iSECpartners
part of nccgroup

Funderbolt

Adventures in Thunderbolt DMA Attacks

Russ Sevinsky

Background

iSECpartners part of nccgroup

- Thunderbolt
  - Apple and Intel collaboration
  - Expansion port
  - PCI Express (PCIe) and DisplayPort using the same port
- DMA
  - Direct Memory Access
  - Processor becomes bottleneck for high-speed transfers
  - Lets devices read and write directly to RAM

Background

iSECpartners part of nccgroup

- Why external buses matter for security experts?
  - Digital Forensics
    - Getting data to solve a mystery
  - User protection
    - So RAM contents can be safe
  - Sneaky DRM
    - Bus encryption

Background

iSECpartners part of nccgroup

- Current DMA research
  - I/O Attacks in Intel-PC Architectures and Countermeasures[1]
  - Understanding DMA Malware[2]
- Current Thunderbolt attacks?
  - Daisy chaining Thunderbolt and Firewire[3]
  - Inception[4]
  - De Mysteriis Dom Jobsivs (Mac EFI Rootkits)[5]

Background

iSECpartners part of nccgroup

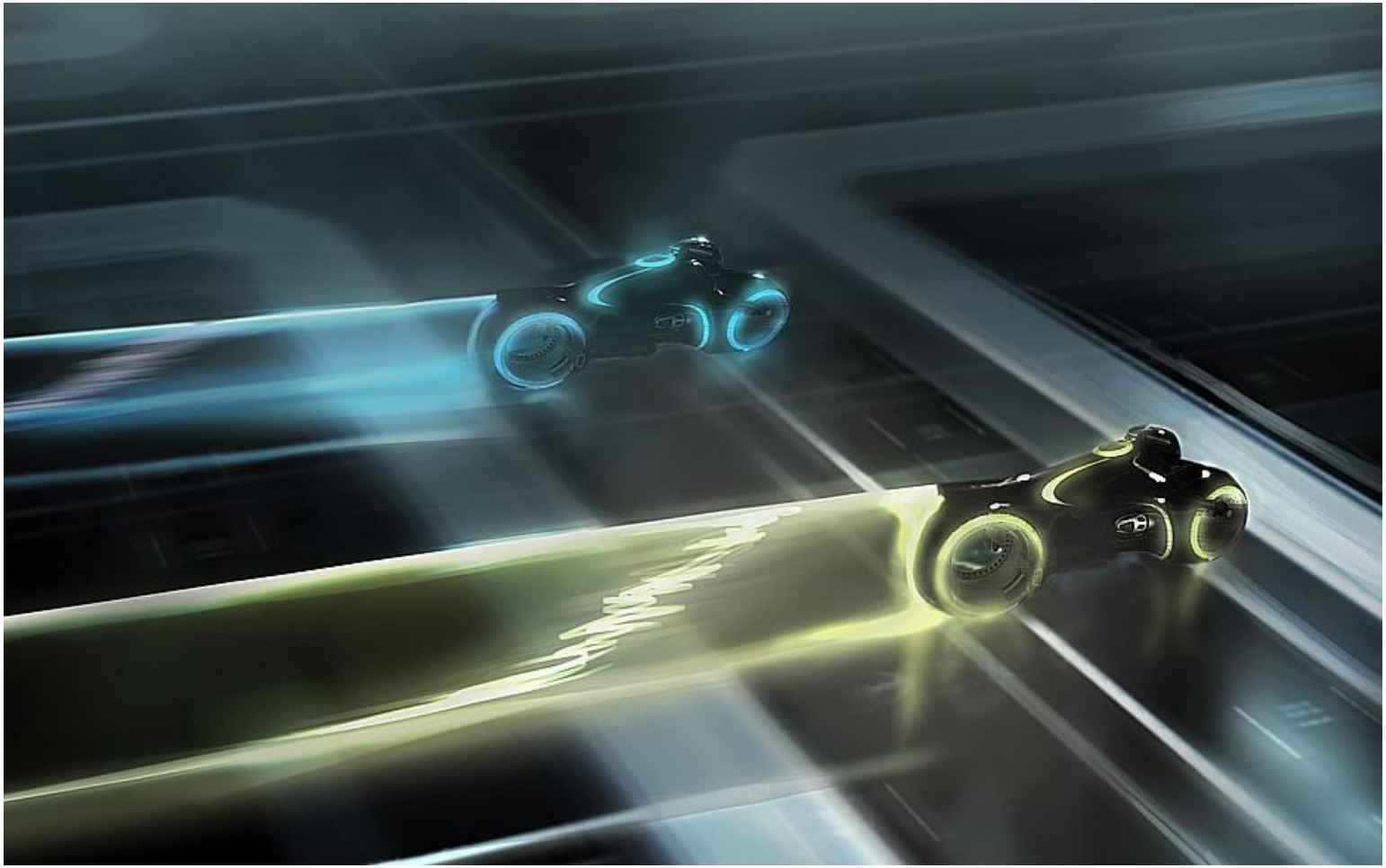
- Mitigations?
  - Epoxy (really?)
  - Input/Output Memory Management Units (IOMMUs)
    - Maps physical memory addresses to logical addresses
    - Think "VM for DMA"
    - Prevents devices from requesting physical addresses directly
    - Currently not implemented on Apple hardware
  - Secure Configurations[6]
    - Prevents attacks when computer is locked
    - Boot attacks and social engineering still possible

Background

iSECpartners part of nccgroup

A Trip Down Memory Lanes

iSECpartners
part of nccgroup



A Trip Down Memory Lanes

iSECpartners part of nccgroup

- PCI Express (PCIe)
  - High-speed serial bus
  - Data sent via "lanes"
  - A lane is made up of differential wire pairs
    - One + and one – wire
    - Helps to reduce noise
  - One lane (x1) is made up of two differential pairs
    - Transmit pair (PET)
    - Receive pair (PER)

A Trip Down Memory Lanes

iSECpartners part of nccgroup

- PCIe (cont)
  - Four lanes (x4) has eight wires, etc…
  - All lanes CAN use another differential pair for clock
    - REFCLK
    - Not required (could use a XTAL)
  - So per spec, x1 only needs 4 wires for data communication!
    - PET and PER
  - Typical x1 setups use a REFCLK

A Trip Down Memory Lanes

iSECpartners part of nccgroup

- PCIe (cont)
  - PCIe device types
    - Endpoints (Legacy and Native)
    - Switch/Bridge
    - Root Complex
  - Legacy endpoints
    - More permissive than Native endpoints for backwards compatibility
    - Supports "Locked" transactions, IO transactions and 32-bit addressing only

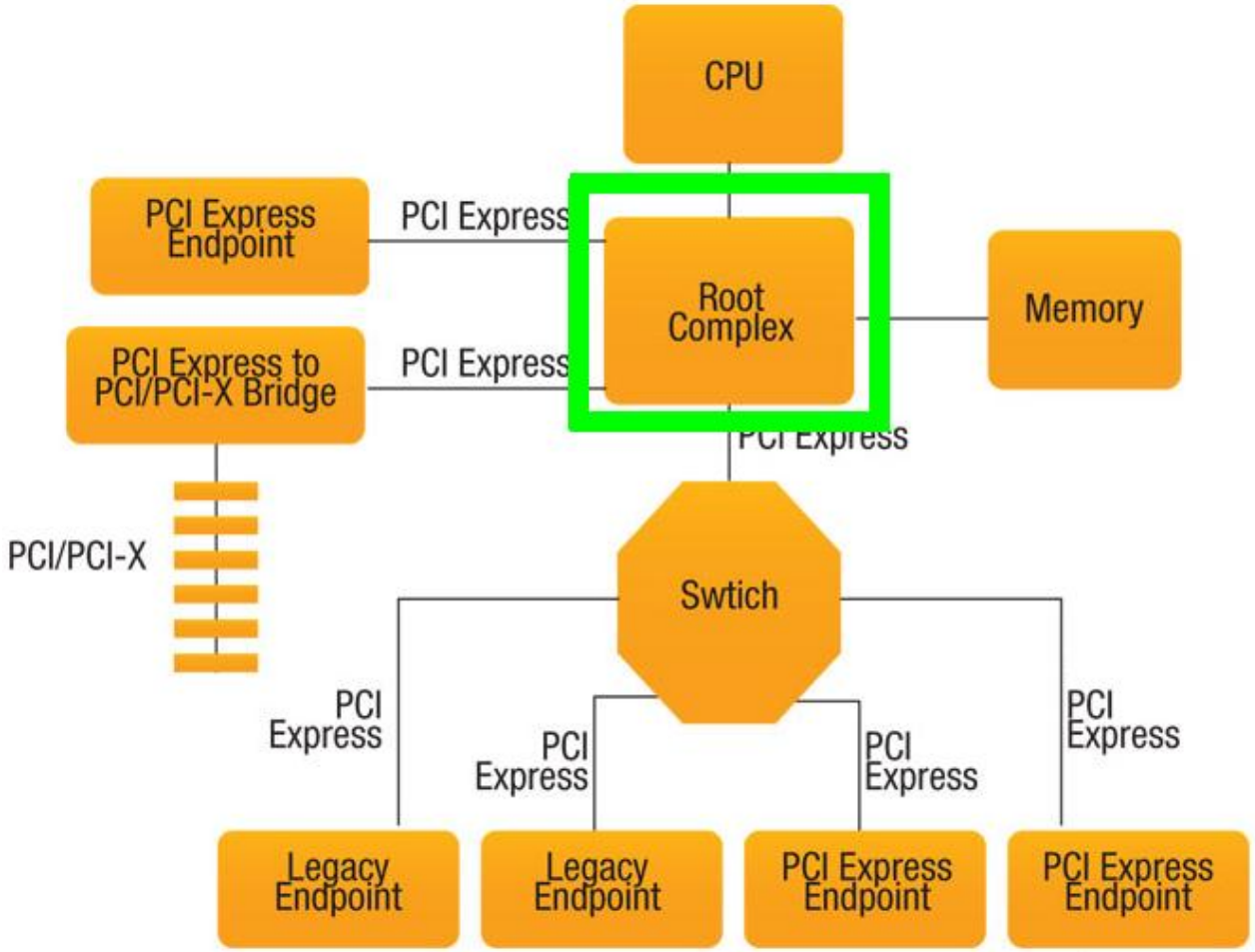
A Trip Down Memory Lanes

iSECpartners part of nccgroup

- PCIe (cont)
  - Data sent via "packets" called Transaction Layer Packet (TLP)
  - Point-to-point topology
    - No arbitration
    - Devices do not need the be "granted" access to the bus
  - Packets routed by address
    - Peer-to-peer transfers are possible
  - Packets going to RAM go through "Root Complex"

A Trip Down Memory Lanes

iSECpartners part of nccgroup



A Trip Down Memory Lanes

iSECpartners part of nccgroup

- PCIe (cont)
  - PCIe devices are discovered via "enumeration"
    - Starts at Bus 0 (root complex), Device 0, Function 0
    - Checks if it's a bridge or an endpoint
    - Traverses tree of devices
    - Assigns ids and addresses
  - Hot plug device?
    - Enumerate just that port
  - Device info stored in expansion ROMs and read into configuration space

How My Adventures Went

iSECpartners part of nccgroup

- Improvised Tools for Analysis
  - Multimeter
  - Soldering station
  - Heat gun
  - Desoldering tools
  - Ethernet cable
  - Epoxy (really?)
  - Logic Analyzer
  - Image Editor

How My Adventures Went

iSECpartners part of nccgroup

- Reversing Thunderbolt – The Process
  - Research a product
  - Take it apart
  - Locate important ICs
  - Trace connections between ICs
  - Look for datasheets
  - Sniff buses
  - Develop a map

How My Adventures Went

iSECpartners part of nccgroup

- Looking at consumer products
  - Buffalo MiniStation Thunderbolt/USB3 Hard Drive
    - 500GB and 1TB model
    - USB3 and Thunderbolt
    - Decent form factor for reversing
  - Apple Thunderbolt to Gigabit Ethernet Adapter
    - Tiny
    - Small
    - Little

How My Adventures Went

iSECpartners part of nccgroup

- Buffalo MiniStation Thunderbolt/USB3 Hard Drive
  - Excellent Anandtech review[7]
  - Tear-down instructions
  - Identified ICs for us!

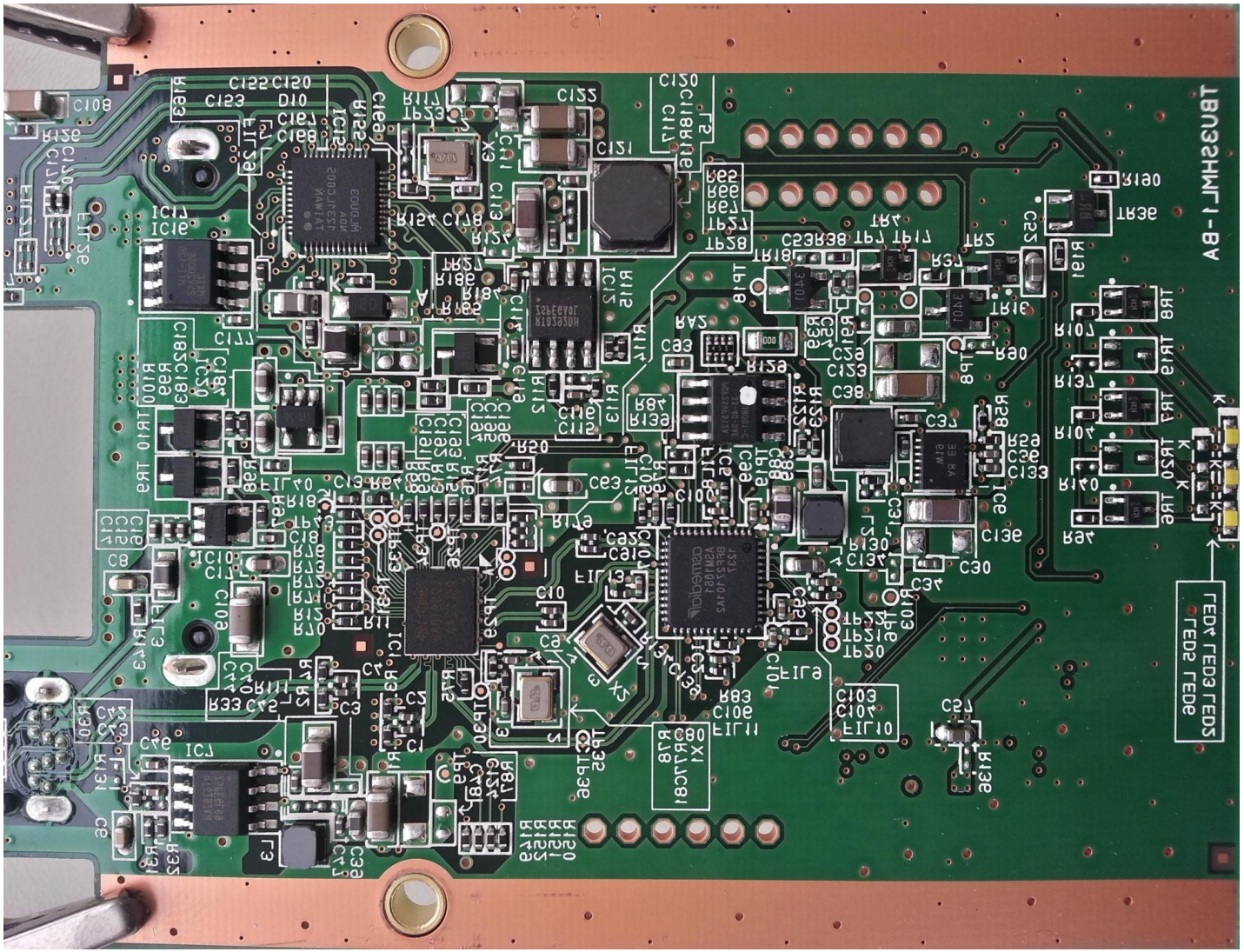
How My Adventures Went

iSECpartners part of nccgroup

- Main ICs
  - MLDU03
    - Medial Logic USB3.0 to SATA 6G Bridge
  - ASM1061
    - ASMedia PCIe to SATA Controller
  - DSL2210 (Peak Ridge)
    - Intel Thunderbolt Controller
    - Supports PCIe x1
  - LPC1114
    - NXP ARM Cortex Mo

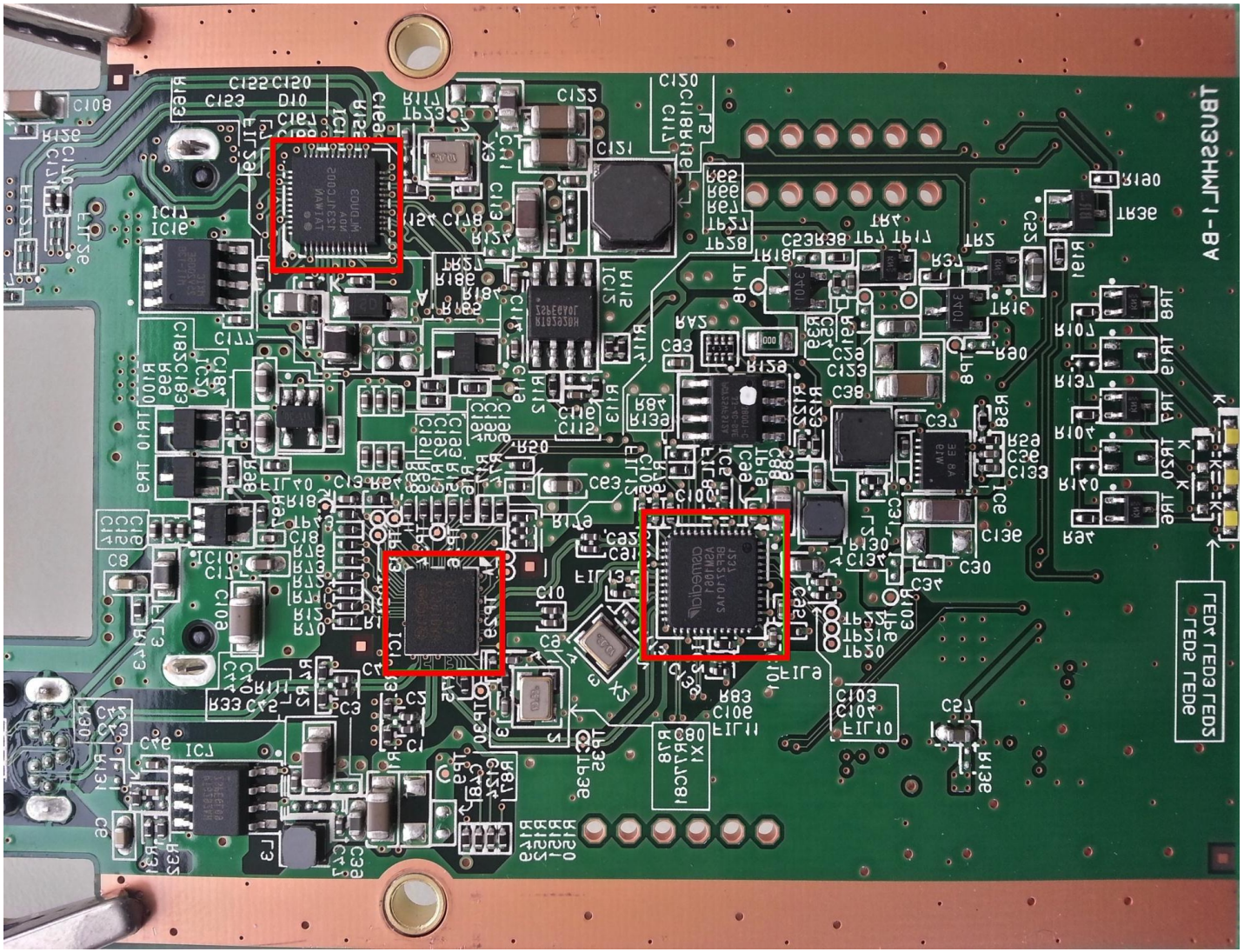
How My Adventures Went

iSECpartners
part of nccgroup



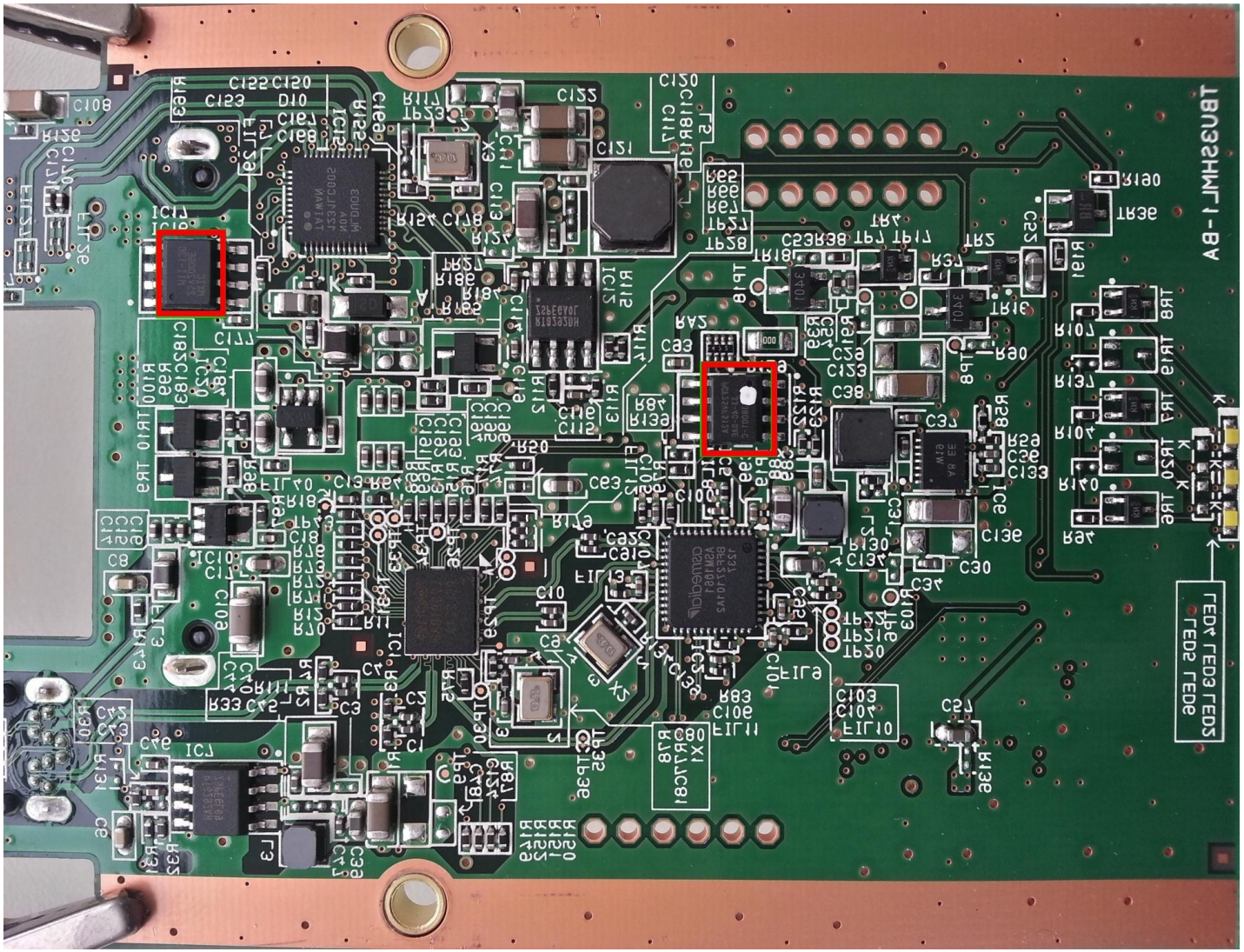
How My Adventures Went

iSECpartners
part of nccgroup



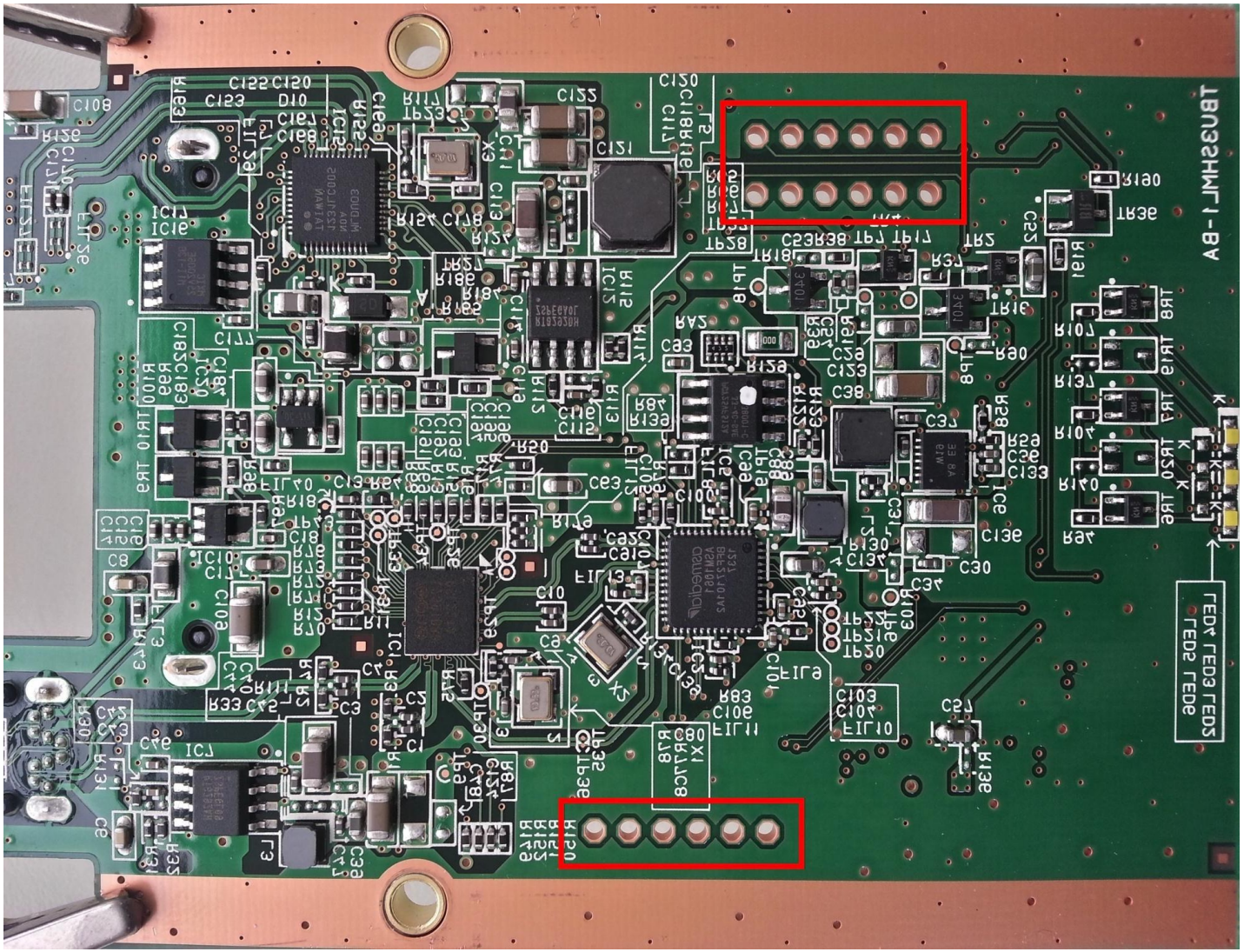
How My Adventures Went

iSECpartners
part of nccgroup



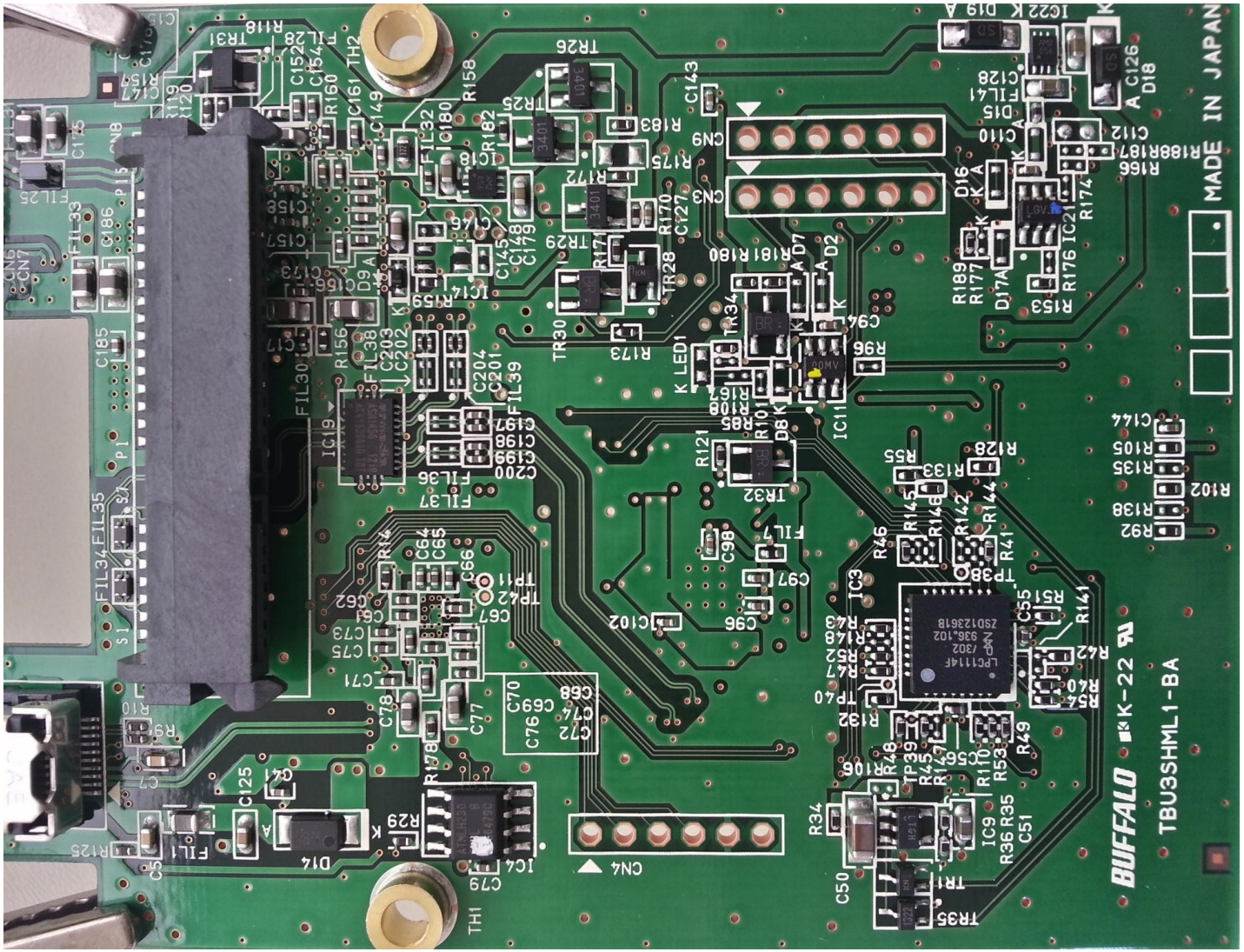
How My Adventures Went

iSECpartners
part of nccgroup

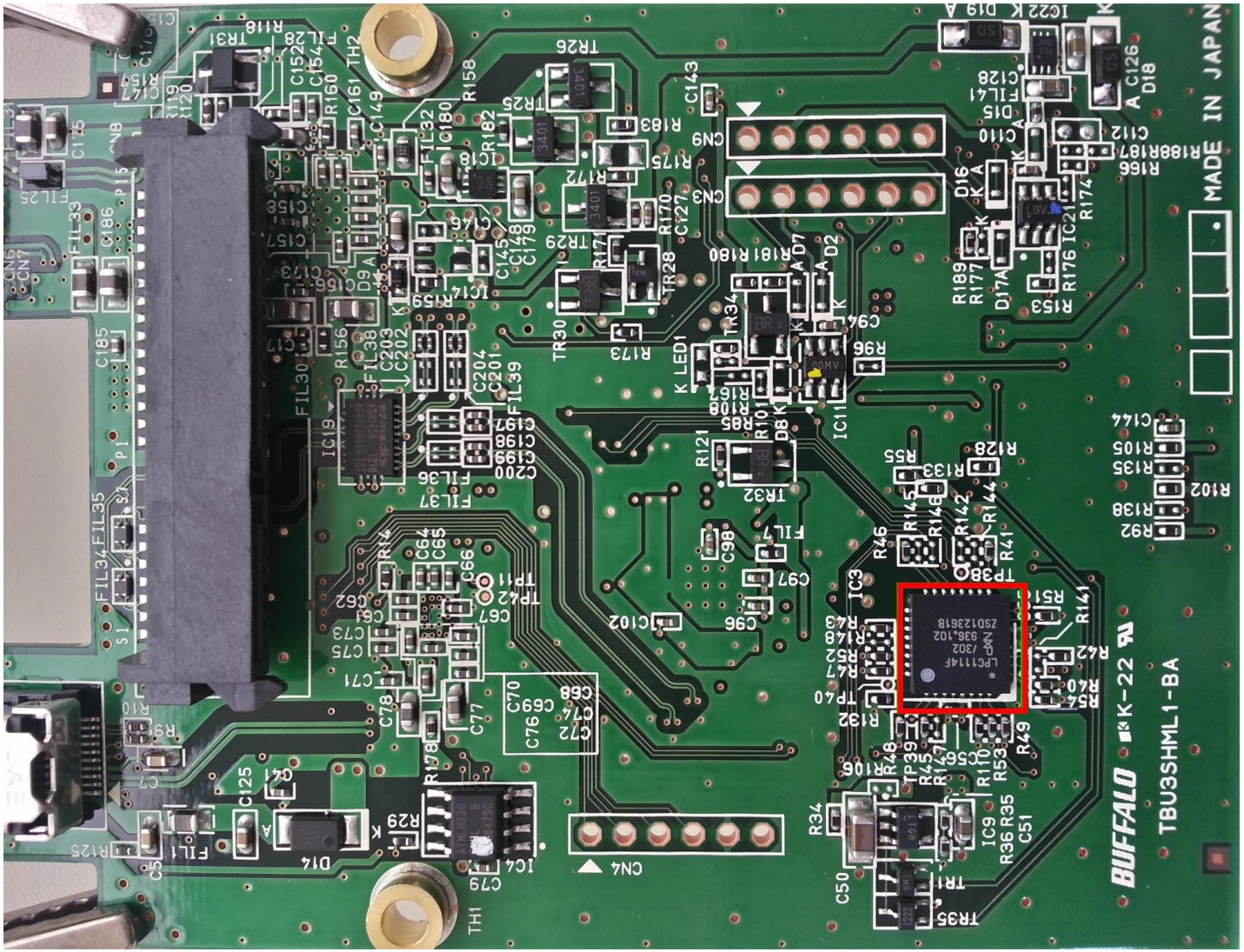


How My Adventures Went

iSECpartners
part of nccgroup

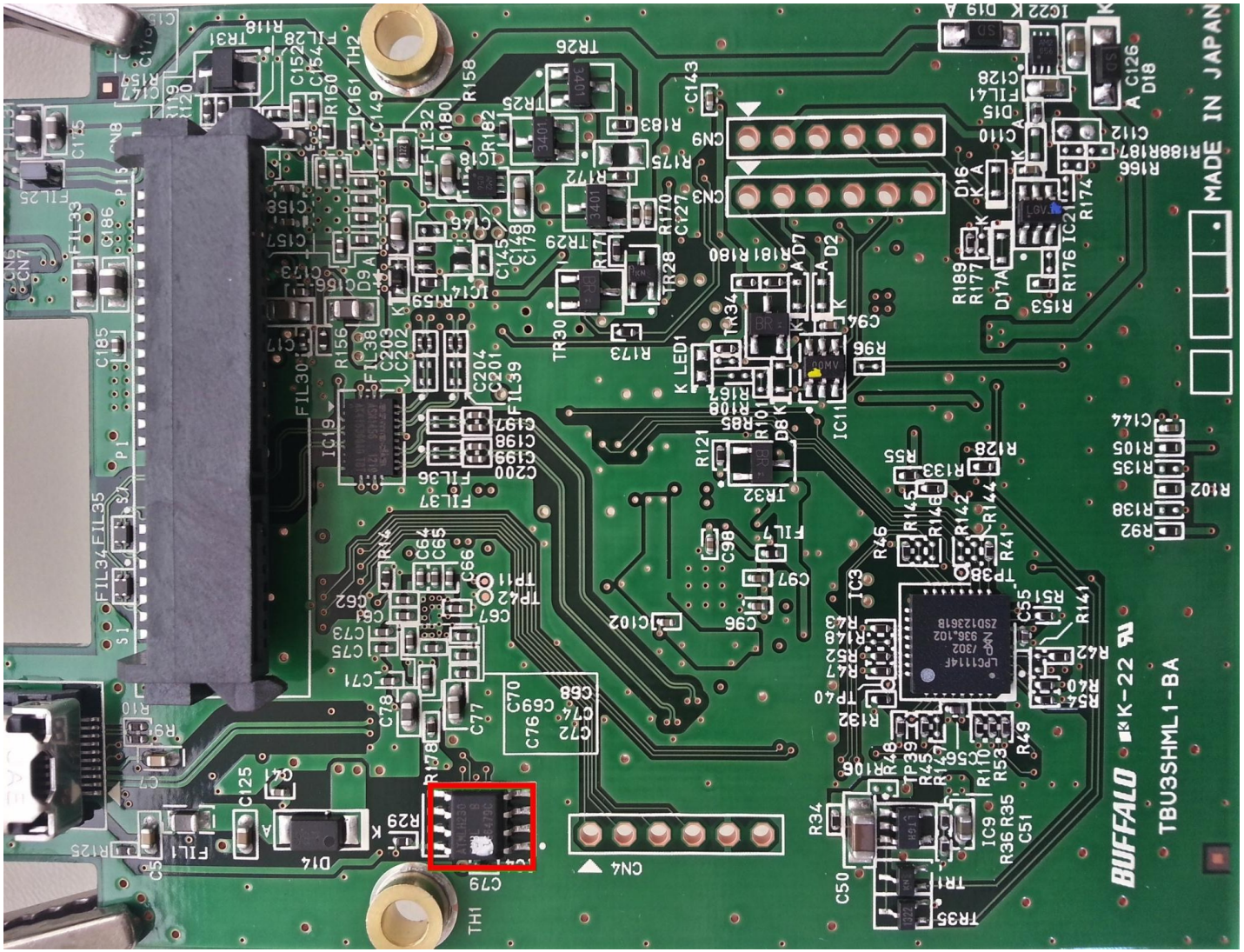


How My Adventures Went



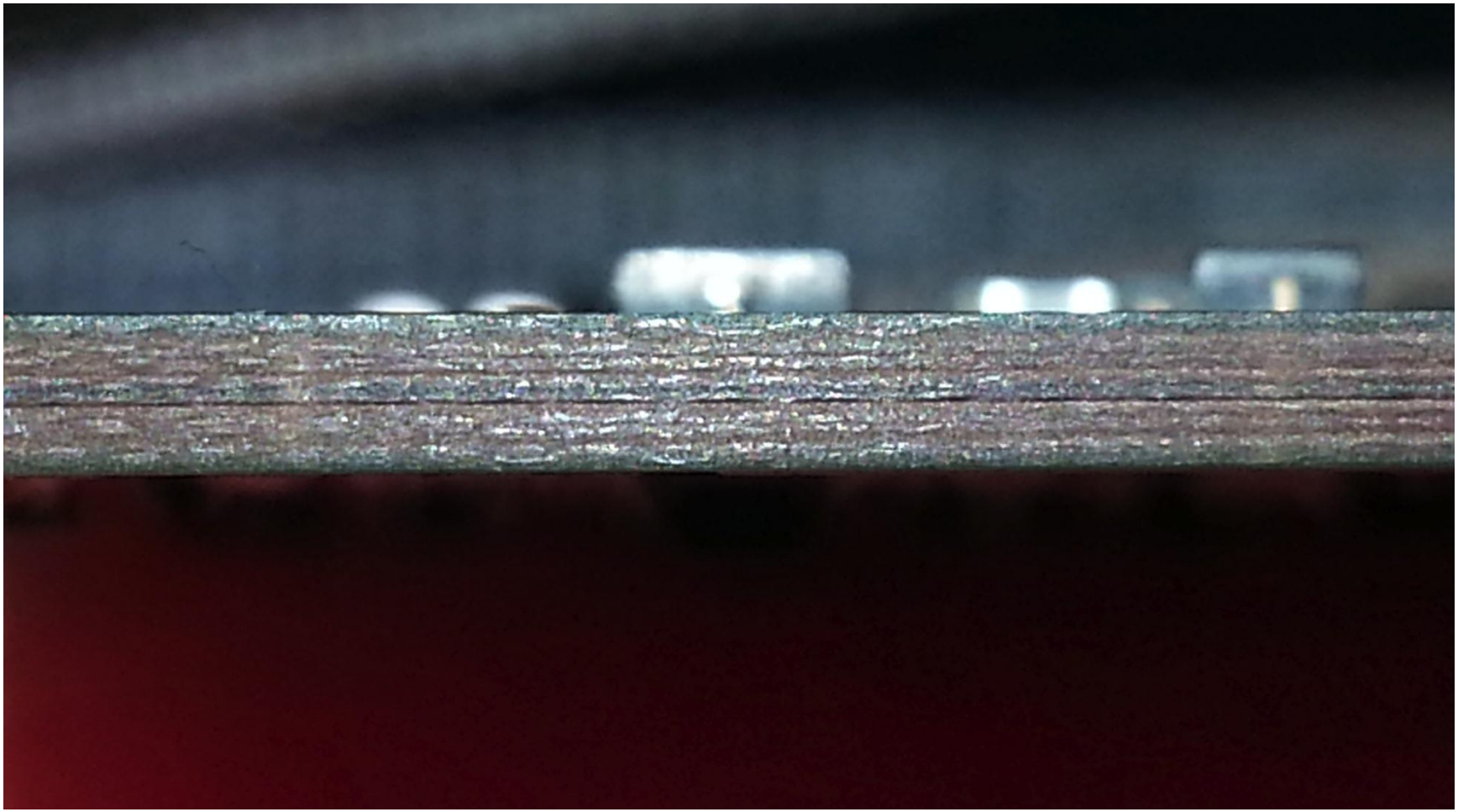
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

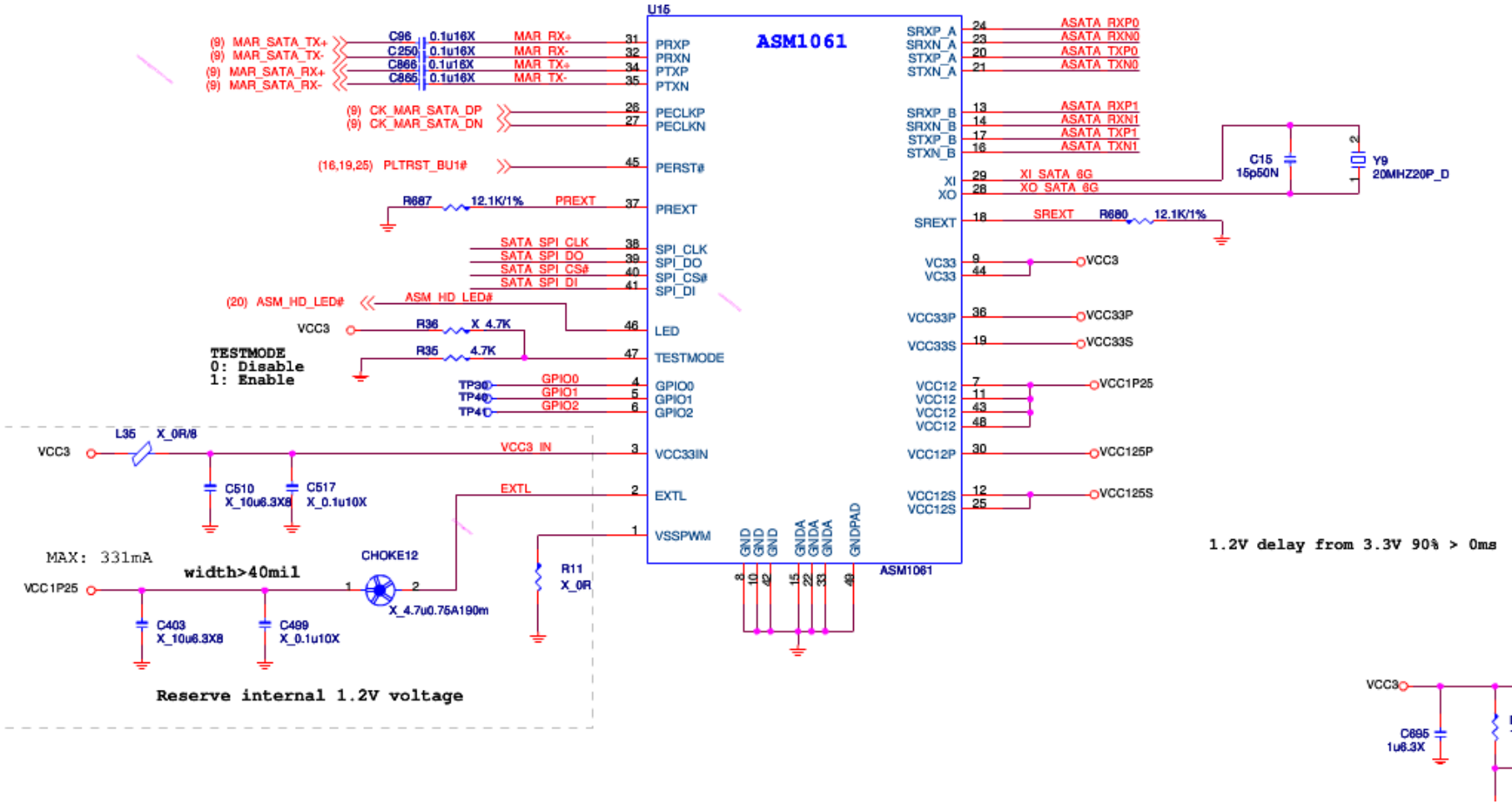
iSECpartners part of nccgroup

- ASMedia ASM1061
  - PCIe/SATA Controller
  - Datasheets?
  - ROMs/Flashes?

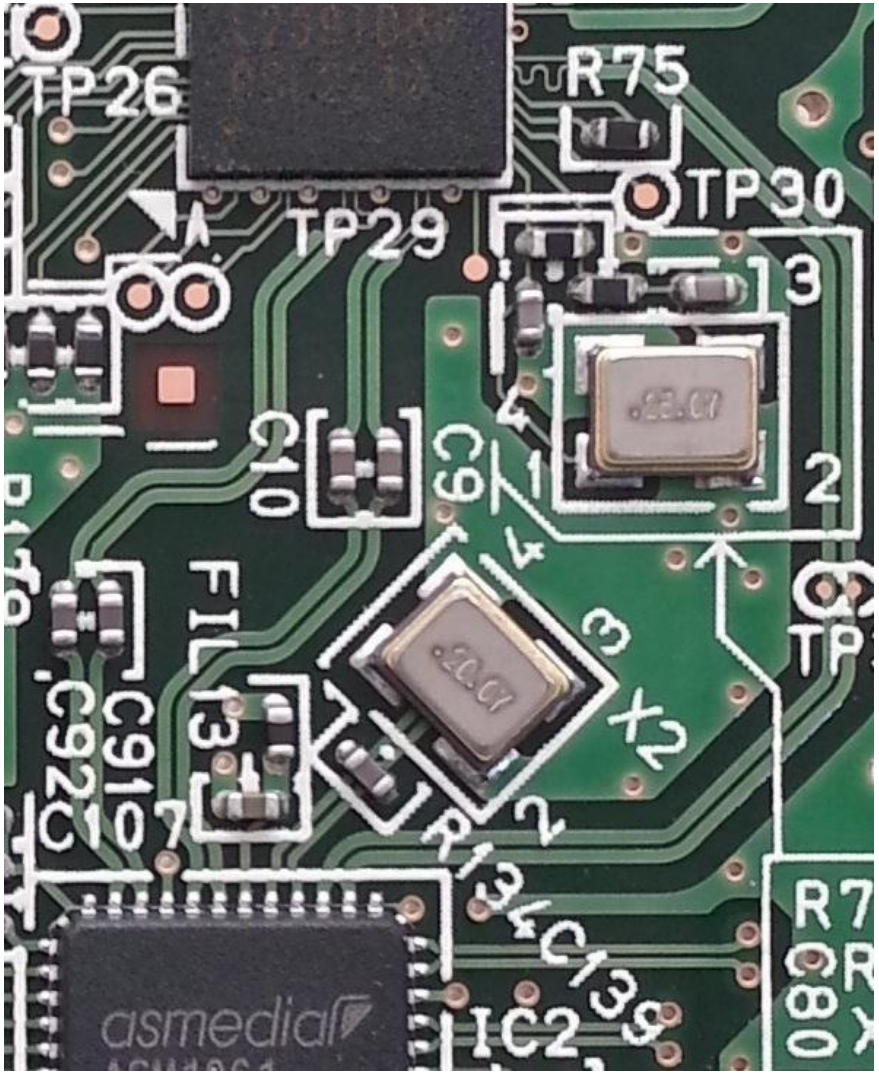
How My Adventures Went

iSECpartners
part of nccgroup

ASM1061 SATA6G

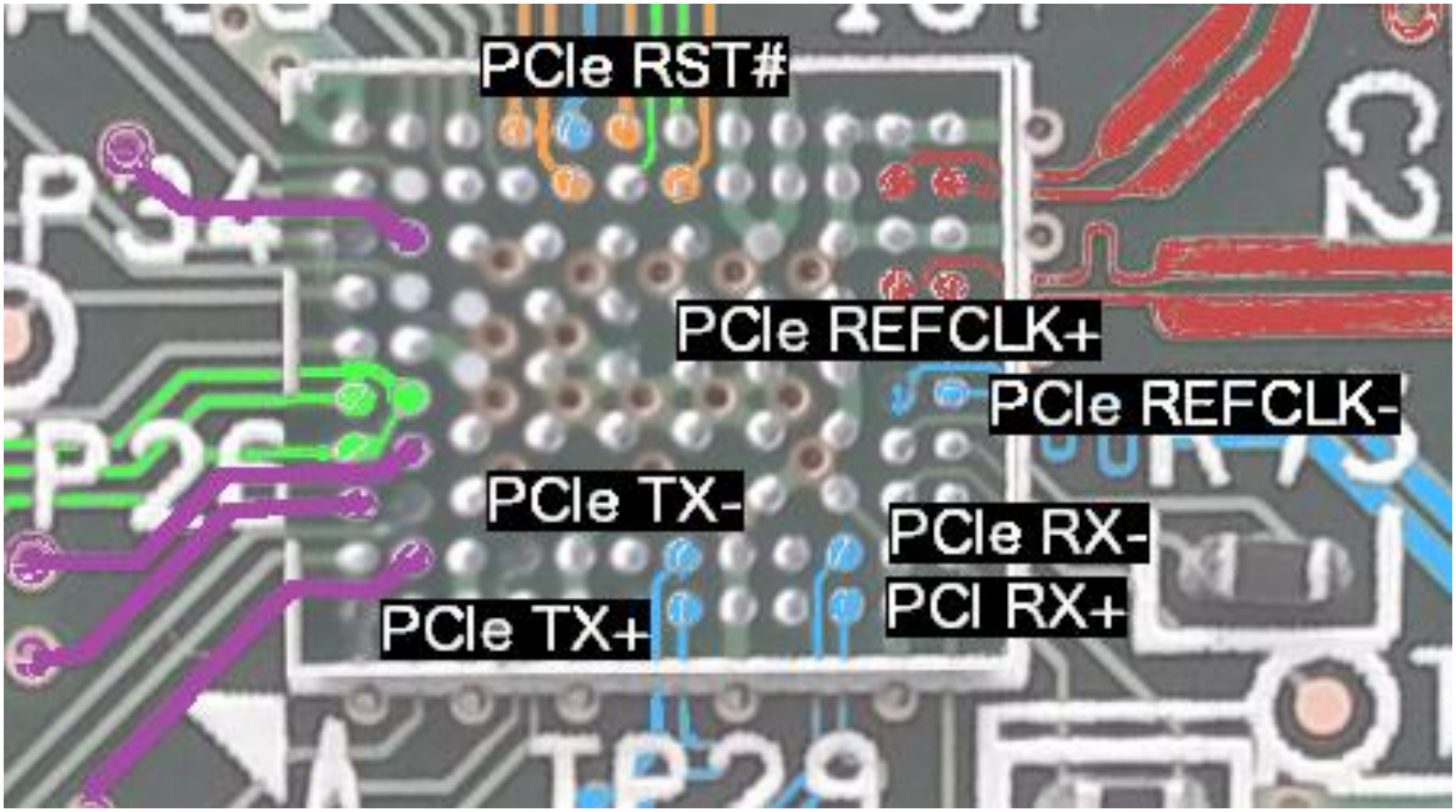


How My Adventures Went



How My Adventures Went

iSECpartners part of nccgroup



PCIe

How My Adventures Went

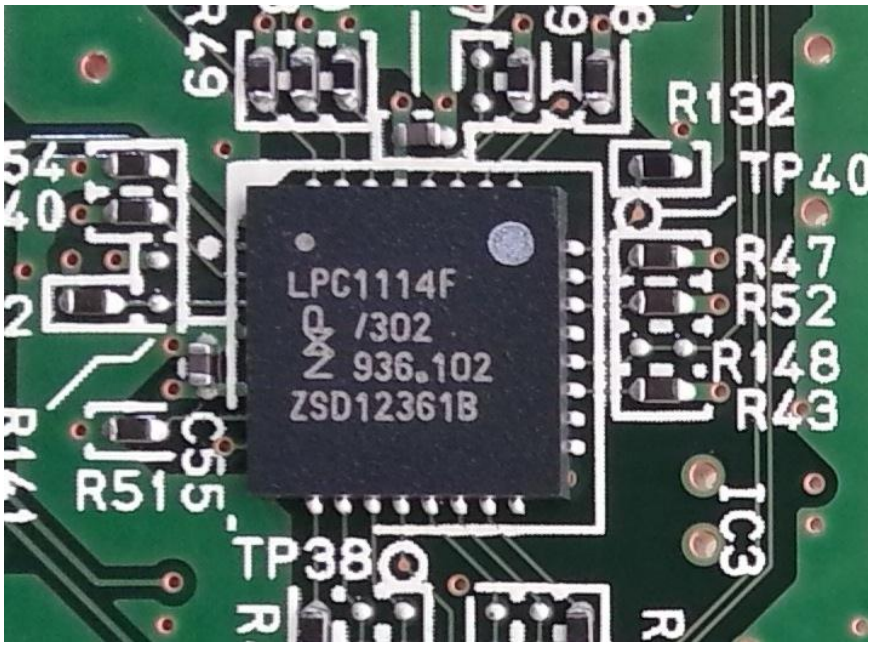
iSECpartners part of nccgroup

- Patch PCIe Controllers' SPI ROM to send DMA read requests?

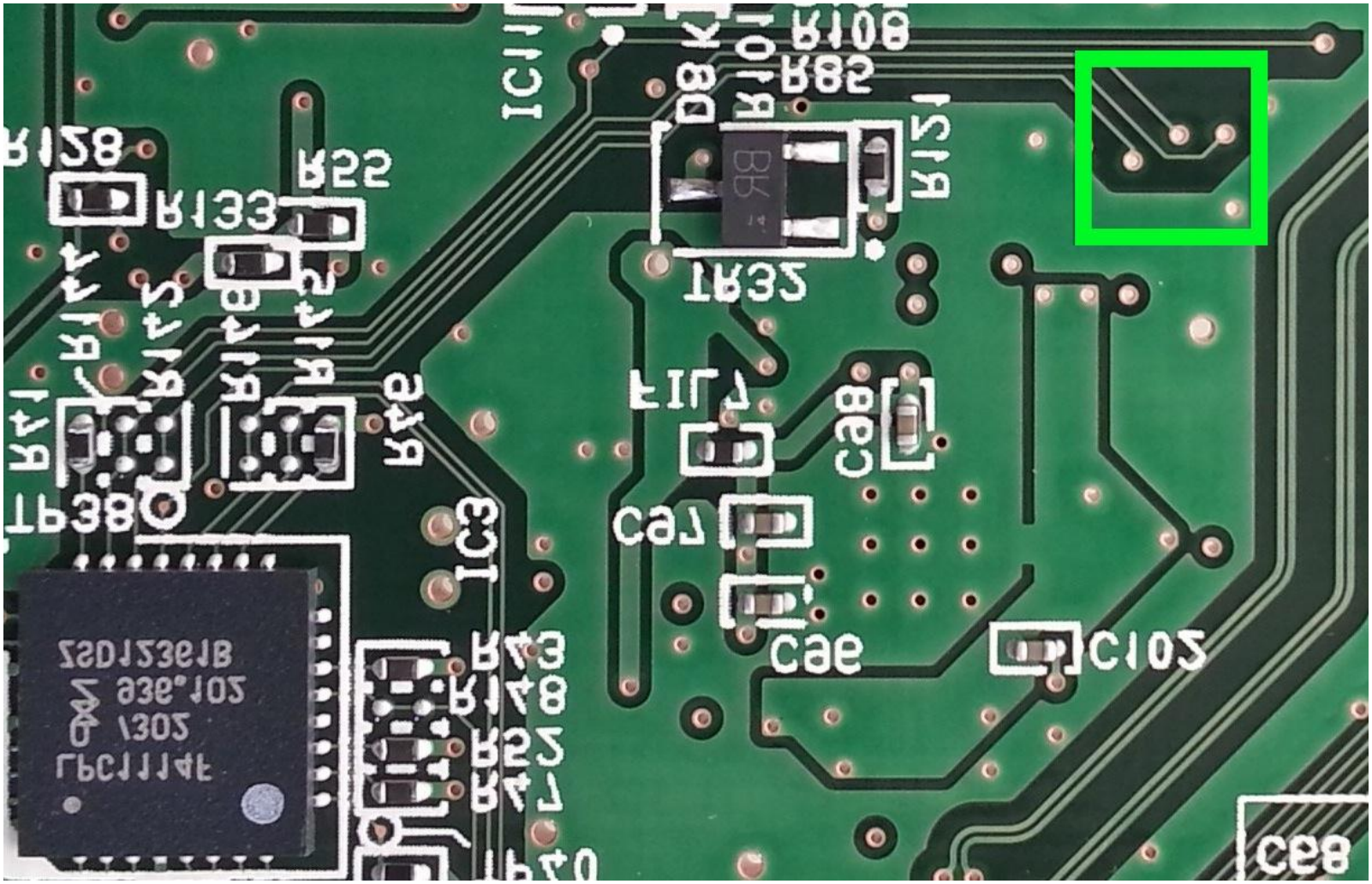
How My Adventures Went

iSECpartners part of nccgroup

- NXP LPC1114
  - ARM Cortex Mo
  - Used for… ??
  - No ROMs or Flashes
  - TONS of info online
  - Connects into DSL2201
    - How do I know?

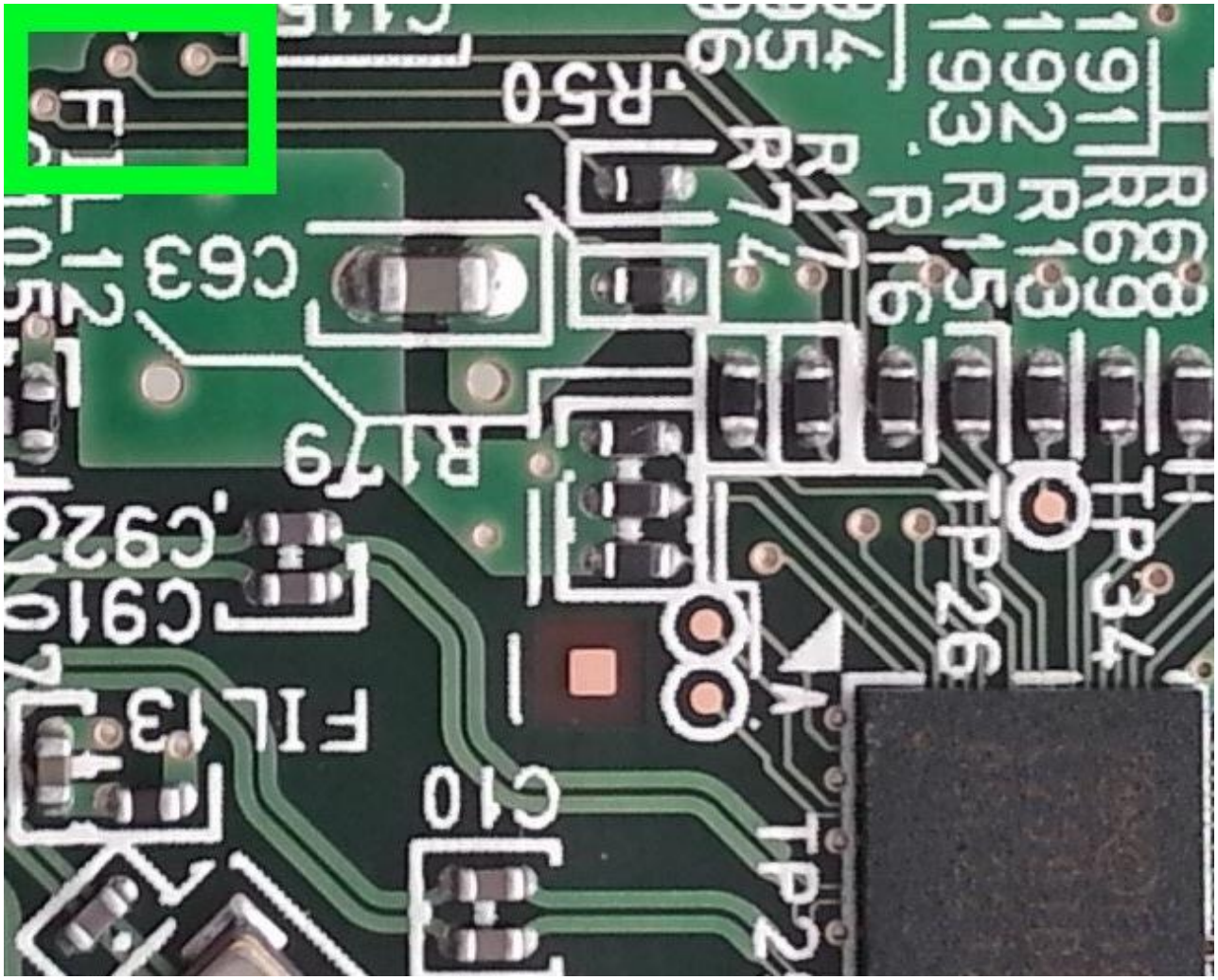


How My Adventures Went



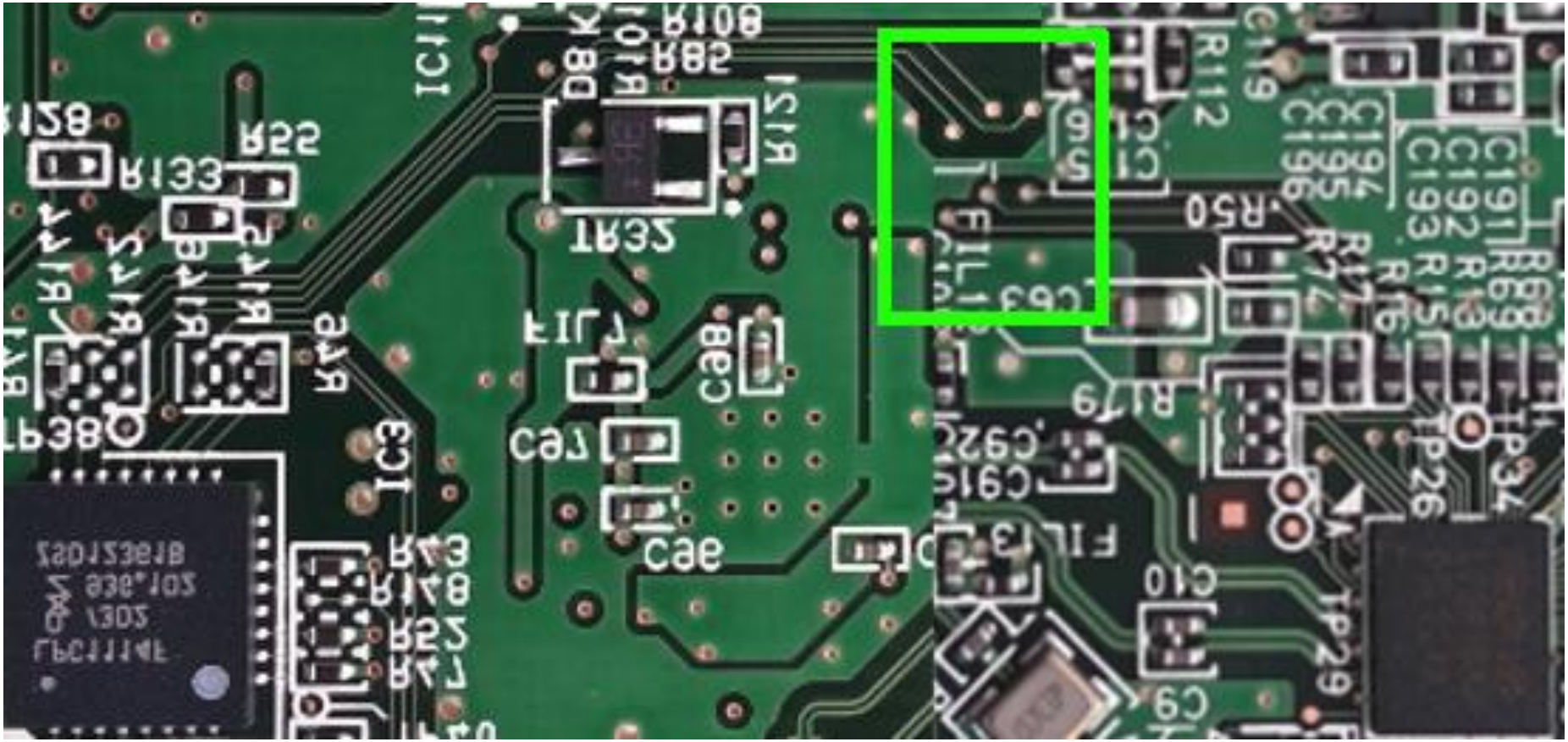
How My Adventures Went

iSECpartners
part of nccgroup



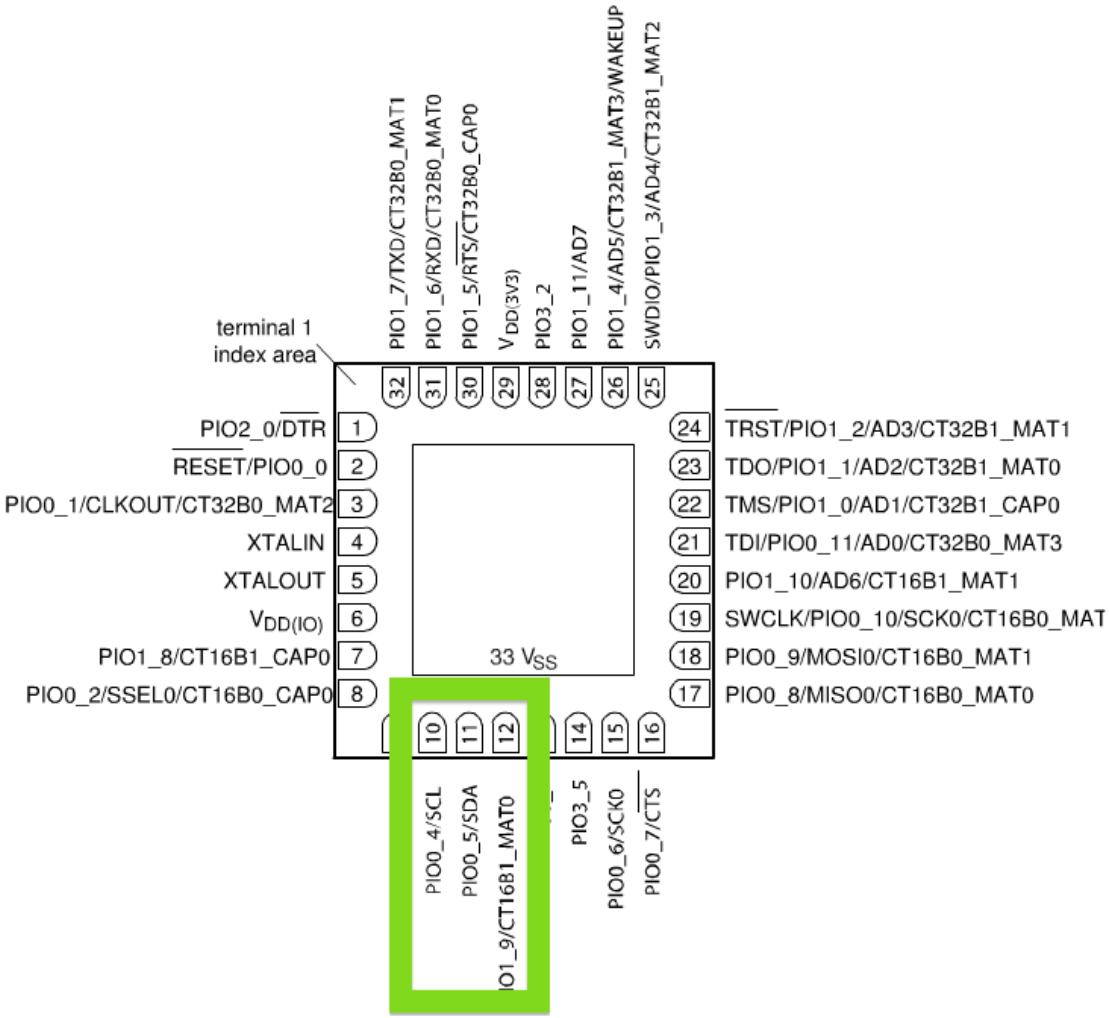
How My Adventures Went

iSECpartners
part of nccgroup



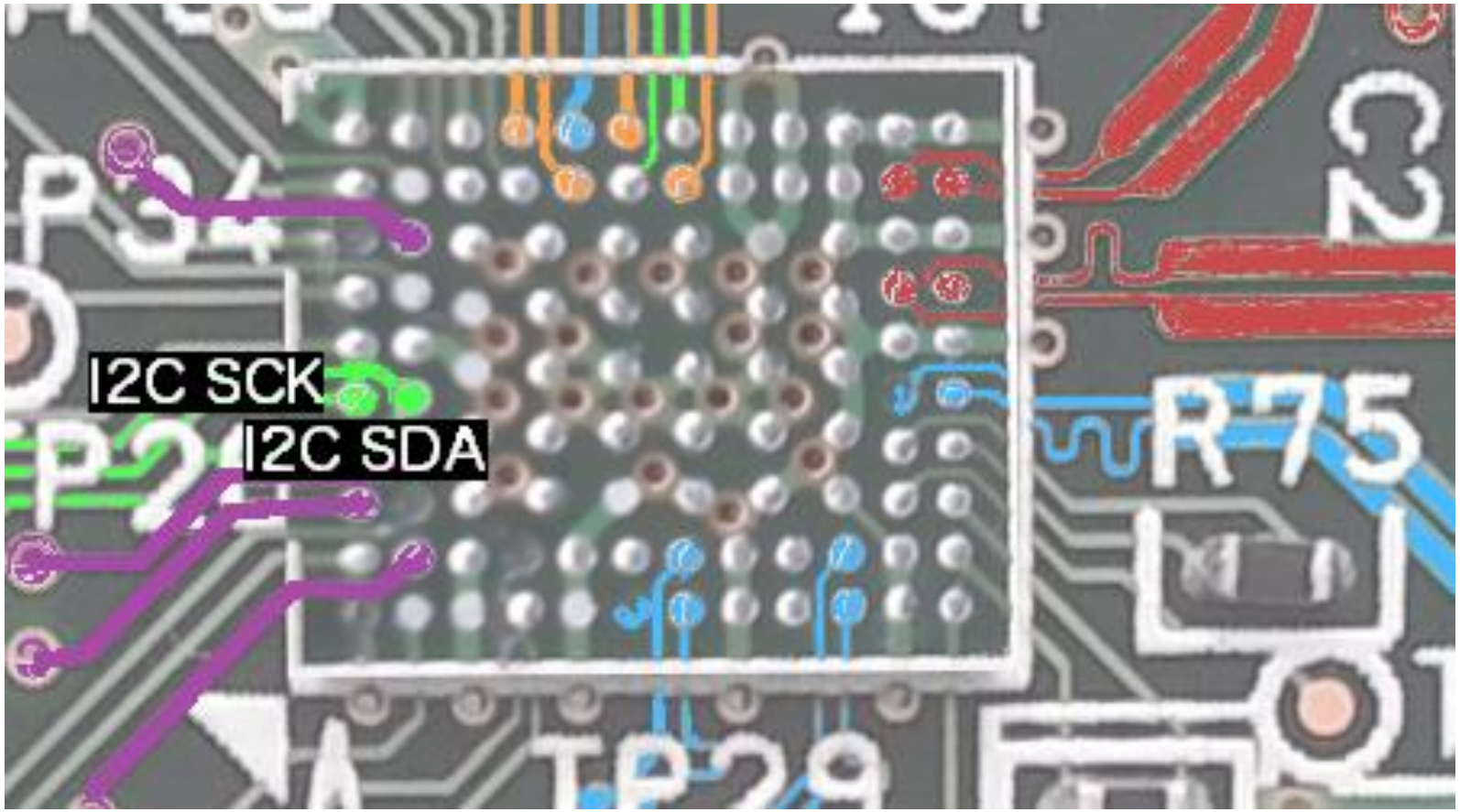
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup

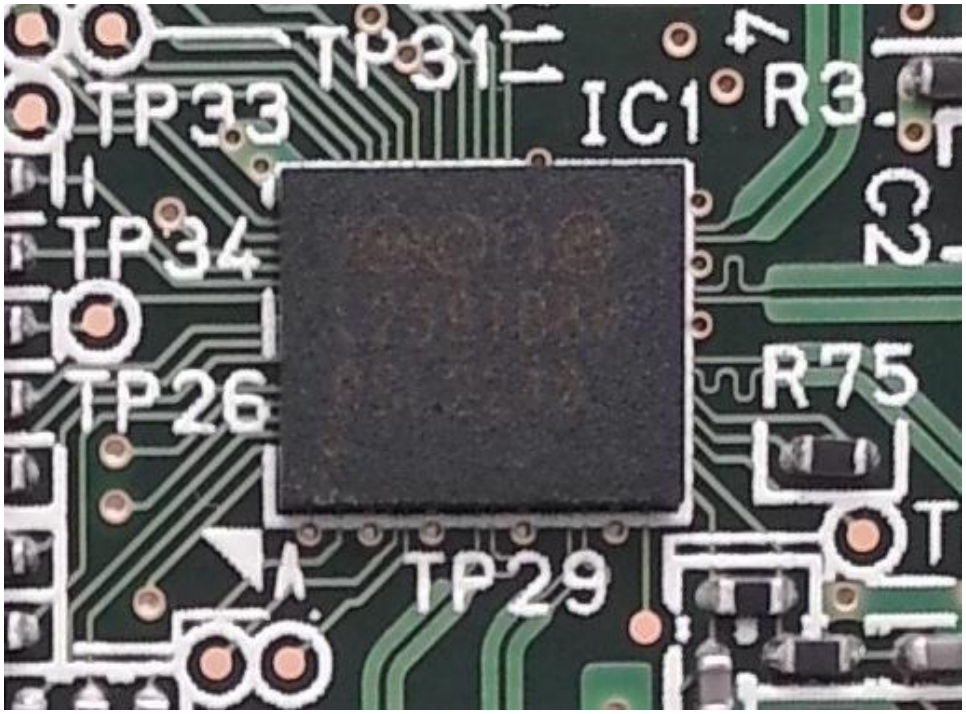


ARM

How My Adventures Went

iSECpartners part of nccgroup

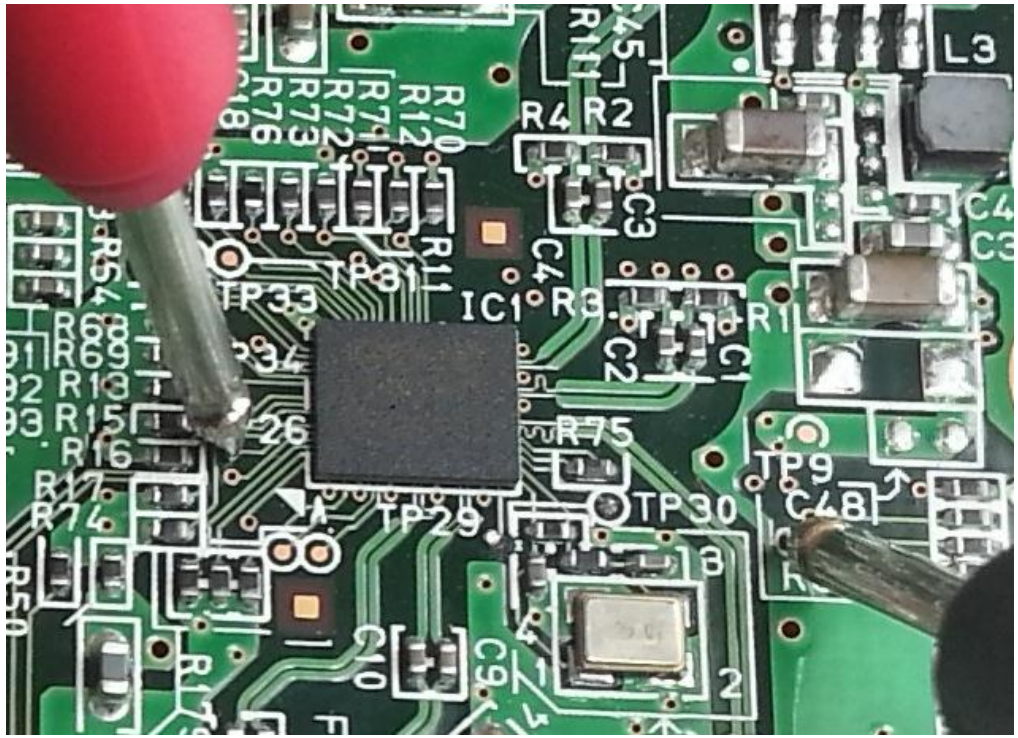
- Intel DSL2210
  - Thunderbolt Controller
  - No Datasheets
  - Promo info only
  - ROMs/Flashes?



How My Adventures Went

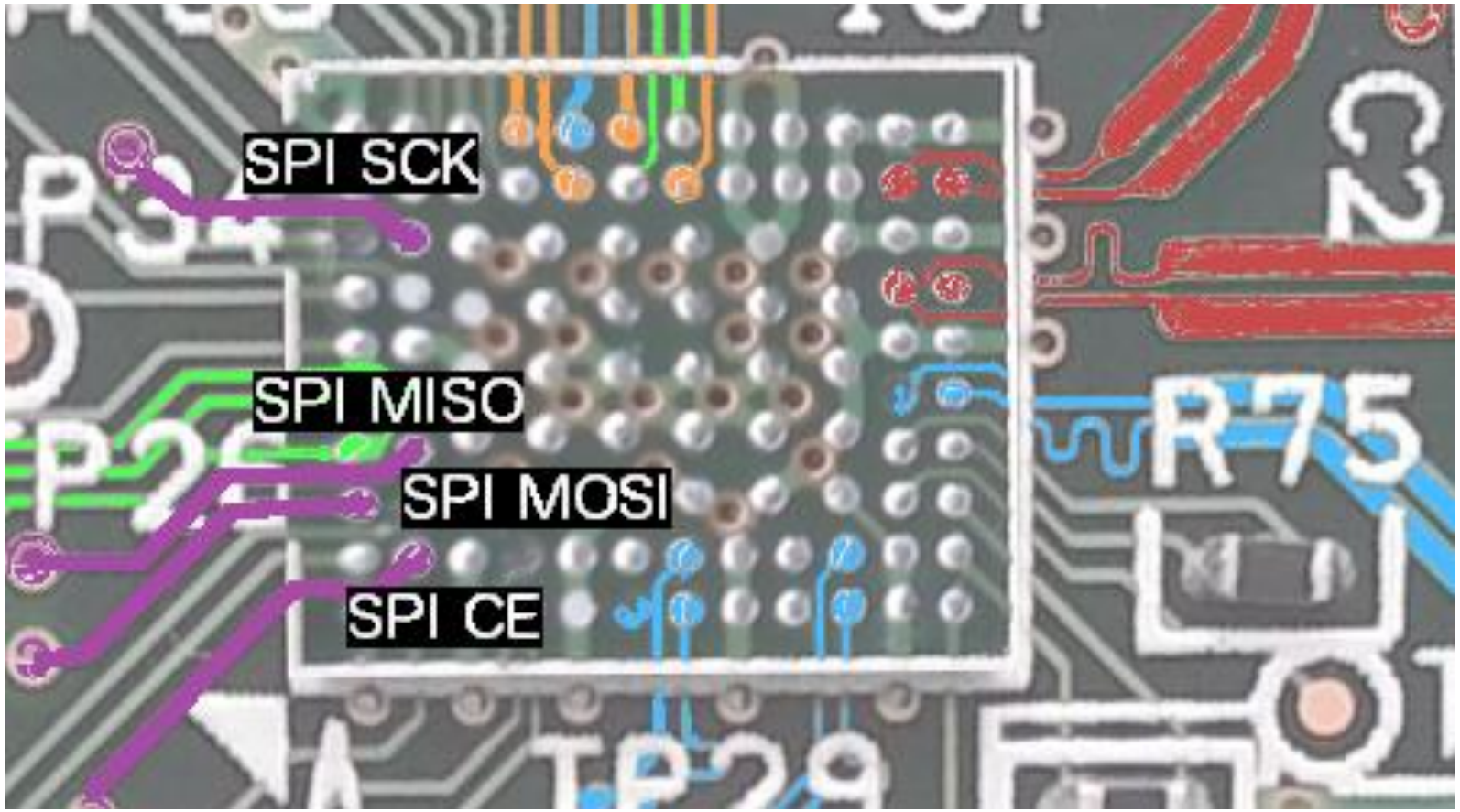
iSECpartners part of nccgroup

- Continuity testing SPI ROM…
  - Beep! It's Thunderbolt!
  - hasROM = TRUE;



How My Adventures Went

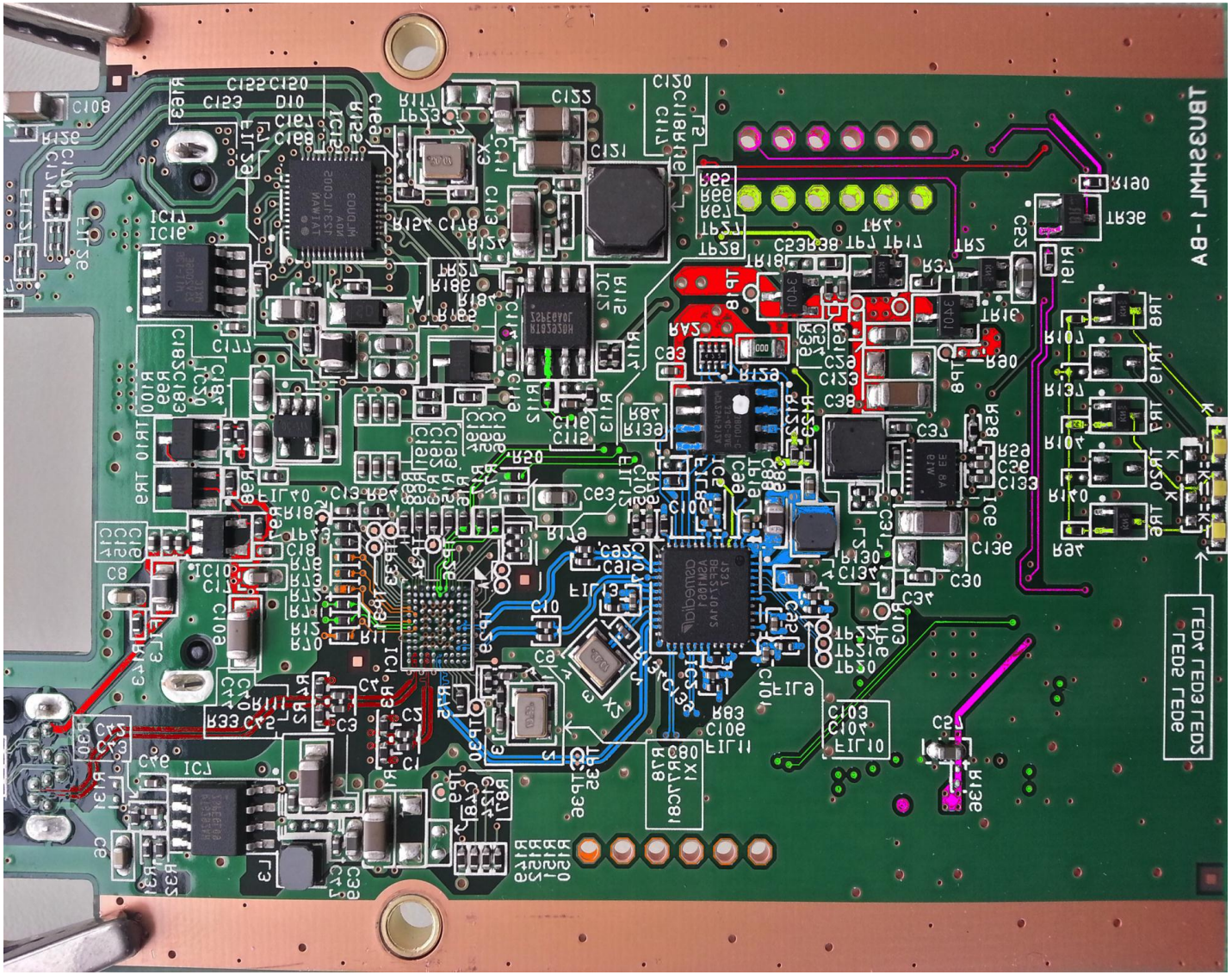
iSECpartners
part of nccgroup



SPI

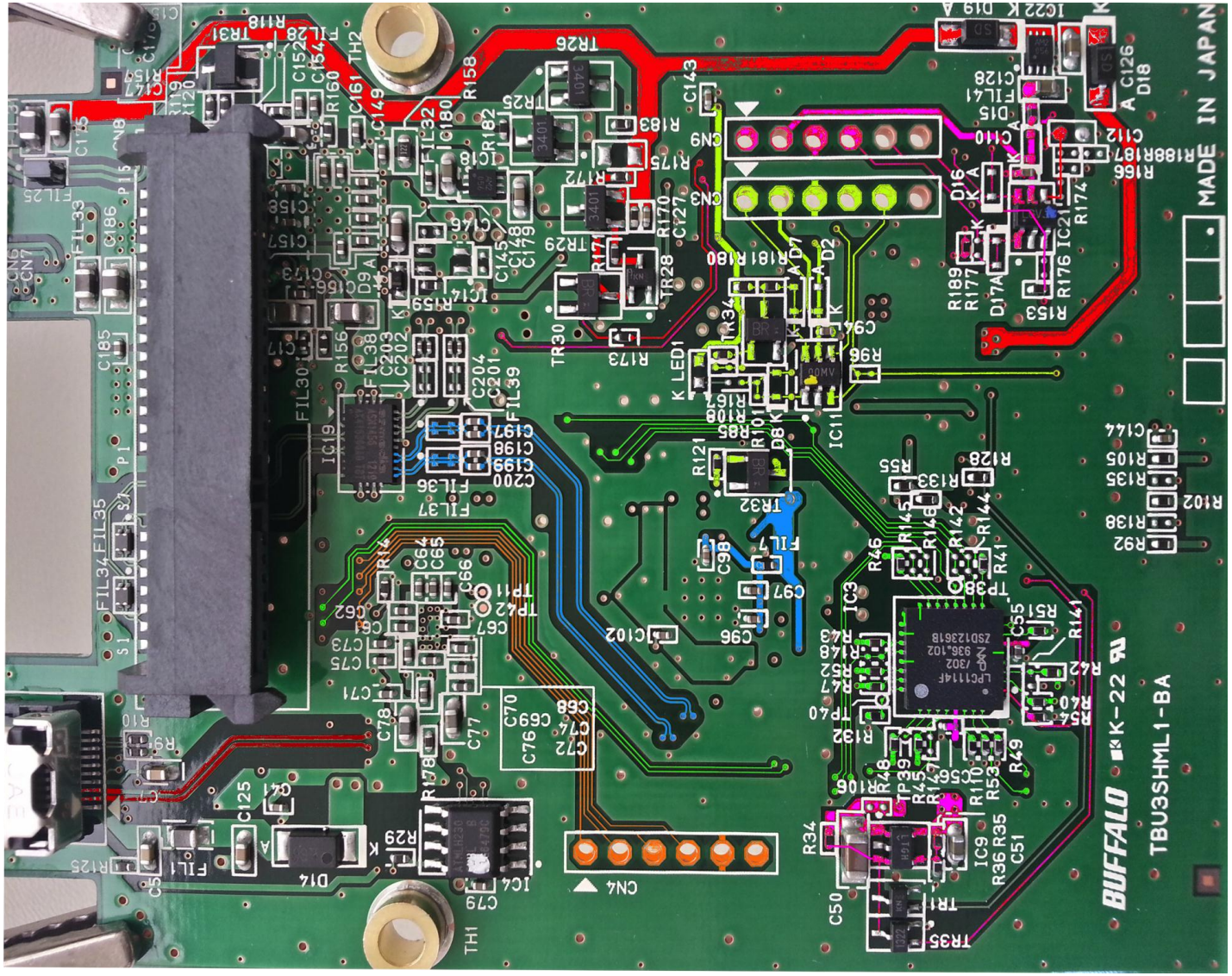
How My Adventures Went

iSECpartners
part of nccgroup



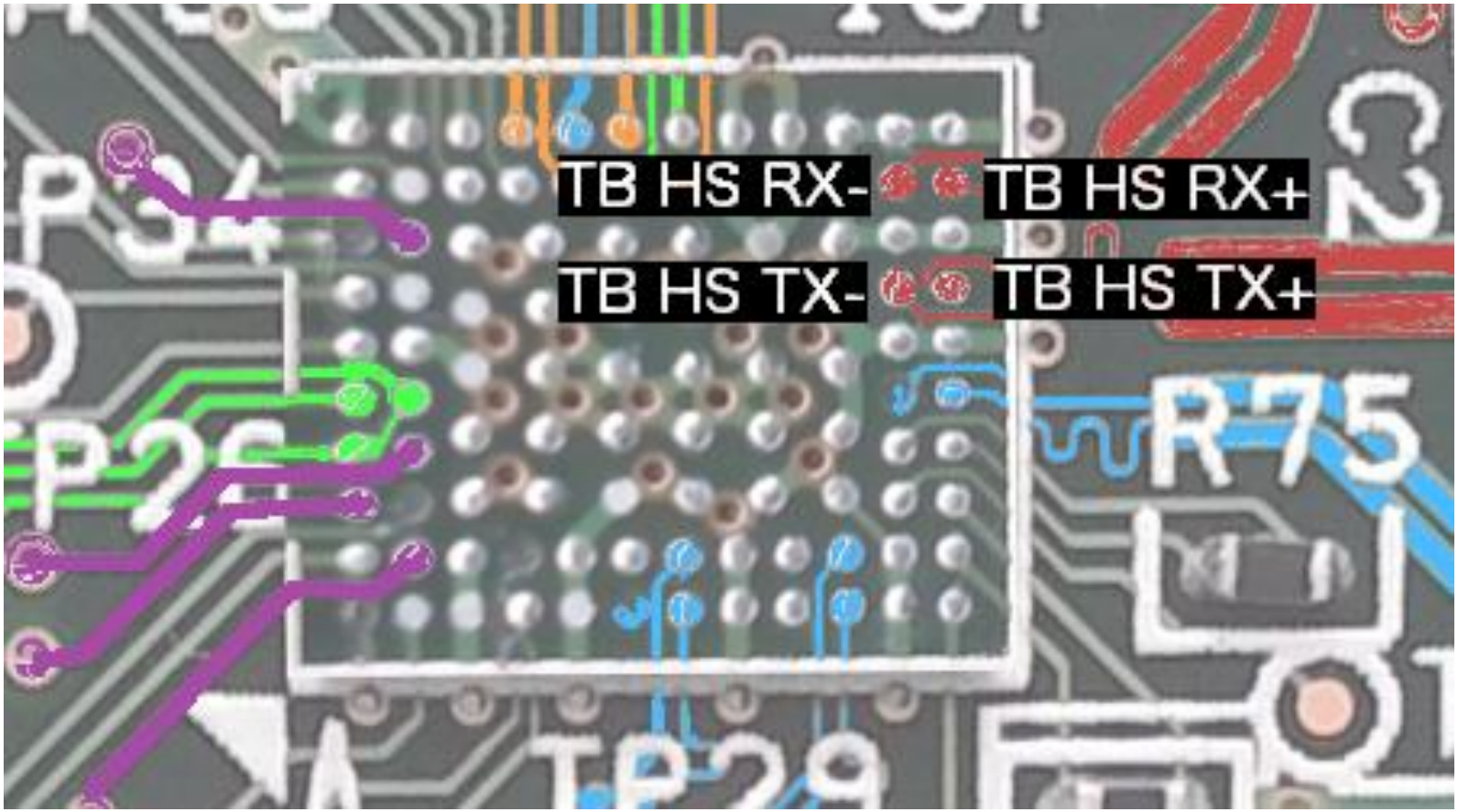
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup



Thunderbolt Connector

How My Adventures Went

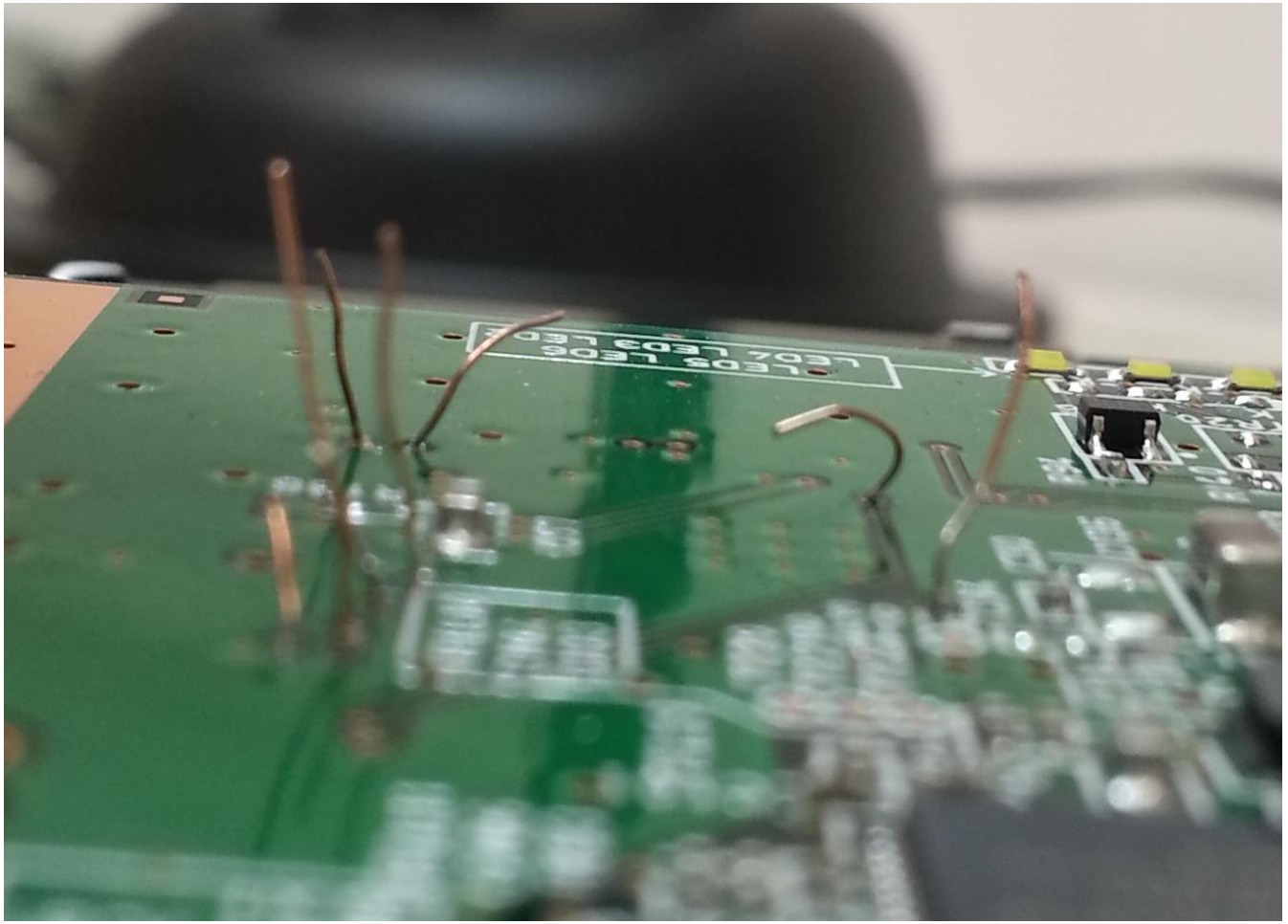
iSECpartners part of nccgroup

- Thunderbolt Connector
  - 1 pair of HighSpeed lanes
    - TX and RX
  - All others pulled to ground
  - "LowSpeed" lines go to ARM?

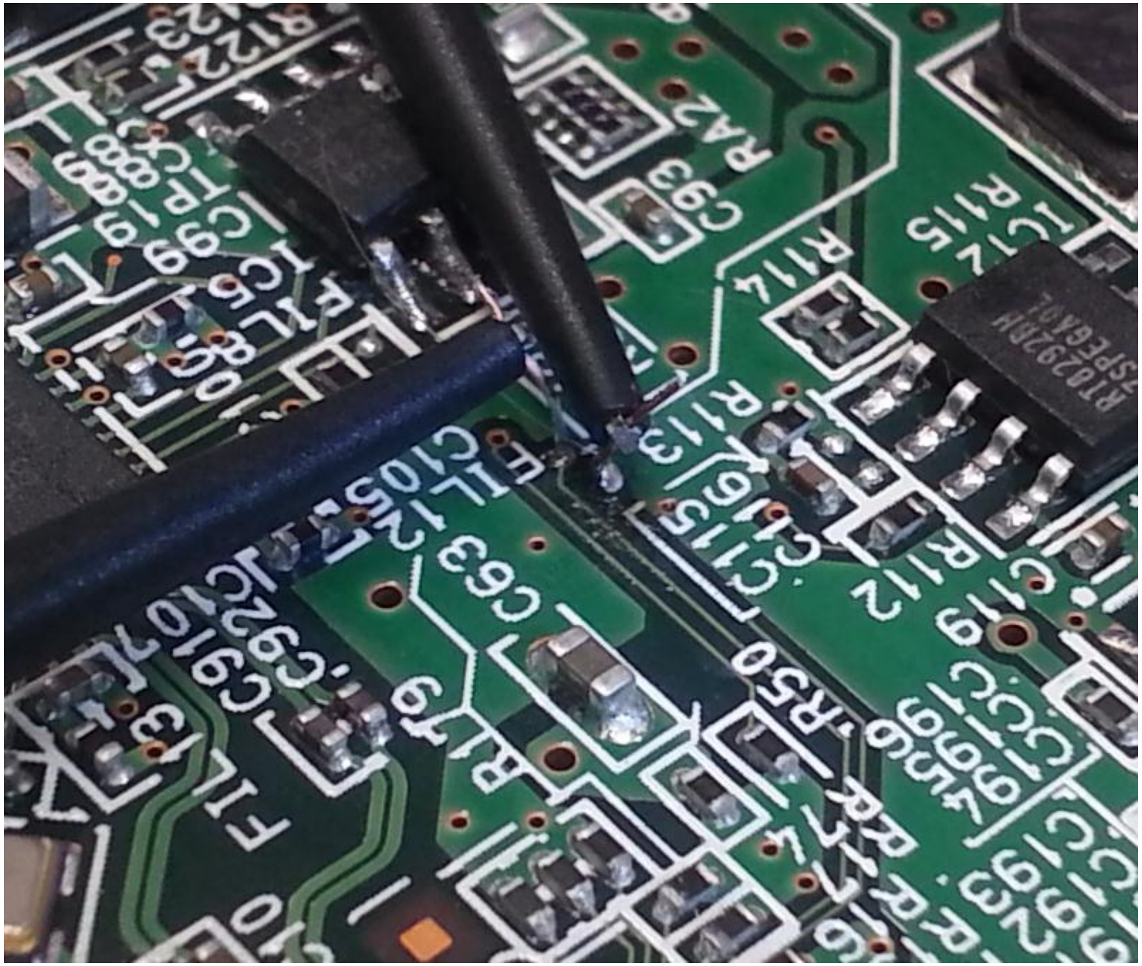
Pin out		
Pin 1	GND	Ground
Pin 2	HPD	Hot plug detect
Pin 3	HS0TX(P)	HighSpeed transmit 0 (positive)
Pin 4	HS0RX(P)	HighSpeed receive 0 (positive)
Pin 5	HS0TX(N)	HighSpeed transmit 0 (negative)
Pin 6	HS0RX(N)	HighSpeed receive 0 (negative)
Pin 7	GND	Ground
Pin 8	GND	Ground
Pin 9	LSR2P TX	LowSpeed transmit
Pin 10	GND	Ground (reserved)
Pin 11	LSP2R RX	LowSpeed receive
Pin 12	GND	Ground (reserved)
Pin 13	GND	Ground
Pin 14	GND	Ground
Pin 15	HS1TX(P)	HighSpeed transmit 1 (positive)
Pin 16	HS1RX(P)	HighSpeed receive 1 (positive)
Pin 17	HS1TX(N)	HighSpeed transmit 1 (negative)
Pin 18	HS1RX(N)	HighSpeed receive 1 (negative)
Pin 19	GND	Ground
Pin 20	DPPWR	Power

How My Adventures Went

iSECpartners
part of nccgroup

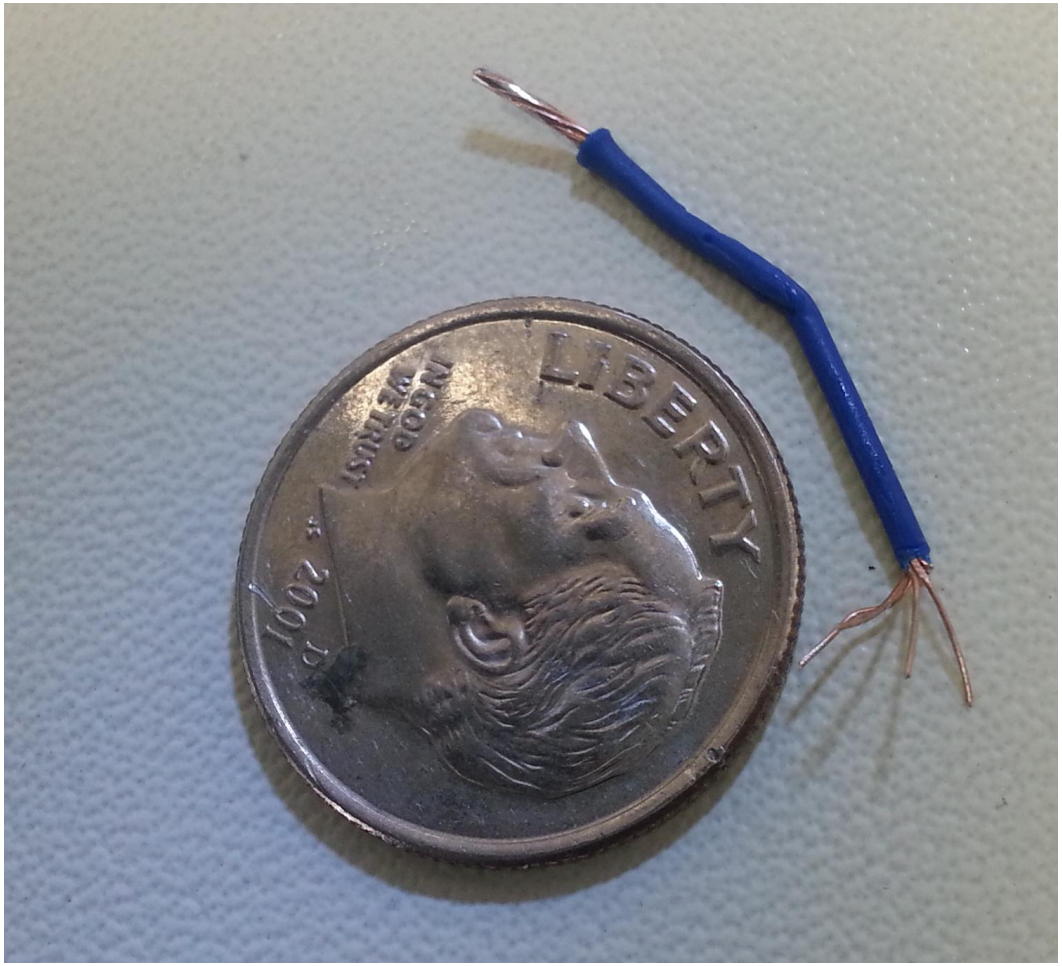


How My Adventures Went



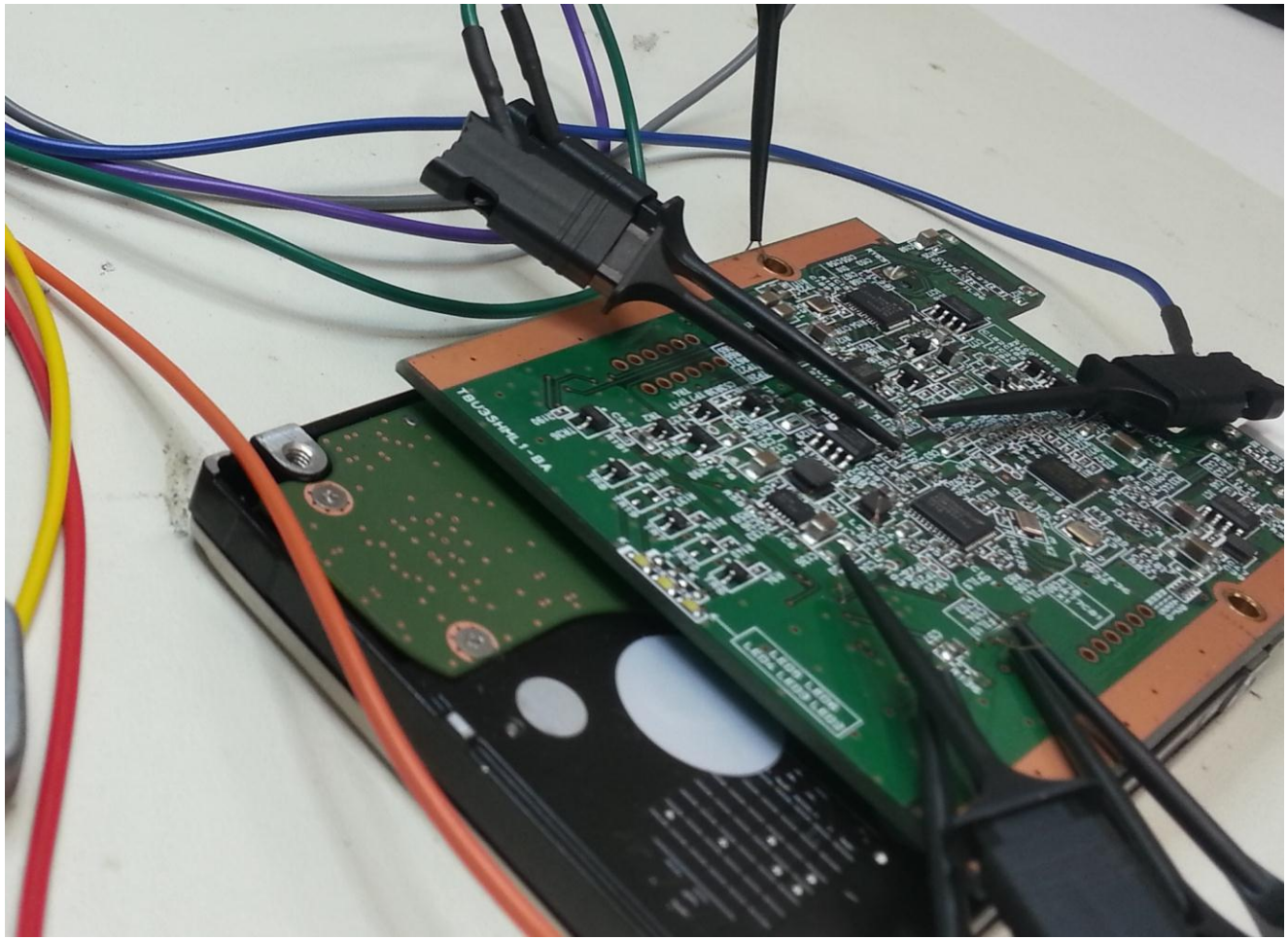
How My Adventures Went

iSECpartners
part of nccgroup



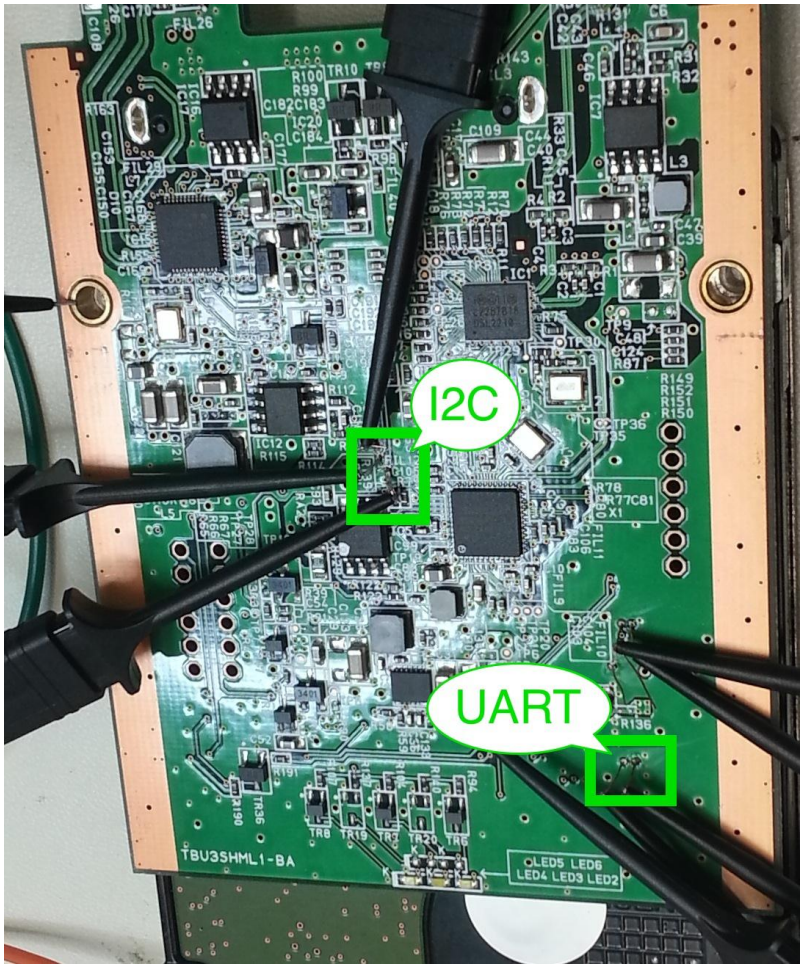
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup

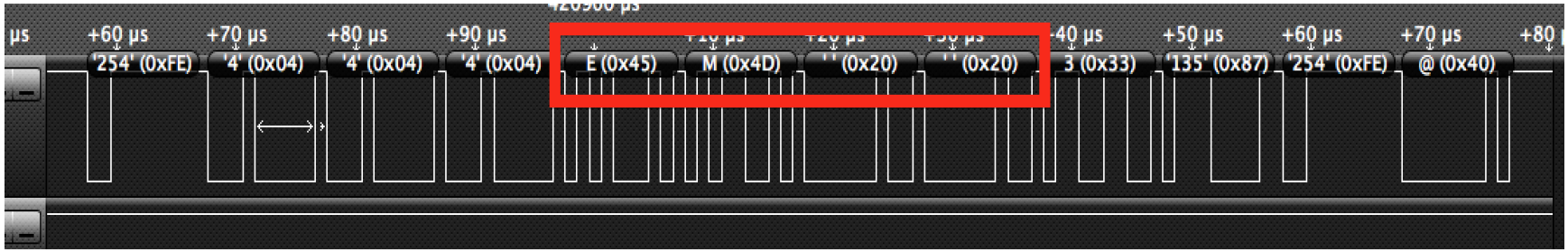


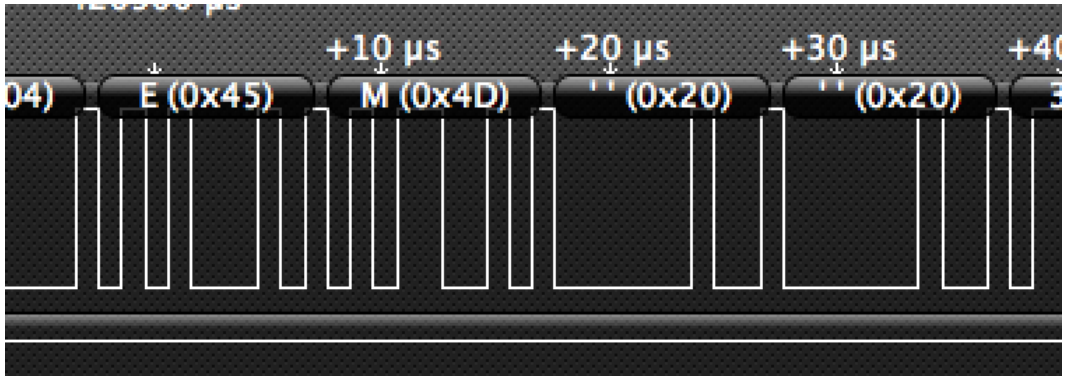
How My Adventures Went

iSECpartners
part of nccgroup

How My Adventures Went

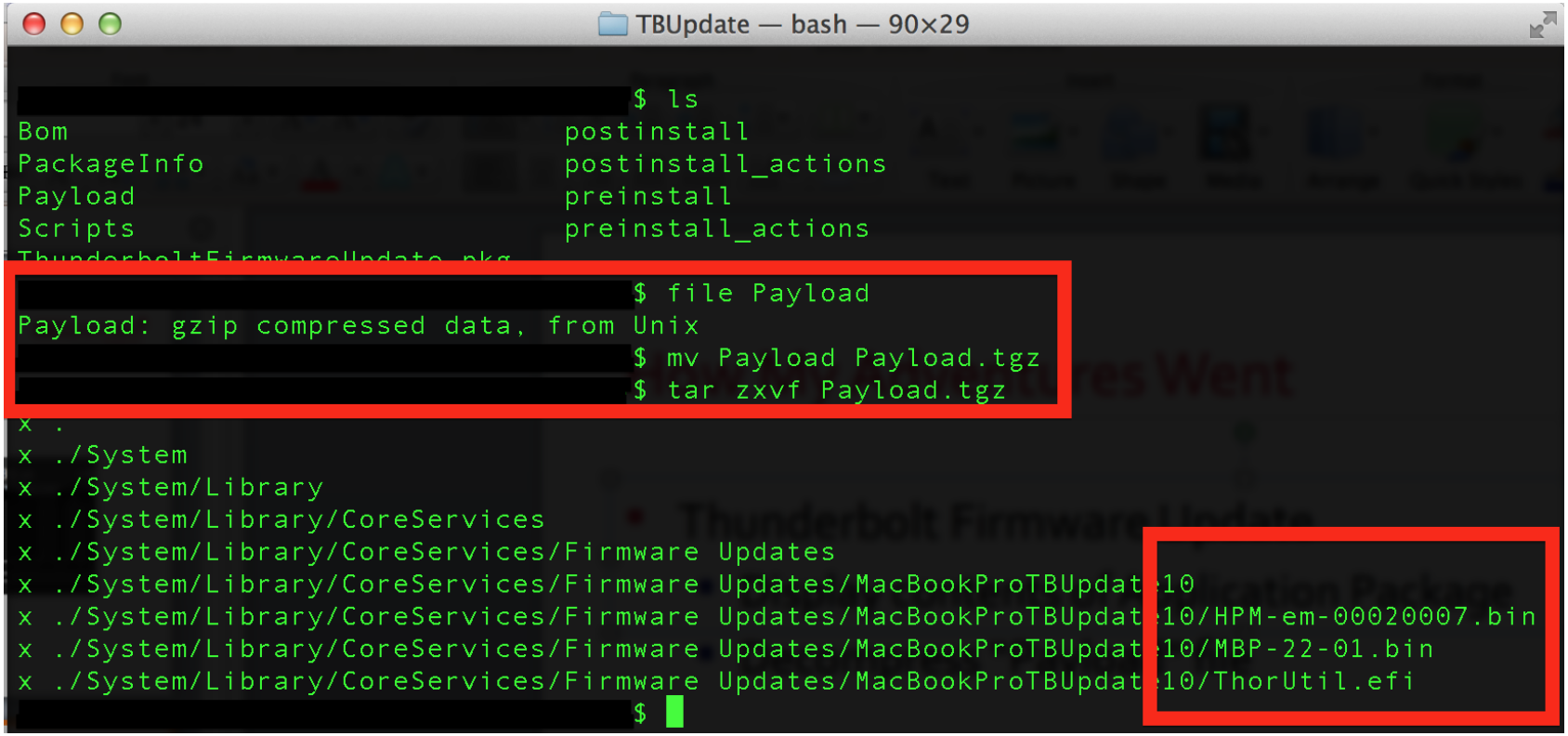
- ARM UART Traffic
  - String "EM "





How My Adventures Went

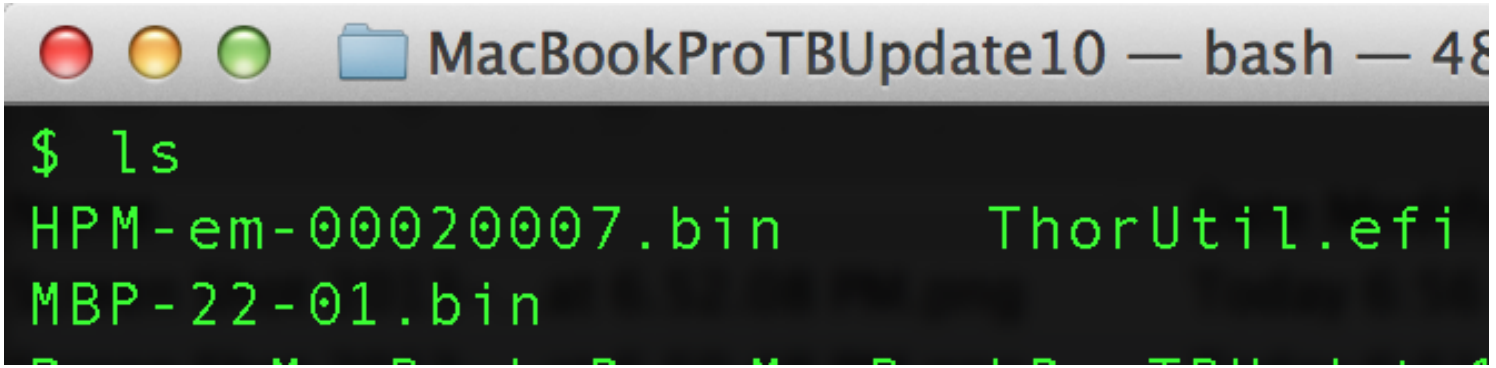
- Thunderbolt Firmware Update
  - Display contents of Application Package
  - Decompress “Payload” file



How My Adventures Went

iSECpartners part of nccgroup

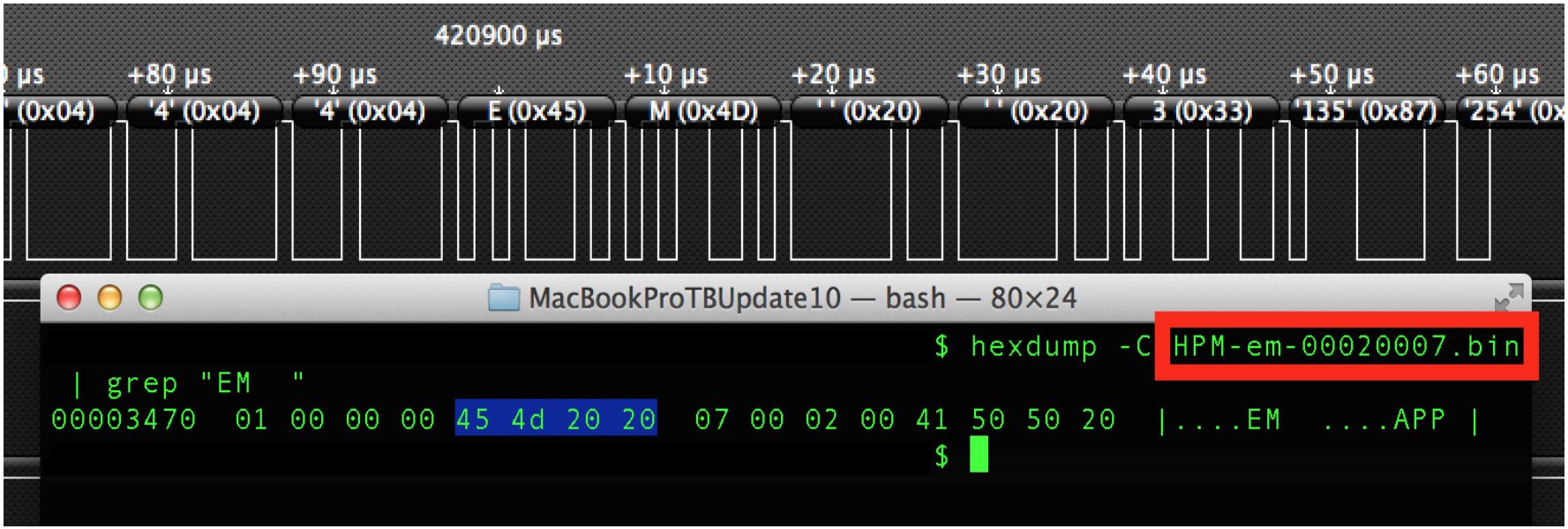
- Two Firmwares for Thunderbolt?
  - One is probably ARM
  - Let's look for string "EM "



How My Adventures Went

iSECpartners part of nccgroup

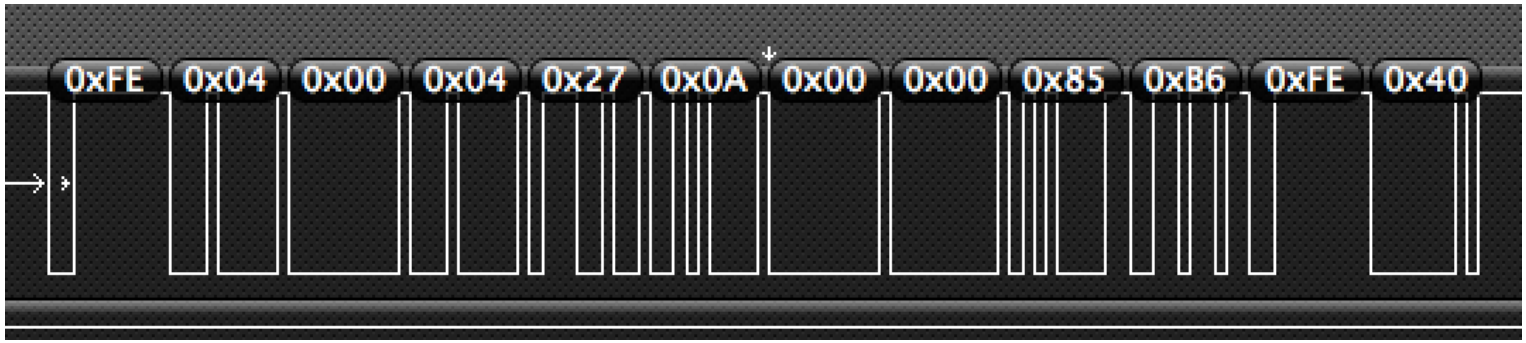
Jackpot!



How My Adventures Went

iSECpartners part of nccgroup

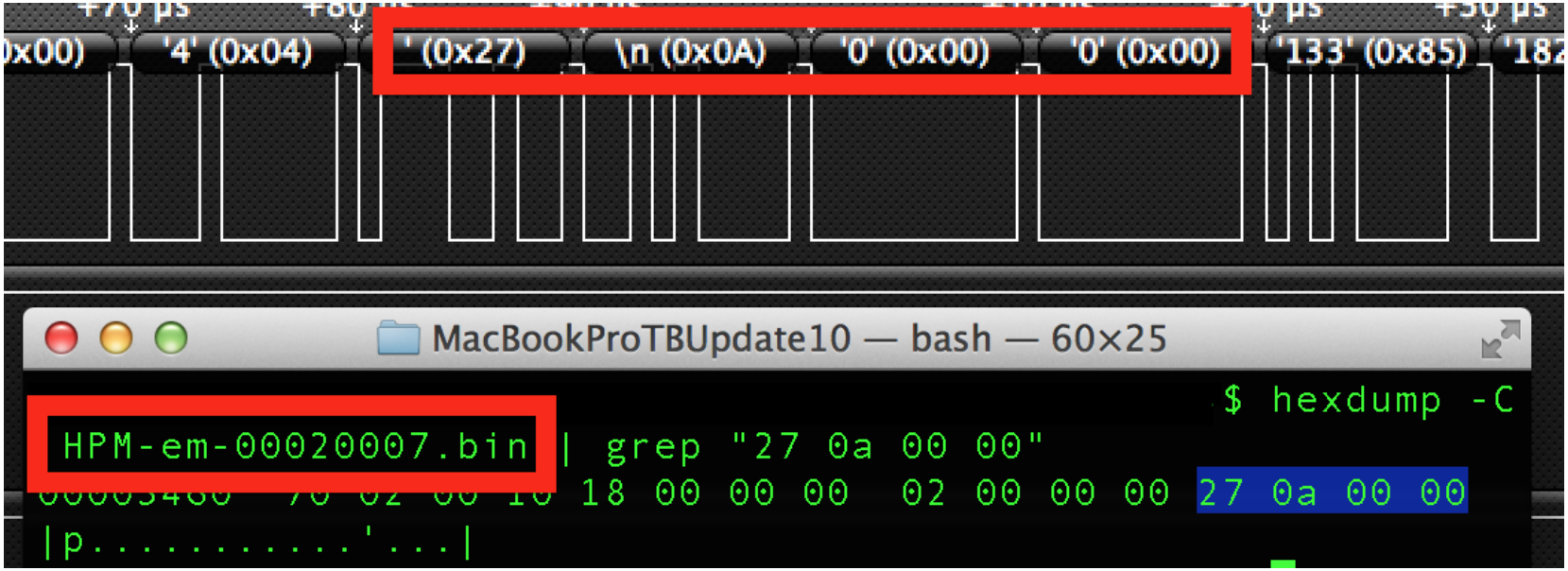
- Round 2…
  - String "\x27\x0a\x00\x00"



How My Adventures Went

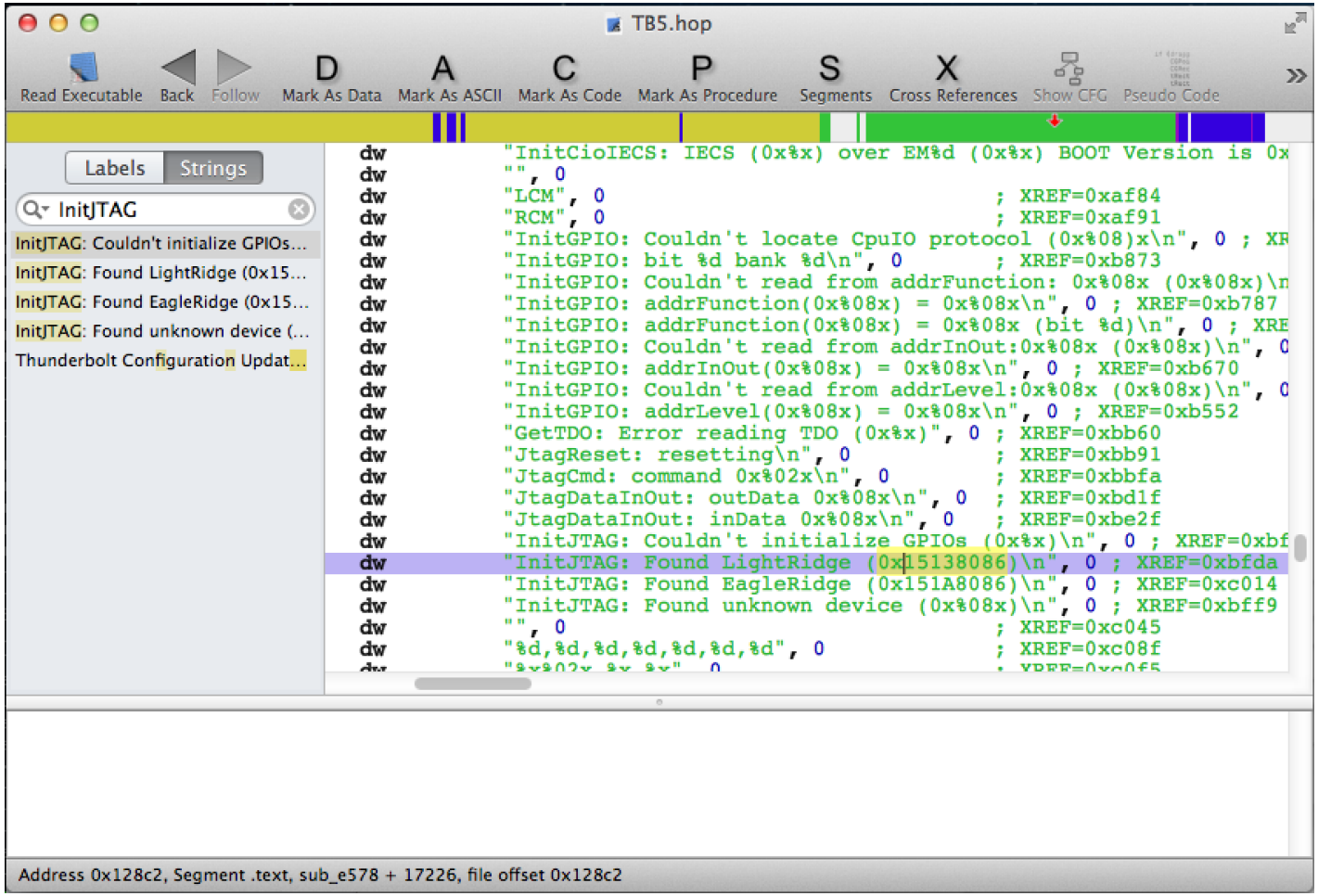
iSECpartners part of nccgroup

Successaroo!



How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

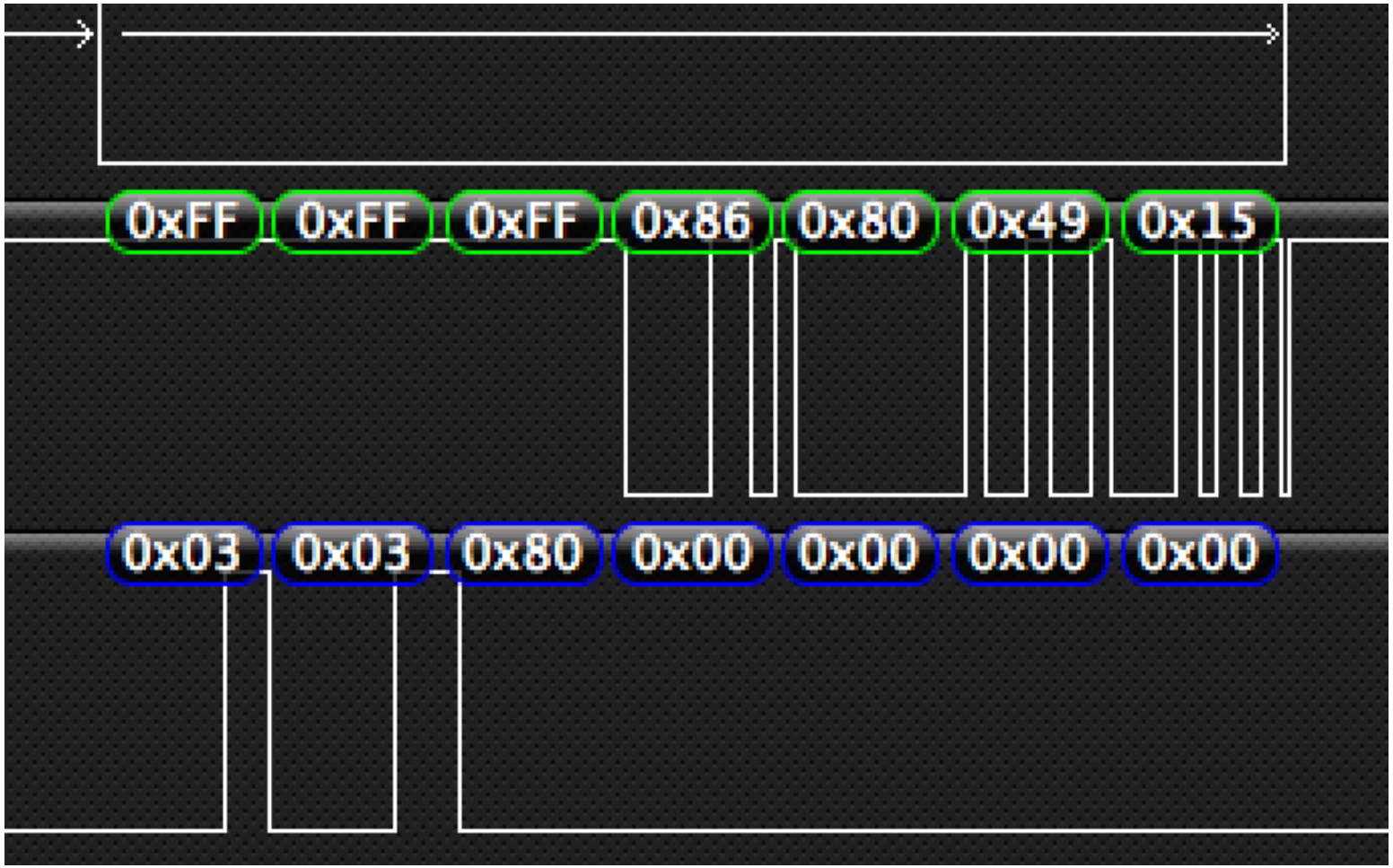
iSECpartners part of nccgroup

GitHub, Inc. [US] https://github.com/aosm/IOPCIFamily/blob/master/IOPCIBridge.cpp

```
379                             // hot plug bridge, but use legacy if avail
380                             uint8_t line = device->configRead8(kIOPCIConfigInterruptLine);
381                             if (tunnelLink)
382                             {
383                                     tunnelLink =   (0x15138086 != vendorProd)
384                                                     && (0x151a8086 != vendorProd)
385                                                     && (0x151b8086 != vendorProd)
386                                                     && (0x15498086 != vendorProd)
387                                                     && ((0x15478086 != vendorProd) || ((revIDClass & 0xff) > 1));
388                                     DLOG("tunnel bridge 0x%08x, %d, msi %d\n",
389                                                     vendorProd, (revIDClass & 0xff), tunnelLink);
390                             }
391                             if (tunnelLink || (line == 0) || (line == 0xFF))
392                             {
393                                     // no legacy ints, need one MSI
394                                     numVectors = 1;
395                             }
```

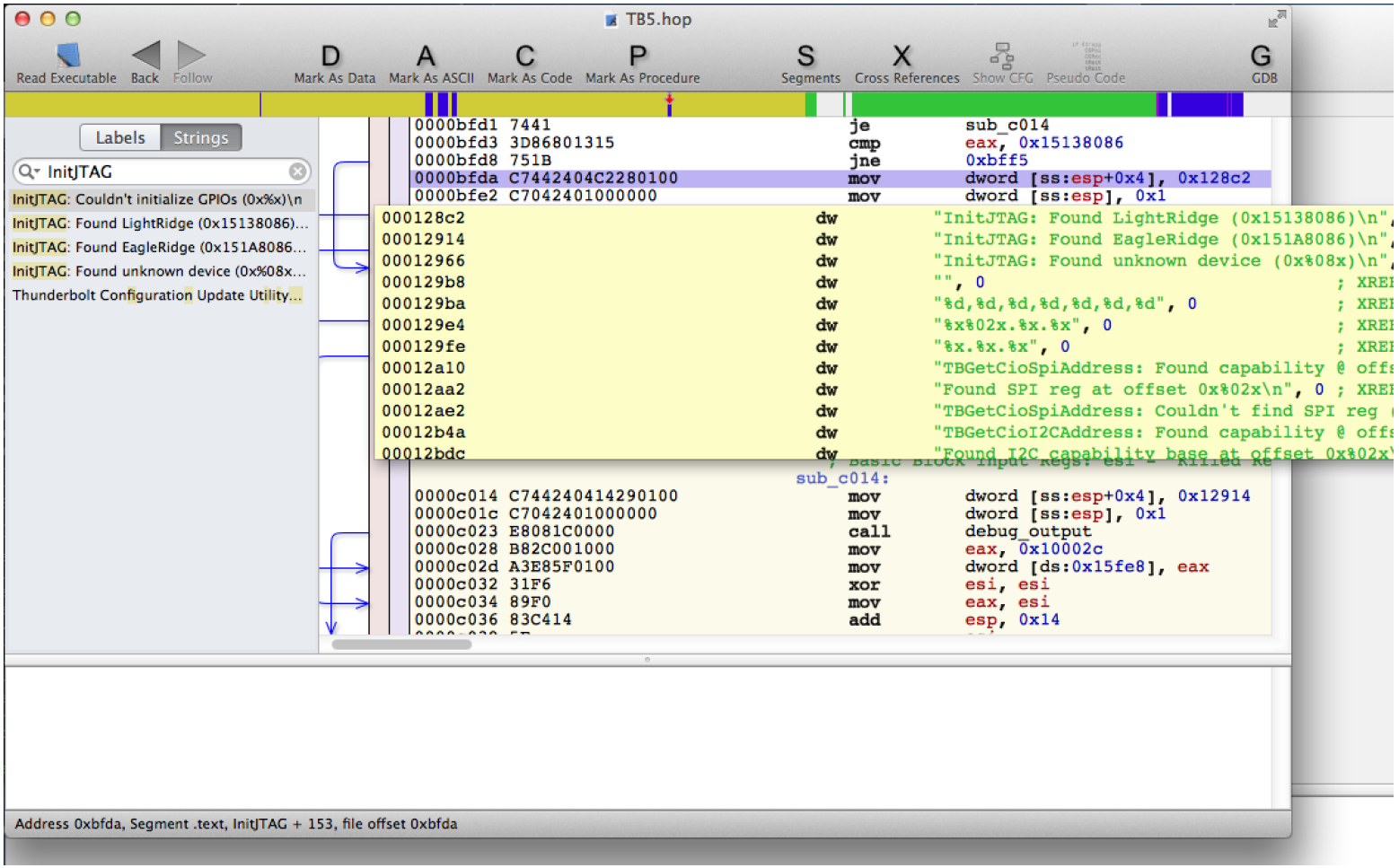
How My Adventures Went

iSECpartners
part of nccgroup



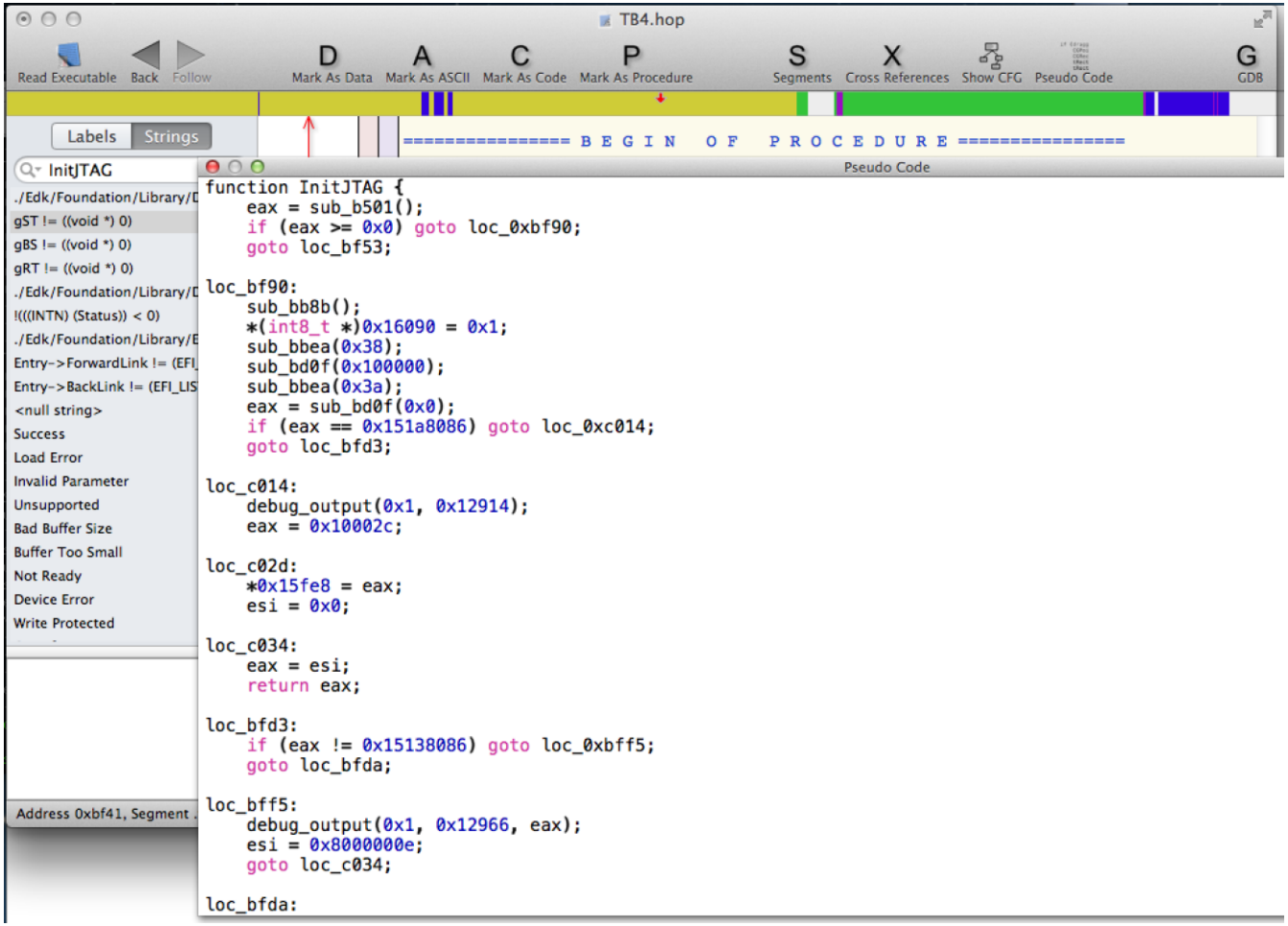
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners part of nccgroup



How My Adventures Went

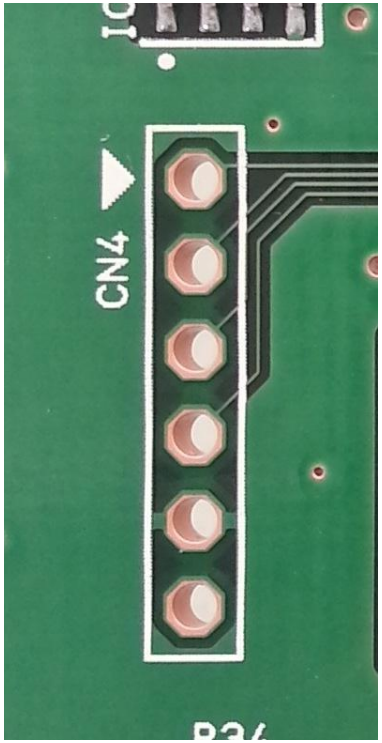
iSECpartners part of nccgroup

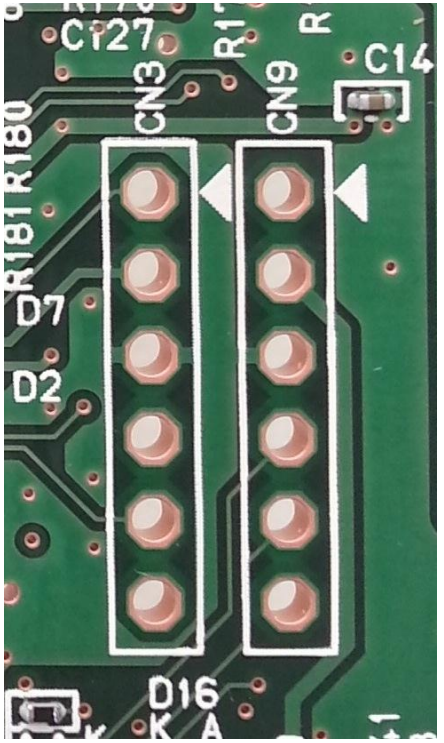
```
function InitJTAG {
    eax = InitGPIO();
    if (eax >= 0x0) {
        sub_bb8b();
        *(int8_t *)0x16090 = 0x1;
        sub_bbea(0x38);
        sub_bd0f(0x100000);
        sub_bbea(0x3a);
        eax = sub_bd0f(0x0);
        if (eax == 0x151a8086) {
           debug_output(0x1, "InitJTAG: Found EagleRidge (0x151A8086)\n");
           eax = 0x10002c;
        }
        else if (eax != 0x15138086) {
           debug_output(0x1, "InitJTAG: Found unknown device (0x%08x)\n", eax);
           esi = 0x8000000e;
        }
        else {
            debug_output(0x1, "InitJTAG: Found LightRidge (0x15138086)\n");
            eax = 0x100028;
        }
        *0x15fe8 = eax;
        esi = 0x0;
    }
    else
    {
       eax = debug_output(0x7, "InitJTAG: Couldn't initialize GPIOs (0x%x)\n", esi);
       if (**0x14a84 <= 0x6) {
          *(int16_t *)(*0x14a88 + eax * 0x2) = 0x100;
       }
       *(*0x14a88 + 0x10) = esi;
    }

    return esi;
}
```

How My Adventures Went

iSECpartners part of nccgroup

- Header rows
  - CN3 = LED Voltages
  - CN9 = Power rails
  - CN4 = JTAG!





How My Adventures Went

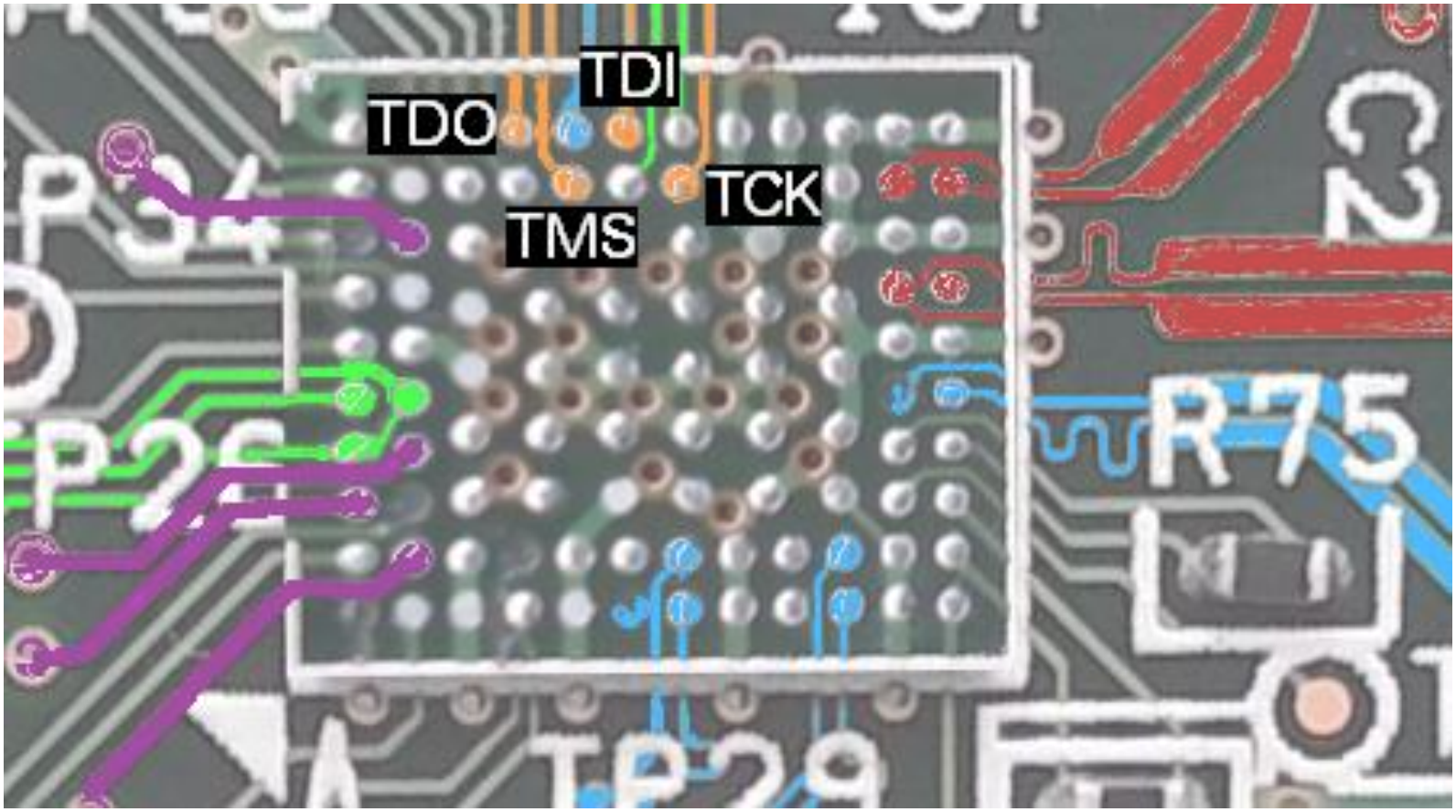
iSECpartners part of nccgroup

- JTAG Reversing
  - Trail and error
  - They make devices for this □
  - Pin 1 => TCK
  - Pin 2 => TDI
  - Pin 3 => TMS
  - Pin 4 => TDO

```
jtag> cable ft2232 vid=0x0403 pid=0x8a98
Connected to libftdi driver.
jtag> idcode
Reading 0 bytes of idcode
Read 00000000(0x00) 00000000(0x00) 00000000(0x00) 00000000(0x00)
jtag> detect
IR length: 6
Chain length: 1
Device Id: not supported (bit 0 was not a 1)
jtag>
```

How My Adventures Went

iSECpartners
part of nccgroup



JTAG

How My Adventures Went

iSECpartners part of nccgroup

- JTAG Reversing
  - ARM Cortex Mo uses SWD, not JTAG…
  - Obfuscated with a start sequence
  - We saw this code earlier… □

```
jtag> discovery
Detecting IR length ... 6
Detecting DR length for IR 111111 ... 1
Detecting DR length for IR 000000 ... 25
Detecting DR length for IR 000001 ... 25
Detecting DR length for IR 000010 ... warning: TDO seems to be stuck at 1
-1
Detecting DR length for IR 000011 ... warning: TDO seems to be stuck at 1
-1
```

How My Adventures Went

iSECpartners part of nccgroup

- Thunderbolt Device ROM
  - **Vendor Name**
  - **Device Name**
  - Vendor ID
  - Device ID
  - Device Revision
  - UID

HD-PATU3:

Vendor Name:	BUFFALO INC.
Device Name:	HD-PATU3
Vendor ID:	0x29
Device ID:	0x1
Device Revision:	0x1
UID:	0x002900010005A0E0
Route String:	3
Firmware Version:	5.1
Port:	
Status:	Device connected
Link Status:	0x2
Port Micro Firmware Version:	0.2.5
Cable Firmware Version:	0.1.24

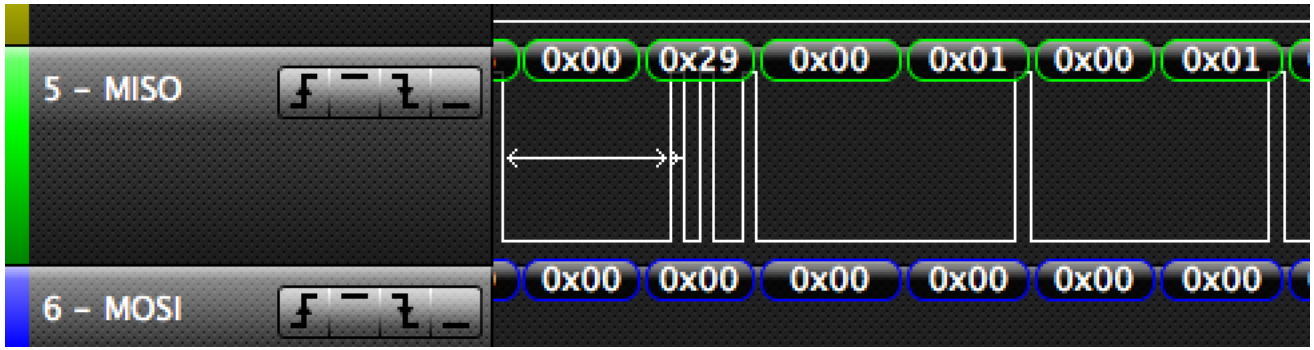
How My Adventures Went

iSECpartners part of nccgroup

- Thunderbolt Device ROM
  - Vendor Name
  - Device Name
  - **Vendor ID**
  - **Device ID**
  - **Device Revision**
  - UID

HD-PATU3:

Vendor Name:	BUFFALO INC.
Device Name:	HD-PATU3
Vendor ID:	0x29
Device ID:	0x1
Device Revision:	0x1
UID:	0x002900010005A0E0
Route String:	3
Firmware Version:	5.1
Port:	
Status:	Device connected
Link Status:	0x2
Port Micro Firmware Version:	0.2.5
Cable Firmware Version:	0.1.24



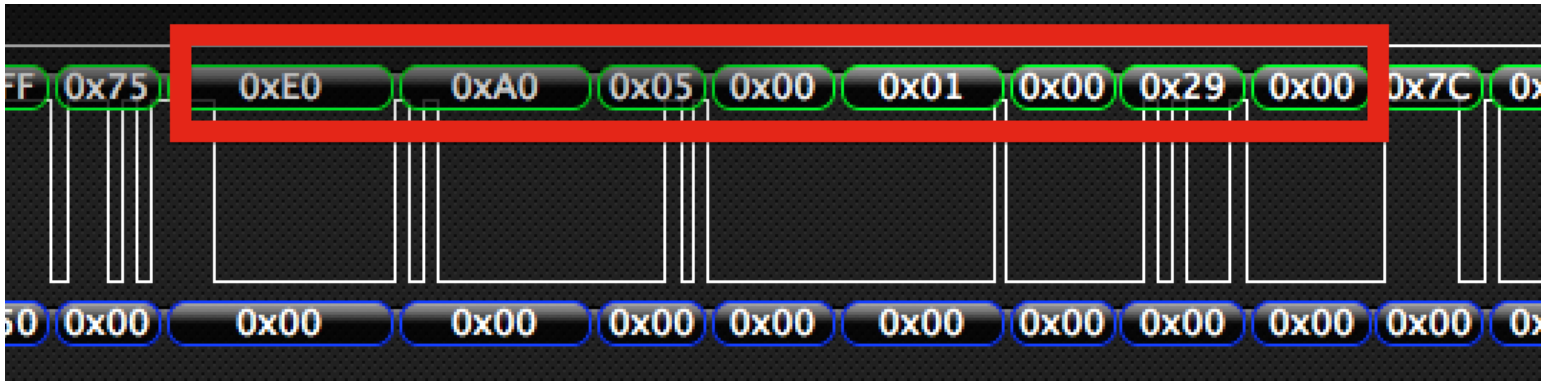
How My Adventures Went

iSECpartners part of nccgroup

- Thunderbolt Device ROM
  - Vendor Name
  - Device Name
  - Vendor ID
  - Device ID
  - Device Revision
  - **UID**

HD-PATU3:

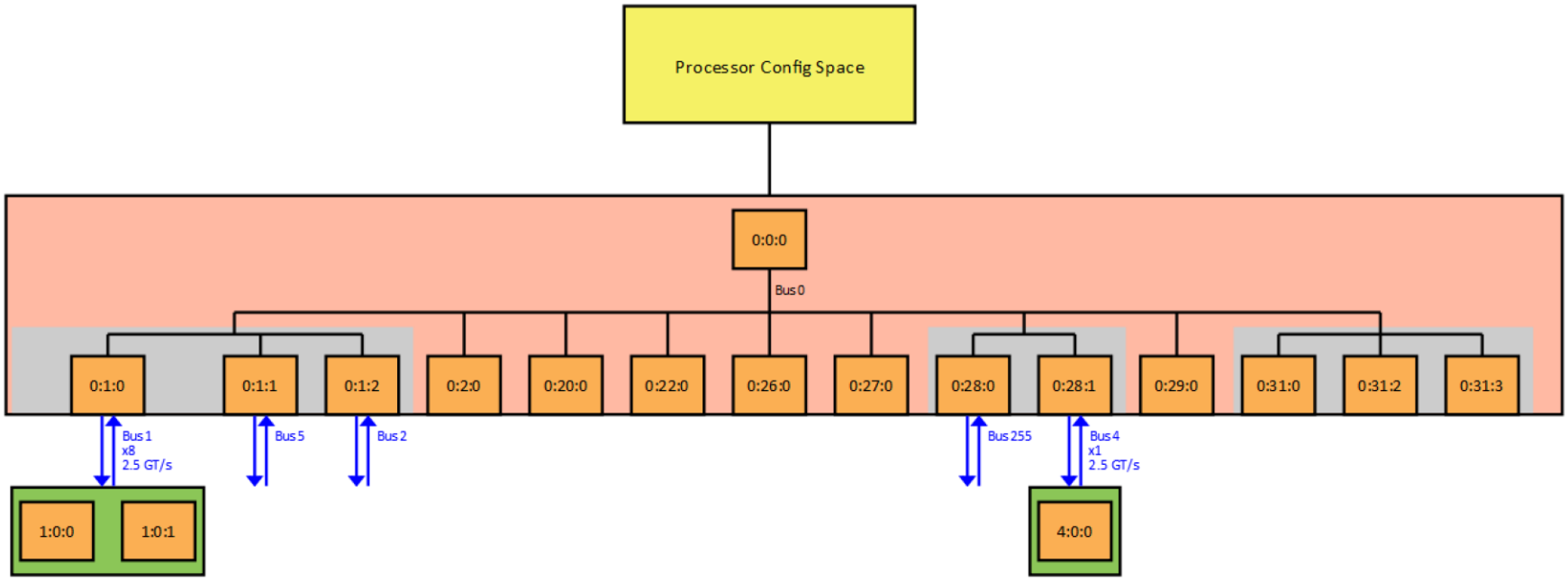
Vendor Name:	BUFFALO INC.
Device Name:	HD-PATU3
Vendor ID:	0x29
Device ID:	0x1
Device Revision:	0x1
UID:	0x002900010005A0E0
Route String:	3
Firmware Version:	5.1
Port:	
Status:	Device connected
Link Status:	0x2
Port Micro Firmware Version:	0.2.5
Cable Firmware Version:	0.1.24



How My Adventures Went

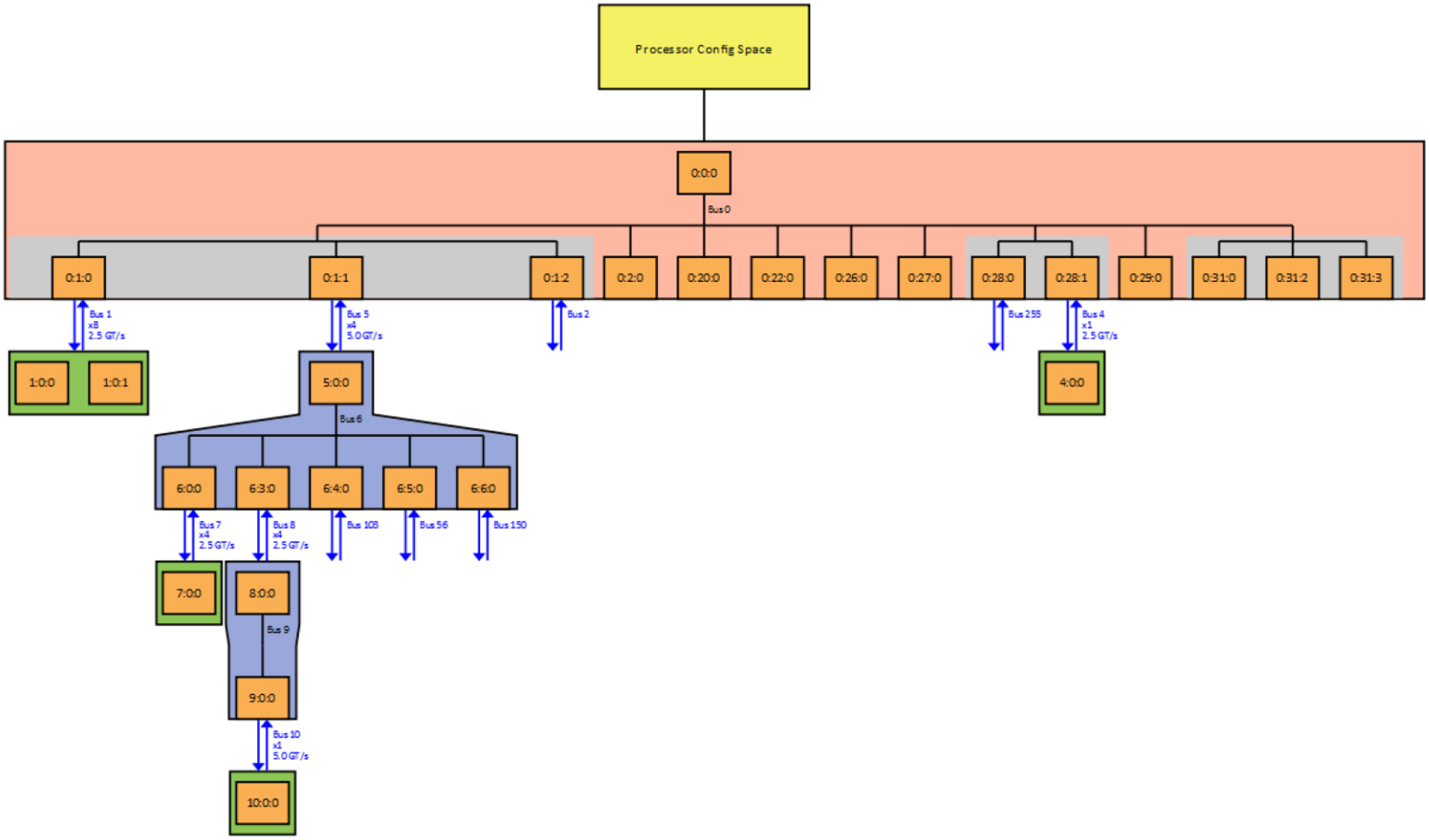
iSECpartners part of nccgroup

- PCIe Info
  - Thunderbolt is a PCIe Bridge



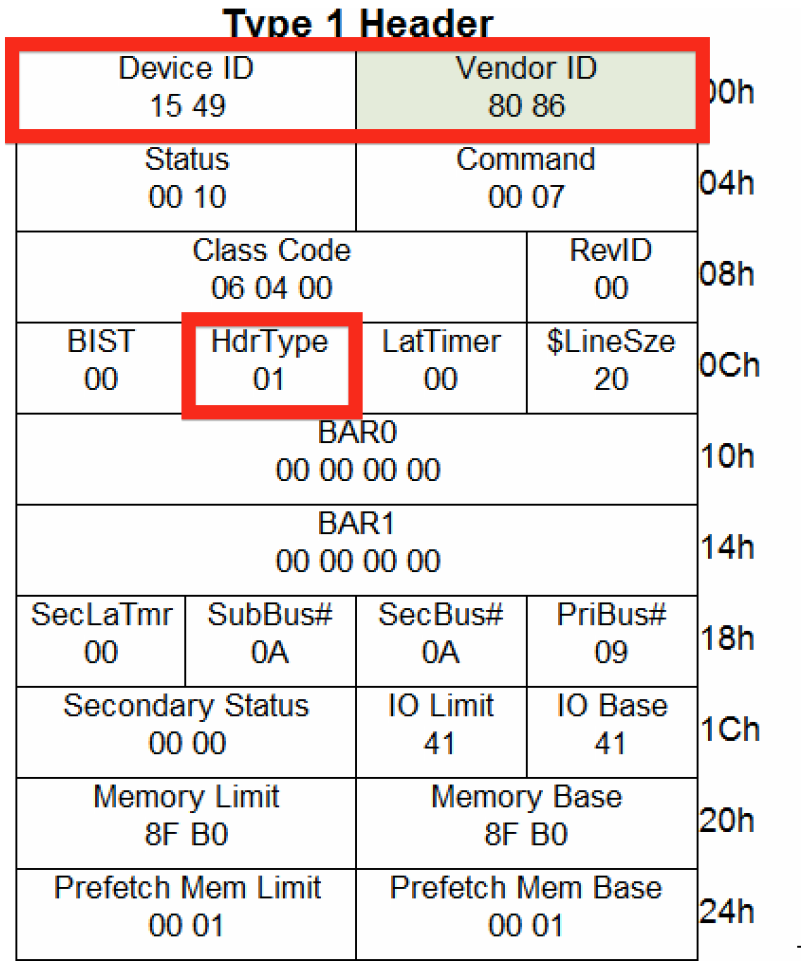
How My Adventures Went

iSECpartners part of nccgroup



How My Adventures Went

iSECpartners part of nccgroup



How My Adventures Went

iSECpartners part of nccgroup

B:D:F	Class	Device Description	Device Type
2! 0:1:1 (0,5,196)	PCI/PCI bridge	Intel Corporation Xeon E3-1200 v2/3rd Gen Core processor PCI...	Root Port
2! 5:0:0 (5,6,196)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	Switch Upstream Port
6:0:0 (6,7,7)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	Switch Downstream Port
7:0:0	System peripheral	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	PCIe Endpoint
2! 6:3:0 (6,8,10)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	Switch Downstream Port
8:0:0 (8,9,10)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Controller [Cactus Ridg...	Switch Upstream Port
9:0:0 (9,10,10)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Controller [Cactus Ridg...	
10:0:0	SATA controller - AHCI 1.0	ASMedia Technology Inc. ASM1062 Serial ATA Controller	Leg. PCIe Endpoint
6:4:0 (6,103,103)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	
6:5:0 (6,56,56)	PCI/PCI bridge	Intel Corporation DSL3510 Thunderbolt Port [Cactus Ridge]	Switch Downstream Port

decode raw **10:0:0 - ASMedia Technology Inc. ASM1062 Serial ATA Controller**

Type 0 Header

Device ID 06 12		Vendor ID 1B 21		00h
Status 00 10		Command 04 06		04h
Class Code 01 06 01			RevID 01	08h
BIST 00	HdrType 00	LatTimer 00	$LineSze 20	0Ch
BAR0 00 00 40 21				10h
BAR1				

Base Address Register 0

31 n 2 1 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 1

BAR0

Address: 4020h
Type: IO

The BARs are used to determine what type of address space(s) each function may need and
requested by that BAR. If a function supports decoding addresses larger than 32 bits, two con

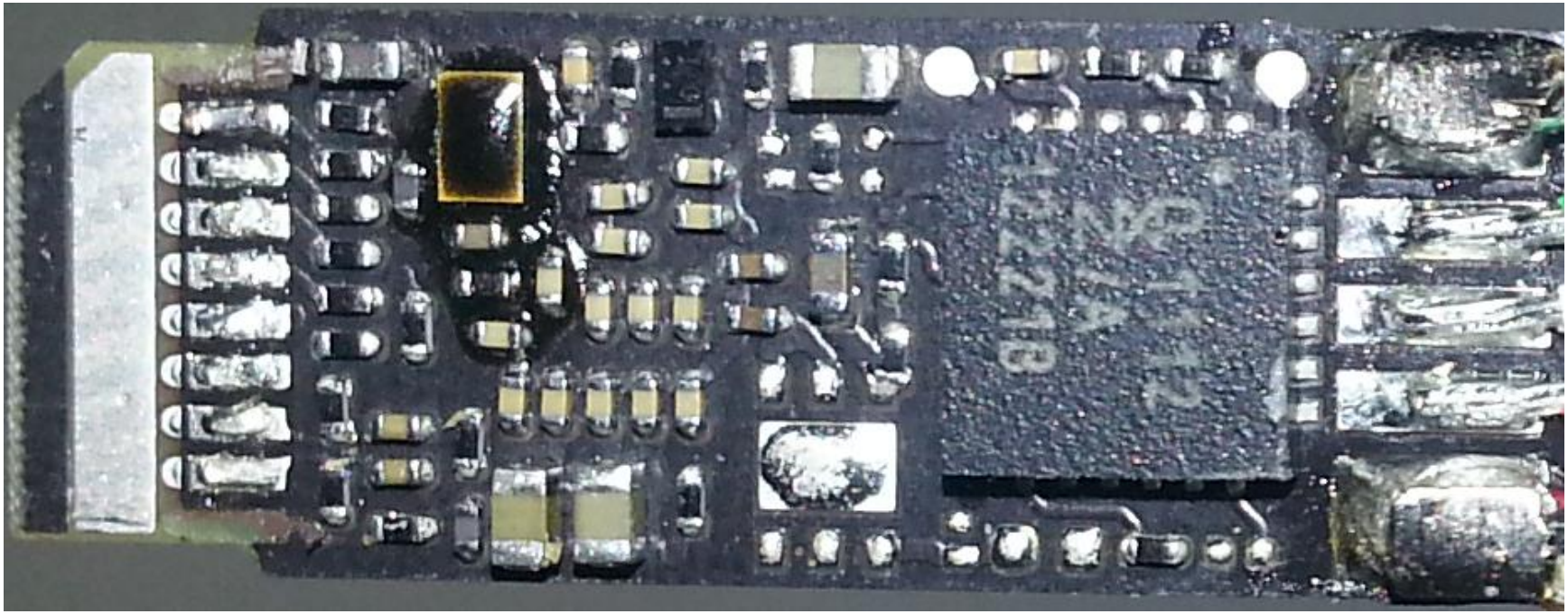
How My Adventures Went

iSECpartners part of nccgroup

- Gigabit Ethernet Adapter
  - Researching the product
  - Taking it apart
  - Attack vectors

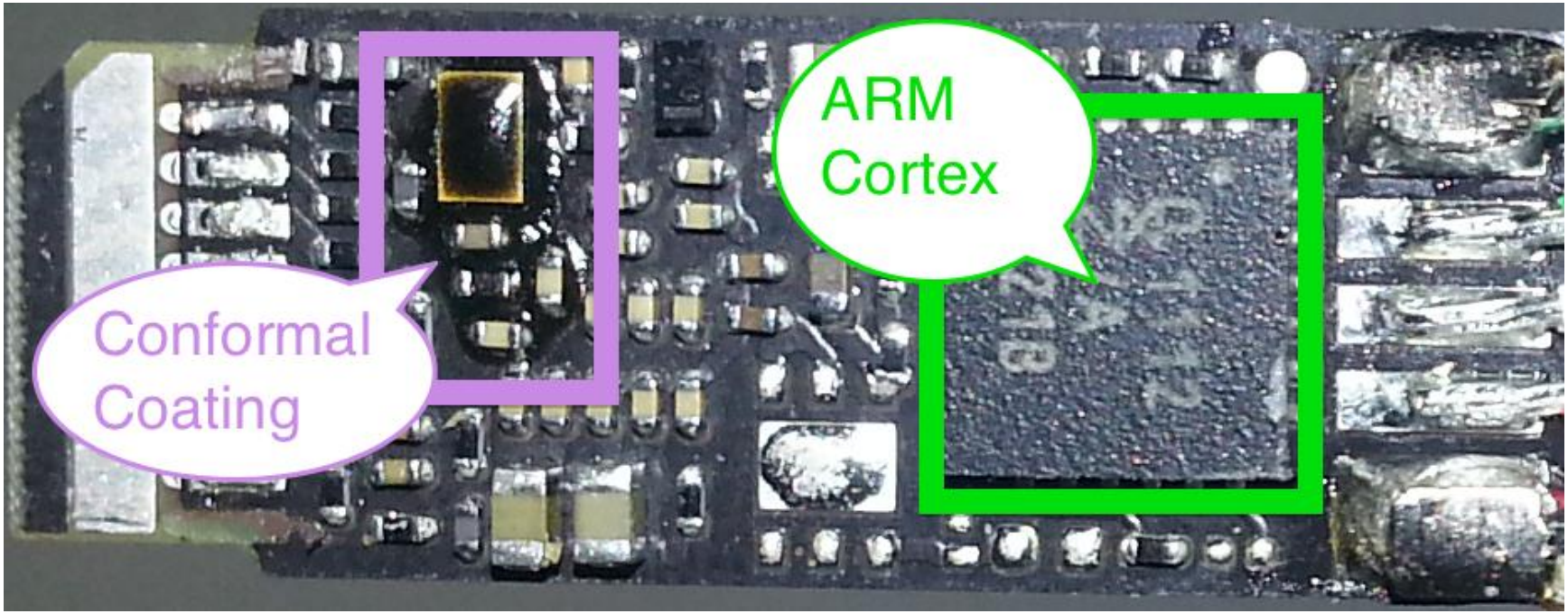
How My Adventures Went

iSECpartners
part of nccgroup



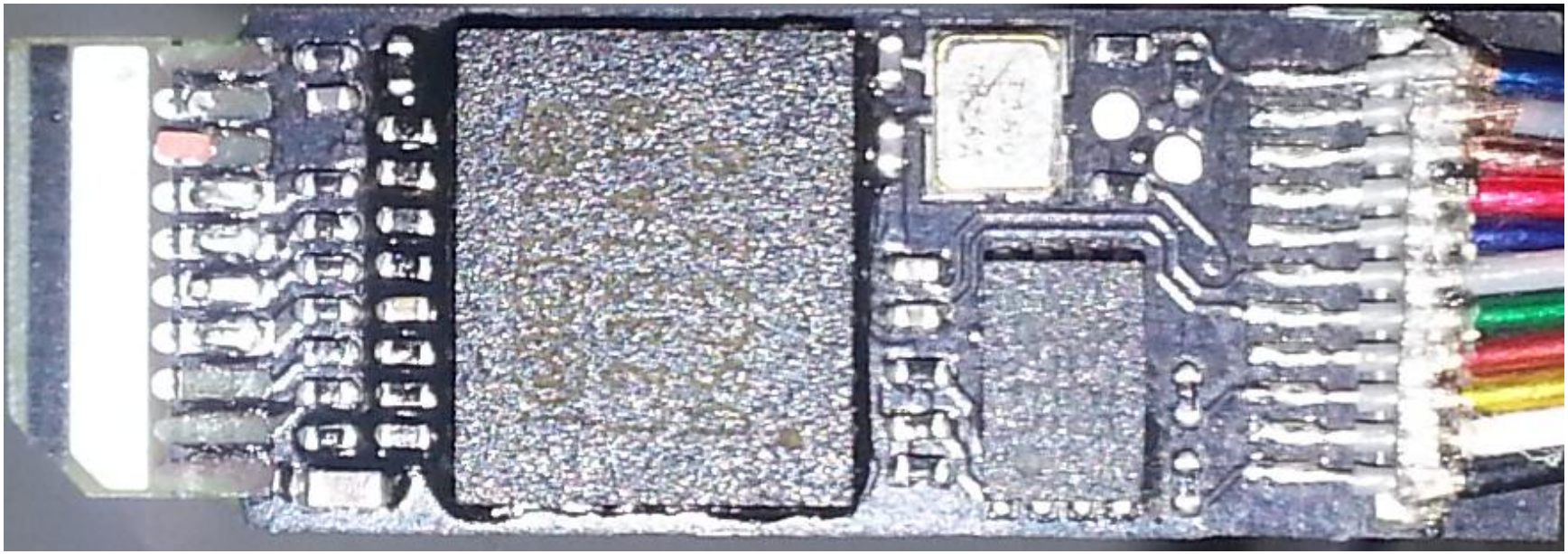
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners part of nccgroup

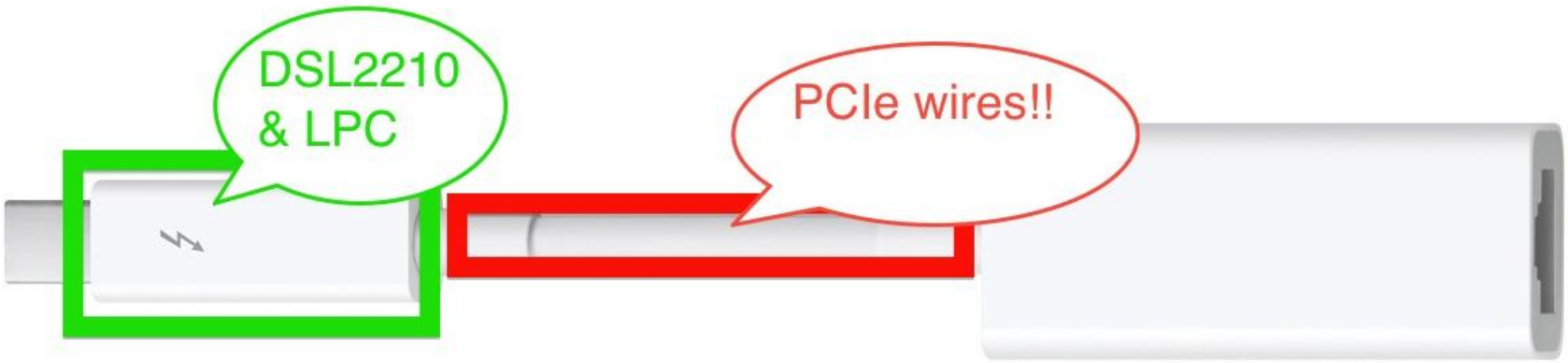


How My Adventures Went

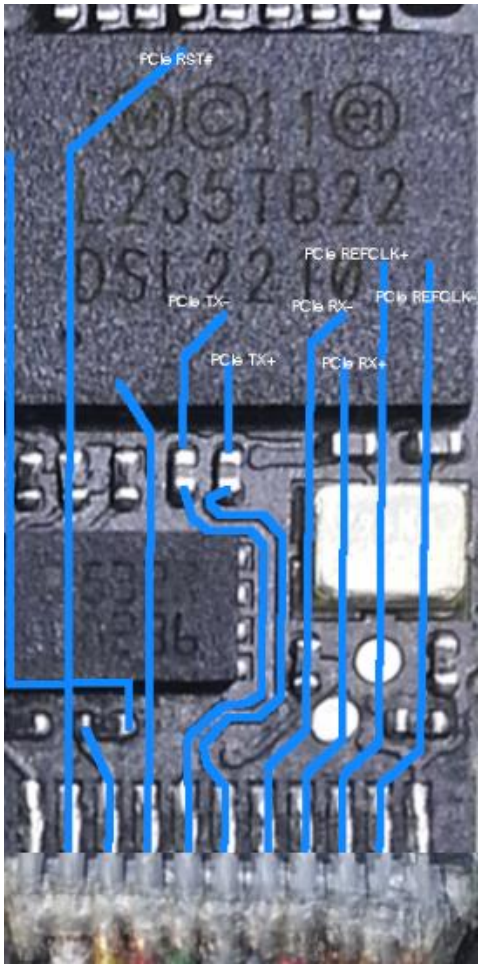
iSECpartners
part of nccgroup

How My Adventures Went

iSECpartners part of nccgroup

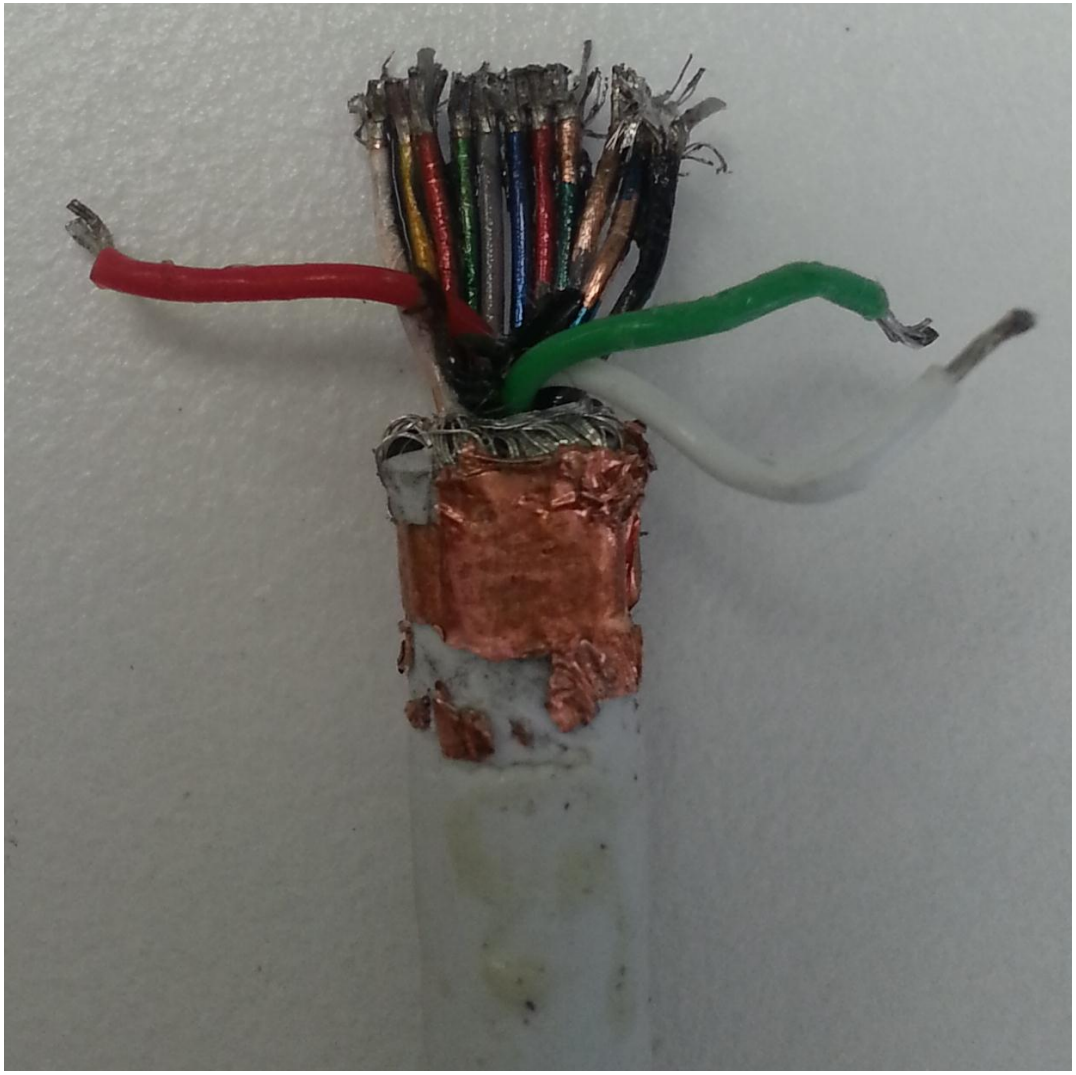


How My Adventures Went



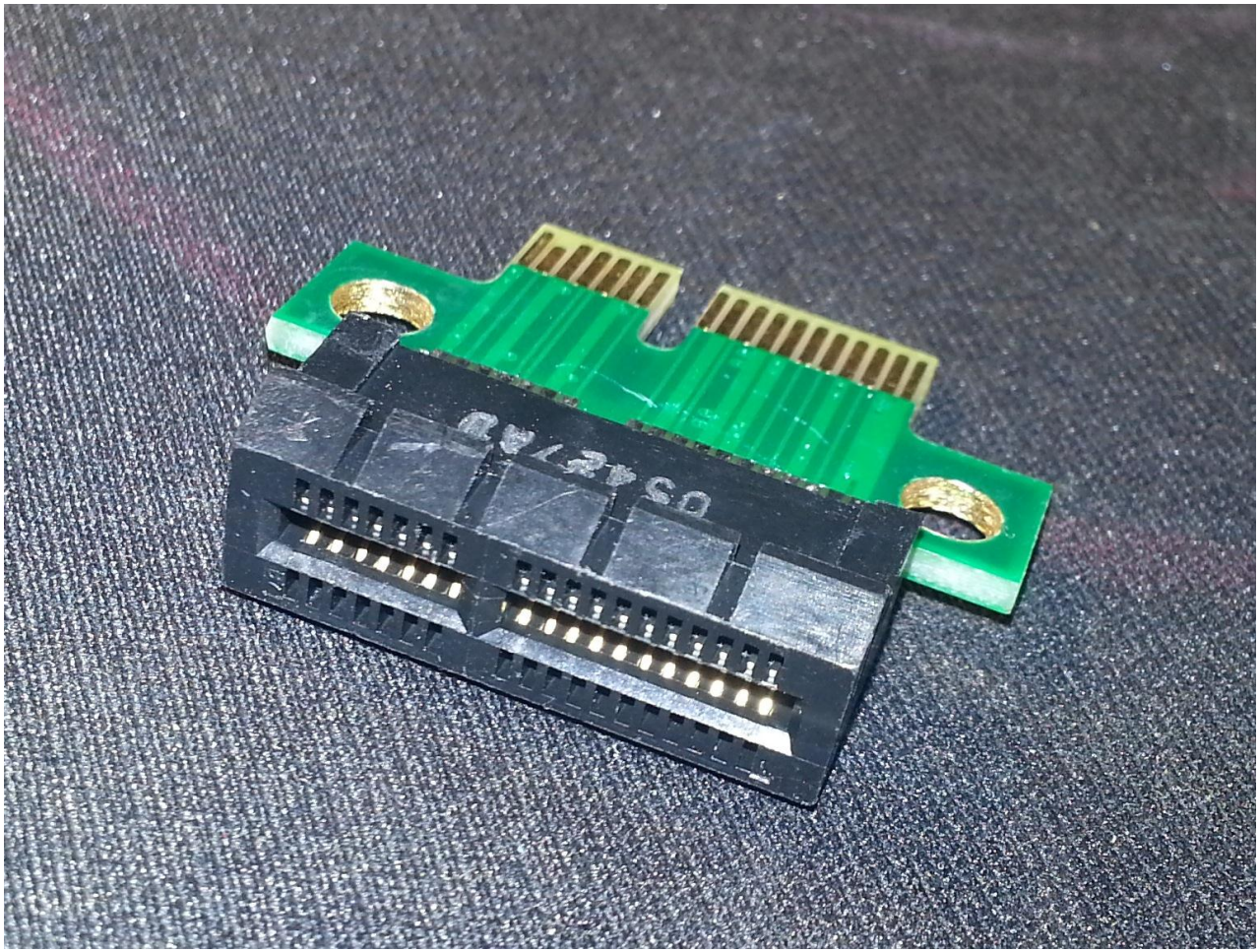
How My Adventures Went

iSECpartners part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup



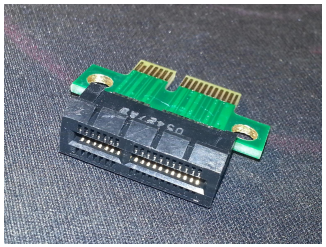
How My Adventures Went

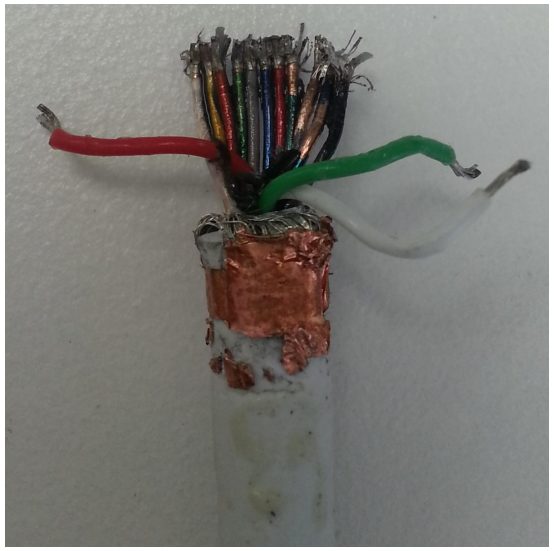
iSECpartners part of nccgroup

- Altera Cyclone IV GX Transceiver Starter Kit
  - Hard IP for PCIe
  - PCIe x1
  - ~$400

How My Adventures Went

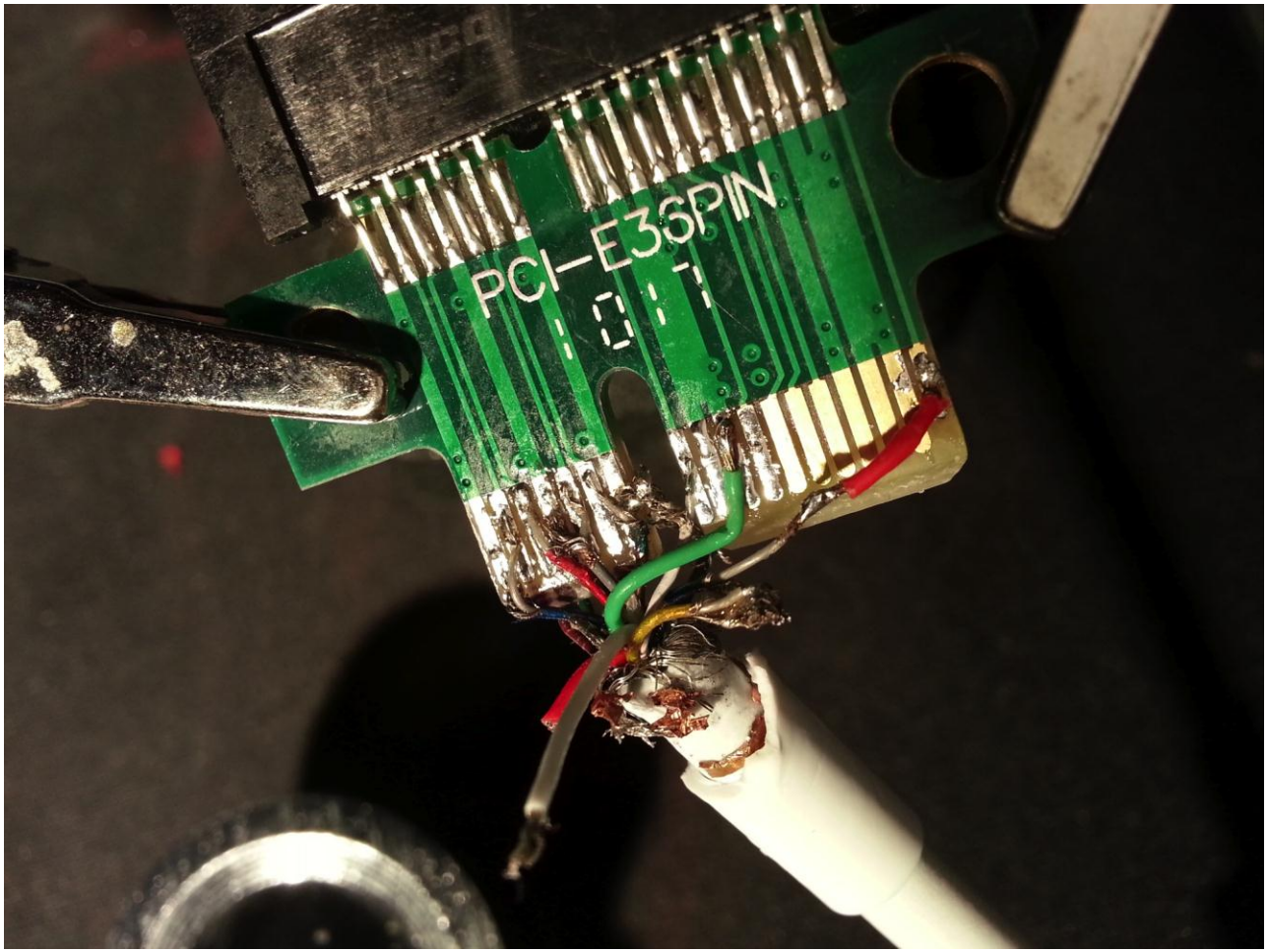
iSECpartners part of nccgroup





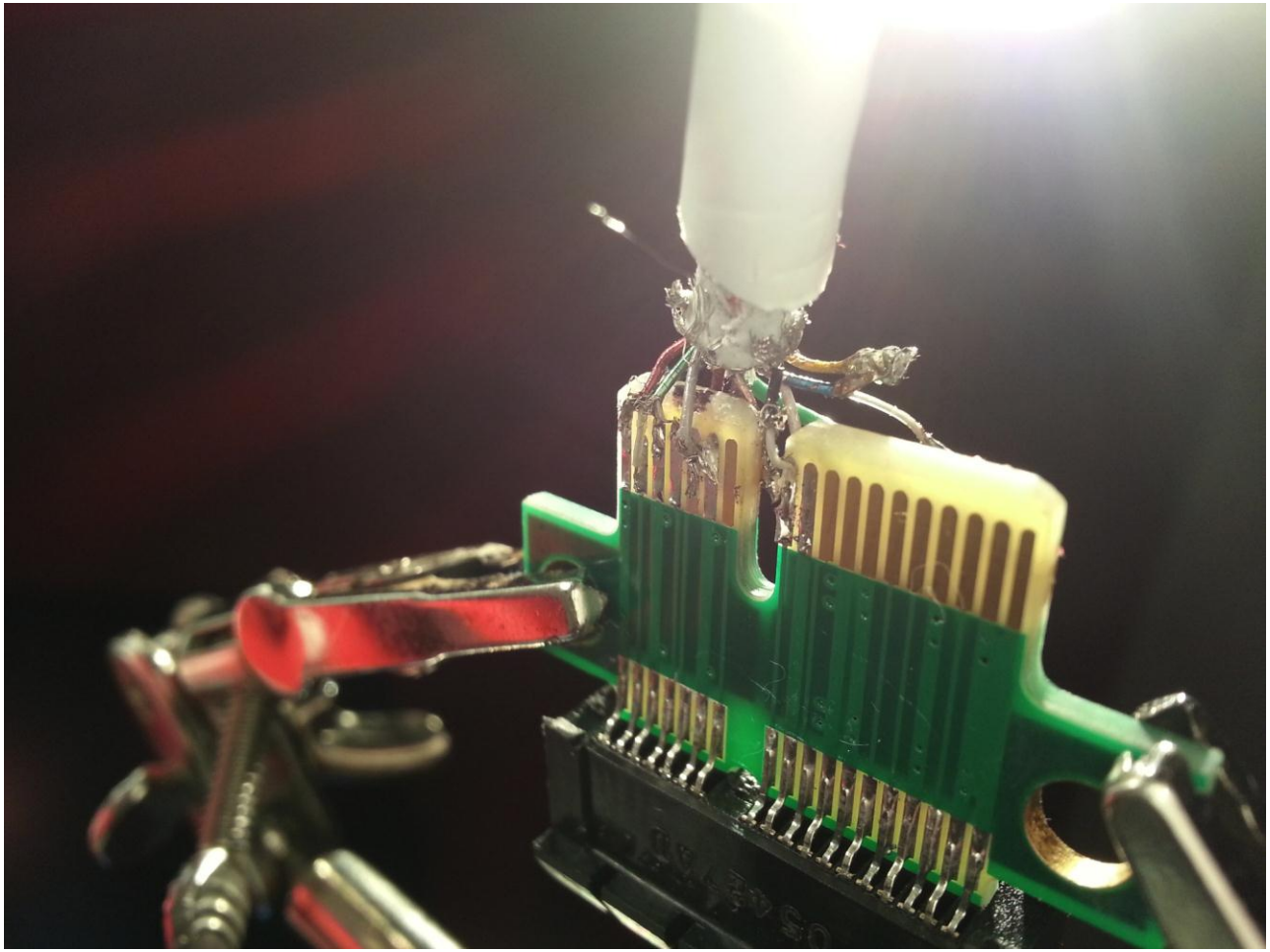
How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners
part of nccgroup



How My Adventures Went

iSECpartners part of nccgroup

- Tips and Tricks
  - Get A LOT of devices!
  - Heat up everything SLOWLY!
  - Continuity testing WINS
  - Sniff EVERYTHING
  - Read all ROMs/Flashes

Thank You

iSECpartners part of nccgroup

- Russ Sevinsky
  - Security Consultant at iSEC Partners
  - rsevinsky@isecpartners.com

- Special thanks to:
  - Everyone @ iSEC, specifically
    - Jesse Burns
    - Mike Warner
  - Craig Heffner

References

1.) "I/O Attacks in Intel-PC Architectures and Countermeasures"

http://www.syssec-project.eu/media/page-media/23/syssec2011-s1.4-sang.pdf

2.) "Understanding DMA Malware":
http://www.stewin.org/papers/dimvap15-stewin.pdf

3.) "Adventures with Daisy in Thunderbolt-DMA-land: Hacking Macs through the Thunderbolt interface":
http://www.breaknenter.org/2012/02/adventures-with-daisy-in-thunderbolt-dma-land-hacking-macs-through-the-thunderbolt-interface/

References

4.) Inception: http://www.breaknenter.org/projects/inception/

5.) "De Mysteriis Dom Jobsivs" Blackhat Paper: http://reverse.put.as/wp-content/uploads/2011/06/De_Mysteriis_Dom_Jobsivs_Black_Hat_Paper.pdf

6.) "Protecting yourself against Firewire DMA attacks on 10.7.x": http://derflounder.wordpress.com/2012/02/05/protecting-yourself-against-firewire-dma-attacks-on-10-7-x/

7.) Anandtech Buffalo Ministation Review:http://www.anandtech.com/show/6127/buffalo-ministation-thunderbolt-review-an-external-with-usb-30-and-thunderbolt

iSECpartners
part of nccgroup

UK Offices

Manchester - Head Office
Cheltenham
Edinburgh
Leatherhead
London
Thame

European Offices

Amsterdam - Netherlands
Munich – Germany
Zurich - Switzerland

North American Offices

San Francisco
Atlanta
New York
Seattle

Australian Offices

Sydney