CENSUS
Cybersecurity Engineering

Attacking Hexagon: Security Analysis of Qualcomm's aDSP

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$ whoami

- Security Researcher at CENSUS S.A.
- Reverse Engineering, Exploitation, Code Audit
- I fight Androids

Agenda

- Introduction to Hexagon and aDSP
- System Architecture
- FastRPC Framework
- Custom code on aDSP
- Attack Surface
- Fuzzing
- Conclusions

▷ aDSP and Hexagon

▷ Qualcomm aDSP

- Low power, high performance DSP coprocessor
- Exists in all modern Qualcomm SoCs
- Hexagon Architecture
  - Same as Qualcomm baseband

Qualcomm aDSP

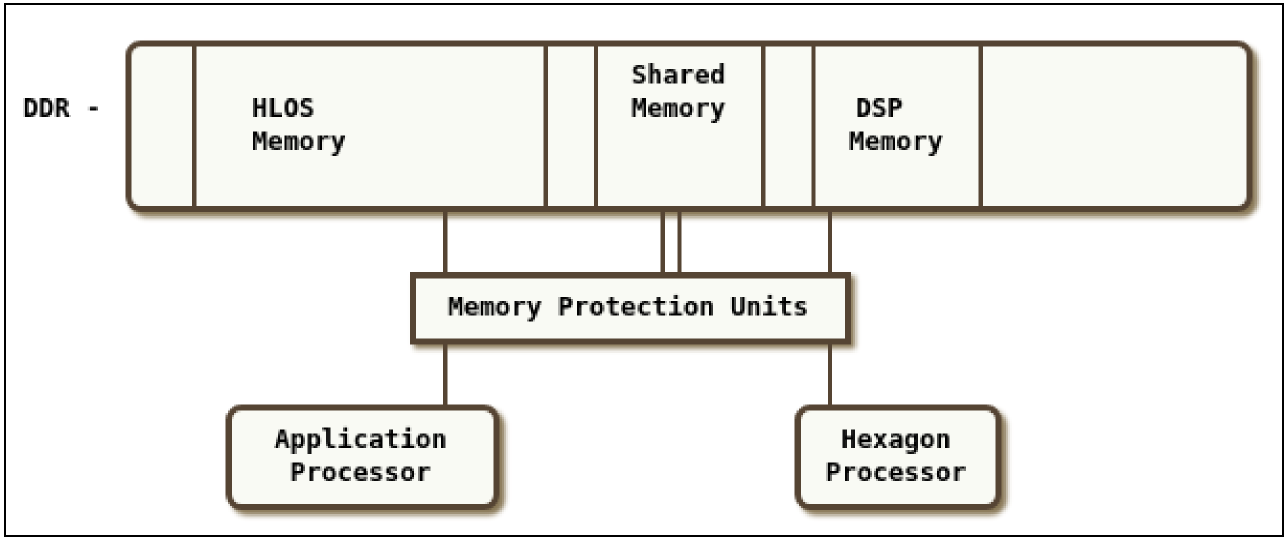
- Runs its own OS, QuRT
  - Runs Hexagon ELF files
  - Again same as Qualcomm baseband
- Provides shared objects that can be called from Android userspace in an RPC manner
- Machine Learning, Computer Vision, Audio Decoding

▷ Qualcomm aDSP

- Qualcomm Shared Memory Subsystem
  - Application Processor -> aDSP communication
  - Also used for other subsystems like baseband and Wi-Fi

- aDSP needs access to main system memory
  - Argument Passing
  - Results

▷ Qualcomm aDSP - Memory



HLOS = High Level OS (Android, Windows)

* As shown in the Qualcomm SDK Documentation

Qualcomm aDSP - Memory

- Memory Protection Unit
  - Makes sure aDSP can access only specific memory
- Internal aDSP MMU
  - QuRT provides page tables for address translation from virtual to physical
- Limited TLB Entries
  - Large Contiguous Buffers are preferred

Qualcomm aDSP - Memory

- Memory Carveout
  - Android ION Allocator - Contiguous
  - Specific ION Heap
  - ION buffers can be mapped to aDSP
- SMMU
  - System Memory Management Unit
  - Analogous to IOMMU in x86
  - Buffers only appear to be contiguous

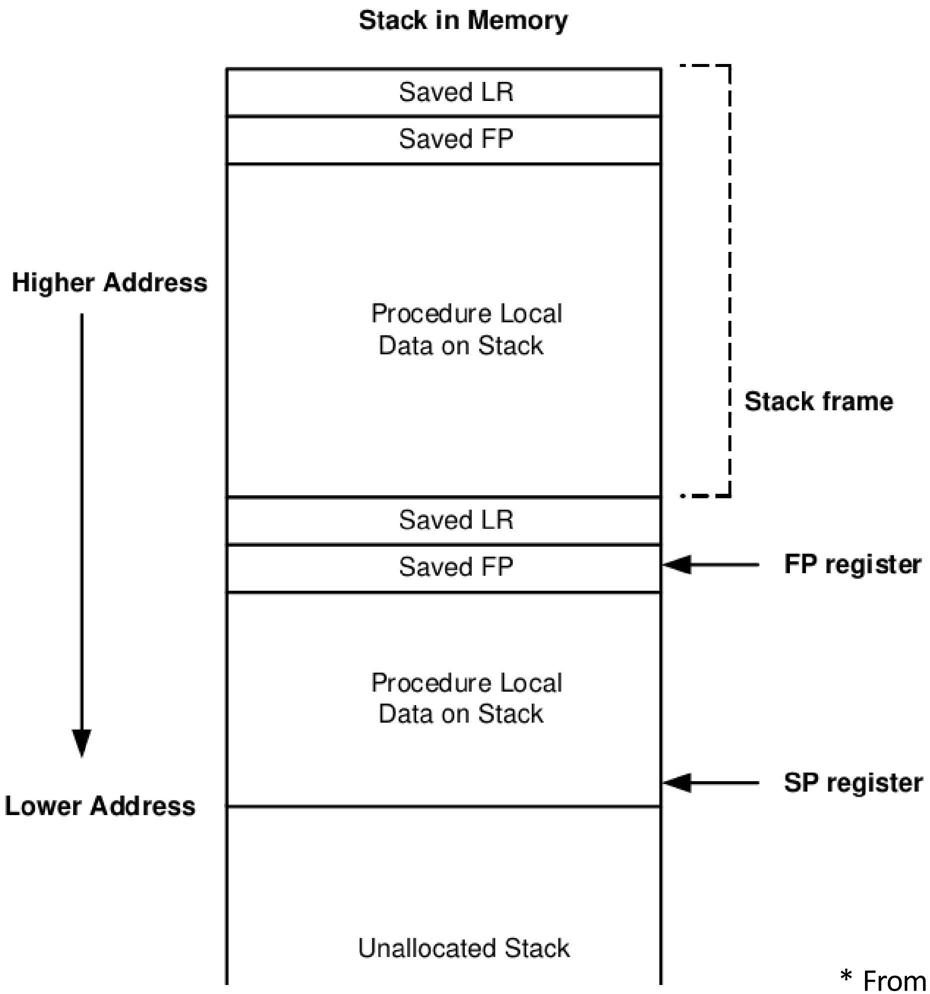
▷ Hexagon Architecture

- Specifically designed for DSP use cases
- VLIW 32-bit Instruction Set
- Little-endian
- Instruction Packets, compound instructions
- 4 execution units

Hexagon Architecture

- Registers R0 – R31
- Stack Pointer, Frame Pointer, Link Register
- Special hardware synchronization primitives
- Not your typical assembly language

▷ Hexagon Architecture



* From Hexagon V62 Programmers Manual

Hexagon Architecture

```
@ START OF FUNCTION CHUNK FOR fastcvadsp_skel_invoke

loc_1F940:
{ allocframe (#off_50) }
{ r5 = extractu (r1, #byte_4, #byte_4)
  r6 = extractu (r1, #byte_8, #byte_8)
  r3 = and (r1, #byte_F)
  memd (r29 + #dword_48) = r17:16 }
{ r4 = extractu (r1, #byte_8, #byte_10)
  r3 = add (r6, r3)
```

```
loc_1F95C:
  r16 = r0
  memd (r29 + #byte_28) = r25:24 }
{ memd (sp + #dword_40) = r19:18 ; memd (sp + #byte_38) = r21:20 }
{ r5 += add (r3, r4)
  r3 = r2 ; memd (sp + #byte_30) = r23:22 }
{ p0 = cmp.gt (r5, #byte_7) ; if (p0.new) jump:nt loc_1F980
```

- Instruction packets are denoted in { … }
  - Instructions are executed in parallel

Hexagon Hardware Security Mitigations

- Only on Hexagon V61 and greater
- FRAMELIMIT Register
  - In frame allocation, if SP < FRAMELIMIT throw exception
- FRAMEKEY Register
  - Return address XOR FRAMEKEY
  - Different for every hardware thread
  - Changes "regularly" as per documentation but no other information provided

QuRT

- Qualcomm Real Time OS
- Runs on aDSP and baseband
- Privilege modes:
  - QuRT OS
  - Guest OS (root)
  - User
- Scheduling, resource management, address translation

▷ QuRT Mitigations

- No ASLR
- Stack cookies
- W^X
  - Can't write to executable memory
  - Can't execute data memory
- Heap corruption protection

▷ QuRT

- Binary can be found in TrustZone applets folder
  - /firmware/image/
- Files: adsp.mdt, adsp.b[0-9]
- Can be reassembled by https://github.com/laginimaineb/unify_trustlet

▷ FastRPC Framework

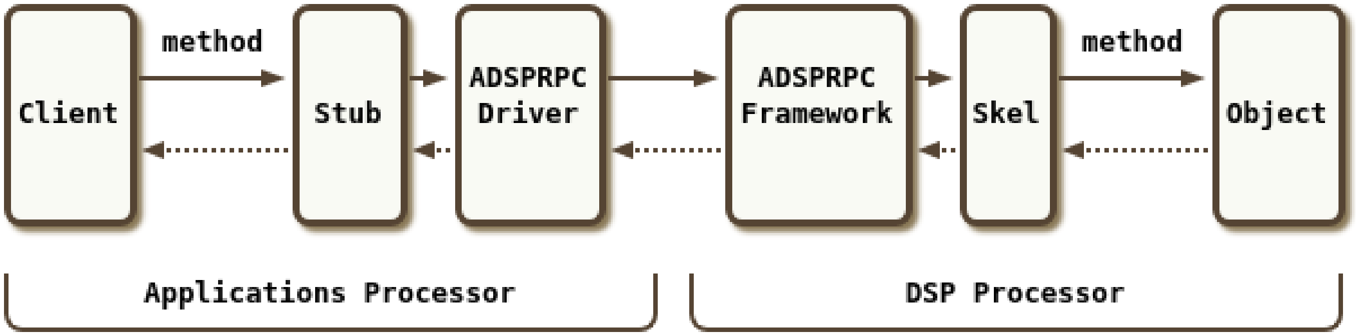
FastRPC

- Communication between APPS processor and aDSP
- Qualcomm Shared Memory Subsystem

- Intermediate Libraries
  - On the Android userpace - Stub
  - On the aDSP - Skel

- Kernel Driver

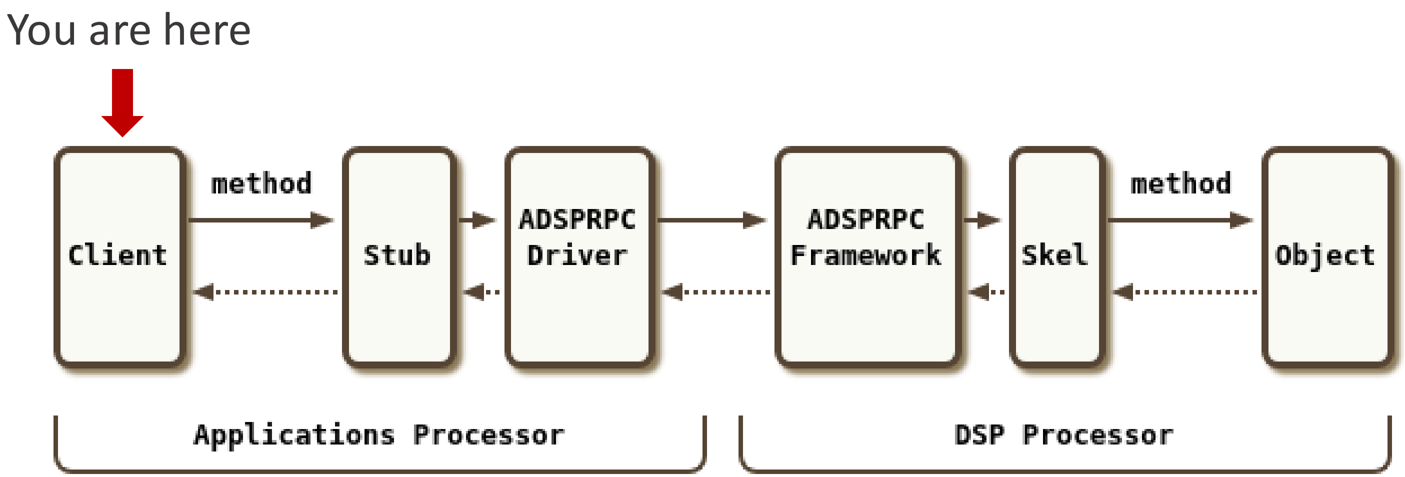
FastRPC



- The diagram shows the "simplified version"!

* From Hexagon DSK Documentation

FastRPC



- Say we want to use aDSP from an Android App
  - Windows on Arm would be pretty much the same
- Which libraries and functions can we call ?

FastRPC – Remote Filesystem

- /vendor/lib/rfsa/adsp
- Holds all libraries accessible for RPC
- Available libraries vary between vendors

FastRPC – Available Libraries

```
-rw-r--r-- 1 root root  1263616 2018-02-13 12:44 libfastcvadsp.so
-rw-r--r-- 1 root root   550172 2017-03-08 03:55 libfastcvadsp_skel.so
-rw-r--r-- 1 root root    82272 2017-03-08 03:55 libobjectMattingApp_skel.so
-rw-r--r-- 1 root root    99808 2017-03-08 03:55 libscveBlobDescriptor_skel.so
-rw-r--r-- 1 root root   429140 2017-03-08 03:55 libscveCleverCapture_skel.so
-rw-r--r-- 1 root root   635648 2017-03-08 03:55 libscveFaceRecognition_skel.so
-rw-r--r-- 1 root root    41780 2017-03-08 03:55 libscveObjectSegmentation_skel.so
-rw-r--r-- 1 root root   399744 2017-03-08 03:55 libscveT2T_skel.so
-rw-r--r-- 1 root root  1487612 2017-03-08 03:55 libscveTextReco_skel.so
```

- Libraries for computer vision, face recognition etc.

FastRPC – Available Libraries

- For every library libXXXXX.so
  - XXXXXX specifies the library *name*
  - libXXXXX_skel.so
    - Unmarshalls parameters and calls actual implementation

FastRPC – libadsprpc.so

- Use the library name to get a remote *handle*
- We can use the handle to *invoke* a function on aDSP

- libadsprpc.so
  - remote_handle_open("libname", &handle)
  - remote_handle_invoke(handle, sc, args)

▷ FastRPC – libadsprpc.so

- remote_handle_invoke(int handle, int sc, remote_arg_t* args)
- Argument sc: 0xAABBCCDE
  - AA: Method index and attributes
  - BB: Number of input buffers
  - CC: Number of output buffers
  - D: Number of input handles
  - E: Number of output handles

FastRPC – libadsprpc.so

- remote_arg_t* args

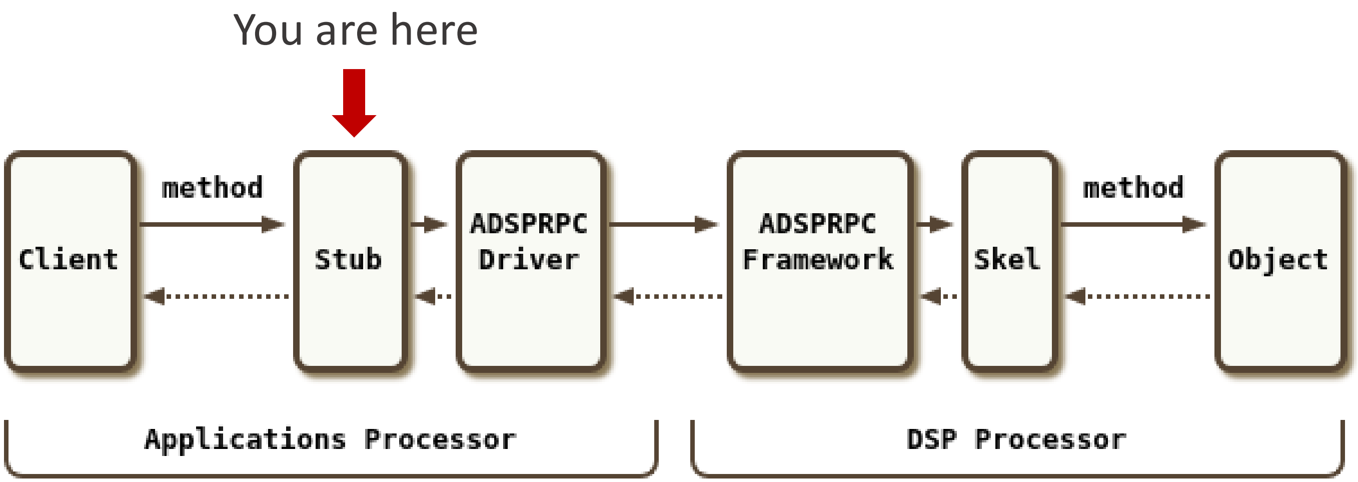
```
struct remote_buf {
        void *pv;                   /* buffer pointer */
        ssize_t len;                /* length of buffer */
};

union remote_arg {
        struct remote_buf buf;      /* buffer info */
        uint32_t h;                 /* remote handle */
};
```

▷ FastRPC – libadsprpc.so

```
remote_arg_t args[] =
    .buf = {
        .pv = 0xdeadbee1,  /* Input #1 */
        .len = 0x1000
    },
    .buf = {
        .pv = 0xdeadbee2,  /* Input #2 */
        .len = 0x1000
    },
    .buf = {
        .pv = 0xdeadbee3,  /* Output #1 */
        .len = 0x1000
    }
}
```

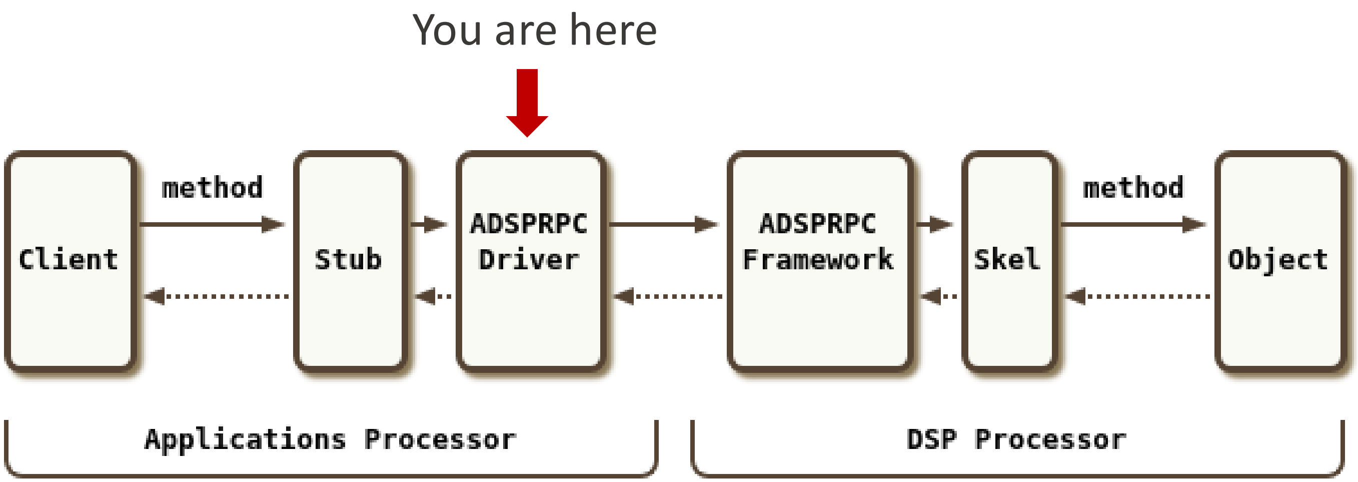
- Eg. Remote_handle_invoke(handle, 0x11020100, args)
  - Call method with index 0x11
  - 2 Input arguments, 1 Output argument

▷ FastRPC – Stub



- Autogenerated 'stub' libraries call remote_handle_open/invoke from libadsprpc.so
- Transparent to userspace
- Remote_handle_open/invoke are ioctl wrappers

FastRPC - Kernel



- Kernel driver interface
  - /dev/adsprpc-smd
  - Protected by SELinux permissions
  - ioctl()

FastRPC – IOCTL interface

- FASTRPC_IOCTL_INIT
- FASTRPC_IOCTL_INVOKE
- FASTRPC_IOCTL_MMAP
- FASTRPC_IOCTL_INVOKE_FD
- FASTRPC_IOCTL_SETMODE

FastRPC – IOCTL interface

- FASTRPC_IOCTL_INIT
- Load a user provided ELF to aDSP
  - ELF mapped to ION buffer
  - Pass ION pointer and file descriptor to ELF
  - Also pass memory buffer (?)
- libadsprpc loads '/dsp/fastrpc_shell_0'
- Lots of other Hexagon binaries under /dsp

▷ FastRPC – fastrpc_shell_0

- Hexagon ELF executable
  - Loads libXXXXX_skell.so, libXXXXX.so
  - Delegates execution
  - Provides a few remote functions on its own
    - adsp_ps – Show processes running on aDSP

▷ FastRPC – Kernel

- remote_handle_open() calls the following IOCTLs
  - FASTRPC_IOCTL_INIT
    - Loads 'fastrpc_shell_0' unto aDSP
  - FASTRPC_IOCTL_INVOKE
    - Invokes a remote function with a hardcoded handle!

FastRPC – Kernel

- FASTRPC_IOCTL_INVOKE
  - remote_handle_invoke() is a thin wrapper for this
  - Same Arguments: handle, sc, remote_args
  - Calls a remote function on aDSP

▷ FastRPC – Kernel

- FASTRPC_IOCTL_INVOKE
  - Called during remote_handle_open()
  - With handle = 1
  - A handle for system functions of some sort
  - Transfers execution to aDSP in order to get a proper handle for the library
- Actually all IOCTLs lead to a FASTRPC_IOCTL_INVOKE code with handle = 1 and different method index

FastRPC – Kernel

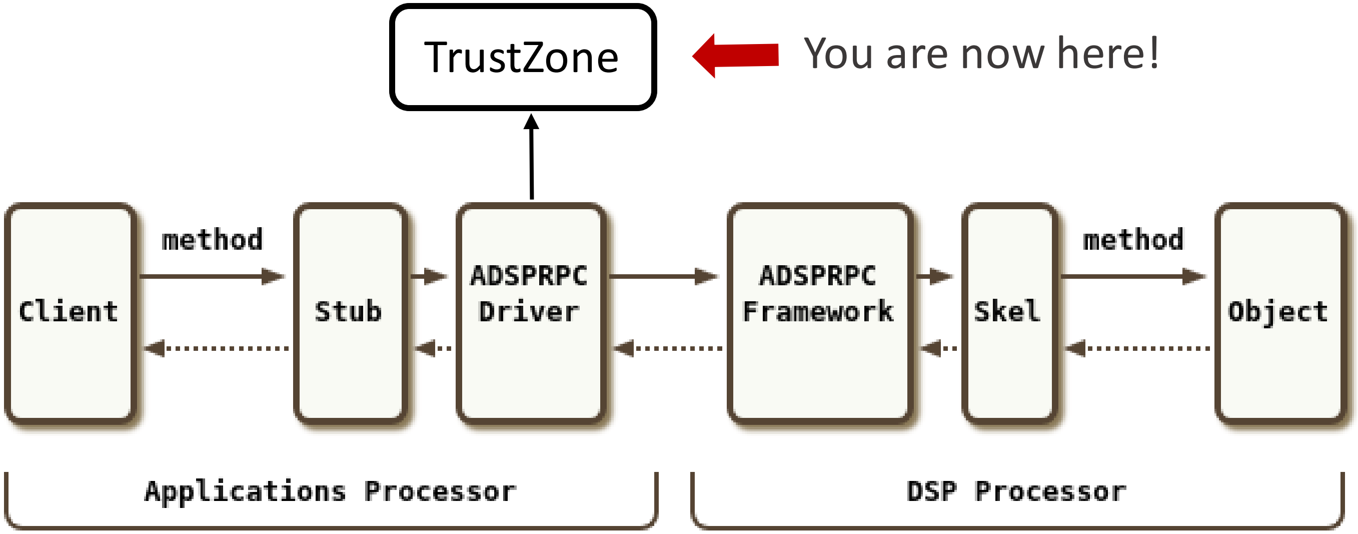
- Finally, a valid library handle is returned
- We can now call
  - remote_handle_invoke(handle, sc, args)
    - FASTRPC_IOCTL_INVOKE
  - Qualcomm Shared Memory Subsystem
  - But how are arguments passed to aDSP ?

▷ FastRPC – Kernel

```
int hyp_assign_table(struct sg_table *table,
                        u32 *source_vm_list, int source_nelems,
                        int *dest_vmids, int *dest_perms,
                        int dest_nelems)
{
        ...
        desc.args[0] = virt_to_phys(info_list->list_head);
        desc.args[1] = info_list->list_size;
        desc.args[2] = virt_to_phys(source_vm_copy);
        desc.args[3] = sizeof(*source_vm_copy) * source_nelems;
        desc.args[4] = virt_to_phys(dest_info_list->dest_info);
        desc.args[5] = dest_info_list->list_size;
        desc.args[6] = 0;

        desc.arginfo = SCM_ARGS(7, SCM_RO, SCM_VAL, SCM_RO, SCM_VAL, SCM_RO,
                                SCM_VAL, SCM_VAL);
```

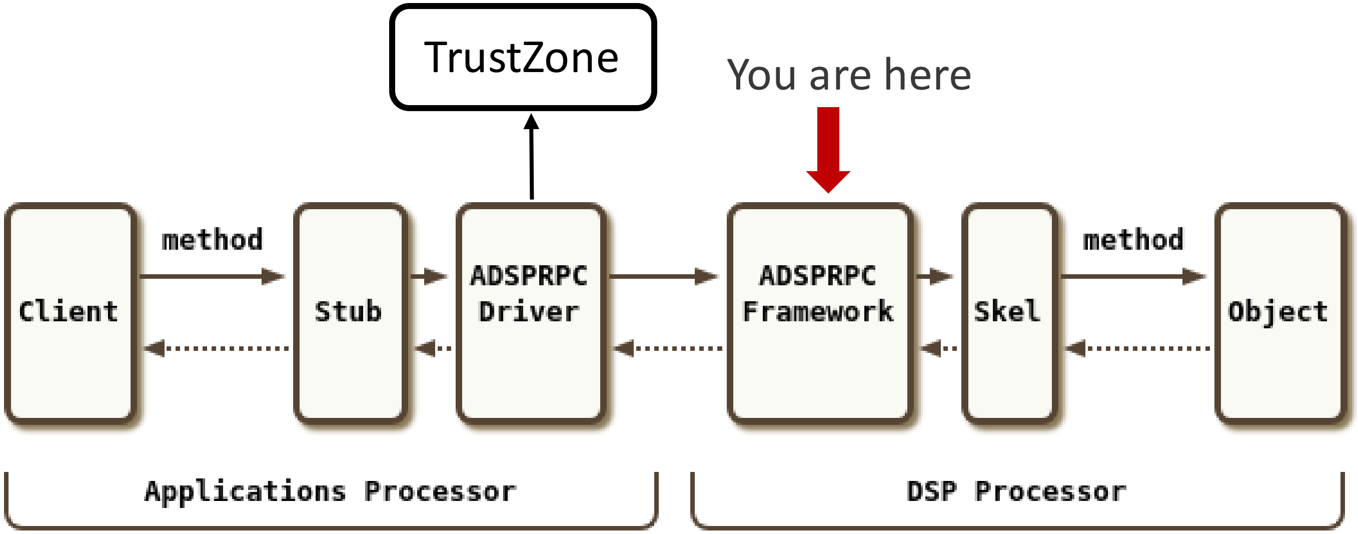
- FASTRPC_IOCTL_INVOKE
  - Maps remote_args to Hexagon
  - fastrpc_buf_alloc -> hyp_assign_phys -> hyp_assign_table
  - Calling TrustZone with an SCM call

FastRPC – TrustZone



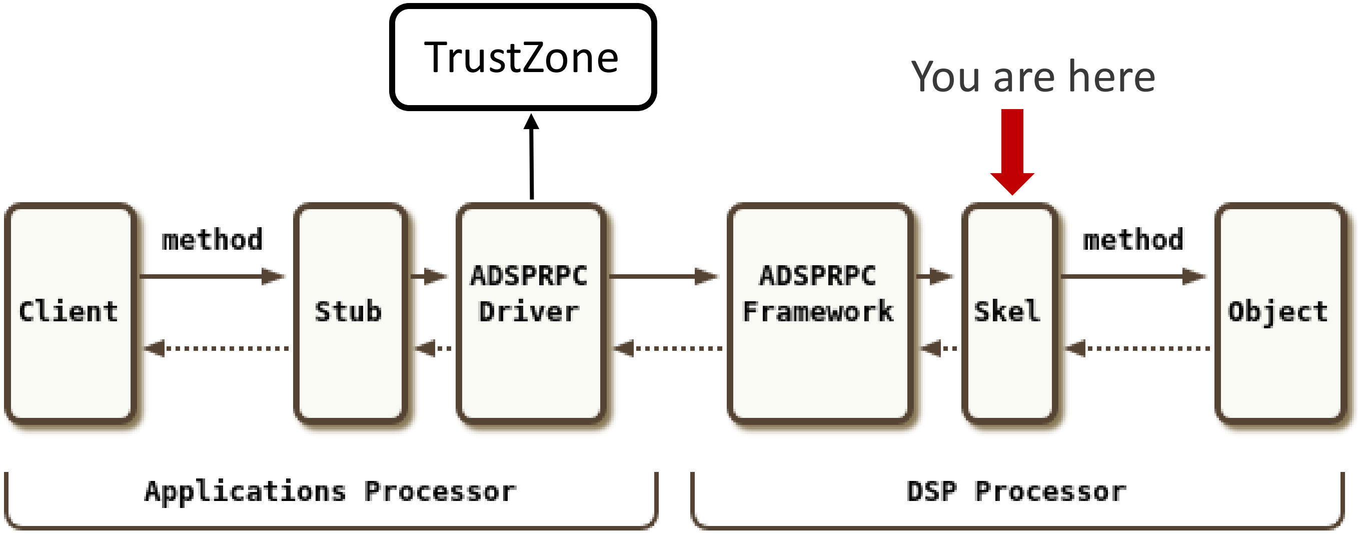
- TrustZone
- Make argument memory accessible to aDSP
- MPU/SMMU Page Table Entries

FastRPC - QuRT



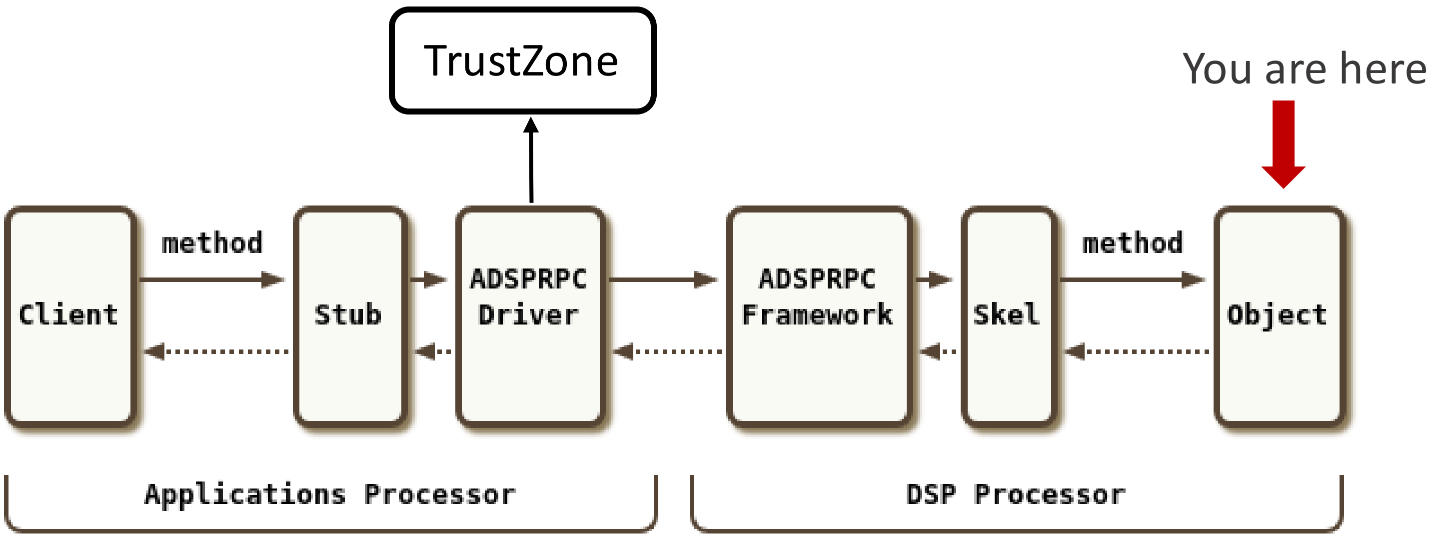
- QuRT passes execution to fastrpc_shell_0
- For the specific handle opened earlier, load skel library

FastRPC - Skel



- Skel library unmarshalls arguments
- Call actual function implementation based on method index

FastRPC - Library



- Skel library unmarshalls arguments
- Call actual function implementation based on method index

▷ FastRPC – Conclusion

- Now we know how to FastRPC works
- There are still many missing pieces
  - TrustZone maping memory to aDSP
  - How QuRT delegates execution to libraries
  - We also saw calls with handle = 3 from the libadsprpc.so library but we could also perform our tests without them

▷ Custom code on aDSP

▷ Custom code on aDSP

- Hexagon SDK
  - Based on LLVM
  - Full toolchain - Compiler, readelf, objdump, simulator!
  - Utilities
  - Documentation

Custom code on aDSP

- Put our code in remote filesystem and call it from userspace
- Remote filesystem is read-only
  - Get root and remount
- Remote libraries must be signed
  - Bypass sign check ?
  - Development board

Custom code on aDSP

- Intrinsyc Open-Q 820
  - ARM Development Board
  - MSM 8996/Snapdragon 820 (same as Pixel)
  - Exposes JTAG pins
  - Debug Fuse is enabled!

▷ Custom code on aDSP

- Debug Fuse
  - TrustZone
  - Enables execution of custom libraries on aDSP
- Create testsig.so and upload to remote filesystem
  - Generated by Hexagon SDK utilities
  - Needs device serial number
- And we can run our code on the development board

Calculator Example

- Example code provided in Hexagon SDK
- Calculations performed on aDSP
- Python build script and custom makefiles
- Autogenerated stub/skel libraries

▷ Modified Example

```
int calculator_sum(int* vec, int vecLen, int64_t* out)
{
  *out = (int64_t)out;
  return 0;
}
```

```
msm8996:/vendor/bin # ./calculator

- starting calculator test
- ret = 55cf38
```

- We modify original calculator example
- We see aDSP's virtual address of 'out'

▷ Hardware Debugging

- Lauterbach32
  - Hardware Debugging
  - A few tens of thousands of $
- OpenOCD and something like a Bus Blaster ?
  - No luck in my tests, but I am not the hardware type
  - There are some Lauterbach32 scripts that should be useful for bus offsets etc

Software Debugging

- Hexagon SDK says debugging is supported on MSM8998 development boards
  - Not tested since I had MSM8996
- Qualcomm DIAG interface
  - Also used in baseband and Wi-Fi research
- Inject our own debugger in aDSP similar to "Exploring Qualcomm Baseband via ModKit" presentation

▷ Attack Surface

Attack Surface

- Android Apps
  - stub libraries (marshalling)
- Kernel Driver
- aDSP
  - skel libraries (unmarshalling)
  - Implementation libraries

Attack Surface

- Remotely, an attacker could send data that could be handled by aDSP/FastRPC code
  - Eg. Send audio/video that needs further processing
  - Browsers, messengers, etc
  - Attack on marshalling/unmarshaling libraries and implementation libraries on aDSP
- Locally, an attacker could also attack the kernel driver directly

Attack Surface

- aDSP
  - A large number of libraries are exposed to userspace
  - Audio/video decoding, numerical calculations
    - Always a red flag for exploitation
  - System functions

- Open Question: Even after successful exploitation, do we cross a security boundary ?

Attack Surface

- Exploiting a library on aDSP, we are in QuRT userspace
  - QuRT privilege escalation ?
  - TrustZone communication ?
- MPU blocks aDSP from accessing the whole memory
  - Maybe that's more than enough ?
- In newer SoCs, there are also cDSP and mDSP
  - Compute DSP, modem DSP
  - Offload work to baseband processor just like aDSP!

- Fuzzing

▷ FastCV

- Computer Vision Library by Qualcomm
- Provides ARM, GPU and Hexagon implementations
- Present on many Qualcomm Android devices

▷ FastCV

- 500+ available functions
  - Matrix multiplication
  - Hamming Distance
  - Allocate/deallocate structures
  - etc
- Available on aDSP through the "fastcvadsp" handle

FastCV

- On remote filesystem:
  - Libfastcvadsp_skel.so
    - Parameter unmarshall
  - Libfastcvadsp.so
    - Actual implementation
- Hexagon disassembler ?

Hexagon Disassemblers

- IDA Pro and Ghidra do not support Hexagon natively
- hexagon-llvm-objdump
  - Provided by Hexagon SDK
  - Does NOT work for some binaries (?)
- https://github.com/programa-stic/hexag00n
  - Some immediate operands are decoded incorrectly
  - Ask me how I know

▷ Hexagon Disassemblers

- Radare2
  - Supported in newer versions including instruction packets
- Capstone internal build
  - Not public :(
- https://github.com/gsmk/hexagon
  - Less issues than the others
  - Register pairs are "different" than separate registers

▷ Ghidra Hexagon Support

- Ghidra makes adding support for new architecture easier
- SLEIGH Processor Specification Language
- Bonus: Decompiler
- I have implemented a few opcodes but there is a long way to go

▷ Ghidra Hexagon Support

```
define token instr(32)
    iclass = (28, 31)
    Rs = (16, 20)
    Rd = (0, 4)
    s16_lo = (5, 13)
    s16_hi = (21, 27)
;

:^ Rd = "add"(Rs, s16) is iclass=0b1011 & Rs & Rd
      & s16_hi & s16_lo [ s16 = (s16_hi << 9) + s16_lo; ]
{
    Rd = Rs + s16;
}
```

- Calculate immediate value, model instruction behavior inside braces
- Caret "^" denotes that Rd is not actually an instruction mnemonic
- Question to you: how to set "add" as the mnemonic ?

▷ Ghidra Hexagon Support

```
                         undefined std_toupper()
      undefined             r0:1             <RETURN>
                         std_toupper
0007e824 e2 73 e0 bf                     r2 = add(r0,0xff9f)
```

- Verified with gmsk/hexagon, radare2
- Still a long way to go

FastCV Skel library

```
.globl fastcvadsp_skel_invoke
fastcvadsp_skel_invoke:

@ FUNCTION CHUNK AT LOAD:0001F940 SIZE 000001C4 BYTES
@ FUNCTION CHUNK AT LOAD:0001FB10 SIZE 00000218 BYTES

{ allocframe (#off_58) }

loc_1ED14:
{ immext (#0x62B80)
  r7 = add (pc, ##loc_62B94)
  r2 = r0 ; memd (sp + #off_50) = r17:16 } @ r2 = sc
{ r5 = extractu (r2, #byte_5, #byte_18) @ r5 = Method Index
  memd (sp + #dword_48) = r19:18 ; memd (sp + #dword_40) = r21:20 }
{ r6 = r1 ; memd (sp + #byte_38) = r23:22 } @ r1 = remote_args_ptr
```

- We use gmsk/hexagon plugin in IDA
- Every skel library has a skel_invoke function
- R0 = sc, R1 = remote_args pointer

▷ FastCV Skel library

```
loc_1ED44:                @ 0x810c0
  r3 = memw (r7 + ##0xFFFFF814) }
{ p0 = cmp.gtu (r5, #byte_1F)
  immext (#0xFFFFF800)
  r4 = memw (r7 + ##0xFFFFF818) } @  = 0x810c4
{ immext (#0xFFFFF800)
  r16 = memw (r7 + ##0xFFFFF81C) @ = 0x810c8
  immext (#0xFFFFF800)
  r17 = memw (r7 + ##0xFFFFF820) } @ = 0x810cc
{ if (p0) jump loc_1F880 }
```

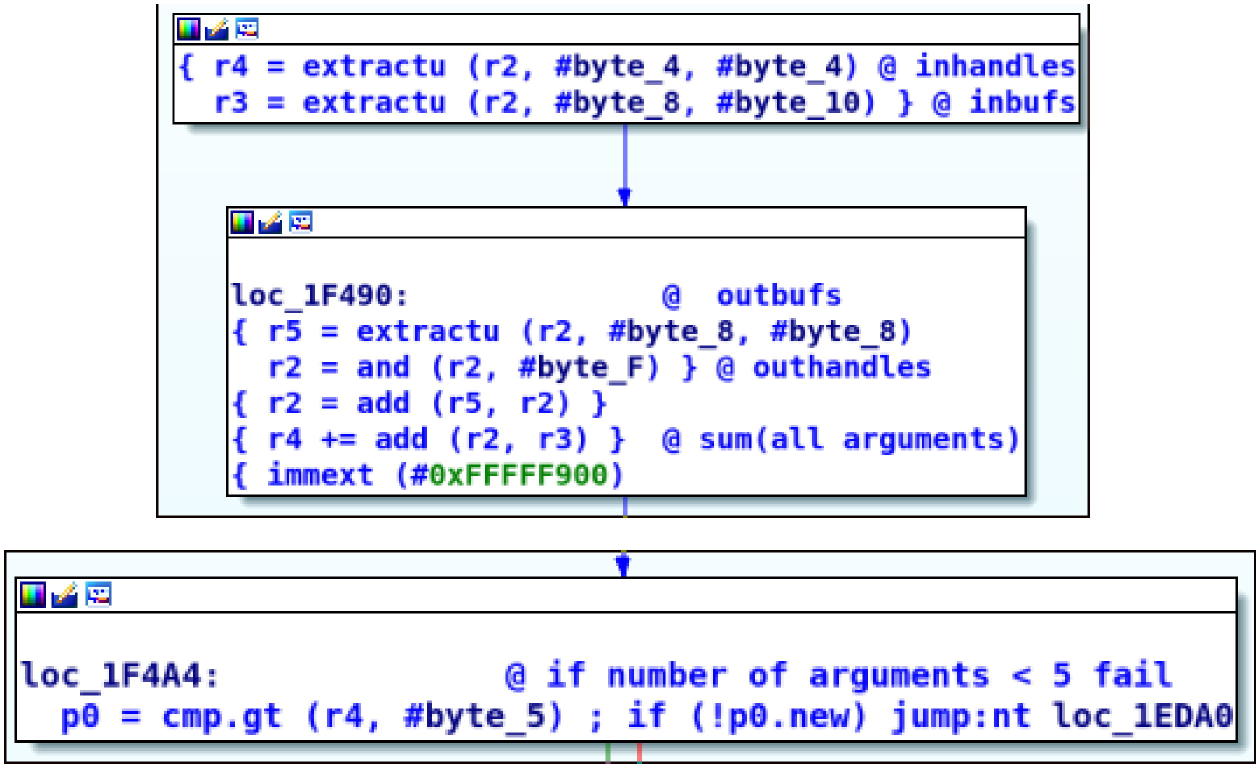
- If method index > 0x1F return

FastCV Skel library

```
{ immext (#0xB40)
  r7 = add (pc, ##byte_B50) } @ PC = 0x1f8bc

                        @ DATA XREF: fastcvadsp_fcvICPJacobianErrorSE3f32Q+1DC↓o
{ r5 = memw (r7 + r5 << #byte_2) } @ offset = *(0x1f8bc + (index << 2))
{ r5 = add (r5, r7) }
{ jumpr r5 }            @ jump (0x1f8bc + offset)
```

- Else (if method index <= 0x1F):
  - Get offset from PC + (method index << 2)
  - Add offset to PC and jump
  - Let's take offset 0xFFFFFBD0

▷ FastCV Skel library



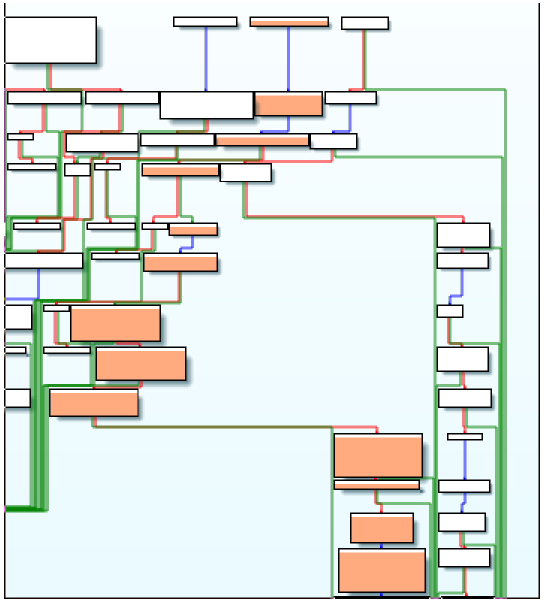
- Validate number of arguments is correct

FastCV Skel library

```
  if (p0.new) r2 = memw (r6 + #byte_4) }
{ r4 = #byte_14          @ r2 = remote_args[0].len
  if (!cmp.gtu (r4.new, r2)) jump:t loc_1F4BC }
```

- Check if length of first remote_arg > 14

▷ FastCV Skel library



- More checks for argument lengths
- Unmarshalling parameters, arithmetic shifts, etc
- A few basic blocks later ...

FastCV Skel library

```
loc_1F5A0:
  r0 = r19
  r22 = memw (r6 + r3 << #byte_3)
  r20 = memw (r6 + #byte_10) }
{ r21 = memw (r6 + #byte_8) }
{ call sub_4B240 }
{ r5:4 = combine (r18, r19)
  r3:2 = combine (r17, r20)
  r1:0 = combine (r16, r21)
  r6 = add (r29, #off_20) }
{ call fastcvadsp_fcvCrossProduct3x1f32Q
  memw (sp + #byte_0) = r23 ; memw (sp + #byte_4) = r6 }
```

- Finally call fastcvadsp_fcvCrossProduct3x1f32Q

▷ FastCV Fuzzing

- We know how to call functions on the aDSP
- We analyzed how FastCV expects arguments
- A large number of complex functions are exposed
- Let's create the simplest fuzzer ever for FastCV

FastCV Fuzzing

- Get a remote handle for FastCV
- Buffers with random data, but how many ? Method index?
  - For a sleepless night, parse FastCV header file, get expected number of argument, create a proper 'sc'
  - Reverse FastCV stub libraries and get 'sc' for each function

FastCV Fuzzing

- We don't *need* any of this
- Skel library does not complain if we send more arguments than it expects!
- Try random method index (<= 0x1F) and hope for the best

▷ FastCV Fuzzing

```
130|msm8996:/data/local/tmp # ./fastrpc-fuzz
[+] Got handle: 0xa9f0d530, ret: 0x0
[+] invoke function index: 170, sc: 0xa080800, ret: e
[+] invoke function index: 195, sc: 0x3080800, ret: 0
[+] invoke function index: 104, sc: 0x8080800, ret: e
[+] invoke function index: 185, sc: 0x19080800, ret: e
[+] invoke function index: 120, sc: 0x18080800, ret: e
[+] invoke function index: 40, sc: 0x8080800, ret: e
[+] invoke function index: 89, sc: 0x19080800, ret: e
[+] invoke function index: 4, sc: 0x4080800, ret: ffffffff
[+] invoke function index: 29, sc: 0x1d080800, ret: 27
[+] invoke function index: 99, sc: 0x3080800, ret: 27
[+] invoke function index: 71, sc: 0x7080800, ret: 27
[+] invoke function index: 152, sc: 0x18080800, ret: 27
[+] invoke function index: 105, sc: 0x9080800, ret: 27
```

- After a few calls we get –1 as return value
- Then only 0x27 ???

▷ FastCV Fuzzing

```
#define FASTRPC_ENOSUCH 39

static int fastrpc_internal_invoke(struct fastrpc_file *fl, uint32_t mode,
                                   uint32_t kernel,
                                   struct fastrpc_ioctl_invoke_fd *invokefd)
{
        ...
        if (!kernel) {
                VERIFY(err, 0 == context_restore_interrupted(fl, invokefd,
                                                              &ctx));
                if (err)
                        goto bail;
                if (fl->sctx->smmu.faults)
                        err = FASTRPC_ENOSUCH;
```

- Kernel sets up SMMU for aDSP
- Sets fault handler for SMMU
- If fault return 0x27 = 39

▷ Fuzzing

- No luck in FastCV
- Let's try for the shrouded in mystery handle #1
- No need to remote_handle_open, we can invoke this handle directly just like the kernel!

Crashes

```
[1563109.065921] Fatal error on adsp!
[1563109.068361] adsp subsystem failure reason:     :Excep  :0:Exception detected:frpck_0_0.
[1563109.083902] L-Notify: Generel: 8
[1563109.195904] Kernel panic - not syncing: subsys-restart: Resetting the SoC - adsp crashed.
```

- System reboots on our development board with Android 7
- Tested on Pixel 3 with Snapdragon 845 (SD845) does not crash with latest firmware
- Evaluation
  - Analyze QuRT
  - Find function handler for handle = 1
  - Hexagon Simulator
  - Debug

Conclusions

- aDSP is a very interesting exploitation target
- We can now fuzz libraries on aDSP
- Run our own code on aDSP for further investigation
- There is a lot of research waiting to be done here

Future Work

- Proper disassembler/decompiler
- Investigate security boundary
- Debug
- Modern SoCs offer subsystems similar to aDSP
  - Apple Neural Engine
  - Google Pixel Visual Core
  - Huawei Neural Processing Unit

▷ References

1. A Journey Into Hexagon Dissecting a Qualcomm Baseband, Seamus Burke DEF CON 26 2018
2. Exploring Qualcomm Baseband via ModKit, Tencent Blade Team, CanSecWest 2018
3. Baseband exploitation in 2013: Hexagon challenges, Ralf-Philipp Weinmann PacSec 2013

Thank you!

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