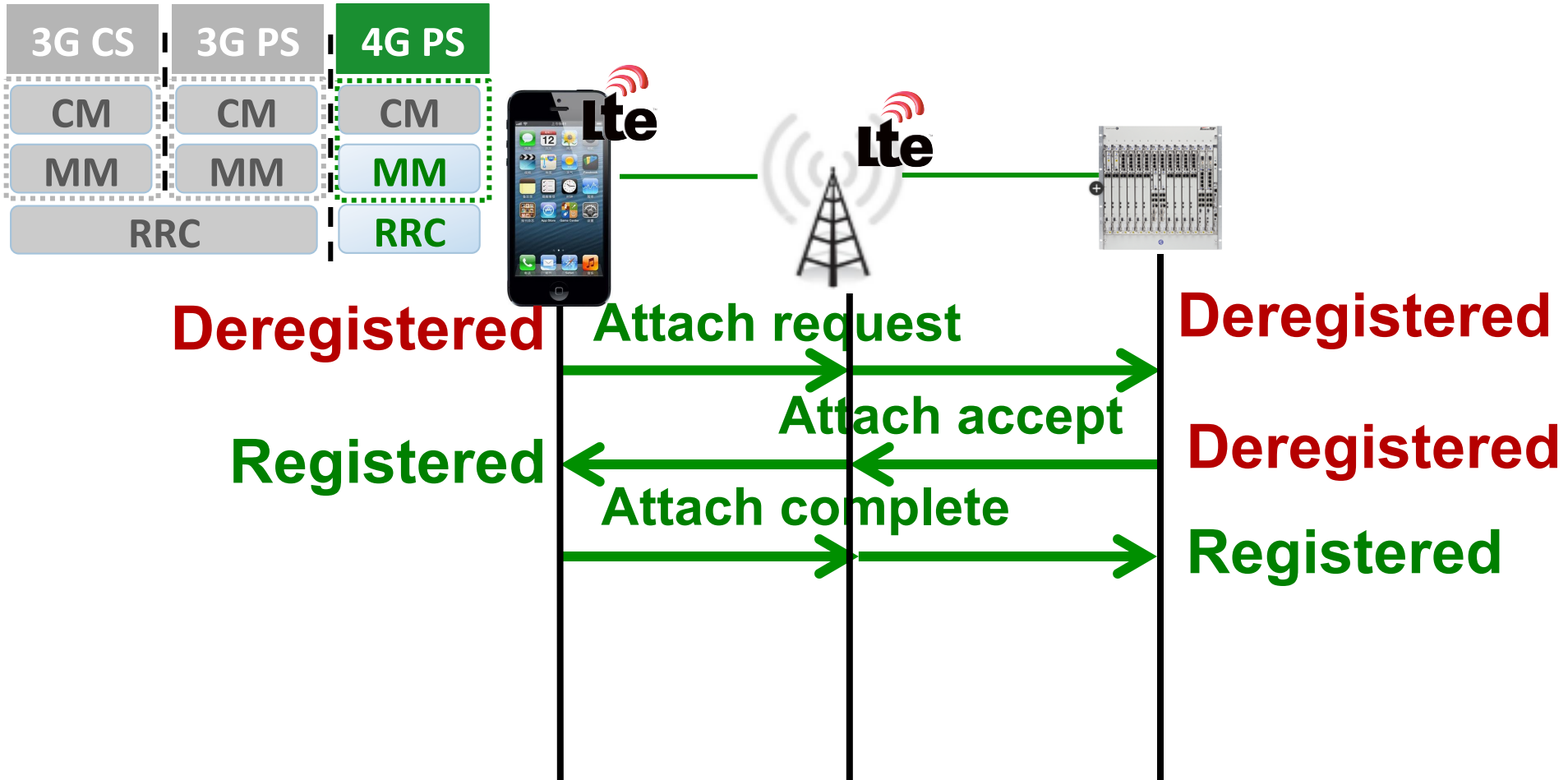
Improper cooperation: cross-domain+system

- **Real-world impact**
  - 62.1% 4G users being stuck in 3G after the call
  - Stuck in 3G for 39.6s in average
- **Lessons: a design defect**
  - 3G CS and 3G PS are **indirectly** coupled in RRC
  - Inconsistent state transition with all 3G→4G options
- **Proposed remedies**
  - Revise the RRC state transition for possible settings

Improper cooperation: Cross-Layer

How and why?

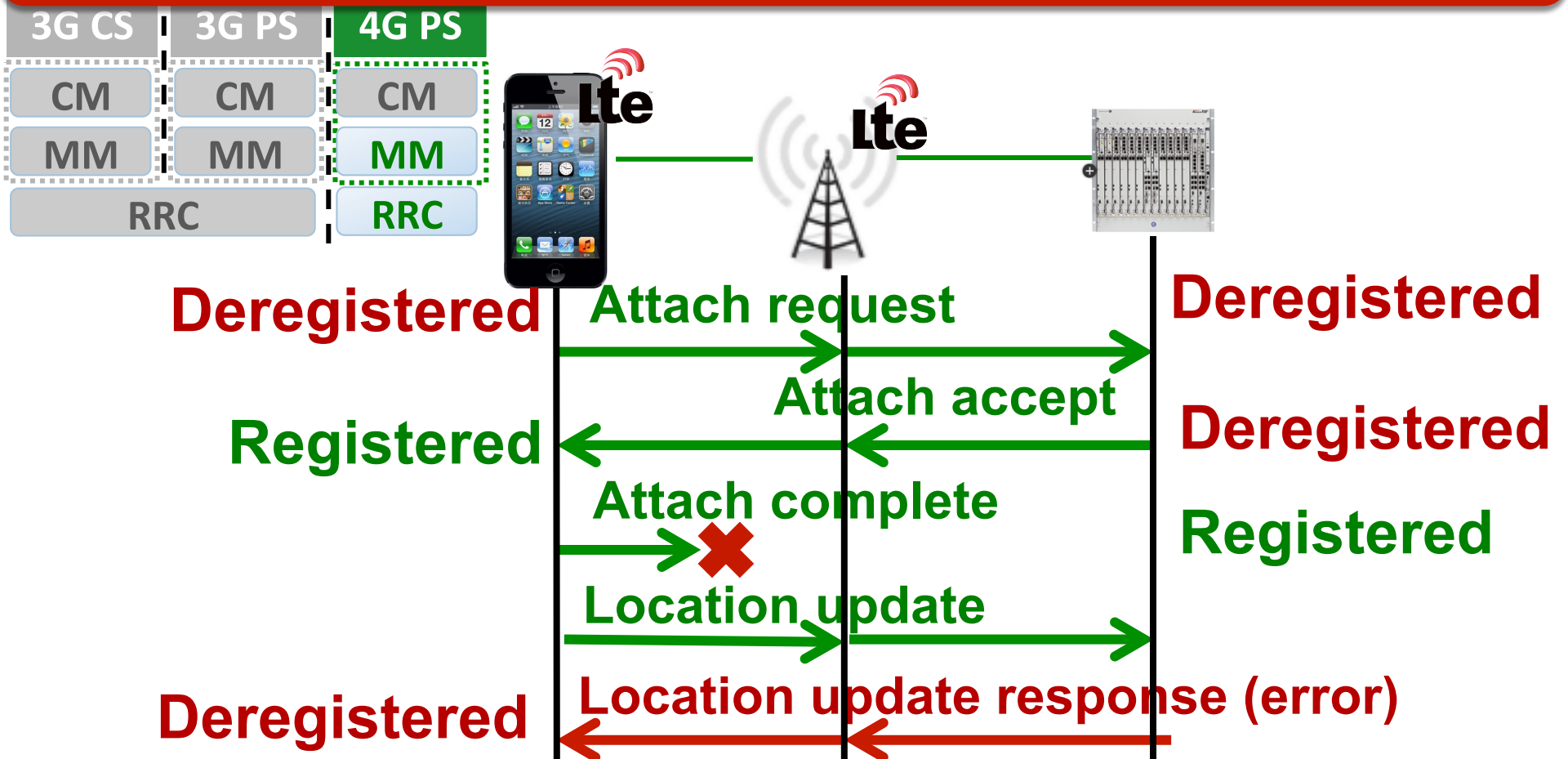
- Problem Scenario: Signaling loss for registration

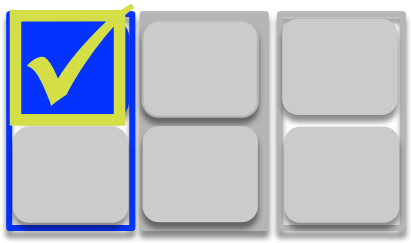


Improper cooperation: Cross-Layer

How and why?

"out-of-service" right after being attached





Improper cooperation: Cross-Layer

How and why?

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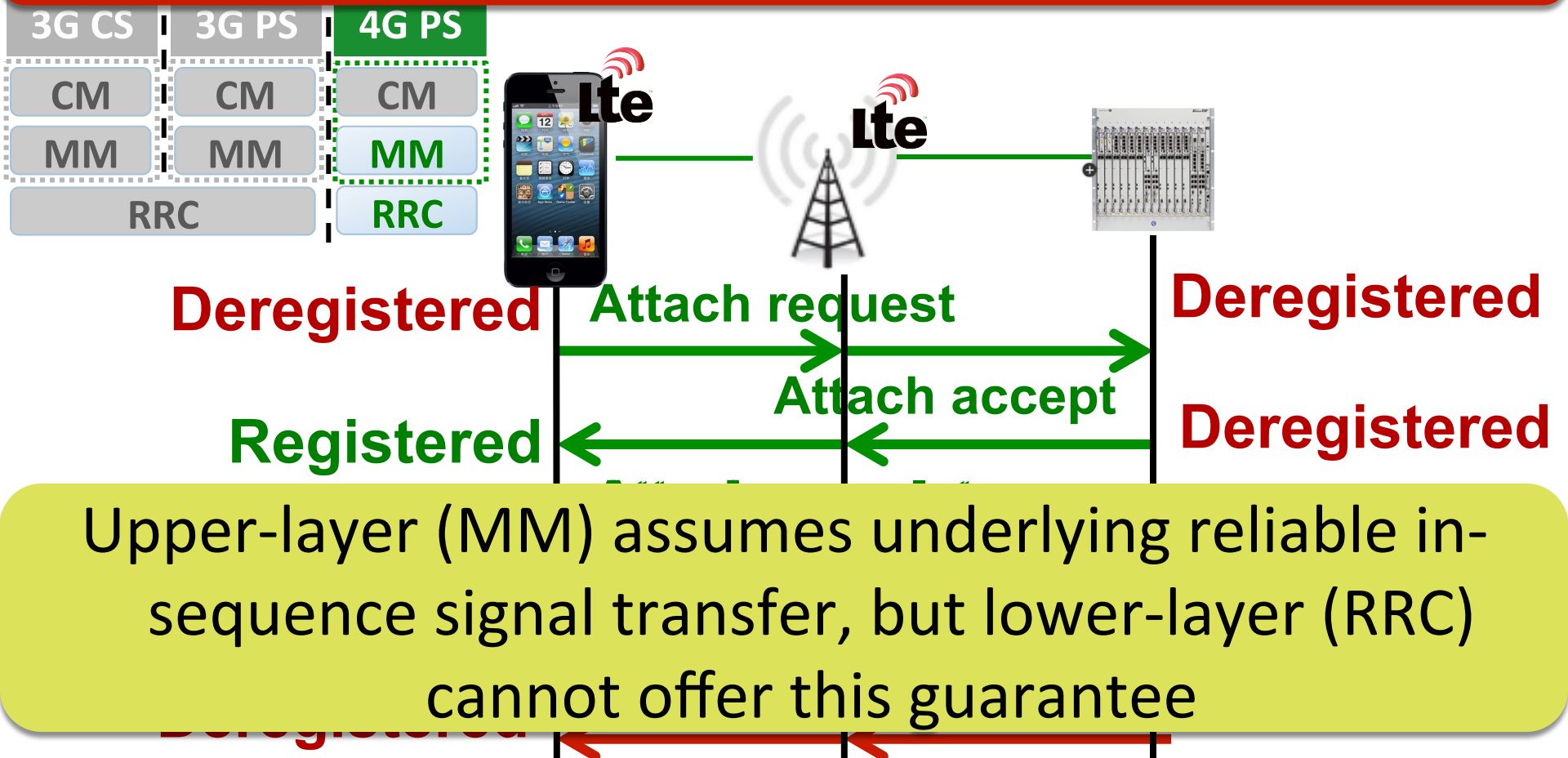
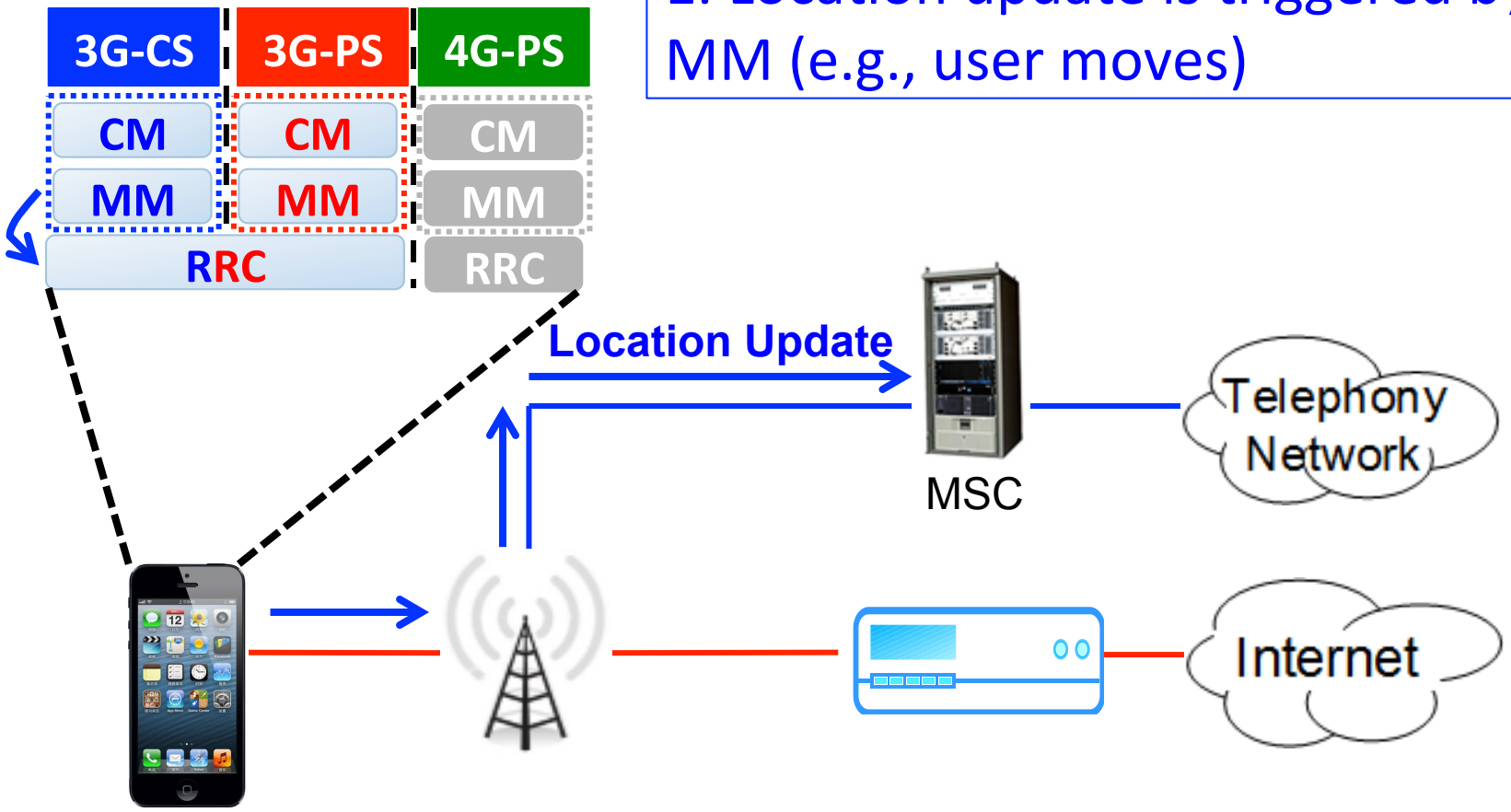


Upper-layer (MM) assumes underlying reliable in-sequence signal transfer, but lower-layer (RRC) cannot offer this guarantee

Unnecessary Coupling: Cross-layer

- Scenario: voice/data request with location update

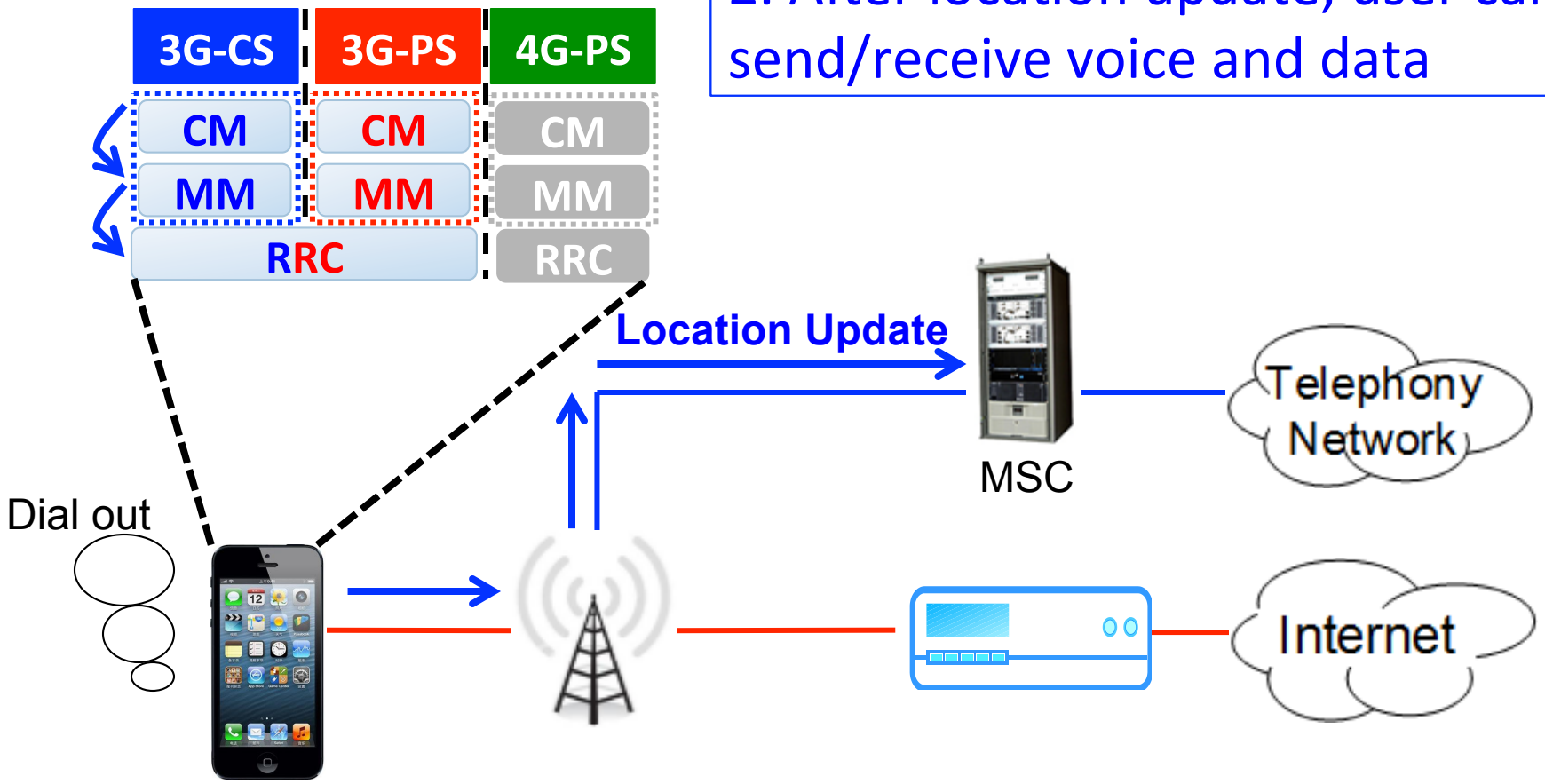
1. Location update is triggered by MM (e.g., user moves)



Unnecessary Coupling: Cross-layer

- Scenario: voice/data request with location update

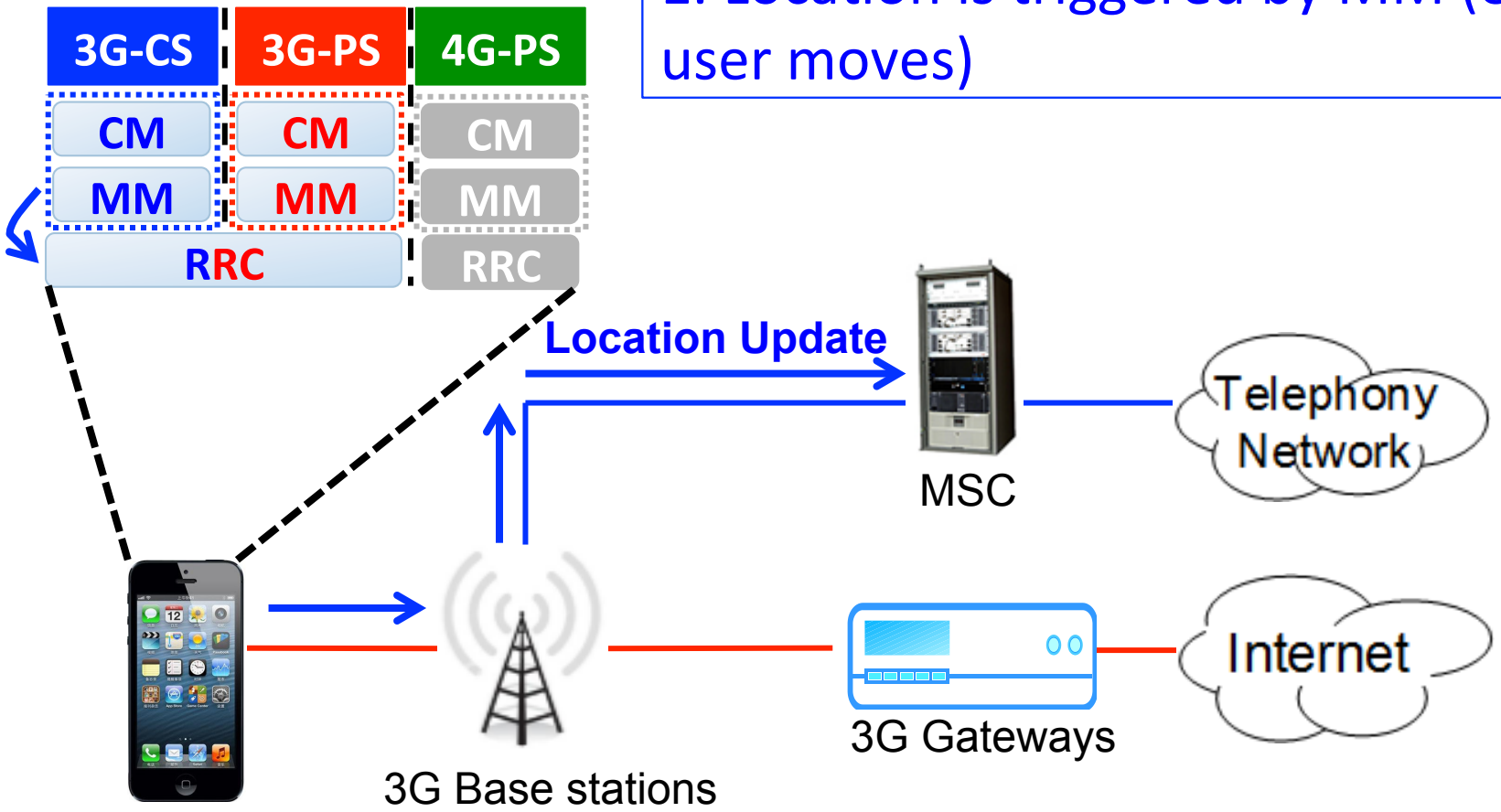
2. After location update, user can send/receive voice and data



Unnecessary Coupling: Cross-layer
How and why?

- Problematic Scenario: voice/data request during the location update

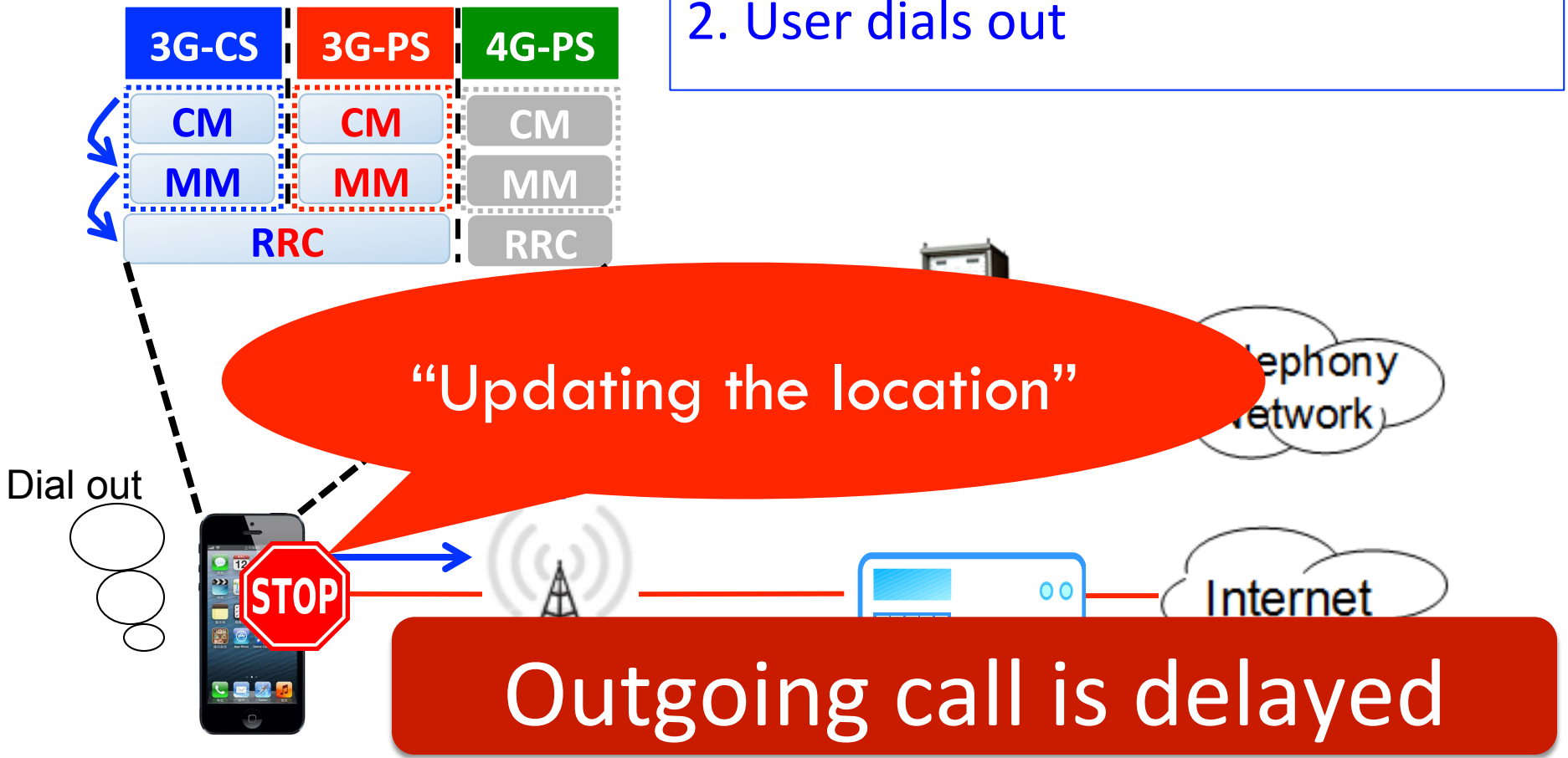
1. Location is triggered by MM (e.g., user moves)



Unnecessary Coupling: Cross-layer
How and why?

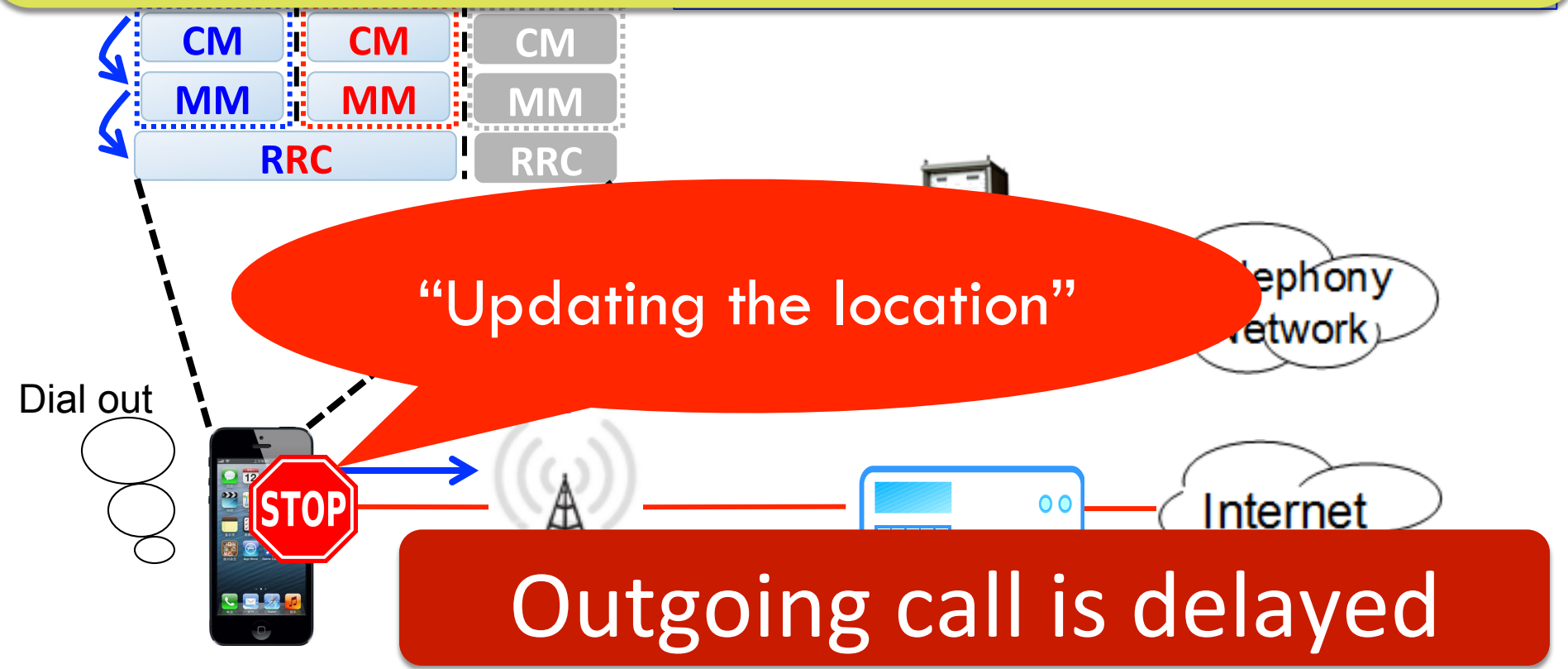
- Problematic Scenario: voice/data request during the location update

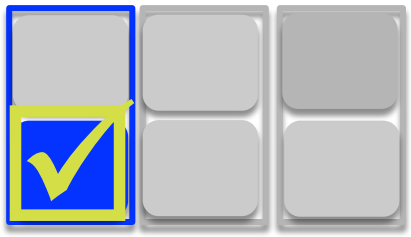
2. User dials out



Unnecessary Coupling: Cross-layer
How and why?

"Without user location, the cellular network cannot route user voice/data."



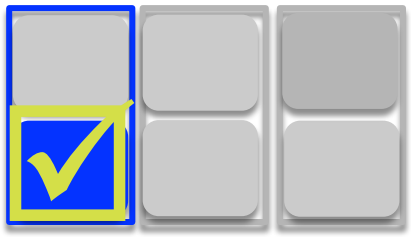


Unnecessary Coupling: Cross-layer
How and why?

~~*"Without user location, the cellular network cannot route user voice/data."*~~

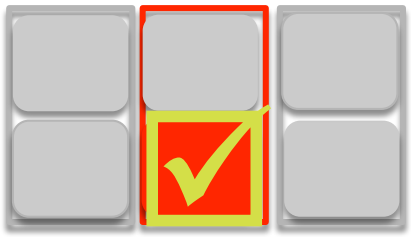
Outgoing voice/data requests can be routed without user location

Unnecessary prioritization of location update over outgoing call/data



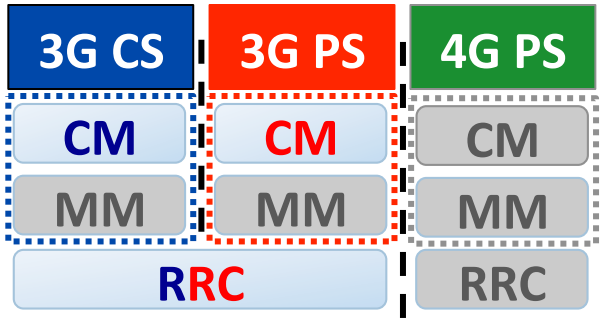
Unnecessary Coupling: Cross-layer

- **Real-world Impact**
  - up to 8.3s call delay and 4.1s data delay
  - 7.6% of outgoing calls occur during location update
- **Lessons: a design defect**
  - outgoing data/voice requests and location update are independent, but they are artificially correlated
- **Proposed remedies**
  - Decouple location update and outgoing data/voice requests
  - E.g., two parallel MM threads for different purposes



Unnecessary Coupling: Cross-domain

- Scenario: dial a call during data service in 3G



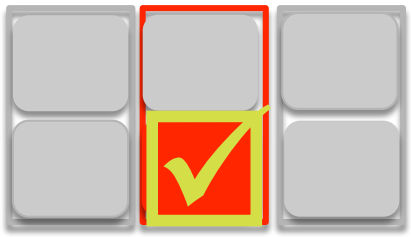
Circuit Switching (CS)

Packet Switching (PS)

3G

10Mbps

10Mbps



Unnecessary Coupling: Cross-domain

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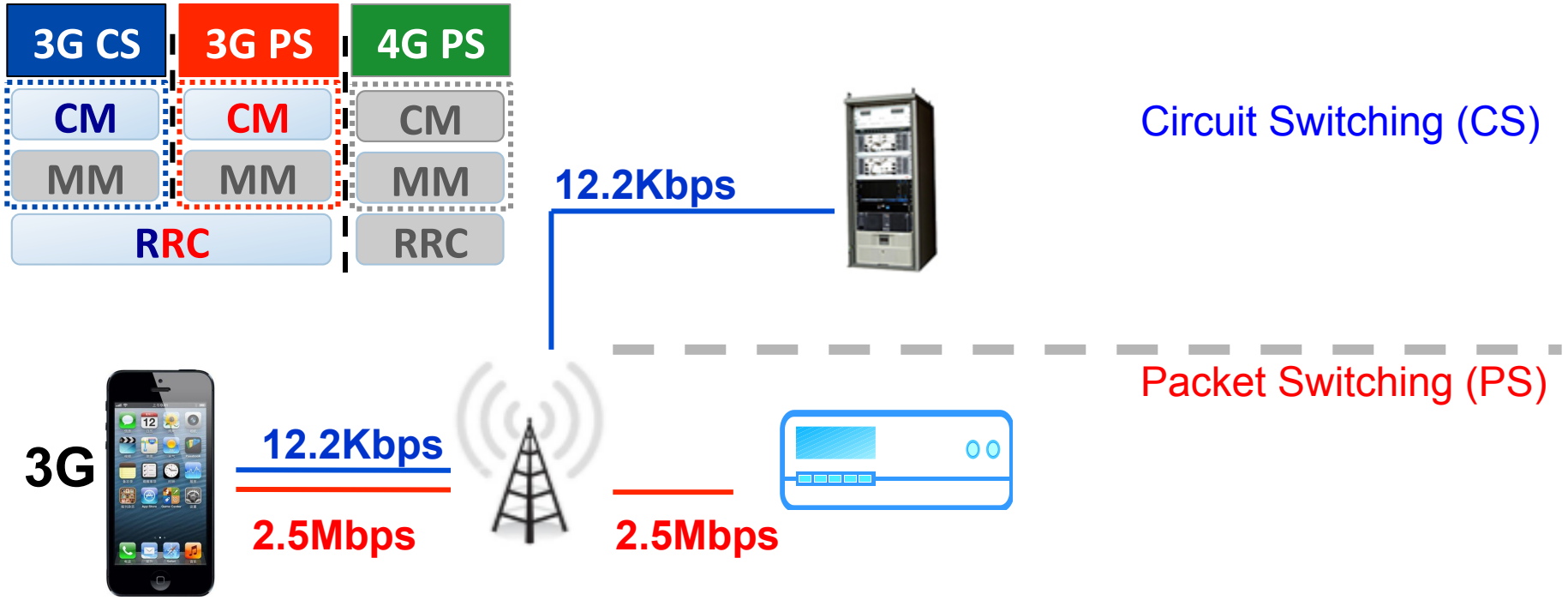
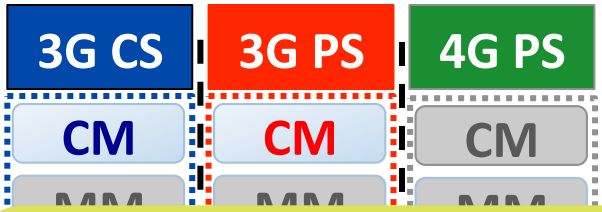


Data service rate declines up to 74%

Unnecessary Coupling: Cross-domain

- Scenario: dial a call during data service in 3G



Circuit Switching (CS)

Voice: low rate, low loss (e.g., 16QAM)

Data: high rate, loss tolerant (e.g., 64QAM)

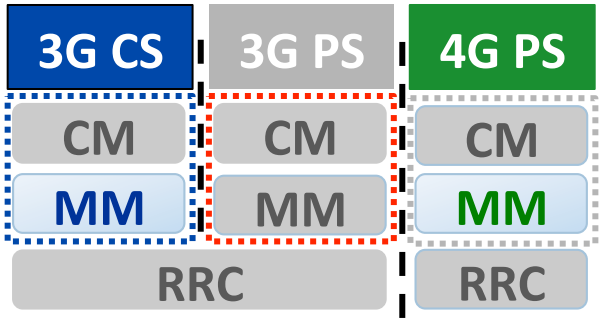
2.5Mbps

2.5Mbps

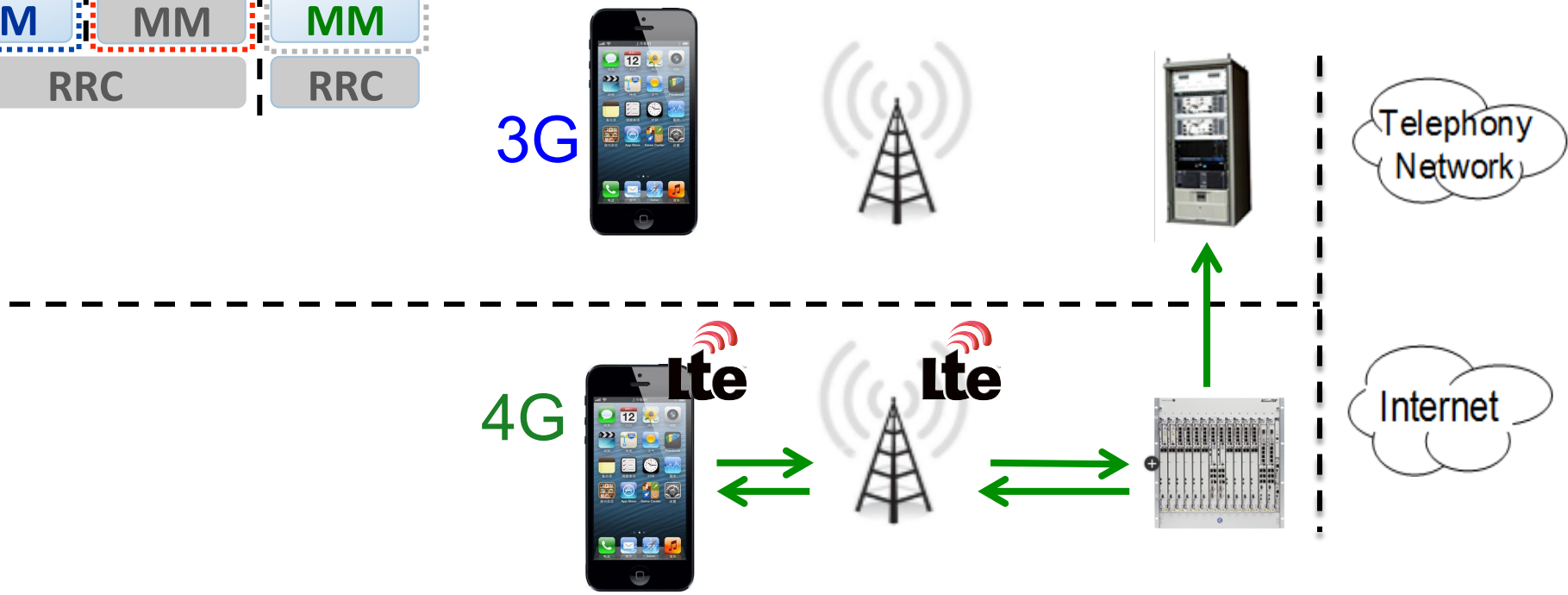
Voice and data have competing demands on the channel, but they have to share the radio channel

Unnecessary Coupling: Cross-system

- Scenario: Location update in 3G and 4G

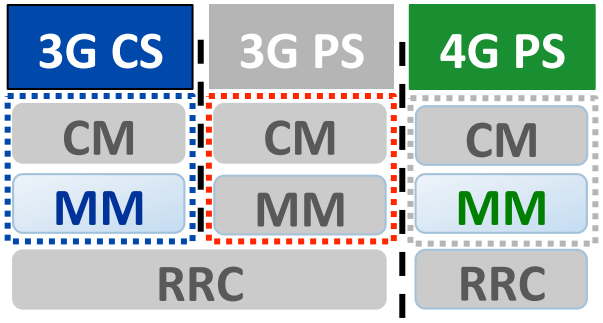


1. Update 4G location, and notify 3G MSC

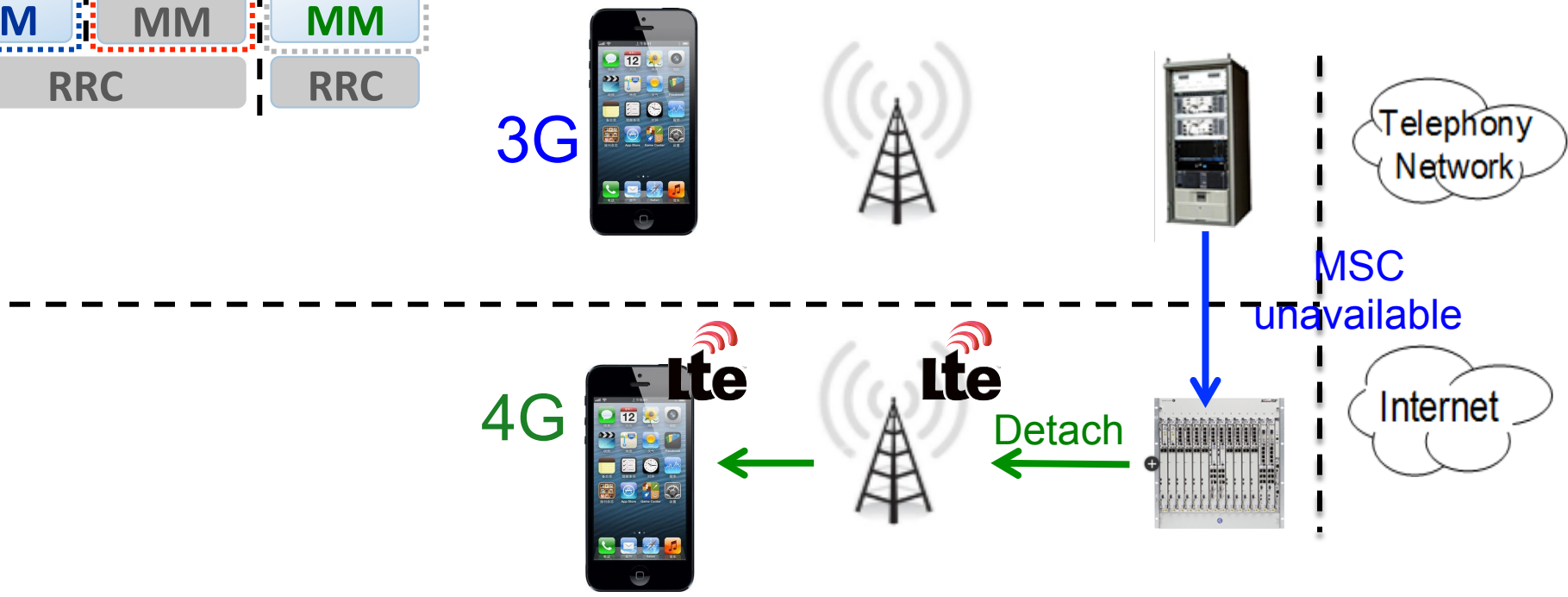


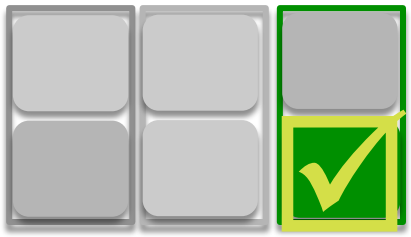
Unnecessary Coupling: Cross-system

- Scenario: Location update in 3G and 4G



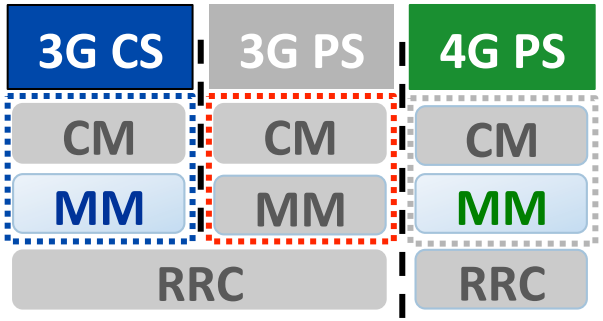
2. 3G location update fails, so 4G deregisters the network





Unnecessary Coupling: Cross-system

- Scenario: Location update in 3G and 4G



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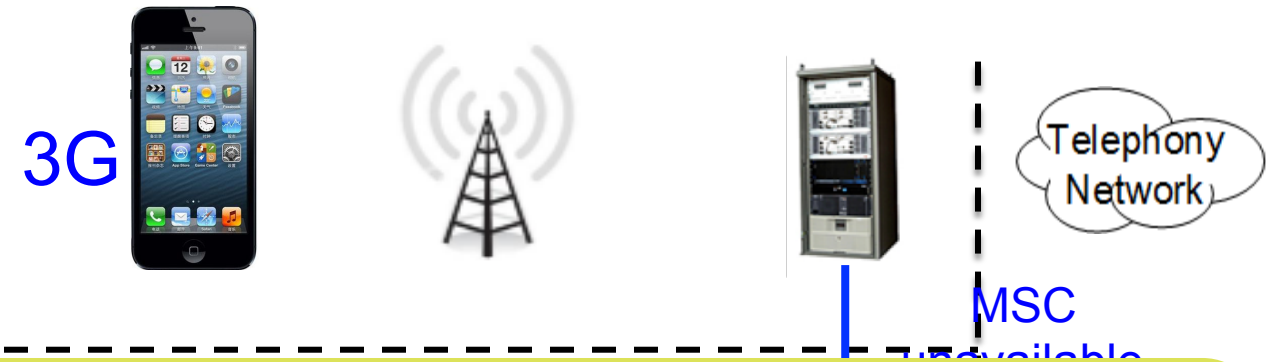

3G internal failures are exposed to 4G devices

Conclusion

- Uncover problems in signaling protocol interactions in cellular networks
- Three Lessons
  - The layering rule should be fully honored (optimistic assumptions, coupled actions)
  - Inter-domain difference should be well recognized (coupling independent services)
  - Hybrid systems are not properly coordinated (context sharing, fault isolation)
- More rigorous efforts are needed