Exploiting Qualcomm WLAN And Modem Over-The-Air

- Xiling Gong, Peter Pi
- Tencent Blade Team

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About Us

Xiling Gong (@GXiling)

Senior security researcher at Tencent Blade Team.

Focus on Android Security, Qualcomm Firmware Security.

Speaker of BlackHat, CanSecWest.

Peter Pi(@tencent_blade)

Senior security researcher at Tencent Blade Team.

Find many vulnerabilities of vendors like Google, Microsoft, Apple, Qualcomm, Adobe and Tesla.

The #1 Researcher of Google Android VRP in year 2016.

Speaker of BlackHat, CanSecWest, HITB, GSEC and Hitcon.

About Tencent Blade Team

- Founded by Tencent Security Platform Department in 2017
- Focus on security research in the areas of AIoT, Mobile devices, Cloud virtualization, Blockchain, etc
- Report 200+ vulnerabilities to vendors such as Google, Apple, Microsoft, Amazon
- We talked about how to break Amazon Echo at DEFCON26
- Blog: https://blade.tencent.com

Agenda

- Introduction and Related Work
- The Debugger
- Reverse Engineering and Attack Surface
- Vulnerability and Exploitation
- Escaping into Modem
- Escaping into Kernel
- Stability of Exploitation
- Conclusions

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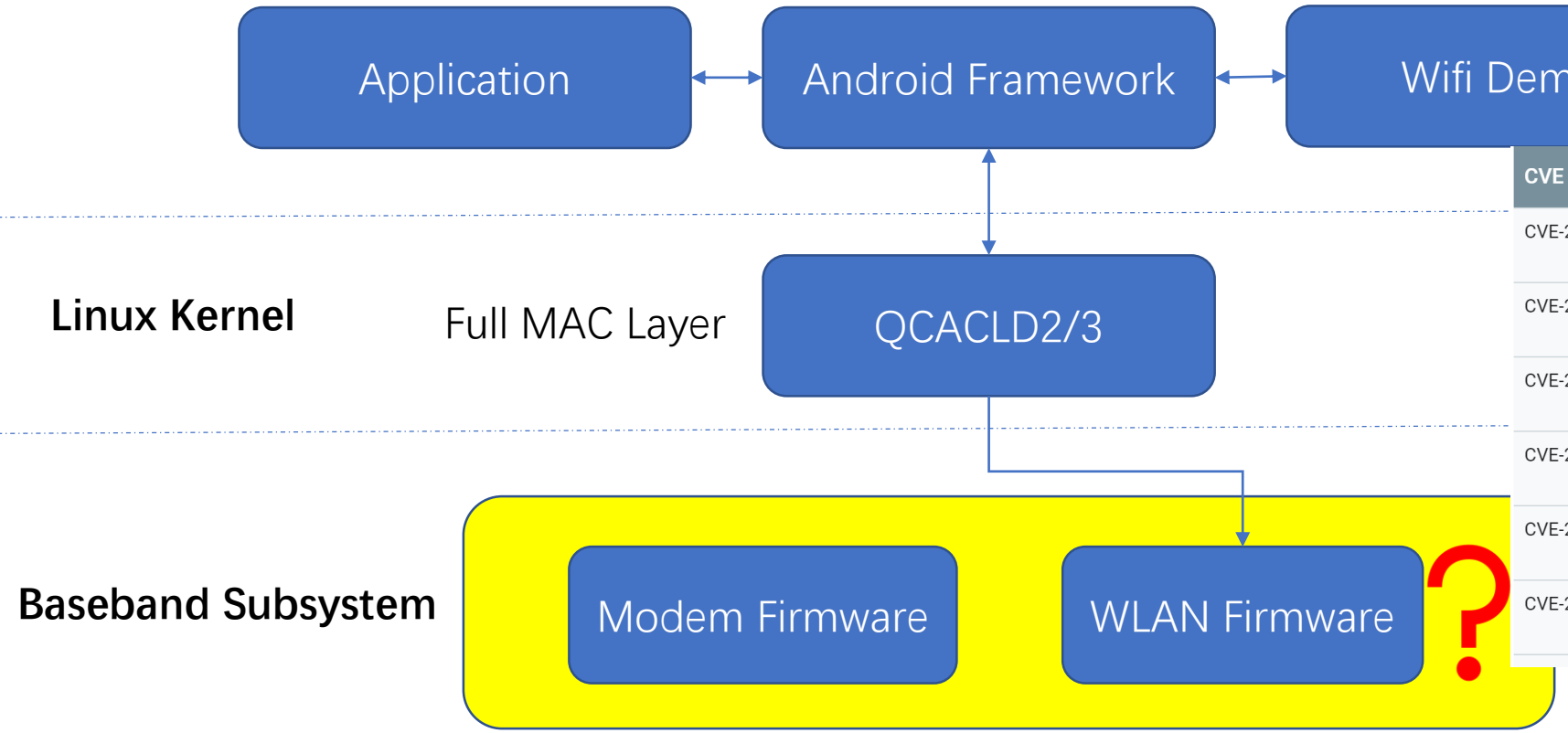
Introduction

- Broadcom WIFI Chip
  - 2017, Gal Beniamini
    - Over The Air: Exploiting Broadcom’s Wi-Fi Stack
  - 2017, Nitay Artenstein, BlackHat USA 2017
    - BROADPWN: REMOTELY COMPROMISING ANDROID AND IOS VIA A BUG IN BROADCOM'S WI-FI CHIPSETS
- Marvel WIFI Chip
  - 2019, Denis Selyanin
    - Zero Nights 2018 , Researching Marvell Avastar Wi-Fi: from zero knowledge to over-the-air zero-touch RCE
    - Blog 2019, Remotely compromise devices by using bugs in Marvell Avastar Wi-Fi: from zero knowledge to zero-click RCE
- **How about Qualcomm WIFI?**

Qualcomm WLAN (MSM8998)



CVE	References	Type	Severity	Component
CVE-2018-11940	A-79377832 QC-CR#2254946	N/A	Critical	WLAN HOST
CVE-2017-17772	A-72957385 QC-CR#2153003 [2]	N/A	High	WLAN HOST
CVE-2018-11294	A-109741680 QC-CR#2197481	N/A	High	WLAN HOST
CVE-2018-5855	A-77527719 QC-CR#2193421	N/A	High	WLAN HOST
CVE-2018-11299	A-109741946 QC-CR#2186953	N/A	High	WLAN HOST
CVE-2018-11826	A-111127853 QC-CR#2205957	N/A	High	WLAN HOST

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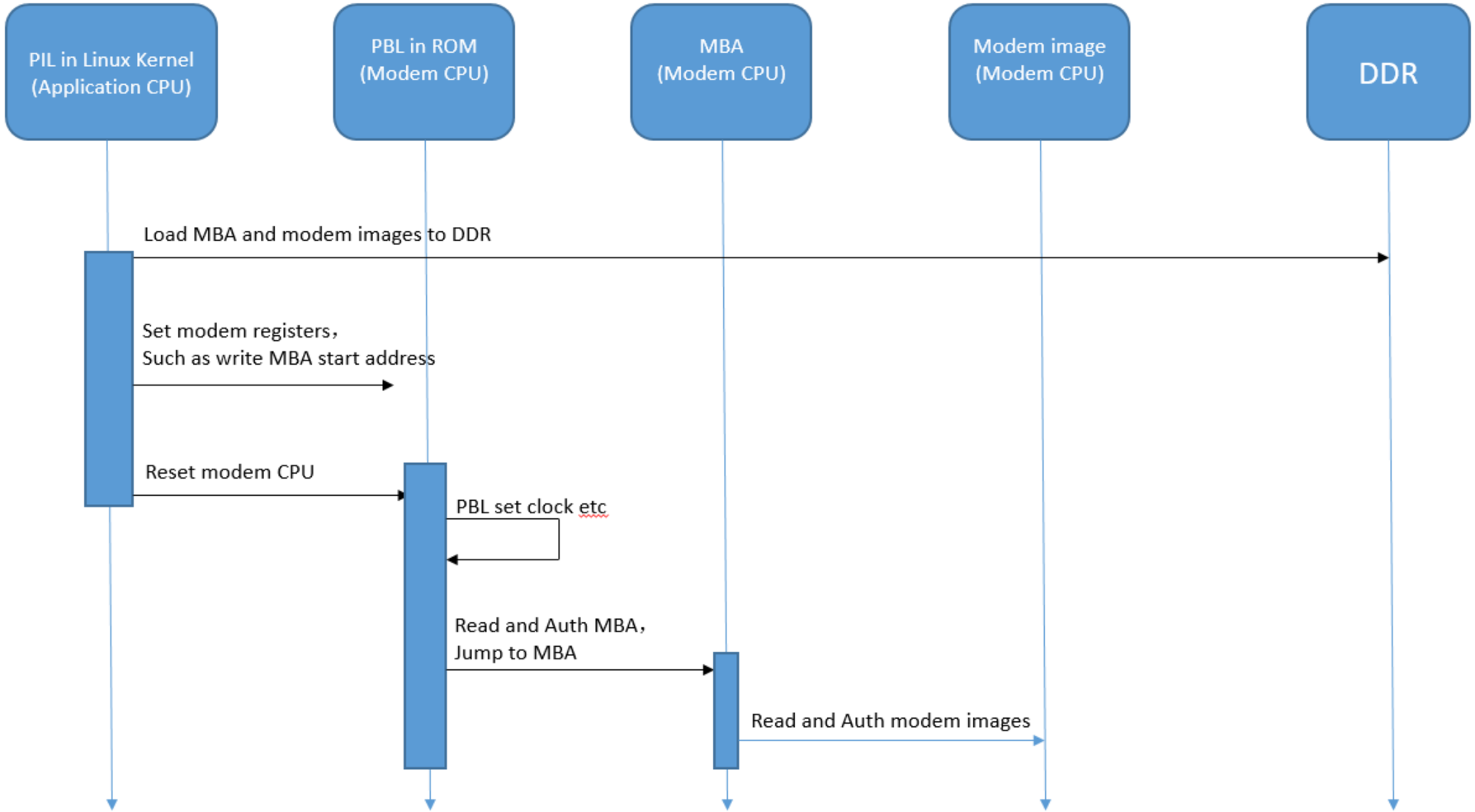
MBA and Modem images

- Modem Boot Authenticator
- mba.mbn
- modem.mdt
- modem.b00 – modem.b20
- Image format

```
sailfish:/firmware/radio $ ls -l
total 55824
-r--r----- 1 system root      244 1980-01-01 00:00 mba.b00
-r--r----- 1 system root     4584 1980-01-01 00:00 mba.b01
-r--r----- 1 system root   154064 1980-01-01 00:00 mba.b02
-r--r----- 1 system root    10144 1980-01-01 00:00 mba.b03
-r--r----- 1 system root    31588 1980-01-01 00:00 mba.b04
-r--r----- 1 system root      896 1980-01-01 00:00 mba.b05
-r--r----- 1 system root   213888 1980-01-01 08:00 mba.mbn
-r--r----- 1 system root     4828 1980-01-01 00:00 mba.mdt
-r--r----- 1 system root      884 1980-01-01 00:00 modem.b00
-r--r----- 1 system root     5224 1980-01-01 00:00 modem.b01
-r--r----- 1 system root     5460 1980-01-01 08:00 modem.b02
-r--r----- 1 system root   196608 1980-01-01 08:00 modem.b03
-r--r----- 1 system root  2816788 1980-01-01 08:00 modem.b04
-r--r----- 1 system root  3288155 1980-01-01 08:00 modem.b05
-r--r----- 1 system root   163280 1980-01-01 08:00 modem.b06
-r--r----- 1 system root   735936 1980-01-01 08:00 modem.b07
-r--r----- 1 system root  2081092 1980-01-01 08:00 modem.b08
-r--r----- 1 system root 15348816 1980-01-01 08:00 modem.b09
-r--r----- 1 system root   343648 1980-01-01 08:00 modem.b10
-r--r----- 1 system root   488448 1980-01-01 08:00 modem.b11
-r--r----- 1 system root 11529496 1980-01-01 08:00 modem.b12
-r--r----- 1 system root  7234272 1980-01-01 08:00 modem.b13
-r--r----- 1 system root    82368 1980-01-01 08:00 modem.b15
-r--r----- 1 system root   529821 1980-01-01 08:00 modem.b16
-r--r----- 1 system root  9789440 1980-01-01 08:00 modem.b17
-r--r----- 1 system root    77824 1980-01-01 08:00 modem.b18
-r--r----- 1 system root  1323008 1980-01-01 08:00 modem.b19
-r--r----- 1 system root   406932 1980-01-01 08:00 modem.b20
-r--r----- 1 system root     6108 1980-01-01 08:00 modem.mdt
dr-xr-x--- 4 system root    16384 2011-07-06 01:30 modem_pr
-r--r----- 1 system root      472 1980-01-01 00:00 qdsp6m.qdb
-r--r----- 1 system root       27 1980-01-01 00:00 radiover.cfg
-r--r----- 1 system root       27 1980-01-01 00:00 version.cfg
sailfish:/firmware/radio $
```

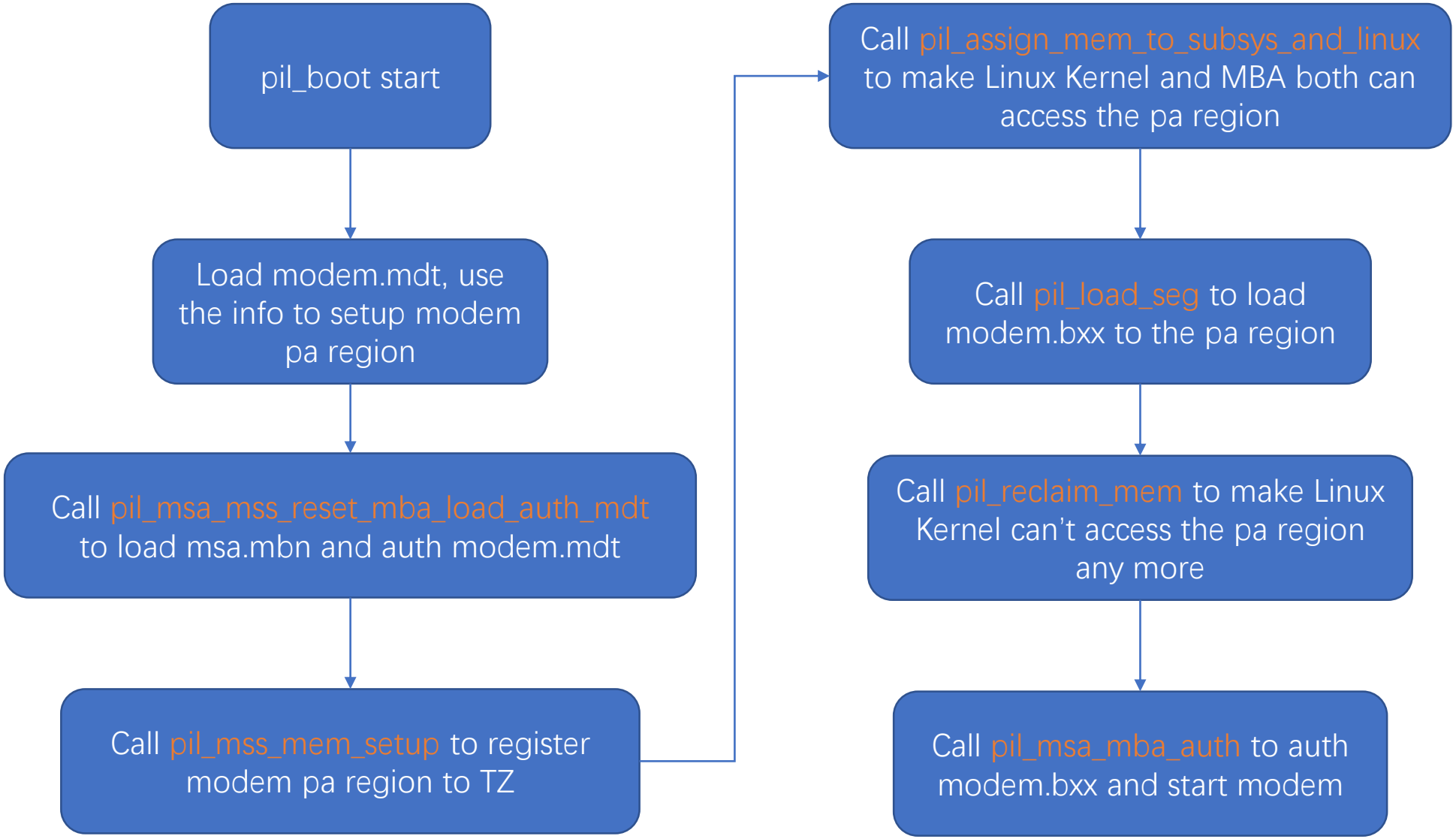
Modem Secure Boot



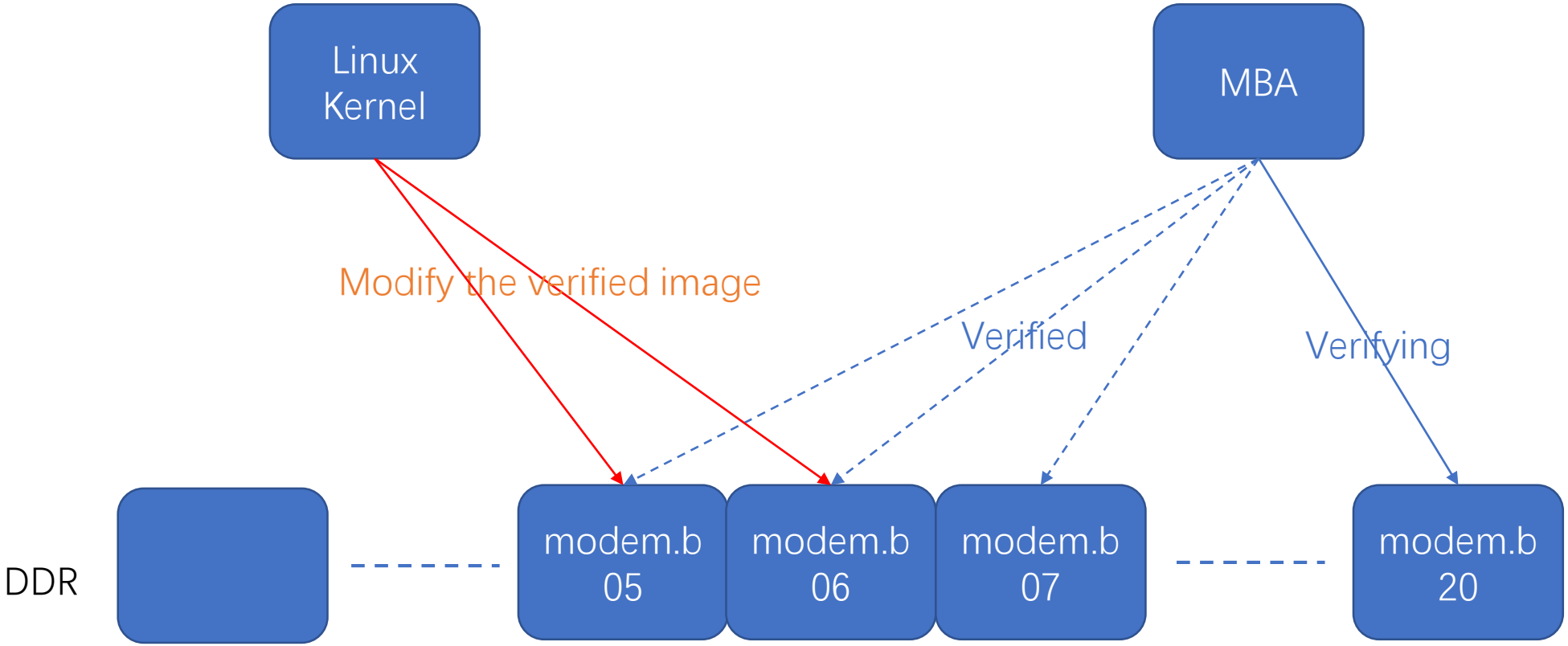
pil_boot

- The pil_boot function in Linux Kernel describes the boot flow of modem.
- Load mba.mbn, modem.mdt and modem.bxx to physical memory.
- Trigger MBA and modem images to be verified and run in Modem Processor.
- Linux Kernel can restart Modem Processor at any time, will hit pil_boot each time when restart.

pil_boot


pil_boot start
Load modem.mdt, use the info to setup modem pa region
Call pil_msa_mss_reset_mba_load_auth_mdt to load msa.mbn and auth modem.mdt
Call pil_mss_mem_setup to register modem pa region to TZ
Call pil_assign_mem_to_subsys_and_linux to make Linux Kernel and MBA both can access the pa region
Call pil_load_seg to load modem.bxx to the pa region
Call pil_reclaim_mem to make Linux Kernel can't access the pa region any more
Call pil_msa_mba_auth to auth modem.bxx and start modem

TOCTOU Vulnerability

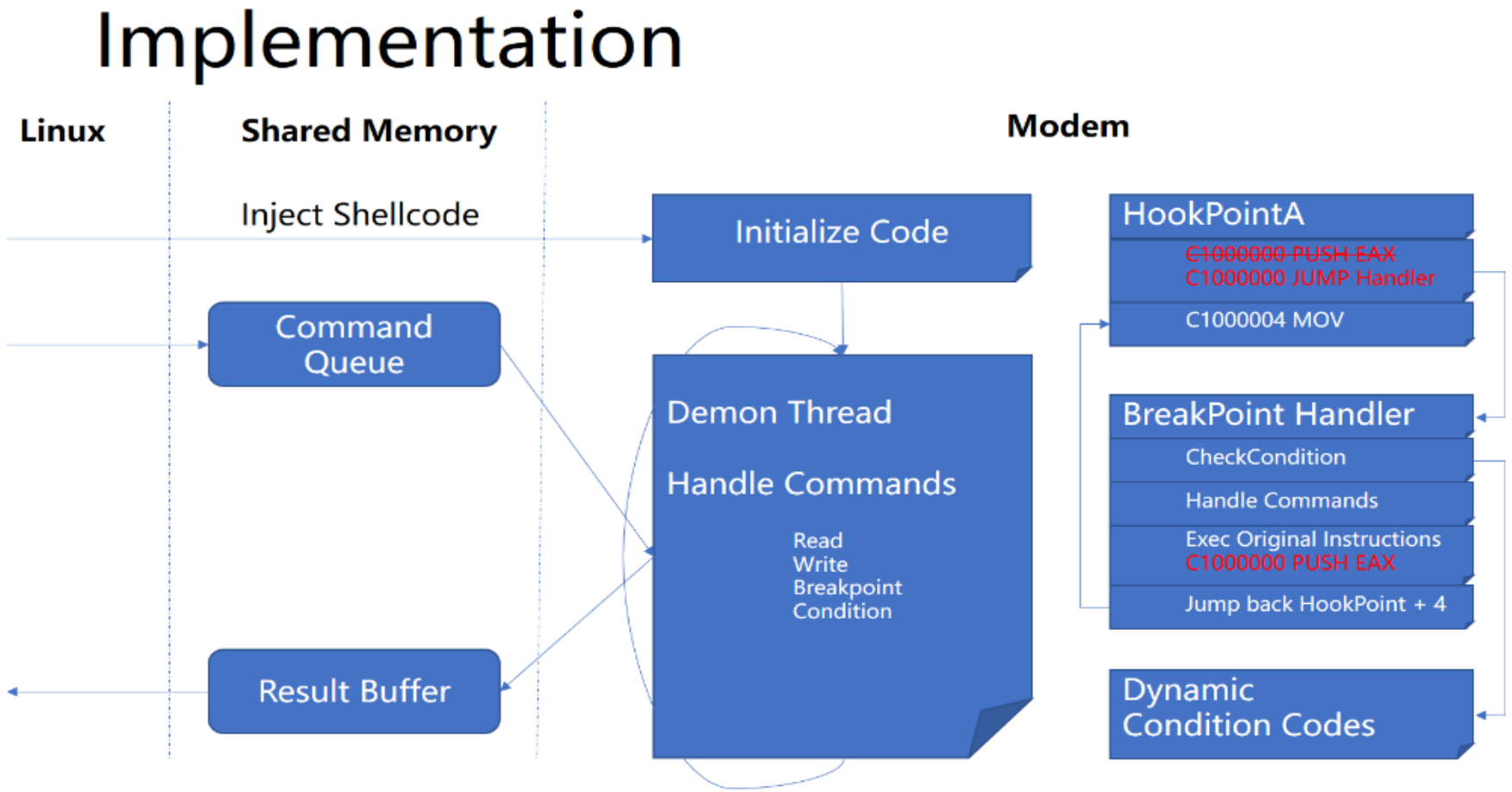


POC

```
@@ -840,24 +868,33 @@ int pil_boot(struct pil_desc *desc)
            goto err_deinit_image;
    }

-   if (desc->subsys_vmid > 0) {
-       ret =  pil_reclaim_mem(desc, priv->region_start,
-               (priv->region_end - priv->region_start),
-               desc->subsys_vmid);
-       if (ret) {
-           pil_err(desc, "Failed to assign %s memory, ret - %d\n",
-                           desc->name, ret);
-           goto err_deinit_image;
-       }
-       hyp_assign = false;
-   }
-
    ret = desc->ops->auth_and_reset(desc);
    if (ret) {
        pil_err(desc, "Failed to bring out of reset\n");
        goto err_auth_and_reset;
    }
    pil_info(desc, "Brought out of reset\n");
+
+   if (modem_dbg_cfg) {  // just a switch can be set in userspace to enable our test
+       list_for_each_entry(seg, &desc->priv->segs, list) {
+           pil_modify_seg(desc, seg); // self defined function to modify segments
+       }
+   }
+
+   if (modem_dbg_cfg == 0) {
+       if (desc->subsys_vmid > 0) {
+           ret =  pil_reclaim_mem(desc, priv->region_start,
+                   (priv->region_end - priv->region_start),
+                   desc->subsys_vmid);
+           if (ret) {
+               pil_err(desc, "Failed to assign %s memory, ret - %d\n",
+                           desc->name, ret);
+               goto err_deinit_image;
+           }
+           hyp_assign = false;
+       }
+   }
```

Debug Server Injection



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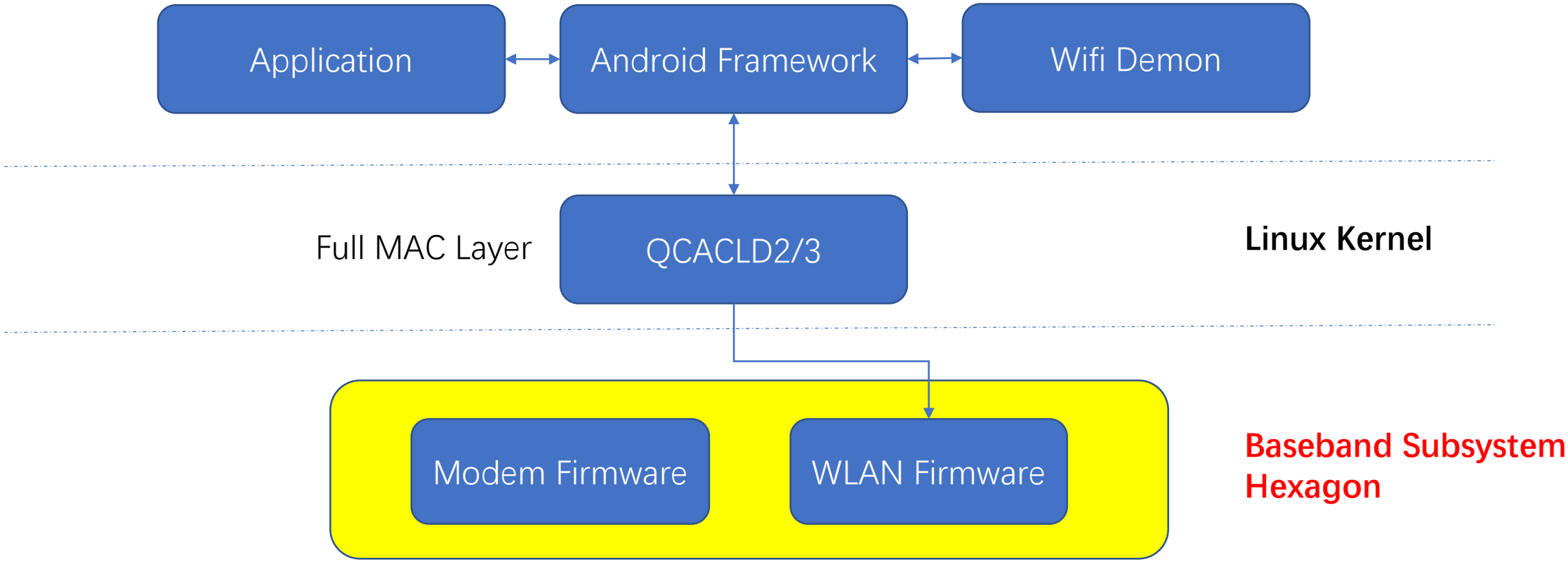
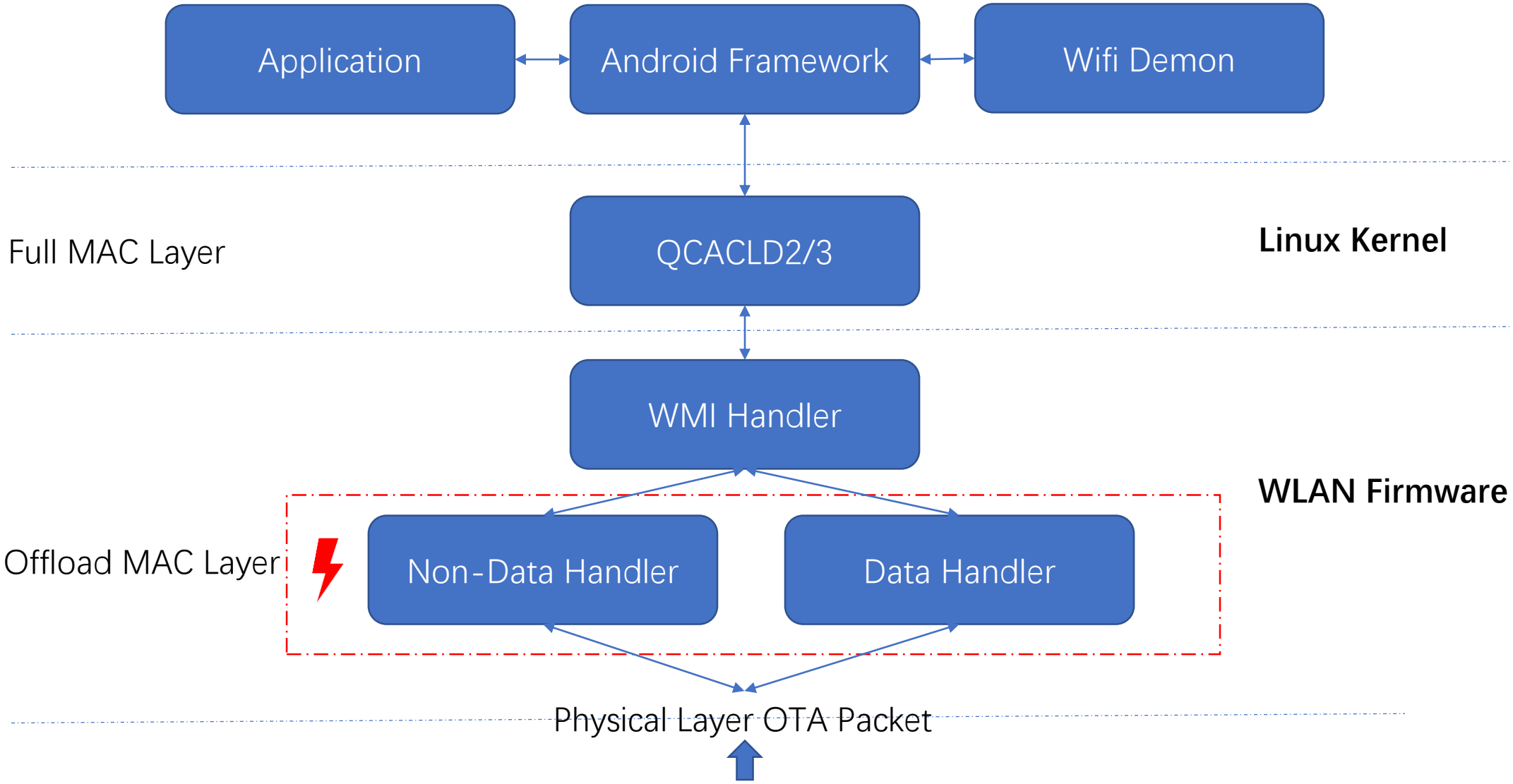
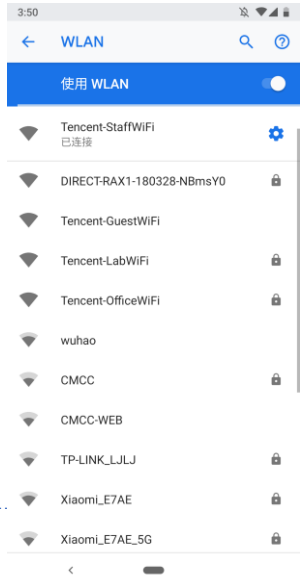
Qualcomm WLAN

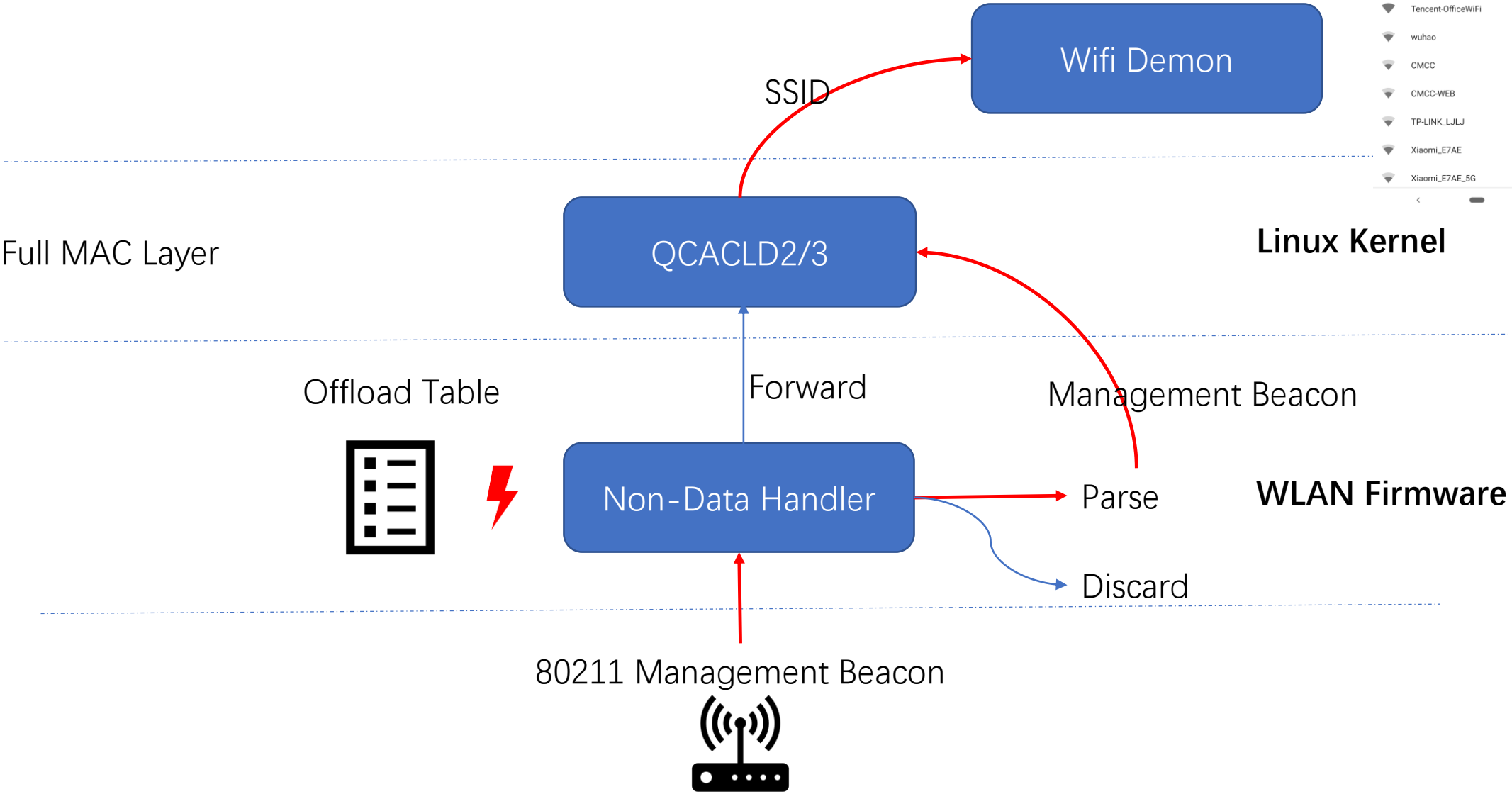


Qualcomm WLAN Architecture



Example - Management Beacon





Firmware

- Modem load WLAN Firmware from
  /vendor/firmware/wlanmdsp.mbn
- IDA Disassembler
  - https://github.com/programa-stic/hexag00n/tree/master/ida
  - https://github.com/gsmk/hexagon
- Qualcomm SDK
  - https://developer.qualcomm.com/software/hexagon-dsp-sdk/tools
- Instruction Reference
  - https://developer.qualcomm.com/download/hexagon/hexagon-v5x-programmers-reference-manual.pdf?referrer=node/6116

Reverse Engineering – Hint From Qualcomm

String Table

Strings window | IDA View-A

Address	Length	Type	String
LOAD:B0287...	00000023	C	wlan pdev host configured oui init
LOAD:B0287...	0000001D	C	validate oui cmd buff length
LOAD:B0287...	0000001E	C	wlan config vendor oui action
LOAD:B0287...	00000014	C	wlan pdev set param
LOAD:B0287...	0000000F	C	wmi fips event
LOAD:B0287...	00000028	C	wlan vdev get active vdev count per mac
LOAD:B0287...	00000027	C	wlan pdev get hw mode transition event
LOAD:B0287...	00000017	C	dispatch wlan init cmd
LOAD:B0287...	00000014	C	memstats timer func
LOAD:B0287...	00000018	C	dispatch wlan pdev cmds
LOAD:B0287...	0000001A	C	wlan pdev resume send evt

Import Function

- qurt exception raise nonfatal
- msg v2 send 2
- msg v2 send 3
- MMPM Init Ext
- DALSYS Init
- Diag LSM Init
- dog hb task
- dog hb init
- msg v2 send var
- hexagon udivsi3

WMI Handler

drivers/staging/fw-api-fw/wmi_unified.h

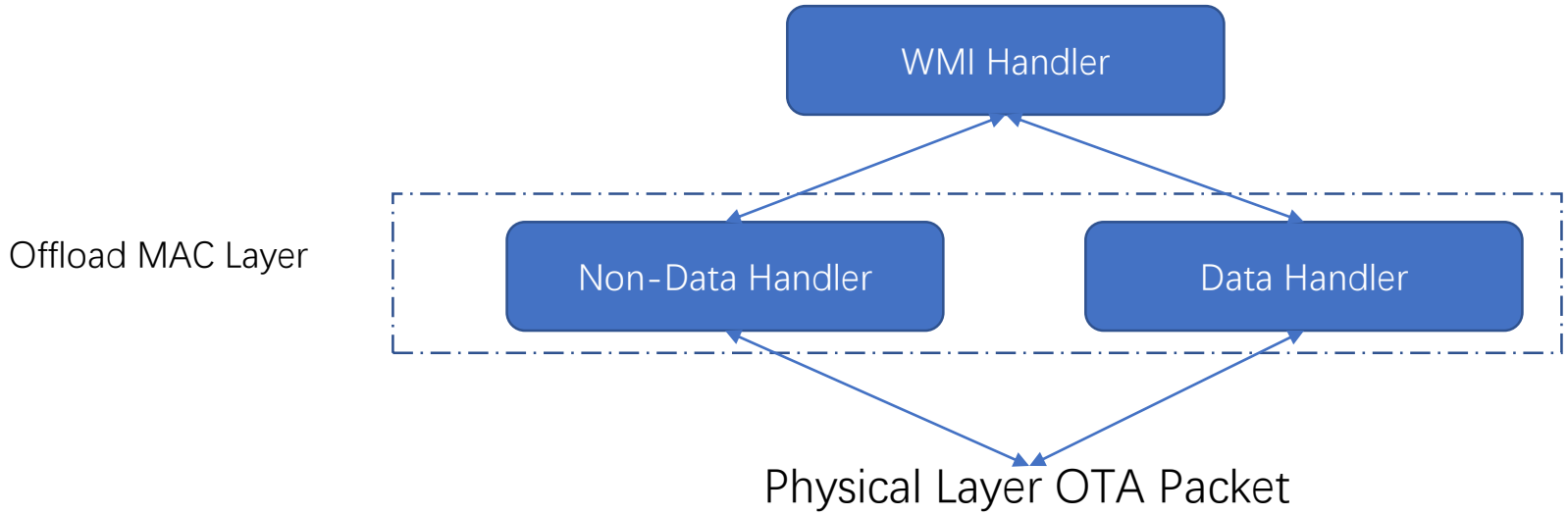
```
/**
 * Command IDs and commange events
 */
typedef enum {
    /** initialize the wlan sub system */
    WMI_INIT_CMDID = 0x1,

    /* Scan specific commands */

    /** start scan request to FW  */
    WMI_START_SCAN_CMDID = WMI_CMD_GRP_START_ID(WMI_GRP_SCAN),
    /** stop scan request to FW  */
    WMI_STOP_SCAN_CMDID,
    /** full list of channels as defined by the regulatory that will be used by scanner
    WMI_SCAN_CHAN_LIST_CMDID,
    /** overwrite default priority table in scan scheduler   */
    WMI_SCAN_SCH_PRIO_TBL_CMDID,
    /** This command to adjust the priority and min.max_rest_time
     * of an on ongoing scan request.
     */
    WMI_SCAN_UPDATE_REQUEST_CMDID,
```

Reverse Engineering

- Targets To Reverse
  - WMI Handlers
    - Handle WMI commands from Linux Kernel
    - Send back WMI indication to Linux Kernel
  - Offload Handlers
    - Handle OTA Packets



WMI Handlers

drivers/staging/fw-api-fw/wmi_unified.h

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    /** overwrite default priority table in scan scheduler   */
    WMI_SCAN_SCH_PRIO_TBL_CMDID,
    /** This command to adjust the priority and min.max_rest_time
     * of an on ongoing scan request.
     */
    WMI_SCAN_UPDATE_REQUEST_CMDID,
```

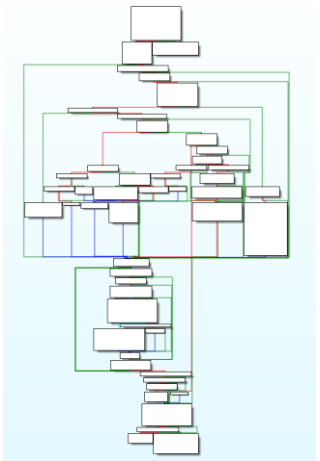
0x03001

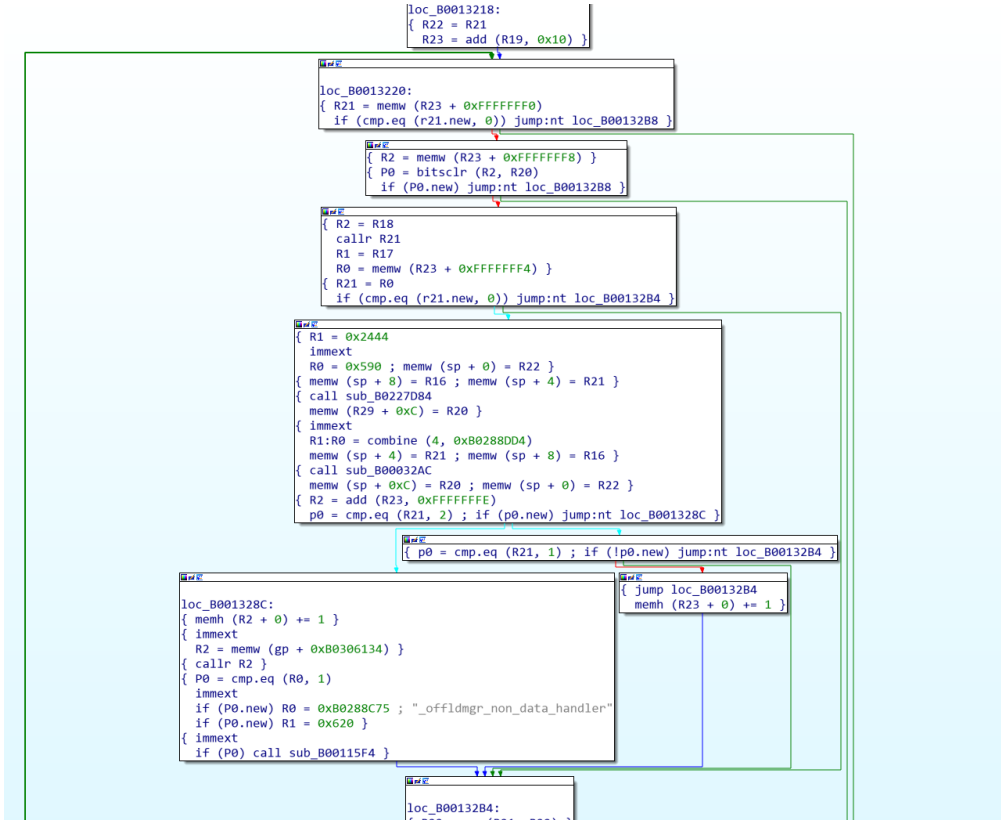
```
LOAD:B0301D00 F4 69 02 B0          dd sub_B00269F4
LOAD:B0301D04 01 30                dw 0x3001
LOAD:B0301D06 00 00 00 00          dd 0
```

Offload Handlers

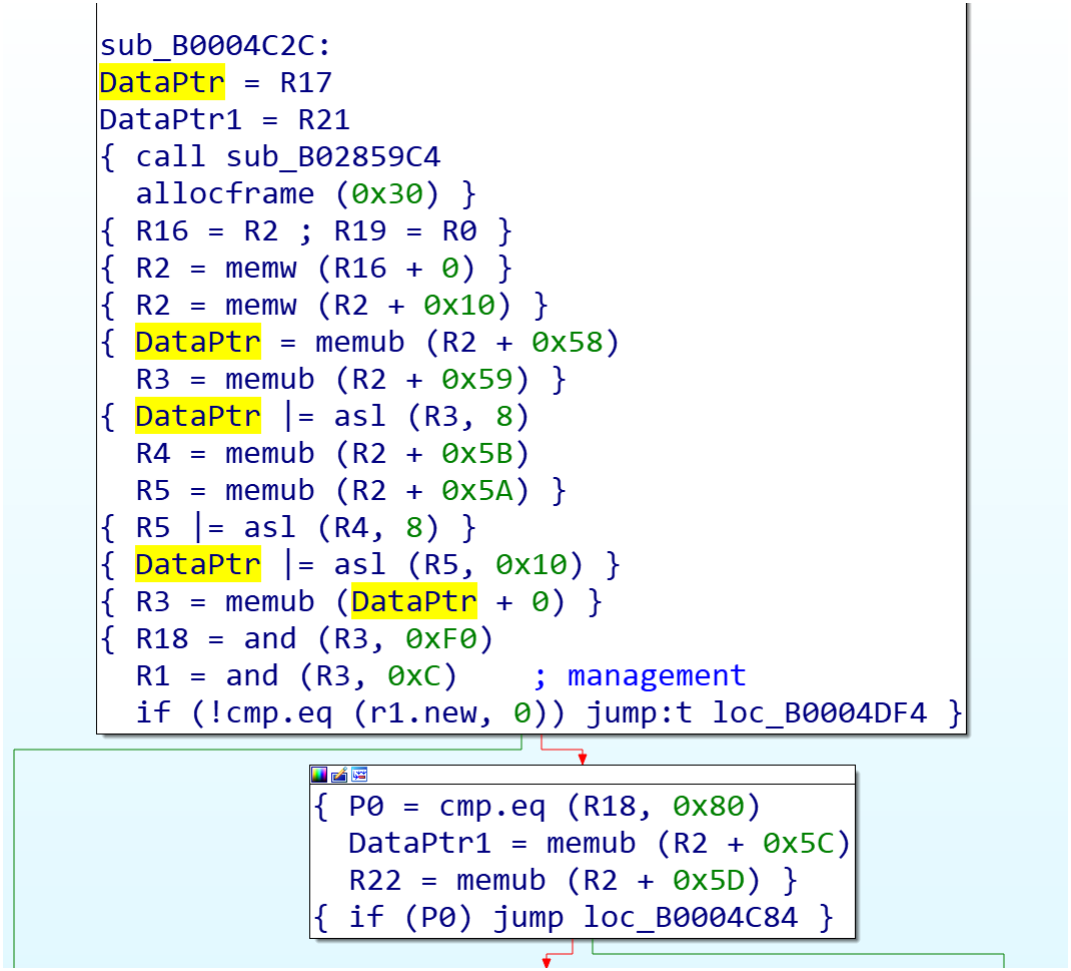
LOAD:B0288...	00000020	C	offldmgr protocol data handler
LOAD:B0288...	0000001B	C	offldmgr non data handler

```
LOAD:B0288C55 5F 6F 66 66+a_offldmgr_prot:db "_offldmgr_protocol_data_handler"
LOAD:B0288C55 6C 64 6D 67+                ; DATA XREF: _offldmgr_protocol_data_handler+B0↑r
LOAD:B0288C55 72 5F 70 72+                db 0
LOAD:B0288C75 5F 6F 66 66+a_offldmgr_non_:db "_offldmgr_non_data_handler"
LOAD:B0288C75 6C 64 6D 67+                ; DATA XREF: _offldmgr_non_data_handler+32C↑r
LOAD:B0288C75 72 5F 6E 6F+                ; _offldmgr_non_data_handler+3C8↑r
LOAD:B0288C75 6E 5F 64 61+                db 0
```





Sample Offload Handler



OTA Packet Data Pointer
=
[0x5B | 0x5A | 0x59 | 0x58]

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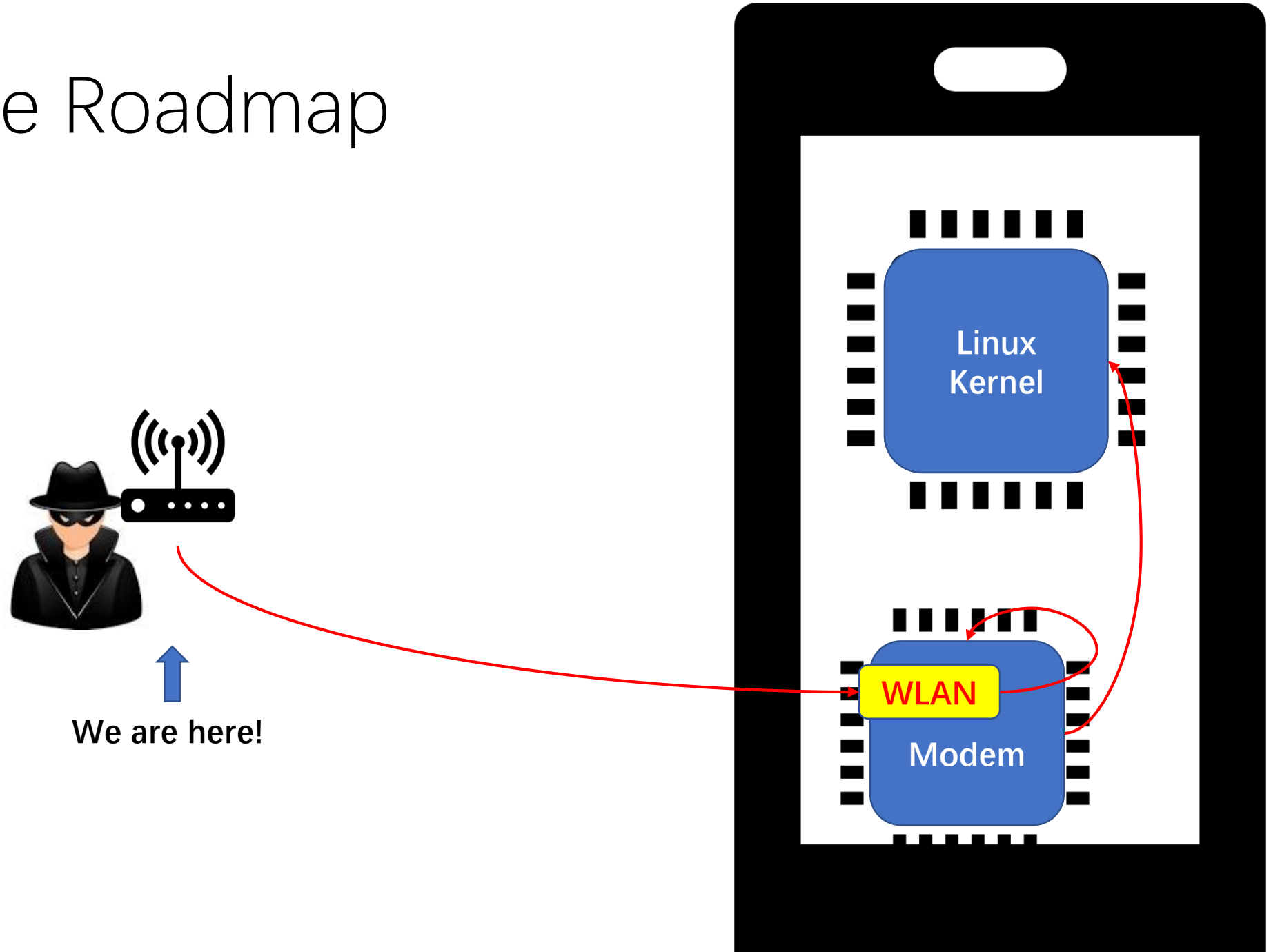
The Roadmap

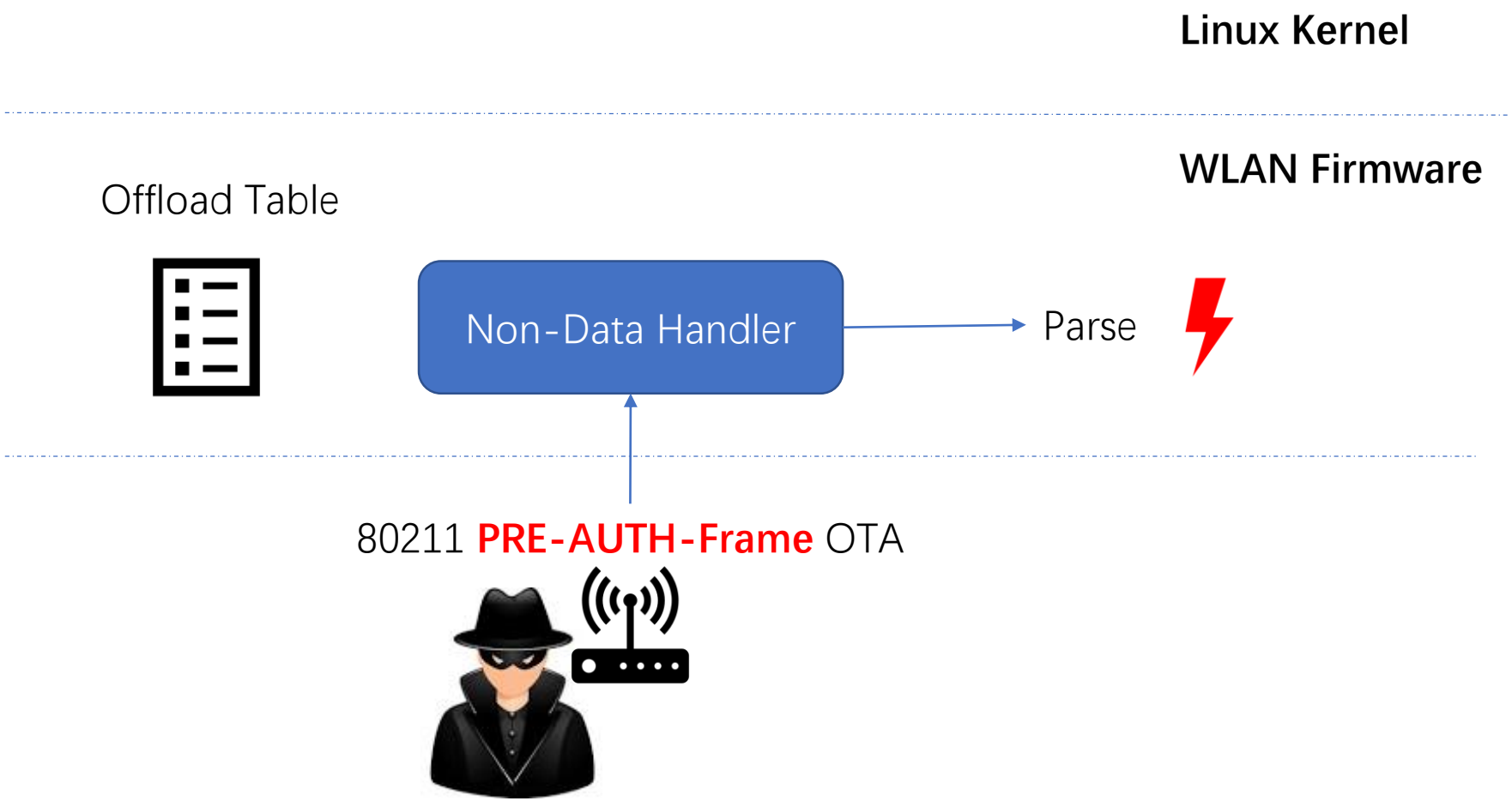


Mitigation Table (WLAN & Modem)

Mitigation	Status
Heap ASLR	Y
Heap Cookie	Y
Stack Cookie	Y
W^X	Y
FRAMELIMIT*	Y
FRAMEKEY**	Y
Code & Global Data ASLR	N
CFI	N

***FRAMELIMIT Register -** if SP < FRAMELIMIT throw exception
****FRAMEKEY Register -** Return Address XOR FRAMEKEY. A random integer different for every thread

The Vulnerability (CVE-2019-10540)



The Vulnerability (CVE-2019-10540)

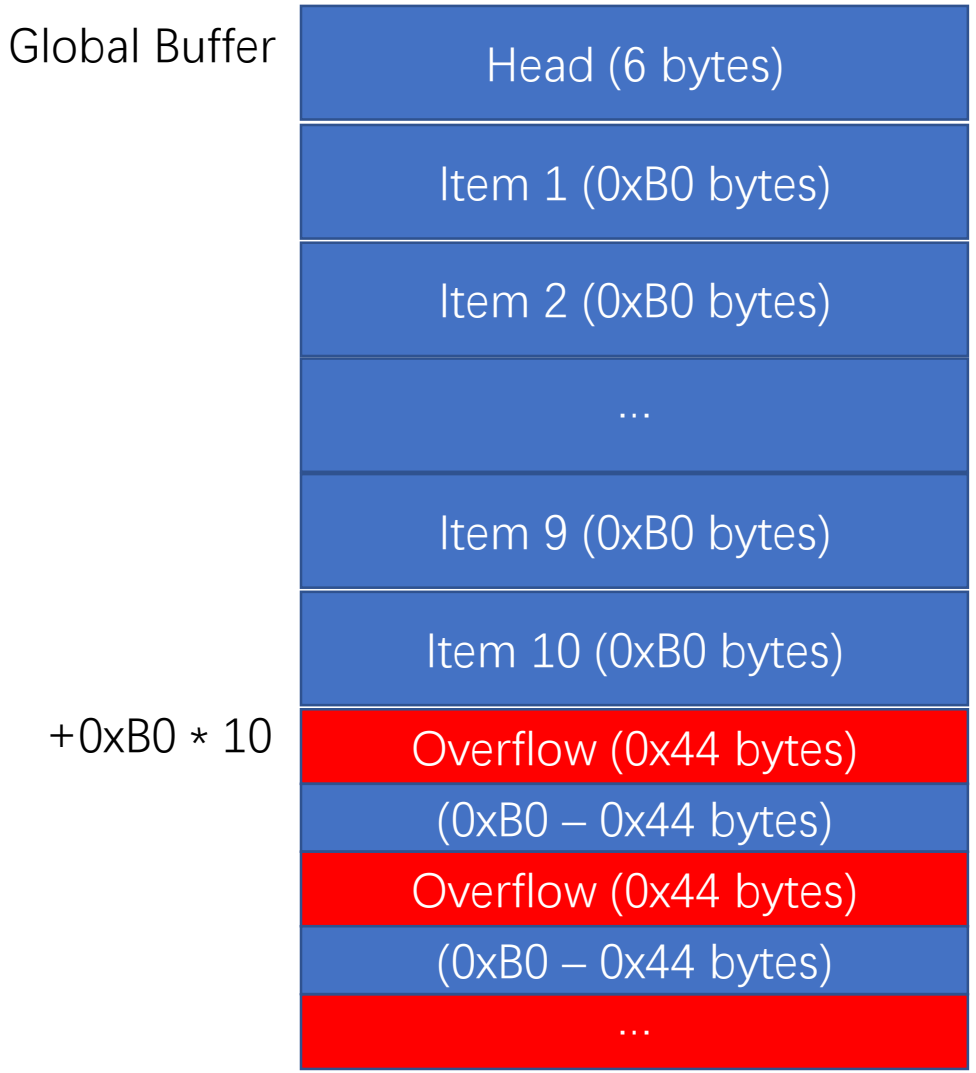
Copy items from packet into Global Static Buffer.
Max Item Count = 10
Send 11 items -> Overflow!

```
[GLOBAL] char *GlobalBuffer[10 * 0xB0 + 6];

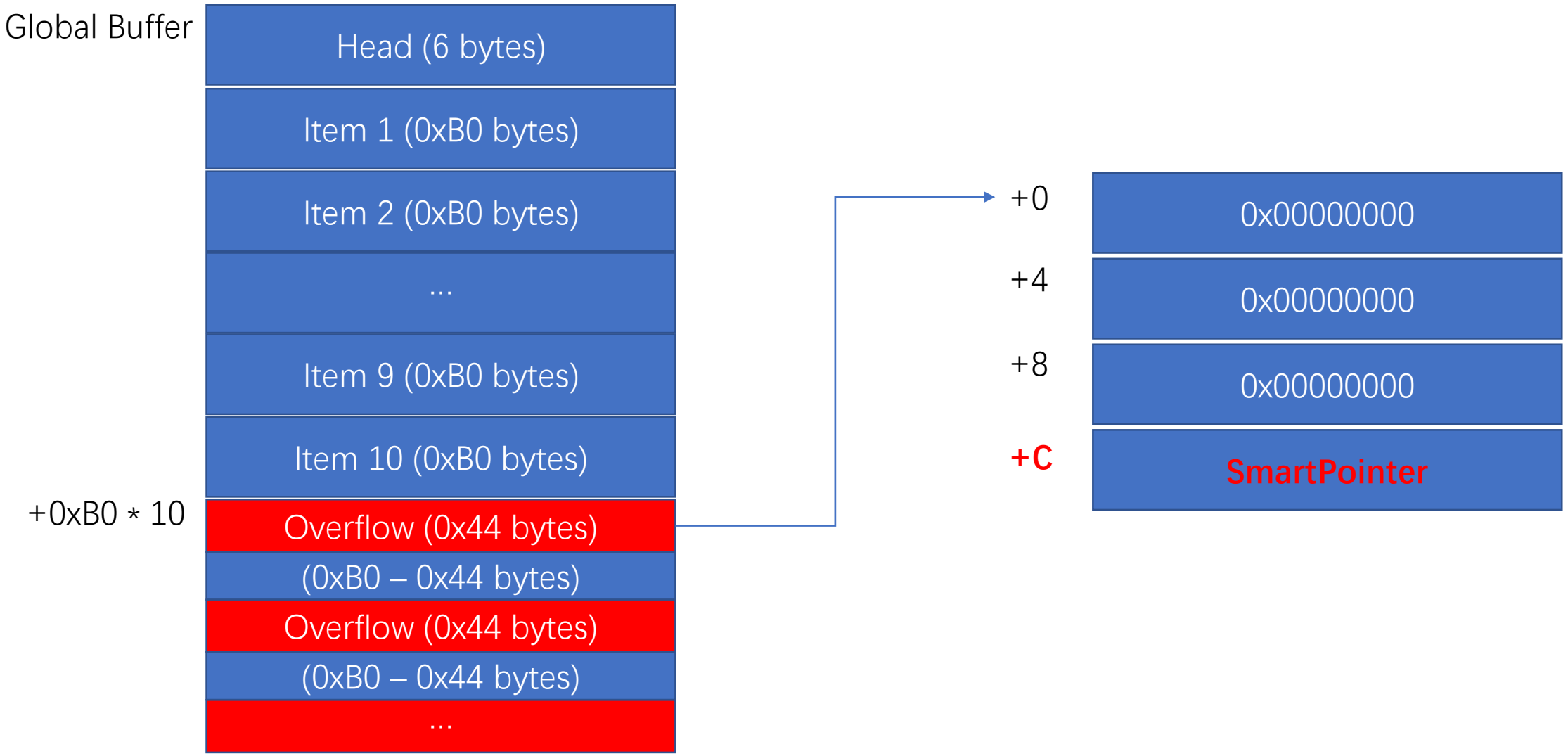
unsigned int itemCount = 0;
for (unsigned int i = 0; i < Length; i += 0x44) {
        memcpy (GlobalBuffer + 6 + itemCount * 0xB0,
                OTA_DataPtr + i,
                0x44);
        itemCount++;
}
```

* Translated and simplified the code flow

Data & Address of Overflow



Smart Pointer Around Overflow Memory



Usage Of Smart Pointer

```
Char **AddressOfSmartPointer = GlobalBuffer + 6 + 0xB0 * 11 + 0xC;
char *SmartPointer = *AddressOfSmartPointer;
char *MacAddress = OTA_DataPtr + 0x10;
char *BYTE_C = OTA_ DataPtr + 0x10 + 0x20;
char *BYTE_D = OTA_ DataPtr + 0x10 + 0x21;
char *BYTE_14 = OTA_ DataPtr + 0x10 + 0x22;
if (TestBit(SmartPointer, 0) == 1) {
        if (memcmp(SmartPointer + 6, MacAddress, 6) == 0) {
                *(SmartPointer + 0xC) = *BYTE_C;
                *(SmartPointer + 0xD) = *BYTE_D;
                *(SmartPointer + 0x14) = *BYTE_14;
        }
}
```

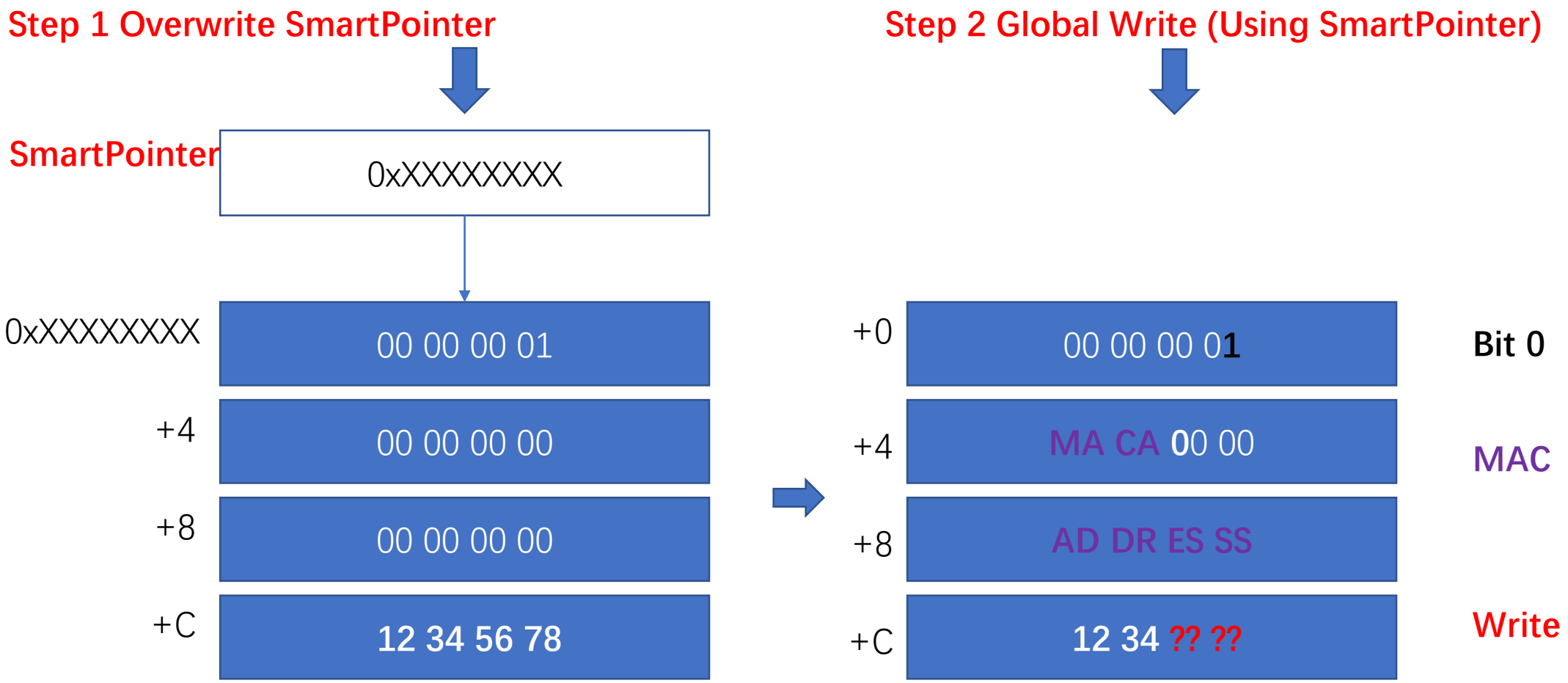
* Translated and simplified the code flow

Usage Of Smart Pointer

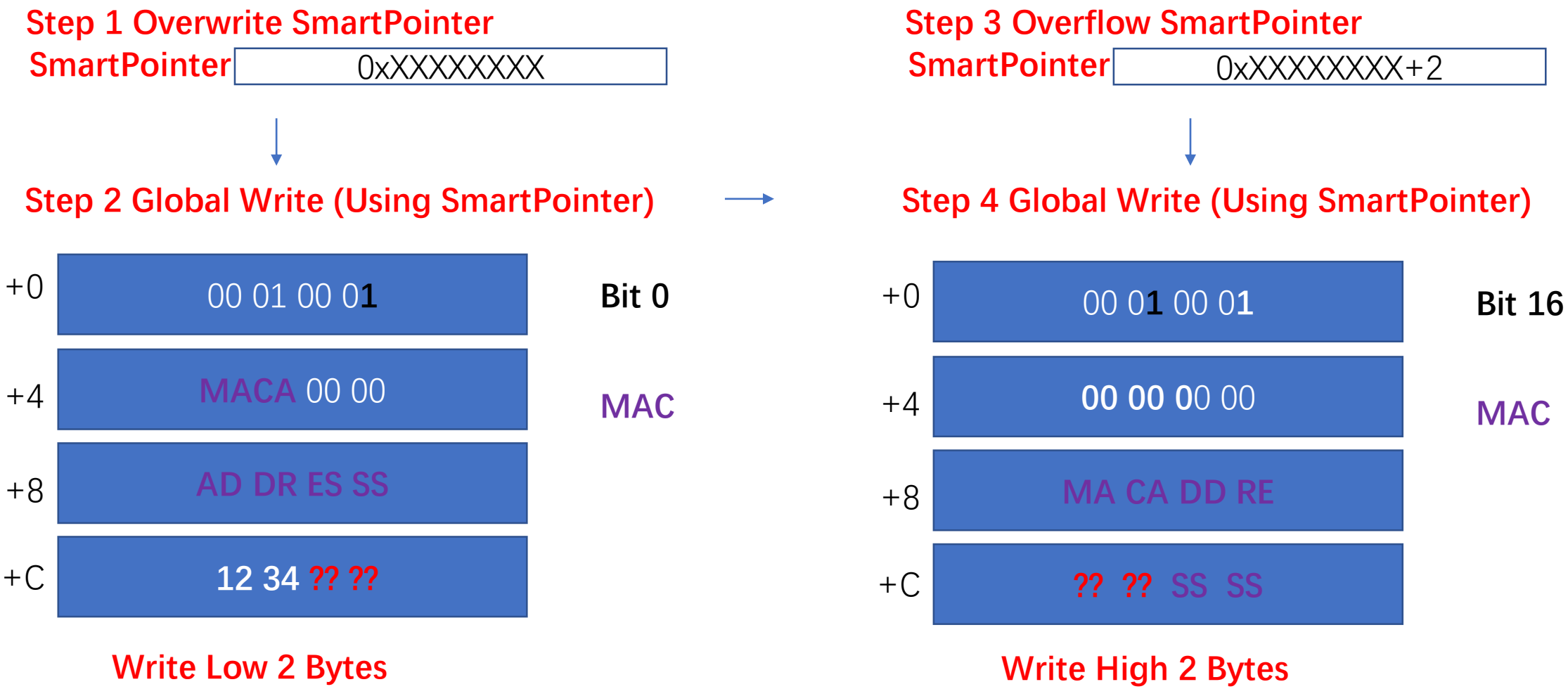
```
Char **AddressOfSmartPointer = GlobalBuffer + 6 + 0xB0 * 11 + 0xC;
char *SmartPointer = *AddressOfSmartPointer;        // ← Overwrite with vulnerability
char *MacAddress = OTA_DataPtr + 0x10;
char *BYTE_C = OTA_ DataPtr + 0x10 + 0x20;
char *BYTE_D = OTA_ DataPtr + 0x10 + 0x21;
char *BYTE_14 = OTA_ DataPtr + 0x10 + 0x22;
if (TestBit(SmartPointer, 0) == 1) {                // ← The only constraint, Bit0 == 1
        if (memcmp(SmartPointer + 6, MacAddress, 6) == 0) {
                                                    // ← From OTA Data, could be bypass
                *(SmartPointer + 0xC) = *BYTE_C;    // ← Overwrite 0xC
                *(SmartPointer + 0xD) = *BYTE_D;    // ← Overwrite 0xD
                *(SmartPointer + 0x14) = *BYTE_14;
        }
}
```

* Translated and simplified the code flow

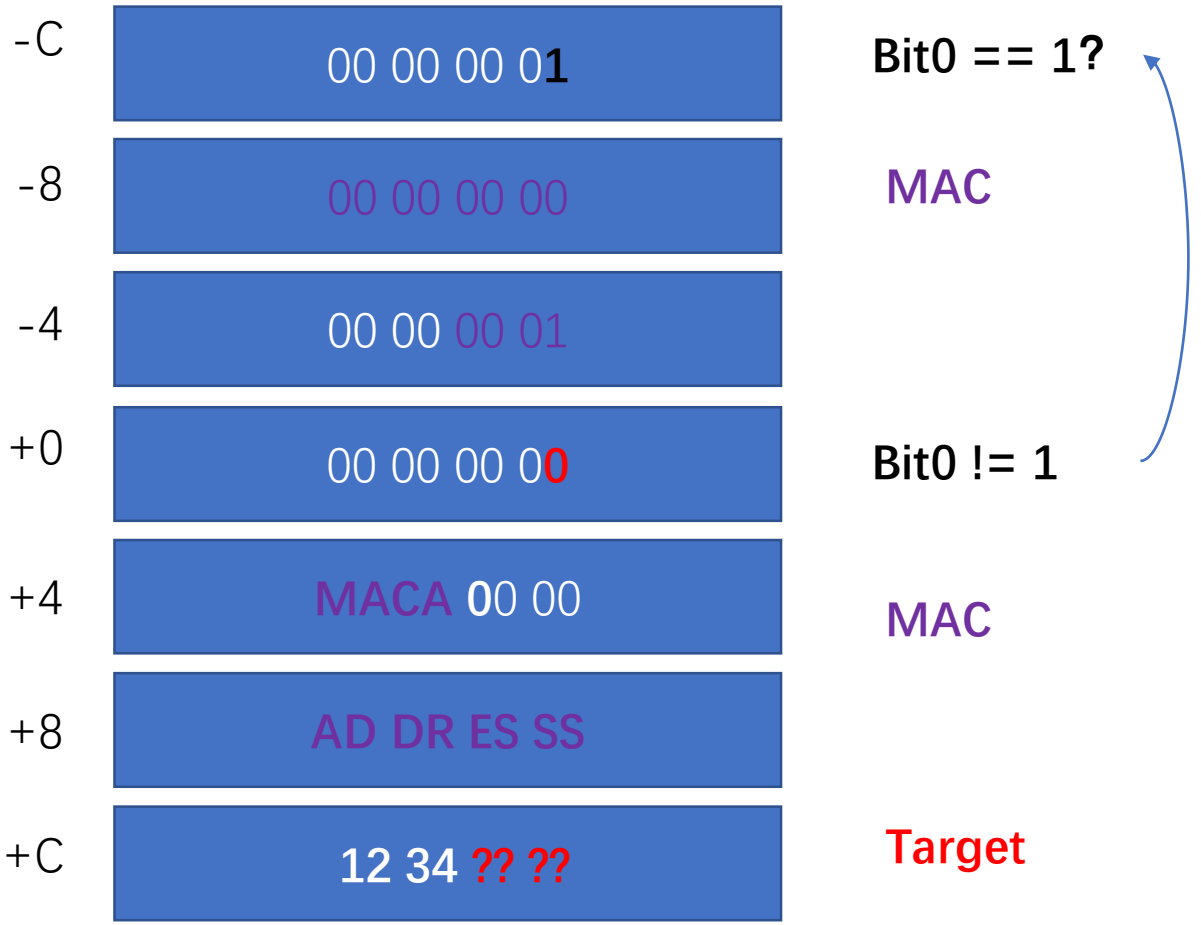
Global Write With Constraint



Global Write With Constraint
How to write 4 bytes?



Global Write With Constraint
The Bit0 != 1?



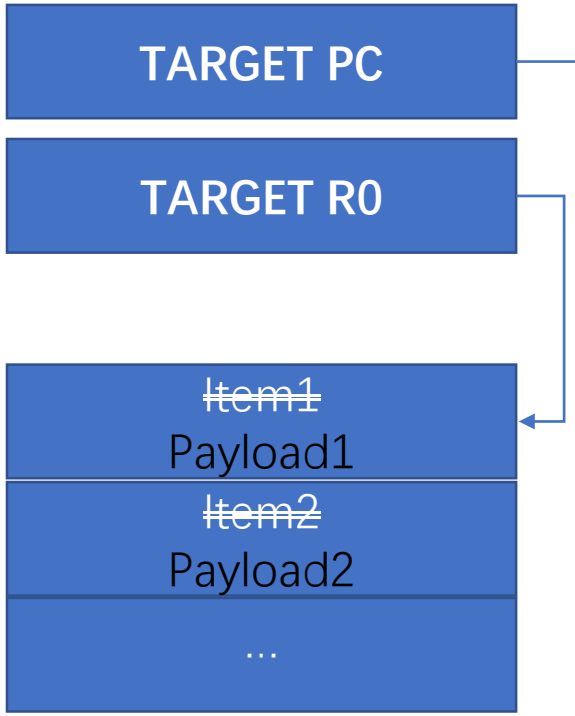
Control PC & R0

Address	Value
00	0x00010000
+04	0x00010001
+08	0x00000000
+0C	0x00000001
+10	0x00000000
+14	0x00000000
+18	0x00000000
+1C	0x00000000
+20	0x00000000
+24	0x12345678(PC)
+28	0x87654321(R0)

Address	Value
+00	0x00010000
+04	0x00010001
+08	0x00000000
+0C	0x00010001
+10	0x00010001
+14	0x00000000
+18	0x00010001
+1C	0x00010001
+20	0x00000000
+24	TARGET PC
+28	TARGET R0

SmartPointer

Transform To Arbitrary Write



FOP Gadget

```
LOAD:B000DBD8 24 01 23 00
LOAD:B000DBDC 04 01 22 82
LOAD:B000DBE0 00 40 9F 52
LOAD:B000DBE4 03 00 02 A2
```

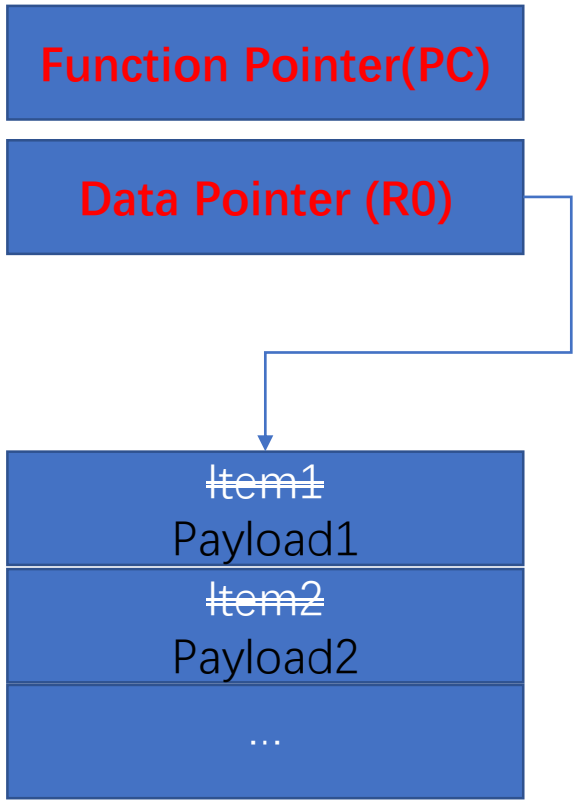
```
{ R3 = memw (R2 + 0) ; R4 = memw (R2 + 4) }
{ R2 = memw (R2 + 8) ; memw (R0 + 4) = R4 }
{ jumpr R31
  memw (R0 + 8) = R2 ; memw (R0 + 0) = R3 }
```

Run Useful FOP Gadget

Step 1 Arbitrary Write Overwrite function pointer →

Step 2 Arbitrary Write Overwrite data pointer →

Step 3 Send payload packet and trigger the PC →



Memory Mapping RWX

CreateMapping(args, ⋯)

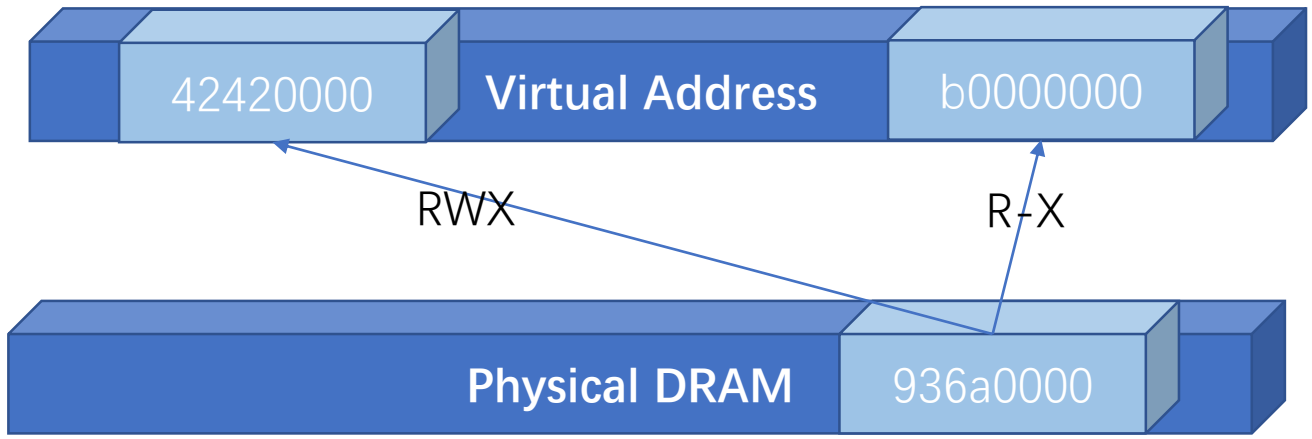
R0 = 0x42420000
Virtual Address

R1 = 0x936a0000
Physical Address

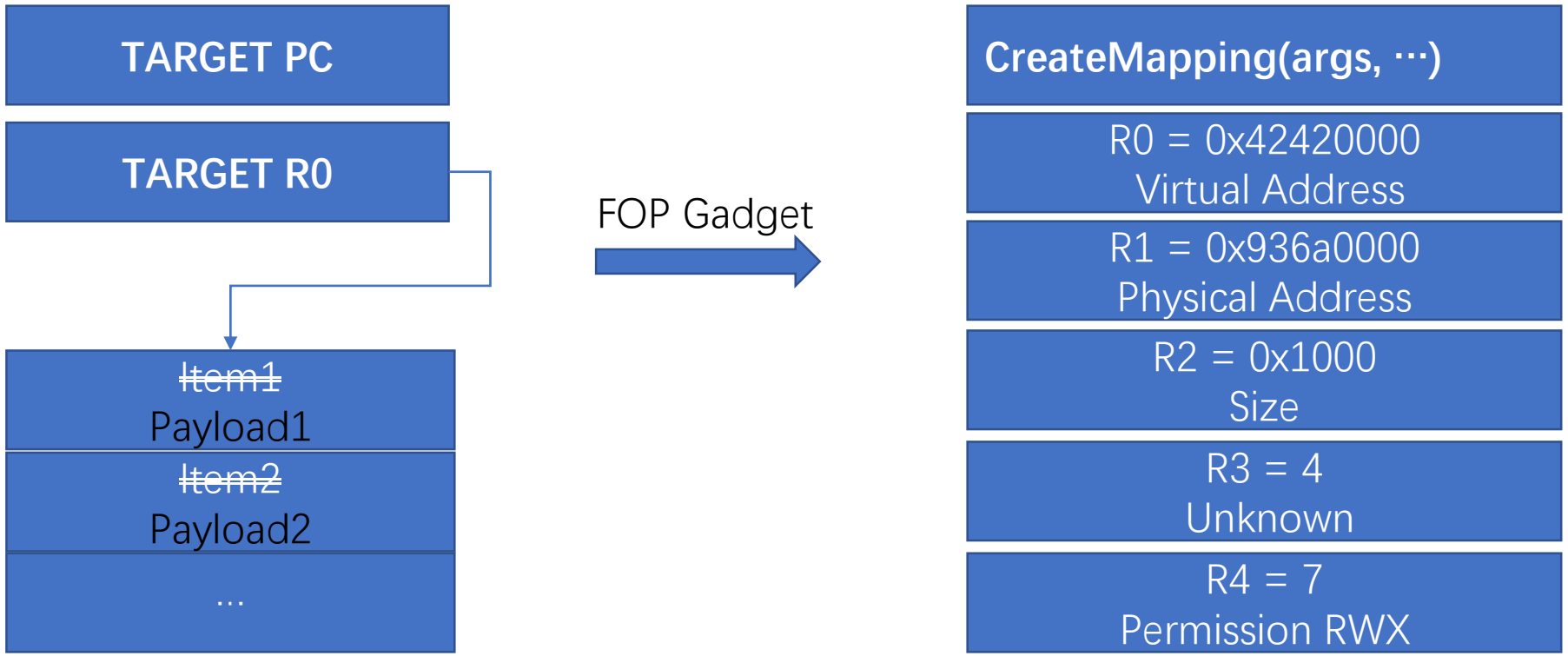
R2 = 0x1000
Size

R3 = 4
Unknown

R4 = 7
Permission RWX



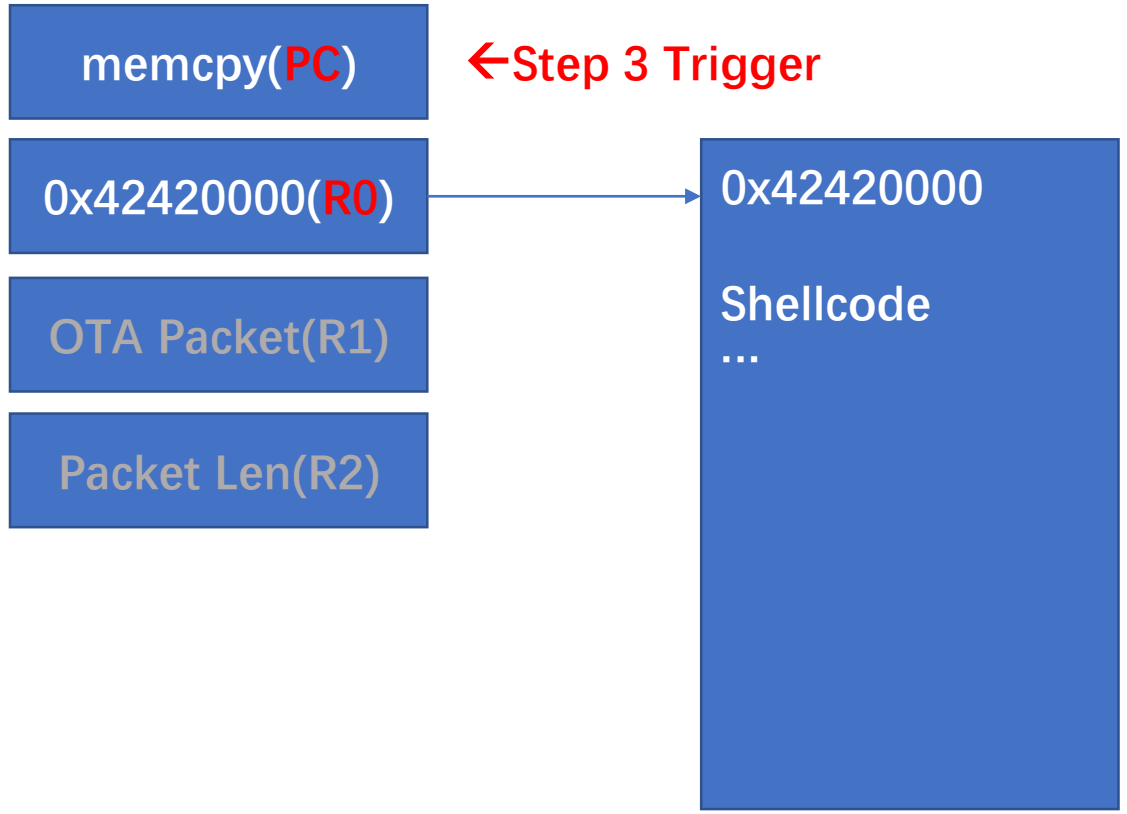
Memory Mapping RWX



Copy Shellcode to 0x42420000

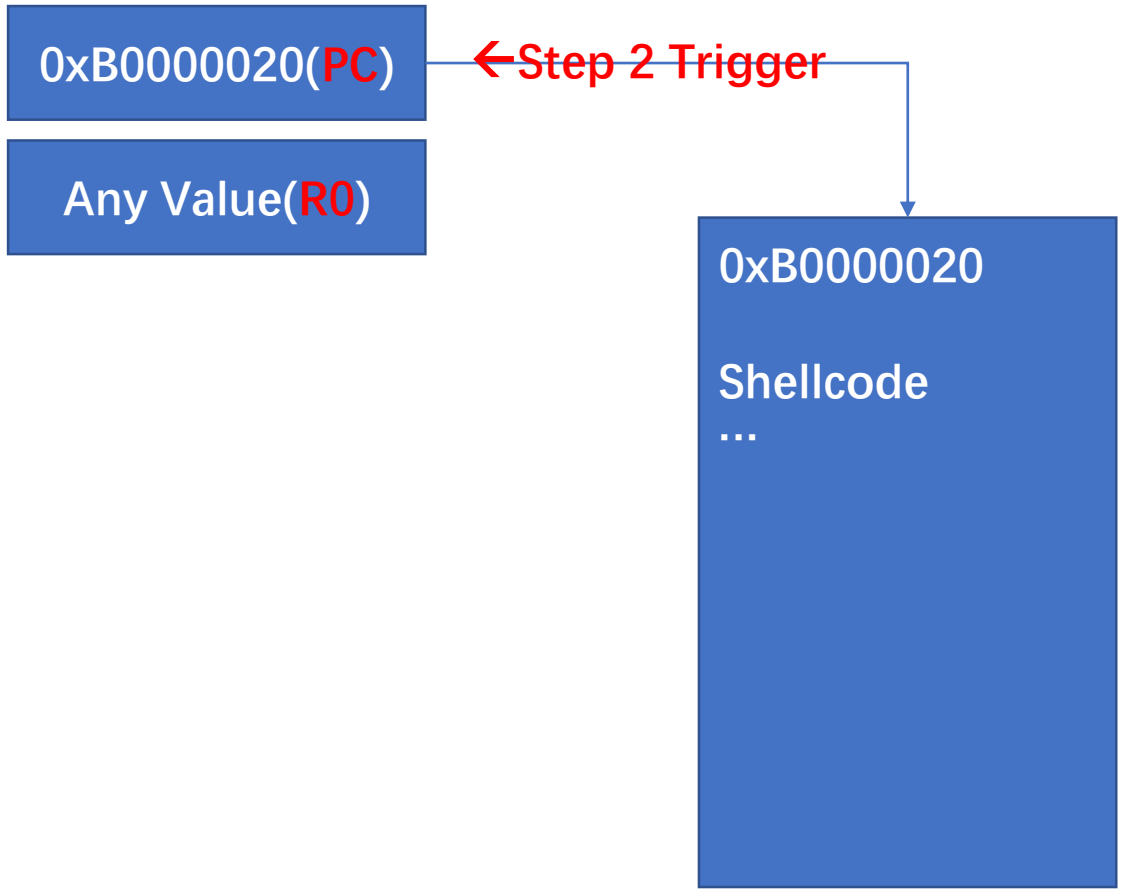
Step 1 Arbitrary Write Overwrite function pointer →

Step 2 Arbitrary Write Overwrite data pointer →



Trigger Shellcode

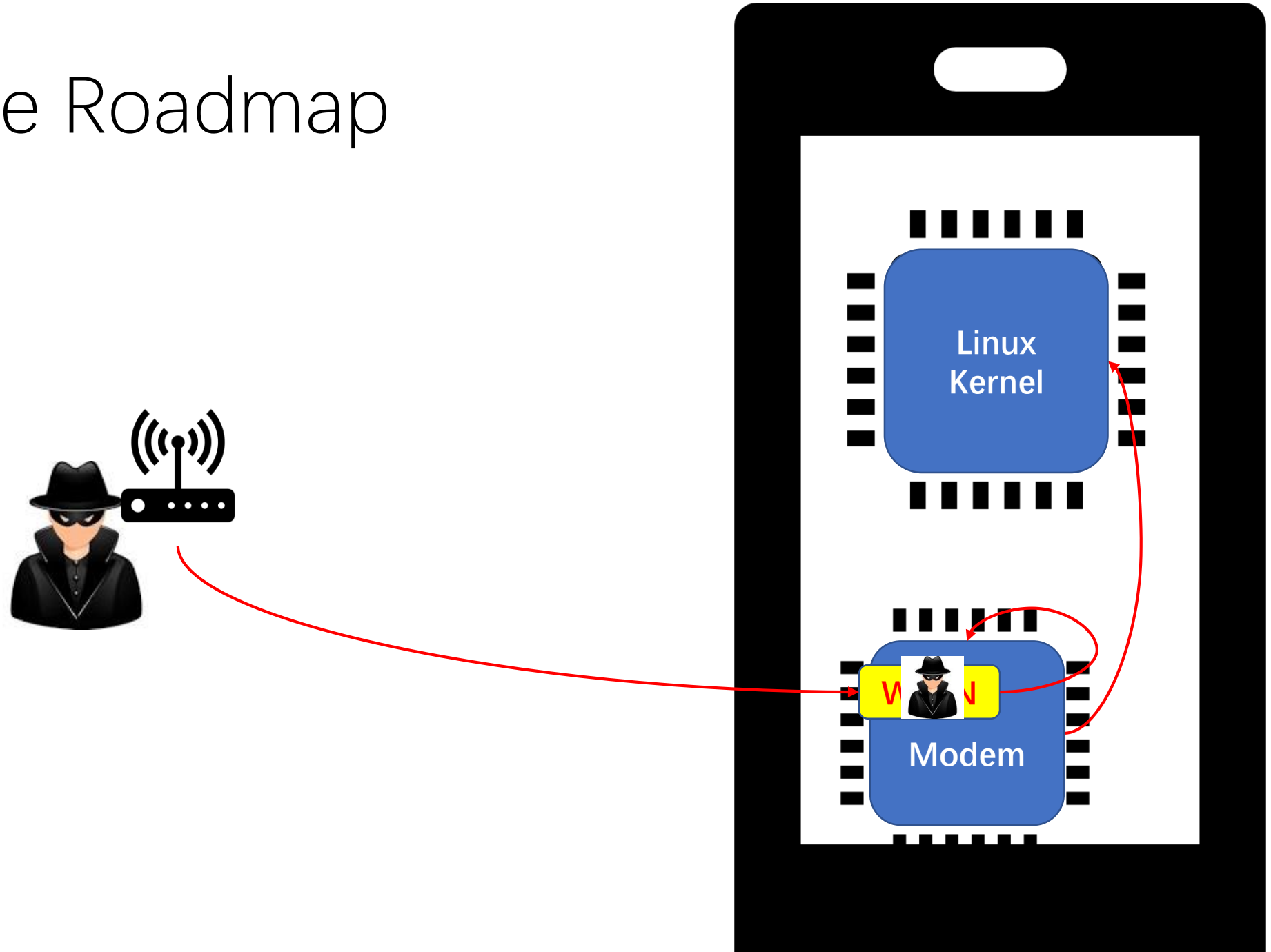
Step 1 Arbitrary Write Overwrite function pointer →



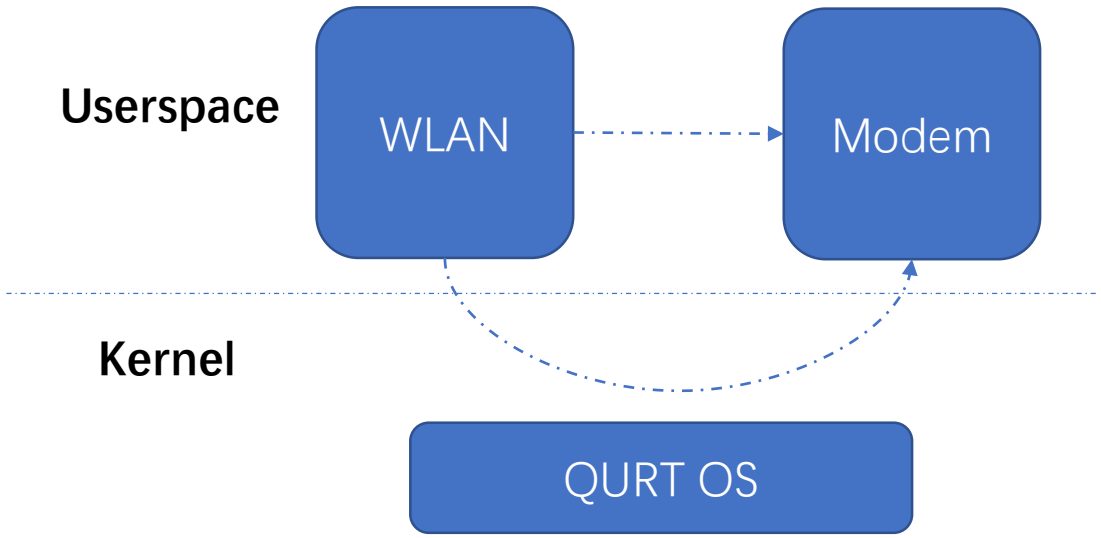
Agenda

- Introduction and Related Work
- The Debugger
- Reverse Engineering and Attack Surface
- Vulnerability and Exploitation
- **Escaping into Modem**
- Escaping into Kernel
- Stability of Exploitation
- Conclusions

The Roadmap



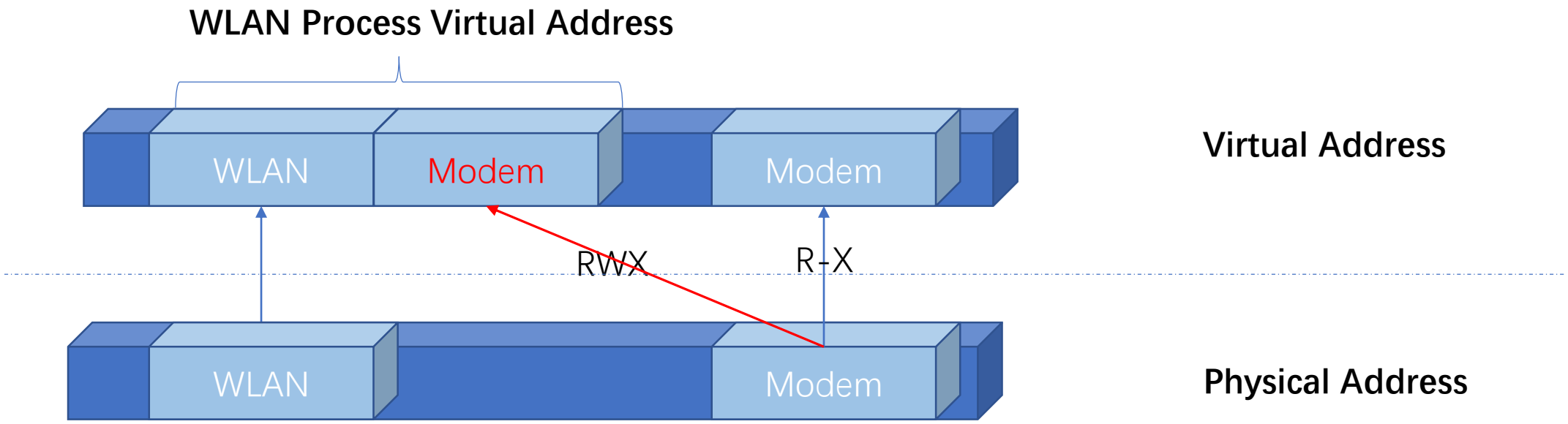
From WLAN to Modem



Actions From WLAN	Eligible?
TLB Set*	N
Write Modem Data	N
Call Modem Complex Function**	N
Call Modem Simple Code Snippet***	Y
Map Modem Memory	**Y**

* TLB is a Hexagon Instruction to modify the Memory Page Attribute
** Complex Function uses the resource of Modem, or calls System Call
*** Simple Code Snippet mean code has only register operation

Map Modem Memory into WLAN



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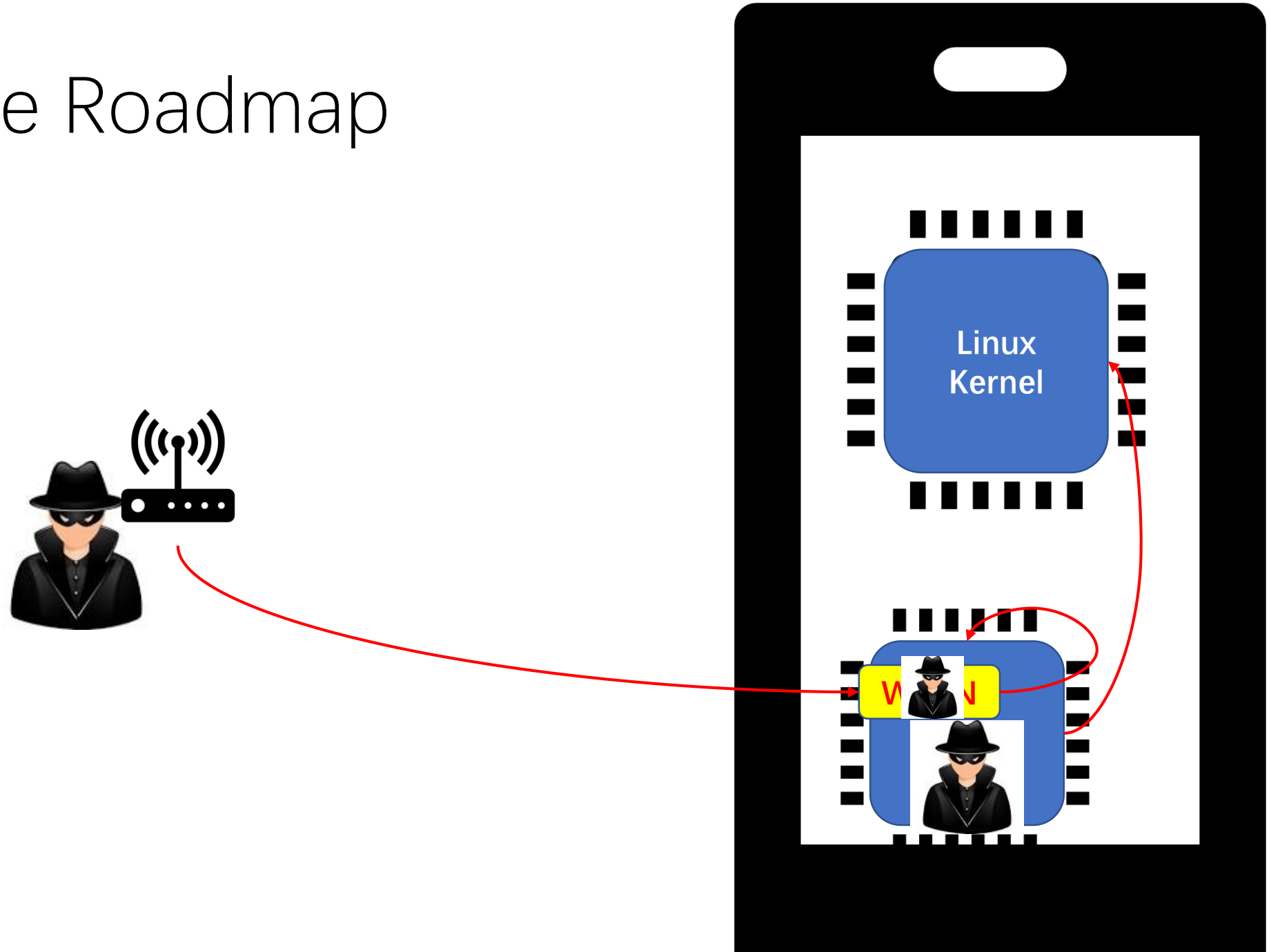
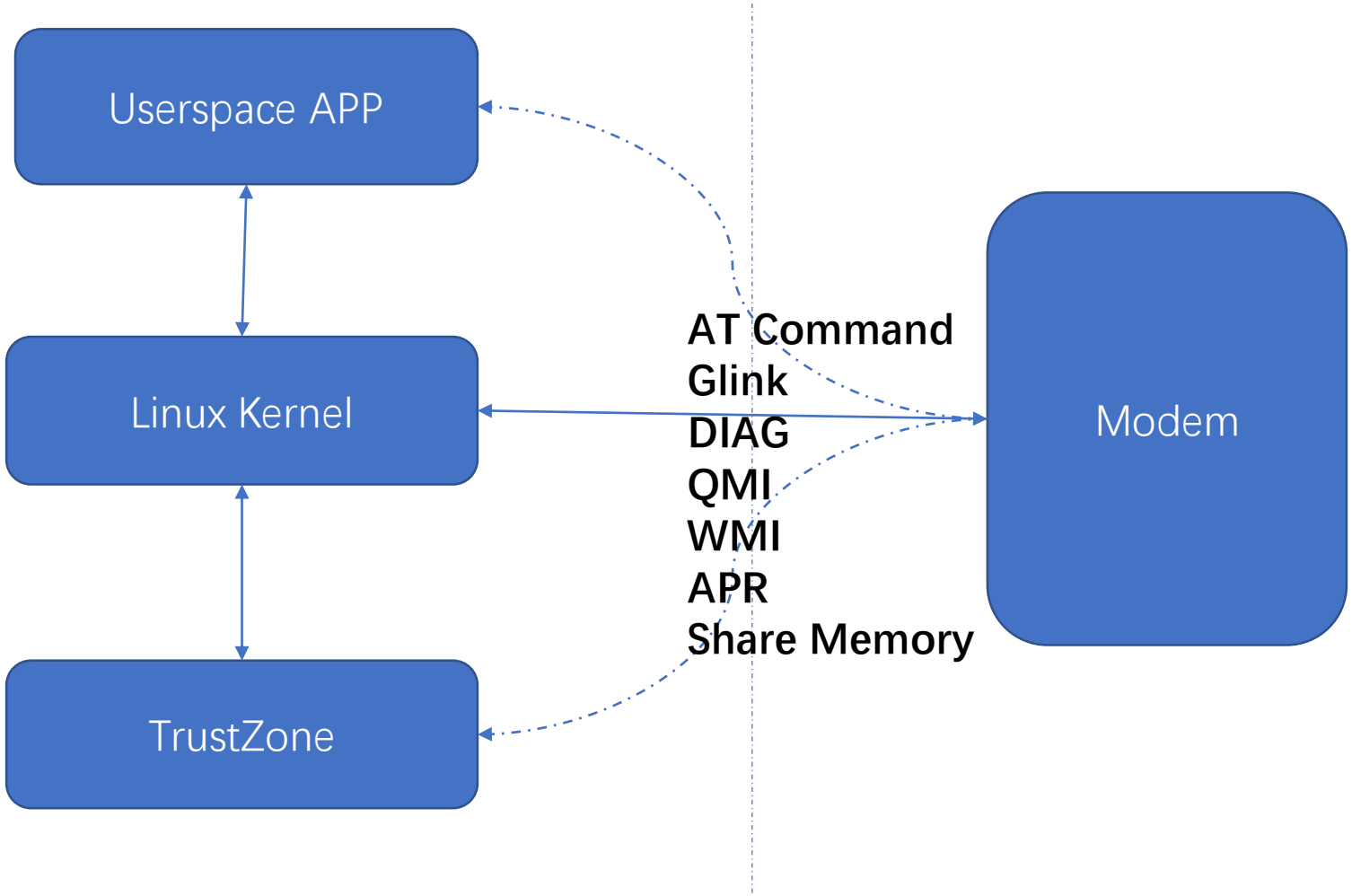


The Attack Surfaces



- We’ve found

An arbitrary memory read/write vulnerability

Could bypass all the mitigations of Linux Kernel

From Modem into Linux Kernel

- In these attack surfaces
- But we are unable to disclose the detail now

Agenda

- Introduction and Related Work
- The Debugger
- Reverse Engineering and Attack Surface
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- Escaping into Kernel
- **Stability of Exploitation**
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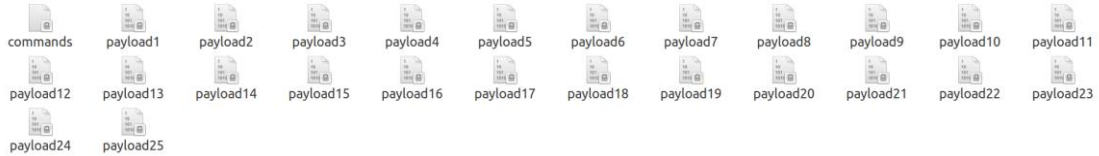
Deliver the Payload Over-The-Air

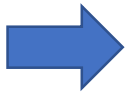


Pixel 2XL

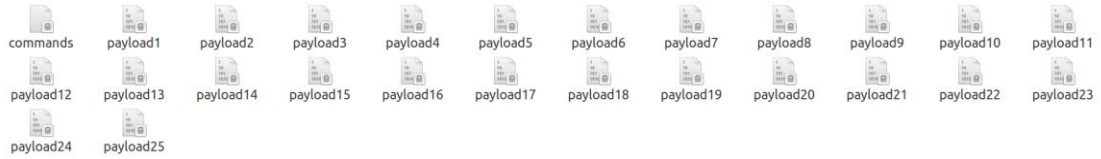
Packet Losing Rate 90%+!

Deliver the Payloads Using Pixel2

Pixel 2

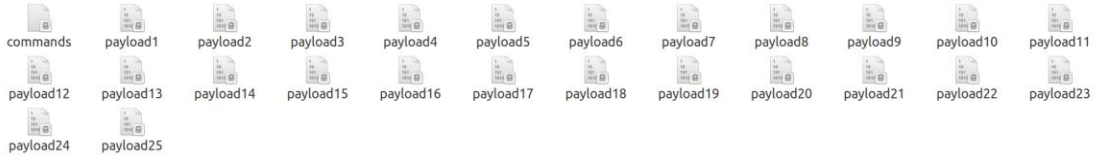


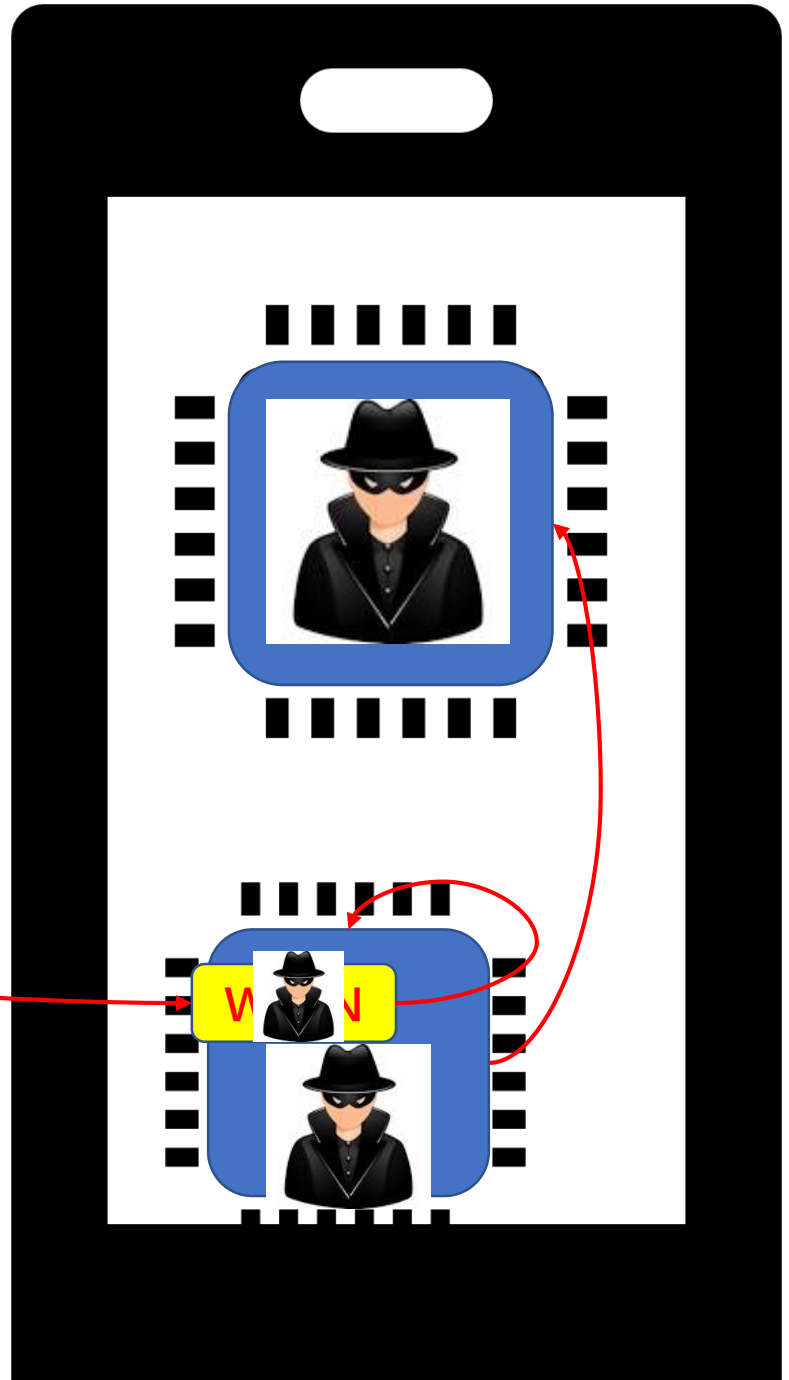
Pixel 2XL



The Roadmap

Pixel 2





Pixel 2XL

Demo

Future Works

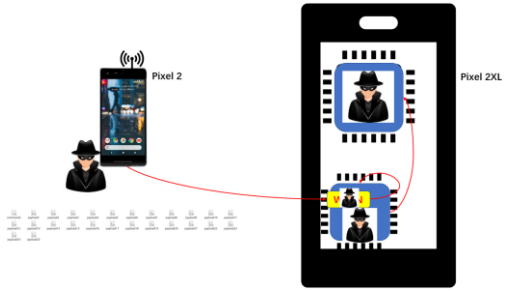
- There are still lots of mystery in the WLAN.
  - We were only reversed a small part of the code
  - Lots of functions are unknown
- How to fuzz the WLAN Firmware?
  - Reverse engineering is quite…
  - How to fuzz closed source target and Hexagon architecture effectively?
- Translate Hexagon Instruction to C?
  - IDA/Ghidra F5 plugin?

Timeline

- 2019-2-14 Find the Modem debug vulnerability on MSM8998
- 2019-3-24 Find the WLAN issue and report to Google
- 2019-3-28 Google forwards the issue to Qualcomm
- 2019-4-24 Google confirms the WLAN issue as Critical
- 2019-5-08 Find the WLAN into Linux Kernel issue and report to Google
- 2019-5-24 Google confirms the WLAN into Linux Kernel issue
- 2019-5-28 Submit the full exploit chain (OTA→WLAN→Kernel) to Google
- 2019-6-04 Google reply unable to reproduce the full exploit chain
- 2019-6-17 Improve the stability and submit to Google
- 2019-7-19 CVE Assigned by Google
- 2019-7-20 Qualcomm confirms issues will be fixed before October
- 2019-8-0? Google release the fix for Google Pixel2/Pixel3

Takeaways

- The full exploit chain into Android Kernel
  - OTA → WLAN → Modem → Kernel



- The Qualcomm WLAN vulnerability and exploitation

- The Qualcomm Baseband Debugger

THANK YOU

https://blade.tencent.com