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BRIEFINGS

# Cracking the 5G Fortress: Peering Into 5G's Vulnerability Abyss

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Contributors: Abdullah Al Ishtiaq, Syed Md Mukit Rashid, Weixuan Wang, Tianwei Wu, Syed Rafiul Hussain

# Who We Are

Kai Tu

PhD Student

Mobile Network and Device Security, Automatic Vulnerability Discovery

hellotkk.github.io

Yilu Dong

PhD Student

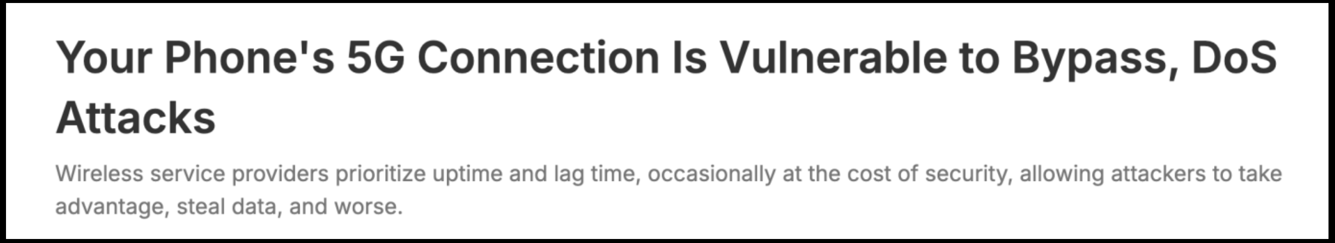
Cellular Networks, Applied Cryptography, and Software Testing

yilud.me

# 5G Network Roles and Applications

# Why is 5G Baseband Security Important?

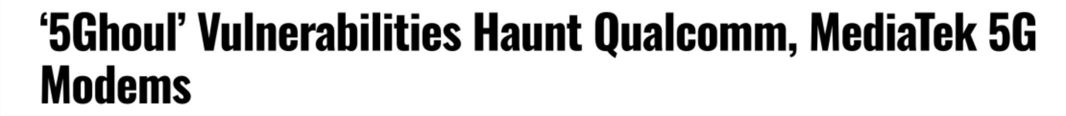
- Users will run into critical problems if basebands are not secure.



Your Phone's 5G Connection Is Vulnerable to Bypass, DoS Attacks

Wireless service providers prioritize uptime and lag time, occasionally at the cost of security, allowing attackers to take advantage, steal data, and worse.

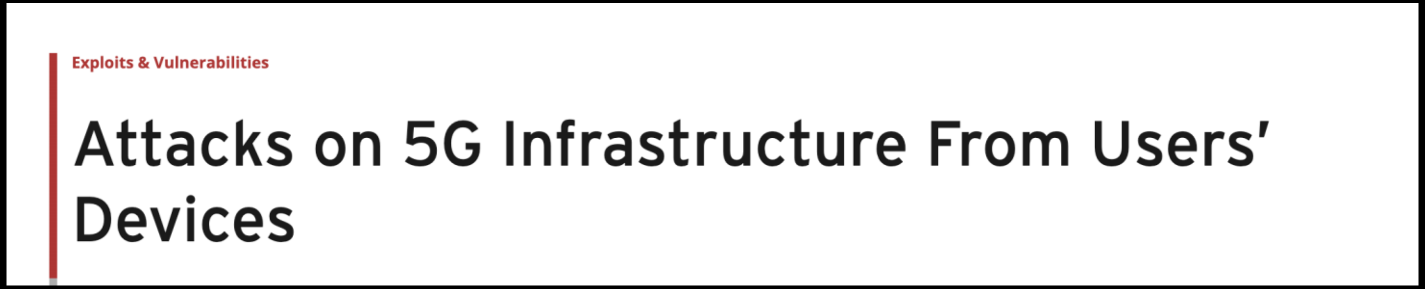
Source:https://www.darkreading.com/mobile-security/your-phone-s-5g-connection-is-exposed-to-bypass-dos-attacks



‘5Ghoul’ Vulnerabilities Haunt Qualcomm, MediaTek 5G Modems

Source: https://www.securityweek.com/5ghoul-vulnerabilities-haunt-qualcomm-mediatek-5g-modems/

- Compromised 5G device may also affect other components in 5G network.



Exploits & Vulnerabilities

Attacks on 5G Infrastructure From Users’ Devices

Source: https://www.trendmicro.com/en_us/research/23/i/attacks-on-5g-infrastructure-from-users-devices.html

# We are curious...

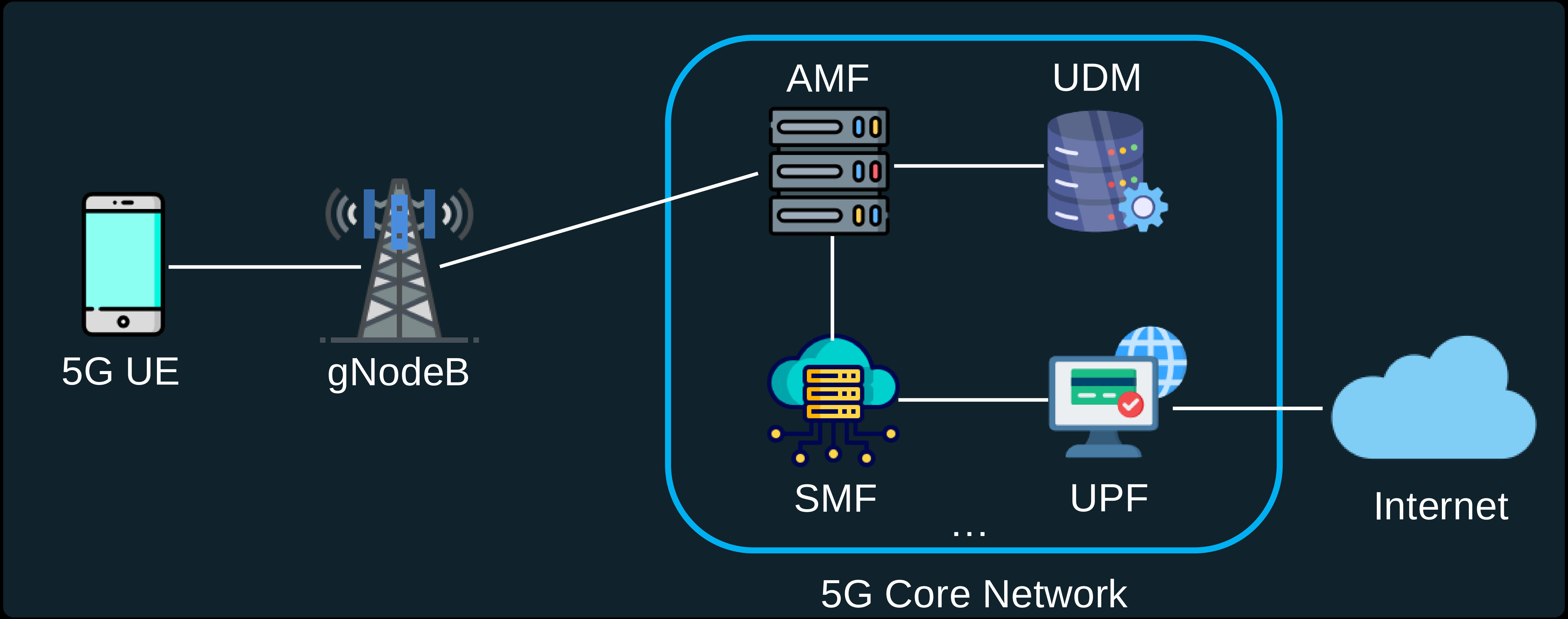
How secure are the 5G devices?

Can we develop an automated way to test them?

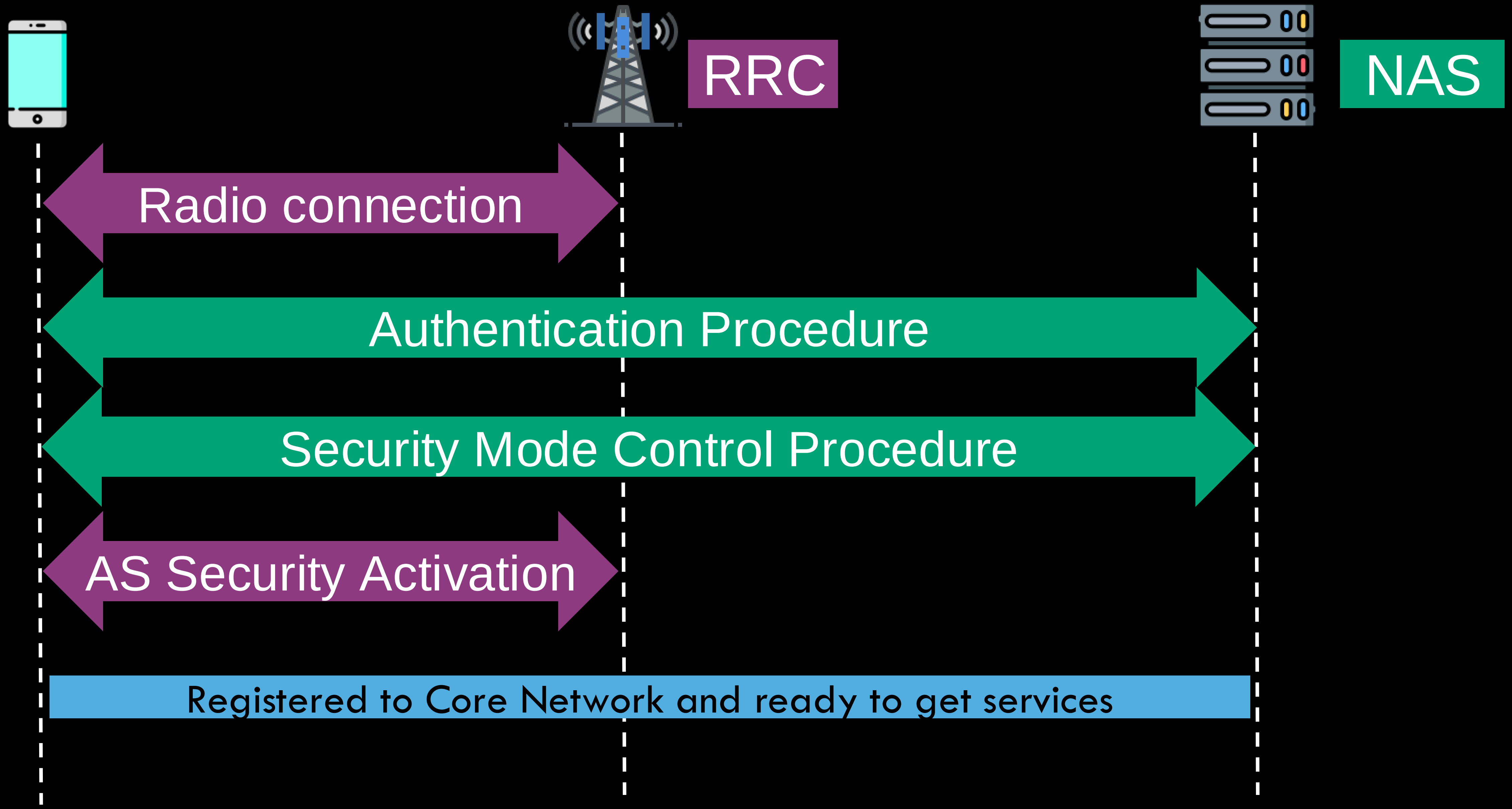
# What we Are Going to Talk About Today

- 5G cellular network overview
- Workflow of our automated 5G baseband testing tool
- Summary of findings
- 5G AKA bypass end-to-end exploitations demos
- Impact and Status
- Takeaways

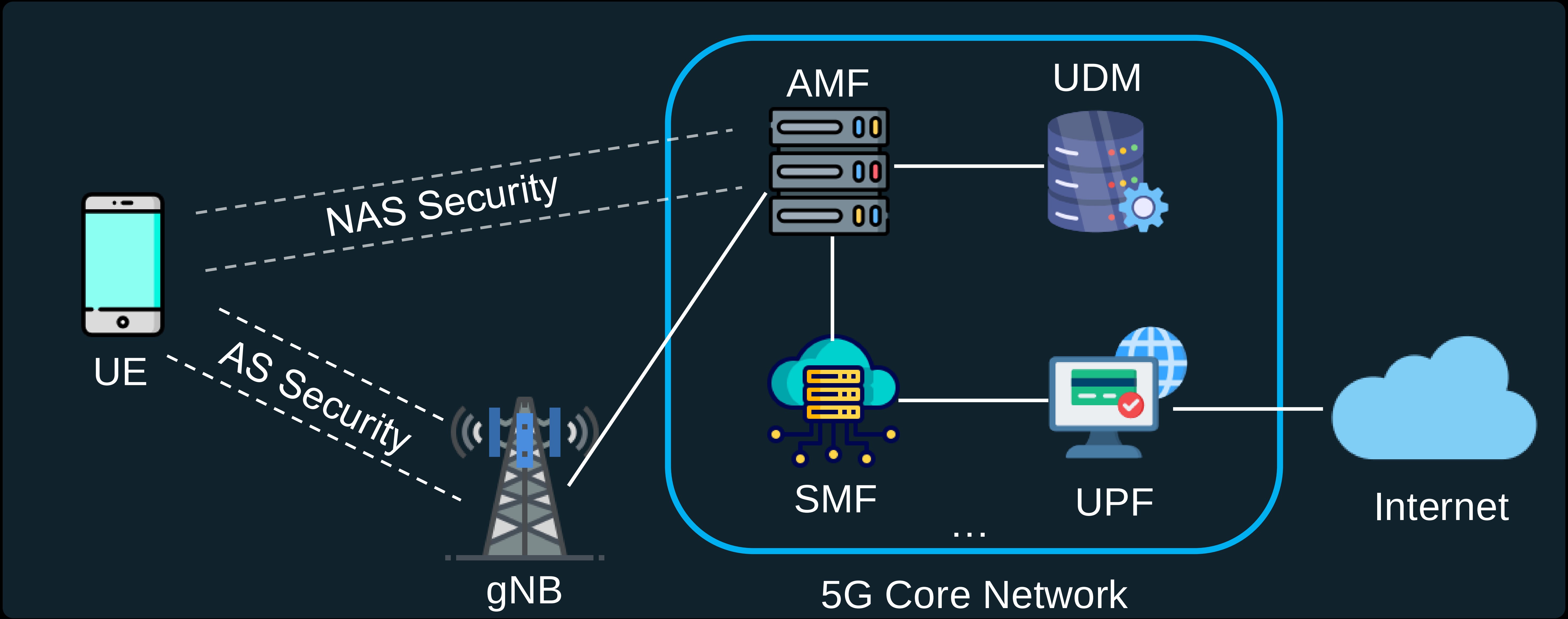
# 5G Network Architecture



# 5G Control Plane


RRC
NAS
Radio connection
Authentication Procedure
Security Mode Control Procedure
AS Security Activation
Registered to Core Network and ready to get services

# Our Scope


UE
NAS Security
AS Security
gNB
AMF
UDM
SMF
UPF
...
5G Core Network
Internet

# Baseband Protocol Implementation - Easy Work?

**Why can protocol implementations in commercial basebands go wrong?**

# Baseband protocol is hard to Implement…

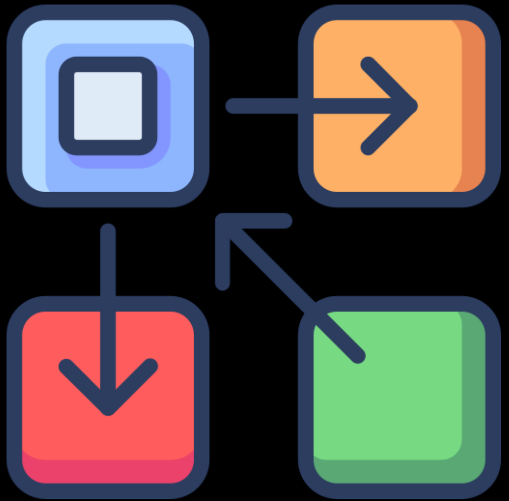
Hundreds of documents

Difficult to understand

Conflicts and underspecifications

# Non-compliant behavior may lead to...

Exploitable vulnerabilities

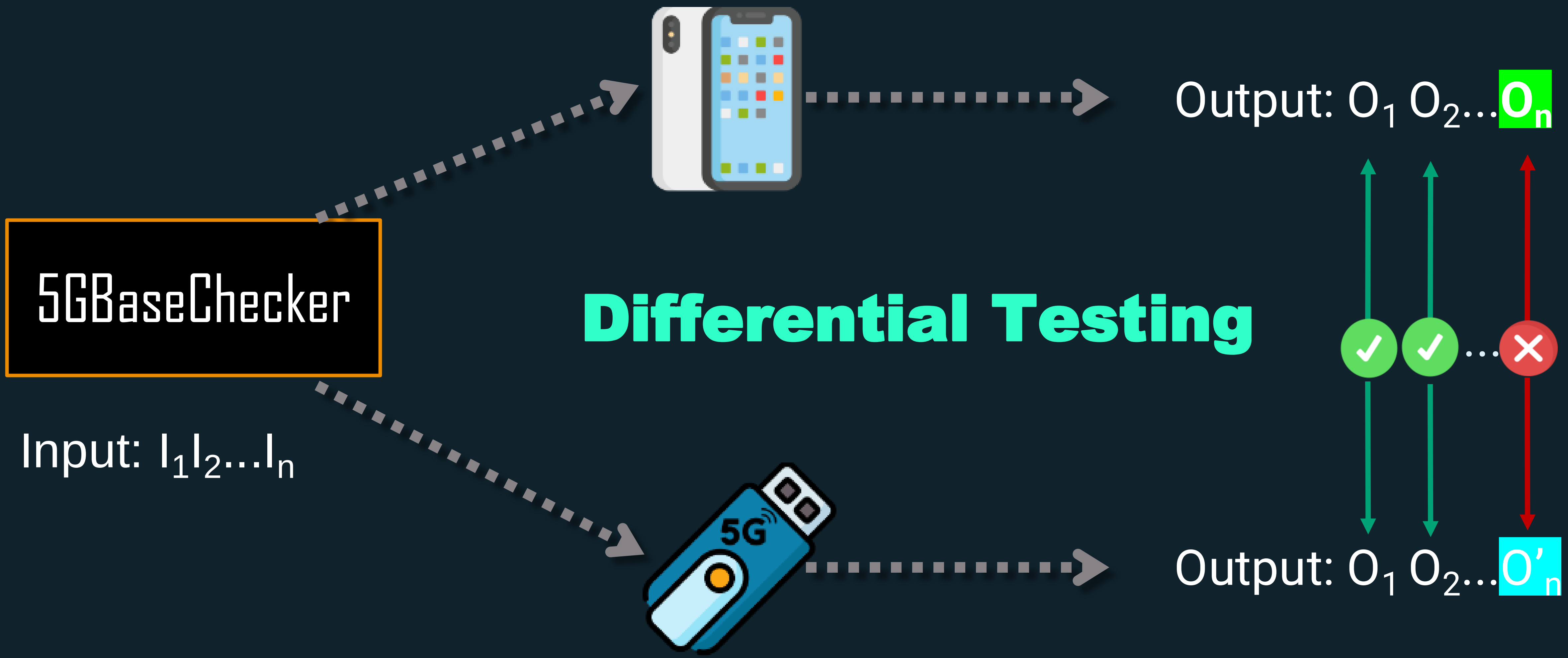


Interoperability issues

# Our Goal

Is it possible to develop an automated framework to identify security policy violations in 5G UE implementations efficiently?

# Key Intuition of 5GBaseChecker



5GBaseChecker

Input: $I_1 I_2 \ldots I_n$

Differential Testing

Output: $O_1\ O_2 \ldots O_n$

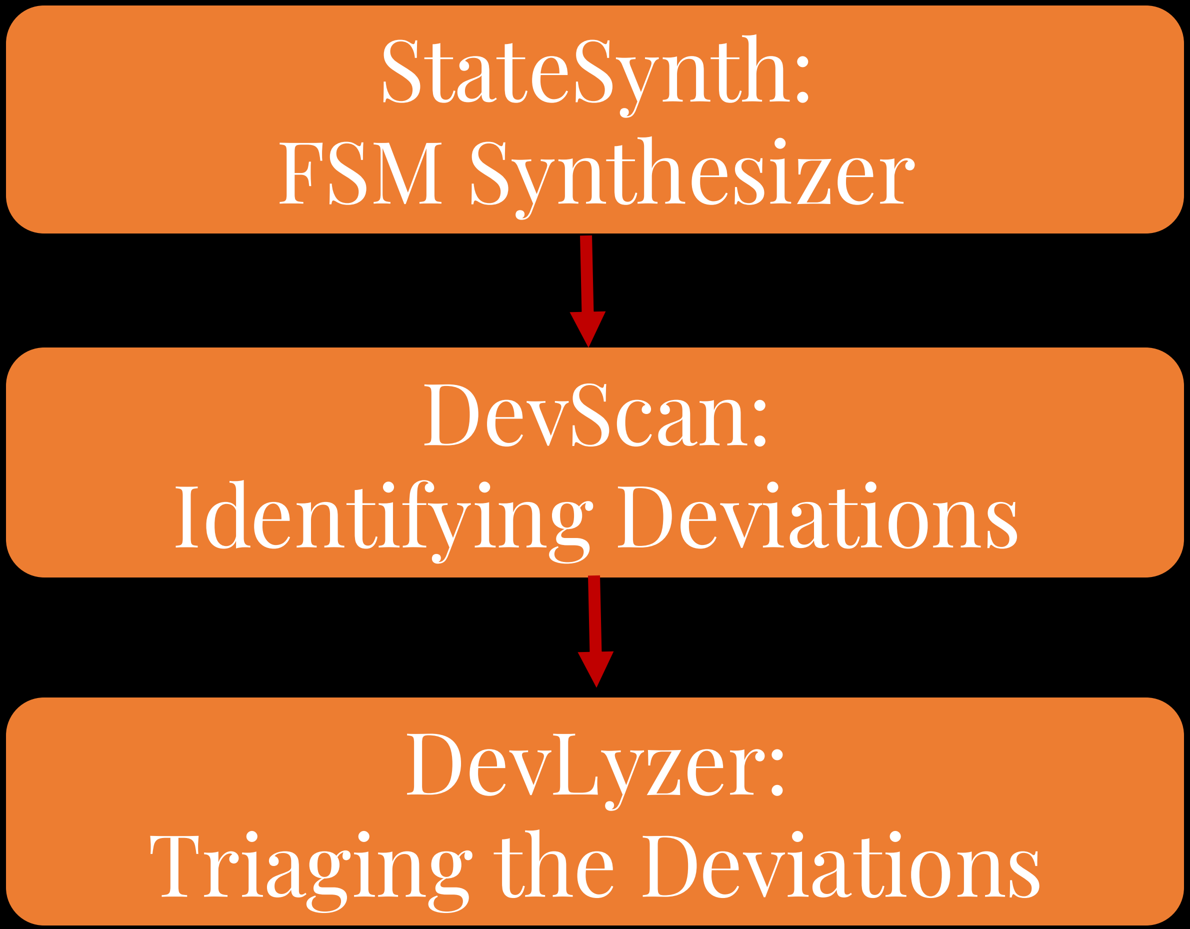
Output: $O_1\ O_2 \ldots O'_n$

# How to Generate Input

- Generate random input sequences will not work…

- Build Finite State Machine (FSM) for each baseband, then identify the differences among FSMs!

# High-Level Workflow of 5GBaseChecker



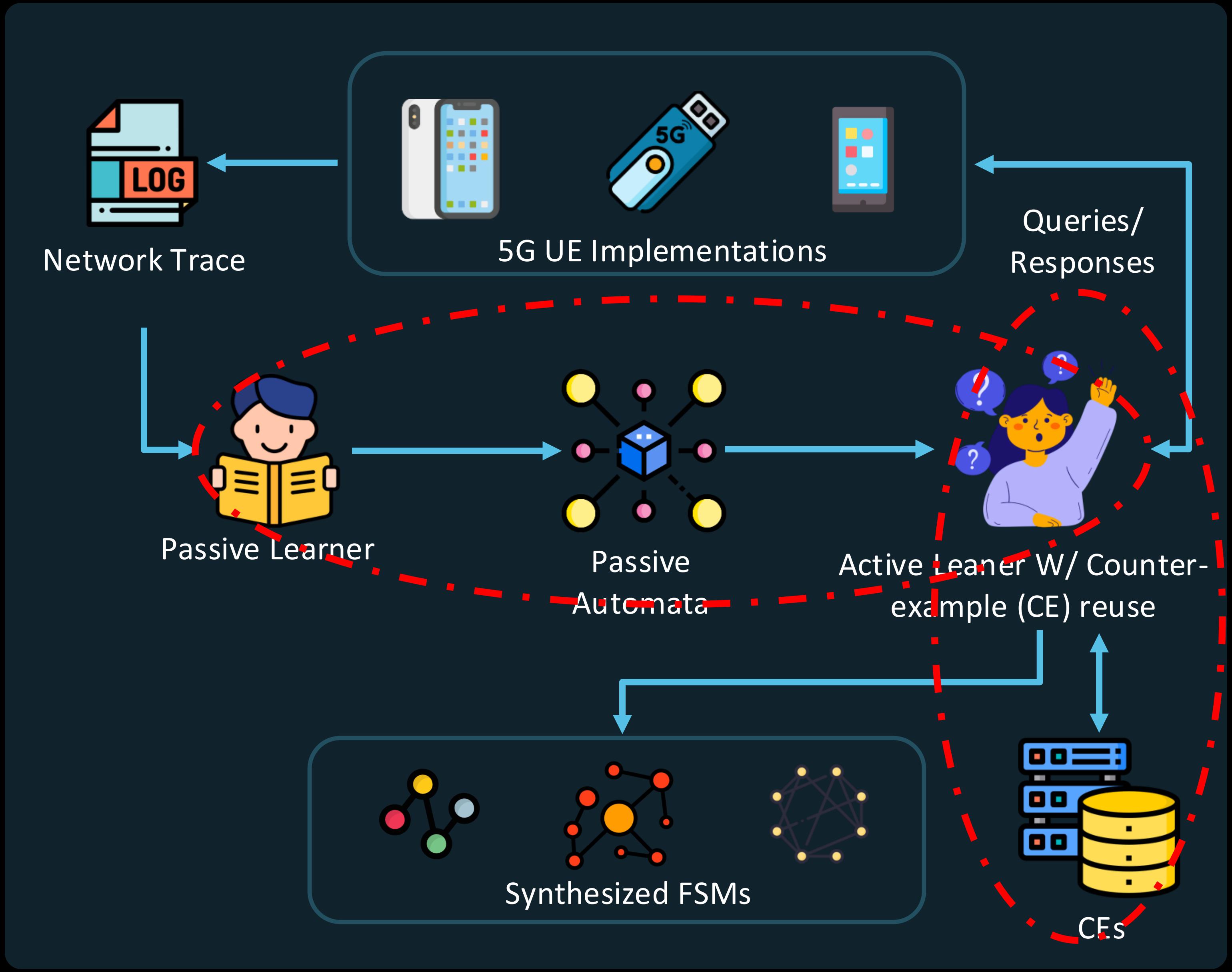
StateSynth:
FSM Synthesizer

DevScan:
Identifying Deviations

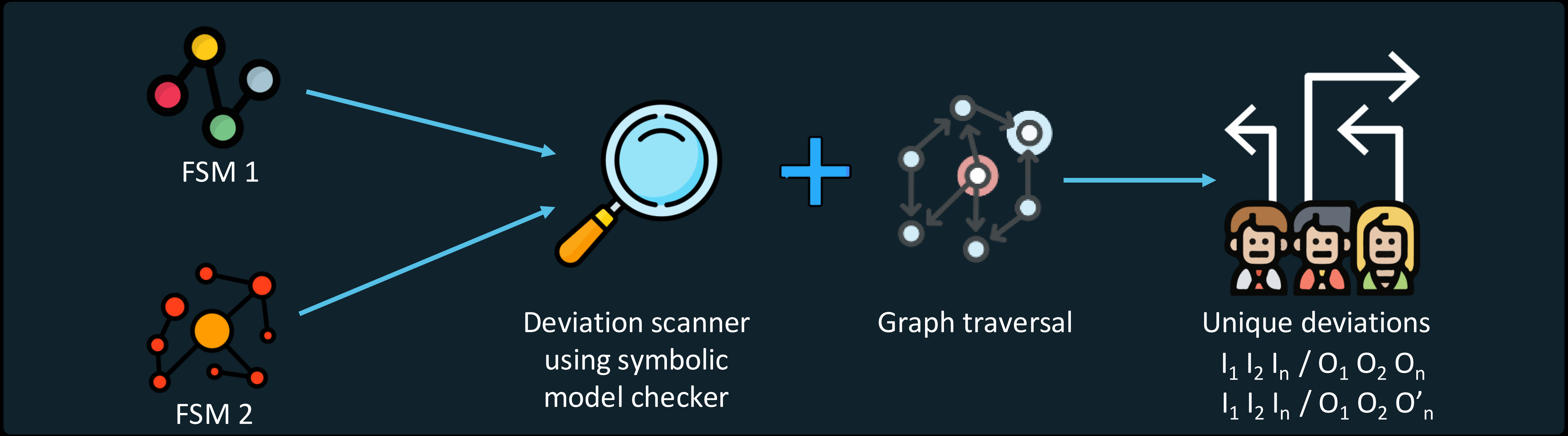
DevLyzer:
Triaging the Deviations

# StateSynth: Constructing FSM

- **StateSynth** module extracts finite state machines (FSMs) from 5G baseband implementations.
- StateSynth's hybrid and collaborative FSM learning technique significantly improves FSM learning efficiency.

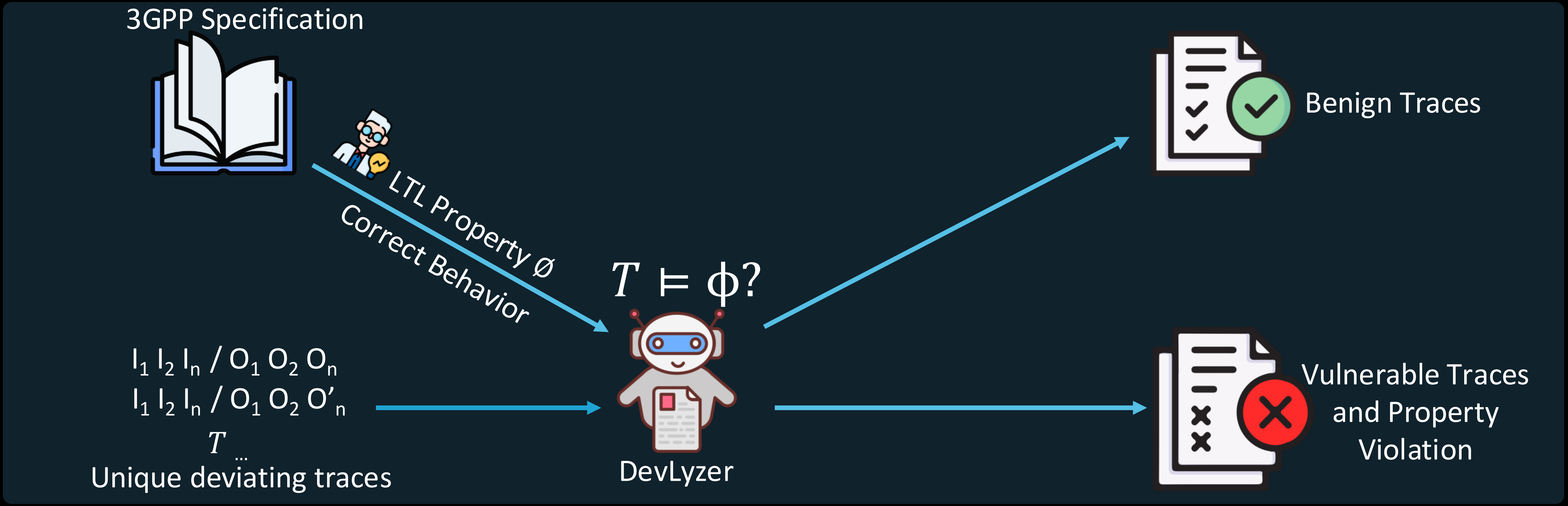


# DevScan: Identifying Deviations


FSM 1
FSM 2
Deviation scanner using symbolic model checker
Graph traversal
Unique deviations
$I_1$ $I_2$ $I_n$ / $O_1$ $O_2$ $O_n$
$I_1$ $I_2$ $I_n$ / $O_1$ $O_2$ $O'_n$

- **DevScan** uses symbolic model checking technique to automatically identifies the deviations between FSMs.

# DevLyzer: Triaging Deviations



- **DevLyzer** aids human experts to triage the deviations found by DevScan.

# Summary of Vulnerabilities

- 13 vulnerabilities in 17 devices from 5 different baseband vendors and 2 open-source implementations
- 3 types of flaws and 4 types of impacts
- Demo: 5G AKA Bypass

MEDIATEK

UNISOC

SAMSUNG Exynos

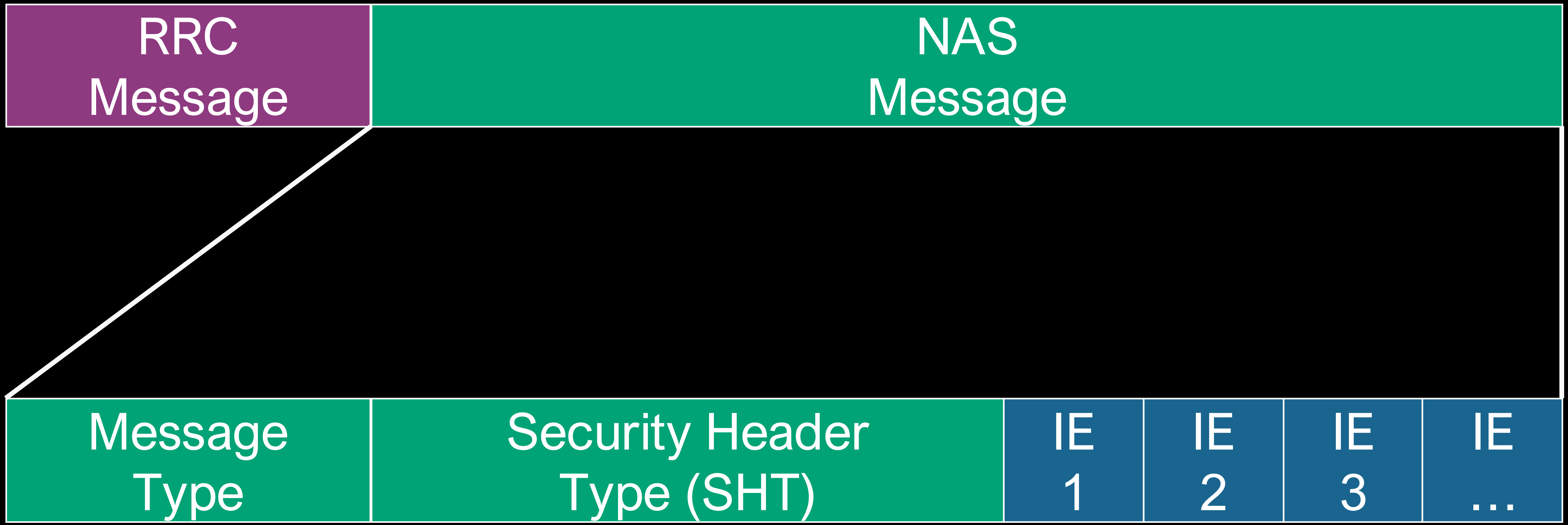
Qualcomm

HISILICON

# Types of Flaws

- Accepting invalid Security Header Types
- Accepting message types that should not be accepted in a certain state
- Mishandling Information Elements (IEs)

# 5G Control-Plane Message Structure



RRC Message

NAS Message

Message Type

Security Header Type (SHT)

IE 1

IE 2

IE 3

IE …

# Impact of Vulnerabilities Found

Information Leak

Phishing

Downgrade

Denial-of-Service

# Impact of Vulnerabilities Found

- Information Leak
- Phishing
- Downgrade
- Denial-of-Service

# Impact of Vulnerabilities Found

- Information Leak
- Phishing
- Downgrade
- Denial-of-Service

# Impact of Vulnerabilities Found

Information Leak

Phishing

Downgrade

Denial-of-Service

# Impact of Vulnerabilities Found

Information Leak

Phishing

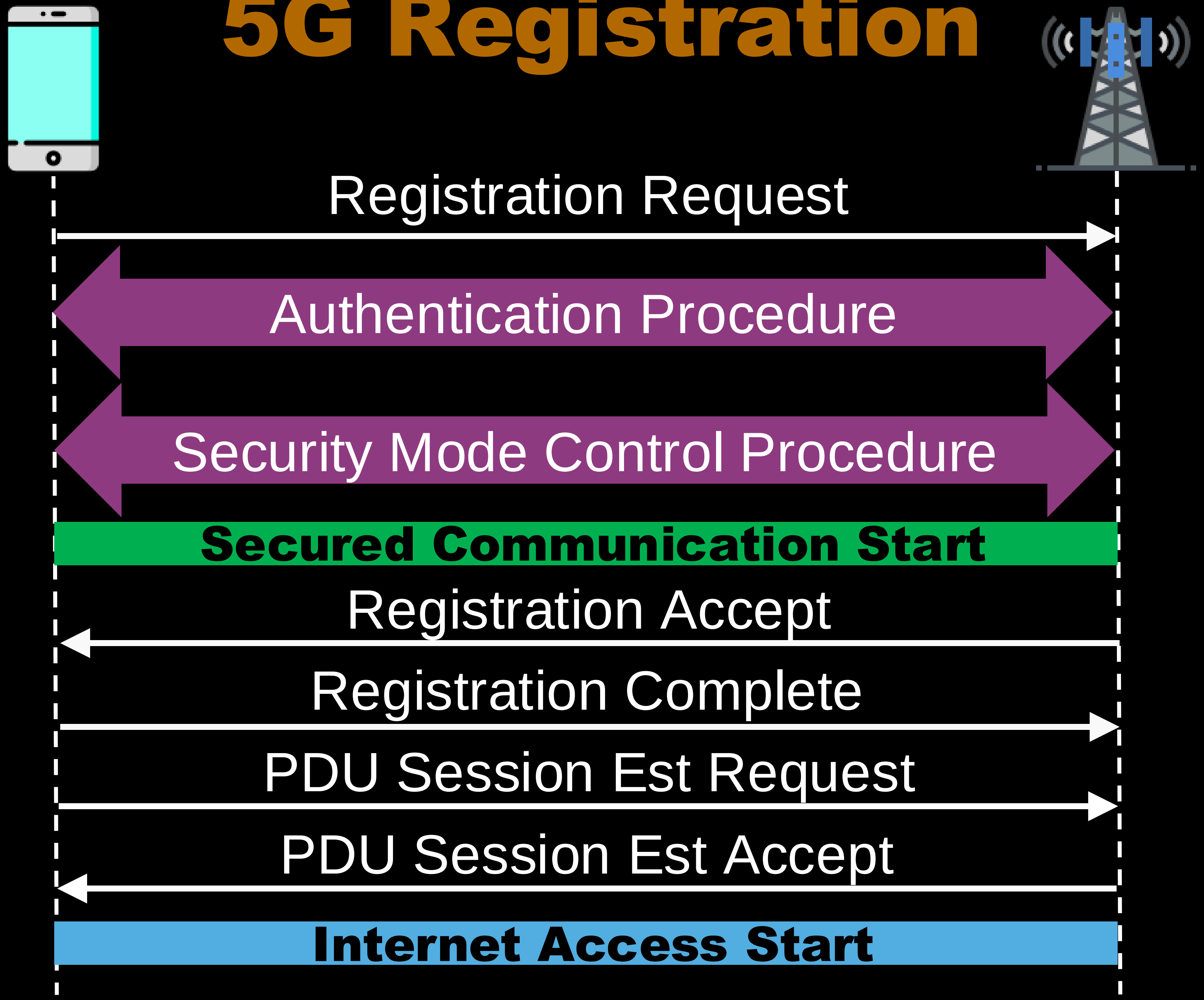
Downgrade

Denial-of-Service

# 5G AKA Bypass

- Bypass 5G Authentication and Key Agreement procedure
  - CVE-2023-50804
- Found in Exynos basebands (Exynos 5123 and Exynos 5300)
- No mutual authentication between the phone and the network
- Attacker can provide services to the user
  (Send SMS, provide Internet access, etc. )

# 5G Registration



Registration Request

Authentication Procedure

Security Mode Control Procedure

**Secured Communication Start**

Registration Accept

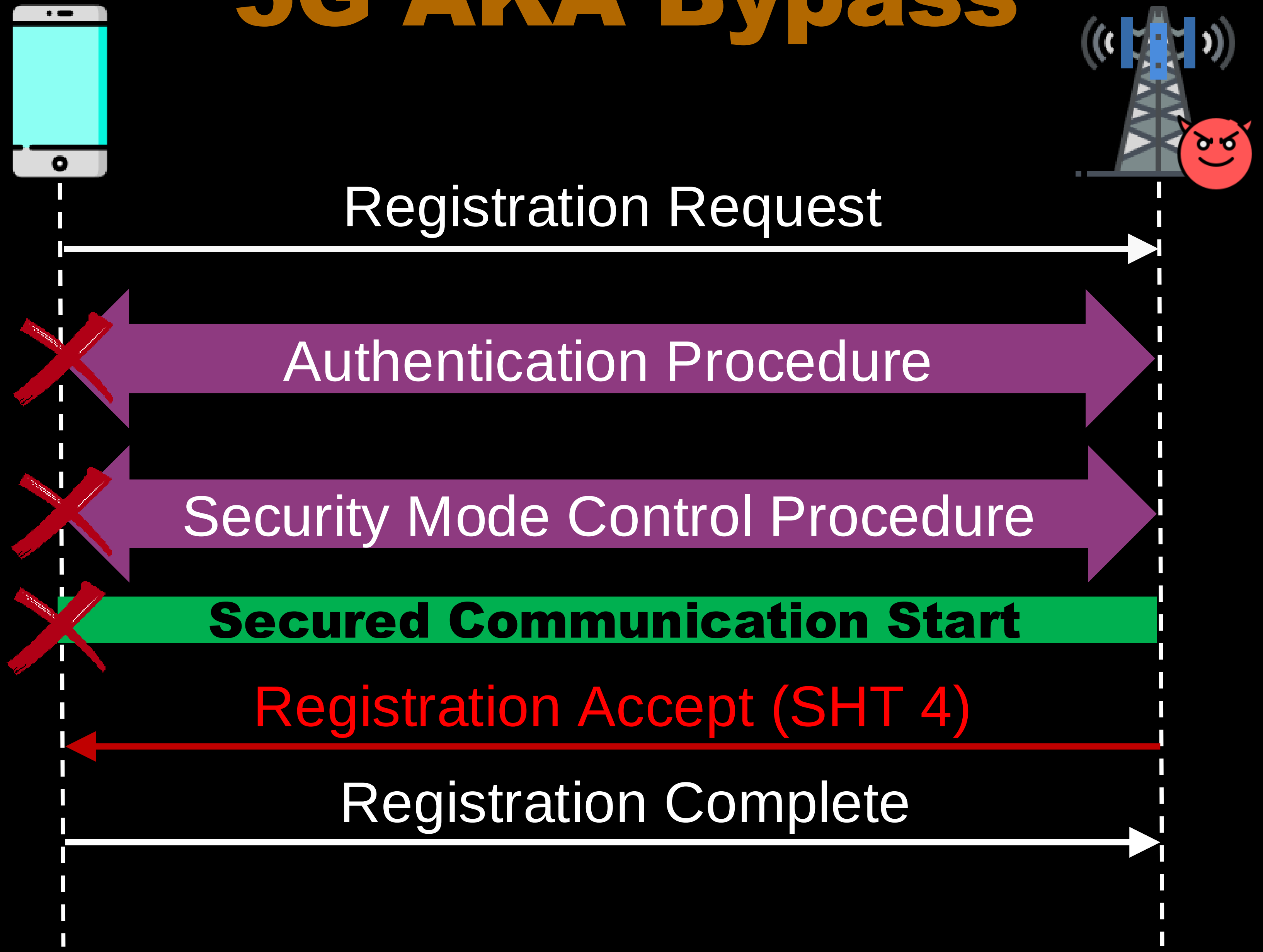
Registration Complete

PDU Session Est Request

PDU Session Est Accept

**Internet Access Start**

# 5G AKA Bypass



Registration Request

Authentication Procedure

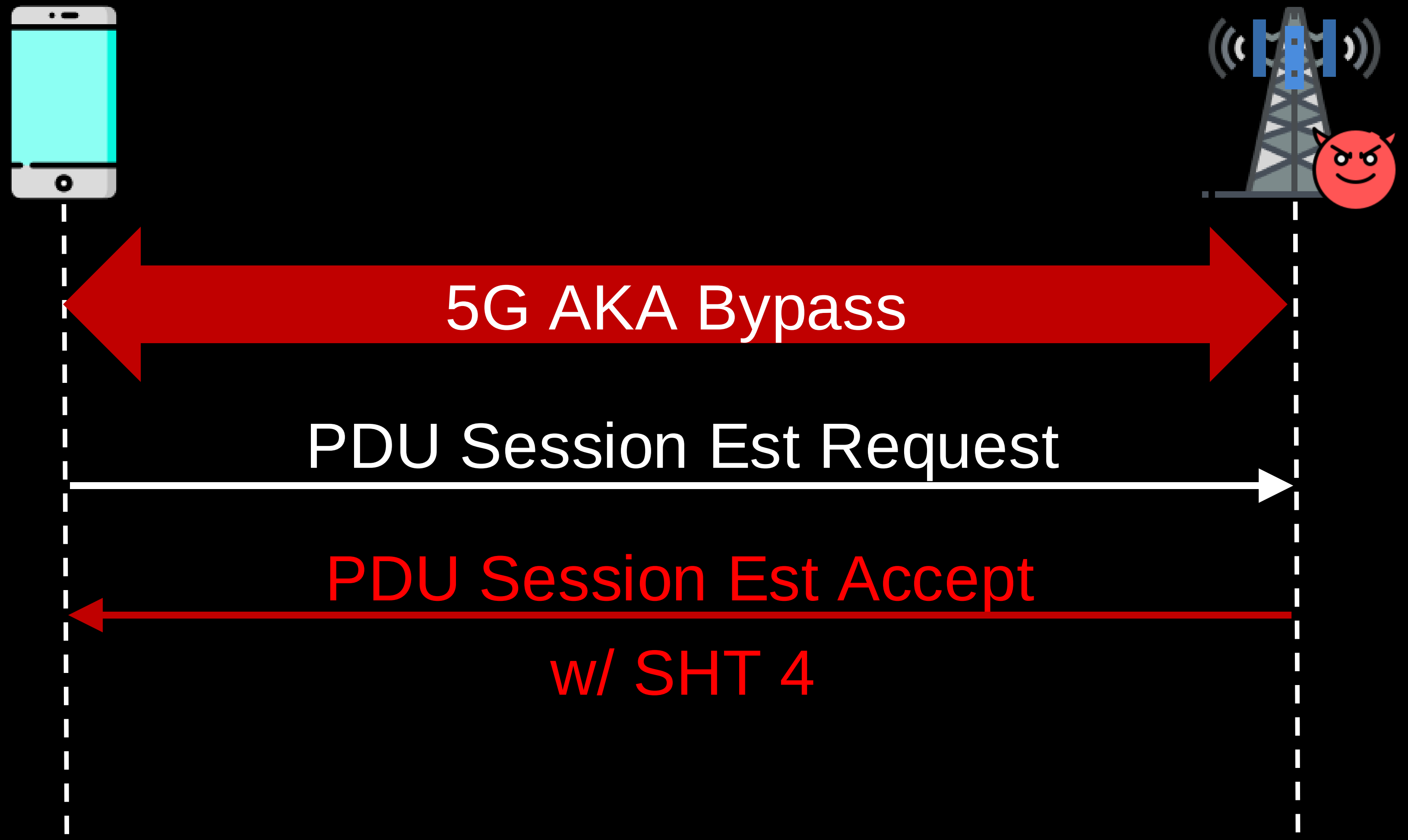
Security Mode Control Procedure

**Secured Communication Start**

Registration Accept (SHT 4)

Registration Complete

# Demo: Internet Traffic Eavesdropping



5G AKA Bypass

PDU Session Est Request

PDU Session Est Accept

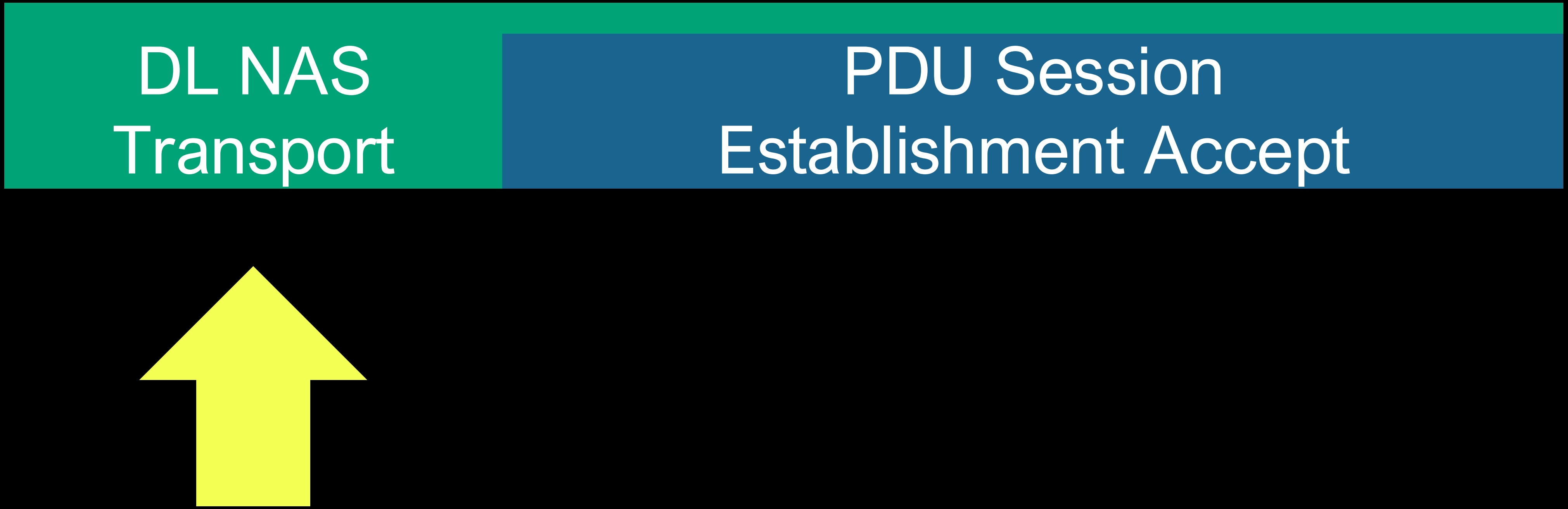
w/ SHT 4

# Assemble the Attack Message

PDU Session
Establishment Accept

Establishes a PDU session
for Internet access

# Assemble the Attack Message



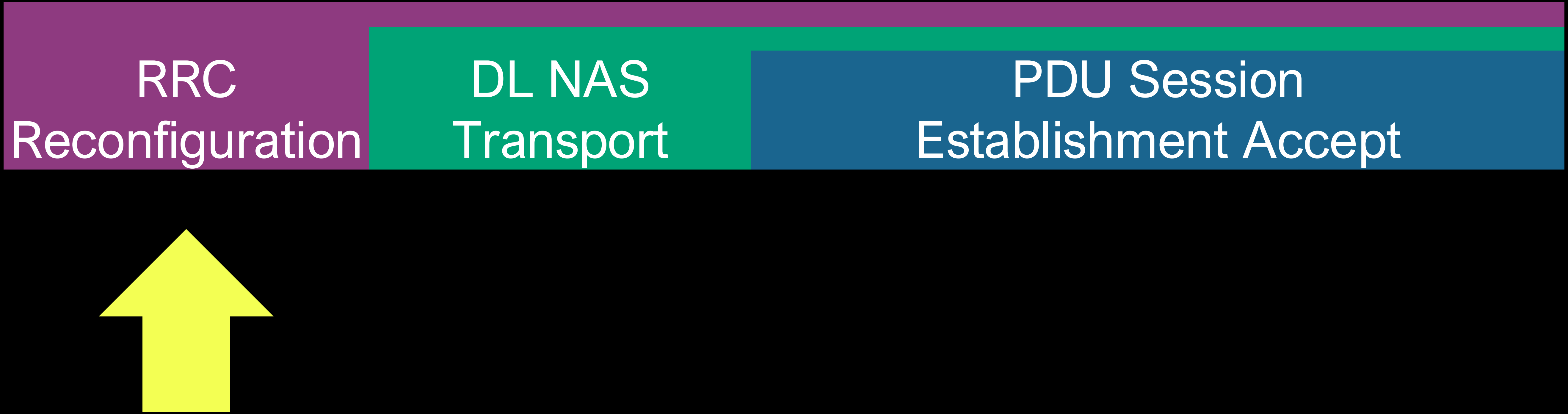
DL NAS Transport

PDU Session Establishment Accept

With Security Header Type 4

Same as CVE-2023-50804

# Assemble the Attack Message



w/ prohibited IE(s)

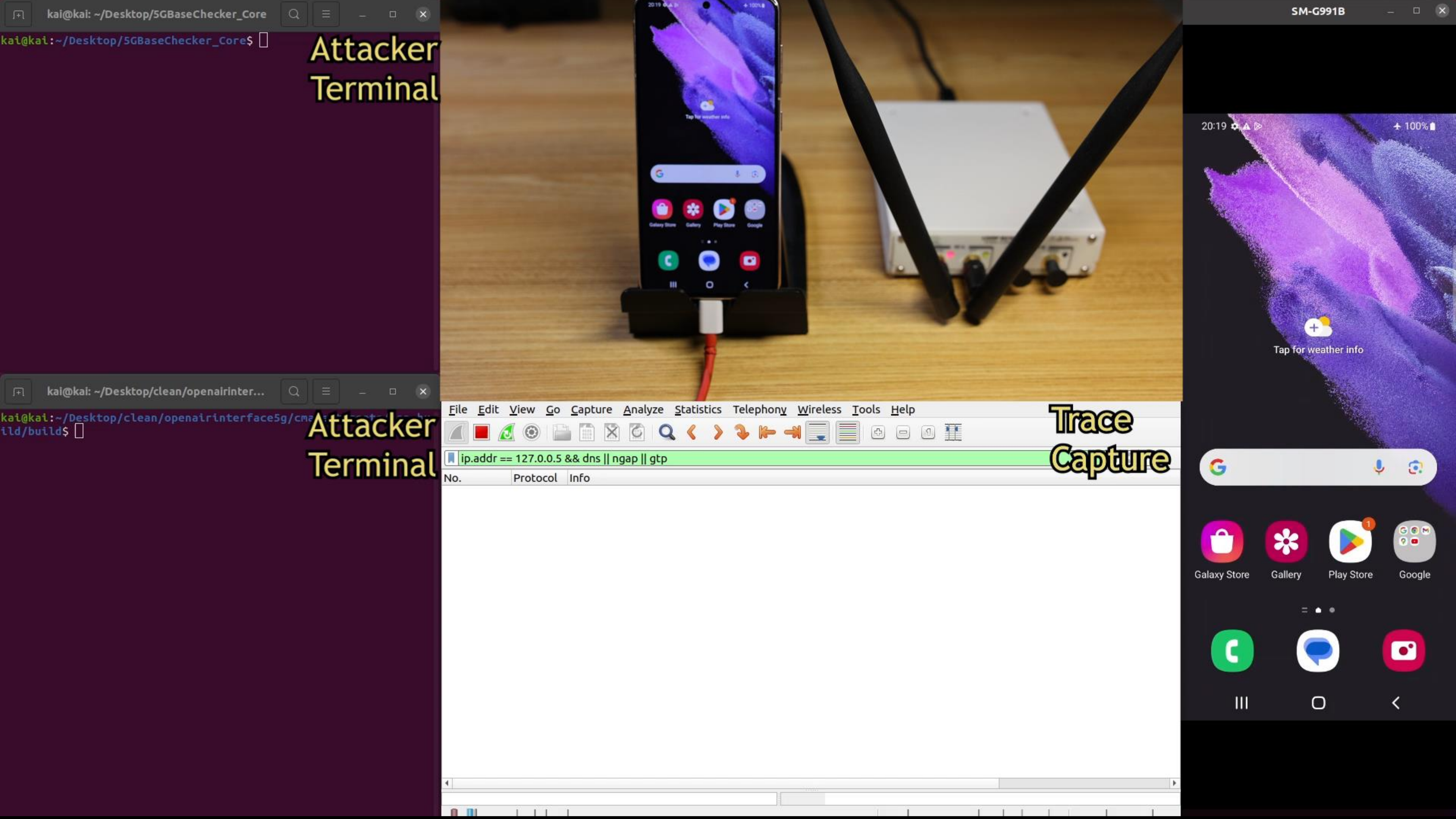
drb-ToAddModList

CVE-2024-29152

# Attack Setup

- Hardware: SDR (USRP B210)

- Software: OpenAirInterface + Open5GS

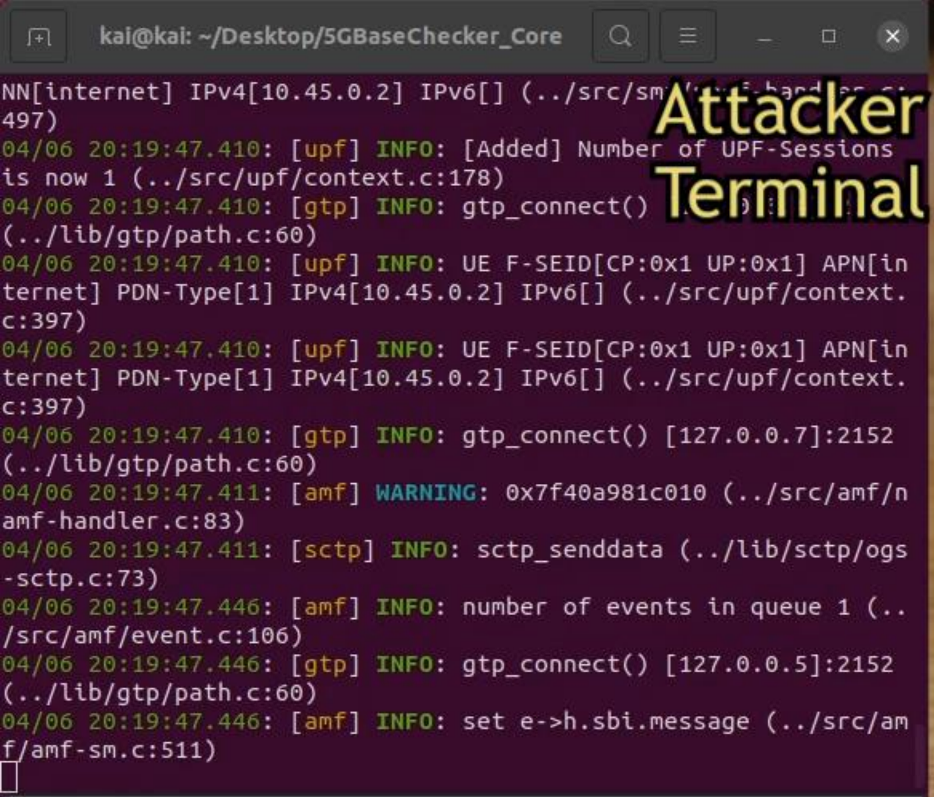

kai@kai: ~/Desktop/5GBaseChecker_Core
Attacker Terminal
kai@kai: ~/Desktop/clean/openairinter...
Attacker Terminal
Trace Capture
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
SM-G991B
20:19
100%
Tap for weather info
Galaxy Store
Gallery
Play Store
Google

```
kai@kai:~/Desktop/5GBaseChecker_Core$ 
```

```
kai@kai:~/Desktop/clean/openairinterface5g/cma
ild/build$ 
```

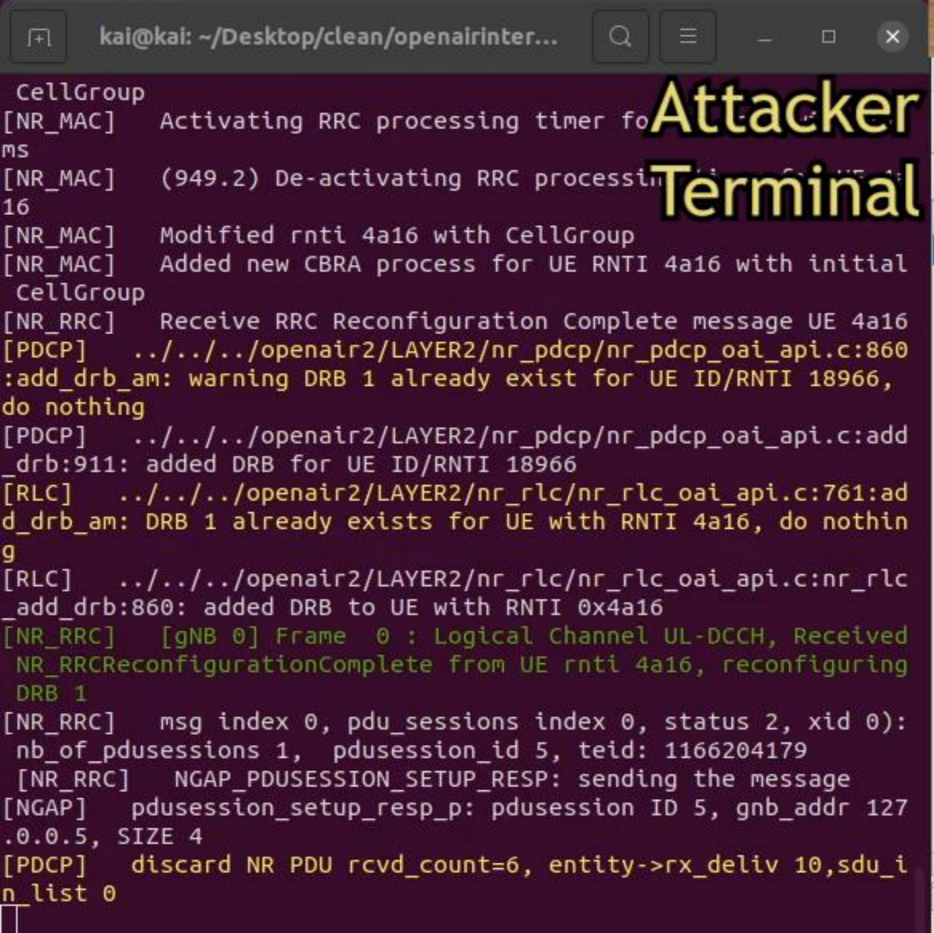
ip.addr == 127.0.0.5 && dns || ngap || gtp

| No. | Protocol | Info |
|---|---|---|



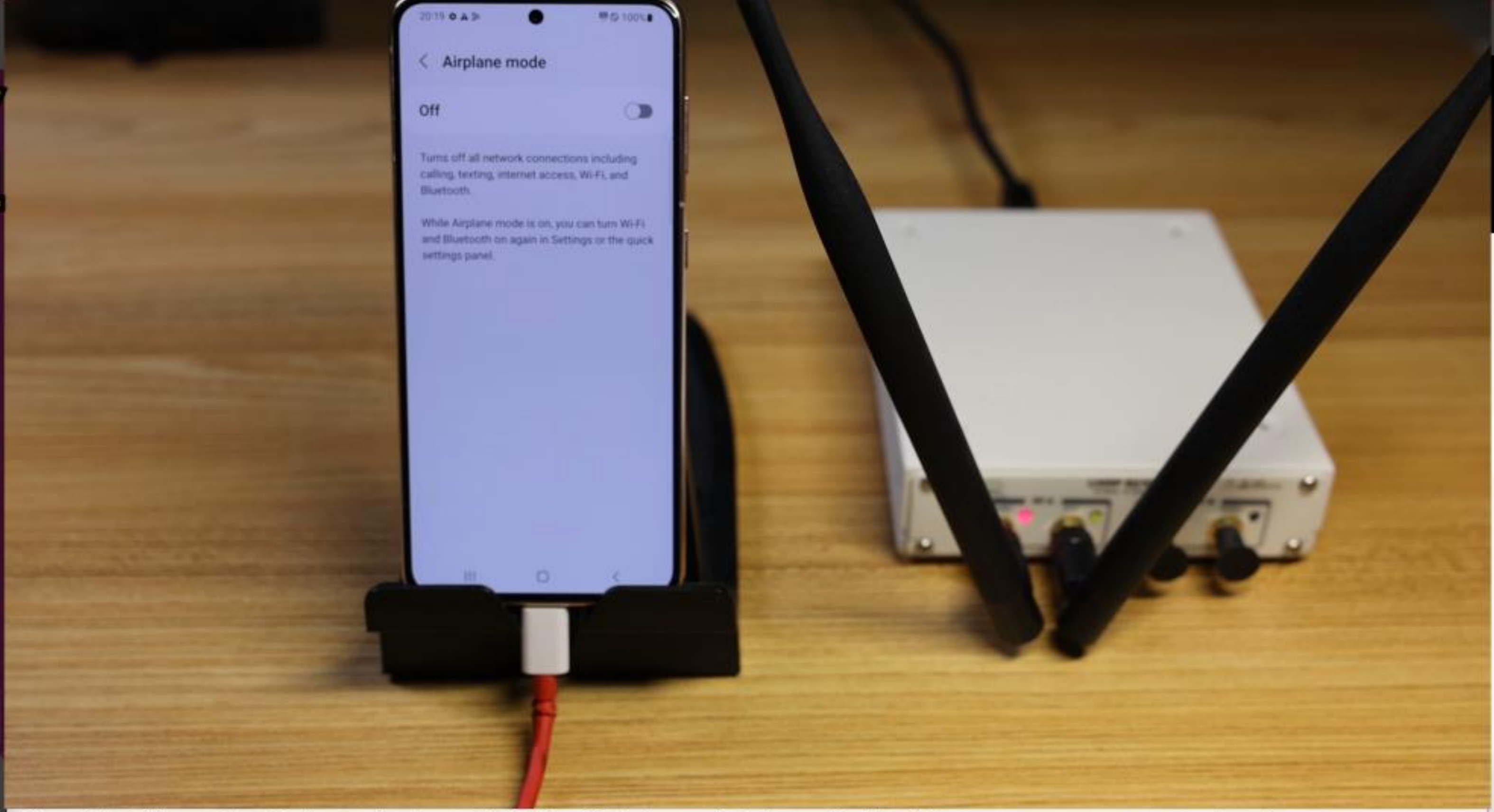
Attacker Terminal

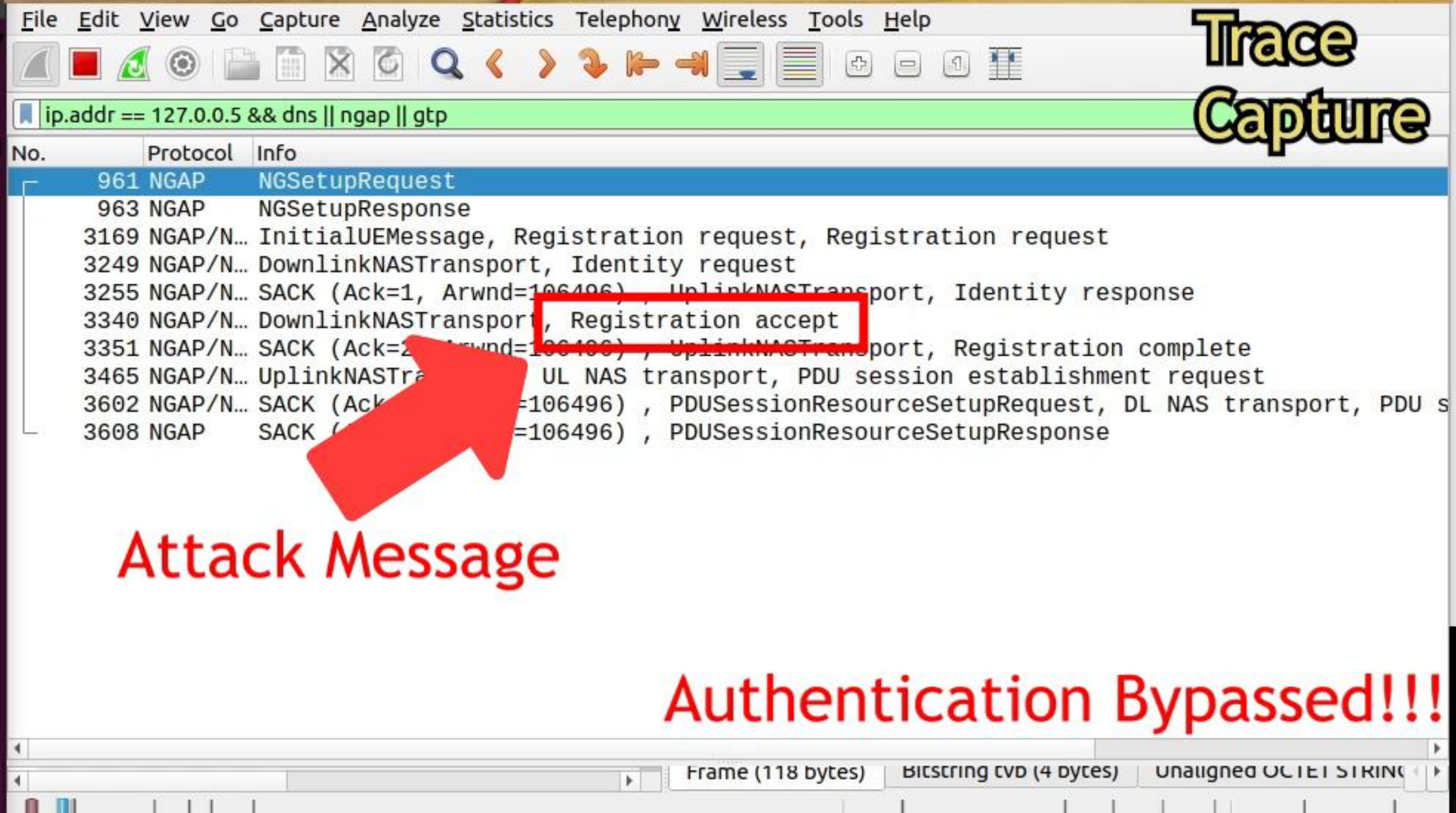
```
NN[internet] IPv4[10.45.0.2] IPv6[] (../src/sm
497)
04/06 20:19:47.410: [upf] INFO: [Added] Number of UPF-Sessions
is now 1 (../src/upf/context.c:178)
04/06 20:19:47.410: [gtp] INFO: gtp_connect()
(../lib/gtp/path.c:60)
04/06 20:19:47.410: [upf] INFO: UE F-SEID[CP:0x1 UP:0x1] APN[in
ternet] PDN-Type[1] IPv4[10.45.0.2] IPv6[] (../src/upf/context.
c:397)
04/06 20:19:47.410: [upf] INFO: UE F-SEID[CP:0x1 UP:0x1] APN[in
ternet] PDN-Type[1] IPv4[10.45.0.2] IPv6[] (../src/upf/context.
c:397)
04/06 20:19:47.410: [gtp] INFO: gtp_connect() [127.0.0.7]:2152
(../lib/gtp/path.c:60)
04/06 20:19:47.411: [amf] WARNING: 0x7f40a981c010 (../src/amf/n
amf-handler.c:83)
04/06 20:19:47.411: [sctp] INFO: sctp_senddata (../lib/sctp/ogs
-sctp.c:73)
04/06 20:19:47.446: [amf] INFO: number of events in queue 1 (..
/src/amf/event.c:106)
04/06 20:19:47.446: [gtp] INFO: gtp_connect() [127.0.0.5]:2152
(../lib/gtp/path.c:60)
04/06 20:19:47.446: [amf] INFO: set e->h.sbi.message (../src/am
f/amf-sm.c:511)
```



Attacker Terminal

```
 CellGroup
[NR_MAC]   Activating RRC processing timer fo
ms
[NR_MAC]   (949.2) De-activating RRC processi
16
[NR_MAC]   Modified rnti 4a16 with CellGroup
[NR_MAC]   Added new CBRA process for UE RNTI 4a16 with initial
 CellGroup
[NR_RRC]   Receive RRC Reconfiguration Complete message UE 4a16
[PDCP]   ../../../openair2/LAYER2/nr_pdcp/nr_pdcp_oai_api.c:860
:add_drb_am: warning DRB 1 already exist for UE ID/RNTI 18966,
do nothing
[PDCP]   ../../../openair2/LAYER2/nr_pdcp/nr_pdcp_oai_api.c:add
_drb:911: added DRB for UE ID/RNTI 18966
[RLC]   ../../../openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:761:ad
d_drb_am: DRB 1 already exists for UE with RNTI 4a16, do nothin
g
[RLC]   ../../../openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:nr_rlc
_add_drb:860: added DRB to UE with RNTI 0x4a16
[NR_RRC]   [gNB 0] Frame  0 : Logical Channel UL-DCCH, Received
 NR_RRCReconfigurationComplete from UE rnti 4a16, reconfiguring
 DRB 1
[NR_RRC]   msg index 0, pdu_sessions index 0, status 2, xid 0):
 nb_of_pdusessions 1,  pdusession_id 5, teid: 1166204179
 [NR_RRC]   NGAP_PDUSESSION_SETUP_RESP: sending the message
[NGAP]   pdusession_setup_resp_p: pdusession ID 5, gnb_addr 127
.0.0.5, SIZE 4
[PDCP]   discard NR PDU rcvd_count=6, entity->rx_deliv 10,sdu_i
n_list 0
```





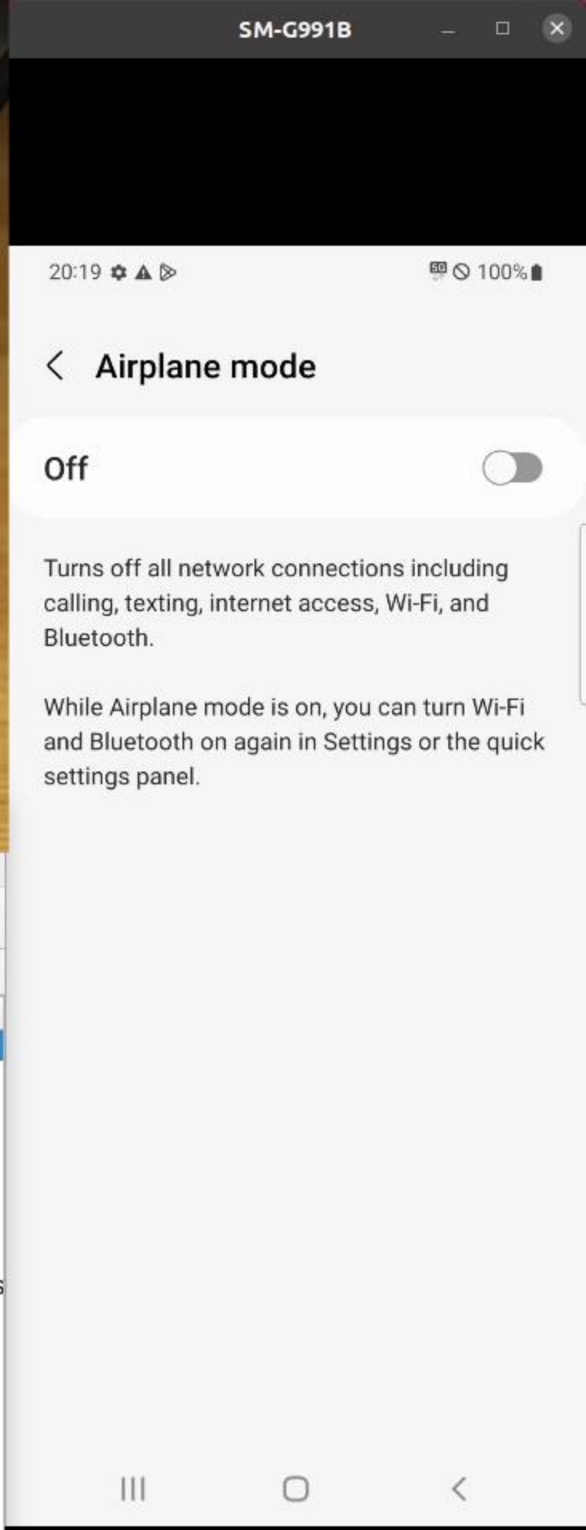
Trace Capture

ip.addr == 127.0.0.5 && dns || ngap || gtp

```
No.  Protocol Info
 961 NGAP     NGSetupRequest
 963 NGAP     NGSetupResponse
3169 NGAP/N… InitialUEMessage, Registration request, Registration request
3249 NGAP/N… DownlinkNASTransport, Identity request
3255 NGAP/N… SACK (Ack=1, Arwnd=106496) , UplinkNASTransport, Identity response
3340 NGAP/N… DownlinkNASTransport, Registration accept
3351 NGAP/N… SACK (Ack=2                 port, Registration complete
3465 NGAP/N… UplinkNASTra                UL NAS transport, PDU session establishment request
3602 NGAP/N… SACK (Ack                  =106496) , PDUSessionResourceSetupRequest, DL NAS transport, PDU s
3608 NGAP     SACK (                    =106496) , PDUSessionResourceSetupResponse
```

Attack Message

Authentication Bypassed!!!

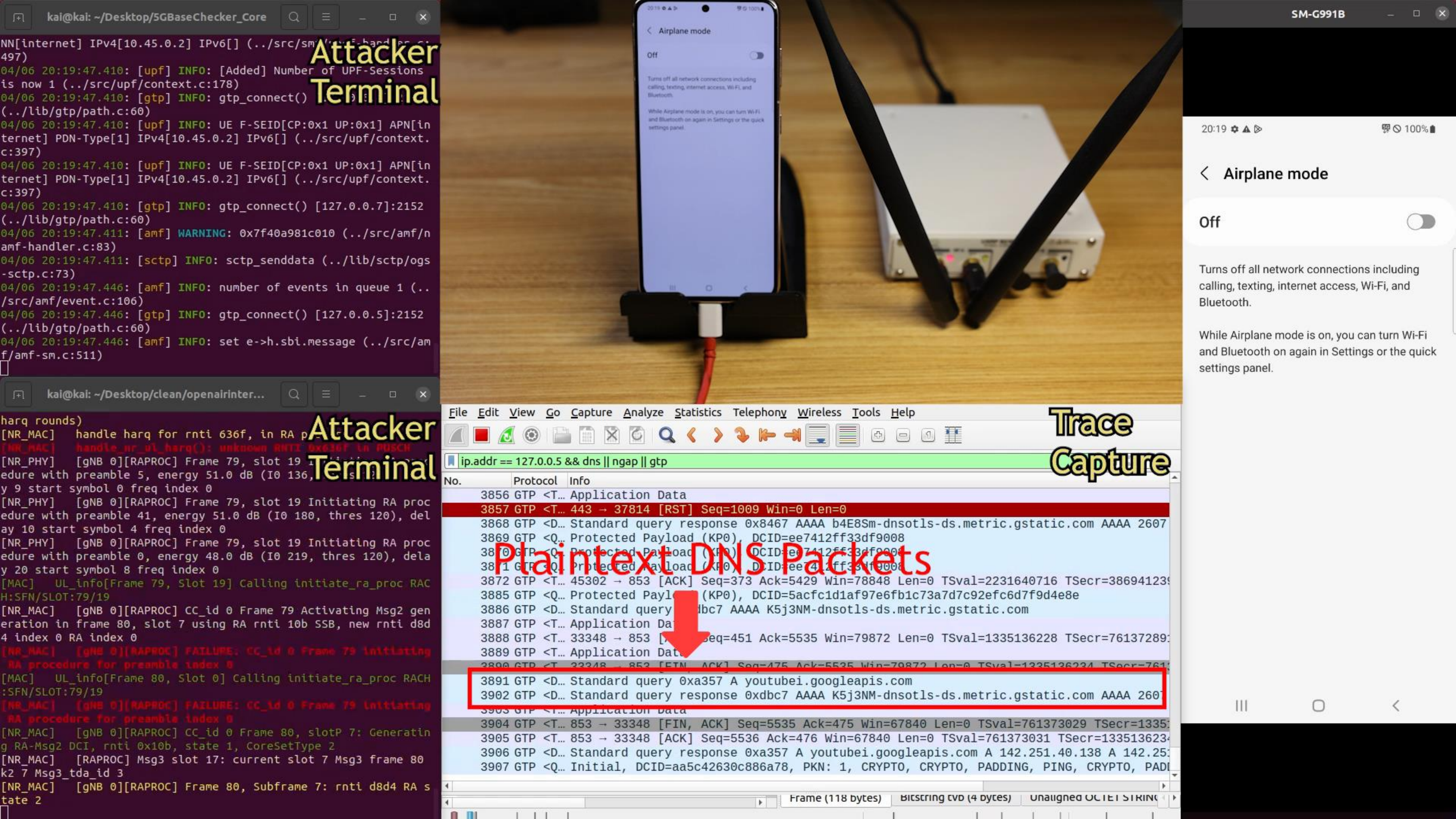


Airplane mode

Off

Turns off all network connections including calling, texting, internet access, Wi-Fi, and Bluetooth.

While Airplane mode is on, you can turn Wi-Fi and Bluetooth on again in Settings or the quick settings panel.


kai@kai: ~/Desktop/5GBaseChecker_Core
Attacker Terminal
kai@kai: ~/Desktop/clean/openairinter...
Attacker Terminal
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
Trace Capture
Plaintext DNS Packets
SM-G991B

```
NN[internet] IPv4[10.45.0.2] IPv6[] (../src/sm
497)
04/06 20:19:47.410: [upf] INFO: [Added] Number of UPF-Sessions
is now 1 (../src/upf/context.c:178)
04/06 20:19:47.410: [gtp] INFO: gtp_connect()
(../lib/gtp/path.c:60)
04/06 20:19:47.410: [upf] INFO: UE F-SEID[CP:0x1 UP:0x1] APN[in
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c:397)
04/06 20:19:47.410: [upf] INFO: UE F-SEID[CP:0x1 UP:0x1] APN[in
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c:397)
04/06 20:19:47.410: [gtp] INFO: gtp_connect() [127.0.0.7]:2152
(../lib/gtp/path.c:60)
04/06 20:19:47.411: [amf] WARNING: 0x7f40a981c010 (../src/amf/n
amf-handler.c:83)
04/06 20:19:47.411: [sctp] INFO: sctp_senddata (../lib/sctp/ogs
-sctp.c:73)
04/06 20:19:47.446: [amf] INFO: number of events in queue 1 (..
/src/amf/event.c:106)
04/06 20:19:47.446: [gtp] INFO: gtp_connect() [127.0.0.5]:2152
(../lib/gtp/path.c:60)
04/06 20:19:47.446: [amf] INFO: set e->h.sbi.message (../src/am
f/amf-sm.c:511)
```

```
harq rounds)
[NR_MAC]   handle harq for rnti 636f, in RA p
[NR_MAC]   handle_nr_ul_harq(): unknown RNTI 0x636f in PUSCH
[NR_PHY]   [gNB 0][RAPROC] Frame 79, slot 19
edure with preamble 5, energy 51.0 dB (I0 136,
y 9 start symbol 0 freq index 0
[NR_PHY]   [gNB 0][RAPROC] Frame 79, slot 19 Initiating RA proc
edure with preamble 41, energy 51.0 dB (I0 180, thres 120), del
ay 10 start symbol 4 freq index 0
[NR_PHY]   [gNB 0][RAPROC] Frame 79, slot 19 Initiating RA proc
edure with preamble 0, energy 48.0 dB (I0 219, thres 120), dela
y 20 start symbol 8 freq index 0
[MAC]   UL_info[Frame 79, Slot 19] Calling initiate_ra_proc RAC
H:SFN/SLOT:79/19
[NR_MAC]   [gNB 0][RAPROC] CC_id 0 Frame 79 Activating Msg2 gen
eration in frame 80, slot 7 using RA rnti 10b SSB, new rnti d8d
4 index 0 RA index 0
[NR_MAC]   [gNB 0][RAPROC] FAILURE: CC_id 0 Frame 79 initiating
 RA procedure for preamble index 0
[MAC]   UL_info[Frame 80, Slot 0] Calling initiate_ra_proc RACH
:SFN/SLOT:79/19
[NR_MAC]   [gNB 0][RAPROC] FAILURE: CC_id 0 Frame 79 initiating
 RA procedure for preamble index 0
[NR_MAC]   [gNB 0][RAPROC] CC_id 0 Frame 80, slotP 7: Generatin
g RA-Msg2 DCI, rnti 0x10b, state 1, CoreSetType 2
[NR_MAC]   [RAPROC] Msg3 slot 17: current slot 7 Msg3 frame 80
k2 7 Msg3_tda_id 3
[NR_MAC]   [gNB 0][RAPROC] Frame 80, Subframe 7: rnti d8d4 RA s
tate 2
```

ip.addr == 127.0.0.5 && dns || ngap || gtp

```
No.     Protocol Info
   3856 GTP <T… Application Data
   3857 GTP <T… 443 → 37814 [RST] Seq=1009 Win=0 Len=0
   3868 GTP <D… Standard query response 0x8467 AAAA b4E8Sm-dnsotls-ds.metric.gstatic.com AAAA 2607
   3869 GTP <Q… Protected Payload (KP0), DCID=ee7412ff33df9008
   3870 GTP <Q… Protected Payload (KP0), DCID=ee7412ff33df9008
   3871 GTP <Q… Protected Payload (KP0), DCID=ee7412ff33df9008
   3872 GTP <T… 45302 → 853 [ACK] Seq=373 Ack=5429 Win=78848 Len=0 TSval=2231640716 TSecr=38694123
   3885 GTP <Q… Protected Payl   (KP0), DCID=5acfc1d1af97e6fb1c73a7d7c92efc6d7f9d4e8e
   3886 GTP <D… Standard query   dbc7 AAAA K5j3NM-dnsotls-ds.metric.gstatic.com
   3887 GTP <T… Application Da
   3888 GTP <T… 33348 → 853 [    Seq=451 Ack=5535 Win=79872 Len=0 TSval=1335136228 TSecr=76137289
   3889 GTP <T… Application Dat
   3890 GTP <T… 33348 → 853 [FIN, ACK] Seq=475 Ack=5535 Win=79872 Len=0 TSval=1335136234 TSecr=761
   3891 GTP <D… Standard query 0xa357 A youtubei.googleapis.com
   3902 GTP <D… Standard query response 0xdbc7 AAAA K5j3NM-dnsotls-ds.metric.gstatic.com AAAA 260
   3903 GTP <T… Application Data
   3904 GTP <T… 853 → 33348 [FIN, ACK] Seq=5535 Ack=475 Win=67840 Len=0 TSval=761373029 TSecr=1335
   3905 GTP <T… 853 → 33348 [ACK] Seq=5536 Ack=476 Win=67840 Len=0 TSval=761373031 TSecr=13351362
   3906 GTP <D… Standard query response 0xa357 A youtubei.googleapis.com A 142.251.40.138 A 142.25
   3907 GTP <Q… Initial, DCID=aa5c42630c886a78, PKN: 1, CRYPTO, CRYPTO, PADDING, PING, CRYPTO, PADD
```

Frame (118 bytes) | Bitstring tvb (4 bytes) | Unaligned OCTET STRING

20:19 100%

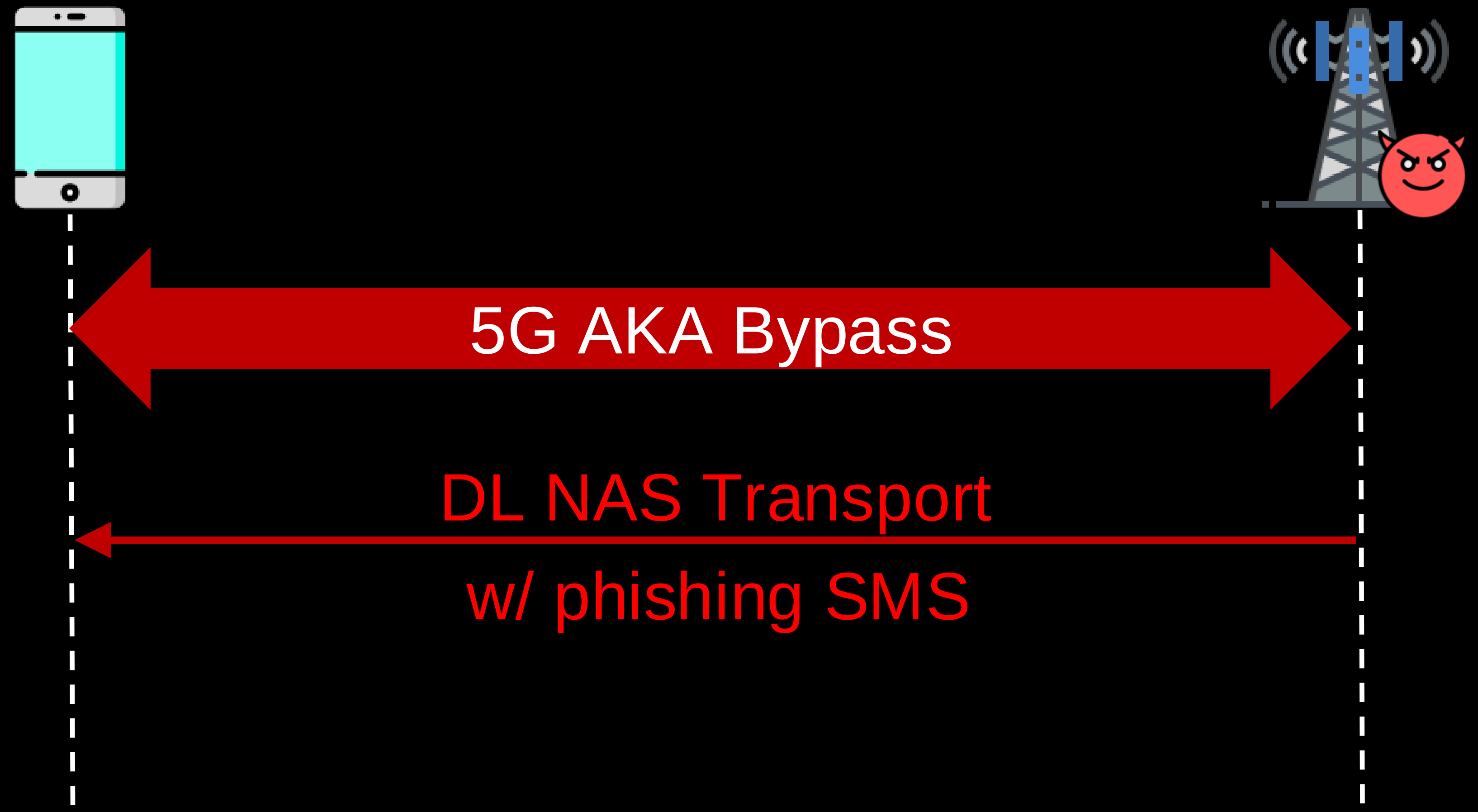
Airplane mode

Off

Turns off all network connections including calling, texting, internet access, Wi-Fi, and Bluetooth.

While Airplane mode is on, you can turn Wi-Fi and Bluetooth on again in Settings or the quick settings panel.

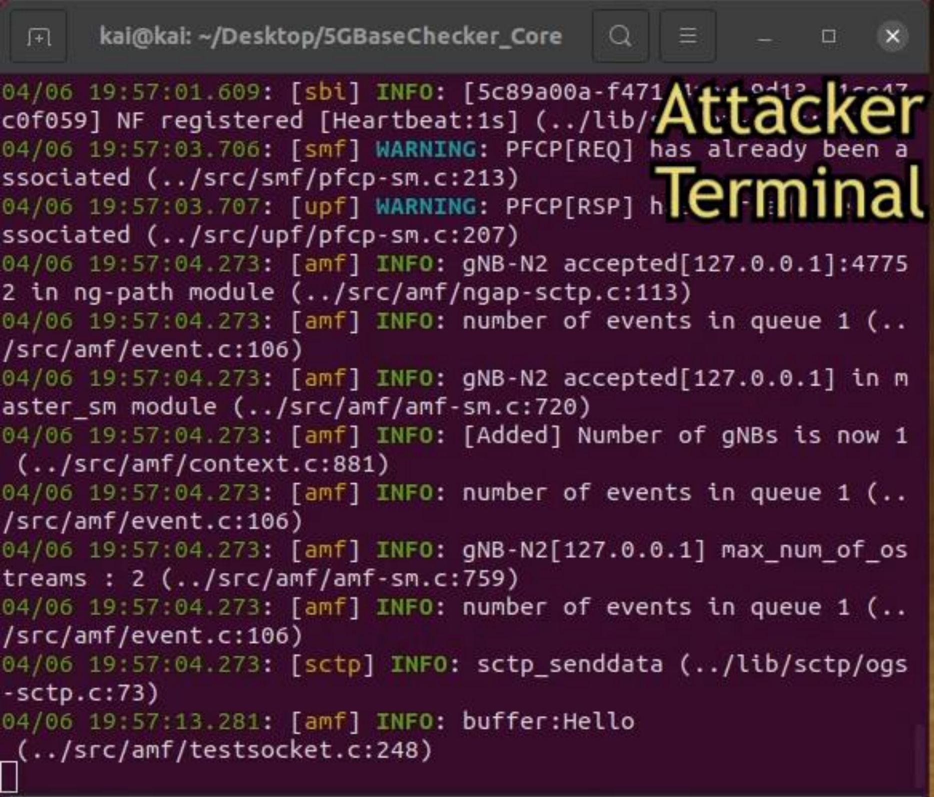
# Demo: Phishing SMS Injection



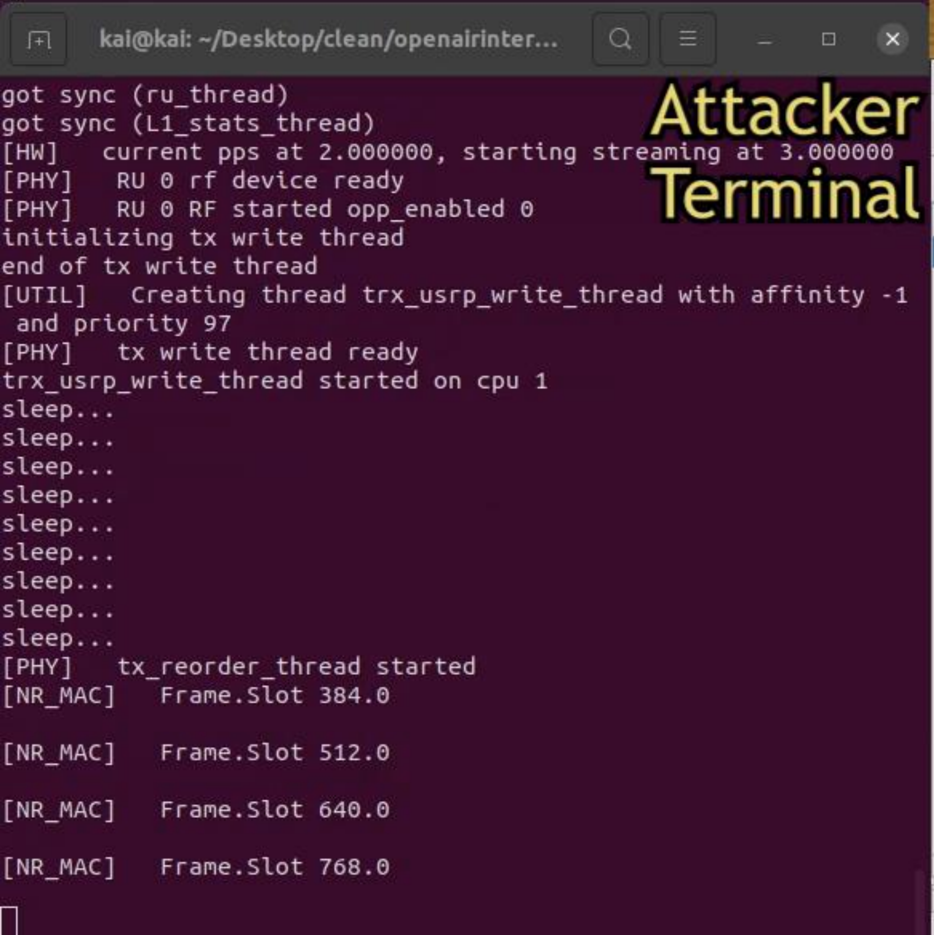
5G AKA Bypass

DL NAS Transport

w/ phishing SMS



```
04/06 19:57:01.609: [sbi] INFO: [5c89a00a-f471
c0f059] NF registered [Heartbeat:1s] (../lib/
04/06 19:57:03.706: [smf] WARNING: PFCP[REQ] has already been a
ssociated (../src/smf/pfcp-sm.c:213)
04/06 19:57:03.707: [upf] WARNING: PFCP[RSP] h
ssociated (../src/upf/pfcp-sm.c:207)
04/06 19:57:04.273: [amf] INFO: gNB-N2 accepted[127.0.0.1]:4775
2 in ng-path module (../src/amf/ngap-sctp.c:113)
04/06 19:57:04.273: [amf] INFO: number of events in queue 1 (..
/src/amf/event.c:106)
04/06 19:57:04.273: [amf] INFO: gNB-N2 accepted[127.0.0.1] in m
aster_sm module (../src/amf/amf-sm.c:720)
04/06 19:57:04.273: [amf] INFO: [Added] Number of gNBs is now 1
 (../src/amf/context.c:881)
04/06 19:57:04.273: [amf] INFO: number of events in queue 1 (..
/src/amf/event.c:106)
04/06 19:57:04.273: [amf] INFO: gNB-N2[127.0.0.1] max_num_of_os
treams : 2 (../src/amf/amf-sm.c:759)
04/06 19:57:04.273: [amf] INFO: number of events in queue 1 (..
/src/amf/event.c:106)
04/06 19:57:04.273: [sctp] INFO: sctp_senddata (../lib/sctp/ogs
-sctp.c:73)
04/06 19:57:13.281: [amf] INFO: buffer:Hello
 (../src/amf/testsocket.c:248)
```

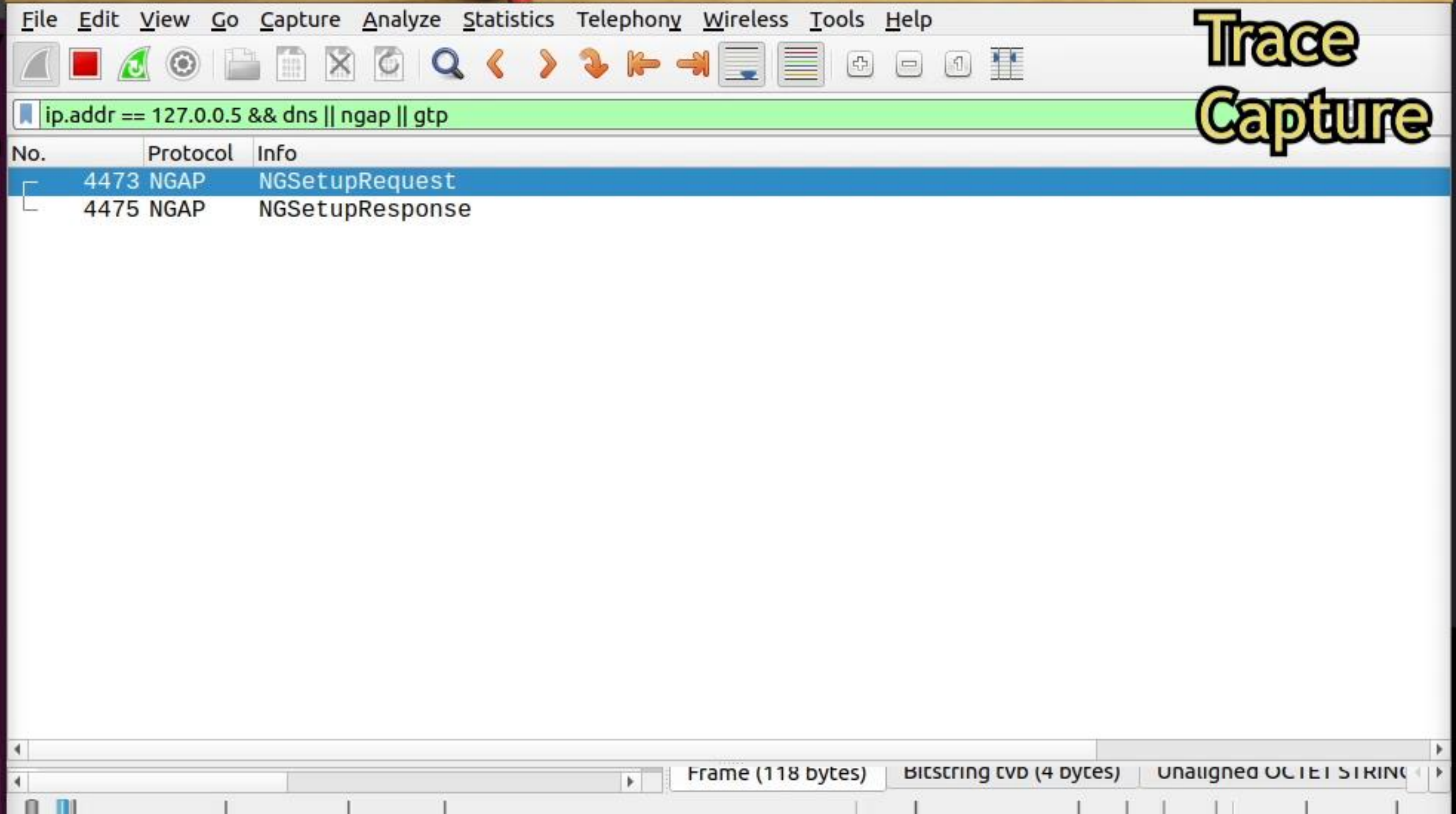


```
got sync (ru_thread)
got sync (L1_stats_thread)
[HW]   current pps at 2.000000, starting streaming at 3.000000
[PHY]   RU 0 rf device ready
[PHY]   RU 0 RF started opp_enabled 0
initializing tx write thread
end of tx write thread
[UTIL]   Creating thread trx_usrp_write_thread with affinity -1
 and priority 97
[PHY]   tx write thread ready
trx_usrp_write_thread started on cpu 1
sleep...
sleep...
sleep...
sleep...
sleep...
sleep...
sleep...
sleep...
sleep...
[PHY]   tx_reorder_thread started
[NR_MAC]   Frame.Slot 384.0

[NR_MAC]   Frame.Slot 512.0

[NR_MAC]   Frame.Slot 640.0

[NR_MAC]   Frame.Slot 768.0
```



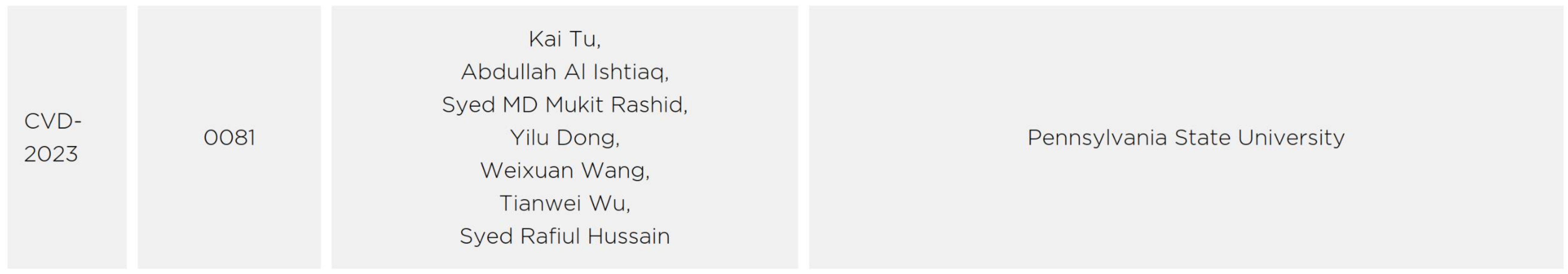
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
Trace Capture

ip.addr == 127.0.0.5 && dns || ngap || gtp

| No. | Protocol | Info |
|---|---|---|
| 4473 | NGAP | NGSetupRequest |
| 4475 | NGAP | NGSetupResponse |

# Disclosure Status

- All uncovered issues are reported to the corresponding vendors
- 12 CVEs assigned and some vendor acknowledgements
  - CVE-2023-52341, -49928, -50804, -49927, -50803, -52343, -52533, -52534, -52342, -52344; CVE-2024-29152, -28818
- GSMA Mobile Security Research Acknowledgements (CVD-2023-0081)



| | | | |
|---|---|---|---|
| CVD-2023 | 0081 | Kai Tu,<br>Abdullah Al Ishtiaq,<br>Syed MD Mukit Rashid,<br>Yilu Dong,<br>Weixuan Wang,<br>Tianwei Wu,<br>Syed Rafiul Hussain | Pennsylvania State University |

# Takeaways

- More security-focused tests are required before shipping the modem products.

- Black-box testing is an efficient method for detecting logical bugs as it requires only input and output analysis, making it more scalable and convenient compared to emulation or rehosting-based approaches.

- We open-sourced our tool 5GBaseChecker at: github.com/SyNSec-den/5GBaseChecker

# Meet Our Team

SyNSec

black hat® USA 2024

# Thank You!