FirmSolo: Enabling dynamic analysis of binary Linux-based IoT kernel modules

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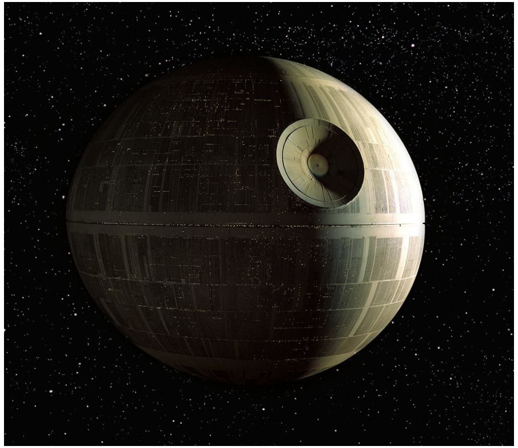
32nd Usenix Security Symposium

Date: 08/11/2023

SeclaBU

BOSTON UNIVERSITY

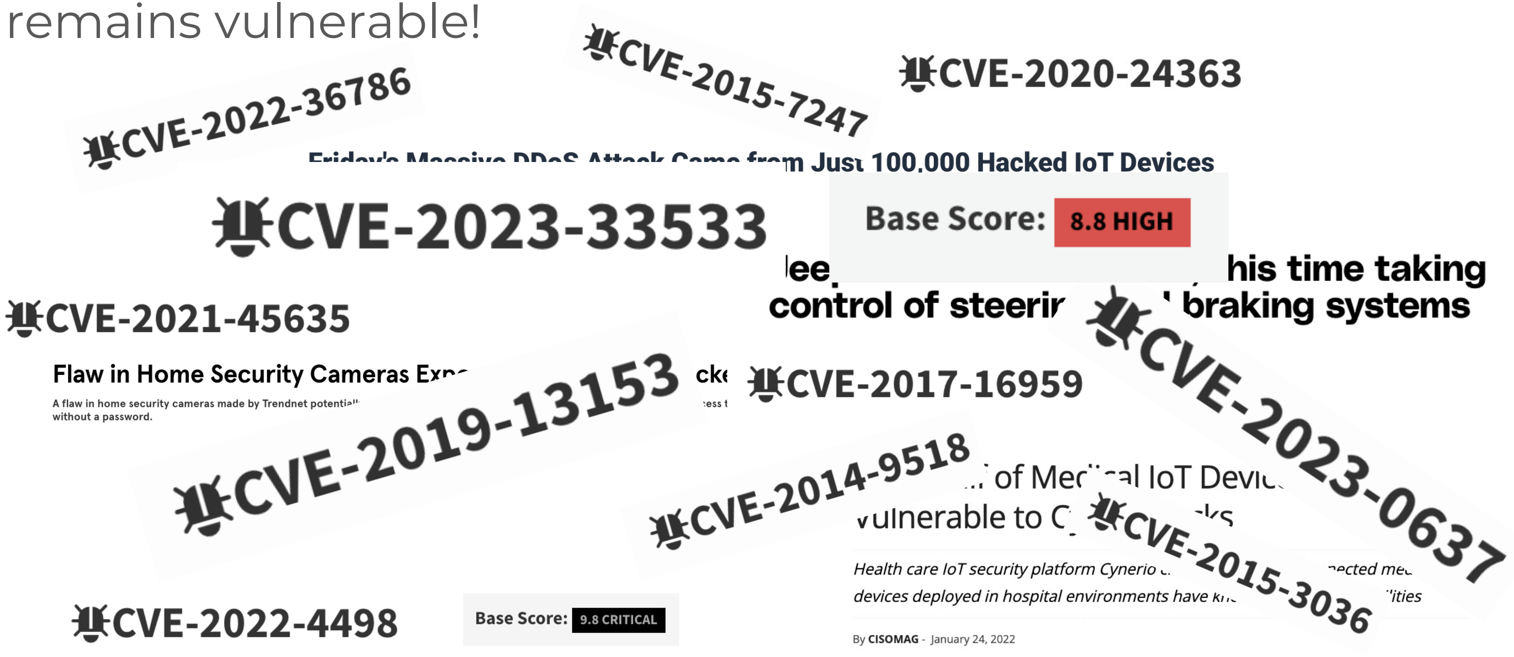
Internet of Things



Sources: https://www.amazon.com/
https://starwars.fandom.com/wiki/R2-D2
https://www.starwars.com/databank/death-star

IoT Security

IoT remains vulnerable!



CVE-2015-7247

CVE-2020-24363

CVE-2022-36786

Friday's Massive DDoS Attack Came from Just 100,000 Hacked IoT Devices

CVE-2023-33533

Base Score: 8.8 HIGH

lee ... his time taking control of steerir ... braking systems

CVE-2021-45635

Flaw in Home Security Cameras Exp ... cke

A flaw in home security cameras made by Trendnet potentiall ... cess t without a password.

CVE-2019-13153

CVE-2017-16959

CVE-2023-0637

CVE-2014-9518

of Medical IoT Devic ... vulnerable to C ... ks

CVE-2015-3036

Health care IoT security platform Cynerio ... nected me ... devices deployed in hospital environments have kn ... lities

By CISOMAG - January 24, 2022

CVE-2022-4498

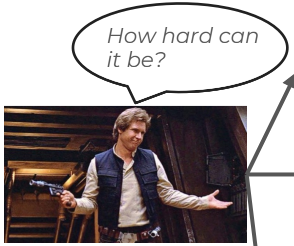
Base Score: 9.8 CRITICAL

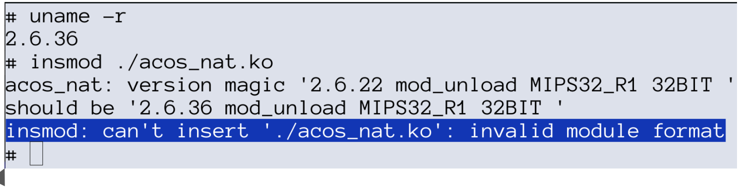
Linux-based IoT Firmware Analysis

- **Prior work primarily focused on user space!**
- Re-hosting
  - State-of-the-art emulators (e.g., QEMU) lack support for IoT hardware
  - Cannot emulate the firmware binary kernels!
- What about the IoT Linux loadable kernel modules (LKM)?
- What if LKMs only in binary form?
  - Frequent in the IoT domain!
  - Might contain vulnerabilities: *Kcode’s NetUSB.ko* (CVE-2015-3036)

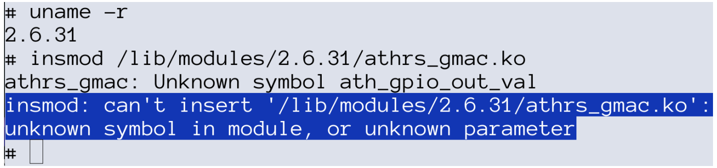
3 Key Challenges

Load IoT LKMs into QEMU supported kernels to dynamically analyze the LKMs

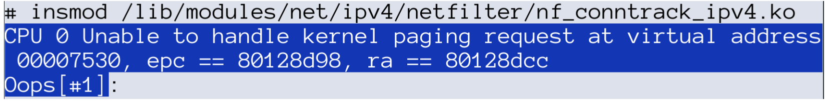




```
# uname -r
2.6.36
# insmod ./acos_nat.ko
acos_nat: version magic '2.6.22 mod_unload MIPS32_R1 32BIT '
should be '2.6.36 mod_unload MIPS32_R1 32BIT '
insmod: can't insert './acos_nat.ko': invalid module format
#
```



```
# uname -r
2.6.31
# insmod /lib/modules/2.6.31/athrs_gmac.ko
athrs_gmac: Unknown symbol ath_gpio_out_val
insmod: can't insert '/lib/modules/2.6.31/athrs_gmac.ko':
unknown symbol in module, or unknown parameter
#
```



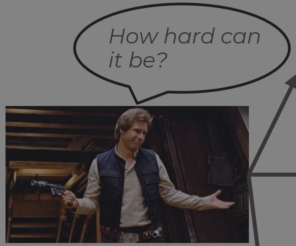
```
# insmod /lib/modules/net/ipv4/netfilter/nf_conntrack_ipv4.ko
CPU 0 Unable to handle kernel paging request at virtual address
 00007530, epc == 80128d98, ra == 80128dcc
Oops[#1]:
```

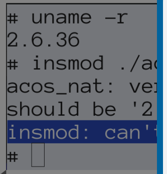
1. The kernel and kernel modules must be of the same version
2. External symbols (functions and data structures) the modules require must be provided:
   - Core kernel
   - Other modules loaded first (module dependencies)
3. The memory layout of data structures must be consistent between the kernel and the kernel modules
   - Misaligned data structure accesses!

3 Key Challenges

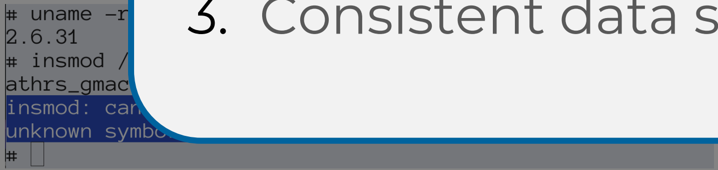
Load IoT LKMs into QEMU supported kernels to dynamically analyze the LKMs

1. Matching kernel version
2. Kernel symbol availability
3. Consistent data structure layouts

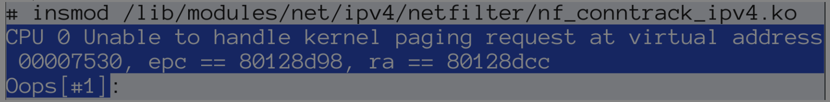




```
# uname -r
2.6.36
# insmod ./ac
acos_nat: ve
should be '2
insmod: can'
#
```



```
# uname -r
2.6.31
# insmod /
athrs_gmac
insmod: can
unknown symbo
#
```



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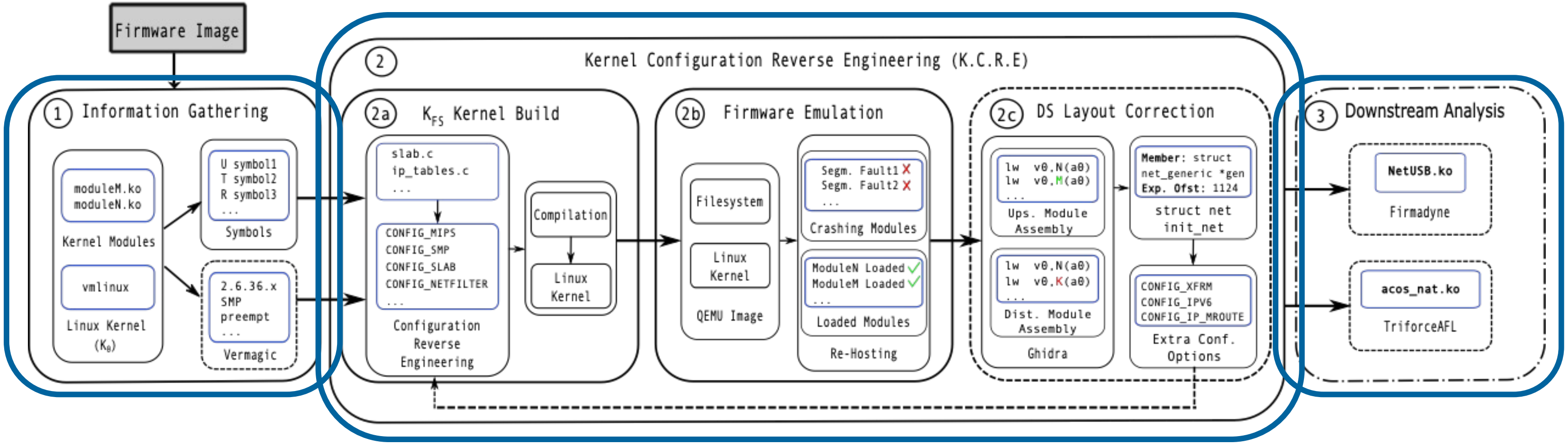
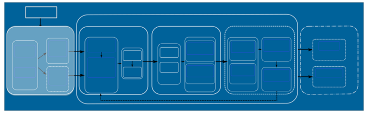
FirmSolo

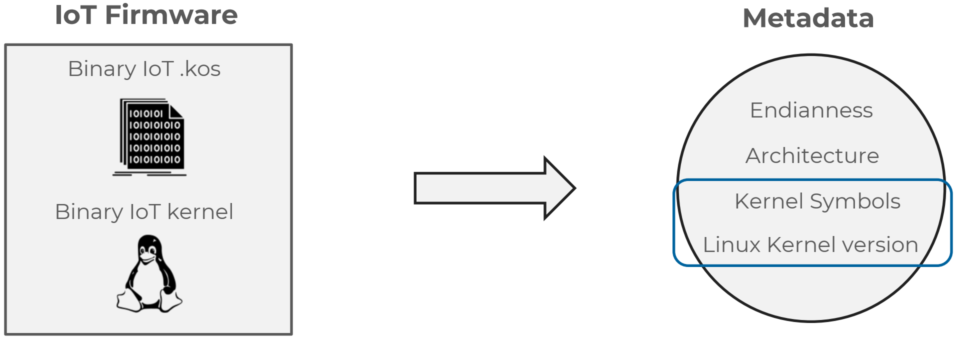
A framework to facilitate dynamic analysis of binary IoT kernel modules at scale



Information Gathering



- Gather metadata about the IoT firmware kernel
  - Used to compile a kernel that can load binary IoT kernel modules



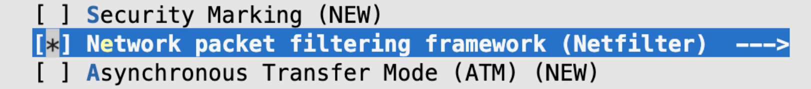
Challenges Revisited

Kernel symbol availability:

- Example:
  - *nf_register_hook*
- Defined in *net/netfilter/core.c*
- Guarded by *CONFIG_NETFILTER*

```
int nf_register_hook(struct nf_hook_ops *reg)
{
        struct nf_hook_ops *elem;
        int err;

        err = mutex_lock_interruptible(&nf_hook_mutex);
...
        list_add_rcu(&reg->list, elem->list.prev);
        mutex_unlock(&nf_hook_mutex);
        return 0;
}
EXPORT_SYMBOL(nf_register_hook);
```



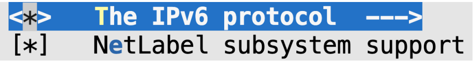
```
[ ] Security Marking (NEW)
[*] Network packet filtering framework (Netfilter)  --->
[ ] Asynchronous Transfer Mode (ATM) (NEW)
```

Consistent data structure layouts:

- Example:
  - *struct net*
- Represents network namespaces

```
struct net {
        atomic_t count;
        struct list_head list;
        struct list_head cleanup_list;
        struct list_head exit_list;
...
#if defined(CONFIG_IPV6)
        struct netns_ipv6 ipv6;
#endif
...
        struct sk_buff_head wext_nlevents;

        /* At offset &net + 0x324 */
        struct net_generic *gen;
};
```



```
<*>   The IPv6 protocol  --->
[*]   NetLabel subsystem support
```

Challenges Revisited

Kernel symbol availability:

- Example:
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        int err;

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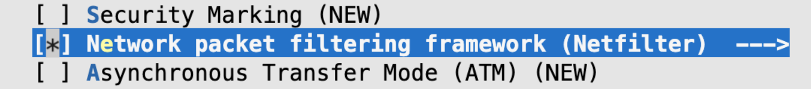
...
        list_add_rcu(&reg->list, elem->list.prev);
        mutex_unlock(&nf_hook_mutex);
        return 0;
}
EXPORT_SYMBOL(nf_register_hook);
```



```
[ ] Security Marking (NEW)
[*] Network packet filtering framework (Netfilter)  --->
[ ] Asynchronous Transfer Mode (ATM) (NEW)
```

Consistent data structure layouts:

- Example:
  - *struct net*
- Represents network namespaces

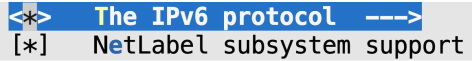
```
struct net {
        atomic_t count;
        struct list_head list;
        struct list_head cleanup_list;
        struct list_head exit_list;
...




        struct sk_buff_head wext_nlevents;

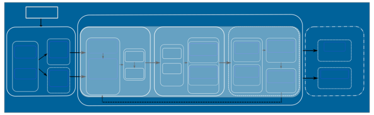
        /* At offset &net + 0x208 */
        struct net_generic *gen;
};
```

Crash!



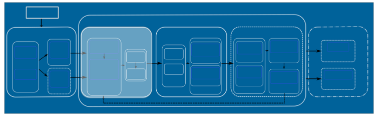
```
<*>   The IPv6 protocol  --->
[*]   NetLabel subsystem support
```

Kernel Configuration Reverse Engineering (K.C.R.E.)

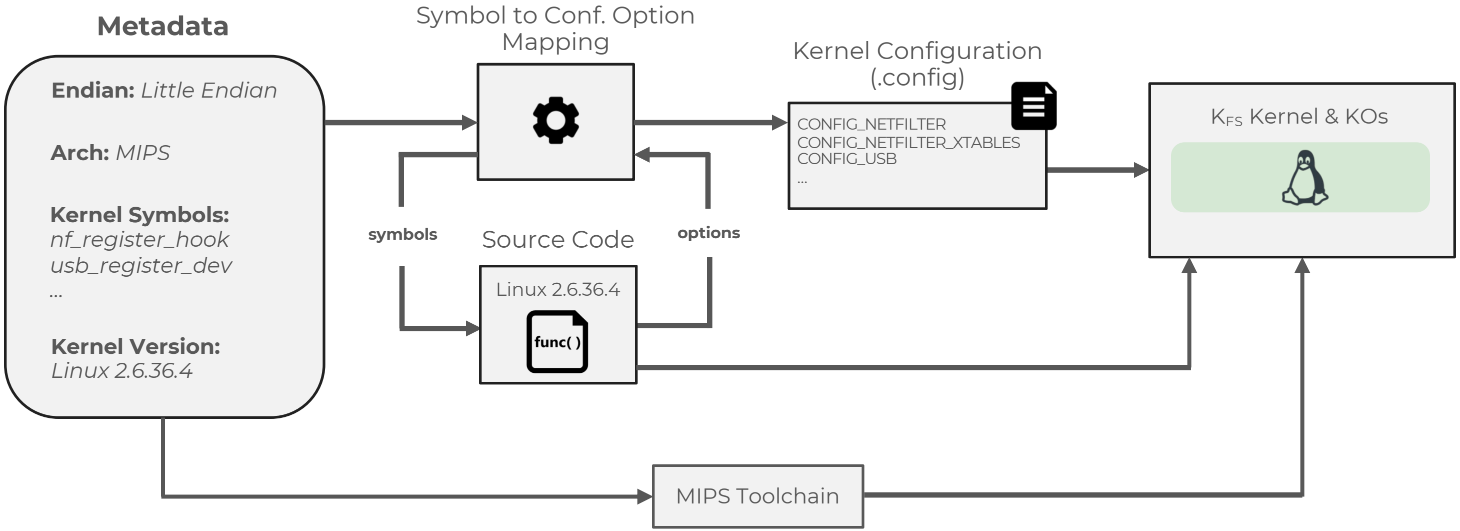


- Reverse engineer the IoT firmware kernel and compile a custom kernel capable of loading binary IoT kernel modules
- Consists of three steps:
  - K_{FS} Kernel build
  - Firmware Emulation
  - Data Structure Layout Correction (D.S.L.C.)

K_{FS} Kernel Build



- Build a kernel that can load binary IoT kernel modules
  - Reconstruct (approximately) the configuration of the IoT firmware kernel



Metadata

Endian: *Little Endian*

Arch: *MIPS*

Kernel Symbols:
nf_register_hook
usb_register_dev
...

Kernel Version:
Linux 2.6.36.4

Symbol to Conf. Option Mapping

symbols

options

Source Code

Linux 2.6.36.4

func( )

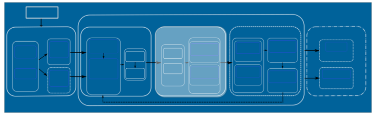
Kernel Configuration (.config)

CONFIG_NETFILTER
CONFIG_NETFILTER_XTABLES
CONFIG_USB
...

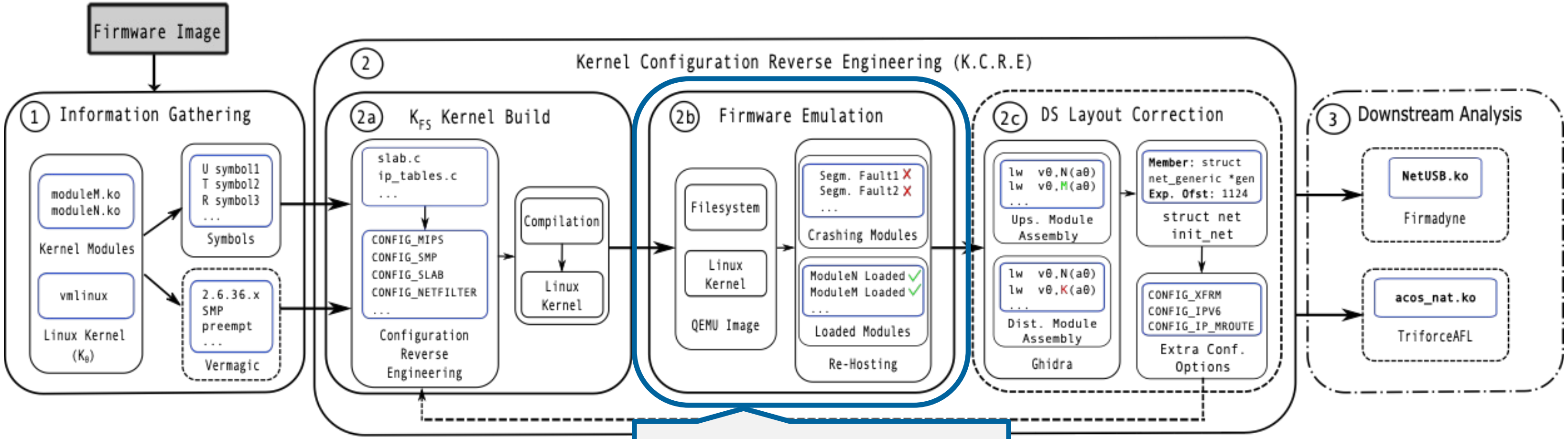
K_{FS} Kernel & KOs

MIPS Toolchain

Firmware Emulation

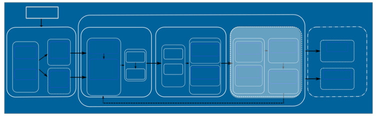


- Find which kernel modules can successfully load
  - Emulate the custom kernel K_{FS} and load the IoT kernel modules



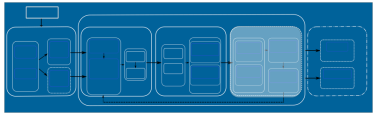
For details refer to the paper

Data Structure Layout Correction (D.S.L.C.)



- Address kernel module crashes related to misaligned data structure accesses
  - Re-introduce the offending kernel module back in the analysis
- Align data structure layouts
  - Find which configuration options when enabled/disabled fix the layout of the offending data structure

IoT vs Upstream kernel module



Example nf_conntrack_proto_gre.ko:

- IoT module Ghidra decompilation:

```
undefined4 proto_gre_net_init(int param_1)
{
bool bVar1;
undefined4 *puVar2;

bVar1 = true;
if (proto_gre_net_id != 0) {
        bVar1 = **(uint **)(param_1 + 0x324) < proto_gre_net_id;
}
...
return 0;
}
```

- IoT module Ghidra disassembly:

```
proto_gre_net_init:

00010058 lw v0,offset proto_gre_net_id &0xffff(v0)
0001005c lw v1,0x324(a0)
00010060 beq v0,zero,LAB_00010070
00010064 _li a0,0x1
00010068 lw a0,0x0(v1)
...
```

- Open-source module Ghidra decompilation:

```
int proto_gre_net_init(net *net)
{
bool bVar1;
undefined4 *puVar2;

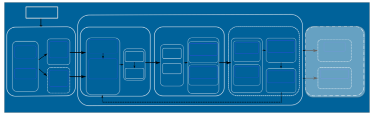
bVar1 = true;
if (proto_gre_net_id != 0) {
        bVar1 = net->gen->len < (uint)proto_gre_net_id;
}
...
return 0;
}
```

- Open-source module Ghidra disassembly:

```
proto_gre_net_init:

00010090 lw v1,offset proto_gre_net_id(v0)
00010094 lw a0,0x208(a0)
00010098 beq v1,zero,LAB_000100a8
0001009c _li v0,0x1
000100a0 lw v0,0x0(a0)
...
```

Downstream Analysis



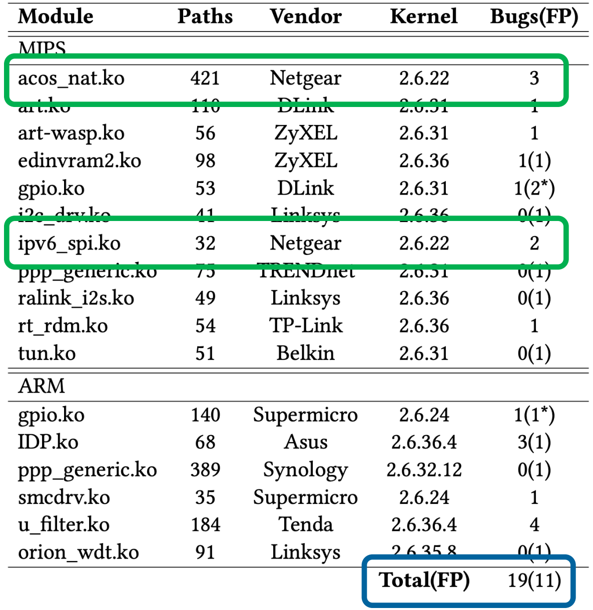
- Two examples of existing downstream analysis systems:
  - TriforceAFL [1]
    - Kernel module fuzzing via modules' IOCTL interface
  - Firmadyne [2]
    - Test against the bugs found by TriforceAFL
    - Test known exploits from ExploitDB [3]
- Others can be added!

[1] https://github.com/nccgroup/TriforceAFL
[2] Chen et al. Towards Automated Dynamic Analysis for Linux-based Embedded Firmware (NDSS 2016)
[3] https://www.exploit-db.com/

Sources: https://en.wikipedia.org/wiki/American_Fuzzy_Lop
https://mobile.twitter.com/exploitdb

Evaluation

- **Dataset:**
  - **1,470** firmware images
  - **56,688** binary kernel modules
- **FirmSolo:**
  - Loads **36,178** (64%) kernel modules
  - Previous work: 0% kernel modules
- **TriforceAFL:**
  - Fuzzed **75** LKMs with an IOCTL interface
  - Triggered **19** previously unknown bugs
  - Confirmed **5** bugs on a physical IoT device



Module	Paths	Vendor	Kernel	Bugs(FP)
MIPS				
acos_nat.ko	421	Netgear	2.6.22	3
art.ko	110	DLink	2.6.31	1
art-wasp.ko	56	ZyXEL	2.6.31	1
edinvram2.ko	98	ZyXEL	2.6.36	1(1)
gpio.ko	53	DLink	2.6.31	1(2*)
i2c_drv.ko	41	Linksys	2.6.36	0(1)
ipv6_spi.ko	32	Netgear	2.6.22	2
ppp_generic.ko	75	TRENDnet	2.6.31	0(1)
ralink_i2s.ko	49	Linksys	2.6.36	0(1)
rt_rdm.ko	54	TP-Link	2.6.36	1
tun.ko	51	Belkin	2.6.31	0(1)
ARM				
gpio.ko	140	Supermicro	2.6.24	1(1*)
IDP.ko	68	Asus	2.6.36.4	3(1)
ppp_generic.ko	389	Synology	2.6.32.12	0(1)
smcdrv.ko	35	Supermicro	2.6.24	1
u_filter.ko	184	Tenda	2.6.36.4	4
orion_wdt.ko	91	Linksys	2.6.35.8	0(1)
			Total(FP)	19(11)

Table: Fuzzer statistics and results for the vulnerable LKMs. The * indicates the False Positive might be an actual bug but requires hardware access to confirm.

Summary

- FirmSolo builds custom Linux kernels that can load binary IoT kernel modules
- Exposes these kernel modules to dynamic analysis
  - Two examples; TriforceAFL and Firmadyne
- Source available at: https://github.com/BUseclab/FirmSolo
- Contact us:
  - jaggel@bu.edu

Thank You!

Link to the paper!

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usenix
ASSOCIATION
AVAILABLE

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FUNCTIONAL