Emulating Samsung's Baseband for Security Testing

Grant Hernandez & Marius Muench

Tyler Tucker, Hunter Searle, Weidong Zhu
Patrick Traynor & Kevin Butler

FICS Research

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Intros

Grant Hernandez

- Recent Ph.D. graduate (University of Florida)
- Works on Android security and firmware analysis
- Just joined Qualcomm's product security team

Marius Muench

- Ph.D. graduate (EURECOM)
- By now PostDoc @ VUSec
- Builds tooling for better dynamic analysis of embedded systems

Outline

- Motivation
- Previous baseband work
- Initial journey in baseband vulnerability research
- Reverse engineering Samsung’s baseband firmware
- Building a baseband emulator
- Emulator based fuzzing with AFL
- n-day and 0-day vulnerability discovery
- Crashing basebands over-the-air
- Conclusions

What is a baseband processor?

- A dedicated device that implements the 2G - 5G cellular protocols
- Seamlessly routes mobile data, calls, SMS, and more while on the go
- The “phone” part of your smartphone
- Each vendor below implements their own baseband
- Typically runs embedded firmware using a Real Time Operating System (RTOS)
- Separate CPU core(s) from the application processor

Qualcomm HISILICON MEDIATEK intel infineon

Why basebands?

- Large attack surface due to multi-mode support of complicated standards
- Some components you can expect to find in a baseband:
    - Custom DSPs and radio drivers
    - Multiple ASN.1 decoders
    - Custom IP stack
    - Multiple voice & video codecs
    - X.509 parsing
    - DNS parsing
    - ...and plenty more obscure protocols unique to cellular
- Remote baseband attacks can be devastating
    - Silent full call & data MITM, independent of operating system
    - Escalation to application processor

Samsung's "Shannon" Baseband

- Present on Samsung smartphones with the EXYNOS chipset (non US phones)
- 2G - 5G "multi-mode" baseband
- Uses ARM Cortex-R ISA
- An interesting vulnerability research target
    - Previously demonstrated over-the-air attacks
    - Less exploit mitigations than application processor
- 2016: Breaking Band (Nico Golde, Daniel Komaromy - REcon)
- 2018: A Walk with Shannon (Amat Cama - Infiltrate)
- 2020: How to Design a Baseband Debugger (David Berard, Vincent Fargues - SSTIC)

Other baseband exploit work

- 2009: Fuzzing the Phone in Your Phone (Collin Mulliner, Charlie Miller - BHUSA)
- 2011: SMS of Death (Collin Mulliner, Nico Golde, J.P. Seifert - USENIX SEC)
- 2011: Baseband Attacks (Ralf-Phillip Weinman - WOOT)
- 2017: Path of Least Resistance: Cellular Baseband to Application Processor Escalation on Mediatek Devices (György Miru - Comsecuris Blog)
- 2018: Exploitation of a Modern Baseband (Marco Grassi, et al. - BHUSA)
- 2018: There is life in the Old Dog yet (Nico Golde - Comsecuris Blog)
- 2019: Touching the Untouchables (LTEFuzz) (Kim et al. (KAIST) - IEEE S&P)
- 2019: Exploiting Qualcomm WLAN and Modem OTA (QualPwn) (Tencent Blade - BHUSA)
- 2020: BaseSAFE: Baseband SAnitized Fuzzing through Emulation (Maier et al. - WiSec)
- ...and more -- but not much more

Introducing ShannonEE

- An Emulation Environment for the Shannon baseband
- Executes baseband firmware directly - no pre-processing required
- No physical devices required, scalable to as many cores as you have available
- Cold boots baseband and brings up most RTOS tasks
- Core Features:
    - Python API for prototyping
    - ModKit & FFI for extending & exploring the baseband
    - Integrated coverage-guided fuzzing with system-level AFL
    - GDB for triaging crashes
    - Support for multiple SoC versions

Quick Demo

```
[21.57221][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5710 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 599
[21.57245][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5711 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 602
[21.57263][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5712 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 604
[21.57279][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5713 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 606
[21.57299][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5714 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 608
[21.57316][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5715 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 611
[21.57332][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5716 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 613
[21.57348][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5717 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 615
[21.57364][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5718 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 617
[21.57380][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5699 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 575
[21.57397][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5700 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 577
[21.57413][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5701 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 579
[21.57429][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5702 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 581
[21.57445][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5703 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 584
[21.57461][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5704 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 586
[21.57477][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5705 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 588
[21.57492][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5706 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 590
[21.57509][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5707 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 593
[21.57525][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5708 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 595
[21.57542][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5709 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 597
[21.57562][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5710 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 599
[21.57578][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5711 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 602
[21.57594][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5712 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 604
[21.57610][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5713 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 606
[21.57626][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5714 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 608
[21.57642][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5715 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 611
[21.57658][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5716 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 613
[21.57674][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5717 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 615
[21.57690][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5718 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 617
[21.57706][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5699 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 575
[21.57722][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5700 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 577
[21.57738][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5701 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 579
[21.57753][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5702 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 581
[21.57769][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5703 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 584
[21.57785][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5704 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 586
[21.57801][EDFS] 0x40fc2d79 0b10: [pal_Reg.c] - Reg_ID: 5705 , pal_RegItemWrite file ../../../PALCommon/C-Common/RF/RF_Drv/HSPA/RF_HSPA_NV.c line 588
[21.5
[21.5
```

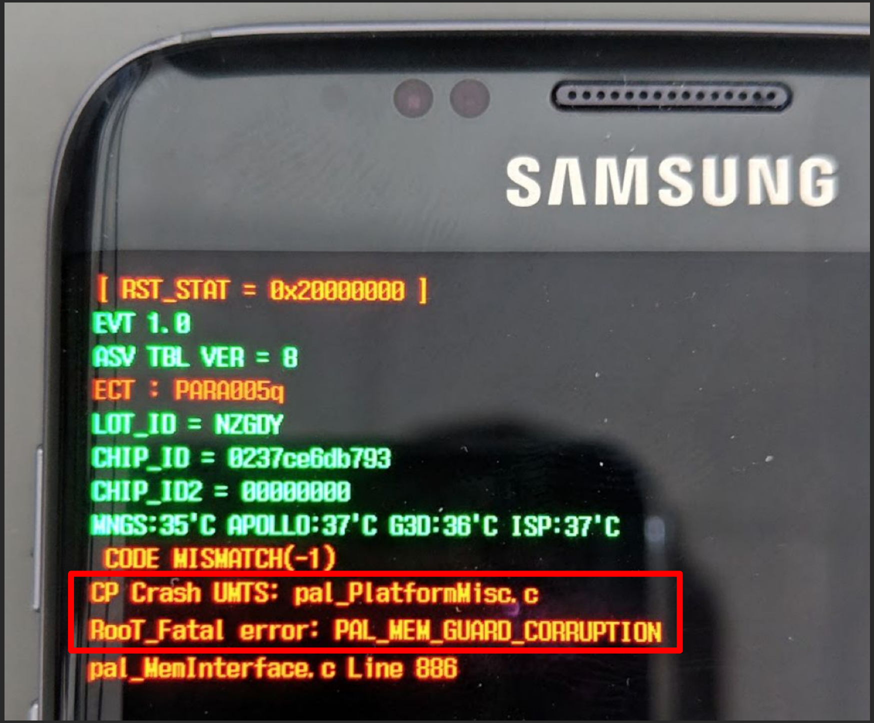
https://drive.google.com/file/d/1PD5o2qhfHE0n_QOSEAvq26uu5MuBNUrc/view?usp=sharing

How did we get here?

Early research attempts (May 2019)

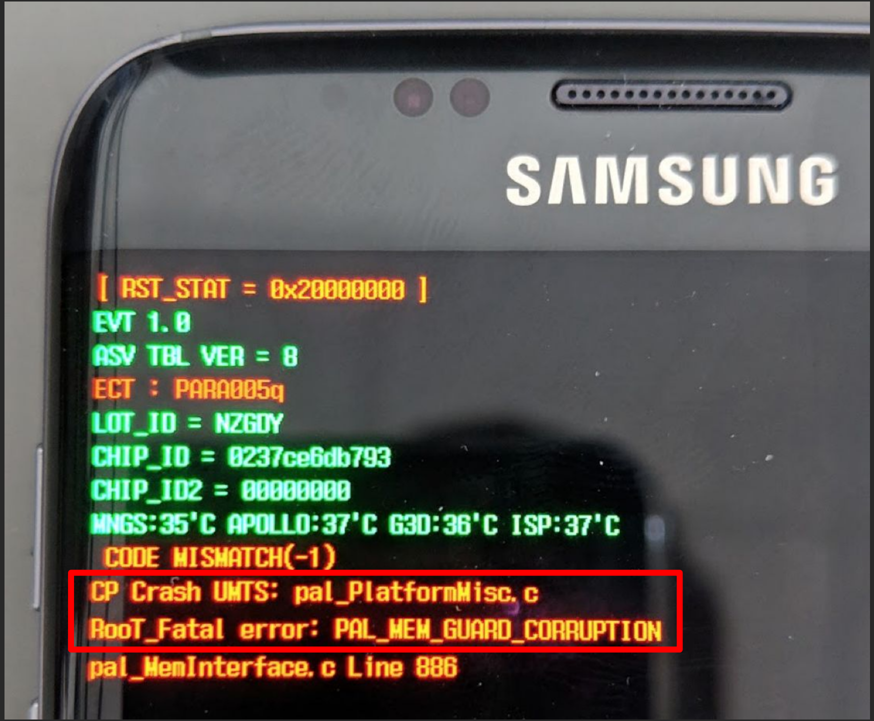
- Static vs. dynamic analysis
- We started on a project to fuzz basebands over-the-air
  - No experience with SDR / cellular, but lots of reversing and exploitation knowledge
  - How hard could it be?
- ✗ Cellular protocols standards are pretty much one big recursive acronym
- ✗ Wrestled with radios and base station code for *months* before finally getting a working setup
- Test setup:
  - Modified a 2G base station's GSM / GPRS downlink (L2 -> L1) packet paths to randomly bitflip packets
  - Targeted a mix of phones, created an ADB logcat monitor for crashes

Crashes without a clue



We got crashes, but no modem dumps due to root!
Next to impossible to identify root cause

Crashes without a clue



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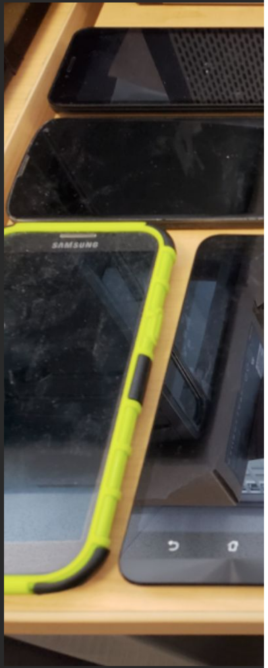
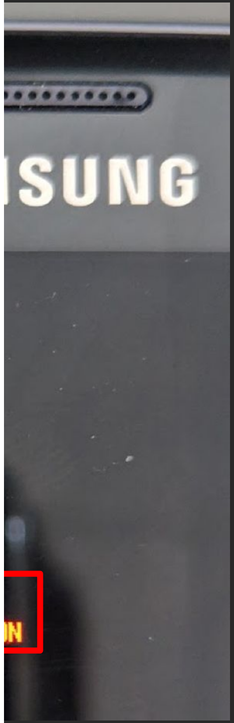
Crash



Comsecuris

So you want to fuzz basebands?

- We **don't** recommend OTA live fuzzing at all!
- Researchers developed fuzzers and found bugs, but:
    - basebands are more fragile than you think: hangs and weird behavior are normal during test
    - often implement spec loosely or only subset
    - state machines are complex, especially in error/repetition cases
    - a significant amount of corruptions do not result in good crashes



We got crashes, but no modem dumps due to root!
Next to impossible to identify root cause

Shannon Anti-debug

```
void modem_print_registers(void)

{
  uint isDeviceLocked;
  undefined4 *puVar1;
  uint uVar2;

  uVar2 = 0;
  isDeviceLocked = get_device_rooted();
  if ((isDeviceLocked & 0xff) == 0) {
    log_early_uart("Device is rooted\n");
    log_early_uart("szError : %s \n",exception_record
    return;
  }
```

Modem stack trace is suppressed if device is unlocked (OS_Fatal_Error)

```
if ((isNonRoot & 0xff) == 0) {
  (&DAT_00002f80)[hexval] = 0xd;
                    // RooT check!!!!!!
  (&DAT_00002f81)[hexval] = 10;
  *(undefined *)(hexval + 0x2f82) = 0x52;
  *(undefined *)(hexval + 0x2f83) = 0x6f;
  (&DAT_00002f84)[hexval] = 0x6f;
  *(undefined *)(hexval + 0x2f85) = 0x54;
  *(undefined *)(hexval + 0x2f86) = 0;
}
```

If device is unlocked, RooT is displayed during modem dumps (bootloader)

To get modem dumps we need root, but rooting suppresses modem logs

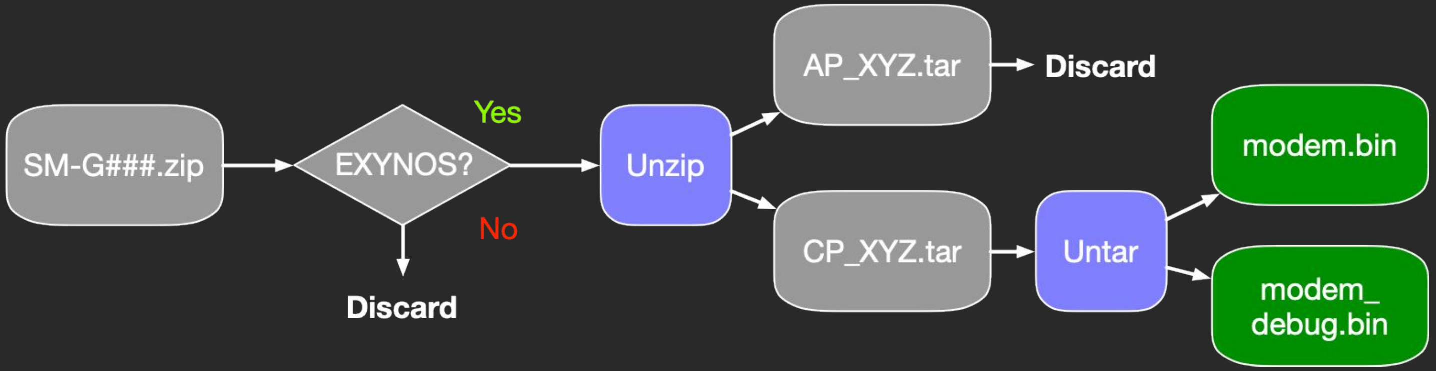
How do we find & debug memory corruptions?

- Modem anti-debug makes on-target difficult without other exploits
- Manual reverse engineering is an option, but basebands are huge (doesn't scale)
  - See https://github.com/grant-h/shannon_s5000/
- Ideal setup:
  - GDB
  - Coverage guided fuzzing
  - Snapshotting
- **The most viable approach for scaling and automating our research is *emulation***

Initial Firmware Reversing

Extracting modem.bin

- Firmware available at SamMobile
- Purchased Samsung S10 for research and targeted SM-G973F firmware



- Previous researchers and papers mentioned that modem.bin is encrypted
  - None of our images were ¯_(ツ)_/¯
- Well reverse engineered already: https://github.com/Comsecuris/shannonRE

```
00000000: 544f 4300 0000 0000 0000 0000 0000 0000  TOC.............
00000010: 0080 0040 1004 0000 0000 0000 0500 0000  ...@............


00000020: 424f 4f54 0000 0000 0000 0000 2004 0000  BOOT........ ...
00000030: 0000 0040 401e 0000 d597 ad57 0100 0000  ...@@......W....
00000040: 4d41 494e 0000 0000 0000 0000 6022 0000  MAIN........`"..
00000050: 0000 0140 a079 5402 3fb1 20ef 0200 0000  ...@.yT.?. .....
00000060: 5653 5300 0000 0000 0000 0000 009c 5402  VSS...........T.
00000070: 0000 8047 60f6 5d00 04e5 2907 0300 0000  ...G`.]...).....
00000080: 4e56 0000 0000 0000 0000 0000 0000 0000  NV..............
00000090: 0000 6045 0000 1000 0000 0000 0400 0000  ..`E............
000000a0: 4f46 4653 4554 0000 0000 0000 00aa 0700  OFFSET..........
000000b0: 0000 0000 0056 0800 0000 0000 0500 0000  .....V..........
```

Entry Name

File Offset

```
00000000: 544f 4300 0000 0000 0000 0000 0000 0000  TOC.............
00000010: 0080 0040 1004 0000 0000 0000 0500 0000  ...@............
```

Load Address Size CRC Count/Entry ID

```
00000020: 424f 4f54 0000 0000 0000 0000 2004 0000  BOOT.......... ...
00000030: 0000 0040 401e 0000 d597 ad57 0100 0000  ...@@......W....
00000040: 4d41 494e 0000 0000 0000 0000 6022 0000  MAIN........`"..
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```

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                    Entry Name                       File Offset

00000000: 544f 4300 0000 0000 0000 0000 0000 0000  TOC.............
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00000020: 424f 4f54 0000 0000 0000 0000 2004 0000  BOOT........ ...
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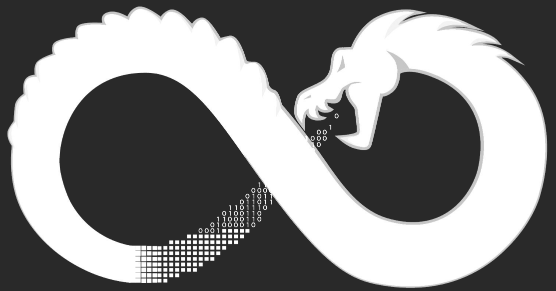
00000030: 0000 0040 401e 0000 d597 ad57 0100 0000  ...@@......W....
00000040: 4d41 494e 0000 0000 0000 0000 6022 0000  MAIN........`"..
00000050: 0000 0140 a079 5402 3fb1 20ef 0200 0000  ...@.yT.?. .....
```

```
00000020: 424f 4f54 0000 0000 0000 0000 2004 0000  BOOT............
00000030: 0000 0040 401e 0000 d597 ad57 0100 0000  ...@@......W....

   ...                          ...                          ...

00000420: 3c00 00ea d8f1 9fe5 d8f1 9fe5 d8f1 9fe5  <...............
00000430: d8f1 9fe5 feff ffea d4f1 9fe5 d4f1 9fe5  ................
00000440: f81b 0000 fc1b 0000 241c 0000 0000 0000  ........$.......
00000450: 004c 4254 0000 0000 0000 0000 0000 0000  .LBT............
00000460: 0000 0000 0000 0000 0000 0000 0000 0000  ................
```

Looks like ARM “always” conditionals!
Let’s disassemble from here :)



Exception Vectors

```
40000000 3c 00 00 ea    b       boot_RESET
                        -- Flow Override: CALL_RETURN (CALL_TERMINATOR)

                        LAB_40000004                                  XREF[1]:
40000004 d8 f1 9f e5    ldr     pc=>boot_UDI,[DAT_400001e4]
40000008 d8 f1 9f e5    ldr     pc=>boot_SWI,[DAT_400001e8]
4000000c d8 f1 9f e5    ldr     pc=>boot_PREFETCH,[DAT_400001ec]
40000010 d8 f1 9f e5    ldr     pc=>boot_DATA_ABORT,[DAT_400001f0]

                        boot_NA                                       XREF[1]:
40000014 fe ff ff ea    b       boot_NA
40000018 d4 f1 9f e5    ldr     pc=>boot_IRQ,[DAT_400001f4]
4000001c d4 f1 9f e5    ldr     pc=>boot_FIQ,[DAT_400001f8]
```

BOOT

Shannon Boot Mode

- Bootloader debug prints using UART
  - Saved to early boot log, can be dumped from kernel as well
- DUMP mode activated during crash dump
- BOOT mode for normal startup
- **Who signals these boot modes?**

```
if (boot_mode == DUMP_MODE) {
  boot_unk_common_setup();
  uart_putc('#');
  boot_crash_or_dump();
  boot_unk_crash();
  uart_puts(s_Done_40000550);
  FUN_40000d84(&DAT_00002e00);
}
else {
  if (boot_mode == BOOT_MODE) {
    boot_unk_common_setup();
    uart_putc('#');
    boot_prepare_mpu_next_ram();
    uart_puts(s_Boot_40000568);
    nextFnPointer = boot_comm_ap();
    if ((void *)0x10000000 < nextFnPointer) {
      boot_stage2(nextFnPointer);
      goto LAB_400004f0;
    }
    r0 = s_XxX!_40000570;
  }
  else {
    r0 = s_Unknown_4000055c;
  }
  uart_puts(r0);
}
```

A side-quest to the Samsung Kernel

- Examined the Samsung S10's kernel sources to better understand the modem's boot
  - Samsung S10 Kernel - https://github.com/grant-h/SM-G973F-Kernel
- `drivers/misc/modem_v1`
  - modem_io_device.c - dev node ioctl handler (for booting), read/write for commands
  - link_device_memory.h - **Contains structs on shared memory regions**
- Cellular Boot Daemon (CBD) communicates with `/dev/umts_boot0` (modem_v1)
  - IOCTL_MODEM_RESET - Reset and await new boot
  - IOCTL_SECURITY_REQUEST - Establish modem bootloader secure boot
  - IOCTL_MODEM_ON, IOCTL_MODEM_BOOT_ON - Start boot process
  - IOCTL_MODEM_DL_START - Download code to modem memory
  - IOCTL_MODEM_BOOT_OFF - Finalizes boot process

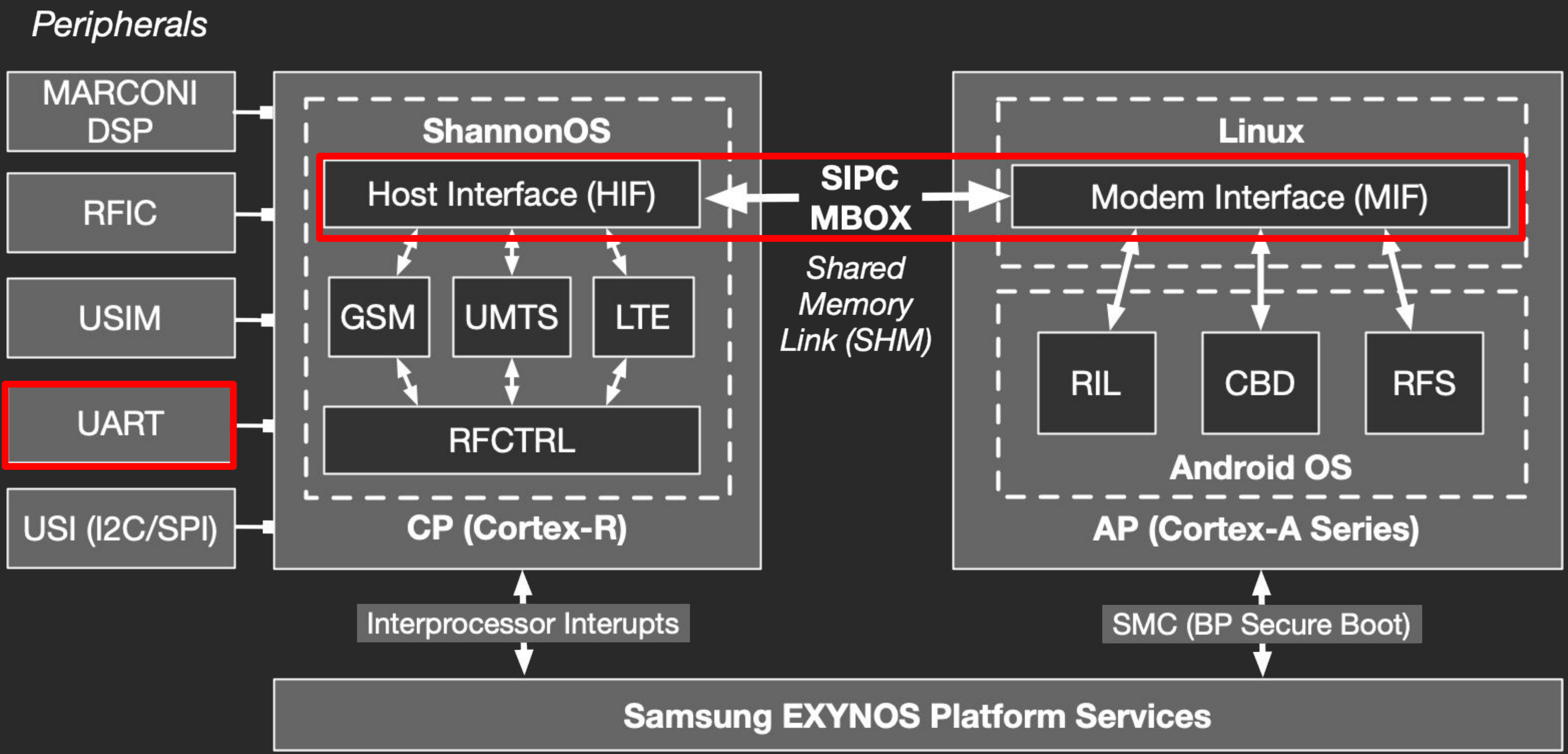
Cross-core Comms

- Modem driver in Linux maps shared memory region between CP and AP for DMA-based IPC (ring buffers)
- Commands are queued in a full-duplex fashion
- Commands come from Samsung RIL

link_device_memory.h

```c
struct __packed shmem_4mb_phys_map {
	u32 magic;
	u32 access;

	u32 fmt_tx_head, fmt_tx_tail;
	u32 fmt_rx_head, fmt_rx_tail;

	u32 raw_tx_head, raw_tx_tail;
	u32 raw_rx_head, raw_rx_tail;
	 ...
	char fmt_tx_buff[SHM_4M_FMT_TX_BUFF_SZ];
	char fmt_rx_buff[SHM_4M_FMT_RX_BUFF_SZ];
	 ...
	char raw_tx_buff[SHM_4M_RAW_TX_BUFF_SZ];
	char raw_rx_buff[SHM_4M_RAW_RX_BUFF_SZ];
};
```

```c
#define MEM_IPC_MAGIC     0xAA
#define MEM_CRASH_MAGIC   0xDEADDEAD
#define MEM_BOOT_MAGIC    0x424F4F54
#define MEM_DUMP_MAGIC    0x44554D50
```


Peripherals
MARCONI DSP
RFIC
USIM
UART
USI (I2C/SPI)
ShannonOS
Host Interface (HIF)
GSM
UMTS
LTE
RFCTRL
CP (Cortex-R)
SIPC MBOX
Shared Memory Link (SHM)
Linux
Modem Interface (MIF)
RIL
CBD
RFS
Android OS
AP (Cortex-A Series)
Interprocessor Interupts
SMC (BP Secure Boot)
Samsung EXYNOS Platform Services

Emulation: The first steps

Choose your weapon

avatar^2 + QEMU

Displaying the Boot UART

```c
if (boot_mode == DUMP_MODE) {
  boot_unk_common_setup();
  uart_putc('#');
  boot_crash_or_dump();
  boot_unk_crash();
  uart_puts(s_Done_40000550);
  FUN_40000d84(&DAT_00002e00);
}
else {
  if (boot_mode == BOOT_MODE) {
    boot_unk_common_setup();
    uart_putc('#');
      boot_stage2(nextFnPointer);
      goto LAB_400004f0;
    }
    r0 = s_XxX!_40000570;
  }
  else {
    r0 = s_Unknown_4000055c;
  }
  uart_puts(r0);
}
```

```python
self.create_peripheral(UARTPeripheral,
0x84000000, 0x1000, name='boot_uart')
```

```python
class UARTPeripheral(ShannonPeripheral):
    def hw_read(self, offset, size):
        if offset == 0x18:
            return self.status

        return 0

    def hw_write(self, offset, size, value):
        if offset == 0:
            sys.stderr.write(chr(value & 0xff))
            sys.stderr.flush()
        else:
            self.log_write(value, size, "UART")

        return True

    def __init__(self, name, address, size, **kwargs):
        super(UARTPeripheral, self).__init__(name,
           address, size)
        self.status = 0
        self.write_handler[0:size] = self.hw_write
        self.read_handler[0:size] = self.hw_read
```

```
0x405fb812: LOG_clk_per[83000800] <= 30000000
0x405fb812: 00000200 <= LOG_clk_per[83000c00]
0x405fb812: LOG_clk_per[83000c00] <= 00003200
0x405fb812: 00003200 <= LOG_clk_per[83000c00]
0x405fb886: 00000000 <= LOG_clk_per[8300184c]
0x405fb886: LOG_clk_per[8300184c] <= 00100000
0x405fb886: 00100000 <= LOG_clk_per[8300184c]
0x405fb886: LOG_clk_per[8300184c] <= 00100000
0x405fb886: 00000000 <= LOG_clk_per[83001a0c]
0x405fb886: LOG_clk_per[83001a0c] <= 00000004
0x405fba78: 00000000 <= LOG_clk_per[83000004]
0x405fba78: LOG_clk_per[83000004] <= 00000514
0x405fba78: 00000000 <= LOG_clk_per[83000008]
0x405fba78: LOG_clk_per[83000008] <= 00000514
0x405fbb02: 00003200 <= LOG_clk_per[83000c00]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
0x405fbb16: 00003200 <= LOG_clk_per[83000c00]
0x405fbb16: 07000001 <= LOG_clk_per[83000a00]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
405fb16a: 20000000 <= LOG_clk_per[BOOT_CLK_0]
```

https://drive.google.com/file/d/1hrKDB6m0LnSYJ4WzmgpYBqvmlebcyJcw/view?usp=sharing

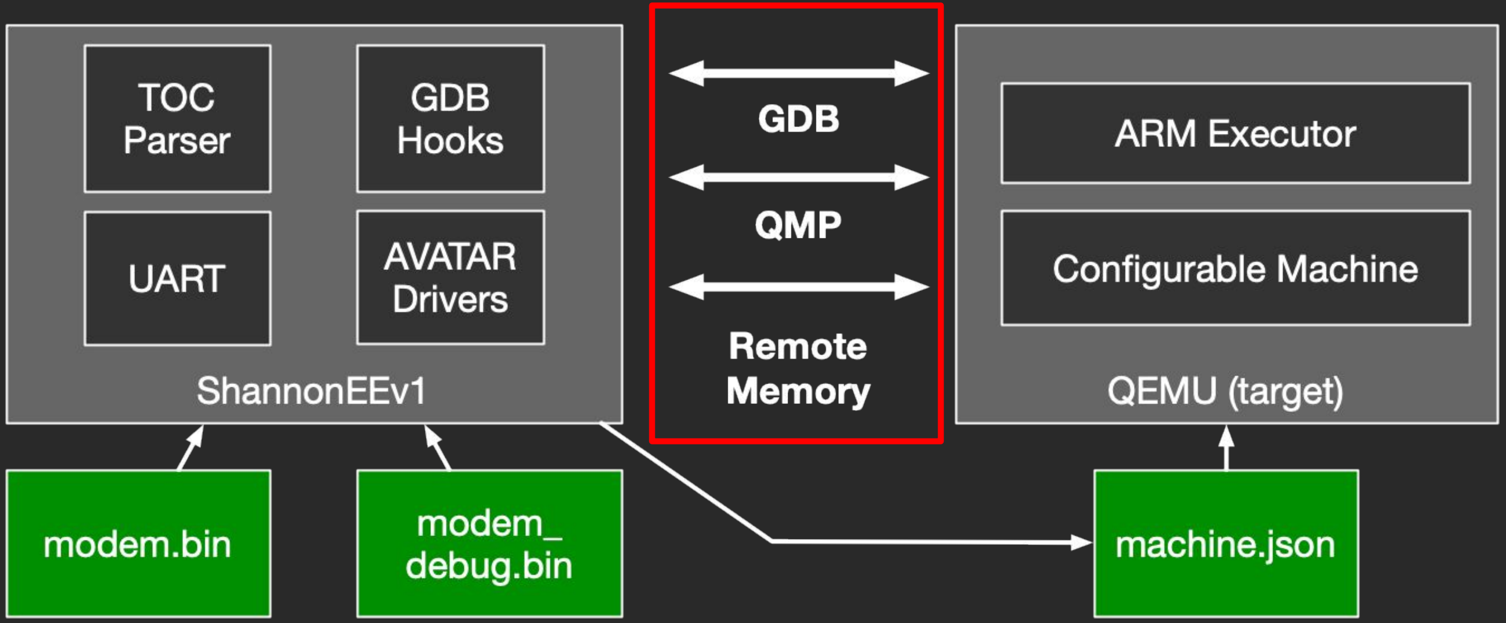
Snapshot support

- Piece of cake with Avatar's remote QMP protocol support
- Care needed to snapshot Avatar PyPeripherals alongside QEMU memory

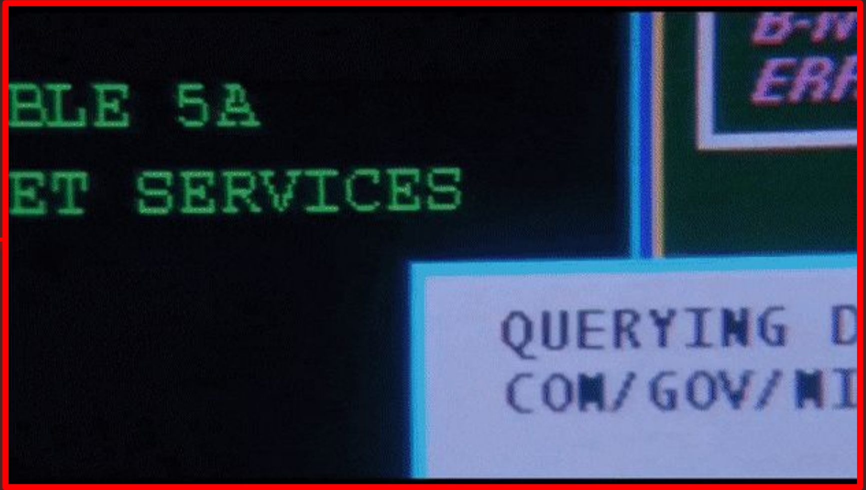
```python
def snapshot(self, snapshot_name):
    monitor = self.qemu.protocols.monitor

    log.info("Performing snapshot " + snapshot_name)

    peripherals = {}
    for mem in self.avatar.memory_ranges:
        if hasattr(mem.data, 'python_peripheral'):
                per = mem.data.python_peripheral
                log.info("Snapshotting " + str(per))
                peripherals[mem.begin] = per

    with open('avatar-snapshot-%s' % snapshot_name, 'wb') as fp:
        pickle.dump(peripherals, fp)

    log.info("Snapshotting qemu state...")
    result = monitor.execute_command('human-monitor-command',
        {"command-line": "savevm %s" % snapshot_name})
    log.info("Snapshot result: " + result)

    self.qemu.cont(blocking=False)
```

The tooling so far

Avatar <-> QEMU IPC is slow
GDB hooks and remote memory are the primary bottleneck



hacking montage

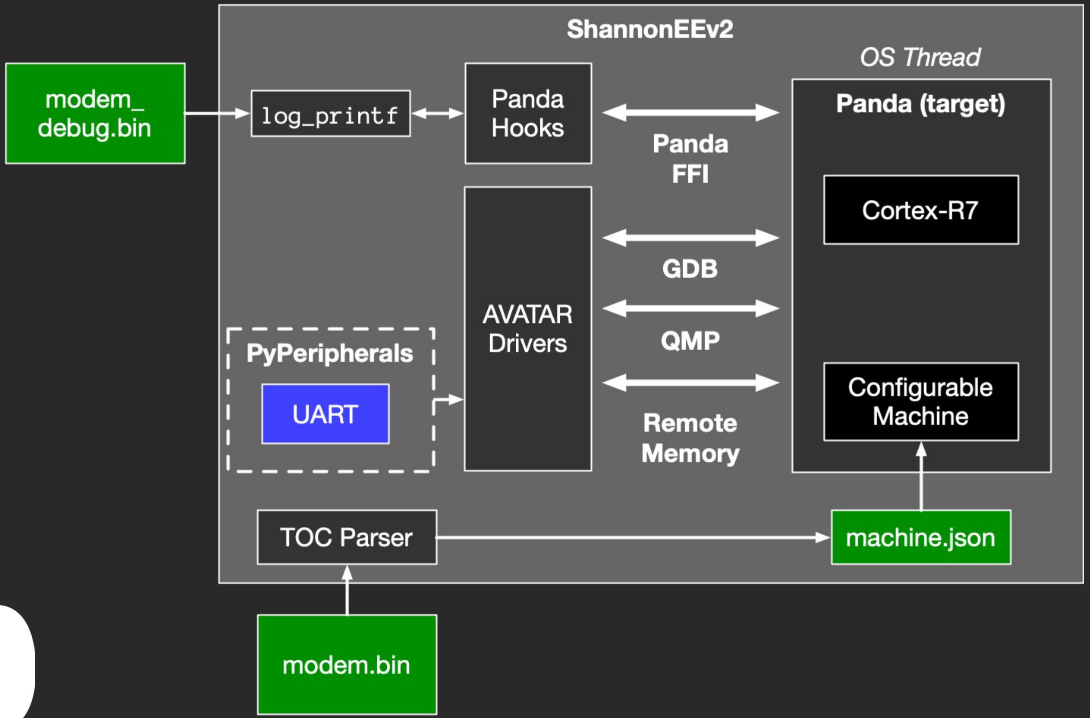


Moving to Panda

- Platform for Architecture-Neutral Dynamic Analysis
- First release in 2013
- Modified QEMU
  - Record & Replay Infrastructure
  - Plugin infrastructure
  - Callbacks to QEMU runtime state
- Already integrated in avatar2-infrastructure
- **Still has the same performance issues!**

Enter PyPanda

- `import panda` -> QEMU as a thread
  - No more IPC!
  - Single python interpreter with FFI for PANDA C functions
  - Can replace all GDB hooks with native panda hooks in Python
- **HUGE speedup!**



Emulating Peripherals: pal_init1()

- A huge monolith function that starts all modem subsystems and tasks
    - Activates malloc heap
    - Loads NV items
    - Starts timers
    - Initializes DSP(s)
    - Starts all tasks
- Iteratively emulated peripherals by watching for crash strings or infinite loops
- MMIO monitoring used to see which peripherals needed more modeling
- Simple automated cyclic-bit pattern heuristic
- **Partially emulated: PMIC, CLK, DSP, SOC, SIPC/SHM, TIMER, GIC**

```
00000040: 4d41 494e 0000 0000 0000 0000 6022 0000  MAIN........`"..
00000050: 0000 0140 a079 5402 3fb1 20ef 0200 0000  ...@.yT.?. .....
```

We reached the banner!

```
[VARIANT/PALVar/Platform_EV/CHIPSET/S5000AP/device/User/src/pal_main.c] - BandSet: Done.
===================================================
            DEVELOPMENT PLATFORM
 - ARM Emulation Baseboard | Cortex-R7

 - Software Build Date : Jul 19 2019 05:03:07
 - Software Builder    :
 - Compiler Version    : ARM RVCT 50.6 [Build 422]

    Platform Abstraction Layer (PAL) Powered by
               CP Platform Part
===================================================
[INFO] OS_Create_Event_Group(0x4177b710, ACPM_PMIC_RX_EVENT)
[VARIANT/PALVar/Platform_EV/HAL/Common/driver/Acpm/src/hw_Acpm.c] - [ACPM] Shannon OS
[_ShannonOS_3.2_R8_AC5]
```

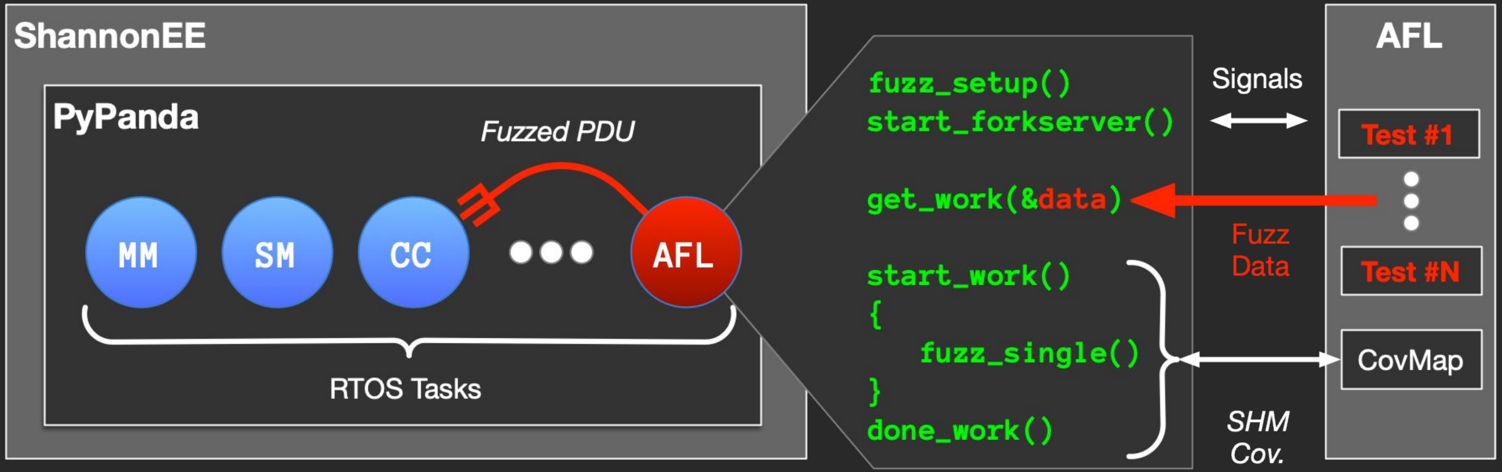
Fuzz’n’Roll

Enter Triforce-AFL

- Originally developed in 2017
- Invokes AFL from within the guest via hypercalls
- We combined the patch-set with some afl++ additions
    - Better coverage-collection
    - Persistent mode
- **Fuzzing from within using the AFL Task**

Using the ModKit for the AFL Task

- Wrote our own **ModKit**
- Inject custom tasks inside the emulated baseband
- C-based compiled modules
- Dynamic baseband symbol resolution for a nice FFI
  - Provides access to recovered Shannon symbols
- Mods dynamically linked into RWX page in baseband memory



Task Targeting

- Target the task message queues
- Increases accuracy as significant processing before radio payloads
  - No need for manual rehosting of functions, just need the right message IDs
- Inter-task messaging
  - pal_SendMsg(QID, msg)
  - pal_RecvMsg(QID)

```c
struct qitem_header {
  union {
    struct {
      uint16_t src; // source queue
      uint16_t dst; // destination queue
    };
    uint32_t dir;
  };
  uint16_t size; // size of the payload
  uint16_t msgId; // [msgGroup:8][msgNumber:8]
} PACKED;
```

GSM SM (GPRS) Fuzzing Harness

```c
struct qitem_sm {
  struct qitem_header header;
  char *pdu; // payload inline
} PACKED;
```

- Harness run by AFL Task to play nice with the RTOS scheduler

```c
const char TASK_NAME[] = "AFL_GSM_SM\0";
static pal_qid_t qid;
// called once before forkserver
int fuzz_single_setup()
{
  // dynamically look up the QID
  qid = queuename2id("SM");

  struct qitem_sm * init =
malloc(sizeof(struct qitem_sm));

  init->header.size = 0;
  // 0x3407 SMREG_INIT_REQ
  init->header.msgId = 0x3407;
  pal_SendMsg(qid, init);

  return 1;
}
```

GSM SM fuzz_single()

```c
// called for each test case
void fuzz_single()
{
  uint32_t input_size;
  uint16_t size;

  struct qitem_sm * item =
    malloc(sizeof(struct qitem_sm));
  char * pdu = malloc(AFL_MAX_INPUT);

  item->pdu = pdu;

  char * buf = getWork(&input_size);

  // Only target the RADIO_MSGs
  item->header.msgGroup = 0x3414;
  item->header.size = size;

  memcpy(item->pdu, buf, size);

  // memory range to collect coverage
  startWork(0, 0xffffffff);

  // immediately reschedules to target task
  pal_SendMsg(qid, item);
  // returns here when task done processing
  doneWork(0);
}
```

```
                 american fuzzy lop 2.06b (GSM_MM)

  process timing                                        overall results
       run time :  0 days, 0 hrs, 0 min, 52 sec        cycles done :  0
  last new path :  0 days, 0 hrs, 0 min, 0 sec         total paths :  93
last uniq crash :  none seen yet                      uniq crashes :  0
 last uniq hang :  0 days, 0 hrs, 0 min, 27 sec         uniq hangs :  2
  cycle progress                    map coverage
 now processing :  1 (1.08%)          map density :  942 (0.04%)
paths timed out :  0 (0.00%)       count coverage :  1.64 bits/tuple
  stage progress                    findings in depth
 now trying :  calibration         favored paths :  11 (11.83%)
stage execs :  38/40 (95.00%)       new edges on :  52 (55.91%)
total execs :  18.8k               total crashes :  0 (0 unique)
 exec speed :  960.0/sec             total hangs :  28 (2 unique)
  fuzzing strategy yields                               path geometry
  bit flips :  n/a, n/a, n/a                             levels :  2
 byte flips :  n/a, n/a, n/a                            pending :  93
arithmetics :  n/a, n/a, n/a                           pend fav :  11
 known ints :  n/a, n/a, n/a                          own finds :  80
 dictionary :  n/a, n/a, n/a                           imported :  0
      havoc :  0/0, 0/0                                variable :  91
       trim :  0.00%/4, n/a
```

https://drive.google.com/file/d/1zGFQmlkJ7VuT-K-wDlnJo4nhwJl7GpvL/view?usp=sharing

Bugs, Bugs, Bugs!

N-day Rediscovery

- Let’s rediscover an n-day in Shannon
- Targeted ~2017 Galaxy S7 firmware (Amat’s research environment)
- Built harness for GSM & GPRS radio packet handlers
  - Call control (CC)
  - Mobility Management (MM)
  - Session management (SM)

- **AFL automatically rediscovered the GPRS PDP_NETWORK_ACCEPT crash from “A Walk with Shannon”!**

0-day Fuzzing

- **Target**: the GSM and GPRS protocol stacks (2 and 2.5G)
- Why 2G?
  - Lowest hanging fruit in baseband,
  - Trivial fake base station based attack model (no mutual authentication in 2G)
- Coverage guided fuzzing generated test cases (blank initial seeds)
- Coverage debugging using PANDA and plotting using GHIDRA's Dragondance

- Ran across 30 CPU cores for 5 days of CPU time (highly scalable)
- **Rediscovered two n-days (S7 Edge) and one 0-day (S10) vulnerability!**
  - In disclosure process with Samsung
- LTE is next on our list :)

“Call of Death” n-day

- On the S7 we discovered a previously unknown overflow in the parsing of the call setup bearer Information Element (IE) (3GPP 24.008 - 5.2.2)
- This packet is incorrectly parsed by the baseband when a call is incoming
- Heap based buffer overflow
- **We confirmed that this vulnerability is no longer!**
  Bounds checking has been added in the latest modem versions

ShannonEE Triage

```
[2.17512][AFL] 0x4500013d pal_MsgSendTo(CC (23))
[2.17539][CC] 0x40d3e3c7 0b101: [cc_Main.c] - CC TASK
[2.17570][CC] 0x40d3de45 0b10: [cc_Main.c] - cc_UpdStackId :CcCurrentStackId: 0
[2.17612][CC] 0x4088ddb9 0b101: [cc_MsgDescription.c] - cc_MapSubTypeToMessageNum SubType = 5
[2.17990][CC] 0x40d3dfcf 0b101: [cc_Main.c] - [StackNo] 0
[2.18022][CC] 0x40d3e051 0b100: [cc_Main.c] - CC <== <RADIO MSG> SETUP_IND
[2.18059][CC] 0x40d3e245 0b1010: [cc_Main.c] - PRIVACY! MT message : SETUP
<..snip..>
[2.18775][CC] 0x40d3a7d5 0b100: [cc_PduCodec.c] - ---------- Displaying Information Elements --------
[2.18814][CC] 0x40d39beb 0b100: [cc_PduCodec.c] - Received SETUP From Network
[2.18846][CC] 0x40d39c05 0b100: [cc_PduCodec.c] - 2 Mandatory IE ->...[24.008]-9.3.23.2
[2.18870][CC] 0x40d39c21 0b100: [cc_PduCodec.c] -  BearerCapabilityOne -> ...
[2.19013][CC] 0x408a775b 0b101: [cc_MtCallEstablishment.c] - Entering cc_DecodeSetupIndMsg....[24.008] -
5.2.2...
[2.19066][CC] 0x408a7841 0b10: [cc_MtCallEstablishment.c] - TransactionId -> 11
[2.19164][CC] 0x40d407a7 0b100: [cc_Main.c] - Bearer 1 Capability ->.....
[2.19230][CC] 0x40d40997 0b100: [cc_Main.c] - Network Transfer Capability -> CC_NTWK_SPEECH_BEARER
<..snip..>
[2.20447][CC] 0x4103e933 0b100: [bc_utilities.c] - Setting BC_LENGTH_OF_BEARER (0) = 0x82
[ERROR] FATAL ERROR (CC): from 0x40fc1e69 [pal_PlatformMisc.c:146 - Fatal error:PAL_MEM_GUARD_CORRUPTION
pal_MemInterface.c Line 886]
```

```
Breakpoint 4, 0x40fc8960 in ?? ()
[ Legend: Modified register | Code | Heap | Stack | String ]
──────────────────────────────────────────────────────────── registers ──
$r0   : 0x43694ae8  →  0x30303030  →  0x00000000  →  0xea000023  →  0x00000000  →  [loop detected]
$r1   : 0x43694afc  →  0x30303030  →  0x00000000  →  0xea000023  →  0x00000000  →  [loop detected]
$r2   : 0x30303030  →  0x00000000  →  0xea000023  →  0x00000000  →  [loop detected]
$r3   : 0x43694a7c  →  0xaaaaaaaa  →  0x00000000  →  0xea000023  →  0x00000000  →  [loop detected]
$r4   : 0x43694a80  →  0x00000004
$r5   : 0x00000004  →  0xe59ff15c
$r6   : 0x43694aa0  →  0x30308004
$r7   : 0x000008c6  →  0x0000e311
$r8   : 0x408a61e0  →  0x2e2f2e2e
$r9   : 0x00000000  →  0xea000023
$r10  : 0x42ef9494  →  0x43694aa0
$r11  : 0x42c97838  →  0x00000000
$r12  : 0x00000000  →  0xea000023
$sp   : 0x42ef9448  →  0x00000041
$lr   : 0x40fc88bb  →  0x00f04f90
$pc   : 0x40fc8960  →  0x3faaf1b2
$cpsr: [negative zero CARRY overf
──────────────────────────────────────────────────────────── stack ──
0x42ef9448│+0x0000: 0x00000041
0x42ef944c│+0x0004: 0x46e47ad4
0x42ef9450│+0x0008: 0x00000000
0x42ef9454│+0x000c: 0x41697775
0x42ef9458│+0x0010: 0x00000000
0x42ef945c│+0x0014: 0x00000000
0x42ef9460│+0x0018: 0x41697775
0x42ef9464│+0x001c: 0x00000041
──────────────────────────────────────────────────────────── code:arm:ARM ──
   0x40fc8954                  add    r1,  r3
   0x40fc8956                  it     eq
   0x40fc8958                  subeq  r1,  #28
 → 0x40fc8960                  cmp.w  r2,  #2863311530  ; 0xaaaaaaaa
   0x40fc8964                  bne.n  0x40fc896c
   0x40fc8966                  adds   r0,  r0,  #4
   0x40fc8968                  cmp    r1,  r0
   0x40fc896a                  bhi.n  0x40fc895e
   0x40fc896c                  cmp    r0,  r1
──────────────────────────────────────────────────────────── threads ──
[#0] Id 1, stopped 0x40fc8960 in ?? (), reason: BREAKPOINT
──────────────────────────────────────────────────────────── trace ──
[#0] 0x40fc8960 → cmp.w r2,  #2863311530        ; 0xaaaaaaaa
[#1] 0x40fc88ba → str r0,  [sp,  #16]
─────────────────────────────────────────────────────────────────────
gef➤  x/16wx $r0
0x43694ae8:     0x30303030      0x30303030      0x30303030      0x30303030
0x43694af8:     0x30303030      0x30303030      0x30303030      0x30303030
0x43694b08:     0x30303030      0x30303030      0x30303030      0x30303030
0x43694b18:     0x30303030      0x30303030      0x43693030      0x4378ba20
gef➤
```

```
gef➤  shell xxd -e ./cc-crash-min
00000000: 30303030 30303030 30303030 30303030  0000000000000000
00000010: 80040533 30303030 30303030 30303030  3...000000000000
00000020: 30303030 30303030 30303030 30303030  0000000000000000
00000030: 30303030 30303030 30303030 30303030  0000000000000000
00000040: 30303030 30303030 30303030 30303030  0000000000000000
00000050: 30303030 30303030 30303030 30303030  0000000000000000
00000060: 30303030 30303030 30303030 30303030  0000000000000000
00000070: 30303030 30303030 30303030 30303030  0000000000000000
00000080: 30303030 30303030 30303030 30303030  0000000000000000
00000090: 30303030                             0000
```

Over-the-air Reproduction

Experimental Setup

- **SDR**: bladeRF x40 ($420)
- **Base station**: YateBTS (modified with exploit payload)
- **Target device**: Samsung S10 / S7
- **SIM Card**: Osmocom USIM (for easy phone connection)
- Thanks to Tyler Tucker for recording the demo and managing the test setup!

https://youtu.be/Bhs054ma5OQ

Crash Triggered!

```
RILD2    : Read: MODEM not Online - IO_STATUS [2]
chatty   : uid=10142(com.sec.android.inputmethod) identical 1 line
SKBD     : and isTosAccept false
CASS     : Modem status : 0x04 -> 0x02
CASS     : CP CRASH_EXIT
RILD2    : IoChannelReader poller stopped
boot     : cbd: m: status_loop: deviceOff = 0
boot     : cbd: m: status_loop: get event 2
boot     : cbd: m: status_loop: DBG_LOW, wait onrestart by rild
SKBD     : and isTosAccept false
RILD2    : DoModemSilentReset()
```

Output of `adb logcat` during S7 crash

Let’s wrap it up

Remaining Challenges & Future Work

- Cellular-tailored stateful fuzzing is a requirement to get deeper code coverage

- The physical layer is ignored - what are we missing by not supporting it?
  - DSPs are attack surface too

- A holistic analysis of baseband attack surface
  - What has been covered and what remains

Takeaways

- We need scalable tools to keep up with the ever increasing amount of cellular protocol implementations and attack surface, especially with widespread 5G on the horizon.

- Building a baseband emulator, even with undocumented hardware configurations can be done. We can bring this methodology to other basebands.

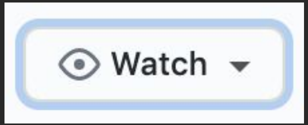
- We MUST emulate basebands for the level of introspection required to debug memory corruptions. Over-the-air testing alone is not sufficient.

Releases

https://github.com/grant-h/ShannonBaseband

- GHIDRA Tools
  - Shannon firmware loader
  - Debug annotation script
  - Auto-renamer
- Shannon reversing details
  - Export of 2017 Shannon image (reversed)
  - On-device log parser (.BTL) and file format info
- Firmware samples

https://github.com/grant-h/ShannonEE



- **ShannonEE** (will be released after disclosures + QA)

Acknowledgements

NSF/SRC CNS-1815883

NWO 628.001.030 ("TROPICS")

AFOSR FA8560-18-S-1201

AFRL/AFOSR-2018-003

ONR OTA-N00014-20-1-2205

Thanks!

@Digital_Cold

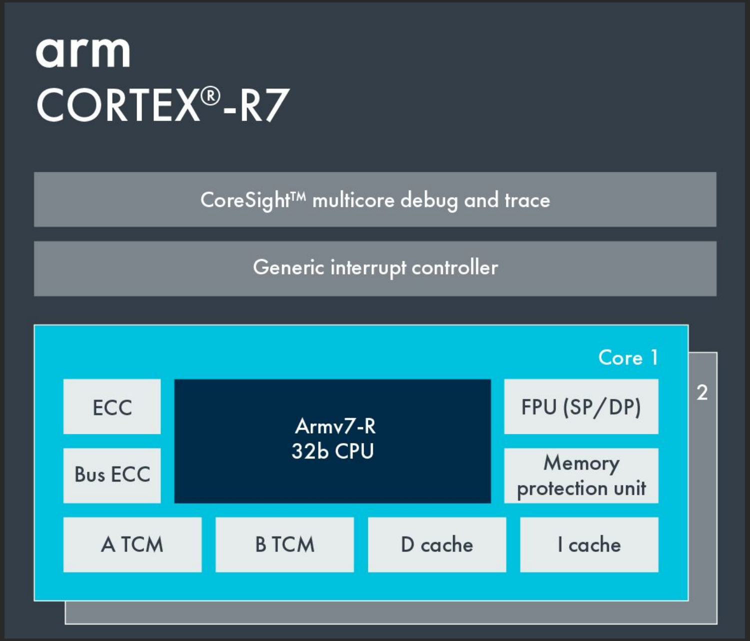
@nSinusR

Backup Slides

CPU Support

Shannon CPU Support

- ARM Cortex-R7 (identified from strings and previous work)
- QEMU doesn't support this ARM variant
  - This seems like it could derail things before they even get started
- QEMU does support the R5
- **What would be required to get the R7 working?**
  - Time to read the processor documentation



Taken from https://developer.arm.com/ip-products/processors/cortex-r/cortex-r7

```diff
diff --git a/target/arm/cpu.c b/target/arm/cpu.c
index 04b062c..9f6d05e 100644
--- a/target/arm/cpu.c
+++ b/target/arm/cpu.c
@@ -1132,6 +1132,15 @@ static void cortex_r5_initfn(Object *obj)
     define_arm_cp_regs(cpu, cortexr5_cp_reginfo);
 }

+static void cortex_r7_initfn(Object *obj)
+{
+    ARMCPU *cpu = ARM_CPU(obj);
+
+    cortex_r5_initfn(obj);
+    // granth: not sure how many there actually are
+    cpu->pmsav7_dregion = 32;
+}
+
 static const ARMCPRegInfo cortexa8_cp_reginfo[] = {
     { .name = "L2LOCKDOWN", .cp = 15, .crn = 9, .crm = 0, .opc1 = 1, .opc2 = 0,
       .access = PL1_RW, .type = ARM_CP_CONST, .resetvalue = 0 },
@@ -1573,6 +1582,7 @@ static const ARMCPUInfo arm_cpus[] = {
     { .name = "cortex-m4",   .initfn = cortex_m4_initfn,
                              .class_init = arm_v7m_class_init },
     { .name = "cortex-r5",   .initfn = cortex_r5_initfn },
+    { .name = "cortex-r7",   .initfn = cortex_r7_initfn },
     { .name = "cortex-a7",   .initfn = cortex_a7_initfn },
```

Not much after all :)

ShannonLoader for GHIDRA

- Automates the extraction of TOC entries into memory regions
- Extracts MPU tables for extra RAM/MMIO regions, allowing for XREFs
- Resolves overlapping memory regions and applies MPU permissions (RO/RW, X)
- Useful for batch loading of modem firmware (e.g. when BinDiffing)

Name:	**ShannonLoader**
Description:	**A loader for Samsung's Shannon modem binaries.**
Author:	**Grant Hernandez**
Created-on:	**3/1/2020**
Version:	**9.1.2**

Cross-version Support

Automated memory map extraction

- MPU enables coarse-grained permission control (rwx) over memory regions
- ShannonEE parses MPU configurations to automatically create regions in Panda
- Uses binary patterns ([0-255] based regex) to reliably find MPU signature

```
00000000 - 00002e40 TOC_BOOT_LOW (rwx)
00002e40 - 00008000 SPLIT_2e40_51c0 (r-x)
00100000 - 00120000 MPU22_00100000 (rw-)
04000000 - 04020000 MPU1_04000000 (r-x)
04800000 - 04804000 MPU2_04800000 (rw-)
40000000 - 40002e40 TOC_BOOT (rwx)
40002e40 - 40010000 SPLIT_40002e40_d1c0 (r-x)
40010000 - 43010000 TOC_MAIN (rwx)
43010000 - 45600000 SPLIT_43010000_25f0000 (rwx)
45600000 - 45700000 NV (rw-)
45700000 - 46000000 MPU3_45700000 (rwx)
...
47300000 - 47382000 SPLIT_47300000_82000 (rw-)
47382000 - 47382100 DSPPeripheral (<class 'hw.DSPPeripheral.DSPPeripheral'>)
...
```

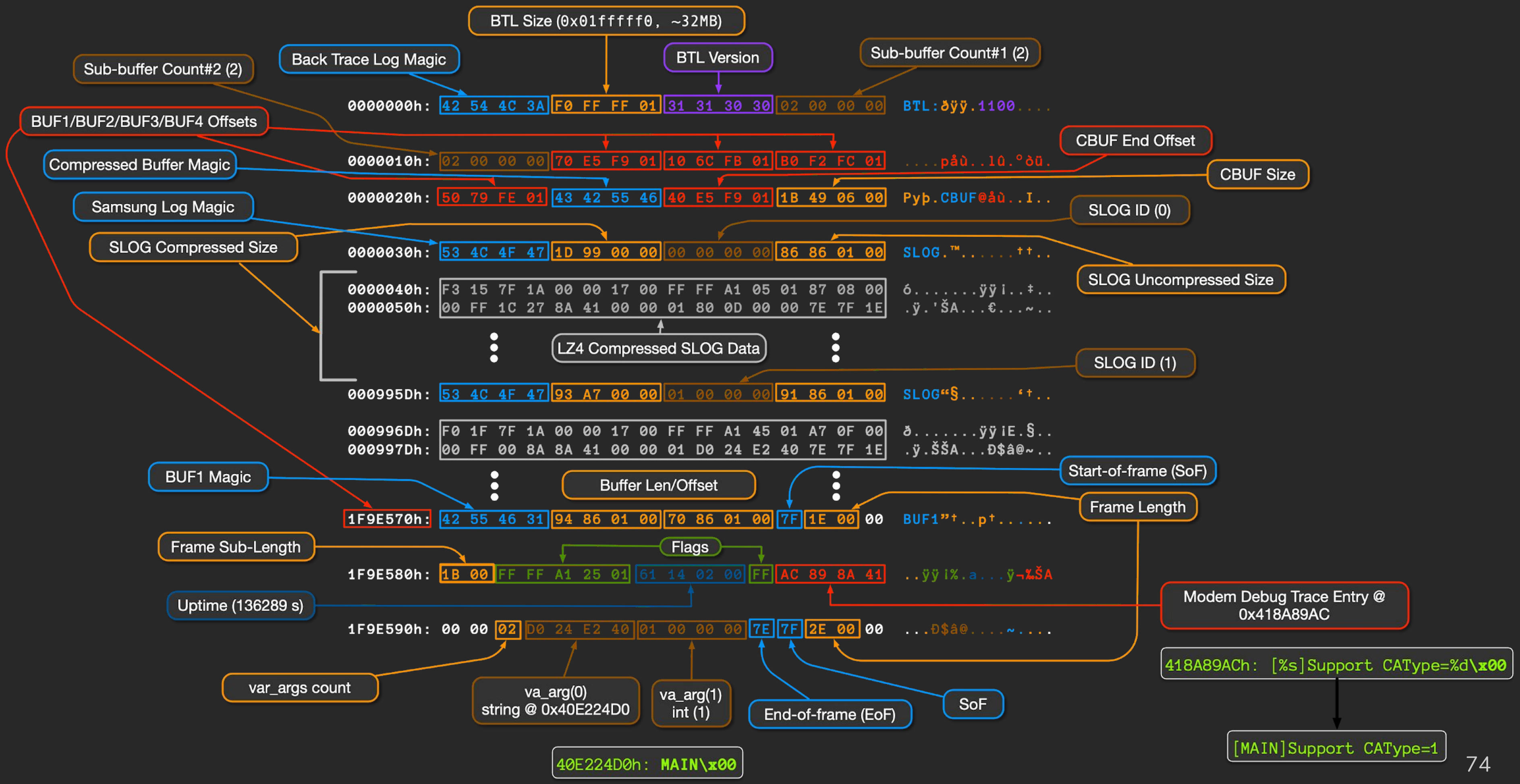
Multi-SoC

```
class S355AP(ShannonSOC):
    peripherals = [
      SOCPeripheral(DSPPeripheral, 0x4751b000, 0x100, name="DSPPeripheral",sync=[137, 292]),
      SOCPeripheral(PMICPeripheral, 0x96450000, 0x1000, name="PMIC"),
      SOCPeripheral(S355DSPBufferPeripheral, 0x47504000, 0x1000, name="DSPB"),
    ]

    CHIP_ID = 0x03550000
    SIPC_BASE = 0x95b40000
    SHM_BASE = 0x48000000
    SOC_BASE = 0x83000000
    SOC_CLK_BASE = 0x83002000
    CLK_PERIPHERAL = S355APClkPeripheral
    TIMER_BASE = SOC_BASE + 0xc000

    name = "S355AP"
```

Backtrace Logging

Modem Backtrace Logging (BTL)

- Dumped on crash, but can be manually extracted (.BTL files)
- Reverse engineered BTL task
- LZ4 encoded log ring buffer in baseband memory
  - Log entries are pointers to format strings in modem_debug.bin
  - Varargs are pointers or literals, depending on format specifier
- Not 100% reverse engineered, but good enough to compare ShannonEE with real modem logging



BTL Size (0x01fffff0, ~32MB)
Back Trace Log Magic
BTL Version
Sub-buffer Count#1 (2)
Sub-buffer Count#2 (2)
BUF1/BUF2/BUF3/BUF4 Offsets
CBUF End Offset
Compressed Buffer Magic
CBUF Size
Samsung Log Magic
SLOG ID (0)
SLOG Compressed Size
SLOG Uncompressed Size
0000000h: 42 54 4C 3A F0 FF FF 01 31 31 30 30 02 00 00 00 BTL:ðÿÿ.1100....
0000010h: 02 00 00 00 70 E5 F9 01 10 6C FB 01 B0 F2 FC 01 ....påù..lû.°òü.
0000020h: 50 79 FE 01 43 42 55 46 40 E5 F9 01 1B 49 06 00 Pyþ.CBUF@åù..I..
0000030h: 53 4C 4F 47 1D 99 00 00 00 00 00 00 86 86 01 00 SLOG.™......††..
0000040h: F3 15 7F 1A 00 00 17 00 FF FF A1 05 01 87 08 00 ó.......ÿÿ¡..‡..
0000050h: 00 FF 1C 27 8A 41 00 00 01 80 0D 00 00 7E 7F 1E .ÿ.'ŠA...€...~..
LZ4 Compressed SLOG Data
SLOG ID (1)
000995Dh: 53 4C 4F 47 93 A7 00 00 01 00 00 00 91 86 01 00 SLOG“§......‘†..
000996Dh: F0 1F 7F 1A 00 00 17 00 FF FF A1 45 01 A7 0F 00 ð.......ÿÿ¡E.§..
000997Dh: 00 FF 00 8A 8A 41 00 00 01 D0 24 E2 40 7E 7F 1E .ÿ.ŠŠA...Ð$â@~..
BUF1 Magic
Buffer Len/Offset
Start-of-frame (SoF)
Frame Length
1F9E570h: 42 55 46 31 94 86 01 00 70 86 01 00 7F 1E 00 00 BUF1”†..p†......
Frame Sub-Length
Flags
1F9E580h: 1B 00 FF FF A1 25 01 61 14 02 00 FF AC 89 8A 41 ..ÿÿ¡%.a...ÿ¬‰ŠA
Uptime (136289 s)
Modem Debug Trace Entry @ 0x418A89AC
1F9E590h: 00 00 02 D0 24 E2 40 01 00 00 00 7E 7F 2E 00 00 ...Ð$â@....~....
418A89ACh: [%s]Support CAType=%d\x00
var_args count
va_arg(0) string @ 0x40E224D0
va_arg(1) int (1)
End-of-frame (EoF)
SoF
[MAIN]Support CAType=1
40E224D0h: MAIN\x00