Overcoming State: Finding Baseband Vulnerabilities by Fuzzing Layer-2

Speakers: Dyon Goos & Marius Muench

About Us

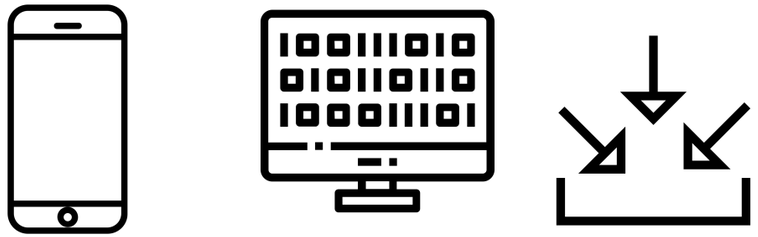
Dyon:

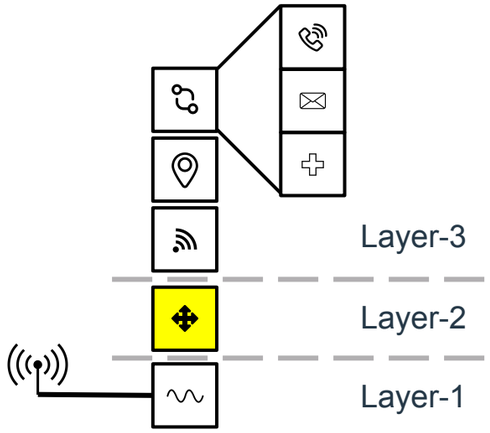
- Independent security researcher
- MSc (Vrije Universiteit Amsterdam)
- Spent the last 2 years in baseband stacks :)

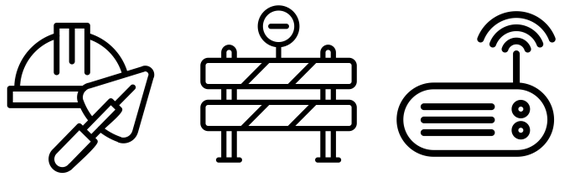
Marius:

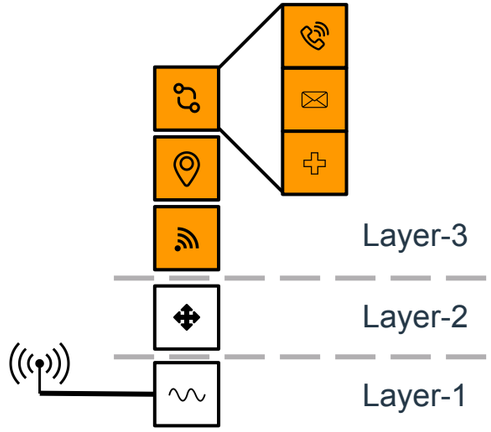
- Assistant Professor (University of Birmingham), UK
- Baseband research since 2018
- Co-creator of FirmWire
- Captures flags with Tasteless

This talk

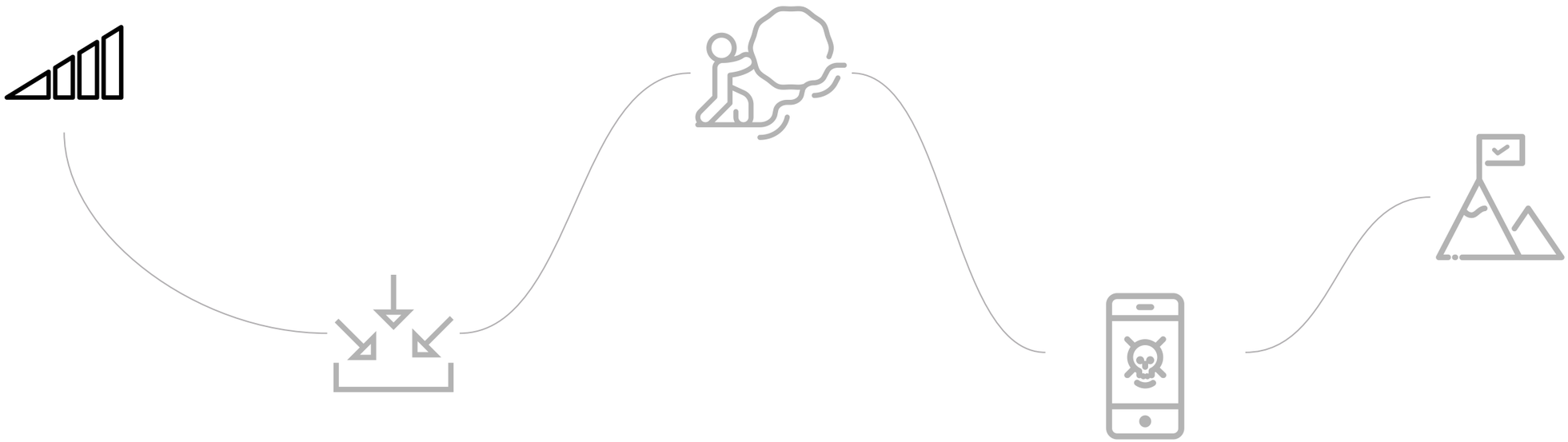






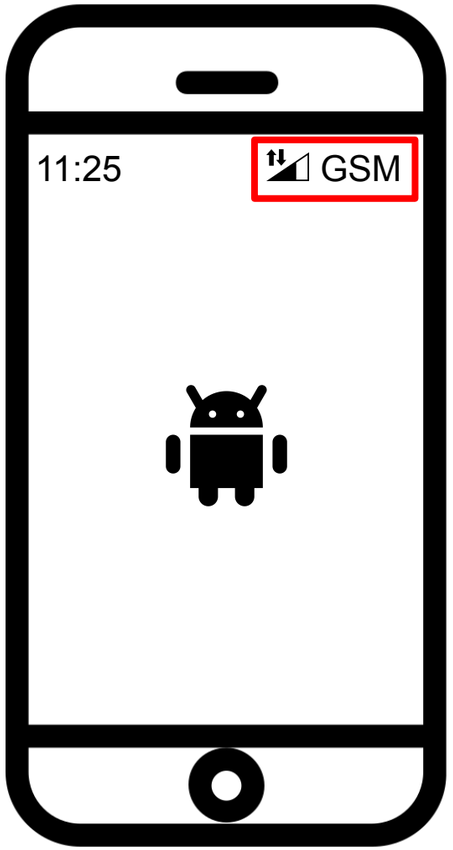


Basebands



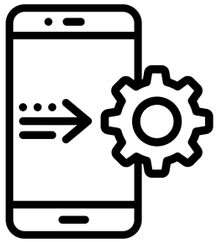
Basebands

- Modern phones are a collection of processors
  - Including: Application Processor (AP) & Cellular Processor (CP)
- CP also referred to as “Baseband”
  - Implements most layers of cellular communication stack
- Lucrative attack surface
  - Myriad of parsers, legacy code, obscure features



The code running on basebands

Custom Real-Time Operating Systems (RTOS), providing:

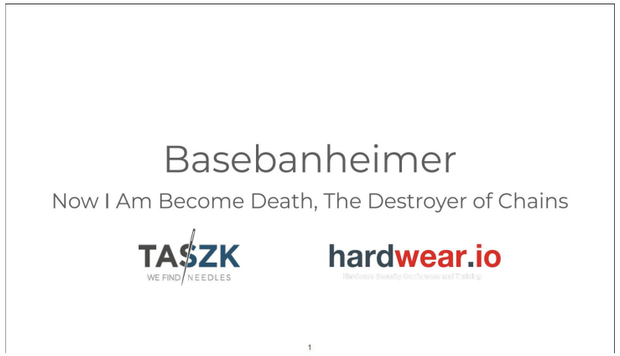


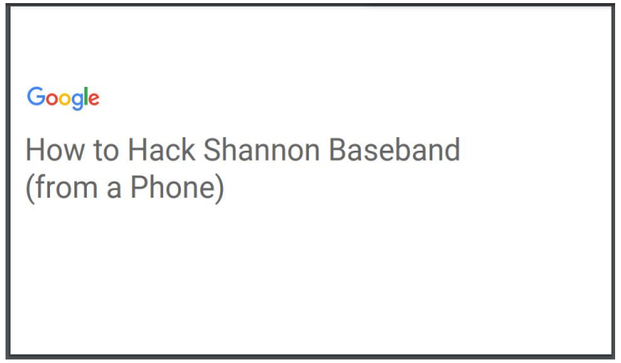
- Core OS functionality:
  - Scheduler, timers, interrupts
  - Messaging

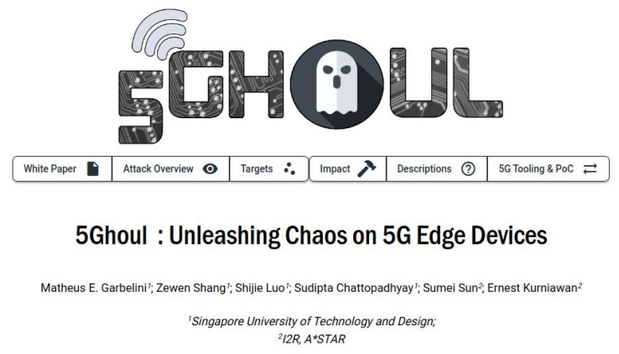
- Cellular stack implementation:
  - Stack is split into “tasks”
  - Tasks communicate via message queues

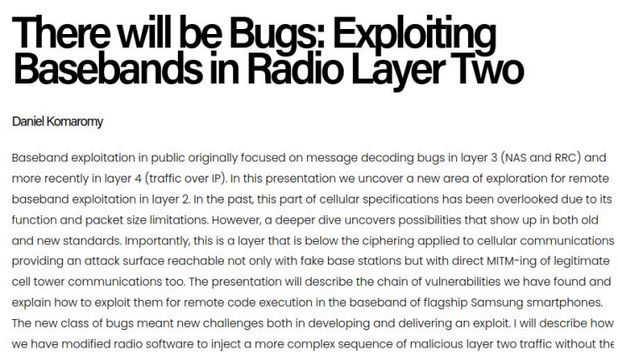
Baseband Security Research

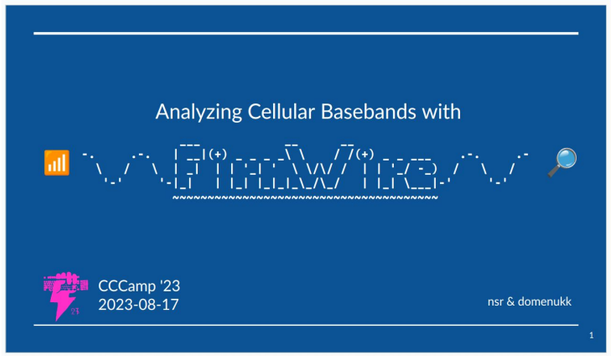
Plenty of attention in recent years, e.g.:

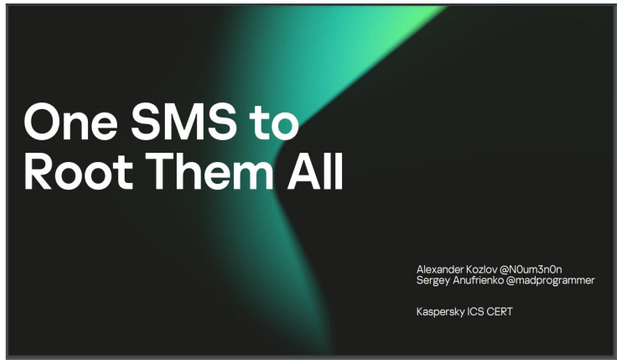












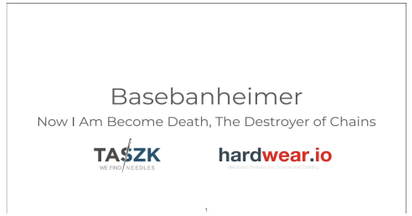
What about Layer-2?

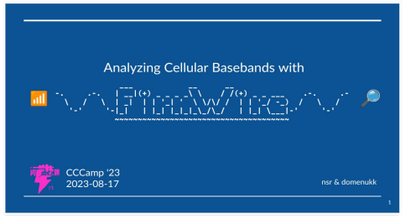
When we started, most research/findings focus on cellular L3 (or higher)

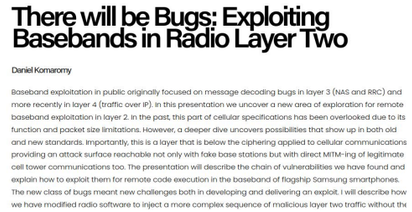
🤔 Let's have a look at layer-2 ourselves!

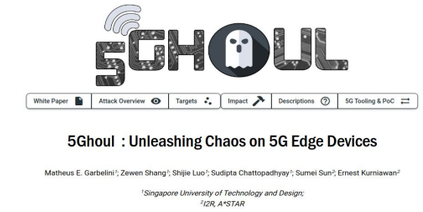
⇒ Let's start with the lowest hanging fruits:

- GSM Layer-2
- Fuzzing

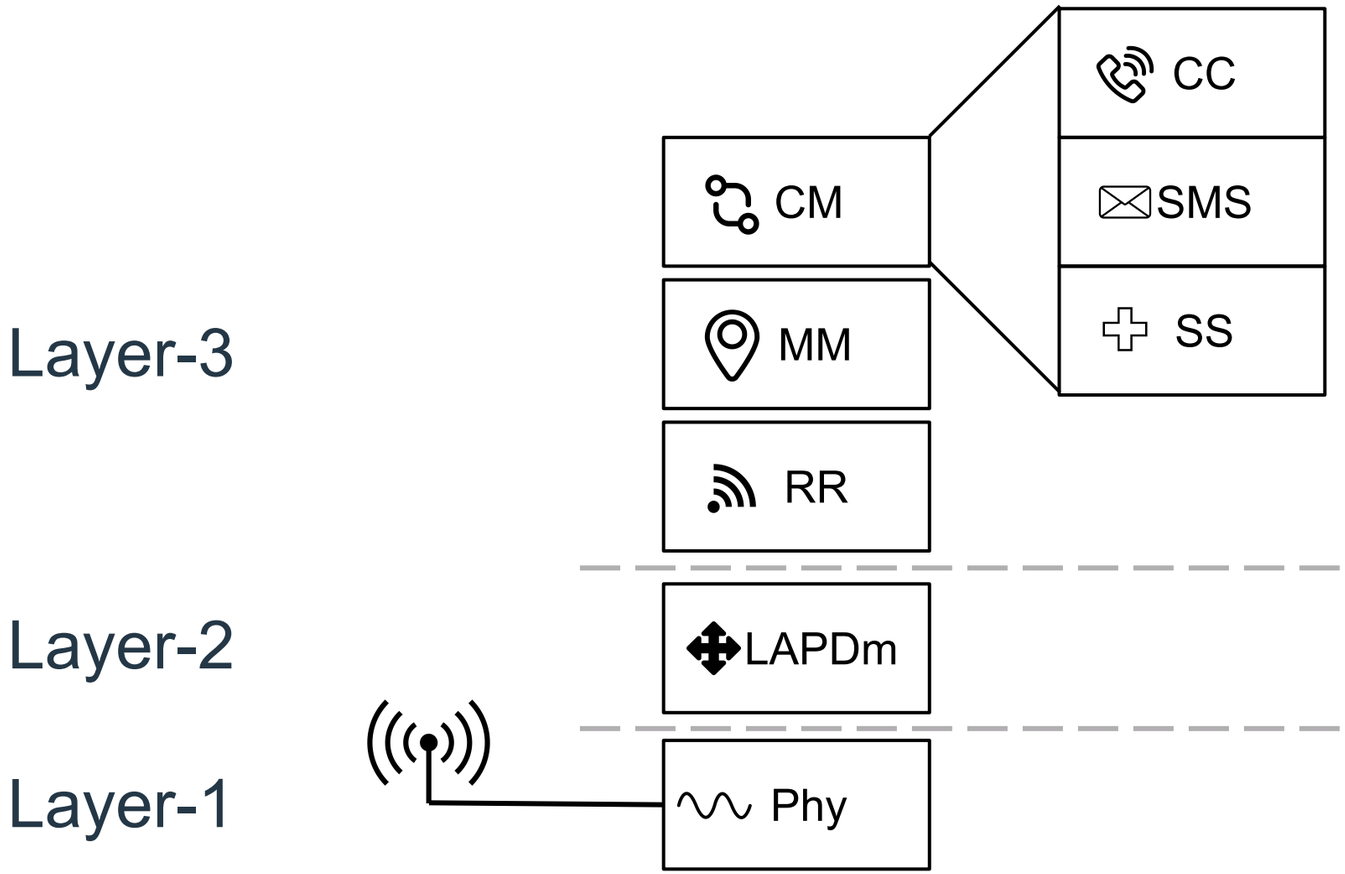








GSM Protocol Stack



RR : Radio Resource
MM : Mobility Management
CM : Connection Management

CC : Call Control
SMS : Short Messaging Service
SS : Supplementary Services

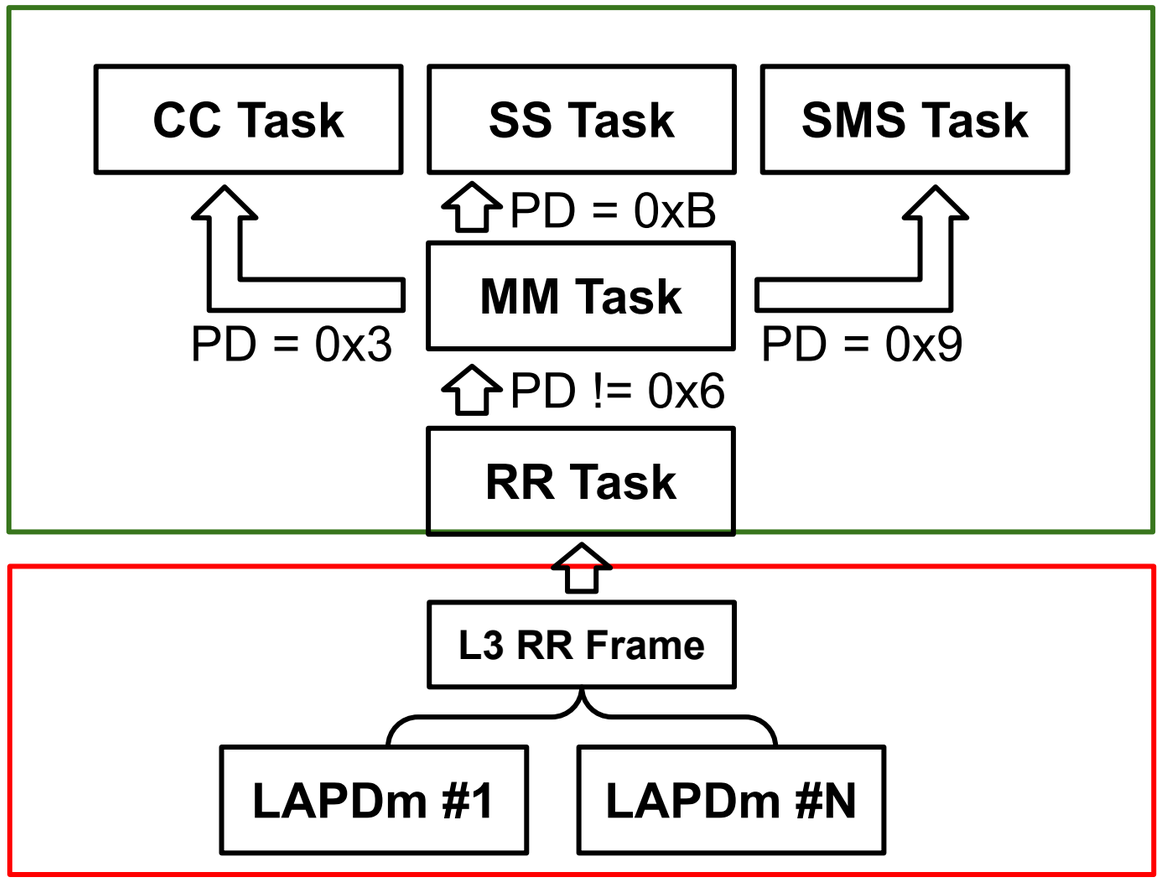
LAPDm : Link Access Protocol on the Dm Channel (LAPDm)

Phy : Physical

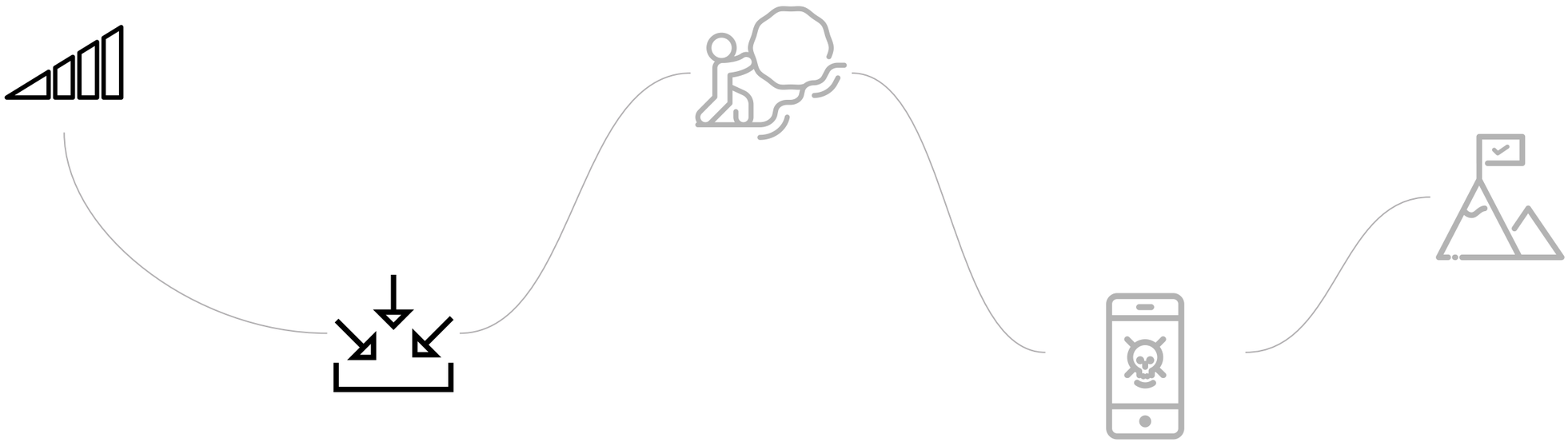
GSM Layer 2

- Link Access Protocol on the Dm Channel (LAPDm).
- Frame Concatenation
- PD: *information[0] & 0xF.*

```
struct LAPDM_frame{
        uint8_t addr;
        uint8_t ctrl;
        uint8_t len;
        uint8_t information[N];
} PACKED;
```



Our approach to fuzzing



Our Fuzzing Campaigns: FirmWire

- Full-system baseband emulator
  - Baseband emulation from boot
  - Fuzzing support via AFL++
  - Support for MTK & Exynos firmware

- Advantages:
  - Analyzable logs
  - Coverage tracking
  - Task-interaction

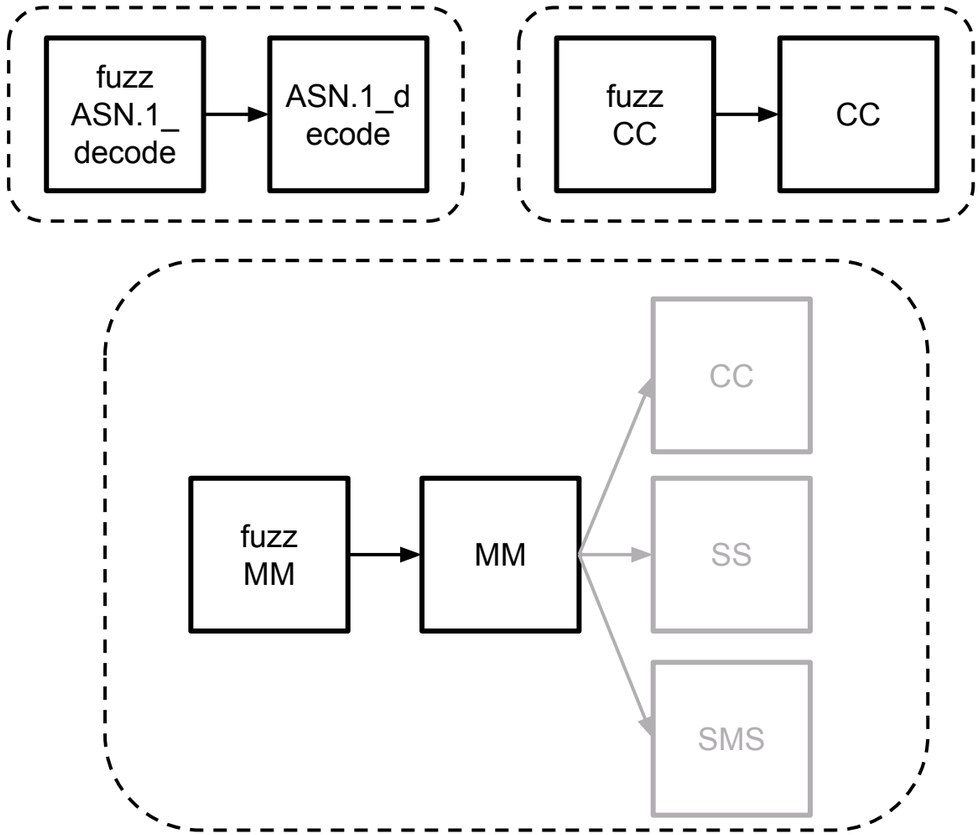
Fuzzing in FirmWire

- Requires injection of “Fuzzing Task”
  - Written in C, AFL wrapper present
  - Appears like an ordinary task for emulated CP
  - Sends messages to other tasks

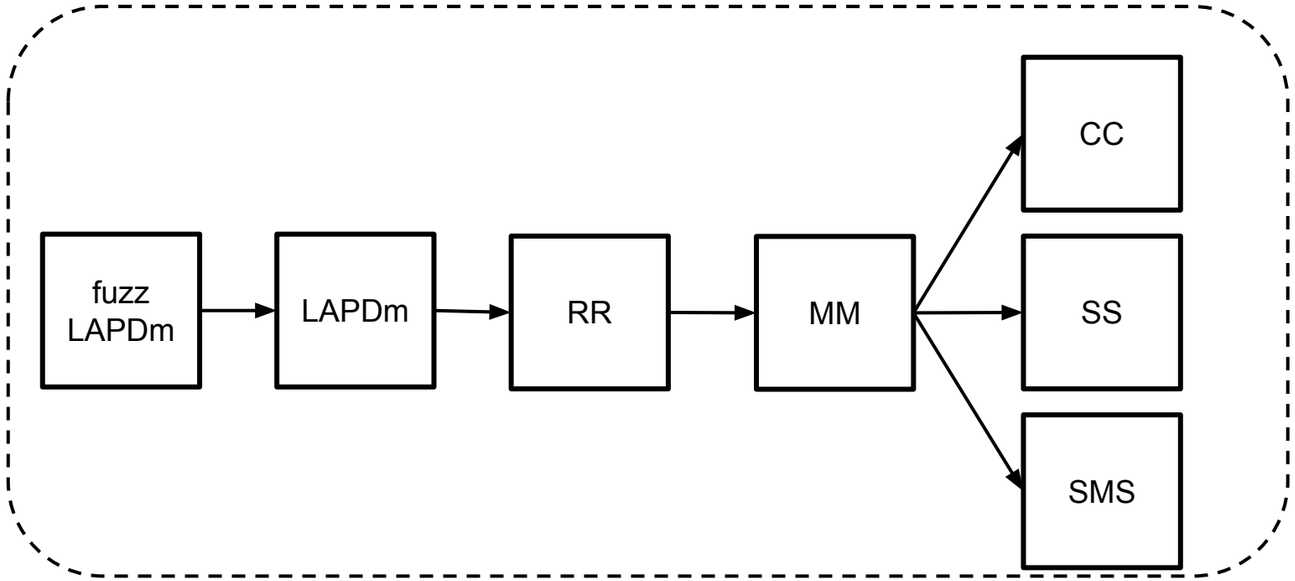
```c
#include <shannon.h>
#include <afl.h>

const char TASK_NAME[] = "AFL_DEMO\0";
static uint32_t qid;

int fuzz_single_setup()
{
    qid = queuename2id("TARGET_TASK_QUEUE");
    struct qitem_target * init =
      pal_MemAlloc(4, sizeof(struct qitem_target),
      __FILE__, __LINE__);

    // setup init payload
    [...]

    pal_MsgSendTo(qid, init, 2);
    return 1;
}
```

The Plan: Fuzzing Layer-2

Existing Fuzzers (non-OTA)



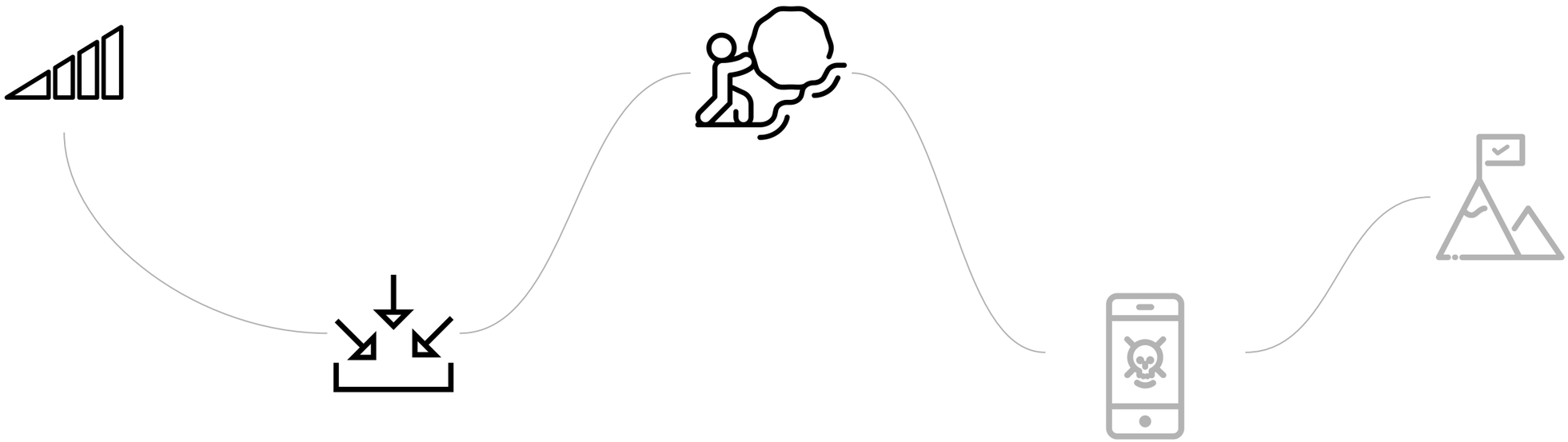
Our Approach (GSM)



The Target: Galaxy S10e Firmware

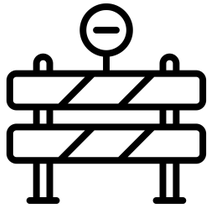
- Latest phone model supported by FirmWire
- Released date: 2019
- Firmware date: March 2023
  - Original FirmWire bugs are patched

Challenges

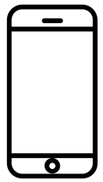


The Challenges

Need to create fuzzing tasks



How to deal with complex baseband state

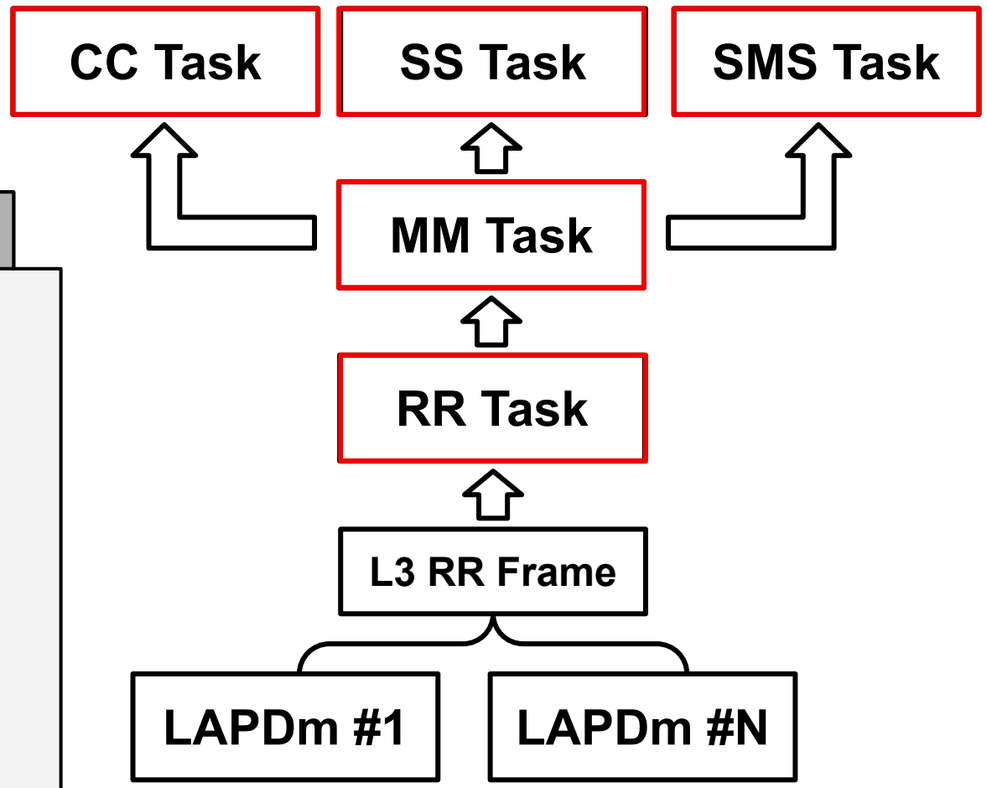


No support for recent phones

Challenge 1: Creating fuzzing tasks

Sending initialization messages

```
//Initialize SMS task
struct qitem_sms * init_sms =
    pal_MemAlloc(4, sizeof(struct qitem_sms),
    __FILE__, __LINE__);

init_sms->header.op = 0;
init_sms->header.op2 = 0x8a;
init_sms->header.size = sizeof(struct qitem_sms_init_req);
init_sms->header.msgGroup = 0x2d07;
pal_MsgSendTo(queuename2id("SMS"), init_sms, 2);
```

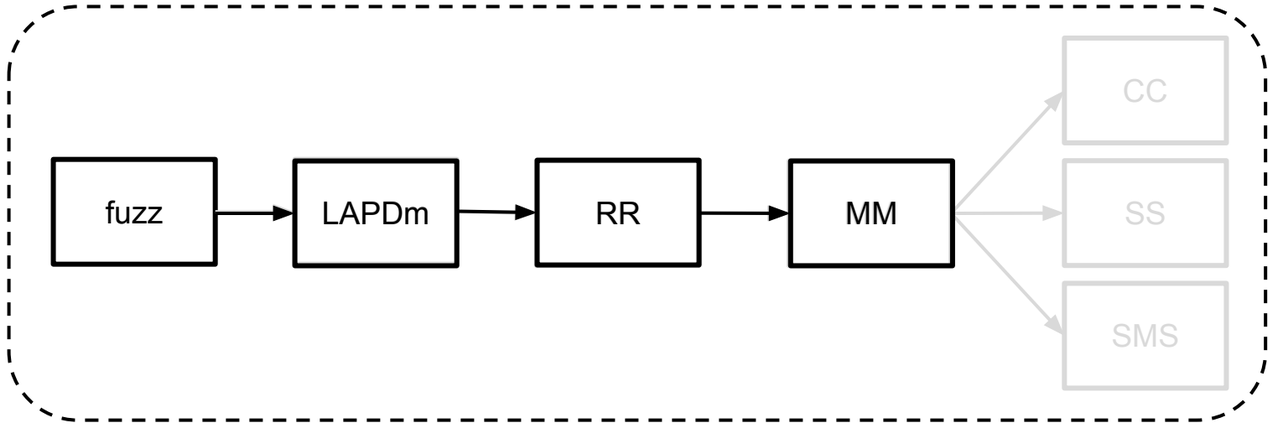


- All tasks are initialized, we should now be able to start fuzzing ….

AW DANG IT

…. but we initialized all tasks?

```
[GRR] 0x40f0f8d7 0b10: [../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_dedi.c] - Receive Data from Network (BTS)
[GRR] 0x40f0f907 0b10: [../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_dedi.c] - (CIO)## - In SemRecBtsData, TID : 0x0,
[MM] 0x40f439af 0b10: [../../../HEDGE/NASL3/MM/Code/Src/mm_Main.c] - STACK ID - 0
[MM] 0x40f43561 0b10: [../../../HEDGE/NASL3/MM/Code/Src/mm_Main.c] - MM Message Count -> 5
[MM] 0x40f5546d 0b10: [../../../HEDGE/NASL3/MM/Code/Src/mm_CellIndication.c] -  Resetting Sent Req Status
[MM] 0x41359a0f 0b1: [../../../HEDGE/NASL3/MM/Code/Src/mm_Utilities.c] - TRAP MESSAGE !!! - Invalid Request for
this State in mm_DecodeRrDataIndMsg !!!
```



Challenge 2 : Initialize the state

(1) Identifying crucial state beyond task initialization

```
iVar2 = mm_GetState();
uVar3 = CONCAT44(iVar2 + -6,iVar2);
switch(iVar2) {
case 6:
case 7:
case 8:
case 9:
case 0xd:
case 0xf:
  break;
default:
  mm_printTrapMessage("mm_DecodeRrDataIndMsg",iVar2 + -6,local_10,local_c);
  return;
}
```

returns *(uint8_t*) 0x42e22f58

[1.67198][MM] 0x41359a0f 0b1: [../../../HEDGE/NASL3/MM/Code/Src/mm_Utilities.c] - TRAP MESSAGE !!! - Invalid Request for this State in mm_DecodeRrDataIndMsg !!!

Challenge 2: Initialize the state

(2a) Fix up the state variables

- We need to fake a valid connection state

```
#ifdef SAMSUNG_S10e
....
uint32_t rr_state_addr = 0x4182cdcc;
uint32_t rr_cur_dlci_addr = 0x4182cfe0;

uint32_t glapd_state_addr = 0x42c5cacc;
uint32_t mm_state_addr = 0x42e22f58;
....
#endif
```

- Simple state constants, as well as ..

```
....
// make sure the baseband is in RR state 8
*(uint16_t*)rr_state_addr = 0x8;
//make sure the lapdm state is 2
*(uint8_t*)glapd_state_addr=0x2;
*(uint8_t*)(glapd_state_addr+0x2) = 0x1;
//make sure the mm state is 9
*(uint8_t*)mm_state_addr = 0x9;
//set the DLCI
*(uint8_t*)rr_cur_dlci_addr = 0x4;
....
```

Challenge 2: Initialize the state

(2b) .. more advanced state

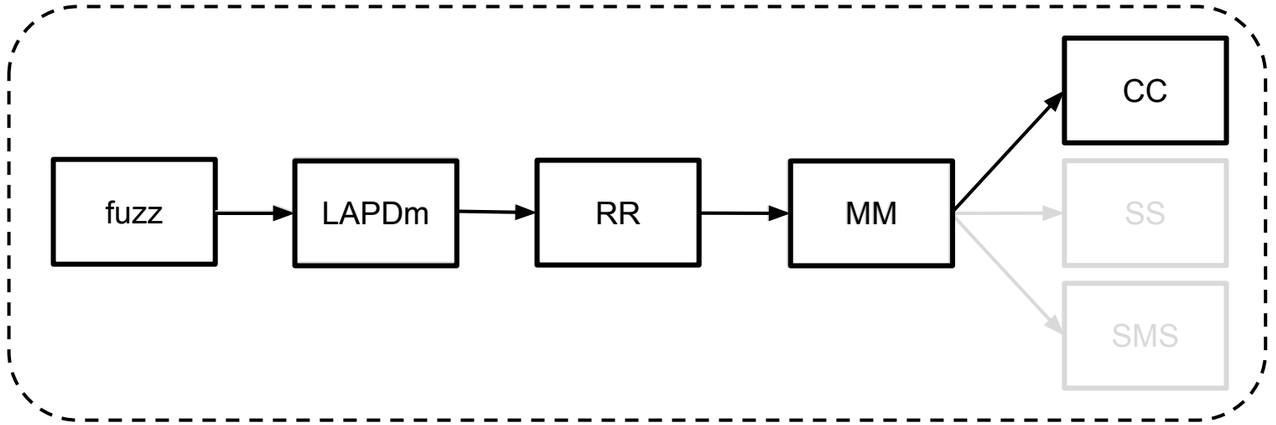
```
#ifdef SAMSUNG_S10e
....
uint32_t rr_serv_cell_addr = 0x4182cdd8;
....
#endif

struct rr_servingCell{
  uint16_t arfcn;
  uint16_t rxLvl;
  uint8_t[0x17] unk;
  uint8_t[0x3] mnc_mmc;
  uint16_t lac;
  uint8_t[0xd0] unk2;
} PACKED;
```

Wait, unknown?

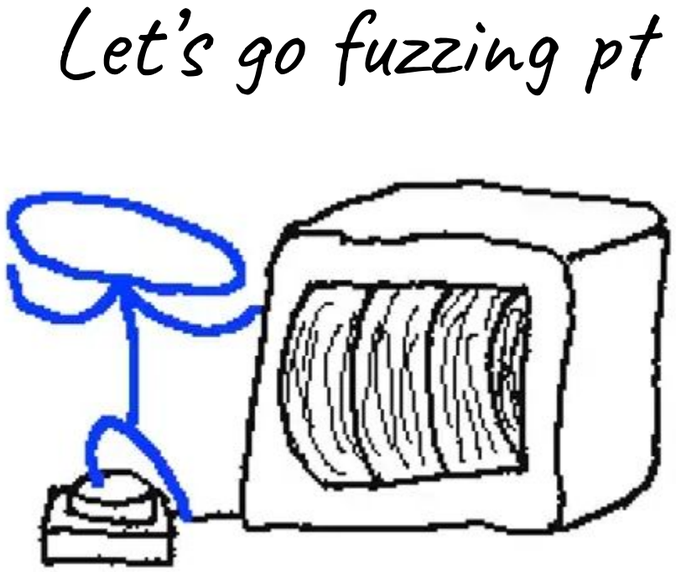
Only restore crucial state

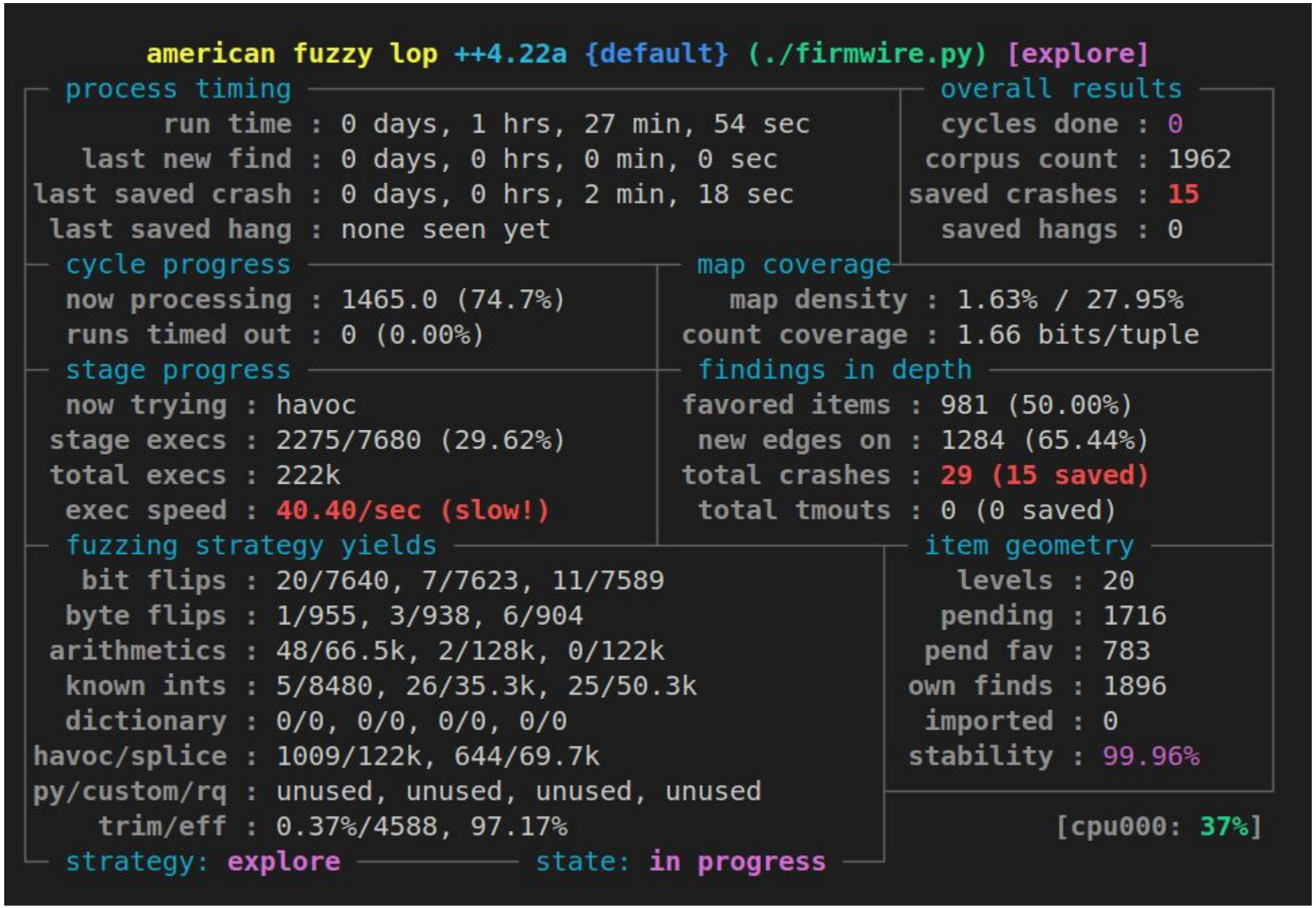
```
....
struct rr_servingCell *rr_servCell;
rr_servCell = alloc(0xec);
memset(rr_servCell, 0x0, 0xec);

rr_servCell->arfcn = 0x35d;
rr_servCell->mnc_mmc = 0x1869f;
rr_servCell->lac = 0x3e8;

*rr_serv_cell_addr = rr_servCell;
....
```

```
[GRR] 0x40f0f8d7 0b10: [../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_dedi.c] - Receive Data from Network (BTS)
[MM] 0x40f439af 0b10: [../../../HEDGE/NASL3/MM/Code/Src/mm_Main.c] - STACK ID - 0
[MM] 0x40f43561 0b10: [../../../HEDGE/NASL3/MM/Code/Src/mm_Main.c] - MM Message Count -> 5
[CC] 0x40fe8cfd 0b101: [../../../HEDGE/NASL3/CC/Code/Src/cc_Main.c] - ------------------------ CC TASK
---------------------------
[CC] 0x40fe87e3 0b10: [../../../HEDGE/NASL3/CC/Code/Src/cc_Main.c] - cc_UpdStackId :CcCurrentStackId: 0
[CC] 0x40ac21b1 0b101: [../../../HEDGE/NASL3/CC/Code/Src/cc_MsgDescription.c] - cc_MapSubTypeToMessageNum SubType = 0x5
```



- All tasks (and State) are initialized, we should now be able to start fuzzing ….

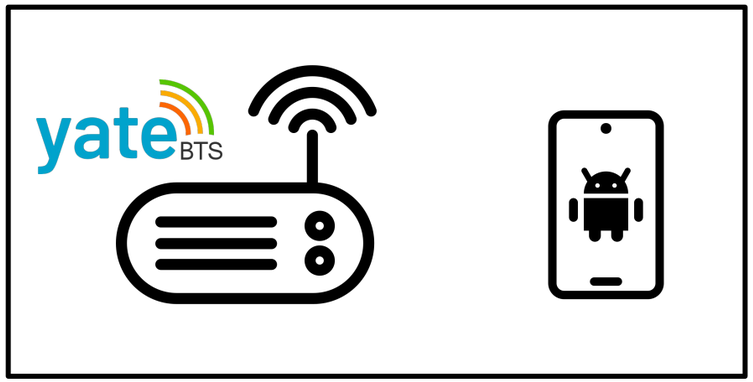



american fuzzy lop ++4.22a {default} (./firmwire.py) [explore]
process timing
run time : 0 days, 1 hrs, 27 min, 54 sec
last new find : 0 days, 0 hrs, 0 min, 0 sec
last saved crash : 0 days, 0 hrs, 2 min, 18 sec
last saved hang : none seen yet
overall results
cycles done : 0
corpus count : 1962
saved crashes : 15
saved hangs : 0
cycle progress
now processing : 1465.0 (74.7%)
runs timed out : 0 (0.00%)
map coverage
map density : 1.63% / 27.95%
count coverage : 1.66 bits/tuple
stage progress
now trying : havoc
stage execs : 2275/7680 (29.62%)
total execs : 222k
exec speed : 40.40/sec (slow!)
findings in depth
favored items : 981 (50.00%)
new edges on : 1284 (65.44%)
total crashes : 29 (15 saved)
total tmouts : 0 (0 saved)
fuzzing strategy yields
bit flips : 20/7640, 7/7623, 11/7589
byte flips : 1/955, 3/938, 6/904
arithmetics : 48/66.5k, 2/128k, 0/122k
known ints : 5/8480, 26/35.3k, 25/50.3k
dictionary : 0/0, 0/0, 0/0, 0/0
havoc/splice : 1009/122k, 644/69.7k
py/custom/rq : unused, unused, unused, unused
trim/eff : 0.37%/4588, 97.17%
item geometry
levels : 20
pending : 1716
pend fav : 783
own finds : 1896
imported : 0
stability : 99.96%
[cpu000: 37%]
strategy: explore
state: in progress

```
[7.17742][REG_SAP] 0x41122839 0b100: [../../../PSS/StackService/CNS/Common/Code/Src/ns_Main.c] - Stack Id: 0
[7.17782][REG_SAP] 0x41122853 0b100: [../../../PSS/StackService/CNS/Common/Code/Src/ns_Main.c] - Creating Inst:
NS_INFORMATION_IND
[7.17820][REG_SAP] 0x4112233b 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_OsInterface.c] - Allocating
memory size(107) from e/Src/ns_OsInterface.c (#163)
[7.17863][REG_SAP] 0x411224a3 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_OsInterface.c] - Memory
allocated for message 0x760D, length 107
[7.18030][REG_SAP] 0x4112233b 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_OsInterface.c] - Allocating
memory size(40) from e/Src/ns_ServiceHandlerEmm.c (#2503)
[7.18108][REG_SAP] 0x4079a4a5 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_MsgInstance.c] -
ns_GetMsgInstance [MsgName : NS_INFORMATION_IND]
[7.18149][REG_SAP] 0x407d9e3d 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_MsgHandler.c] - Message out:
BaseType 0, MsgCat 2, rtsInd 0
[7.18197][REG_SAP] 0x4112233b 0b101: [../../../PSS/StackService/CNS/Common/Code/Src/ns_OsInterface.c] - Allocating
memory size(107) from e/Src/ns_MsgHandler.c (#336)
[7.18285][REG_SAP] 0x407d9a1f 0b11: [../../../PSS/StackService/CNS/Common/Code/Src/ns_MsgHandler.c] - REG_SAP ==>
NS_INFORMATION_IND (Mbx 159)
[7.18330][REG_SAP] pal_MsgSendTo+0x3ff (0x4100460f) pal_MsgSendTo(MTI (159)) - PALMsg<0x760d, REG_SAP (a5) -> MTI
(9f), 99 bytes>
[7.18368][REG_SAP] 0x407d9a1f 0b11: [../../../PSS/StackService/CNS/Common/Code/Src/ns_MsgHandler.c] - REG_SAP ==>
NS_INFORMATION_IND (Mbx 5)
[7.18412][REG_SAP] pal_MsgSendTo+0x3ff (0x4100460f) pal_MsgSendTo(ATI (5)) - PALMsg<0x760d, REG_SAP (a5) -> ATI
(5), 99 bytes>
[ERROR] firmwire.vendor.shannon.hooks: FATAL ERROR (REG_SAP): from 0x40effd05 [pal_PlatformMisc.c:146 - Fatal
error: PAL_MEM_GUARD_CORRUPTION pal_MemInterface.c Line 895]
```

Challenge 3: No support for recent phones

- Our fuzzing targeted a firmware from early 2023
- Confirm vulnerabilities OTA against newer devices
- Collect a bunch of crashing payloads
- Patch open source tooling to allow for automated testing.



OTA Setup

- Hardware

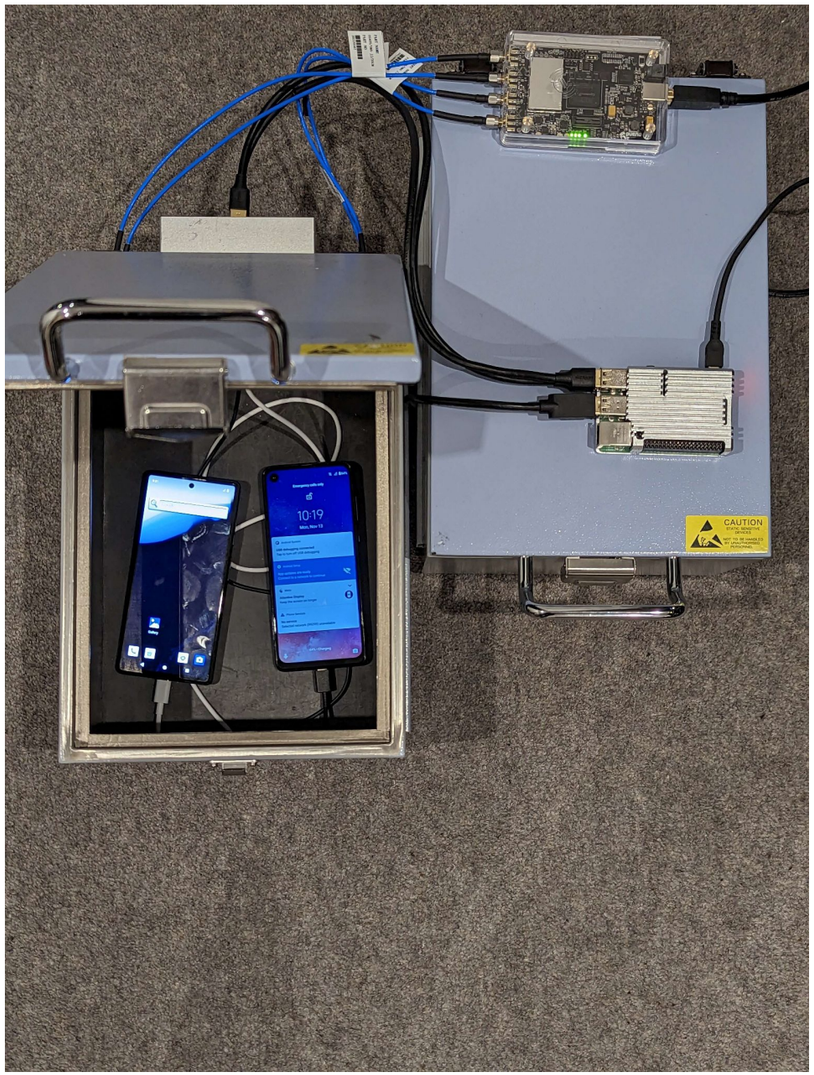
  SDR (BladeRF 2.0 micro xA4)
  USB hub + cables
  Raspberry Pi 4
  Faraday Cage

- Software

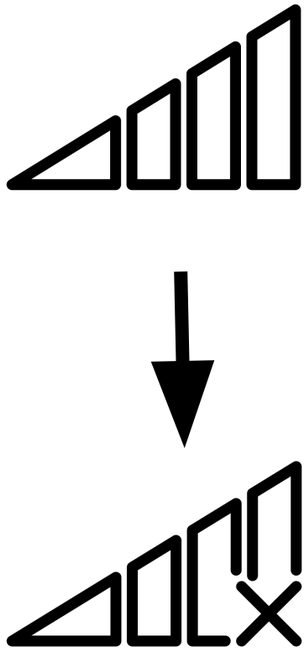
  Open source GSM Base Station software :

  Yate v6.2.1 / YateBTS v6.1.1

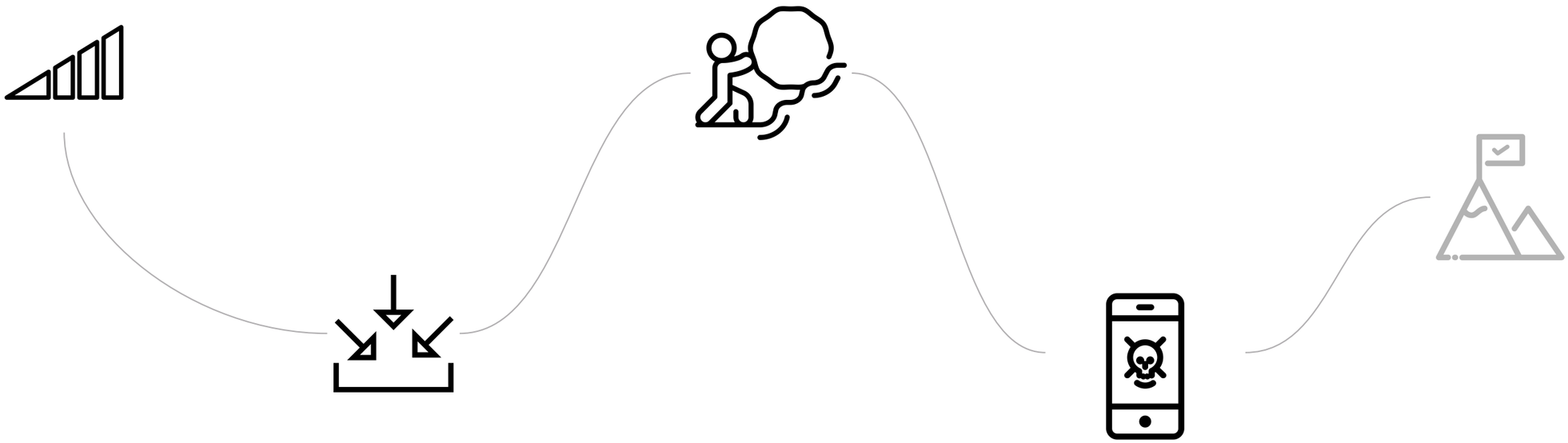
- Tested Phone:
  - Google Pixel 6 and 8
  - Samsung Galaxy S10e, S22, A14



```
02-24 07:11:12.305  1098  1161 D RFSD    : [ModemStateMonitor::OnModemCrashOrReset]
Modem  is STATE_CRASH_EXIT or STATE_CRASH_RESET
02-24 07:11:14.286  1088  1219 D DMD     : ModemStateMonitor : Modem  CRASH!!!₽]
02-24 07:11:14.286  1088  1219 D DMD     : ModemStateMonitor : Check the state again
after 2 seconds later.
02-24 07:11:14.305  1098  1161 D RFSD    : [ModemStateMonitor::OnModemCrashOrReset]
Modem  is STATE_CRASH_EXIT or STATE_CRASH_RESET
02-24 07:11:16.286  1088  1219 D DMD     : ModemStateMonitor : Modem  CRASH!!!₽]
02-24 07:11:16.287  1088  1219 D DMD     : ModemStateMonitor : Check the state again
after 2 seconds later.
02-24 07:11:16.306  1098  1161 D RFSD    : [ModemStateMonitor::OnModemCrashOrReset]
Modem  is STATE_CRASH_EXIT or STATE_CRASH_RESET
02-24 07:11:18.287  1088  1219 D DMD     : ModemStateMonitor : Modem  CRASH!!!₽]
02-24 07:11:18.287  1088  1219 D DMD     : ModemStateMonitor : Check the state again
after 2 seconds later.
```



Found Vulnerabilities



Showcase

	ID	Tested Phones	Affected Protocol	What?	Severity	Reported in
Previously Unknown	CVE-2023-50807	Pixel 6, S22	MM	Heap-based buffer overflow	8.1	Oct-23
	CVE-2023-50805	Pixel 6, 8, S22	RR	Heap-based buffer overflow	8.1	Oct-23
	CVE-2024-28068	S22, A14	SS/GPRS	Null-Pointer Deref	5.3	Jan-24
Duplicates (unpatched at time of testing)	N/A - internal find	Pixel 6, S22, A14	CC/SS	Heap-based buffer overflow	N/A	Jan-24
	N/A - internal find	A14	SMS	Stack-based buffer overflow	N/A	Jan-24
Under Disclosure	CVE-XXXX-YYYYY CVE-XXXX-YYYYY CVE-XXXX-YYYYY	-	-	-	-	-

Example bug : CVE-2023-50807 (MM)

- MM Information message
  - Holds information about the network

05 32 45 8c 03 03 03 …
48 41 41 00 01 04 00 …

IE	Presence	Value
MM PD	M	0x05
MsgType	M	0x32
Full Network Name	O	0x43
Short Network Name	O	0x45
Local Time Zone	O	0x46
Universal time	O	0x47
LSA Identity	O	0x48
Network Daylight Saving Time	O	0x49

Example Bug: CVE-2023-50807 (MM)

05 32 45 8c 03 03 03 …
48 41 41 00 01 04 00 …

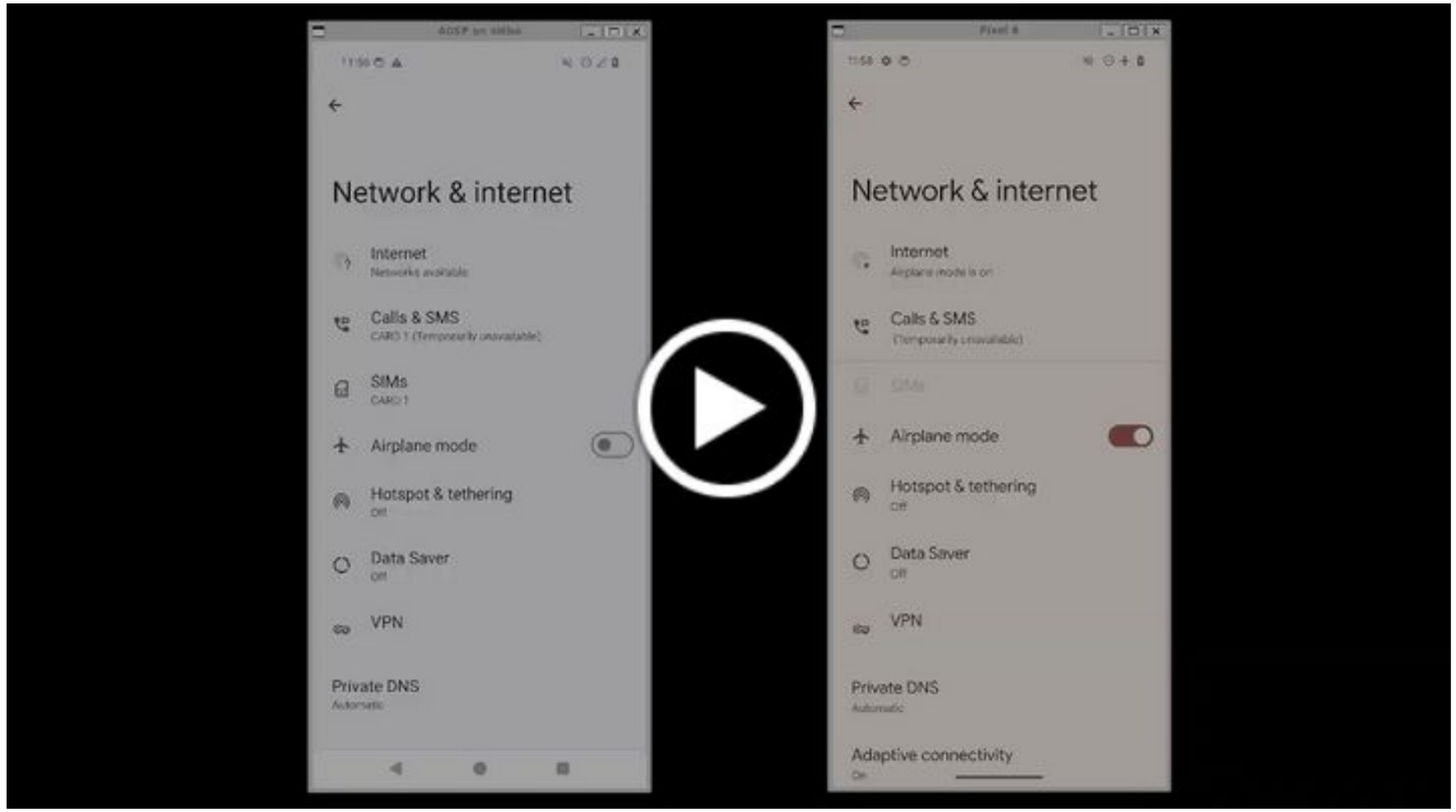
```
void mm_getIe(uint8_t *src, int p2){
  uVar1 = mm_getIeLength(p2);
  if((p2 == 0x3c) && (3 < uVar1)) uVar1 = 3;
  memcpy(src, IE_buf, uVar1);
}
```

```
void ns_ServiceHandlerEmm(..){
  uint8_t* buf = mem_Alloc(0x6f);
  memcpy(buf+0x58, src, IE_len);
}
```

- LSA Identity IE
- LSA Identity IE length

- LSA Identity IE length should be fixed to 3 bytes
  - Value from the first check is not propagated

Demo : Triggering the vulnerability



Defenses

- Recent shift in vendor's approaches:
  - More hardening for basebands (good)!

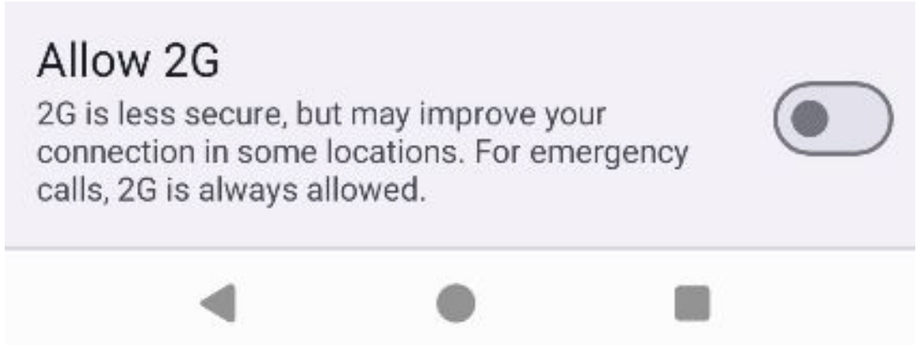
- Recently introduced defenses:
  - Heap Sanitization (Pixel 8)
  - More consistent use of XN
  - Allow 2G

Google Security Blog

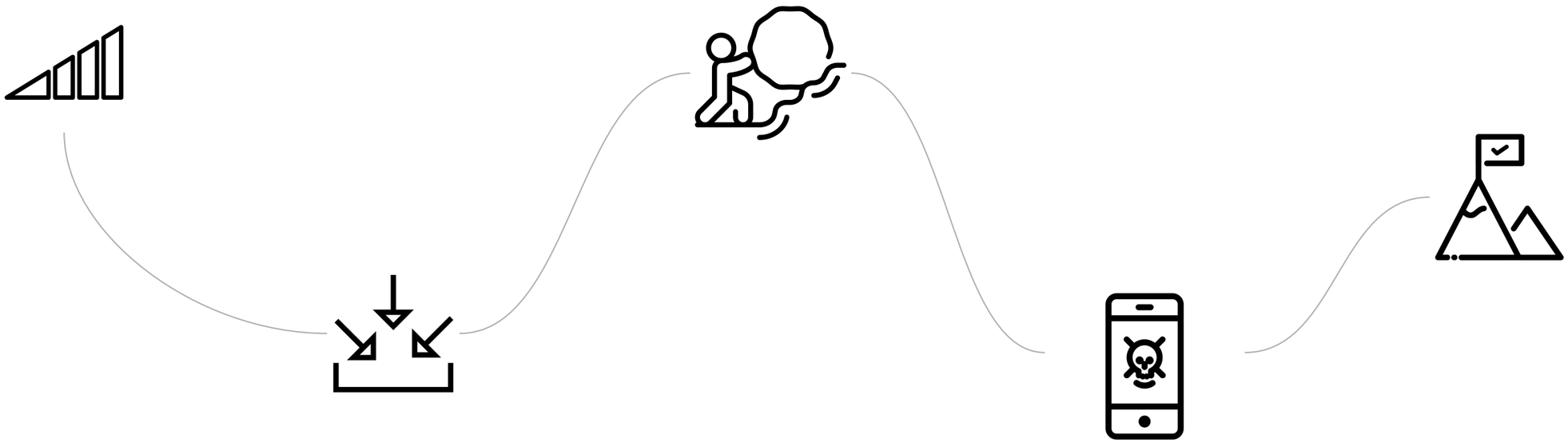
The latest news and insights from Google on security and safety on the Internet

Hardening cellular basebands in Android

December 12, 2023



Wrapping Up



Limitations/Future Work

- State needs to be reversed for every image
  - Potential for automation
- What if we cannot replicate a vulnerability OTA?
  - FirmWire support for firmware targeting recent firmware
- What about 3G/4G/5G?
  - More reversing, more harnessing, more state, more everything

Key Takeaways

- State is key to overcome fuzzing roadblocks when fuzzing across communication stacks

- Fuzzing older firmware images can lead to discovering vulnerabilities in the newest devices

- Despite years of research, critical vulnerabilities still hide in 2G implementations.

Questions