Touching the Untouchables:
Dynamic Security Analysis of the LTE Control Plane

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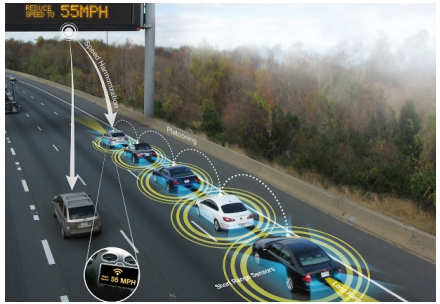
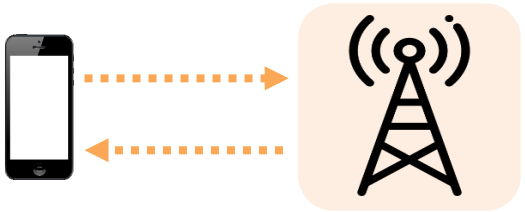
2019 IEEE Symposium on Security and Privacy

LTE communication is everywhere



Autonomous driving
(Cellular V2X)



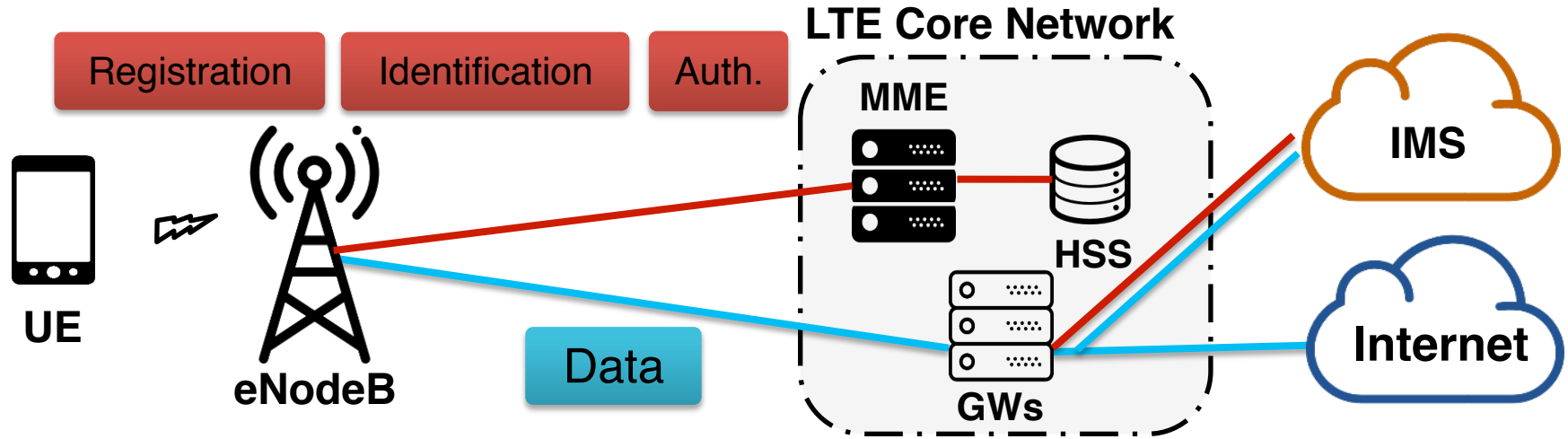
Public safety services
(PS-LTE)

Industrial IoT devices
(NB-IoT, LTE-M)

Railway communication
(LTE-R)

Maritime communication
(LTE-Maritime)

LTE network architecture



- LTE service procedures are separated into **control plane** and **user plane**
- Control plane procedures
  - (De)Registration of mobile phones, mutual authentication, mobility support, …
  - **Always preceded by the user plane procedures**
  - **Might be a good target for adversaries**

*UE: User Equipment, *MME: Mobility Management Entity

Previous studies and its limitations

- Formal analysis of **LTE specification**

LTEInspector: A Systematic Approach for Adversarial Testing of 4G LTE

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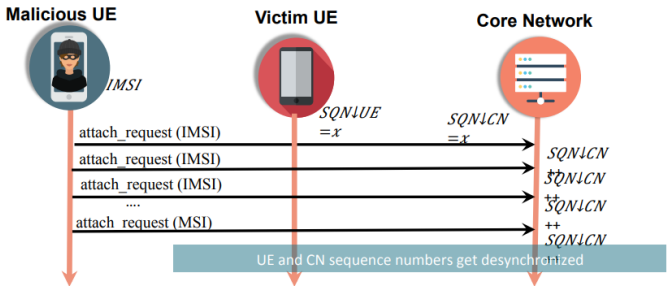

Ambiguities in LTE specification

- include a lot of exception cases
- leave freedom to the carriers and v endors about the implementation d etails
- have protocol conformance test sta ndard but,
  - Only for UE (LTE phone)
  - Do not consider the malicious/inco rrect procedures

Carriers may have implementation bugs even if the spec. is correct

Previous studies and its limitations

Practical Attacks Against Privacy and Availability in 4G/LTE Mobile Communication Systems

Putting LTE Security Functions to the Test: A Framework to Evaluate Implementation Correctness

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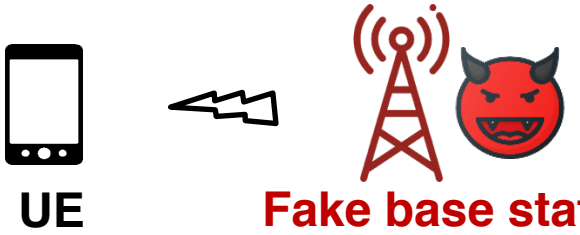
LTE REDIRECTION

Forcing Targeted LTE Cellphone into Unsafe Network

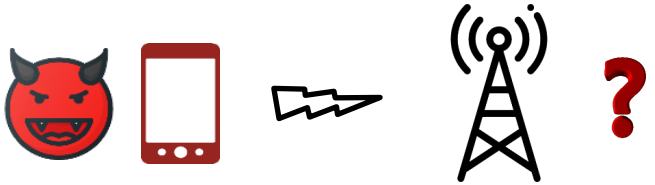
HUANG Lin



UE

Fake base station

- Steal user identity
- Location tracking
- DoS attack



Fake UE

Commercial network

What about a fake LTE phone to inspect commercial networks?

Challenges in active network testing

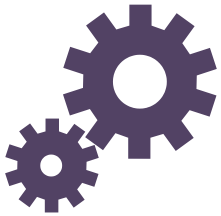
- Difficulties to actively inspect operational LTE networks
  1. Sending malicious signal to a commercial network is not allowed
     - ➔ Got Carriers' Testbed access
  2. It is hard to control baseband chipsets for simulating malicious behavior
     - ➔ Use open-source LTE software (srsLTE, openLTE, and SCAT)
  3. An LTE network is a closed system
     - ➔ Device-side debugging

Goal of our research

- Investigate potential problems of the control plane procedures in LTE
  - **Rooted from either**

Specification problem

Implementation bug

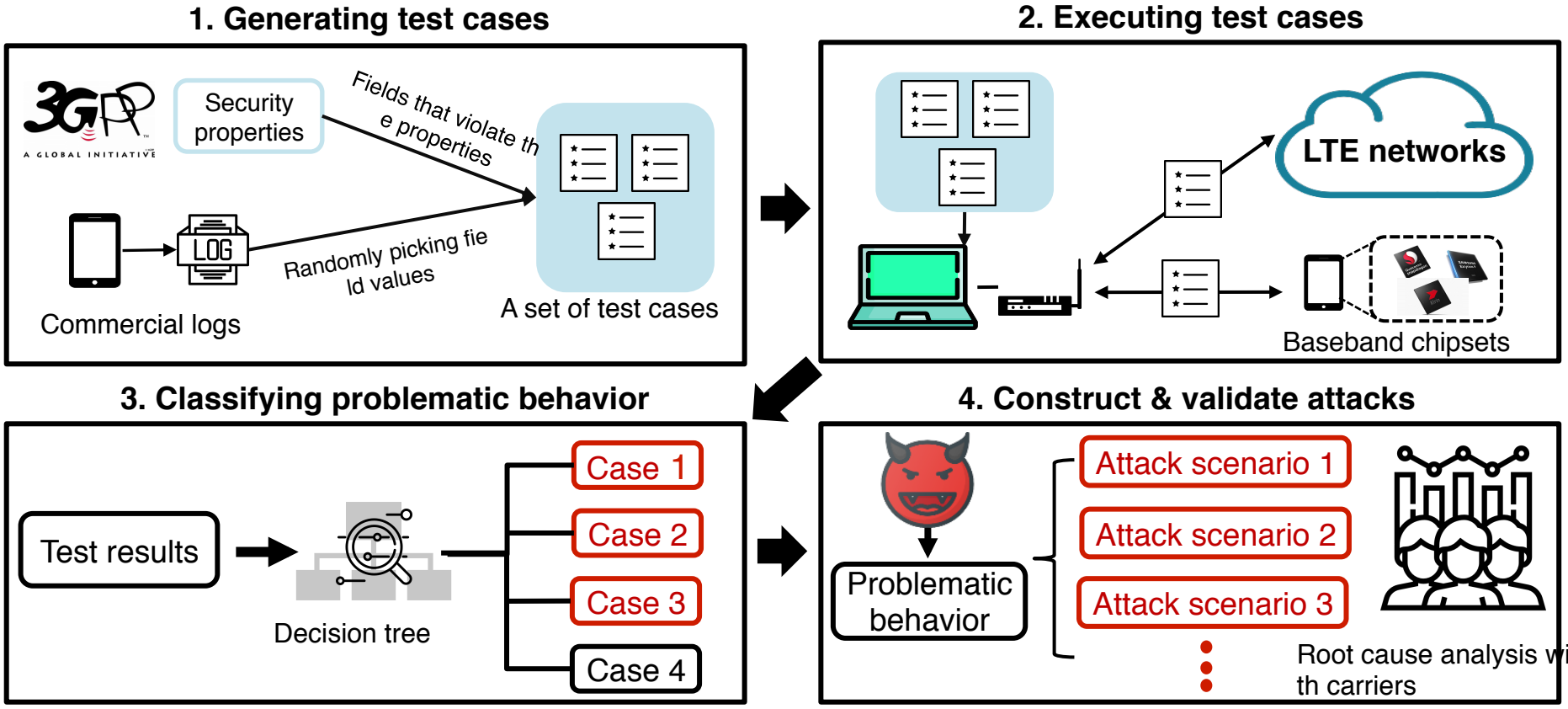


Configuration bug

  - **How?**

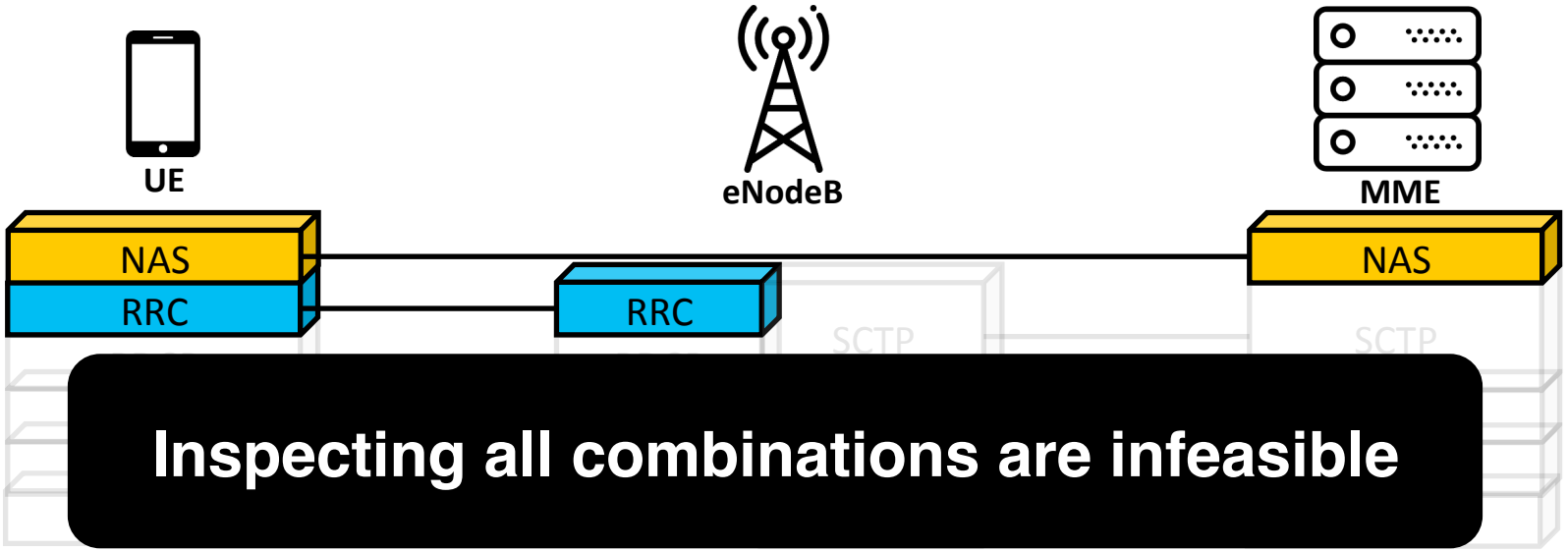
Comprehensive dynamic testing against commercial LTE networks

Overview of LTEFuzz



Generating test cases

- Target control plane protocols: RRC and NAS
- Target procedures
  - Radio connection, network attach/detach, location management, and session manag ement, …



RRC: Radio Resource Control, NAS: Non Access Stratum

Generating test cases

1. **Define basic security properties based on LTE specification**

   Property 1. Plain messages should be handled properly
   - Plain messages by design
   - Plain messages manipulated by an attacker

   Property 2. Invalid security protected messages should be handled properly
   - Invalid security header type
   - Invalid MAC (Messages Authentication Code)
   - Invalid Sequence number

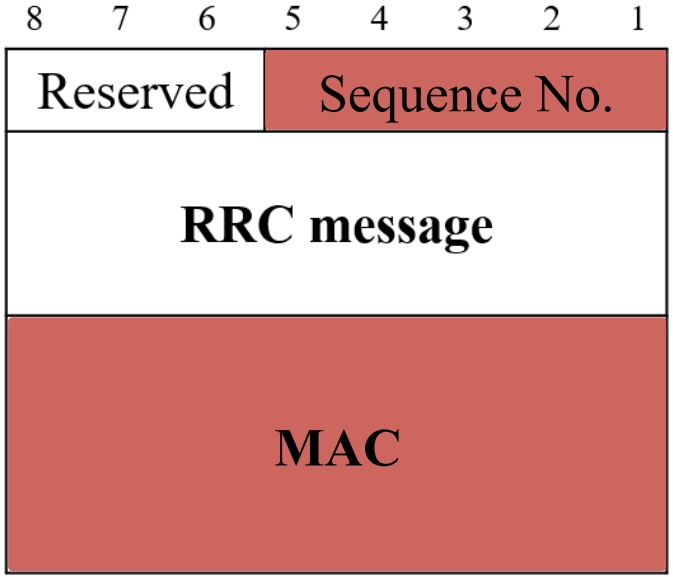
   Property 3. Mandatory security procedures should not be bypassed
   - Authentication
   - Key agreement procedure

Generate test cases that violate the properties

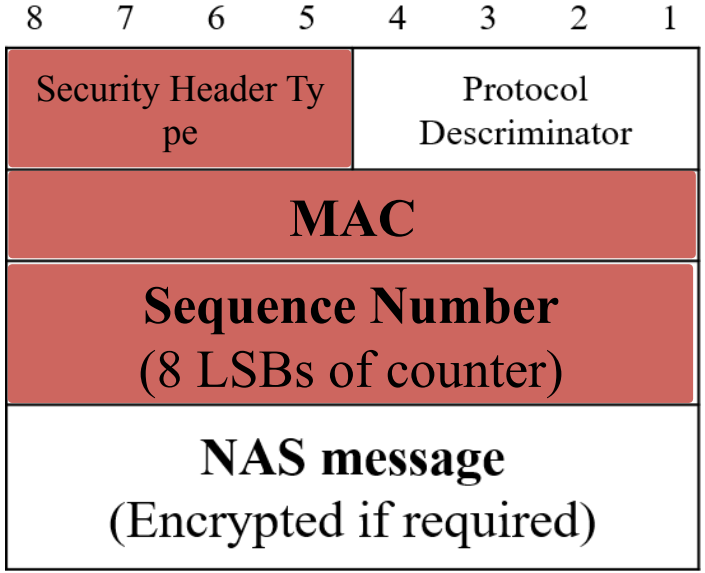
Generating test cases

1. **Define basic security properties based on LTE specification**

RRC test case



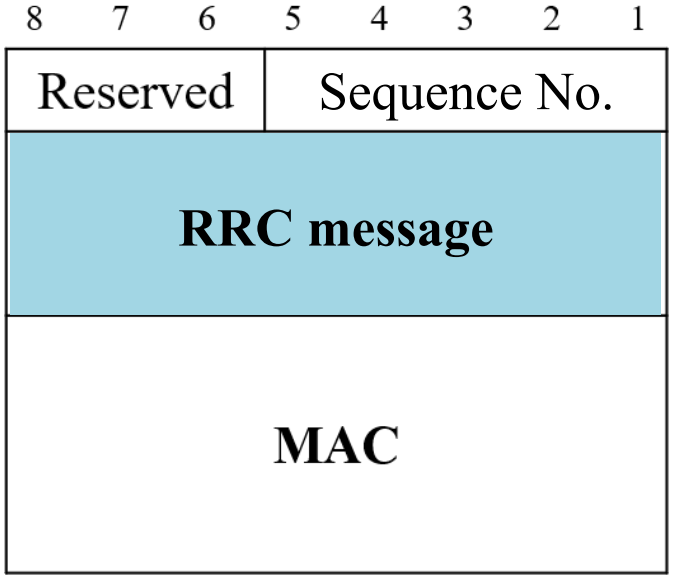
NAS test case



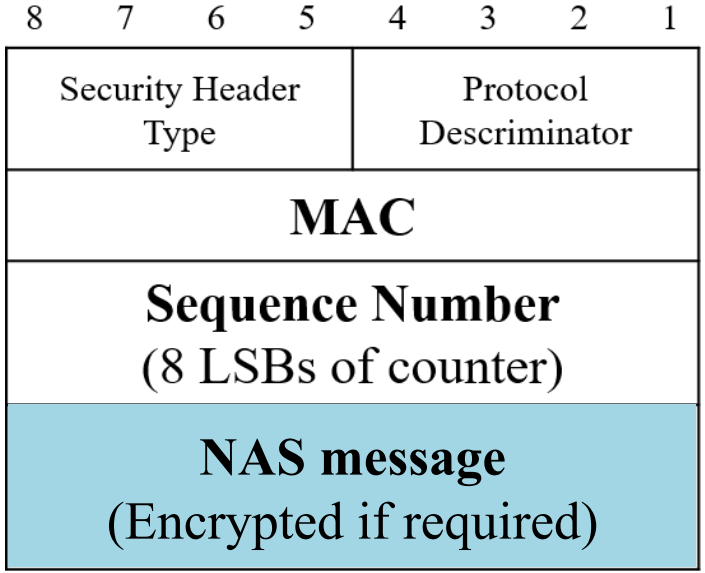
Generating test cases

1. **Define basic security properties based on LTE specification**

RRC test case



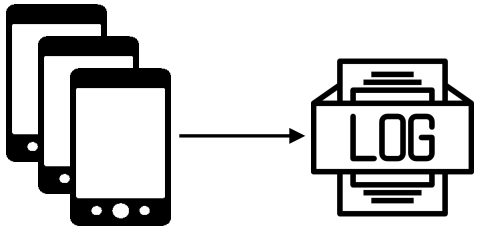
NAS test case



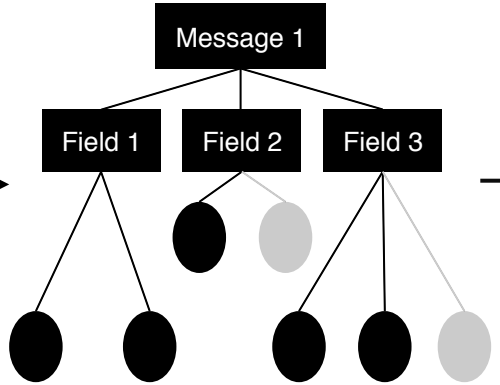
Generating test cases

2. Pick remaining field values randomly from commercial control plane logs

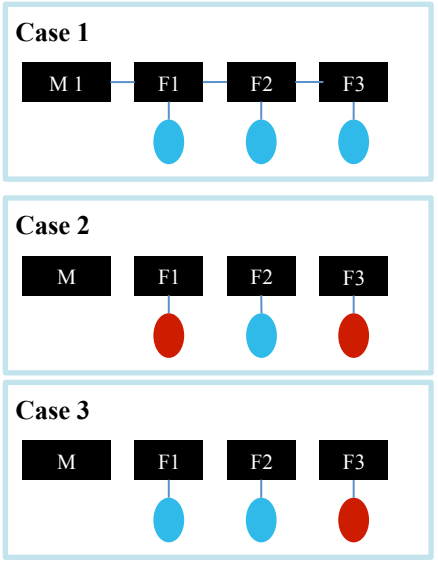
– Not to cause memory corruption errors in the operational networks



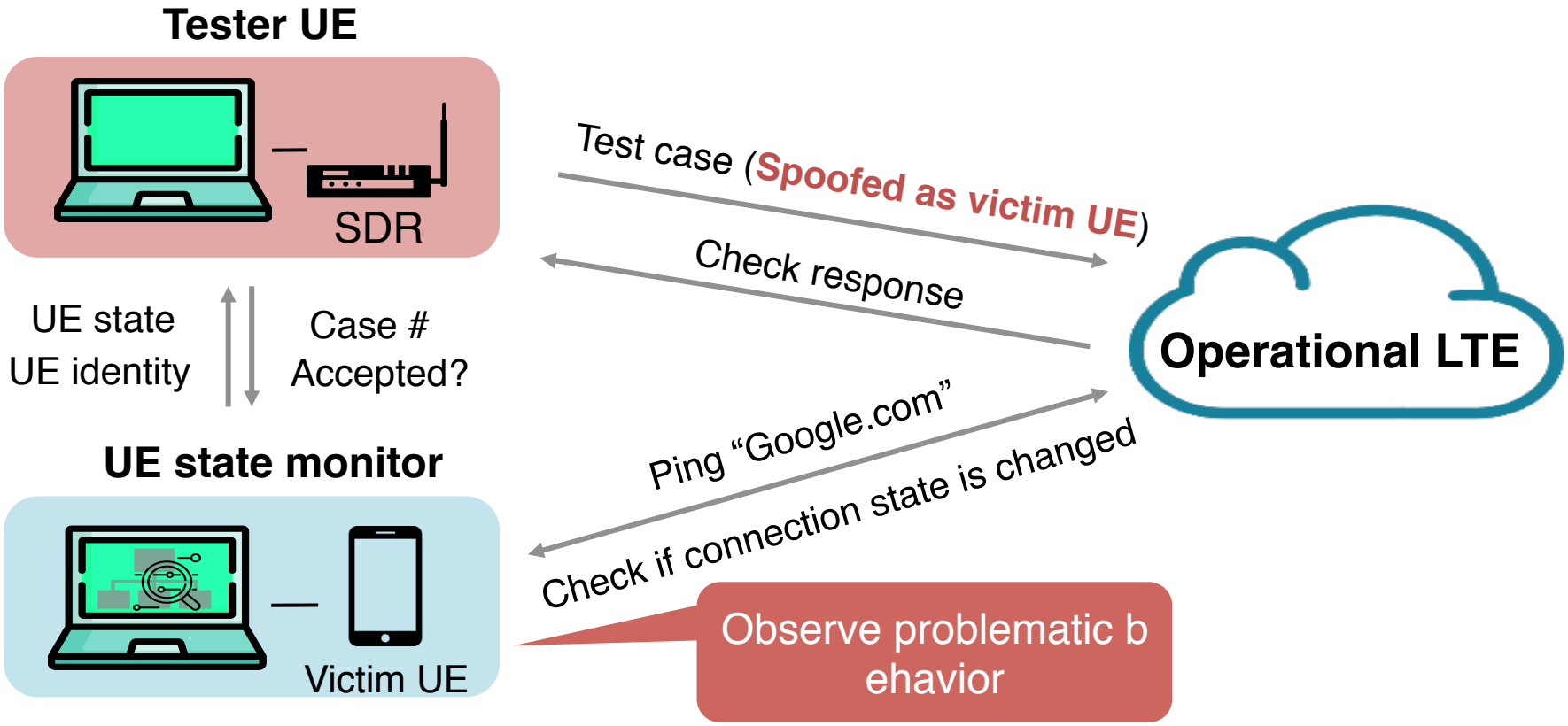
Commercial control plane logs e xtracted from the phones.



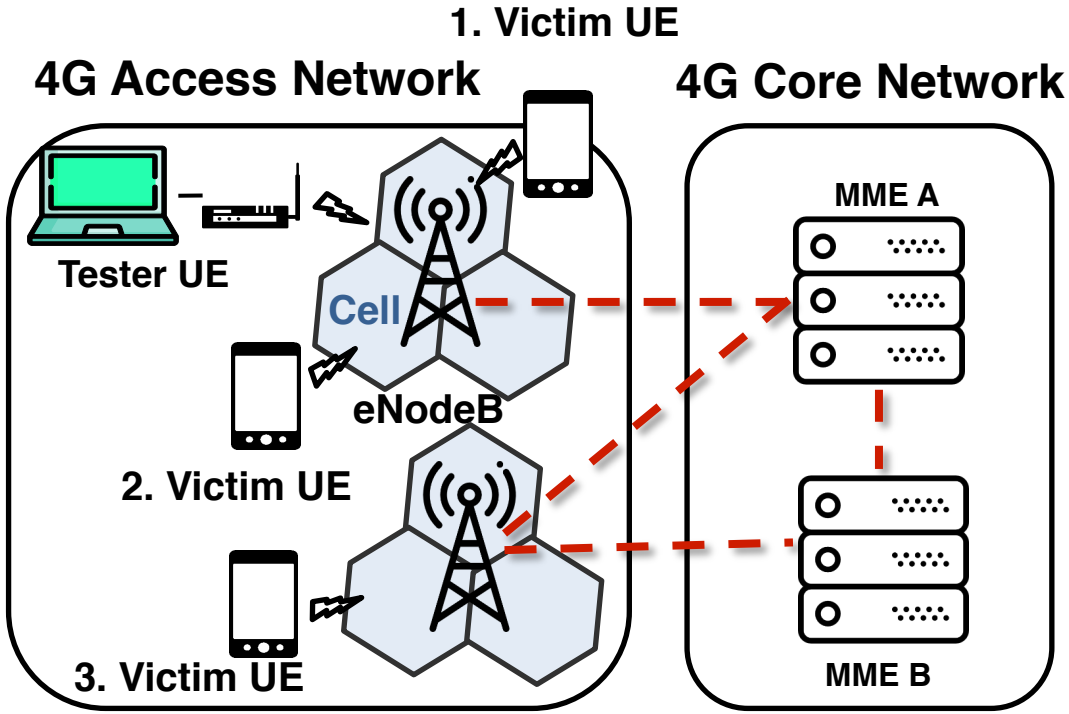
Save the field values which are u sed in the commercial networks



Executing test cases



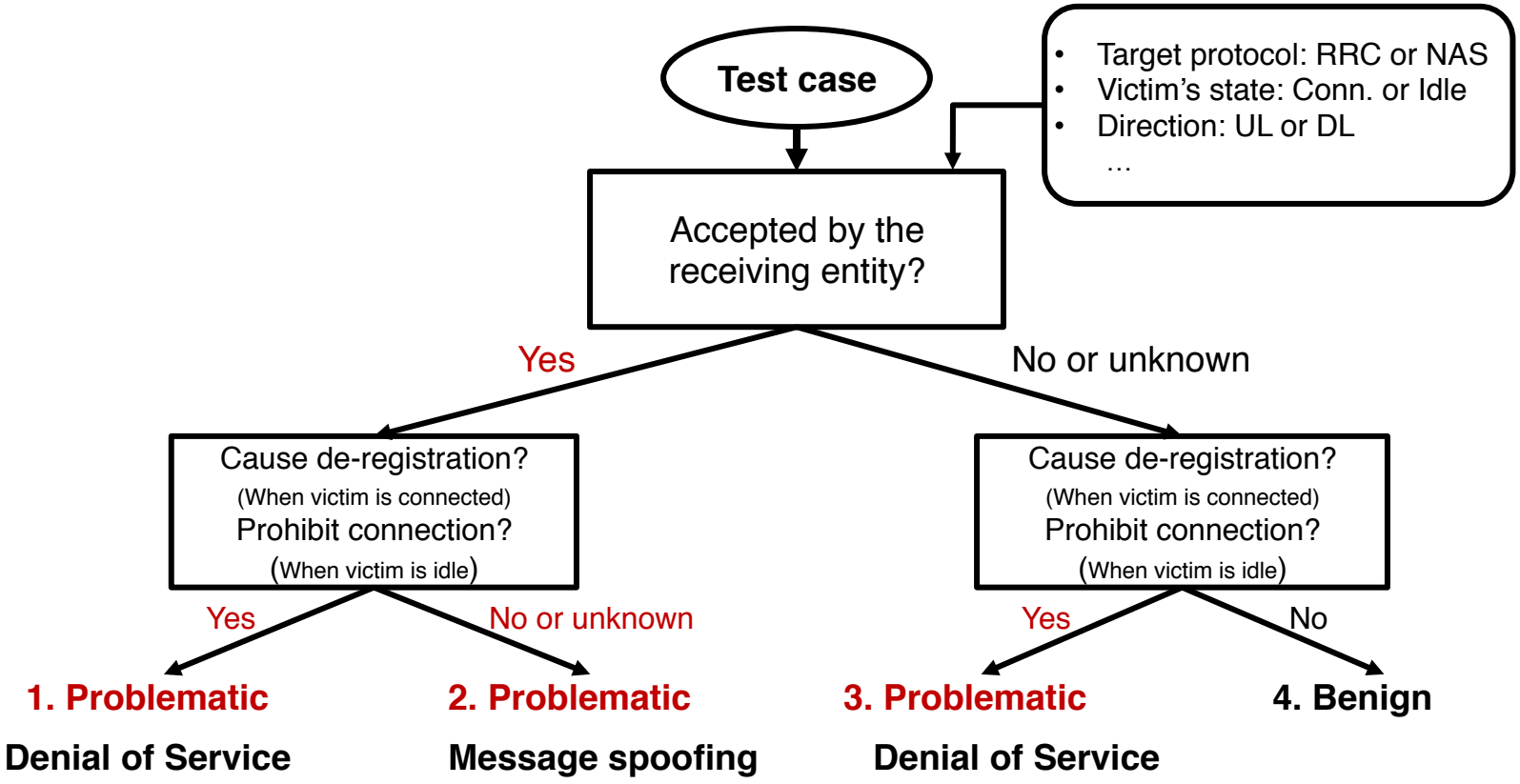
Operational networks are complicated



- Each carrier has different con figurations
- Each carrier deploys different network equipment
- In a single carrier, network eq uipment differs by the service area
- The location of the tester and the victim affects the results

Hard to manually analyze which case is problem

Classifying the problematic behavior



LTEFuzz test environment

Network testing

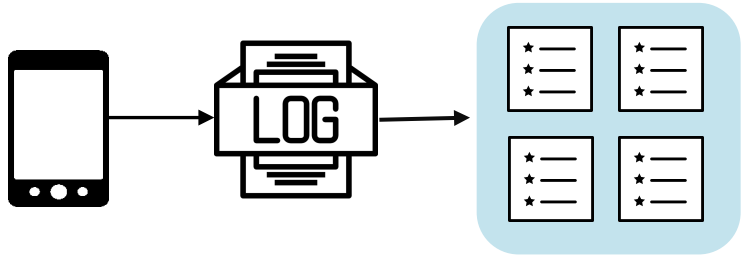
- Target network vendors
  - Carrier A: two MME vendors, one eNB vendor
  - Carrier B: one MME vendor, two eNB vendors

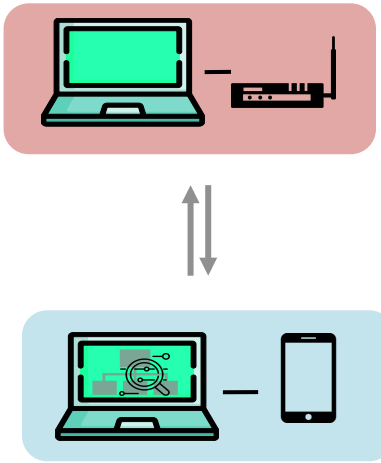
Baseband testing

- Target baseband chipsets
  - Qualcomm, Exynos, HiSilicon, MediaTek

Implementation

- **Test input collector & message generator**
  - 1937 lines of code of C++
- **Tester**
  - Network testing
    - srsUE (fully controllable LTE baseband)
    - (Additional) 550 lines of code of C++
  - Baseband testing
    - openLTE & srsLTE (fully controllable LTE network)
    - (Additional) 840 lines of code of C++
- **UE state monitor & testing automation**
  - *For classifying problematic cases* when each test case is executed
  - Based on Signaling Collection and Analysis Tool (SCAT)
  - 143 lines of code of python for testing automation
    - 80 lines for testing automation, 63 lines for monitoring victim device





Findings

- Test cases classified into problematic behavior
  - Total 51 cases: **36 new** and 15 previously known
  - Categorized into five vulnerability types
    - Unprotected initial procedure cause failure (Property 1-1)
    - Invalid plain requests are accepted (Property 1-2)
    - Messages with invalid integrity protection (Property 2-1)
    - Messages with invalid sequence number (Replay) (Property 2-2)
    - AKA procedure can be bypassed (Property 3)
- Validated with the corresponding carriers and vendors
  - No false positive, but two false negatives
    - *UplinkNAStransport* (for SMS) and *Service request* (response was encrypted)

Test messages	Direction	Property 1-1	Property 1-2 (P)	Property 2-1 (I)	Property 2-2 (R)	Property 3	Affected component
NAS							
Attach request (IMSI/GUTI)	UL	B	DoS	DoS	DoS	-	Core network (MME)
Detach request (UE originating detach)	UL	-	DoS [1]	DoS	DoS	-	Core network (MME)
Service request	UL	-	-	B	Spoofing	-	Core network (MME)
Tracking area update request	UL	-	DoS	DoS	FLU and DoS	-	Core network (MME)
Uplink NAS transport	UL	-	SMS phishing and DoS	SMS phishing and DoS	SMS replay	-	Core network (MME)
PDN connectivity request	UL	B	B	DoS	DoS	-	Core network (MME)
PDN disconnect request	UL	-	B	DoS	selective DoS	-	Core network (MME)
Attach reject	DL	DoS [2]	DoS [3]	-	-	-	Baseband
Authentication reject	DL	DoS [4]	-	-	-	-	Baseband
Detach request (UE terminated detach)	DL	-	DoS [4]	-	-	-	Baseband
EMM information	DL	-	Spoofing [5]	-	-	-	Baseband
GUTI reallocation command	DL	-	B	B	ID Spoofing	-	Baseband
Identity request	DL	Info. leak [6]	B	B	Info. leak	-	Baseband
Security mode command	DL	-	B	B	Location tracking [4]	-	Baseband
Service reject	DL	-	DoS [3]	-	-	-	Baseband
Tracking area update reject	DL	-	DoS [3]	-	-	-	Baseband
RRC							
RRCConnectionRequest	UL	DoS and con. spoofing	-	-	-	-	Core network (eNB)
RRCConnectionSetupComplete	UL	Con. spoofing	-	-	-	-	Core network (eNB)
MasterInformationBlock	DL	Spoofing	-	-	-	-	Baseband
Paging	DL	DoS [4] and Spoofing	-	-	-	-	Baseband
RRCConnectionReconfiguration	DL	-	MitM	DoS	B	-	Baseband
RRCConnectionReestablishment	DL	-	Con. spoofing	-	-	-	Baseband
RRCConnectionReestablishmentReject	DL		DoS			-	Baseband
RRCConnectionReject	DL	DoS	-	-	-	-	Baseband
RRCConnectionRelease	DL	DoS [2]	-	-	-	-	Baseband
RRCConnectionSetup	DL	Con. spoofing	-	-	-	-	Baseband
SecurityModeCommand	DL	-	B	B	B	MitM	Baseband
SystemInformationBlockType1	DL	Spoofing [4]	-	-	-	-	Baseband
SystemInformationBlockType 10/11	DL	Spoofing [4]	-	-	-	-	Baseband
SystemInformationBlockType12	DL	Spoofing [4]	-	-	-	-	Baseband
UECapabilityEnquiry	DL	Info. leak	-	Info. leak	Info. leak	-	Baseband

Index

Specification problem

MME vendors

Baseband vendors

Vuln. From different vendors

B: Benign

- : n/a

P: plain

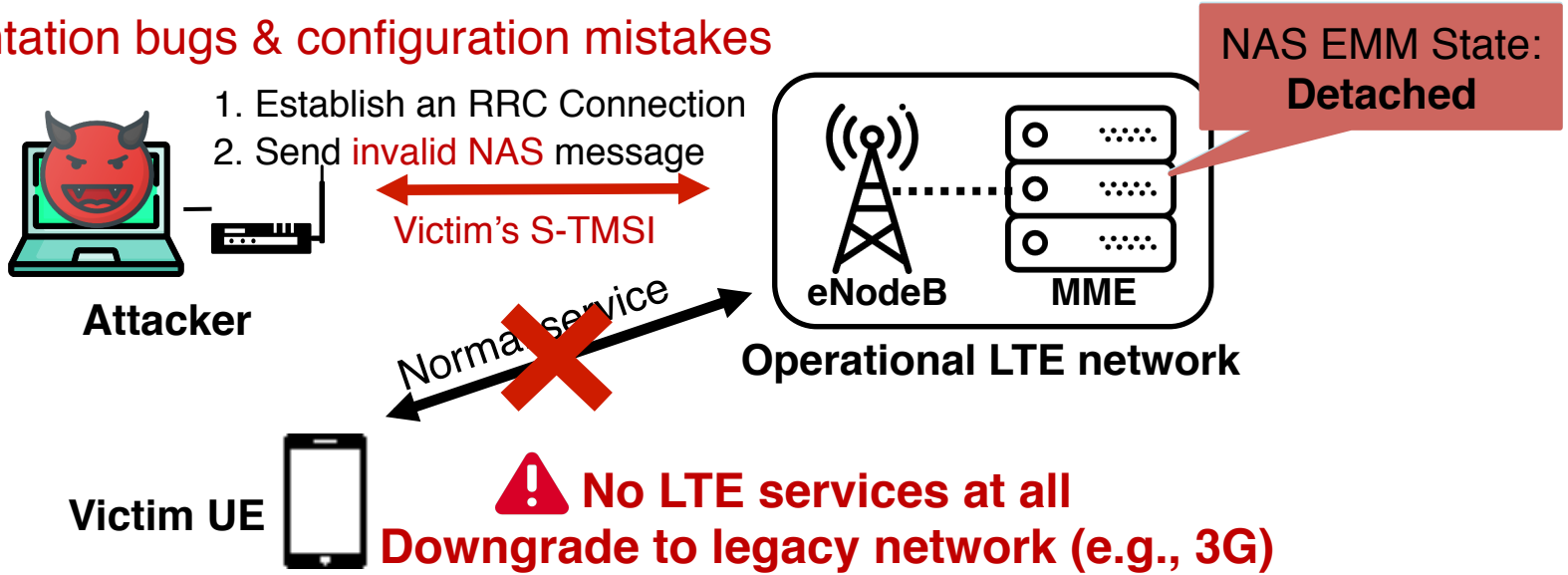
I: Invalid MAC

R: Replay

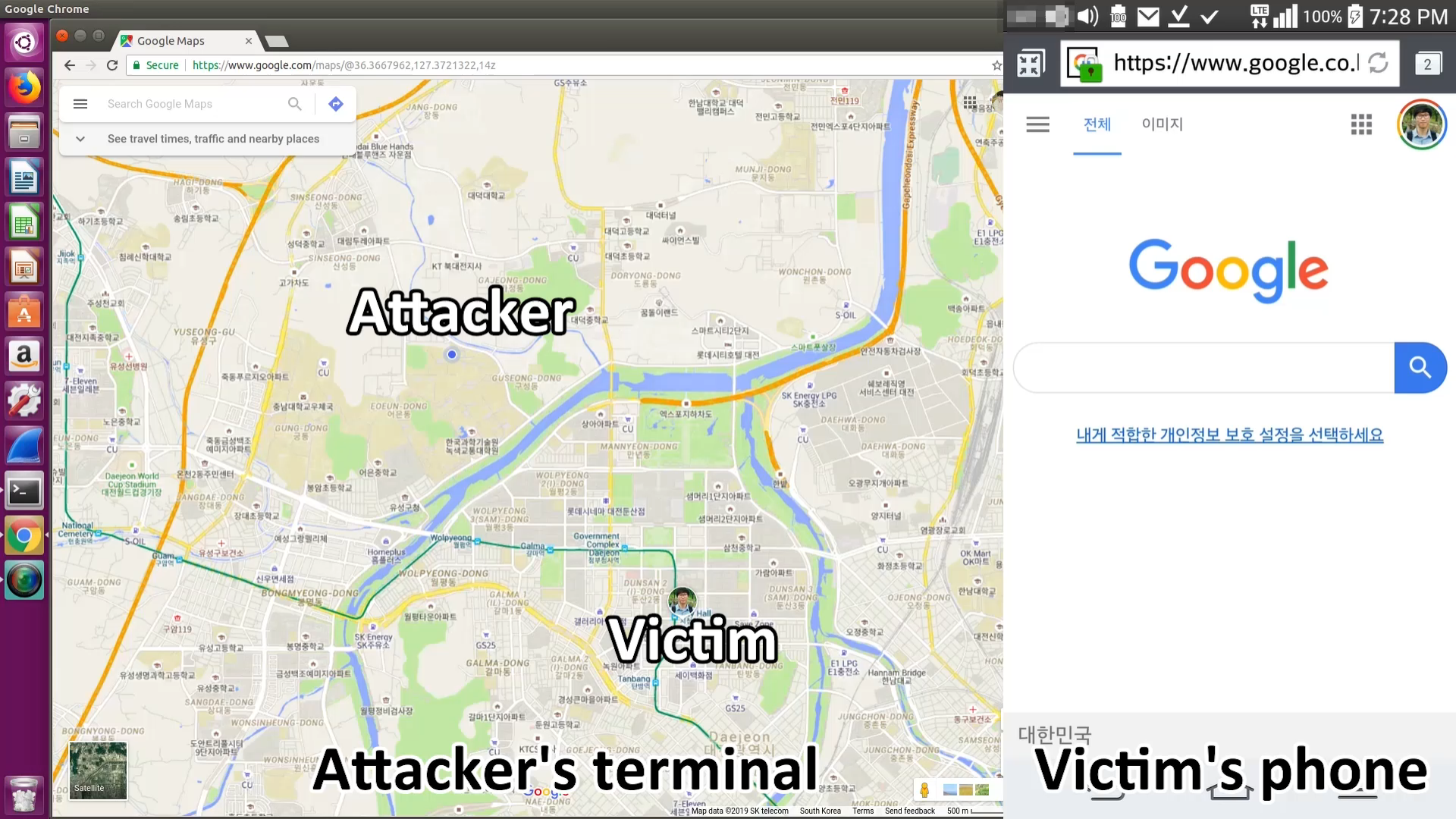
ATTACKS

Remote de-register attack

- **Exploited test case:** 15 cases in NAS (Attach, Detach, TAU, PDN con/discon…)
- An Attacker is *within the same MME pool of the victim UE*
- Implementation bugs & configuration mistakes



- *Nitpick: GUTI in NAS messages are not correctly checked in some MME vendors*


Google Chrome
Google Maps
Secure
https://www.google.com/maps/@36.3667962,127.3721322,14z
Search Google Maps
See travel times, traffic and nearby places
Attacker
Victim
Attacker's terminal
https://www.google.co.
전체
이미지
Google
내게 적합한 개인정보 보호 설정을 선택하세요
대한민국
Victim's phone

Responsible disclosure

- Standard bodies
  - 3GPP
  - GSMA
- Vendors
  - LTE network vendors
    - Validated through the contacted carriers
    - Also validated the fixes created by the vendors
  - Baseband chipset vendors
    - Reported AKA Bypass attack, and replay attack
    - Will be patched soon

Conclusion

- Operational LTE networks are not as secure as we expected!
  - **Complicated deployments (e.g., each network equipment is from different vendors) generate extremely complicated behavior (faults).**

- We have implemented LTEFuzz
  - A semi-automated dynamic testing tool for both networks and devices
  - Using open source LTE software and a simple decision tree
  - Specification problems: 16, Implementation bugs + configuration issues: 35
  - **LTEFuzz considers realistic attack assumptions in operational LTE networ k**
- Future work
  - Extend LTEFuzz to support other control protocols and 5G if allowed

Thank you

Contact: hongilk@kaist.ac.kr
Website: http://ltefuzz.syssec.kr

BACKUP SLIDES

Obtaining valid S-TMSIs

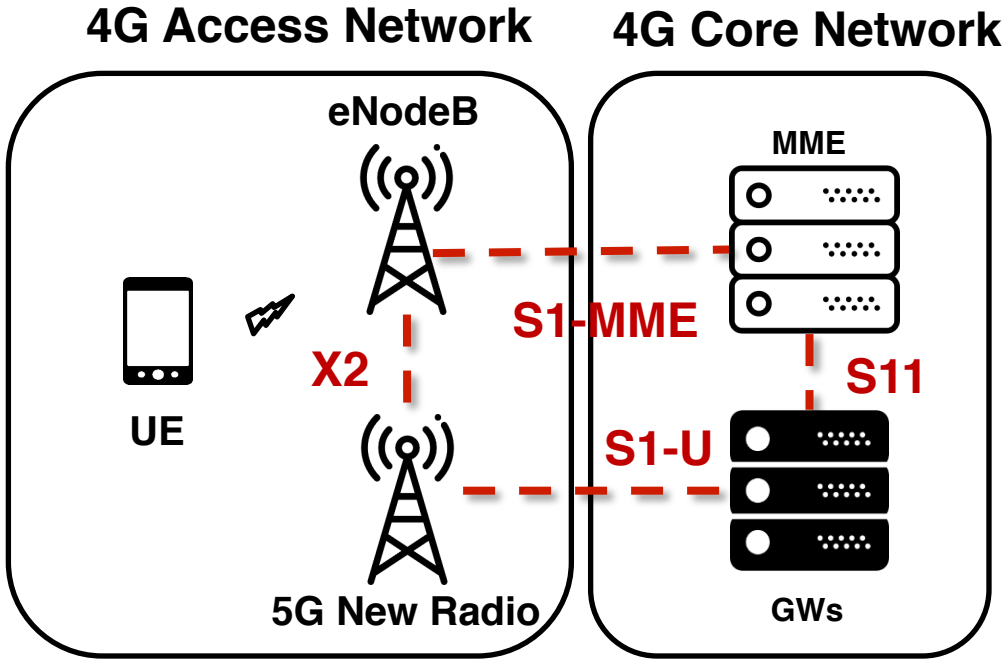
1. Install Fake LTE eNodeB
   - Obtain a UE's S-TMSI in the *TAU request* from the UE.
2. Periodically trigger *Paging* by making calls to the victim UE
   - The attacker listens pagings in a same eNodeB with the victim UE
3. Sniff downlink *RRC Connection setup*

LTE testbed: open source vs. commercial

- Commercial testbed
  - Expensive
  - Hard to change, modify the behaviors
- Open source testbed
  - **Cheap** (Laptop + SDR = 3,500,000 KRW)
  - **Fully controllable** from PHY to A PP layer

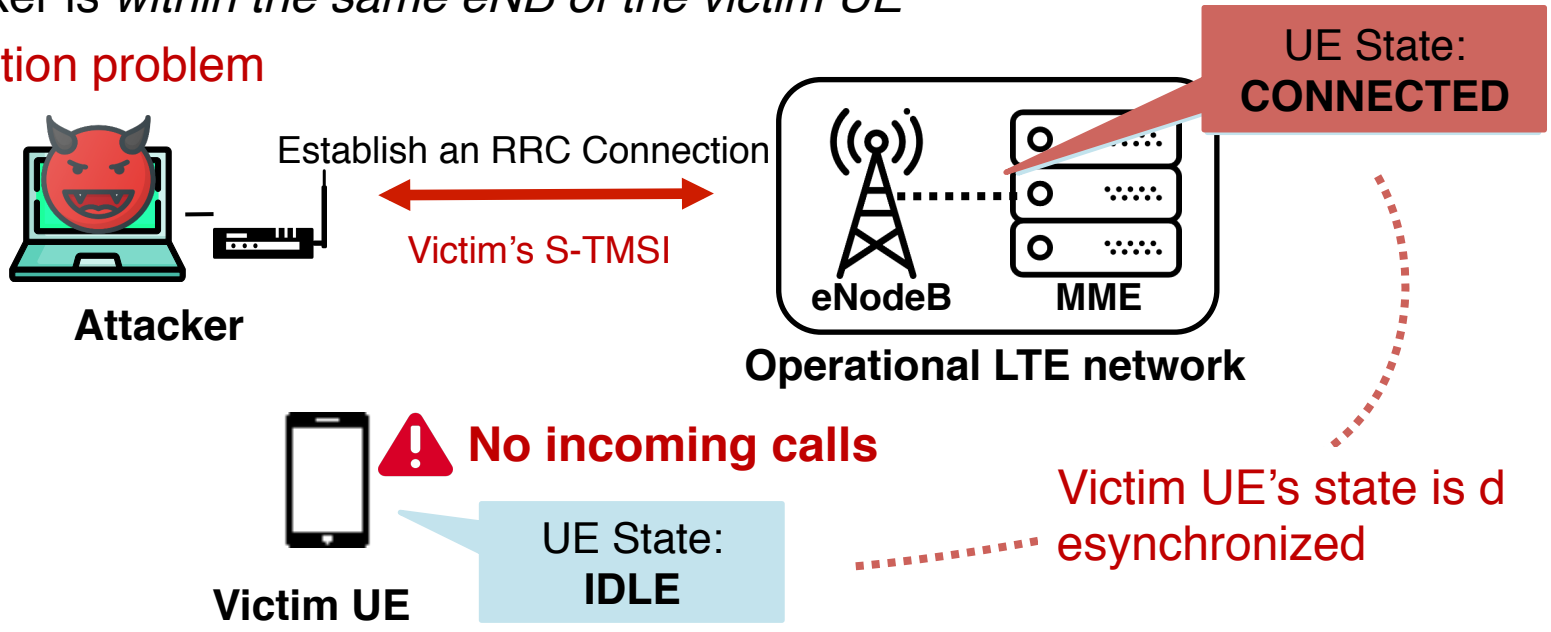
Future work

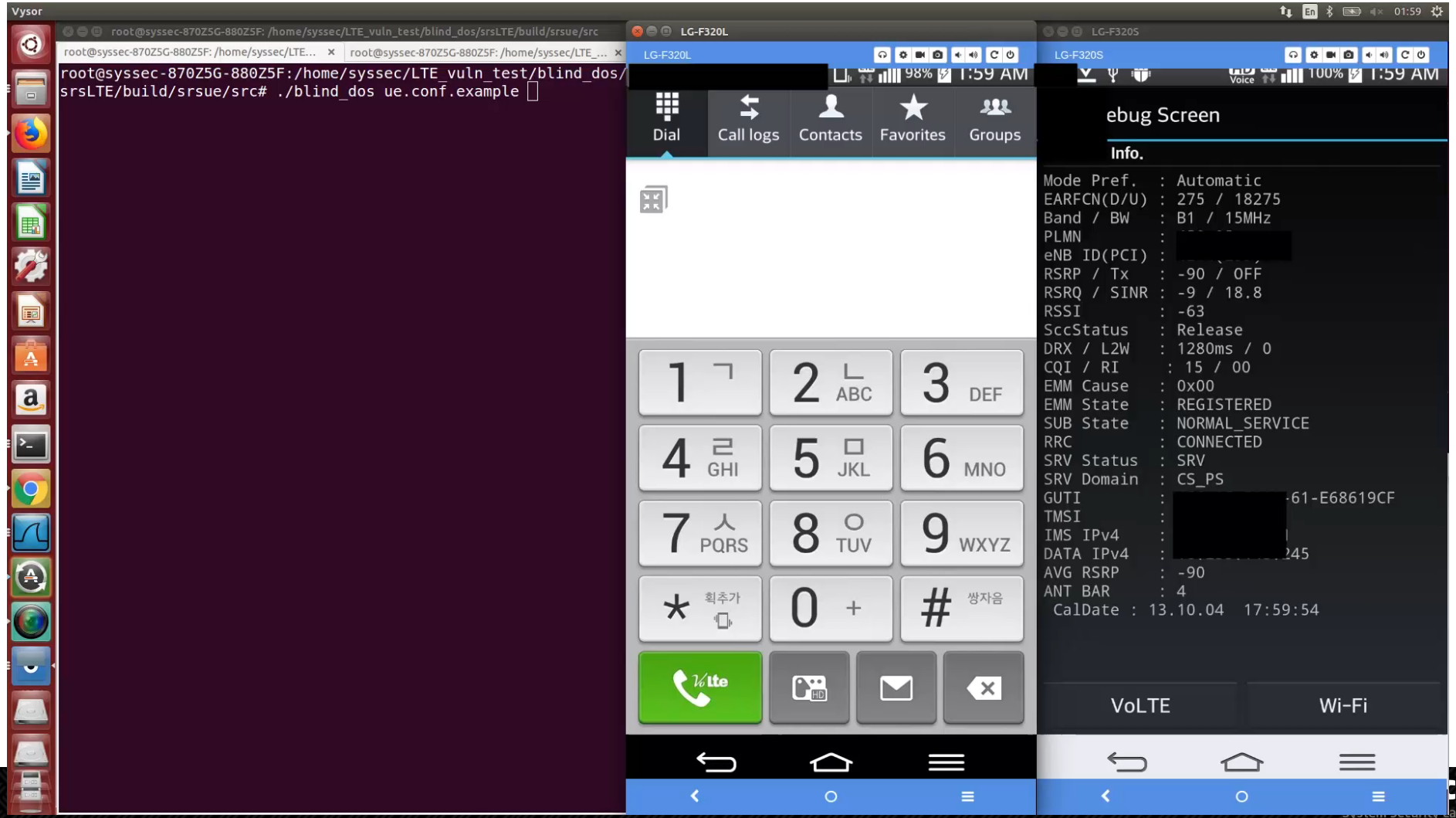
- Extend LTEFuzz to
  - support other protocol layers and interfaces
  - support 5G Non-Standalone (NSA) and Standalone (SA)
  - identify memory corruption b ugs in the baseband chipsets and core networks, if allowe d



Blind DoS attack

- **Exploited test case:** Invalid *RRC Connection request*
- An Attacker deceives the network that the victim UE is in connected state
- An Attacker is *within the same eNB of the victim UE*
- Specification problem



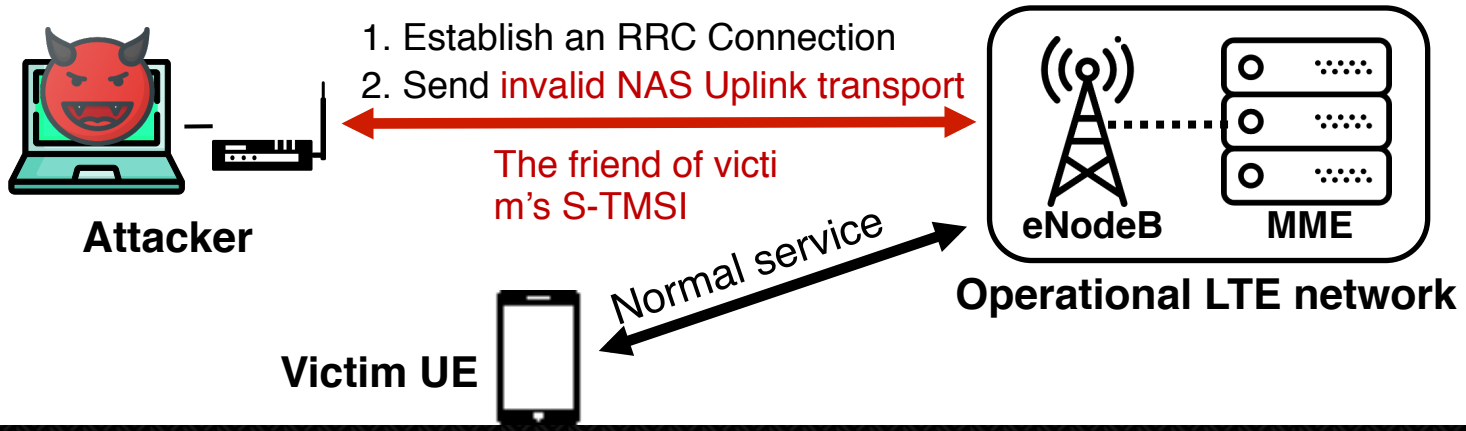

Vysor
root@syssec-870Z5G-880Z5F: /home/syssec/LTE_vuln_test/blind_dos/srsLTE/build/srsue/src
root@syssec-870Z5G-880Z5F: /home/syssec/LTE...
root@syssec-870Z5G-880Z5F: /home/syssec/LTE_...
root@syssec-870Z5G-880Z5F:/home/syssec/LTE_vuln_test/blind_dos/srsLTE/build/srsue/src# ./blind_dos ue.conf.example
LG-F320L
LG-F320L
98% 1:59 AM
Dial
Call logs
Contacts
Favorites
Groups
1
2 ABC
3 DEF
4 GHI
5 JKL
6 MNO
7 PQRS
8 TUV
9 WXYZ
* 확추가
0 +
쌍자음
LG-F320S
LG-F320S
100% 1:59 AM
ebug Screen
Info.
Mode Pref. : Automatic
EARFCN(D/U) : 275 / 18275
Band / BW : B1 / 15MHz
PLMN :
eNB ID(PCI) :
RSRP / Tx : -90 / OFF
RSRQ / SINR : -9 / 18.8
RSSI : -63
SccStatus : Release
DRX / L2W : 1280ms / 0
CQI / RI : 15 / 00
EMM Cause : 0x00
EMM State : REGISTERED
SUB State : NORMAL_SERVICE
RRC : CONNECTED
SRV Status : SRV
SRV Domain : CS_PS
GUTI :
TMSI :
IMS IPv4 :
DATA IPv4 :
AVG RSRP : -90
ANT BAR : 4
CalDate : 13.10.04 17:59:54
VoLTE
Wi-Fi

SMS phishing

- **Exploited test case:** Invalid Uplink NAS transport (SMS transport)
- Message with either no encryption, invalid MAC, or invalid seq. are all accepted
- An Attacker is *within the same MME pool of the victim UE's friend*
- Implementation

Sender: victim's friend
Content: Visit http://evil.com

Does not check the validity



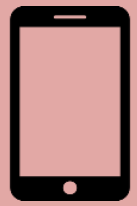
Attacker model

Attacker (Malicious UE)

- No keys for enc./integrity
- Knows the victim UE's identity
- Attacker can locate victim UE:
  - Same cell area
  - Different cell, same eNodeB
  - Different eNodeB, but same MME pool
  - Different MME pool

Malicious behavior as if it is the victim UE

Registered



Victim UE