cp<r>
CHECK POINT RESEARCH

DEF CON 28

Don’t be Silly

It’s Only a Lightbulb

@EyalItkin

Who Am I

- Eyal Itkin
- Vulnerability Researcher
- cp<r> Check Point Research
- Focusing on embedded devices & network protocols

@EyalItkin

Motivation

- 2016 – I heard of a new gadget: smart lightbulbs
- I only need the light when I’m physically in the room
  - Why would I need an app to toggle the switch in the entrance?
- 2018 – More than 400,000 UK households use smart lightbulbs
- OK, there is surely some security problem in it
  - The response: Don’t be silly, it’s only a lightbulb, it’s fine

Prior Work

- A Lightbulb Worm? (@colinoflynn & @eyalr0) – BH USA 2016
- Iot Goes Nuclear: Creating a Zigbee Chain Reaction
  - Authors: Eyal Ronen, Colin O'Flynn, **Adi Shamir** and Achi-Or Weingarten
  - Website: https://eyalro.net/project/iotworm.html
  - War-flying demo: https://youtu.be/Ed1OjAuRARU
- With @eyalr0's help, going to continue their research

So, what did they find?

- Attackers can remotely “steal” a lightbulb from a given ZigBee network, and force it to join their own network
- Attackers that share the same ZigBee network with a target lightbulb can send a malicious firmware update to it
- Even a regular lightbulb can be used to “steal” other lightbulbs

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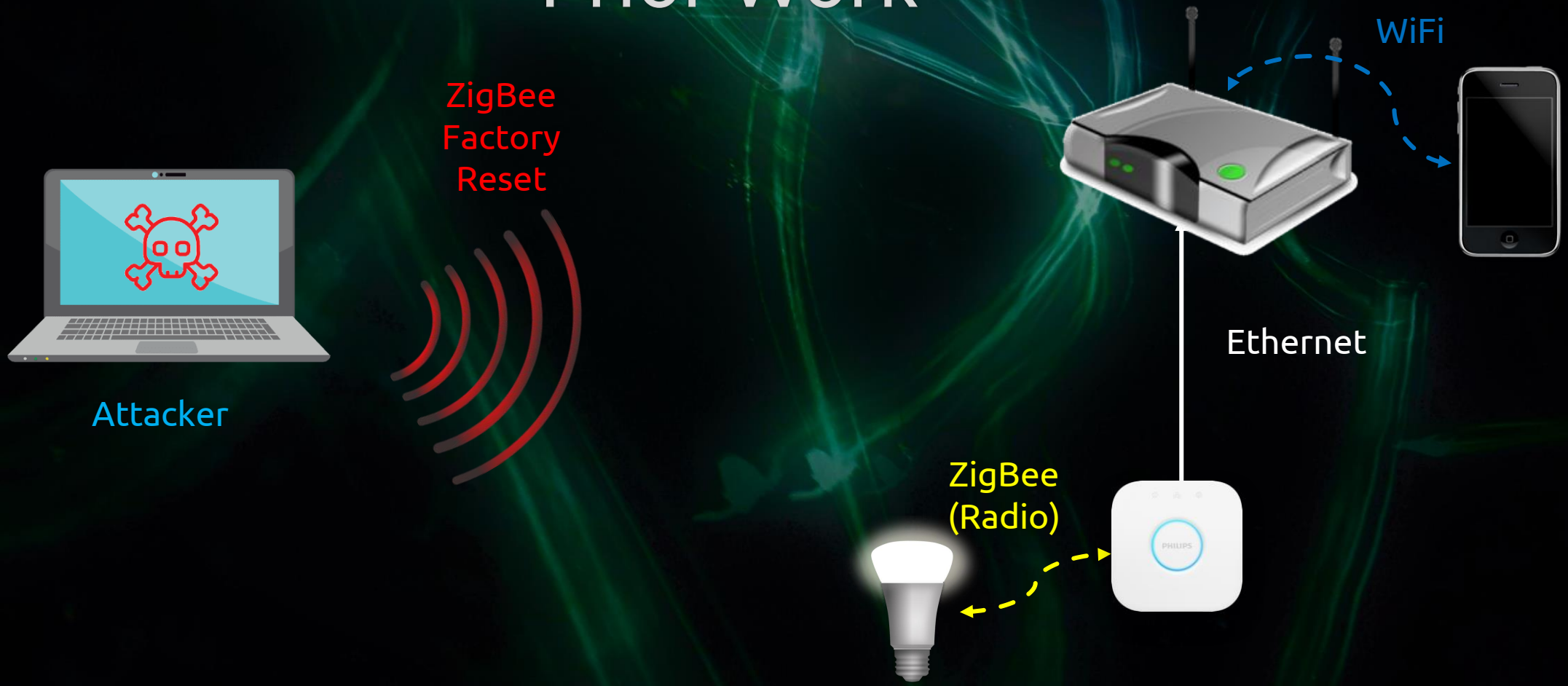
- Even a regular lightbulb can be used to “steal” other lightbulbs

Fixed by the vendor

Prior Work


WiFi
ZigBee
Factory
Reset
Attacker
Ethernet
ZigBee
(Radio)
Attacker
Controlled

Prior Work


ZigBee
Factory
Reset
WiFi
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New Goal: Infiltrate the Network

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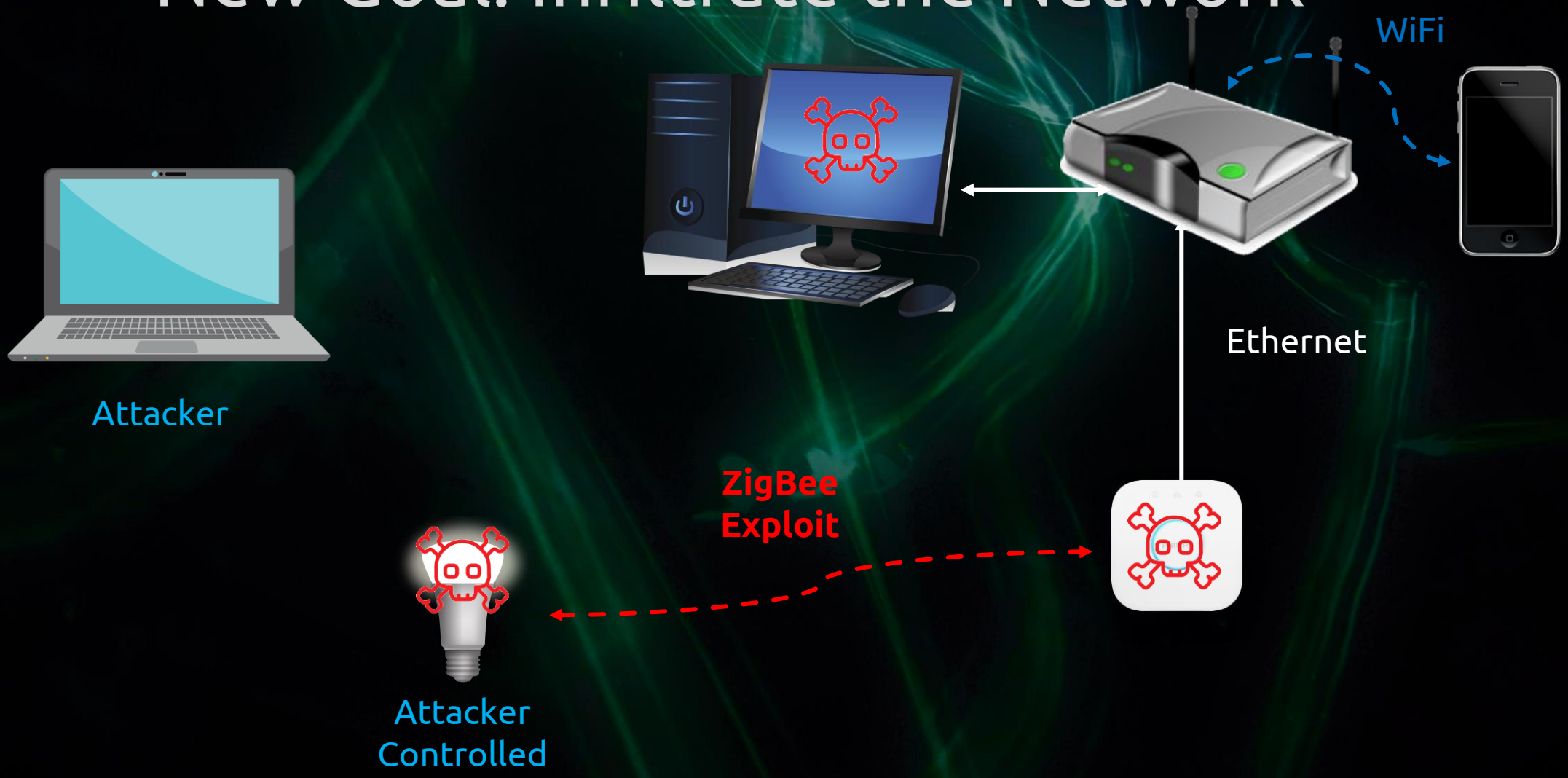
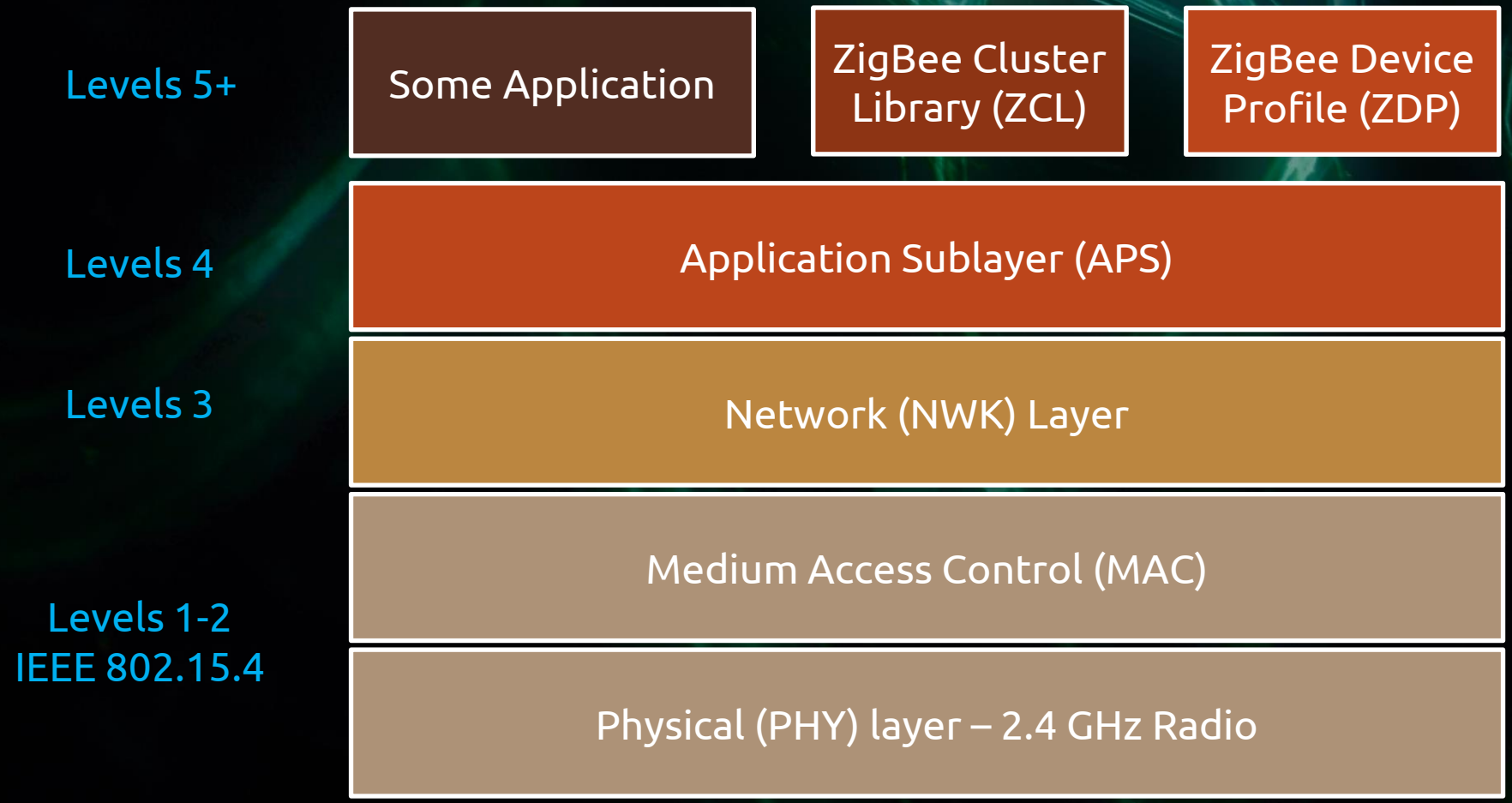


Getting Started

ZigBee 101

- A suite of high level protocols for close proximity networks
- IEEE 802.15.4-based specification
  - low range / power radio (Not to be confused with IEEE 802.11 - WiFi)
  - Maximal Transmission Unit (MTU) of only 127 bytes!
- ZigBee has a full network stack of its own

ZigBee 101


Levels 5+
Some Application
ZigBee Cluster Library (ZCL)
ZigBee Device Profile (ZDP)
Levels 4
Application Sublayer (APS)
Levels 3
Network (NWK) Layer
Levels 1-2
IEEE 802.15.4
Medium Access Control (MAC)
Physical (PHY) layer – 2.4 GHz Radio

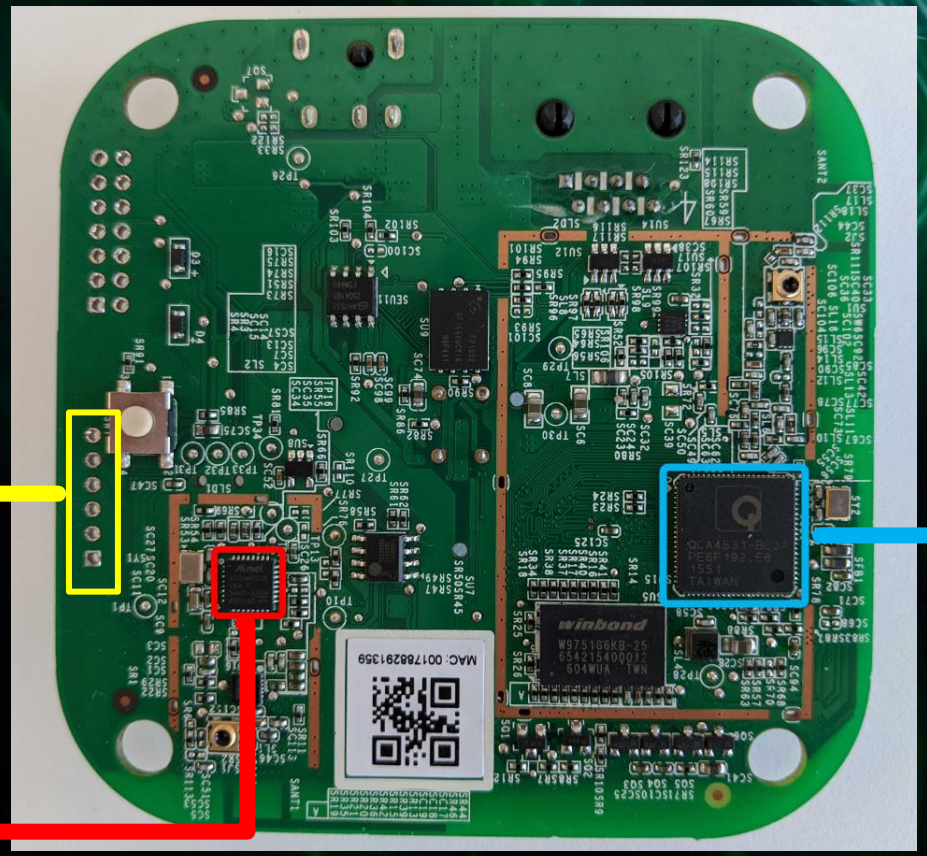
Meet our target

- Philips Hue smart lighting (now under “Signify”)
- Signify controls ~ 31% of the market in the UK
- We are going to focus specifically on the bridge
  - Connected to both ZigBee (radio) and Ethernet
  - Specifically, hardware version v2

Tearing down the bridge

Serial Debug

ZigBee “Modem”
ATSAMR21E18E

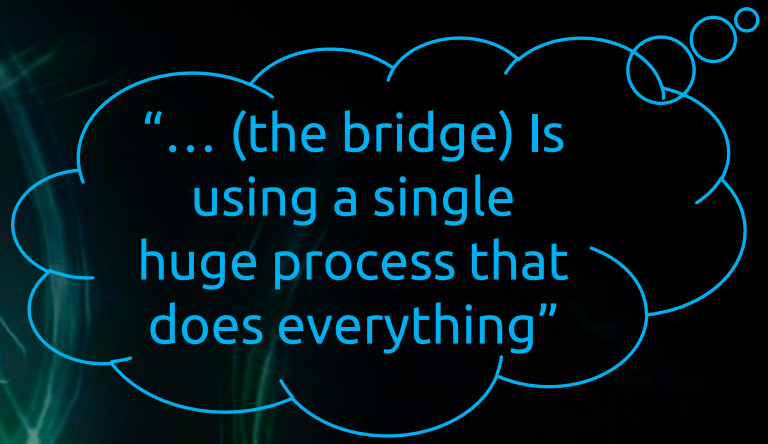


Main CPU
QCA4531-BL3A

Rooting the bridge

- The main CPU is of MIPS architecture
- The operating system is Linux (not an RTOS this time)
- @colinoflynn details in his blog how to root the bridge:
  - http://colinoflynn.com/2016/07/getting-root-on-philips-hue-bridge-2-0/
- Once finished, we get a root SSH connection ☺

ipbridge



- A single process that acts as the “brain”:
  - Parsing incoming ZigBee messages
  - Maintaining protocol state machines
  - …
- ipbridge runs with root privileges ☺
- This is going to be the target process for our research

Looking for Vulnerabilities

Slow start

- Due to technical issues I couldn’t root the bridge
  - Didn’t have the right equipment
  - And the package we ordered got delayed (snail mail) ☹
- Meanwhile, started working on an old firmware version
  - Version from the original research (2016-2017)

Analyzing ipbridge

- At first glance, we saw something odd
- The code expects **strings** in the incoming message
  - The MTU is 127 bytes
  - The message should use **bits**
- What is going on here?

```
.word aConnection          # "Connection"
.word 2
.word 0
.word off_53FF40           # "FindFreePanDone"
.word 3
.word aZdp                 # "Zdp"
.word 2
.word 0
.word off_53FE80           # "SendMgmtPermitJoiningReq"
.word 0x10
.word aZcl                 # "Zcl"
.word 2
.word EI_zcl_main_handler  #
                           # $a0 - input buffer (char *)
                           # $a1 - string name (cmd descriptor ?)
                           #
```

Things get complicated

- We forgot about the ZigBee “Modem”
  - Uses Atmel BitCloud SDK to parse incoming messages
  - Acts as a co-processor that handles the ZigBee lower network layers
- It converts the parsed messages to textual form and sends them over serial to the main CPU
- We don’t have the firmware for it – a black-box…

Living alongside a black-box

- The modem reduces the attack surface on the main CPU
  - Complex parsing is offloaded to the Modem
  - We don’t fully control messages sent to the main CPU
- Adds a huge uncertainty to everything we find
  - Maybe the modem checks it?
- Let’s add it to the list of issues, and hope for the best …

Vulnerability Attempt #1

- The ZigBee Cluster Library (ZCL) manages configurations
  - Offers a READ_ATTRIBUTE / WRITE_ATTRIBUTE interface
  - Supports multiple types:
    - E_ZCL_BOOL (0x10)
    - E_ZCL_UINT8 (0x20)
    - E_ZCL_ARRAY (0x48)
    - E_ZCL_UINT32 (0x23)
- Hmm, variable-sized data type in an embedded device
- This looks promising

Vulnerability Attempt #1

```
B1A0 move    $a0, $s3
B1A4 jal     EI_zcl_read_1_byte  # 1-byte length field
B1A8 sw      $v0, zcl_attribute.one_if_data_two_if_pData($s1)  # Store Word
B1AC sb      $v0, zcl_attribute.data_type_or_pdata_length($s1)  # Store Byt
B1B0 jal     EI_malloc_with_mutex  # Jump And Link
B1B4 li      $a0, 0x2B  # '+'  # buffer of 0x2B bytes (43 bytes)
B1B8 move    $a0, $v0
B1BC move    $a1, $zero
B1C0 li      $a2, 0x2B  # '+'  # Load Immediate
B1C4 jal     memset             # memset(pBuffer, 0, sizeof(buffer) = 0x2B)
B1C8 sw      $v0, zcl_attribute.data_or_pData($s1)  # Store Word
B1CC lw      $a0, zcl_attribute.data_or_pData($s1)  # Load Word
B1D0 lbu     $a1, zcl_attribute.data_type_or_pdata_length($s1)  #
B1D0                          # EI-DBG: Controlled (1-byte) memcpy into a
B1D0                          # EI-DBG: fixed size 0x2B heap buffer.
B1D0                          # EI-DBG: ==> Heap Buffer Overflow :)
B1D4 move    $a2, $s3
B1D8 sw      $s0, 0x38+var_28($sp)  # Store Word
B1DC jal     EI_zcl_read_blob  # Jump And Link
```

Vulnerability Attempt #1

- It isn’t a vulnerability until we have a PoC to trigger it
  - We don’t have the latest firmware yet
  - The Modem could block large ZCL arrays
  - We don’t have radio equipment to transmit the attack and test it
- Finally, the package arrived
  - We can root the bridge and extract the latest firmware

Array? String!

```
1256 lw      $a2, 0x50+pIsError($sp)
1258 jal     UTIL_Fetch_uint8
125C lw      $a0, 0x50+ppData($sp)
125E move    data_type, $v0   # length of the string
1260 li      $v0, 0x10
1262 addiu   $a0, data_type, 1  # length += 1 (no IOF)
1264 sw      $v0, zcl_attribute_value(output_struct)
1266 jal     OSA_MEMORY_Malloc  # malloc(n+1) - no vulnerability this time :(
126A sh      data_type, zcl_attribute_value.size(output_struct)
126C move    $a0, $v0         # allocated pData for the string
126E li      $a1, 0
1270 move    $a2, data_type
1272 jal     EI_memset
1276 sw      $v0, zcl_attribute_value.pData(output_struct)
1278 lw      $v1, 0x50+pIsError($sp)
127A lw      $a0, zcl_attribute_value.pData(output_struct)
127C lw      $a2, 0x50+ppData($sp)
127E lw      $a3, 0x50+pLength($sp)
1280 sw      $v1, 0x50+var_40($sp)
1282 jal     UTIL_Fetch_Buffer
```

Yup, this firmware contains symbols!

Nope, No Vulnerability

- Latest firmware version dropped support for ZCL Arrays
  - Supports ZCL Strings instead
  - Sadly for us, strings are parsed correctly
- Time to search for other vulnerabilities
- Covered most of the firmware, and found nothing…

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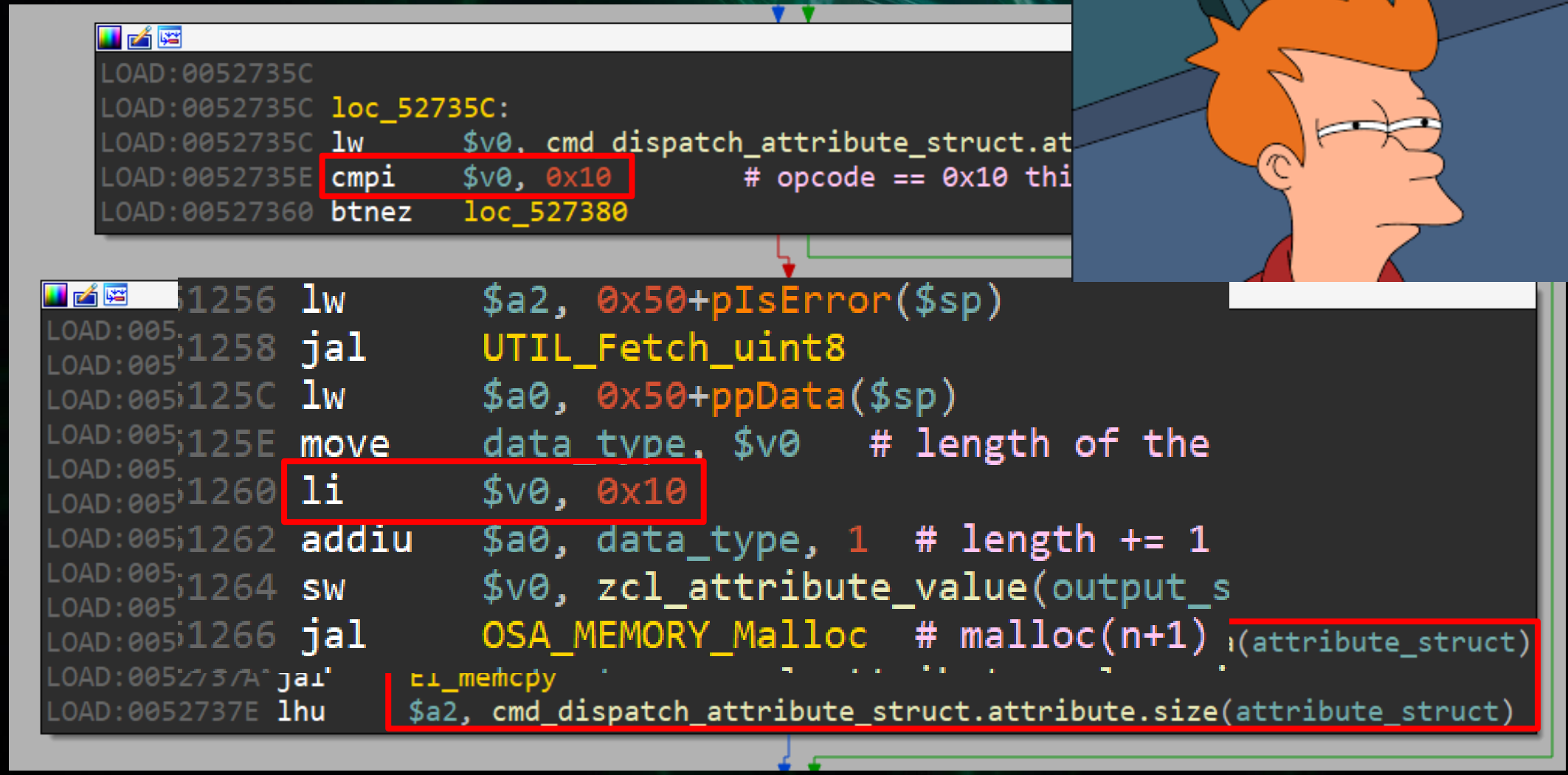
- Time to search for other vulnerabilities
- Covered most of the firmware, and found nothing…
- Who handles the incoming ZCL strings later on?

Vulnerability Attempt #2

```
LOAD:0052735C
LOAD:0052735C loc_52735C:
LOAD:0052735C lw      $v0, cmd_dispatch_attribute_struct.at
LOAD:0052735E cmpi    $v0, 0x10          # opcode == 0x10 thi
LOAD:00527360 btnez   loc_527380
```

```
LOAD:00527362 jal     EI_plt_malloc
LOAD:00527366 li      $a0, 0x2B  #  +'
LOAD:00527368 move    $a0, $v0
LOAD:0052736A li      $a1, 0
LOAD:0052736C li      $a2, 0x2B  # '+'
LOAD:0052736E sw      $v0, 0x1C($s1)
LOAD:00527370 jal     EI_memset
LOAD:00527374 sw      $v0, 0x38+var_18($sp)
LOAD:00527376 lw      $a0, 0x38+var_18($sp)
LOAD:00527378 lw      $a1, cmd_dispatch_attribute_struct.attribute.pData(attribute_struct)
LOAD:0052737A jal     EI_memcpy
LOAD:0052737E lhu     $a2, cmd_dispatch_attribute_struct.attribute.size(attribute_struct)
```

Vulnerability Attempt #2



Vulnerability Attempt #2

- Someone forgot to finish the migration from Array to String
  - Should have been marked with 0x0F for String
  - However, internally they are still marked with 0x10 for Array
- The original vulnerability still exists in the code ☺
  - Just buried a bit deeper, that's all
- Time to start transmitting ZigBee messages

Commissioning?

Playing around with ZigBee

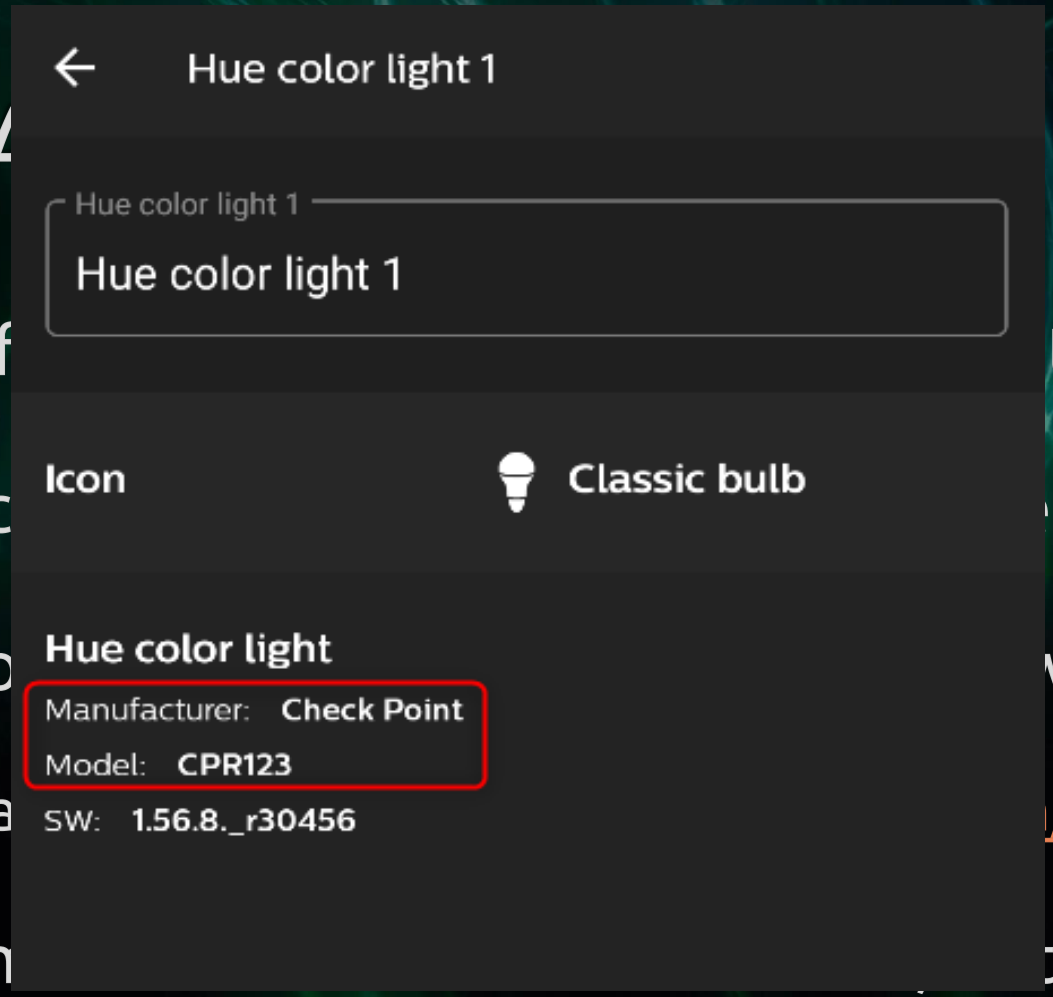
- Like the previous research, chose to use ATMEGA256RFR2-XPRO
  - Support sending/receiving ZigBee IEEE 802.15.4 radio frames
  - Should be computationally equivalent to a lightbulb
- Timing constraints dictate we use C code executed on the board
  - Our entire ZigBee code + exploit will be implemented in C
- The vulnerable flow is accessible during Commissioning

Commissioning?

- The process of pairing and associating a new lightbulb
  - Classic Commissioning
  - Touchlink Commissioning
- The Philips Hue app initiates Classic Commissioning
- In theory, the ZigBee specs explains the entire process
- In practice, a lot of room for vendors to do as they wish

Analyzing the protocol

- No documented flow - What message is supposed to be sent? When?
- Can’t sniff a full conversation – Too many messages, sent too fast…
- We need the (Broadcast) transport crypto key, how do we get it?
  - Not the first to tackle this issue - https://peeveeone.com/?p=166
- Analysis & implementation took a lot of effort, but it worked!



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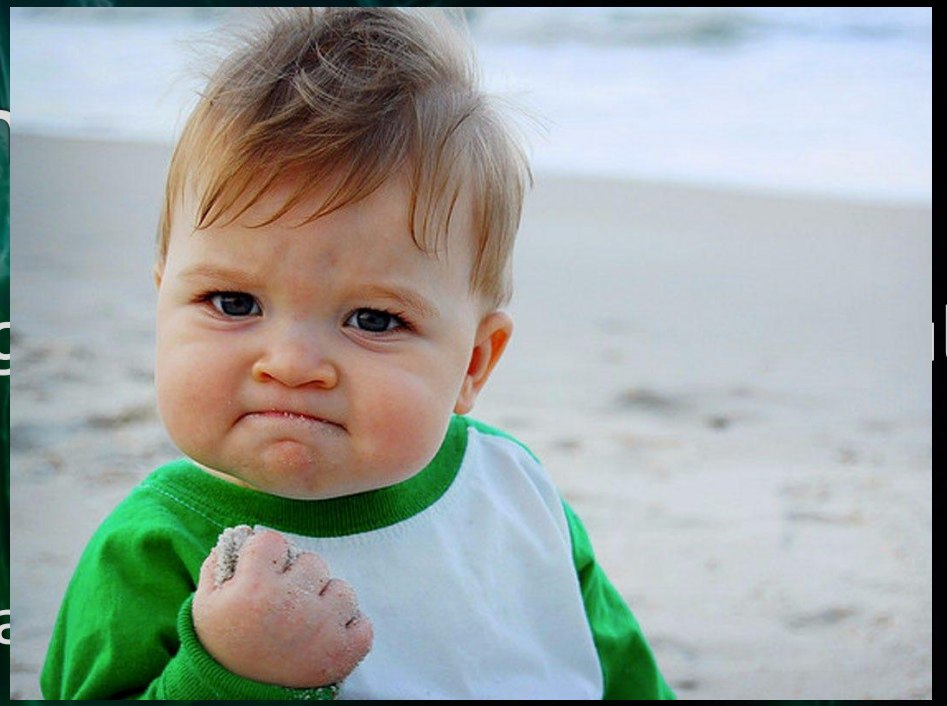
- Can't sniff a full c … s, sent too fast…
- We need the (Bro … v do we get it?
  - Not the first to ta … /?p=166
- Analysis & implen … : it worked!
- We open sourced our full .pcap of a classic commissioning:

github.com/CheckPointSW/Cyber-Research/tree/master/Vulnerability/Smart_Lightbulbs

Lessons Thus Far

- Without user interaction, the bridge won't accept new lightbulbs
  - We have ~1 minute to commission as many lightbulbs as we want
  - The user will see the lightbulb in the app only **after** the "ZCL phase"
- **Good News:** Managed to trigger the vulnerability during the ZCL phase!

Lessons Th



- Without user interaction, the bridg lbs
  - We have ~1 minute to commission as
  - The user will see the lightbulb in the a
- **Good News:** Managed to trigger the vulnerability during the ZCL phase!
  - No state machine check – send whatever response you like
  - However, can only trigger the vulnerability **during** this phase

Let the Exploitation Begin

Vulnerability Recap

- We have a linear buffer overflow over the heap
- Our buffer size is limited to 70 controllable bytes
  - ZCL is quite high in the ZigBee stack, and the initial MTU is only 127 bytes
- We don’t have any byte constraints on our payload
- The destination buffer is allocated on the heap
  - Fixed size of 0x2B (43) bytes

The Heap

- The bridge uses uClibc – (old) embedded libc implementation
  - Chosen heap implementation is malloc-standard (dlmalloc)
- Much like glibc, but with **less** sanity checks
- All of our free buffers will fall into the range of the fastbins
  - Bin for each buffer size (multiple of 8) starting from 0x10
  - Each bin contains a singly-linked list of free()ed buffers

/dev/null fastbin

Code snippet from free():

```
if ((unsigned long)(size) <= (unsigned long)(av->max_fast))
{
    set_fastchunks(av);
    // EI-DBG: Who checks that size >= 0x10?
    // EI_DBG: Lower size will get us indices -1 and -2
    fb = &(av->fastbins[fastbin_index(size)]);
    p->fd = *fb;
    *fb = p;
}
```

```
/* offset 2 to use otherwise unindexable first 2 bins */
#define fastbin_index(sz)       ((((unsigned int)(sz)) >> 3) - 2)
```

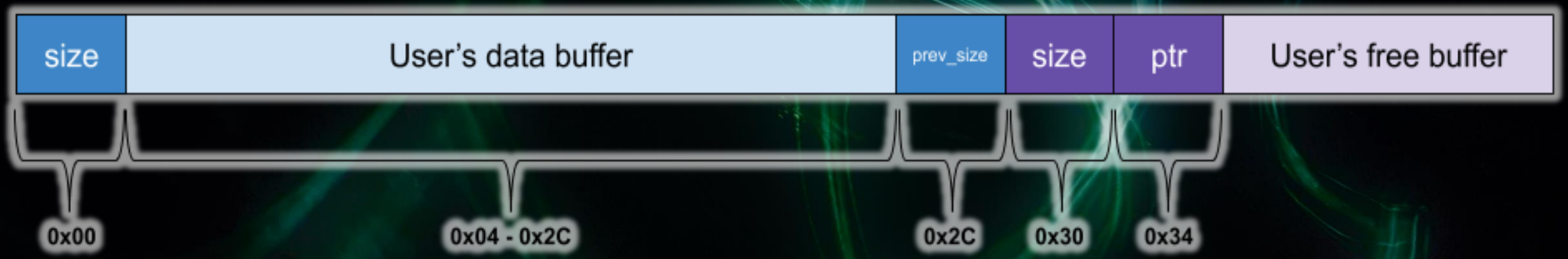
/dev/null fastbin

Code from

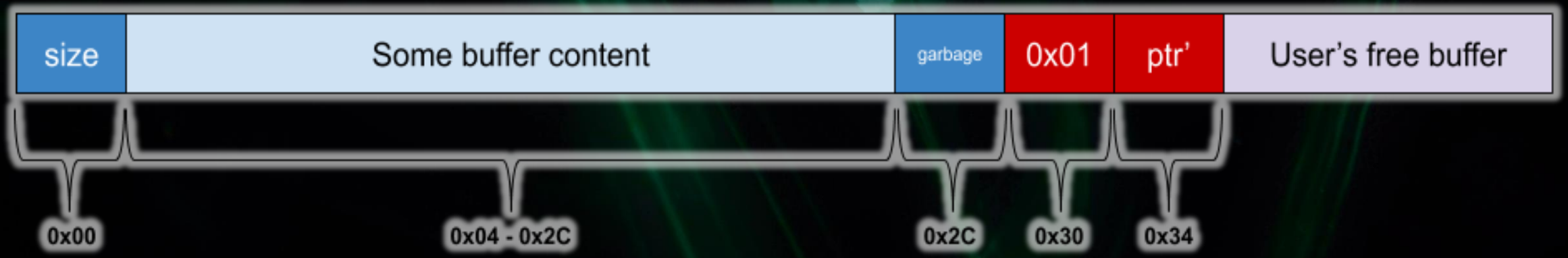
```
struct malloc_state {

  /* The maximum chunk size to be eligible for fastbin */
  size_t  max_fast;   /* low 2 bits used as flags */

  /* Fastbins */
  mfastbinptr      fastbins[NFASTBINS];
```

- Index -1 ➔ Store the buffer on top max_fast – too risky
- Index -2 ➔ Store the buffer on an **unused** variable, creating a ghost linked list acting as /dev/null

Heap Overflow Plan



- Modify only size and ptr



Heap Overflow Plan

Goal: Confuse malloc() to “allocate” a buffer at an arbitrary address

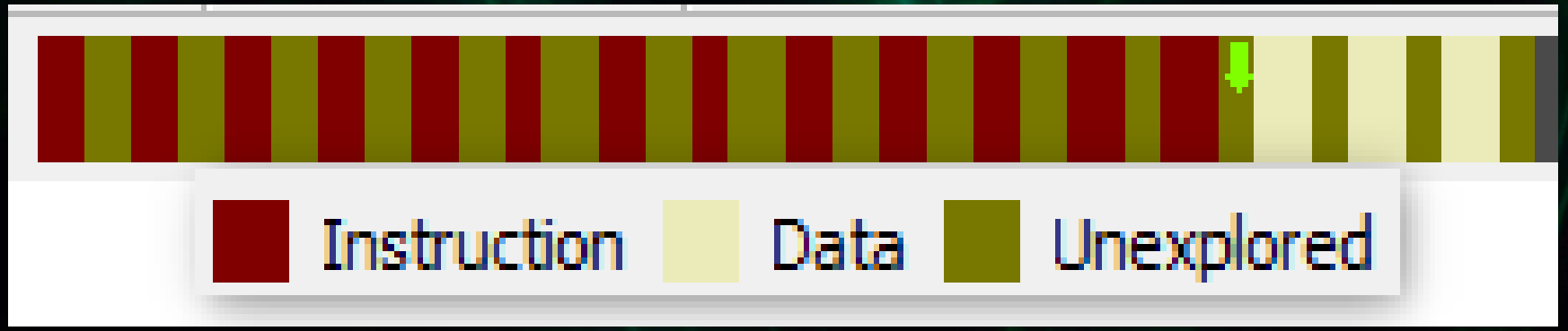
Heap Shaping Strategy

- Overflowed a free fastbin buffer? – **Bingo!** this is what we aim at
- Overflowed a used buffer? – When free()ed it will go to /dev/null
- Overflowed a used buffer that lives forever? – oh well
- Overflowed a free large buffer? – We will probably crash soon ☹
- If done correctly, we will get the desired Malloc-Where

Heap Shaping Strategy

- Malloc-Where will grant us the ability to write on the GOT
  - Global-Offset-Table
  - A table full of function pointers used to execute library functions
- The GOT is at a fixed address ☺
- The modified fptr will jump to our shellcode*
- *Sounds easy on paper, way harder in real life

Shellcode:
Theory vs Reality



Location, Location, Location

- We need to store a **binary** shellcode in a **fixed** global address
- The problem - we get **textual** messages from the ZigBee Modem
- Found only one good candidate for such a buffer
  - The ZigBee “phone book”
  - Array of ZigBee addresses seen / advertised thus far
  - Can hold up to 65 records of 16 bytes each (~ 1KB)

The “Neighbor Record”

- **Bytes 0x00-0x08:** Extended network address - Fully controlled.
- **Bytes 0x09-0x0A:** Short network address - Fully controlled.
- **Bytes 0x0A-0x10:** Misc fields - **Uncontrolled**.
- Oh, and about that
- The bridge is unstable when it gets > 20 records
  - This is going to be a **very** small shellcode

Initial plan

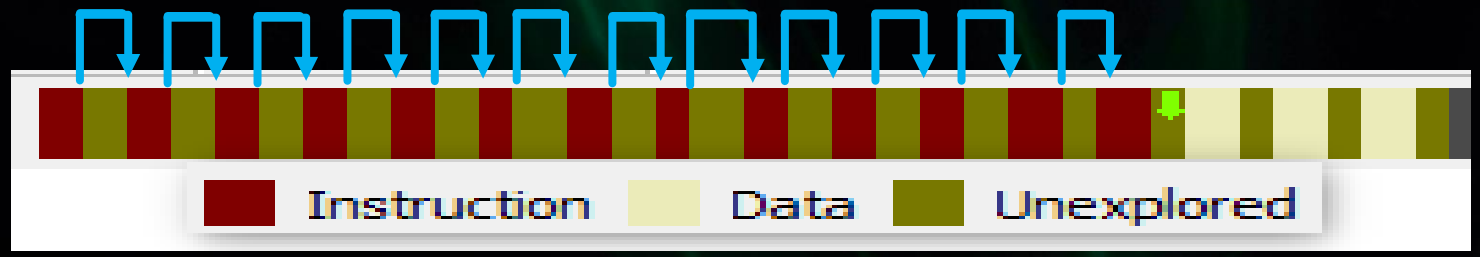
- It seems infeasible to restore the execution flow
- Instead, the shellcode will patch the binary with a backdoor
- After a crash, the daemon will restart with our backdoor
- Problem:
  - The patch and the file-path don’t fit in 10 consecutive bytes (each)

“Ideal” Shellcode

- Use the 10 consecutive bytes per record to build a decoder
- In mips16 a jump to the next record only costs us 2 bytes
- Problems:
  - We need to clear the cache before jumping to the unpacked shellcode
  - If we sleep(), the watchdog kills the process
  - We don’t have enough records to silence the watchdog

“Bold” Shellcode

- We will restore the execution flow, we have no choice
- This means we mprotect() and install the backdoor in RAM!
- A few days, and one hand-crafted shellcode later:
  - The shellcode fully restores the execution (GOT, heap, everything)
  - The shellcode costs us 16 records – well in budget



Connecting the dots

- The backdoor shellcode gives us an Arbitrary-Write primitive
- Our exploit fakes a “legitimate” lightbulb that will leverage it
- Used the Arbitrary-Write to write Scout’s loader to memory
- Upon execution, Scout loaded the full payload - EternalBlue

```
2227 root     61968 S    /usr/sbin/ipbridge -p /home/ipbridge/var -z /dev/ttyZigbee
2278 root         0 SW   [kworker/u2:1]
2287 root       176 S    /tmp/exploit
```

- Time for a demo ☺

Full Exploit Demo

Link: https://www.youtube.com/watch?v=4CWU0DA__bY

Coordinated Disclosure

- Vulnerability was reported to Signify on the 5th of Nov 2019
  - The vendor confirmed the vulnerability on the **same day!** (impressive)
- Signify issued a patch via an automatic update on Jan 2020
  - Full details & Advisory in our blog post – CVE-2020-6007:
  - https://research.checkpoint.com/2020/dont-be-silly-its-only-a-lightbulb/
- All products should have received the update by now

Conclusions

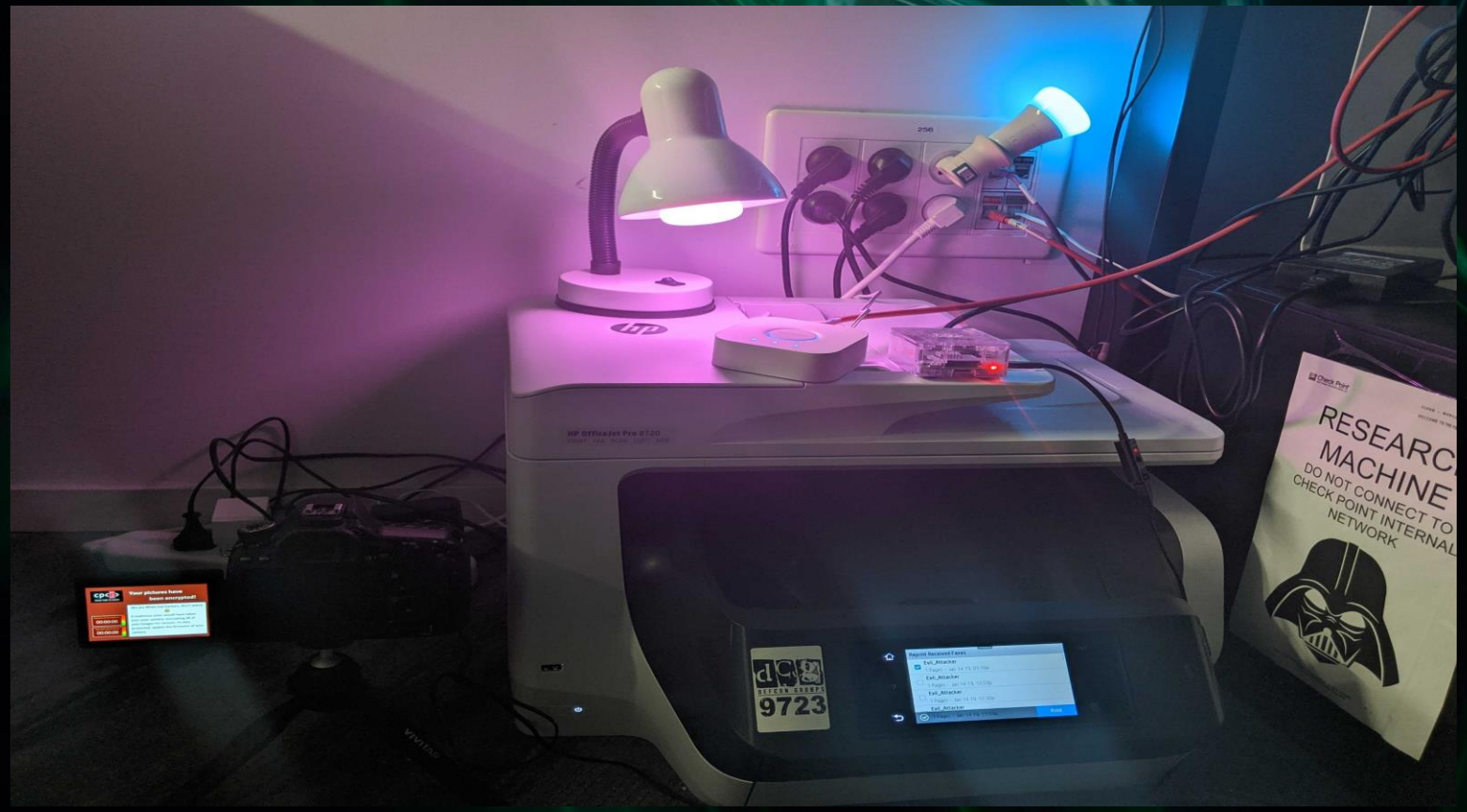
- Even with an MTU of 127 bytes, ZigBee vulns are exploitable
- Security mitigations only work when they are on-by-default
  - Static binary for ipbridge, no stack canaries, writable GOT, …
  - ASLR for heap, stack and loaded libraries (thank you Linux)
- Smart devices are becoming popular by the minute,

  and yet, we can’t even trust our lightbulb…

Kudos

- Special thanks to everyone that helped make this research possible
  - Eyal Ronen (@eyalr0) – Research idea & active guidance
  - Colin O'Flynn (@colinoflynn) – Detailed writeups on rooting the bridge
  - Peter – Publishing the ZigBee transport keys for the lightbulb
  - Yaron Itkin – For the crucial hardware support along the way
    - Thanks little brother ☺
- And finally, to the entire cp<r> CHECK POINT RESEARCH team for their support

Until next time



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