Dive into Apple IO80211Family Vol. II

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Background of this research project

Dive into Apple IO80211FamilyV2

https://www.blackhat.com/us-20/briefings/schedule/index.html#dive-into-apple-iofamilyv-20023

The Apple 80211 Wi-Fi Subsystem

Previously on IO80211Family

Starting from iOS 13 and macOS 10.15 Catalina, Apple refactored the architecture of the 80211 Wi-Fi client extensions and renamed the new generation design to IO80211FamilyV2.

From basic network communication to trusted privacy sharing between all types of Apple devices.

Changes between version 1 and 2

Daemon:	airportd, sharingd …
Framework:	Apple80211, CoreWifi, CoreWLAN …
Family driver V2:	IO80211FamilyV2, IONetworkingFamily
Family driver:	IO80211Family, IONetworkingFamily
Plug-in driver V2:	AppleBCMWLANCore replaces AirPort Brcm series drivers
Plug-in driver:	AirPortBrcmNIC, AirPortBrcm4360/4331, AirPortAtheros40 …
Low-level driver V2:	AppleBCMWLANBusInterfacePCIe …
Low-level driver:	IOPCIFamily …

Vulnerability hunting

Previous work includes an early generation fuzzing framework, a simple code coverage analysis tool, and a Kemon-based KASAN solution.

Classification:

1. Vulnerabilities affecting only IO80211FamilyV2
   1.1. Introduced when porting existing V1 features
   1.2. Introduced when implementing new V2 features
2. Vulnerabilities affecting both IO80211Family (V1) and IO80211FamilyV2
3. Vulnerabilities affecting only IO80211Family (V1)

Vulnerability case study

There are some vulnerabilities that I've analyzed in detail, but others that I can't disclose because they haven't been fixed before Black Hat USA 2020.

Family driver V2:	IO80211FamilyV2, IONetworkingFamily
	CVE-2020-9832 ...
Plug-in driver V2:	AppleBCMWLANCore replaces AirPort Brcm series drivers
	CVE-2020-9834, CVE-2020-9899, CVE-2020-10013 ...
Low-level driver V2:	AppleBCMWLANBusInterfacePCIe ...
	CVE-2020-9833 ...

Two years have passed

All the previous vulnerabilities have been fixed, the overall security of the system has been improved. The macOS Big Sur/Monterey/Ventura has been released, and the era of Apple Silicon has arrived. But, ...

1. Apple IO80211FamilyV2 has been refactored again, and its name has been changed back to IO80211Family. What happened behind this?
2. How to identify the new attack surfaces of the 80211 Wi-Fi subsystem?
3. What else can be improved in security engineering and vulnerability hunting?
4. Most importantly, can we still find new high-quality kernel vulnerabilities?

Never stop exploring

1. Change is the only constant.
2. There are always new attack surfaces, and we need to constantly accumulate domain knowledge.
3. To be honest, too many areas can be improved.
4. Yes, definitely.

Dive into Apple IO80211Family (Again)

Attack surface identification

Demand 1: I'd like to change various settings of the network while sending and receiving data.

- Traditional BSD ioctl, IOKit IOConnectCallMethod series and sysctl interfaces
- Various packet sending and receiving interfaces
- Various network setting interfaces
- Various types of network interfaces

Try fuzzing against both high-level and low-level API interfaces, a good example is Bluetooth HCI:
https://www.blackhat.com/eu-20/briefings/schedule/#please-make-a-dentist-appointment-asap-attacking-iobluetoothfamily-hci-and-vendor-specific-commands-21155

Some new cases from XNU-8020.101.4

ifioctl()
https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/bsd/net/if.c#L2854

ifioctl_nexus()
https://github.com/apple-oss-distributions/xnu/blob/main/bsd/net/if.c#L3288

skoid_create() and sysctl registration
https://github.com/apple-oss-distributions/xnu/blob/main/bsd/skywalk/core/skywalk_sysctl.c#L81

Interfaces integration

Demand 2: I'd like to switch the status or working mode of the kernel state machine randomly for different network interfaces.

```
if ( a3 )
{
  return_value = IO80211Controller::apple80211VirtualRequestIoctl(a1, 0xC03069C9, 0xC, a3, v12);
}
else if ( a4 )
{
  return_value = (*(*a1 + 0xCC0LL))(a1, 0xC03069C9LL, 0xCLL, a4, v12);// IOSkywalkNetworkInterface
}
else
{
  return_value = IO80211Controller::apple80211RequestIoctl(a1, 0xC03069C9, 0xC, a2, v12);
}
```

IO80211FamilyV2 reverse engineering

"ifconfig" command and the default interfaces

Have your fuzzer talked to these interfaces?

```
    ap1: Access Point.
  awdl0: Apple Wireless Direct Link.
   llw0: Low-latency WLAN Interface. (Used by the Skywalk system)
  utun0: Tunneling Interface.
    lo0: Loopback (Localhost)
   gif0: Software Network Interface
   stf0: 6to4 Tunnel Interface
    en0: Physical Wireless
    enX: Thunderbolt/iBridge/Apple T2 Controller
         Bluetooth PAN/VM Network Interface
bridge0: Thunderbolt Bridge
 ......
```

Domain knowledge accumulation

Read the XNU source code and documents.

Look for potential attack surface from XNU test cases:
https://github.com/apple/darwin-xnu/tree/xnu-7195.121.3/tests

Have you read these PoCs before?

net agent

https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/tests/netagent_race_infodisc_56244905.c
https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/tests/netagent_kctl_header_infodisc_56190773.c

net bridge

https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/tests/net_bridge.c

net utun

https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/tests/net_tun_pr_35136664.c

IP6_EXTHDR_CHECK

https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/tests/IP6_EXTHDR_CHECK_61873584.c

Randomly, but not too random

So far, the new generation of Apple 80211 Wi-Fi fuzzing framework integrates more than forty network interfaces and attack surfaces.

But, is the more attack surfaces covered during each test the better? I found that this is not the case.

Summary #1 - Attack surface and domain knowledge

- About network interfaces and attack surfaces

1. We need to accumulate as much domain knowledge as possible by learning XNU source code, documents and test cases.

2. For each round, we should randomly select two or three interface units and test them as fully as possible.

Kernel debugging

From source code learning, static analysis to remote kernel debugging.

Make full use of LLDB and KDK:

- The information provided in the panic log is often not helpful in finding the root cause
- Variable (initial) values sometimes require dynamic analysis
- Kernel heap corruption requires remote debugging

A new case of kernel panic

Without the help of the LLDB debugger, there is probably no answer.

```
[(lldb) bt
* thread #1, stop reason = signal SIGSTOP
  * frame #0: 0xfffffe00295de99c kernel.release.t8112`panic_trap_to_debugger [inlined] DebuggerTrapWithState(db_op=DBOP_PANIC, db_panic_str="%s %s -- exit reason namespace %d subcode 0x%llx description: %
.800s", db_panic_args=0xfffffe3d91ddf9a8, db_panic_options=32, db_panic_data_ptr=0x0000000000000000, db_proceed_on_sync_failure=1, db_panic_caller=18446741875385547616) at debug.c:715:2 [opt]
    frame #1: 0xfffffe00295de95c kernel.release.t8112`panic_trap_to_debugger(panic_format_str="%s %s -- exit reason namespace %d subcode 0x%llx description: %.800s", panic_args=0xfffffe3d91ddf9a8, reason=
0, ctx=0x0000000000000000, panic_options_mask=32, panic_data_ptr=0x0000000000000000, panic_caller=18446741875385547616) at debug.c:1176:2 [opt]
    frame #2: 0xfffffe0029dfca40 kernel.release.t8112`panic_with_options(reason=<unavailable>, ctx=<unavailable>, debugger_options_mask=<unavailable>, str=<unavailable>) at debug.c:1019:2 [opt]
    frame #3: 0xfffffe0029adbb60 kernel.release.t8112`proc_prepareexit [inlined] proc_handle_critical_exit(p=0xfffffe1666dea860, rv=10) at kern_exit.c:0 [opt]
    frame #4: 0xfffffe0029adb948 kernel.release.t8112`proc_prepareexit(p=0xfffffe1666dea860, rv=10, perf_notify=<unavailable>) at kern_exit.c:1801:3 [opt]
    frame #5: 0xfffffe0029adad14 kernel.release.t8112`exit_with_reason(p=0xfffffe1666dea860, rv=10, retval=<unavailable>, thread_can_terminate=1, perf_notify=1, jetsam_flags=0, exit_reason=0xfffffe1b3707d
8b0) at kern_exit.c:1534:2 [opt]
    frame #6: 0xfffffe0029aff834 kernel.release.t8112`postsig_locked(signum=10) at kern_sig.c:3119:3 [opt]
    frame #7: 0xfffffe0029affdbc kernel.release.t8112`bsd_ast(thread=0xfffffe1ffdbc2000) at kern_sig.c:3388:4 [opt]
    frame #8: 0xfffffe00295d6134 kernel.release.t8112`ast_taken_user at ast.c:224:3 [opt]
    frame #9: 0xfffffe002958fcb0 kernel.release.t8112`user_take_ast + 12
    frame #10: 0xfffffe002972b55c kernel.release.t8112`thread_exception_return at sleh.c:726:2 [opt]
    frame #11: 0xfffffe00295e13ec kernel.release.t8112`exception_triage_thread(exception=<unavailable>, code=<unavailable>, codeCnt=<unavailable>, thread=<unavailable>) at exception.c:698:3 [opt]
    frame #12: 0xfffffe002972d2e8 kernel.release.t8112`handle_user_abort(state=<unavailable>, esr=2181038087, fault_addr=7056804912, fault_code=<unavailable>, fault_type=<unavailable>, expected_fault_hand
ler=<unavailable>) at sleh.c:2303:2 [opt]
    frame #13: 0xfffffe002972baa8 kernel.release.t8112`sleh_synchronous(context=0xfffffe24cca2c7b0, esr=2181038087, far=7056804912) at sleh.c:0 [opt]
    frame #14: 0xfffffe002958f784 kernel.release.t8112`fleh_synchronous + 40
    frame #15: 0x00000001a49e4c30
(lldb)
```

A kernel panic on the latest
M2 macOS Ventura 13.0 Beta 4 (22A5311f)

```
| LLDB (F1) | Target (F2) | Process (F3) | Thread (F4) | View (F5) | Help (F6) |
```

```
<Sources>
kernel.release.t8112`proc_prepareexit
0xfffffe0029adb92c  cmp    x8, x19
0xfffffe0029adb930  b.ne   -0x1fff882066c        ; <+2696> [inlined] proc_getpid at kern_proc.c:1051:12
0xfffffe0029adb934  mov    w8, #0x0
0xfffffe0029adb938  b      -0x1fff8820668        ; <+2700> [inlined] proc_handle_critical_exit + 80 at kern_exit.c:1748:23
0xfffffe0029adb93c  mov    w0, #0x5
0xfffffe0029adb940  bl     -0x1fff84fa5a4        ; zone_id_require_ro_panic at zalloc.c:7005
0xfffffe0029adb944  bl     -0x1fff8d645c8        ; __stack_chk_fail at stack_protector.c:36
0xfffffe0029adb948 ◆ldr    x9, [x8, #0x108]
0xfffffe0029adb94c  cbz    x9, -0x1fff8820688    ; <+2668> [inlined] proc_handle_critical_exit + 48 at kern_exit.c
0xfffffe0029adb950  ldr    w10, [x8, #0x28]
0xfffffe0029adb954  cbz    w10, -0x1fff8820688   ; <+2668> [inlined] proc_handle_critical_exit + 48 at kern_exit.c
0xfffffe0029adb958  add    x11, x9, #0x10
0xfffffe0029adb95c  add    x10, x10, x9
0xfffffe0029adb960  cmp    x11, x10
0xfffffe0029adb964  b.hi   -0x1fff8820688        ; <+2668> [inlined] proc_handle_critical_exit + 48 at kern_exit.c
0xfffffe0029adb968  ldr    w12, [x9, #0x4]
0xfffffe0029adb96c  add    x12, x11, x12
0xfffffe0029adb970  cmp    x12, x10
0xfffffe0029adb974  b.ls   -0x1fff88204a0        ; <+3156> [inlined] proc_handle_critical_exit + 536 at kern_exit.c
0xfffffe0029adb978  mov    x24, #0x0
0xfffffe0029adb97c  adrp   x9, -1414
0xfffffe0029adb980  ldr    x9, [x9, #0x620]
0xfffffe0029adb984  cmp    x9, x19
0xfffffe0029adb988  b.ne   -0x1fff8820648        ; <+2732> [inlined] proc_getpid at kern_proc.c:1051:12
0xfffffe0029adb98c  mov    w9, #0x0
0xfffffe0029adb990  b      -0x1fff8820644        ; <+2736> [inlined] proc_handle_critical_exit + 116 at kern_exit.c:1751:58
0xfffffe0029adb994  ldr    w8, [x19, #0x60]
0xfffffe0029adb998  and    w9, w21, #0x7f
0xfffffe0029adb99c  stp    x9, x23, [sp, #0x8]
0xfffffe0029adb9a0  str    x8, [sp]
0xfffffe0029adb9a4  adrp   x0, -1859
0xfffffe0029adb9a8  add    x0, x0, #0x306        ; "pid %d exited -- no exit reason available -- (signal %d, exit %d)\n"
0xfffffe0029adb9ac  bl     -0x1fff8cf6c1c        ; printf at printf.c:875
0xfffffe0029adb9b0  mov    x24, #0x0
0xfffffe0029adb9b4  b      -0x1fff8820620        ; <+2772> [inlined] proc_handle_critical_exit + 152 at kern_exit.c:1756:7
0xfffffe0029adb9b8  ldr    w9, [x19, #0x60]
```

```
<Threads>
◆─process 1
 └─◆─thread #1: tid = 0x0001, stop reas
     ├─frame #0: panic_trap_to_debugger [
     ├─frame #1: panic_trap_to_debugger +
     ├─frame #2: panic_with_options + 68
     ├─frame #3: proc_prepareexit [inline
     ├─frame #4: proc_prepareexit + 2620
     ├─frame #5: exit_with_reason + 468
     ├─frame #6: postsig_locked + 1068
     ├─frame #7: bsd_ast + 1252
     ├─frame #8: ast_taken_user + 216
     ├─frame #9: user_take_ast + 12
     ├─frame #10: thread_exception_return
     ├─frame #11: exception_triage_thread
     ├─frame #12: handle_user_abort + 421
     ├─frame #13: sleh_synchronous + 1320
     ├─frame #14: fleh_synchronous + 40
     └─frame #15:
```

```
<Variables>
◆─(const char [51]) _os_log_fmt "Text page corruption detected in dying process %d\n"
◆─(proc_t) p = 0xfffffe1666dea860
(int) rv = 10
(boolean_t) perf_notify
(int) create_corpse = 0
(int) kr = 0
◆─(rusage_superset *) rup = 0x0000000000000000
◆─(thread_t) self
◆─(uthread *) ut
(exception_type_t) etype = 0
(mach_exception_data_type_t) subcode = 0
(mach_exception_data_type_t) code = 0
◆─(uintptr_t [2]) bt
◆─(backtrace_user_info) btinfo
◆─(task_t) task
(unsigned int) frame_count
```

```
Process:    1    stopped          Thread: 0x0001      Frame:   4  PC = 0xfffffe0029adb948
```

Kernel Debug Kit

"Note: Apple silicon doesn't support active kernel debugging. … you cannot set breakpoints, continue code execution, step into code, step over code, or step out of the current instruction."

Kernel Debug Kit for macOS - Read Me

Asahi Linux

https://asahilinux.org/

An Overview of macOS Kernel Debugging

https://blog.quarkslab.com/an-overview-of-macos-kernel-debugging.html

LLDBagility: Practical macOS Kernel Debugging

https://blog.quarkslab.com/lldbagility-practical-macos-kernel-debugging.html

Summary #2 - Static and dynamic analysis

- About network interfaces and attack surfaces
- About static and dynamic analysis methods

1. We should make full use of LLDB kernel debugging environment, KDK kernels, and public symbols for reverse engineering.
2. At this stage, we need the help of third-party solutions for the Apple Silicon platform.

Kernel address sanitizer

The previous panic is a typical case of corruption, and we need Kernel Address Sanitizer's help.

However, we have to make some fixes because sometimes the built-in tools/KDK kernels don't work very well.

We even need to implement KASAN-like solution to dynamically monitor special features of third-party closed source kernel extensions.

An obstacle case starting from XNU-7195

console_io_allowed()

https://github.com/apple/darwin-xnu/blob/xnu-7195.121.3/osfmk/console/serial_console.c#L162

```
static inline bool
console_io_allowed(void)
{
        if (!allow_printf_from_interrupts_disabled_context &&
            !console_suspended &&
            startup_phase >= STARTUP_SUB_EARLY_BOOT &&
            !ml_get_interrupts_enabled()) {
#if defined(__arm__) || defined(__arm64__) || DEBUG || DEVELOPMENT
                panic("Console I/O from interrupt-disabled context");
#else
                return false;
#endif
        }

        return true;
}
```

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
    frame #0: 0xffffff800e4d82da kernel.kasan`DebuggerTrapWithState [inlined] current_debugger_state at debug.c:176:9 [opt]
Target 0: (kernel.kasan) stopped.
[(lldb) bt                                                                                                                                   ]
* thread #1, stop reason = signal SIGSTOP
  * frame #0: 0xffffff800e4d82da kernel.kasan`DebuggerTrapWithState [inlined] current_debugger_state at debug.c:176:9 [opt]
    frame #1: 0xffffff800e4d82da kernel.kasan`DebuggerTrapWithState(db_op=DBOP_PANIC, db_message="panic", db_panic_str="\"Console I/O from interrupt-disabled context\"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6
c82cc8/Library/Caches/com.apple.xbs/Sources/xnu_kasan/xnu-7195.141.26/osfmk/console/serial_console.c:162", db_panic_args=0xffffffb0c2a0ee30, db_panic_options=0, db_panic_data_ptr=0x0000000000000000, db_proceed_on_s
ync_failure=1, db_panic_caller=18446743524197246046) at debug.c:598:8 [opt]
    frame #2: 0xffffff800e4d9041 kernel.kasan`panic_trap_to_debugger(panic_format_str="\"Console I/O from interrupt-disabled context\"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6c82cc8/Library/Caches/com.apple.x
bs/Sources/xnu_kasan/xnu-7195.141.26/osfmk/console/serial_console.c:162", panic_args=<unavailable>, reason=0, ctx=0x0000000000000000, panic_options_mask=0, panic_data_ptr=<unavailable>, panic_caller=184467435241972
46046) at debug.c:938:2 [opt]
    frame #3: 0xffffff800fc5ed23 kernel.kasan`panic(str=<unavailable>) at debug.c:803:2 [opt]
    frame #4: 0xffffff800e83a45e kernel.kasan`console_write [inlined] console_io_allowed at serial_console.c:162:3 [opt]
    frame #5: 0xffffff800e83a411 kernel.kasan`console_write(str="ethernet MAC address: 60:f8:1d:b4:60:36\n", size=0) at serial_console.c:451:6 [opt]
    frame #6: 0xffffff800e839756 kernel.kasan`console_printbuf_putc(ch=10, arg=0xffffffb0c2a0eff8) at serial_general.c:184:3 [opt]
    frame #7: 0xffffff800e517669 kernel.kasan`__doprnt(fmt="\n", argp=0xffffffb0c2a0efe0, putc=(kernel.kasan`console_printbuf_putc at serial_general.c:160), arg=0xffffffb0c2a0eff8, radix=16, is_log=1) at printf.c:0
:2 [opt]
    frame #8: 0xffffff800e518cb5 kernel.kasan`vprintf_internal(fmt="ethernet MAC address: %02x:%02x:%02x:%02x:%02x:%02x\n", ap_in=0xffffffb0c2a0f170, caller=0xffffff800e45a99b) at printf.c:915:4 [opt]
    frame #9: 0xffffff800e518b55 kernel.kasan`printf(fmt=<unavailable>) at printf.c:938:8 [opt]
    frame #10: 0xffffff800e45a99b kernel.kasan`kdp_raise_exception [inlined] kdp_connection_wait at kdp_udp.c:1214:3 [opt]
    frame #11: 0xffffff800e45a908 kernel.kasan`kdp_raise_exception [inlined] kdp_debugger_loop(exception=<unavailable>, code=<unavailable>, subcode=<unavailable>, saved_state=0xffffffb0c2a0f3a0) at kdp_udp.c:1426:3
 [opt]
    frame #12: 0xffffff800e45a495 kernel.kasan`kdp_raise_exception(exception=<unavailable>, code=3, subcode=0, saved_state=0xffffffb0c2a0f3a0) at kdp_udp.c:2404:2 [opt]
    frame #13: 0xffffff800e4d881e kernel.kasan`handle_debugger_trap(exception=6, code=<unavailable>, subcode=0, state=0xffffffb0c2a0f3a0) at debug.c:1285:3 [opt]
    frame #14: 0xffffff800e8b854f kernel.kasan`kdp_i386_trap(trapno=<unavailable>, saved_state=0xffffffb0c2a0f3a0, result=<unavailable>, va=140462291755008) at kdp_machdep.c:441:2 [opt]
    frame #15: 0xffffff800e8a2a63 kernel.kasan`kernel_trap(state=0xffffffb0c2a0f390, lo_spp=<unavailable>) at trap.c:774:7 [opt]
    frame #16: 0xffffff800e8c091f kernel.kasan`trap_from_kernel + 38
    frame #17: 0xffffff800e8b83e5 kernel.kasan`kdp_call at kdp_machdep.c:338:1 [opt]
    frame #18: 0xffffff800e45834c kernel.kasan`kdp_set_ip_and_mac_addresses [inlined] debugger_if_necessary at kdp_udp.c:692:3 [opt]
    frame #19: 0xffffff800e45832f kernel.kasan`kdp_set_ip_and_mac_addresses(ipaddr=<unavailable>, macaddr=<unavailable>) at kdp_udp.c:800:2 [opt]
    frame #20: 0xffffff800edb9be9 kernel.kasan`ether_inet_prmod_ioctl(ifp=<unavailable>, protocol_family=<unavailable>, command=<unavailable>, data=<unavailable>) at ether_inet_pr_module.c:360:4 [opt]
    frame #21: 0xffffff800ed9261b kernel.kasan`ifnet_ioctl(ifp=<unavailable>, proto_fam=<unavailable>, ioctl_code=<unavailable>, ioctl_arg=0xffffff8ad560b230) at dlil.c:7224:14 [opt]
    frame #22: 0xffffff800f07f360 kernel.kasan`in_ifinit(ifp=<unavailable>, ia=<unavailable>, sin=0xffffff8ad53641fe, scrub=<unavailable>) at in.c:1779:10 [opt]
    frame #23: 0xffffff800f07b076 kernel.kasan`inctl_ifaddr(ifp=0xffffff8ad5364140, ia=0xffffff8ad560b230, cmd=<unavailable>, ifr=0xffffffb000000000) at in.c:730:12 [opt]
    frame #24: 0xffffff800f0765c4 kernel.kasan`in_control(so=<unavailable>, cmd=2151704858, data="en0", ifp=0xffffff8ad5364140, p=<unavailable>) at in.c:1580:11 [opt]
    frame #25: 0xffffff800ed6ba9f kernel.kasan`ifioctl(so=0xffffff8ad9ad9be0, cmd=2151704858, data="en0", p=<unavailable>) at if.c:3302:12 [opt]
    frame #26: 0xffffff800ed7453f kernel.kasan`ifioctllocked(so=0xffffff8ad9ad9be0, cmd=<unavailable>, data=<unavailable>, p=<unavailable>) at if.c:4186:10 [opt]
    frame #27: 0xffffff800f54ba55 kernel.kasan`soioctl(so=<unavailable>, cmd=<unavailable>, data=<unavailable>, p=<unavailable>) at sys_socket.c:266:11 [opt]
    frame #28: 0xffffff800f425eb3 kernel.kasan`fo_ioctl(fp=0xffffff8ad7990180, com=2151704858, data=<unavailable>, ctx=0xffffffb0c2a0fdd0) at kern_descrip.c:5662:10 [opt]
    frame #29: 0xffffff800f53be44 kernel.kasan`ioctl(p=<unavailable>, uap=<unavailable>, retval=<unavailable>) at sys_generic.c:1067:11 [opt]
    frame #30: 0xffffff800f8b2910 kernel.kasan`unix_syscall64(state=0xffffff8ad7c43310) at systemcalls.c:412:10 [opt]
    frame #31: 0xffffff800e8c10e6 kernel.kasan`hndl_unix_scall64 + 22
[(lldb) continue                                                                                                                             ]
Process 1 resuming
(lldb)
```

Code coverage analysis and Kemon

Kemon: An Open Source Pre and Post Callback-based Framework for macOS Kernel Monitoring
https://github.com/didi/kemon
https://www.blackhat.com/us-18/arsenal/schedule/index.html#kemon-an-open-source-pre-and-post-callback-based-framework-for-macos-kernel-monitoring-12085

I have ported Kemon and the kernel inline engine to the Apple Silicon platforms.

Summary #3 - Let's build

- About network interfaces and attack surfaces
- About static and dynamic analysis methods
- About creating tools

1. We have to do fixes because sometimes the built-in tools don't work very well.
2. We even need to implement KASAN-like solution, code coverage analysis tool to dynamically monitor third-party closed source kernel extensions.

Apple SDKs and build-in tools

Apple80211 SDKs
https://github.com/phracker/MacOSX-SDKs/releases

Build-in network and Wi-Fi tools, like airport, skywalkctl, etc.

```
Usage: skywalkctl COMMAND { option | help }
where COMMAND includes:
    channel
    flow
    flow-adv
    flow-owner
    flow-route
    flow-switch
    interface
    memory
    netns
    ......
```

Contribute to the community

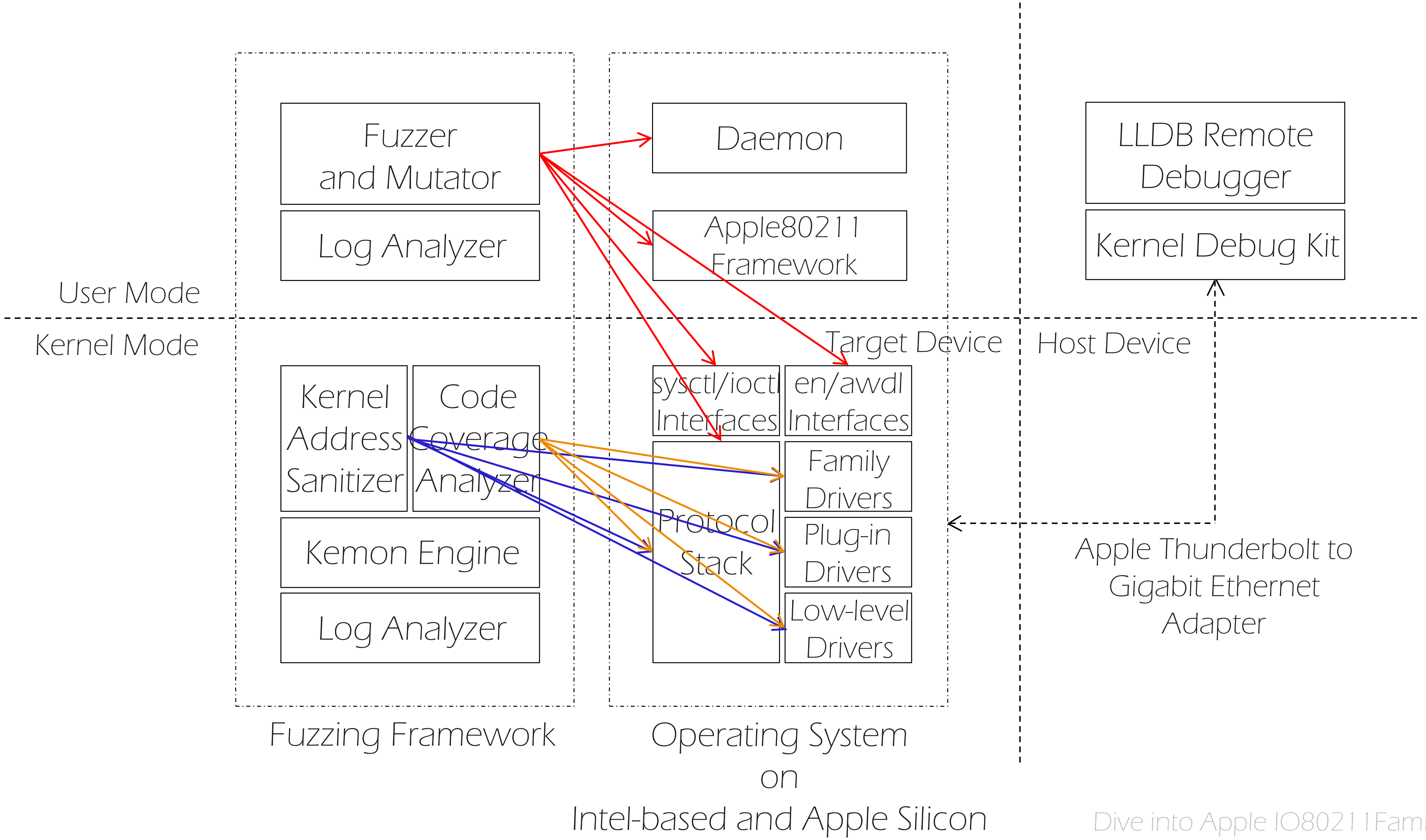
```
#define APPLE80211_IOC_COMPANION_SKYWALK_LINK_STATE            0x162
#define APPLE80211_IOC_NAN_LLW_PARAMS                          0x163
#define APPLE80211_IOC_HP2P_CAPS                               0x164
#define APPLE80211_IOC_RLLW_STATS                              0x165
        APPLE80211_IOC_UNKNOWN (NULL/No corresponding handler) 0x166
#define APPLE80211_IOC_HW_ADDR                                 0x167
#define APPLE80211_IOC_SCAN_CONTROL                            0x168

......

#define APPLE80211_IOC_SOFTAP_EXTENDED_CAPABILITIES_IE         0x192
#define APPLE80211_IOC_ENABLE_PACKET_TS                        0x193
#define APPLE80211_IOC_DISABLE_PACKET_TS                       0x194
#define APPLE80211_IOC_REALTIME_QOS_MSCS                       0x196
#define APPLE80211_IOC_TX_RATE                                 0x19A
#define APPLE80211_IOC_NANPHS_ASSOCIATION                      0x19B
#define APPLE80211_IOC_NANPHS_TERMINATED                       0x19C
#define APPLE80211_IOC_AWDL_MI_BITMAP                          0x19F
#define APPLE80211_IOC_NANPH_SOFTAP_CSA                        0x1A3
#define APPLE80211_IOC_REMOTE_CAMERA_STATE                     0x1A4
```

Summary #4 - The others

- About network interfaces and attack surfaces
- About static and dynamic analysis methods
- About creating tools
- About others

1. Pay attention to the tools provided in the macOS/iOS operating system.
2. We should make full use of the Apple SDKs, and contribute to Wi-Fi developer community.

The big picture



DEMO

Apple 80211 Wi-Fi subsystem fuzzing framework
on the latest
macOS Ventura 13.0 Beta 4 (22A5311f)

Apple 80211 Wi-Fi Subsystem
Latest Zero-day Vulnerability Case Studies

Follow-up IDs and CVEs

Apple product security Follow-up IDs include:
791541097 aka. CVE-2022-32837, 797421595 aka. CVE-2022-26761, 797590499 aka. CVE-2022-26762, OE0896842577 15 aka. CVE-2022-32860, OE089692707433 aka. CVE-2022-32847, OE089712553931, OE089712773100, OE0900967233115, OE0908765113017, OE090916270706, etc.

N-day vulnerabilities

Vulnerabilities CVE-2020-9899 and CVE-2020-10013 haven't been fixed before Black Hat USA 2020, so I can't share their details two years ago. Since these two kernel vulnerabilities are really interesting, the case study part will start with them.

Similarly, there are also some vulnerabilities that haven't been fixed in time this year. I hope we can continue the topic next time.

Case #1 - Kernel stack-based buffer overflow vulnerability

CVE-2020-9899
AirPortBrcmNIC`AirPort_BrcmNIC::setROAM_PROFILE
Kernel Stack Overflow Vulnerability

About the security content of macOS Catalina 10.15.6,
Security Update 2020-004 Mojave, Security Update 2020-004 High Sierra
https://support.apple.com/en-us/HT211289

Broadcom's OSL

The vulnerability is related to Broadcom's OS Independent Layer (OSL).

These legacy codes use byte-to-byte assignment instead of safe string copy functions.

Vulnerable function mistakenly trusts the input parameter and treats it as the exit condition of the assignment loop.

```
if ( input_length )
{
  source = input_buffer + 3;
  destination = stack_variable;
  for ( index = 0LL; index < input_length; ++index )
  {
    *destination = *source;
    *(destination + 1) = *(source + 1);
    *(destination + 2) = *(source + 2);
    *(destination + 3) = *(source + 3);
    *(destination + 4) = *(source + 4);
    *(destination + 5) = *(source + 5);
    *(destination + 3) = *(source + 3);
    *(destination + 4) = *(source + 4);
    *(destination + 5) = *(source + 5);
    *(destination + 6) = *(source + 6);
    *(destination + 7) = *(source + 7);
    source += 4;
    destination += 2;
  }
}

bcmerror = (*(*this + 0xDF0LL))(this, "roam_prof", 0LL, 0LL, &v13, 0x48LL, 1LL, a2);
return osl_error(bcmerror);
```

macOS High Sierra 10.13.5 (17F77)
AirPort_BrcmNIC::setROAM_PROFILE

```
* thread #1, stop reason = EXC_BAD_INSTRUCTION (code=13, subcode=0x0)
    frame #0: 0xffffff7f9d19945d AirPortBrcmNIC`AirPort_BrcmNIC::setROAM_PROFILE(OSObject*, apple80211_roam_profile_band_data*) + 353
AirPortBrcmNIC`AirPort_BrcmNIC::setROAM_PROFILE:
->  0xffffff7f9d19945d <+353>: retq

AirPortBrcmNIC`AirPort_BrcmNIC::setCHANNEL:
    0xffffff7f9d19945e <+0>:   pushq  %rbp
    0xffffff7f9d19945f <+1>:   movq   %rsp, %rbp
    0xffffff7f9d199462 <+4>:   pushq  %r15
Target 0: (kernel.development) stopped.
(lldb) register read
General Purpose Registers:
       rax = 0x0000000000000016
       rbx = 0x9d0c01fcffffff7f
       rcx = 0xffffff7f9d491d20  AirPortBrcmNIC`bcmerrormap
       rdx = 0xffffff7f9d659943  "roam_prof"
       rdi = 0x00000000ffffffe8
       rsi = 0xffffff803e5e9000
       rbp = 0x9d0c2300ffffff7f
       rsp = 0xffffff920d8db8b8
        r8 = 0x000000000000000b
        r9 = 0xffffff820b64d000
       r10 = 0x0000000000000009
       r11 = 0x000000000000000b
       r12 = 0xbae9e000ffffff7f
       r13 = 0x0d8dbb18ffffff81
       r14 = 0x0d8db9c0ffffff92
       r15 = 0x9d0c23aaffffff92
       rip = 0xffffff7f9d19945d  AirPortBrcmNIC`AirPort_BrcmNIC::setROAM_PROFILE(OSObject*, apple80211_roam_profile_band_data*) + 353
    rflags = 0x0000000000010286
        cs = 0x0000000000000008
        fs = 0x0000000000000000
        gs = 0x0000000000000000

(lldb) memory read 0xffffff920d8db8b8-0x100 -c0x200
0xffffff920d8db7b8: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
0xffffff920d8db7c8: 00 00 00 00 00 00 00 00 20 b8 8d 0d 92 ff ff ff  ........ ?...???
0xffffff920d8db7d8: b6 0a 19 9d 7f ff ff ff 60 7d 47 3e 80 ff ff ff  ?....???`}G>.???
0xffffff920d8db7e8: 48 00 00 00 00 00 00 00 43 99 65 9d 7f ff ff ff  H.......C.e..???
0xffffff920d8db7f8: a4 b9 8d 0d 92 ff ff ff 16 00 00 00 00 00 00 00  ??...???........
0xffffff920d8db808: 40 b8 8d 0d 92 ff ff ff 00 e0 5d 3e 80 ff ff ff  @?...???.?]>.???
0xffffff920d8db818: 00 e0 e9 ba 81 ff ff ff b0 b8 8d 0d 92 ff ff ff  .??.?????...???
0xffffff920d8db828: 3e 94 19 9d 7f ff ff ff b0 b8 8d 0d 92 ff ff ff  >....?????...???
0xffffff920d8db838: 49 94 19 9d 7f ff ff ff 02 00 00 00 00 00 80 00  I....???........
0xffffff920d8db848: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db858: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db868: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db878: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db888: 7f ff ff ff fc 01 0c 9d 7f ff ff ff 00 e0 e9 ba  .????....???.??
0xffffff920d8db898: 81 ff ff ff 18 bb 8d 0d 92 ff ff ff c0 b9 8d 0d  .???.?...?????..
0xffffff920d8db8a8: 92 ff ff ff aa 23 0c 9d 7f ff ff ff 00 23 0c 9d  .????#...???.#..
0xffffff920d8db8b8: 01 00 00 00 00 e0 e9 ba 81 ff ff ff c8 69 28 80  .....??.????i(.
0xffffff920d8db8c8: f6 29 0c 9d 7f ff ff ff 00 e0 e9 ba 81 ff ff ff  ?)...???.??.???
0xffffff920d8db8d8: 00 e0 e9 ba 81 ff ff ff 00 e0 5d 3e 80 ff ff ff  .??.???.?]>.???
0xffffff920d8db8e8: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
0xffffff920d8db8f8: 00 e0 5d 3e 80 ff ff ff 80 b9 8d 0d 92 ff ff ff  .?]>.???.?...???
0xffffff920d8db908: 90 02 0c 9d 7f ff ff ff 4c 00 00 00 00 00 00 00  .....???L.......
0xffffff920d8db918: 01 00 00 00 41 41 41 41 08 00 00 00 41 41 41 41  ....AAAA....AAAA
0xffffff920d8db928: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db938: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db948: 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41 41  AAAAAAAAAAAAAAAA
0xffffff920d8db958: 41 41 41 41 41 41 41 41 41 41 41 41 7f ff ff ff  AAAAAAAAAAAA.???
0xffffff920d8db968: fc 01 0c 9d 7f ff ff ff 00 e0 e9 ba 81 ff ff ff  ?....???.??.???
0xffffff920d8db978: 18 bb 8d 0d 92 ff ff ff c0 b9 8d 0d 92 ff ff ff  .?...?????...???
0xffffff920d8db988: aa 23 0c 9d 7f ff ff ff 00 23 0c 9d 01 00 00 00  ?#...???.#......
0xffffff920d8db998: 00 e0 e9 ba 81 ff ff ff c8 69 28 80 00 00 00 00  .??.????i(.....
0xffffff920d8db9a8: 00 00 00 00 00 00 00 00 d8 00 00 00 00 00 00 00  ........?.......
(lldb)
```

Stack canary

Does stack-based buffer overflow vulnerability still make sense today?

CVE-2019-8648 (p101 - p109)
https://i.blackhat.com/USA-19/Thursday/us-19-Huang-Towards-Discovering-Remote-Code-Execution-Vulnerabilities-In-Apple-FaceTime.pdf

simple_mmc_erase_partition_wrap (p6 - p11)
https://i.blackhat.com/asia-21/Thursday-Handouts/as-21-Wang-Racing-The-Dark-A-New-Tocttou-Story-From-Apples-Core.pdf

Summary of case #1 - CVE-2020-9899

1. Stack-based buffer overflow vulnerabilities can still be seen today, especially in legacy code.

2. For CVE-2020-9899, the vulnerable function has no stack canary protection, we can control local variables, RBP and even RIP registers.

3. Exploitation of kernel stack-based buffer overflows in the real world is not as straightforward as in the books. Especially when you don't have a kernel debugger.

Two years have passed

Are there still such high-quality kernel stack-based overwrite vulnerabilities?

Definitely

CVE-2022-32847
AirPort_BrcmNIC::setup_btc_select_profile Kernel Stack Overwrite Vulnerability

About the security content of iOS 15.6 and iPadOS 15.6
https://support.apple.com/en-us/HT213346

About the security content of macOS Monterey 12.5
https://support.apple.com/en-us/HT213345

About the security content of macOS Big Sur 11.6.8
https://support.apple.com/en-us/HT213344

BTCOEX_PROFILES and BTCOEX_CONFIG

The vulnerability is related to "BTCoex Profile" and "BTCoex Config" features.

Stack-based variables are passed between functions, but the vulnerable kernel function mistakenly treats them as normal and trusted inputs.

Case study of CVE-2022-32847

```
Process 1 stopped
* thread #1, stop reason = EXC_BAD_ACCESS (code=10, address=0xd1dd0000)
    frame #0: 0xffffff8005a53fbb
->  0xffffff8005a53fbb: cmpl   $0x1, 0x18(%rbx,%rcx,4)
    0xffffff8005a53fc0: cmovnel %esi, %edi
    0xffffff8005a53fc3: orl    %edi, %edx
    0xffffff8005a53fc5: incq   %rcx

(lldb) register read
General Purpose Registers:
       rax = 0x00000000481b8d16
       rbx = 0xffffffb0d1dcf3f4
       rcx = 0x00000000000002fd
       rdx = 0x0000000000800600
       rbp = 0xffffffb0d1dcf3e0
       rsp = 0xffffffb0d1dcf3c0
       rip = 0xffffff8005a53fbb  AirPortBrcmNIC`AirPort_BrcmNIC::setup_btc_select_profile + 61
       ......
```

Summary of case #1 - CVE-2022-32847

1. Kernel stack overwrite vulnerabilities represented by CVE-2022-32847 can often be found. The root cause is related to stack-based variables being passed and used for calculation or parsing.
2. The stack canary solution can't solve all the problems.

Case #2 - Arbitrary memory write vulnerability

CVE-2020-10013
AppleBCMWLANCoreDbg Arbitrary Memory Write Vulnerability

About the security content of iOS 14.0 and iPadOS 14.0
https://support.apple.com/en-us/HT211850

About the security content of macOS Catalina 10.15.7,
Security Update 2020-005 High Sierra, Security Update 2020-005 Mojave
https://support.apple.com/en-us/HT211849

Boundary checking

A weird kernel-space boundary condition caused this vulnerability.

```
if ( (controlled_destination_buffer + 0x8000000000LL) >> 12 > 0x7FFFFFE )
{
  ret_value = copyout(malloced_source_buffer, controlled_destination_buffer, length);
  *malloced_source_buffer = 0;
  if ( !ret_value )
    goto LABEL_29;
  goto LABEL_25;
}
memmove(controlled_destination_buffer, malloced_source_buffer, length);
*malloced_source_buffer = 0;
```

macOS Catalina 10.15.6 Beta (19G60d)
AppleBCMWLANUserPrint

Don't let the defensive end's show time turn into a showstopper.

Case study of CVE-2020-10013

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
    frame #0: 0xffffff8000398082 kernel`bcopy + 18
kernel`bcopy:
->  0xffffff8000398082  <+18>: rep
    0xffffff8000398083  <+19>: movsb  (%rsi), %es:(%rdi)
    0xffffff8000398084  <+20>: retq

(lldb) register read
General Purpose Registers:
       rcx = 0x0000000000000011
       rsi = 0xffffff81b1d5e000
       rdi = 0xffffff80deadbeef

(lldb) bt
* thread #1, stop reason = signal SIGSTOP
  * frame #0: 0xffffff8000398082 kernel`bcopy + 18
    frame #1: 0xffffff800063abd4 kernel`memmove + 20
    frame #2: 0xffffff7f828e1a64 AppleBCMWLANCore`AppleBCMWLANUserPrint + 260
    ......
```

A complete LPE chain

Combined with kernel information disclosure vulnerabilities, a complete local EoP exploit chain can be formed.

A good information disclosure example is here:

CVE-2020-9833 (p44 - p49)
https://i.blackhat.com/USA-20/Thursday/us-20-Wang-Dive-into-Apple-IO80211FamilyV2.pdf

Summary of case #2 - CVE-2020-10013

1. CVE-2020-10013 is an arbitrary memory write vulnerability caused by boundary checking error.
2. The value to be written is controllable or predictable.
3. Combined with kernel information disclosure vulnerabilities, a complete local EoP exploit chain can be formed. The write primitive is stable and does not require heap Feng Shui manipulation.
4. This vulnerability affects hundreds of AppleBCMWLANCoreDbg handlers!

Two years have passed

Are there still such high-quality arbitrary kernel memory write vulnerabilities?

Definitely

CVE-2022-26762
IO80211Family`getRxRate Arbitrary Memory Write Vulnerability

About the security content of iOS 15.5 and iPadOS 15.5
https://support.apple.com/en-us/HT213258

About the security content of macOS Monterey 12.4
https://support.apple.com/en-us/HT213257

User input sanitization

The vulnerable function forgets to sanitize user-mode pointer.

macOS/iOS/FreeBSD kernel's copyin and copyout:
https://developer.apple.com/documentation/kernel/1441036-copyin
https://developer.apple.com/documentation/kernel/1441088-copyout

Linux kernel's __copy_from_user and __copy_to_user:
https://www.kernel.org/doc/htmldocs/kernel-api/API---copy-from-user.html
https://www.kernel.org/doc/htmldocs/kernel-api/API---copy-to-user.html

Windows kernel's ProbeForRead and ProbeForWrite:
https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/nf-wdm-probeforread
https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/nf-wdm-probeforwrite

Case study of CVE-2022-26762

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
    frame #0: 0xffffff8008b23ed7 IO80211Family`getRxRate(IO80211Controller*, IO80211Interface*,
IO80211VirtualInterface*, IO80211InfraInterface*, apple80211req*, bool) + 166
IO80211Family`getRxRate:
->  0xffffff8008b23ed7 <+166>: movl   %eax, (%rbx)
    0xffffff8008b23ed9 <+168>: xorl   %eax, %eax
    0xffffff8008b23edb <+170>: movq   0xca256(%rip), %rcx
    0xffffff8008b23ee2 <+177>: movq   (%rcx), %rcx

(lldb) register read
General Purpose Registers:
       rax = 0x0000000000000258
       rbx = 0xdeadbeefdeadcafe
       rdi = 0xffffff90345b4dc0
       rsi = 0xffffff8008203ee0
       rbp = 0xffffffd079bcba40
       rsp = 0xffffffd079bcba10
       rip = 0xffffff8008b23ed7  IO80211Family`getRxRate + 166
       ......
```

Summary of case #2 - CVE-2022-26762

1. Compared with CVE-2020-10013, the root cause of CVE-2022-26762 is simpler: the vulnerable function forgets to sanitize user-mode pointer. These simple and stable kernel vulnerabilities are powerful, they are perfect for Pwn2Own.

2. The value to be written is fixed.

3. Kernel vulnerabilities caused by copyin/copyout, copy_from_user/copy_to_user, ProbeForRead/ProbeForWrite are very common. Kernel developers should carefully check all input parameters.

Case #3 - Kernel heap out-of-bounds read and write vulnerability

CVE-2022-32837
IO80211Family`setPropertiesIoctl Kernel Out-of-bounds Access Vulnerability

CVE-2022-32860
AirPort_BrcmNIC::setAWDL_SYNCHRONIZATION_CHANNEL_SEQUENCE
Kernel Out-of-bounds Write Vulnerability

About the security content of iOS 15.6 and iPadOS 15.6
https://support.apple.com/en-us/HT213346

About the security content of macOS Monterey 12.5
https://support.apple.com/en-us/HT213345

Case study of CVE-2022-32837 on Intel-based platform

```
Process 1 stopped
* thread #1, stop reason = EXC_BAD_ACCESS (code=10, address=0x827e4000)
    frame #0: 0xffffff800b101082 kernel`bcopy + 18
kernel`bcopy:
->  0xffffff800b101082 <+18>: rep    movsb   (%rsi), %es:(%rdi)

(lldb) register read
General Purpose Registers:
       rcx = 0x0000000000abcdef
       rdi = 0xffffffa06c08e658
       rsi = 0xffffffd0827e4000

(lldb) bt
* thread #1, stop reason = signal SIGSTOP
  * frame #0: 0xffffff800b101082 kernel`bcopy + 18
    frame #1: 0xffffff800b9b3244 kernel`OSData::initWithBytes [inlined] memmove at loose_ends.c:918:2 [opt]
    frame #2: 0xffffff800b9b323c kernel`OSData::initWithBytes [inlined] __memmove_chk at subrs.c:659:9 [opt]
    frame #3: 0xffffff800b9b323c kernel`OSData::initWithBytes at OSData.cpp:129:3 [opt]
    frame #4: 0xffffff800b9e429e kernel`OSUnserializeBinary at [inlined] OSData::withBytes OSData.cpp:186:17
    ......
```

Case study of CVE-2022-32837 on Apple Silicon

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
    frame #0: 0xfffffe001ce20eac kernel.release.t6000`DebuggerTrapWithState at debug.c:665:2 [opt]
Target 3: (kernel.release.t6000) stopped.

(lldb) di -n OSUnserializeXML
kernel.release.t6000`OSUnserializeXML:
    0xfffffe001d4d3064 <+48>: add    x8, x1, x0
->  0xfffffe001d4d3068 <+52>: ldurb  w8, [x8, #-0x1]
    0xfffffe001d4d306c <+56>: cbz    w8, -0x1ffe2b2cf88        ; <+68> at OSUnserializeXML.y:1437:9

(lldb) register read
General Purpose Registers:
        x0 = 0xfffffe751b9026c8
        x1 = 0x00000000deadbeef
        x2 = 0xfffffe751b9026b8
        x3 = 0x33b97e001d4900a8 (0xfffffe001d4900a8) kernel.release.t6000`OSObject::taggedRelease const at
OSObject.cpp:167
        pc = 0xfffffe001d4d3068  kernel.release.t6000`OSUnserializeXML + 52 at OSUnserializeXML.y:1433:6
        ......
```

```
Kernel slid 0x16e10000 in memory.
Loaded kernel file /Library/Developer/KDKs/KDK_11.6.5_20G527.kdk/System/Library/Kernels/kernel.kasan
warning: 'kernel' contains a debug script. To run this script in this debug session:

    command script import "/Library/Developer/KDKs/KDK_11.6.5_20G527.kdk/System/Library/Kernels/kernel.kasan.dSYM/Contents/Resources/Python/kernel.py"

To run all discovered debug scripts in this session:

    settings set target.load-script-from-symbol-file true

Loading 155 kext modules -----.--------------...--------------.-----.----------.-------------------------------.------------..------------.--------------------.------------------.- done.
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
    frame #0: 0xffffff80170d82da kernel.kasan`DebuggerTrapWithState [inlined] current_debugger_state at debug.c:176:9 [opt]
Target 13: (kernel.kasan) stopped.
(lldb) register read
General Purpose Registers:
       rax = 0x0000000000000001
       rbx = 0x0000000000000000
       rcx = 0x0000000000000000
       rdx = 0xffffff8018946c39  ""%s"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6c82cc8/Library/Caches/com.apple.xbs/Sources/xnu_kasan/xnu-7195.141.26/san/kasan.c:511"
       rdi = 0x0000000000000003
       rsi = 0xffffff801888163a  "panic"
       rbp = 0xffffffa078faec80
       rsp = 0xffffffa078faec40
        r8 = 0x0000000000000000
        r9 = 0x0000000000000000
       r10 = 0x0000000000000000
       r11 = 0x0000000000000008
       r12 = 0x0000000000000000
       r13 = 0xffffff80197e6680  kernel.kasan`percpu_slot_debugger_state
       r14 = 0xffffff8018946c39  ""%s"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6c82cc8/Library/Caches/com.apple.xbs/Sources/xnu_kasan/xnu-7195.141.26/san/kasan.c:511"
       r15 = 0x0000000000000003
       rip = 0xffffff80170d82da  kernel.kasan`DebuggerTrapWithState + 202 [inlined] current_debugger_state at debug.c:176:9
  kernel.kasan`DebuggerTrapWithState + 202 at debug.c:598:8
    rflags = 0x0000000000000046
        cs = 0x0000000000000008
        fs = 0x000000001fff0000
        gs = 0x000000000f1f0000

(lldb) bt
* thread #1, stop reason = signal SIGSTOP
  * frame #0: 0xffffff80170d82da kernel.kasan`DebuggerTrapWithState [inlined] current_debugger_state at debug.c:176:9 [opt]
    frame #1: 0xffffff80170d82da kernel.kasan`DebuggerTrapWithState(db_op=DBOP_PANIC, db_message="panic", db_panic_str="\"%s\"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6c82cc8/Library/Caches/com.apple.xbs/Sourc
es/xnu_kasan/xnu-7195.141.26/san/kasan.c:511", db_panic_args=0xffffffa078faed30, db_panic_options=0, db_panic_data_ptr=0x0000000000000000, db_proceed_on_sync_failure=1, db_panic_caller=18446743524365276617) at debu
g.c:598:8 [opt]
    frame #2: 0xffffff80170d9041 kernel.kasan`panic_trap_to_debugger(panic_format_str="\"%s\"@/System/Volumes/Data/SWE/macOS/BuildRoots/a0c6c82cc8/Library/Caches/com.apple.xbs/Sources/xnu_kasan/xnu-7195.141.26/san/
kasan.c:511", panic_args=<unavailable>, reason=0, ctx=0x0000000000000000, panic_options_mask=0, panic_data_ptr=<unavailable>, panic_caller=18446743524365276617) at debug.c:938:2 [opt]
    frame #3: 0xffffff801885ed23 kernel.kasan`panic(str=<unavailable>) at debug.c:803:2 [opt]
    frame #4: 0xffffff80188795c9 kernel.kasan`kasan_report_internal.cold.1 at kasan.c:511:3 [opt]
    frame #5: 0xffffff80188533bd kernel.kasan`kasan_report_internal(p=<unavailable>, width=<unavailable>, access=<unavailable>, reason=<unavailable>, dopanic=<unavailable>) at kasan.c:511:3 [opt]
    frame #6: 0xffffff8018851533 kernel.kasan`kasan_crash_report(p=<unavailable>, width=<unavailable>, access=<unavailable>, reason=<unavailable>) at kasan.c:521:2 [opt]
    frame #7: 0xffffff801885101a kernel.kasan`kasan_violation(addr=<unavailable>, size=<unavailable>, access=<unavailable>, reason=<unavailable>) at kasan.c:279:2 [opt]
    frame #8: 0xffffff80188521f9 kernel.kasan`kasan_check_free(addr=18446743662184594176, size=256, heap_type=1) at kasan.c:1126:3 [opt]
    frame #9: 0xffffff80170ff5e9 kernel.kasan`kfree_ext(kheap=<unavailable>, data=<unavailable>, size=256) at kalloc.c:1118:2 [opt]
    frame #10: 0xffffff80170ff3b8 kernel.kasan`kfree(addr=<unavailable>, size=<unavailable>) at kalloc.c:1162:2 [opt] [artificial]
    frame #11: 0xffffff801860e0f4 kernel.kasan`::IOFree(inAddress=<unavailable>, size=256) at IOLib.cpp:374:3 [opt]
    frame #12: 0xffffff801a633fbd AirPortBrcmNIC`osl_mfree + 330
    frame #13: 0xffffff801a66198e AirPortBrcmNIC`AirPort_BrcmNIC::setAWDL_SYNCHRONIZATION_CHANNEL_SEQUENCE(OSObject*, apple80211_awdl_sync_channel_sequence*) + 742
    frame #14: 0xffffff801a6708e0 AirPortBrcmNIC`AirPort_BrcmNIC::apple80211VirtualRequest(unsigned int, int, IO80211VirtualInterface*, void*) + 3072
```

Summary of case #3 - CVE-2022-32837 and CVE-2022-32860

1. The root causes of these vulnerabilities are related to the lack of effective input verification, logic errors, integer overflow, etc.

2. Exploitation of vulnerabilities usually requires skills such as heap Feng Shui. A good kernel heap Feng Shui example is here:

A New CVE-2015-0057 Exploit Technology
https://www.blackhat.com/docs/asia-16/materials/asia-16-Wang-A-New-CVE-2015-0057-Exploit-Technology.pdf
https://www.blackhat.com/docs/asia-16/materials/asia-16-Wang-A-New-CVE-2015-0057-Exploit-Technology-wp.pdf

3. This type of vulnerability can be easily captured by KASAN.

Case #4 - Type confusion vulnerability

CVE-2022-26761
IO80211AWDLPeerManager::updateBroadcastMI
Kernel Out-of-bounds Access Vulnerability caused by Type Confusion

About the security content of macOS Monterey 12.4
https://support.apple.com/en-us/HT213257

About the security content of macOS Big Sur 11.6.6
https://support.apple.com/en-us/HT213256

Case study of CVE-2022-26761

The first parameter of the function IO80211AWDLPeerManager::updateBroadcastMI is defined as the IO80211SkywalkInterface, and the size of this object is greater than 0x6860.

```
(lldb) memory read 0xffffffa0431df000
0xffffffa0431df000: 68 f7 7e 16 80 ff ff ff 05 00 00 00 00 00 00 00  h.~.............
0xffffffa0431df010: f0 1f 03 dc 99 ff ff ff 18 f0 1d 43 a0 ff ff ff  ...........C....
0xffffffa0431df020: 18 f0 1d 43 a0 ff ff ff 20 58 90 a8 86 ff ff ff  ...C.... X......
0xffffffa0431df030: 40 58 90 a8 86 ff ff ff 60 58 90 a8 86 ff ff ff  @X......`X......
0xffffffa0431df040: 80 58 90 a8 86 ff ff ff d0 0c bf 0e 95 ff ff ff  .X..............
0xffffffa0431df050: 70 c8 f1 a8 86 ff ff ff 00 00 00 00 00 00 00 00  p...............
0xffffffa0431df060: a0 58 90 a8 86 ff ff ff 00 00 00 00 00 00 00 00  .X..............
0xffffffa0431df070: 28 00 00 00 10 04 00 00 00 00 00 00 64 00 00 00  (...........d...
......
```

Mishandling

However, things get complicated when a function tries to support different subsystems or interfaces. Please note that the following input object is much smaller than 0x6000:

```
(lldb) memory read 0xffffff99c7ac2000
0xffffff99c7ac2000: 38 0e bf 02 80 ff ff ff 03 00 00 00 00 00 00 00  8...............
0xffffff99c7ac2010: a0 c4 53 2e a0 ff ff ff 18 20 ac c7 99 ff ff ff  ..S...... ......
0xffffff99c7ac2020: 18 20 ac c7 99 ff ff ff 80 8d a9 95 86 ff ff ff  . ..............
0xffffff99c7ac2030: a0 8d a9 95 86 ff ff ff c0 8d a9 95 86 ff ff ff  ................
0xffffff99c7ac2040: e0 8d a9 95 86 ff ff ff 00 35 87 61 8b ff ff ff  .........5.a....
0xffffff99c7ac2050: 00 72 56 61 8b ff ff ff 00 00 00 00 00 00 00 00  .rVa............
0xffffff99c7ac2060: 00 8e a9 95 86 ff ff ff 00 00 00 00 00 00 00 00  ................
0xffffff99c7ac2070: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
......
```

Type confusion

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
  frame #0: 0xffffff8004c7ff34
IO80211Family`IO80211AWDLPeerManager::updateBroadcastMI(MIPayloadUpdateReason_t, bool, bool) + 20
IO80211Family`IO80211AWDLPeerManager::updateBroadcastMI:
->  0xffffff8004c7ff34 <+20>: testb $0x2, 0x6568(%rdi)
    0xffffff8004c7ff3b <+27>: je   0xffffff8004c7ffef    ; <+207>

(lldb) register read
General Purpose Registers:
       rax = 0x0000000000000000
       rbx = 0xffffff94fdafd000
       rcx = 0x0000000000000000
       rdx = 0x0000000000000000
       rdi = 0xffffff94fdafd000
       rsi = 0x000000000000000e
       rbp = 0xffffffd0980fb940
       rsp = 0xffffffd0980fb910
       rip = 0xffffff8004c7ff34 IO80211Family`IO80211AWDLPeerManager::updateBroadcastMI + 20
       ......
```

The patch

After reviewing the patch of CVE-2022-26761, I found that there is still a NULL pointer dereference bug in the vulnerable function.

By the way, I found a lot of NULL pointer dereference bugs. Sometimes I have to report them because they slow down my fuzzing efforts.

```
Process 1 stopped
* thread #1, stop reason = signal SIGSTOP
->  0xffffff801bd665f2 <+413>: movq   (%r15), %rcx
    0xffffff801bd665f5 <+416>: movzbl %al, %esi
    0xffffff801bd665f8 <+419>: movq   %r15, %rdi
    0xffffff801bd665fb <+422>: callq  *0xaa0(%rcx)

(lldb) register read
General Purpose Registers:
       r15 = 0x0000000000000000
       ......
```

Summary of case #4 - CVE-2022-26761

1. Callback functions, especially those that support different architectures, interfaces or working modes, and state machine, exception handling need to be carefully designed.
2. Corner cases matter.
3. Security patch is worth auditing.

One more thing

1. Follow-up ID OE0909162707006 is related to kernel heap out-of-bounds write.

2. Follow-up ID OE0908765113017 is related to arbitrary kernel memory access. As far as I know, this is the second time in two years that the same function has been found to be vulnerable. There are other good examples:

CVE-2020-9834 (p43)
https://i.blackhat.com/USA-20/Thursday/us-20-Wang-Dive-into-Apple-IO80211FamilyV2.pdf

CVE-2020-3912 (p38 - p39)
https://i.blackhat.com/eu-20/Thursday/eu-20-Wang-Please-Make-A-Dentist-Appointment-ASAP-Attacking-IOBluetoothFamily-HCI-And-Vendor-Specific-Commands.pdf

Takeaways and The End

From the perspective of kernel development

1. Apple has made a lot of efforts, and the security of macOS/iOS has been significantly improved.
2. All inputs are potentially harmful, kernel developers should carefully check all input parameters.
3. New features always mean new attack surfaces.
4. Callback functions, especially those that support different architectures or working modes, and state machine, exception handling need to be carefully designed.
5. Corner cases matter.

From the perspective of vulnerability research

1. Arbitrary kernel memory write vulnerabilities represented by CVE-2022-26762 are powerful, they are simple and stable enough.

2. Combined with kernel information disclosure vulnerabilities such as CVE-2020-9833, a complete local EoP exploit chain can be formed.

3. Kernel stack out-of-bounds read and write vulnerabilities represented by CVE-2022-32847 can often be found. The root cause is related to stack-based variables being passed and used for calculation or parsing. The stack canary solution can't solve all the problems.

From the perspective of vulnerability research (cont)

4. Vulnerabilities represented by CVE-2022-26761 indicate that handlers that support different architectures or working modes are prone to problems.

5. Vulnerabilities represented by CVE-2020-3912, CVE-2020-9834 and Follow-up ID OE0908765113017 indicate that some handlers with complex logic will be introduced with new vulnerabilities every once in a while, even if the old ones have just been fixed.

6. Security patch is worth auditing.

From the perspective of security engineering and vulnerability hunting

1. It is important to integrate the interfaces and attack surfaces of a subsystem at different levels.

2. It is important to integrate KASAN and code coverage analysis tools.

3. Many work needs to be ported to Apple Silicon platform, such as Kemon.

4. We should combine all available means such as reverse engineering, kernel debugging, XNU resources, Apple SDKs and KDK kernels, third-party tools, etc.

5. If you've done this, or just started, you'll find that Apple did a lot of work, but the results seem to be similar to 2020.

Q&A

wang yu

Cyberserval

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