Zephyr™ Project
Developer Summit
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Best Practices for Debugging Connected Applications running Zephyr

Chris Coleman
Luka Mustafa

Speakers

Chris Coleman

- Co-Founder & CTO, Memfault
- Previously a Firmware Engineer @ Sun Microsystems, Pebble, & Fitbit
- Zephyr TSC member

Luka Mustafa

- Founder & CEO, IRNAS
- Multidisciplinary engineer with EE background
- Designing IoT solutions for industrial applications

Connected Applications

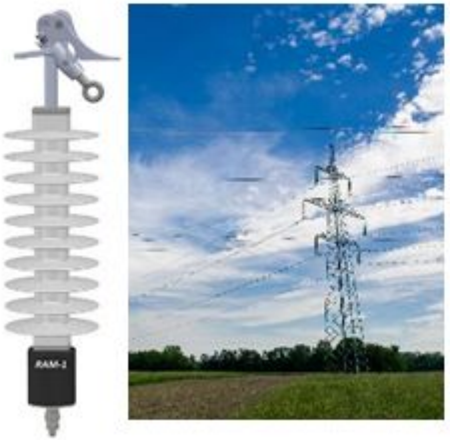
- 22 billion connected devices as of 2018, 50 billion projected by 2030!*
- Connectivity stacks are **complex**
- Many classes of issues
  - Faults / Hangs
  - Performance
  - Security
  - Connectivity interoperability

*Source: https://www.statista.com/statistics/802690/worldwide-connected-devices-by-access-technology/

Example project at IRNAS to set the scene

Industrial Solutions

IoT in Power Transmission Lines



Real-time infrastructure monitoring

Autonomous drainage maintenance system

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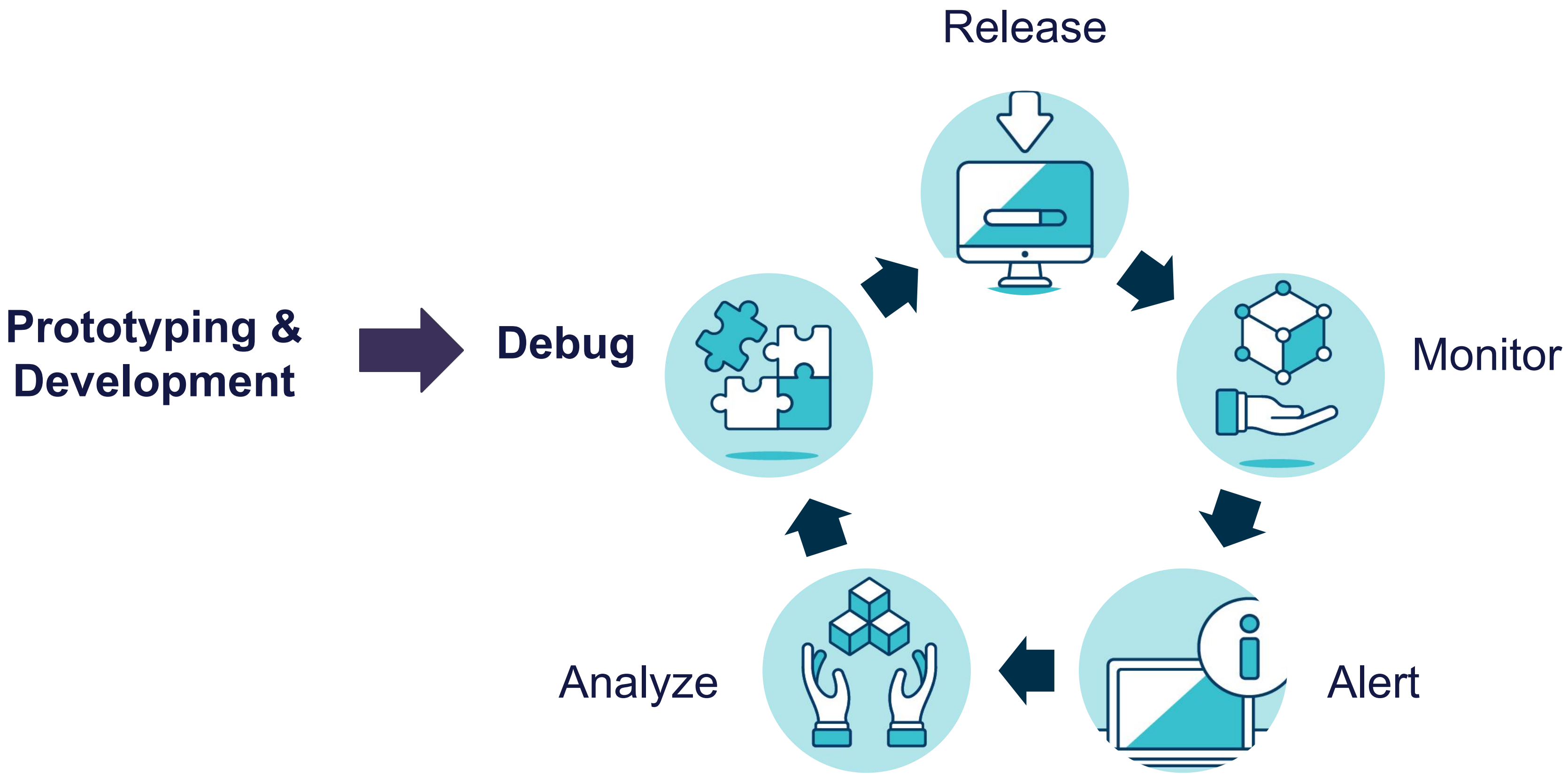
Device lifecycle

Debug Setup


Release
Prototyping &
Development
Debug
Monitor
Analyze
Alert

Agenda

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1 **Local Debug Setup**

2 **Zephyr Debug (K)Config Tips**

3 **Remote Monitoring Best Practices with Examples**

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Local Debug Setup

Local Debug Setup

1. **Reliable** JTAG setup
2. Ability to read/write memory
3. Ability to script common operations

- I use SEGGER J-Link + JLinkGDBServer + GDB

Starting GDB


```
$ west --verbose debug --runner jlink --gdb
arm-none-eabi-gdb-py

-- runners.jlink: J-Link GDB server running on port 2331
runners.jlink: JLinkGDBServer -select usb -port 2331 -if
swd -speed 4000 -device nRF9160_xxAA -silent -singlerun

(gdb) continue
```

Flashing Target

With west:

```
$ west flash
```

Directly via JLinkGDBServer / GDB!

```
(gdb) mon reset
 Resetting target
(gdb) load
`build/zephyr/zephyr.elf' has changed; re-reading symbols.
Start address 0x00015df0, load size 130437
Transfer rate: 25475 KB/sec, 4207 bytes/write.
(gdb)
```

pyserial

```
$ pip install pyserial
$ pyserial-miniterm  - 115200  --raw
--- Available ports:
---  3: /dev/cu.usbmodem0009600050801 'J-Link - CDC DATA interface'
---  4: /dev/cu.usbmodem0009600050803 'J-Link - CDC DATA interface'
---  5: /dev/cu.usbmodem0009600050805 'J-Link - CDC DATA interface'


$ pyserial-miniterm  /dev/cu.usbmodem0009600050801 115200  --raw
uart:~$ *** Booting Zephyr OS build v2.4.99-ncs1-3525-g4d068de3f50f  ***
```

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Zephyr Debug (K)Config Tips

Thread Awareness

```
(gdb) info threads
  Id   Target Id                                           Frame
* 2    Thread 536956136 (idle 00 UNKNOWN PRIO 15)           arch_cpu_idle () at /
  3    Thread 536956408 (main PENDING PRIO 0)               arch_swap (key=0) at
  4    Thread 536955312 (shell_uart PENDING PRIO 14)        arch_swap (key=0) at
  5    Thread 536956696 (sysworkq PENDING PRIO 255)         arch_swap (key=0) at
  6    Thread 536955648 (at_cmd_socket_thread PENDING PRIO 10) arch_swap (key=0) at
```

- `CONFIG_DEBUG_THREAD_INFO=y`
  - `(Originally CONFIG_OPENOCD_SUPPORT=y)`

Debug printing with printk

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```
CONFIG_PRINTK=y
```

```c
void main(void) {
    printk("System Started!\n");
    // ...
}
```

```
uart:~$ System Started!
// ...
```

- Bypasses logging subsystem by default and prints directly to console
- Useful for minimal overhead and guaranteed printing

Console Printing with Logging Subsystem

- CONFIG_LOG=y
- CONFIG_SHELL=y
- Deferred Mode (default)
  - logs are buffered and flushed process on low priority task
  - CONFIG_LOG_MODE_DEFERRED=y
- Immediate Mode (recommend for debug)
  - Logs are flushed from running task.
  - CONFIG_LOG_IMMEDIATE=y
- ⚠️ Leaving logging impacts power consumption
  - Should be disabled for low power applications in production

Zephyr Logging Modules

```
# Kconfig
module = MY_MODULE
module-str = My module
source "${ZEPHYR_BASE}/subsys/logging/Kconfig.template.log_config"

// my_module.c
LOG_MODULE_REGISTER(my_module, CONFIG_MY_MODULE_LOG_LEVEL);

# prj.conf - Choose one of the following:
CONFIG_MY_MODULE_LOG_LEVEL_OFF=y # 0
CONFIG_MY_MODULE_LOG_LEVEL_ERR=y # 1
CONFIG_MY_MODULE_LOG_LEVEL_WRN=y # 2
CONFIG_MY_MODULE_LOG_LEVEL_INF=y # 3 (default)
CONFIG_MY_MODULE_LOG_LEVEL_DBG=y # 4
```

Zephyr Logging Level Options

1. Autogenerated “autoconf.h file contains all active settings:
   - See “build/zephyr/include/generated/autoconf.h”

2. Grep through file for LOG_LEVEL, i.e

```
$ rg "LOG_LEVEL " build/zephyr/include/generated/autoconf.h

60:#define CONFIG_MPSL_LOG_LEVEL 3
68:#define CONFIG_MGMT_FMFU_LOG_LEVEL 3
84:#define CONFIG_MEMFAULT_INTEGRATION_LOG_LEVEL 3
86:#define CONFIG_AGPS_LOG_LEVEL 3
97:#define CONFIG_NRF_MODEM_LIB_LOG_LEVEL 3
// ...
```

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Remote Monitoring Best Practices

Hands on example

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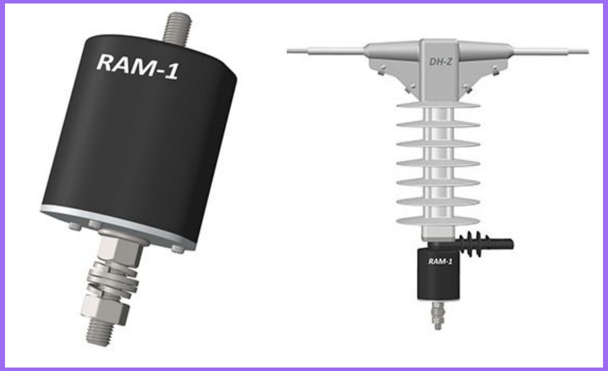
GPS tracker on an animal

- Mobile connectivity issues to be observed and resolved
- Hardware performance monitored
- Track and monitor all issues over time

Static sensor with long lifetime

- All faults must be handled to conserve power
- Operation to be optimized based on the use-case
- Validate upgrades in the field



Remote Monitoring Zephyr with Memfault

- Works on any ARM-based MCU with Zephyr OS
- C-SDK with connectivity agnostic data transport
- Cloud based issue analysis, alerting and deduplication on both device level and fleetwide trends

Memfault

Remotely debug issues with coredumps, events and logs

Continuously monitor devices with Metrics

Deploy OTA updates safely with staged rollouts and targeted device groups

Memfault Zephyr Integration


```
# west.yml
[ ... ]
    - name: memfault-firmware-sdk
    url: https://github.com/memfault/memfault-firmware-sdk
    path: modules/memfault-firmware-sdk
    revision: master


# prj.conf
CONFIG_MEMFAULT=y
CONFIG_MEMFAULT_HTTP_ENABLE=y
```

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Core Properties To Track

Agenda

1 Reboot Reasons

2 Watchdogs

3 Faults & Asserts

4 Connectivity Metrics

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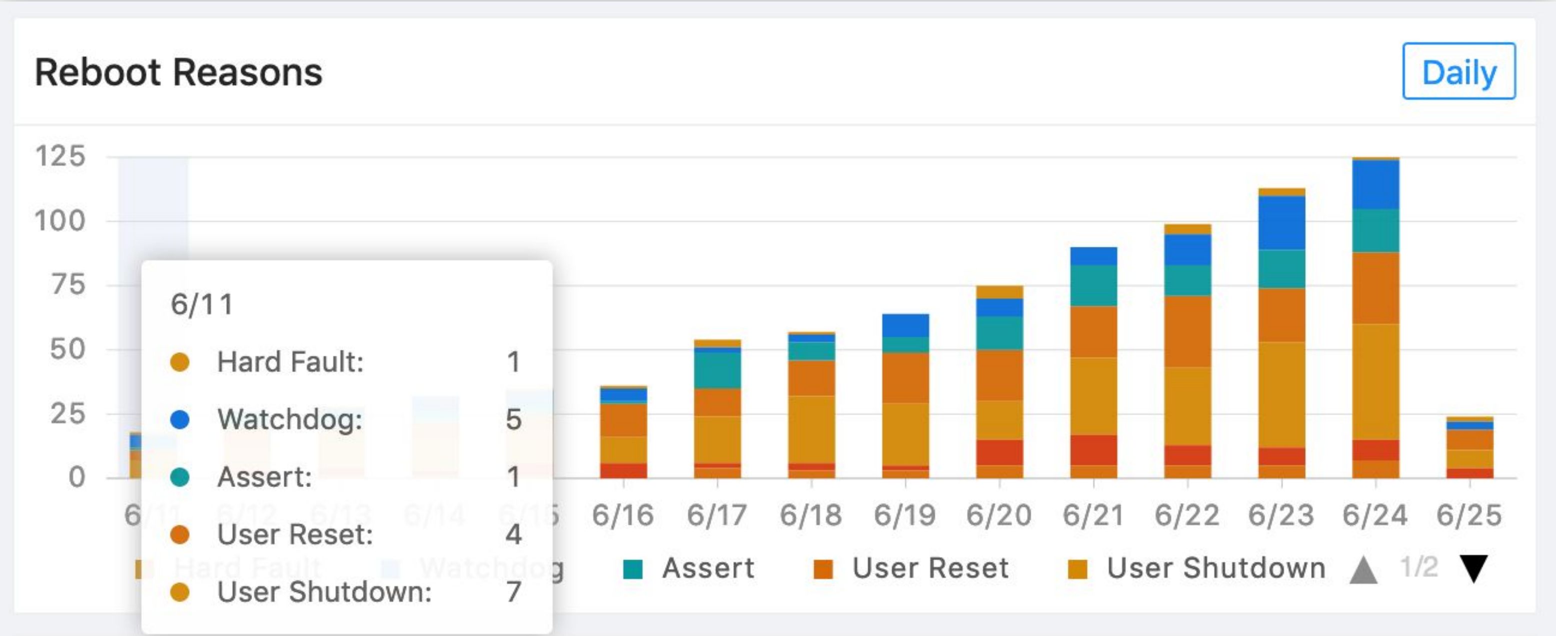
Reboot Reasons

Tracking Device Resets



Leading indicator of fleet health

Tracking Device Resets

Hardware Resets

- Examples
  - PLL & Clock Failures
  - Brown Out
  - Hardware Watchdogs
- Can identify hardware defects

Software Resets

- Examples
  - Firmware Update / OTA
  - Assert
  - User initiated

Tracking Software Resets

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1. Create "noinit" RAM region	`/* memfault-no-init.ld */`
	`KEEP(*(*.mflt_reboot_info));`
	
	`# CMakeLists.txt`
	`zephyr_linker_sources(NOINIT memfault-no-init.ld)`

2. Place C variable in region	`__attribute__((section(".noinit.mflt_reboot_info")))`
	`static uint8_t`
	`s_reboot_tracking[MEMFAULT_REBOOT_TRACKING_REGION_SIZE];`

3. Record reason for reboot	`void fw_update_finish(void) {`
	`    // ...`
	
	`memfault_reboot_tracking_mark_reset_imminent(kMfltRebootReason_F`
	`irmwareUpdate, ...);`
	`    sys_reboot(0);`
	`}`

Capturing Device Resets on Zephyr

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Register init handler that to read bootup information:

```
static int record_reboot_reason() {
  // 1. Read hardware reset reason register. (Check MCU data sheet for register name)
  // 2. Capture software reset reason from noinit RAM
  // 3. Send data to server for aggregation
}

SYS_INIT(record_reboot_reason, APPLICATION, CONFIG_KERNEL_INIT_PRIORITY_DEFAULT);
```

Example: Power supply issue

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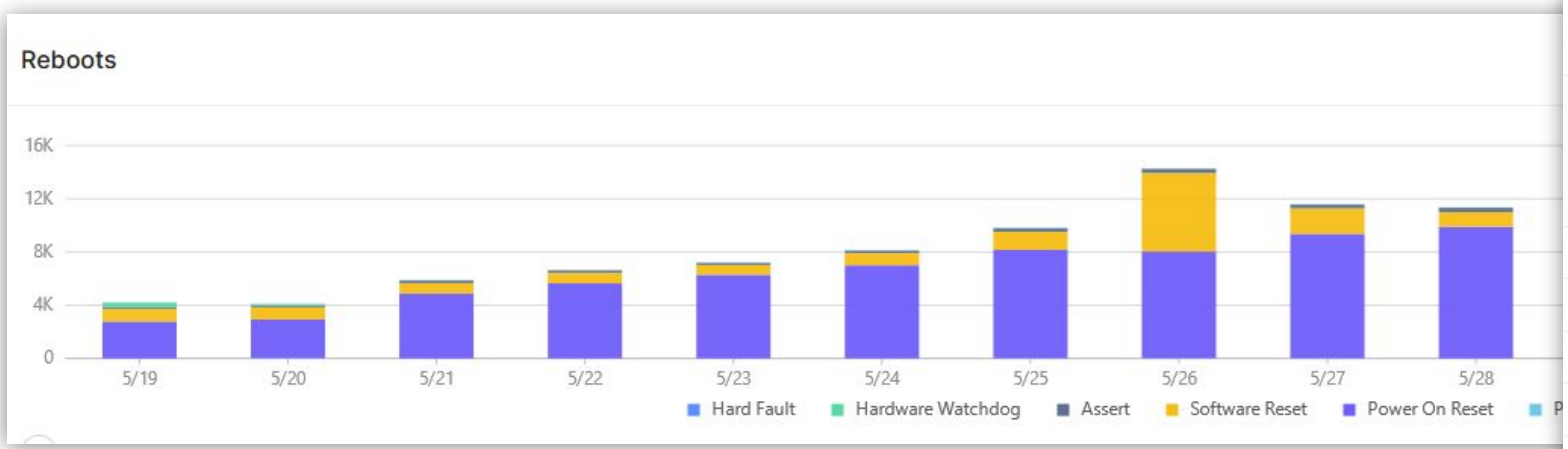

Recent Resets By Device (Last 72 Hours)

device_serial	reboot_reason	reset_count
power		
92	Power on Reset	1,899
08	Power on Reset	1,409
91	Power on Reset	1,269
01	Power on Reset	1,254
62	Power on Reset	1,030
03	Power on Reset	973
33	Power on Reset	890
17	Power on Reset	866
93	Power on Reset	850
22	Power on Reset	810
74	Power on Reset	764
73	Power on Reset	759
13	Power on Reset	716

< 1 2 3 4 5 ••• 115 >

an hour ago

- 12K device reboots a day - ***way too much***
- 99% of reboots contributed by 10 devices
- Bad mechanical part contributing to device constant reboots

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Watchdogs

Defending against Hangs

- Last line of defense against a hung system!
- Can happen for many reasons:
  - Connectivity Stack Blocks on send()
  - Infinite Retry Loop talking to system
  - Deadlock between tasks
  - Corruption
- Two pieces:
  - Hardware Watchdog
    - Built in and/or external peripheral to reset device
  - Software Watchdog
    - Interrupt that fires ahead of hard reset so watchdog can be root caused

Zephyr - Hardware Watchdog API

```
// ...
void start_watchdog(void) {
  // consult device tree for available hardware watchdog
  s_wdt = device_get_binding(DT_LABEL(DT_INST(0, nordic_nrf_watchdog)));

  struct wdt_timeout_cfg wdt_config = {
    /* Reset SoC when watchdog timer expires. */
    .flags = WDT_FLAG_RESET_SOC,

    /* Expire watchdog after max window */
    .window.min = 0U,
    .window.max = WDT_MAX_WINDOW,
  };

  s_wdt_channel_id = wdt_install_timeout(s_wdt, &wdt_config);

  const uint8_t options = WDT_OPT_PAUSE_HALTED_BY_DBG;
  wdt_setup(s_wdt, options);
  // TODO: Start a software watchdog
}

void feed_watchdog(void) {
  wdt_feed(s_wdt, s_wdt_channel_id);
  // TODO: Feed software watchdog
}
```

See Zephyr API for more details:
zephyr/include/drivers/watchdog.h

Zephyr Software Watchdog

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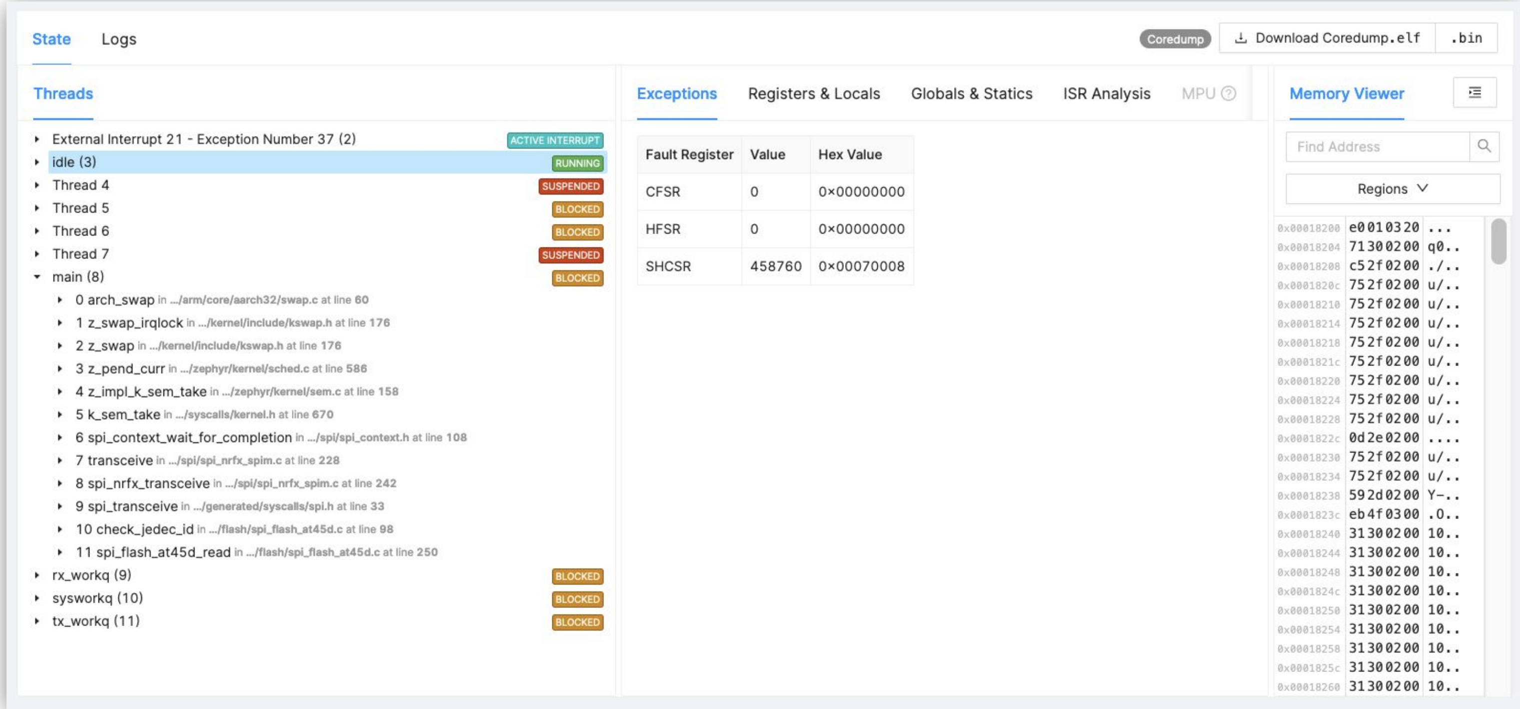
```
static void prv_software_watchdog_timeout(struct k_timer *dummy) {
  MEMFAULT_ASSERT(0);
}

K_TIMER_DEFINE(s_watchdog_timer, prv_software_watchdog_timeout, NULL);
static uint32_t s_software_watchog_timeout_ms = MEMFAULT_WATCHDOG_SW_TIMEOUT_SECS * 1000;

static void prv_start_or_reset(uint32_t timeout_ms) {
  k_timer_start(&s_watchdog_timer, K_MSEC(timeout_ms), K_MSEC(timeout_ms));
}

int memfault_software_watchdog_enable(void) {
  prv_start_or_reset(s_software_watchog_timeout_ms);
  return 0;
}

int memfault_software_watchdog_feed(void) {
  prv_start_or_reset(s_software_watchog_timeout_ms);
  return 0;
}
```

New built in "Task Watchdog" API in 2.6 Release.

Example: SPI driver stuck



- SPI flash degrading over time, incorrect timing of communication
- Traced this on 1% of devices after 16 months of field deployment
- Driver fix and roll-out with next release

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Faults & Asserts

Fault Handler - Register Dump

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```
[00:26:12.826,782] <err> os: ***** BUS FAULT *****
[00:26:12.832,153] <err> os:   Instruction bus error
[00:26:12.837,738] <err> os: r0/a1:  0x00000001  r1/a2:  0x200150c1  r2/a3:  0x00000000
[00:26:12.846,343] <err> os: r3/a4:  0x0badcafe r12/ip:  0x00000001 r14/lr:  0x0001a6cb
[00:26:12.854,919] <err> os:  xpsr:  0x60000000
[00:26:12.860,107] <err> os: s[ 0]:  0x00000001  s[ 1]:  0x00000001  s[ 2]:  0x00000001  s[ 3]:  0x00000001
[00:26:12.870,422] <err> os: s[ 4]:  0x00000001  s[ 5]:  0x00000001  s[ 6]:  0x00000001  s[ 7]:  0x00000001
[00:26:12.880,737] <err> os: s[ 8]:  0x00000001  s[ 9]:  0x00000001  s[10]:  0x00000001  s[11]:  0x00000001
[00:26:12.891,052] <err> os: s[12]:  0x00000001  s[13]:  0x00000001  s[14]:  0x00000001  s[15]:  0x00000001
[00:26:12.901,367] <err> os: fpscr:  0x00000000
[00:26:12.906,524] <err> os: r4/v1:  0x00000001  r5/v2:  0x000135af  r6/v3:  0x2001abf8
[00:26:12.915,130] <err> os: r7/v4:  0x2001ac00  r8/v5:  0xfffffffc  r9/v6:  0x00000001
[00:26:12.923,736] <err> os: r10/v7: 0x00000001  r11/v8: 0x00029f38    psp:  0x2001ab38
[00:26:12.932,342] <err> os: EXC_RETURN: 0xffffffac
[00:26:12.937,835] <err> os: Faulting instruction address (r15/pc): 0x0badcafe
```

Zephyr Fault Handler - Cortex M

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```c
void network_send(void) {
  const size_t packet_size = 1500;
  void *buffer = z_malloc(packet_size);
  // missing NULL check!
  memcpy(buffer, 0x0, packet_size);
  // ...
}
```

```c
// zephyr/arch/arm/core/aarch32/cortex_m/fault.c
void z_arm_fault(uint32_t msp, uint32_t psp,
uint32_t exc_return,
    _callee_saved_t *callee_regs)
{
  // ...

}
```

```c
bool memfault_coredump_save(const
      sMemfaultCoredumpSaveInfo
*save_info) {
  // Save register state
  // Save _kernel and task contexts
  // Save selected .bss & .data regions
}
```

```c
void sys_arch_reboot(int type) {
  // ...
}
```

Zephyr Fault Handler - Memfault Analysis

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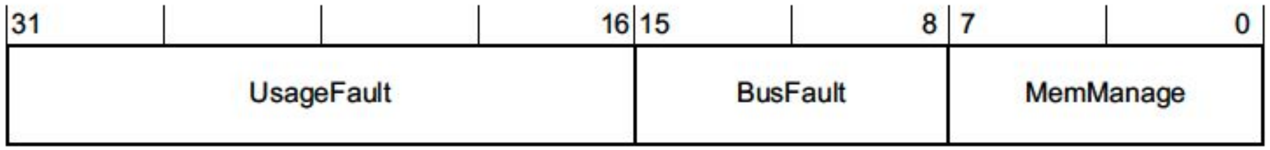
Configurable Fault Status Register (CFSR)



Memfault Analysis

Memfault Analysis
Configurable Fault (i.e UsageFault, BusFault, MemManage) escalated to HardFault
BusFault detected at 0x50008158
Precise BusFault detected! Triggered by Instruction: ‘ldr r1, [r3, #0]’ pc=0x00026fb8

Fault Register	Value	Hex Value
CFSR	33280	0x00008200
HFSR	1073741824	0x40000000
SHCSR	458884	0x00070084

Zephyr Fault Handler - Stacks

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- SVCall (2) ACTIVE INTERRUPT
  - 0 __wrap_z_fatal_error in .../memfault_fault_handler.c at line 52
  - 1 z_do_kernel_oops in .../arm/core/aarch32/fatal.c at line 113
  - 2 _oops in .../aarch32/swap_helper.S at line 482
  - 3 0xffffffac
- main (3) RUNNING
  - 0 __chk_fail in .../libc/newlib/libc-hooks.c at line 308
  - 1 __memcpy_chk
  - 2 __memcpy_ichk in .../include/ssp/string.h at line 83
  - 3 network_send in .../example_app/src/main.c at line 135
- at_cmd_socket_thread (4) READY
- idle 00 (5) READY
- shell_uart (6) BLOCKED
- sysworkq (7) BLOCKED

Zephyr Fault Handler - Globals & Statics

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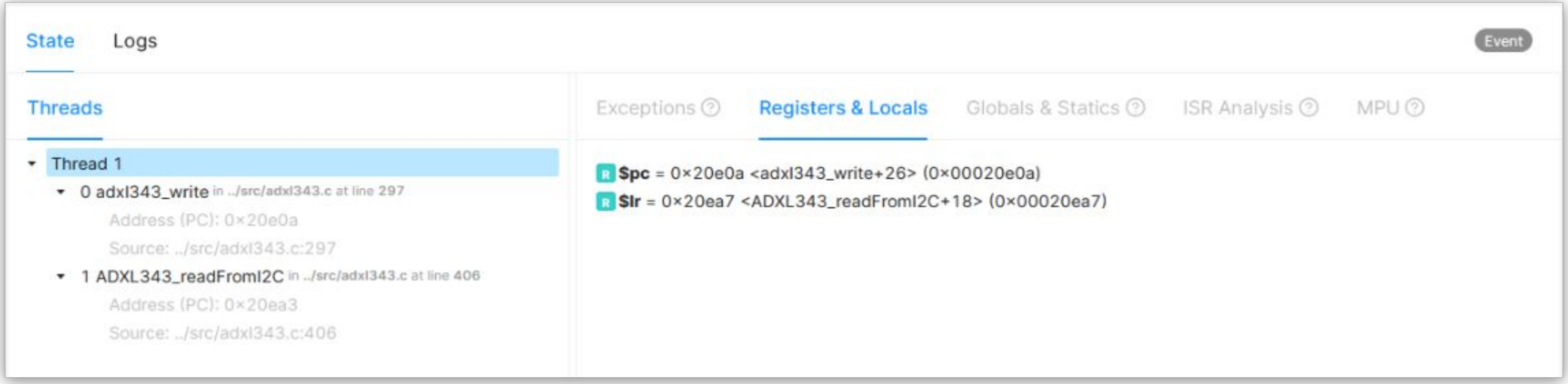
_kernel | Order by | Memory Location

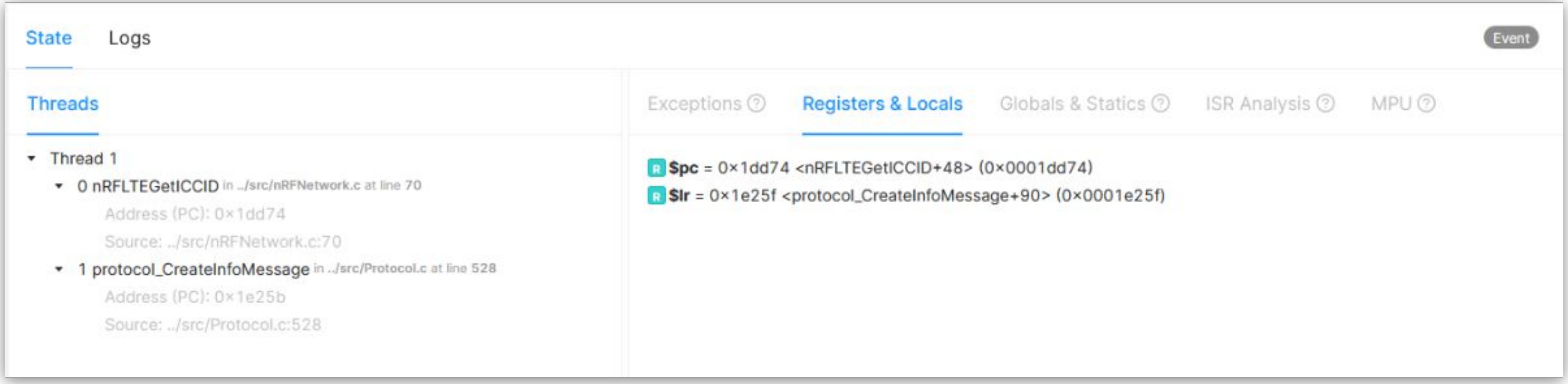
_kernel = z_kernel {...}	@ 0x200162fc
cpus = _cpu[1] {...}	@ 0x200162fc
[0] = _cpu {...}	@ 0x200162fc
nested = uint32_t 0	@ 0x200162fc
irq_stack = char* {...}	@ 0x20016300
current = k_thread* {...}	@ 0x20016304
idle_thread = k_thread* {...}	@ 0x20016308
slice_ticks = int 0	@ 0x2001630c
id = uint8_t 0	@ 0x20016310
timeout_q = sys_dlist_t {...}	@ 0x20016314
idle = int32_t 0	@ 0x2001631c
ready_q = _ready_q {...}	@ 0x20016320
current_fp = k_thread* {...}	@ 0x2001632c
threads = k_thread* {...}	@ 0x20016330
* = k_thread {...}	@ 0x20014aa0
z_sys_post_kernel = _Bool 1	@ 0x2001a567

Example: Accelerometer fault



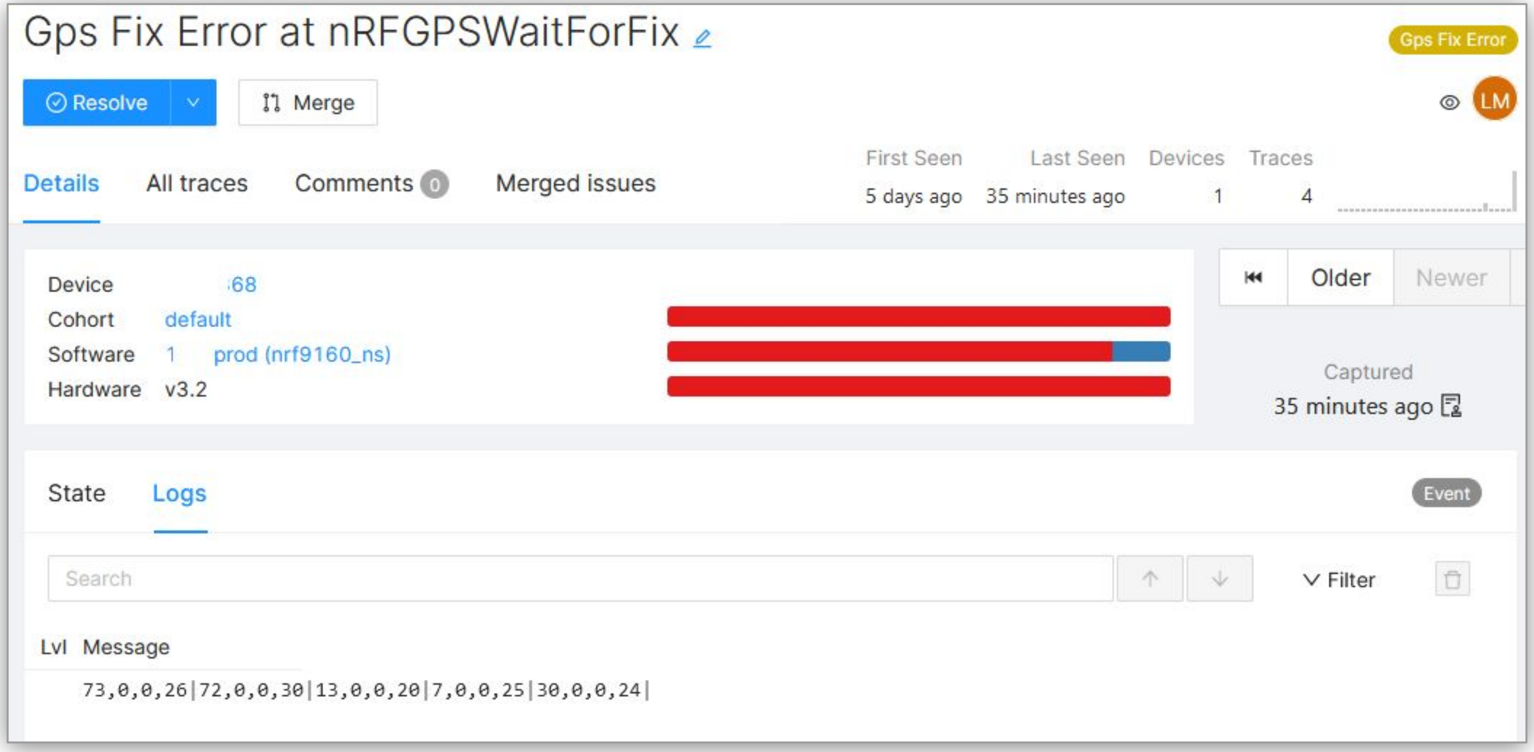
- Non-critical fault - asserting trace to see
- Traced this on 3% of devices - non-critical but good to fix
- Either HW related or race-condition related

Example: SIM card fault



- Failing to read SIM card upon boot
- Traced this on <0.1% of devices - non-critical as devices retry successfully
- HW related

Example: GPS fix failed



- Device GPS fix failing in certain cases
- Understand state of device when that happens
- Have option to log values, for example which satellites have been seen at what signal level

Example: NB-IoT modem GPS wait

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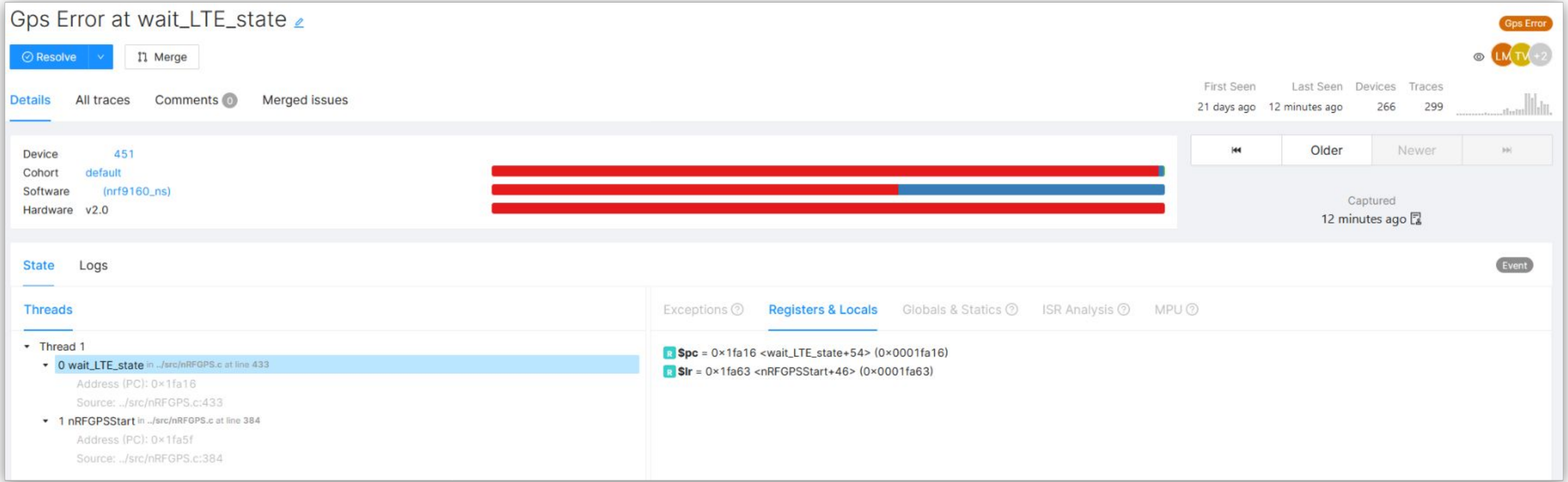
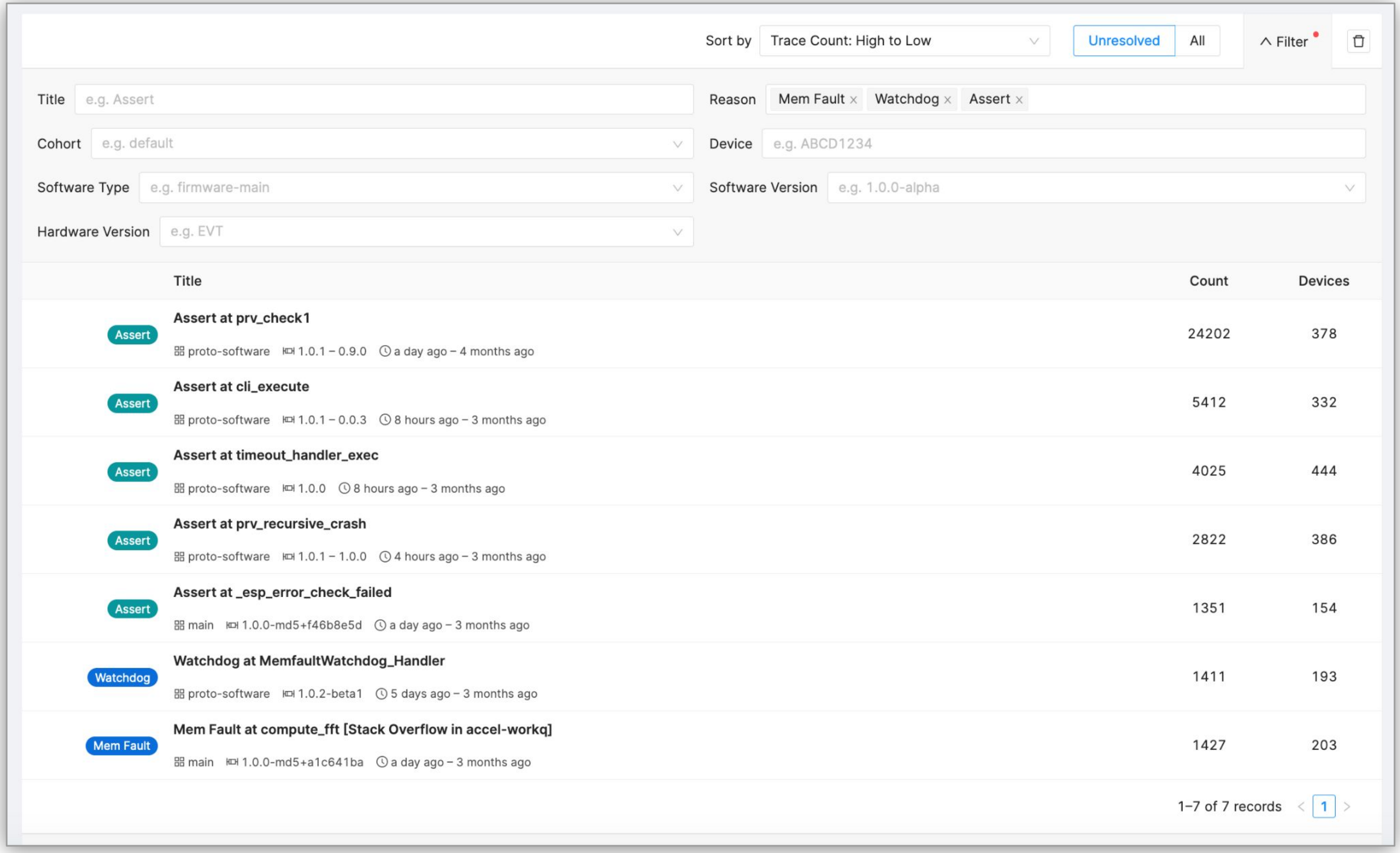


- nRF9160 modem and GPS can not be used at the same time
- Mechanism implemented to prevent this, asserting issue to track how often these events happen
- FW related

Example: Prioritizing Fixes



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Connectivity Metrics

Using Metrics to Monitor Performance

- Not all issues result in resets!
- Many factors can impact connectivity
  - location / RF environment
  - antenna efficiency
  - data being transferred
  - CPU & task utilization, time sleeping
- Enables health comparisons across all devices and between firmware releases

Adding Metrics to Zephyr with Memfault

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1. Define metric

```
MEMFAULT_METRICS_KEY_DEFINE(
   LteDisconnect,
kMemfaultMetricType_Unsigned)
```

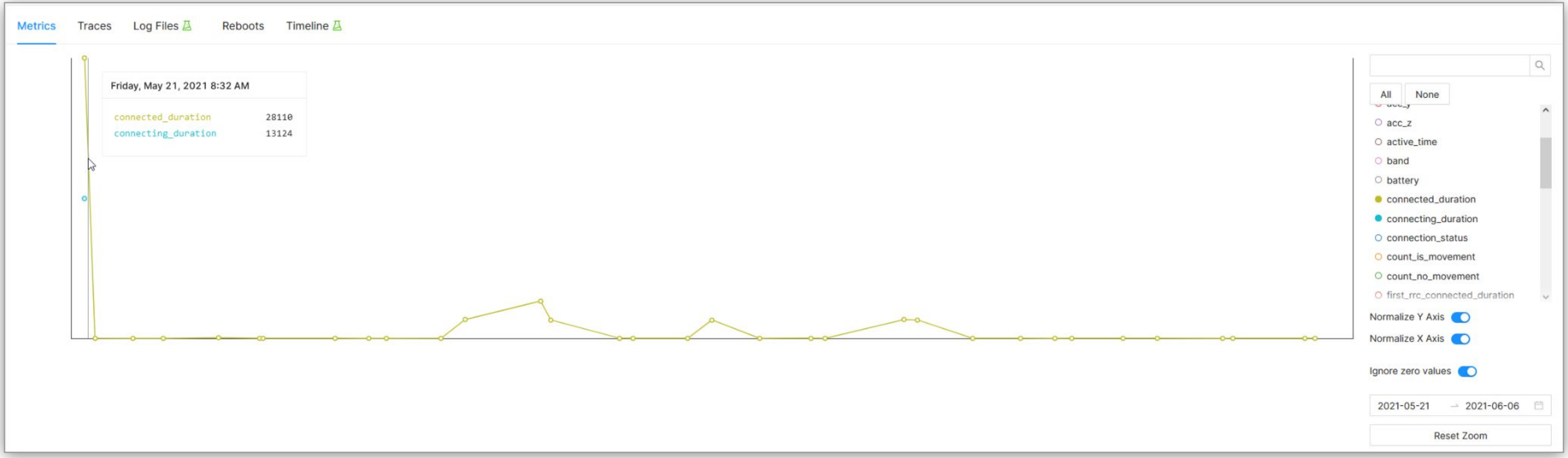
2. Update metric in code

```
void lte_disconnect(void) {
  memfault_metrics_heartbeat_add(
      MEMFAULT_METRICS_KEY(LteDisconnect), 1);
  //...
}
```

Memfault SDK + Cloud

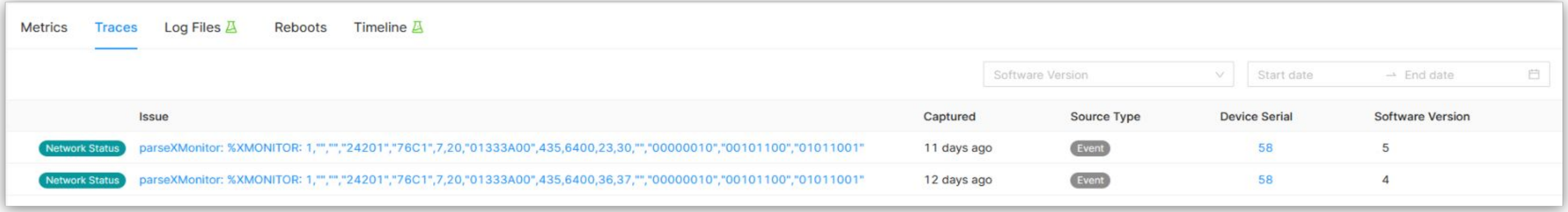
- Serializes and compresses metrics for transport
- Indexes Metrics by device and firmware version
- Exposes web interface for browsing metrics by device and across Fleet

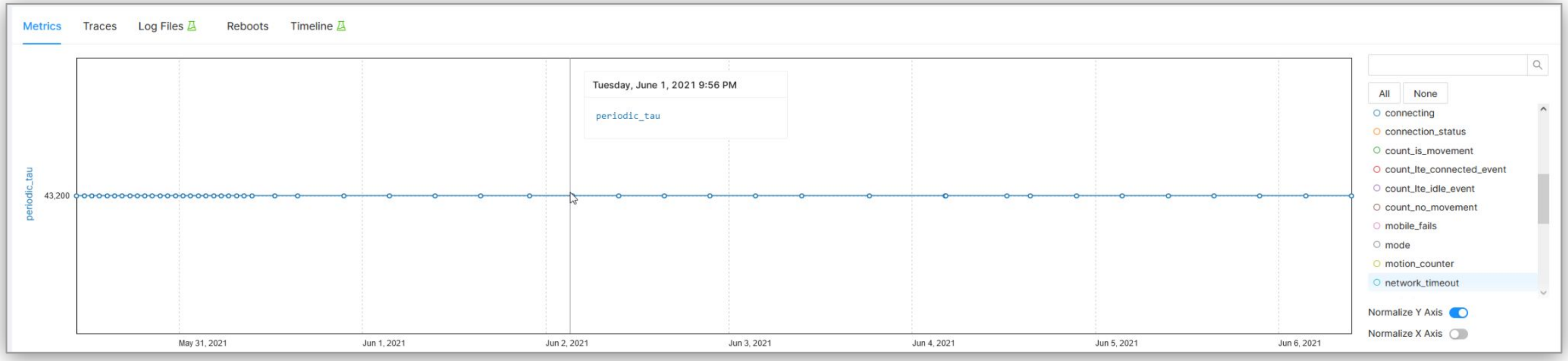
Example: NB-IoT/LTE-M basic connectivity



- **Connected**: Time modem is actively communicating with mobile network
- **Connecting**: Time modem requires to connect to mobile network
- Track activity and power consumption

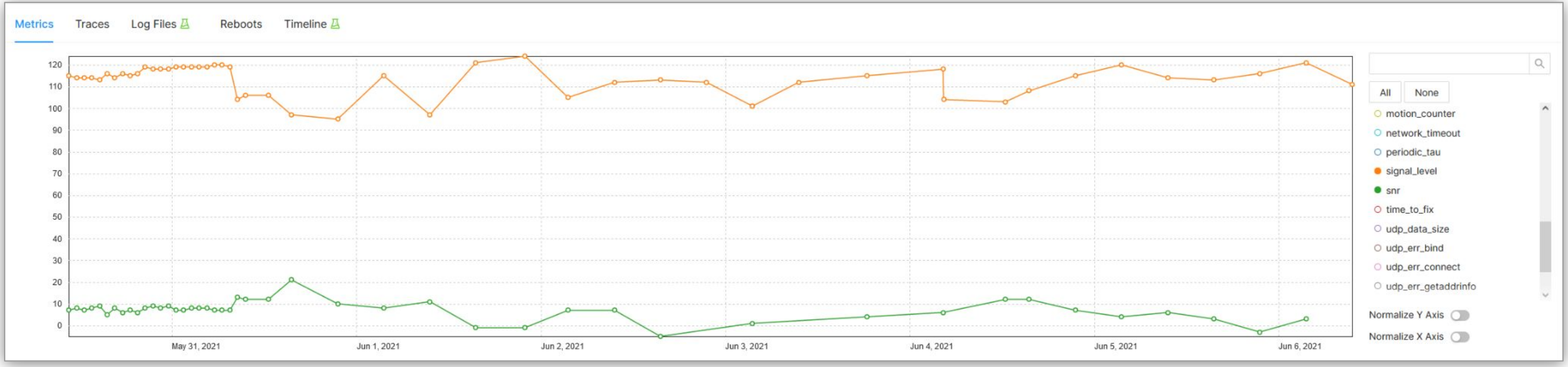
Example: base stations and PSM in NB-IoT/LTE-M





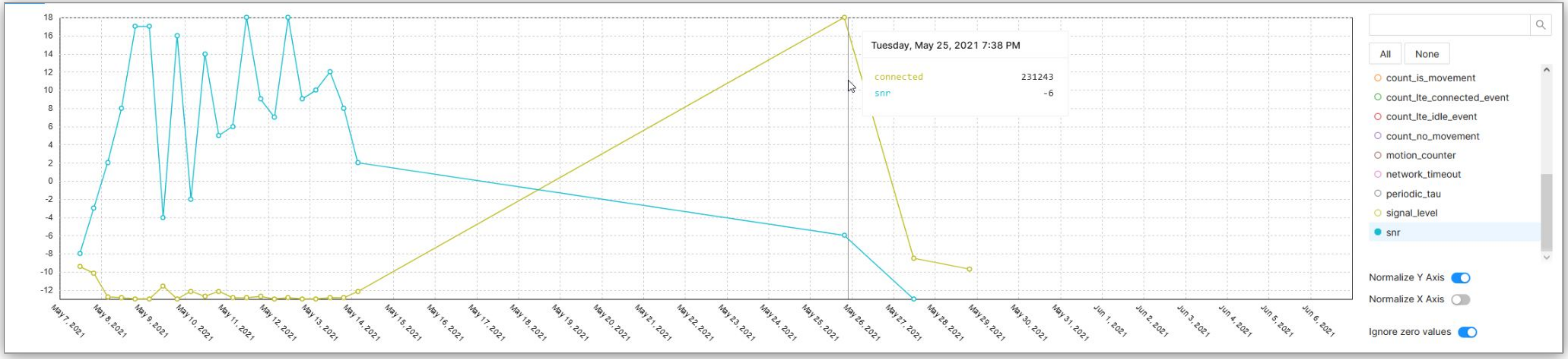
- Tracking base-station response upon connect
  - Check timer responses for PSM/eDRX
  - Check IDs and rough locations
- Correlate issues with particular base-stations or networks

Example: Mobile network signal quality



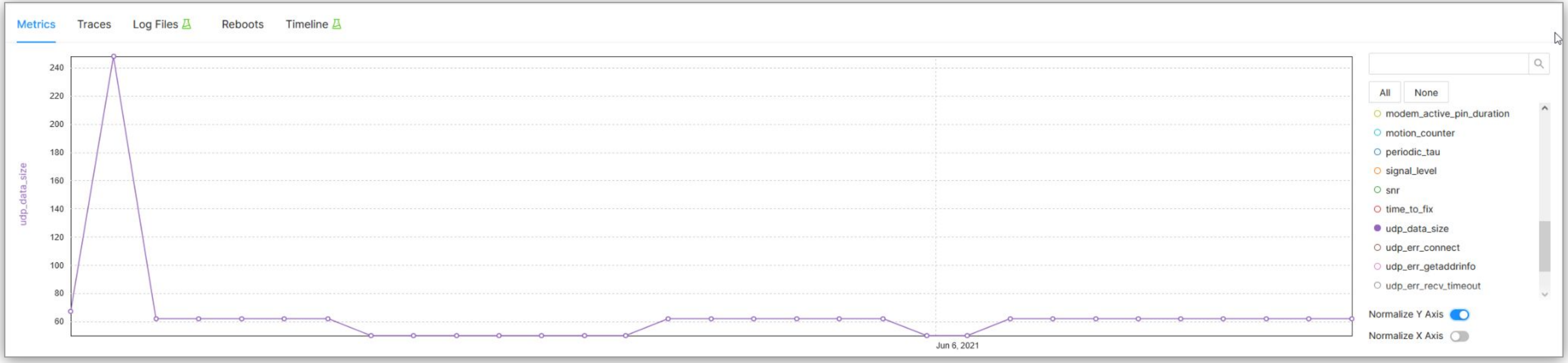
- Signal level: Monitoring quality of coverage for moving device
- SNR: Link quality
- Track what is the average value across fleet

Example: NB-IoT/LTE-M bad coverage



- Connected: Time spend sending data, SNR: Link quality
- Most of the time connected time is low, on bad SNR it significantly increases. 15s ---> 250s, same amount of data to send.
- Introduced a timeout based on SNR, better to skip sending

Example: NB-IoT/LTE-M data size



- UDP data size: Track bytes per send interval
- Post-reboot more data is sent
- Some packets are bigger due to more info or traces
- Track issue of data consumption

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Automated testing

Example: Device cyclic testing

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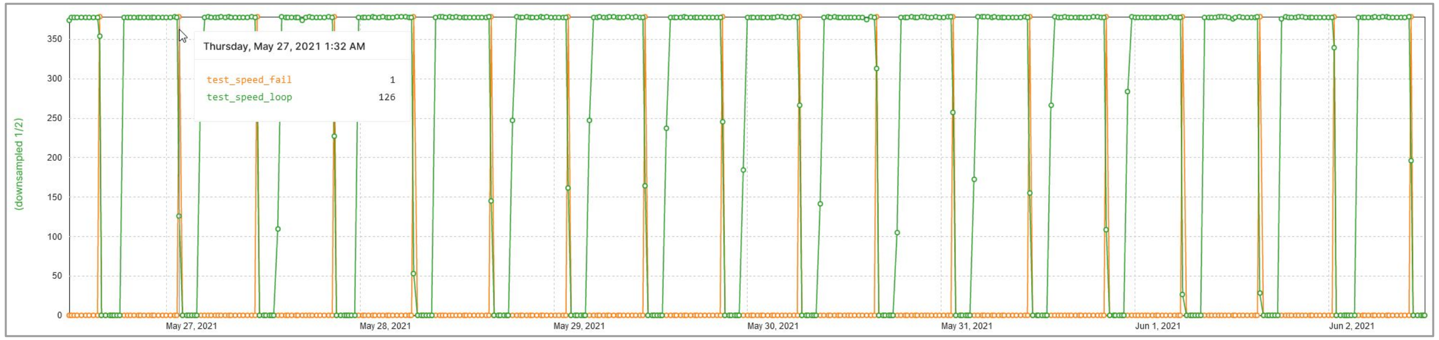
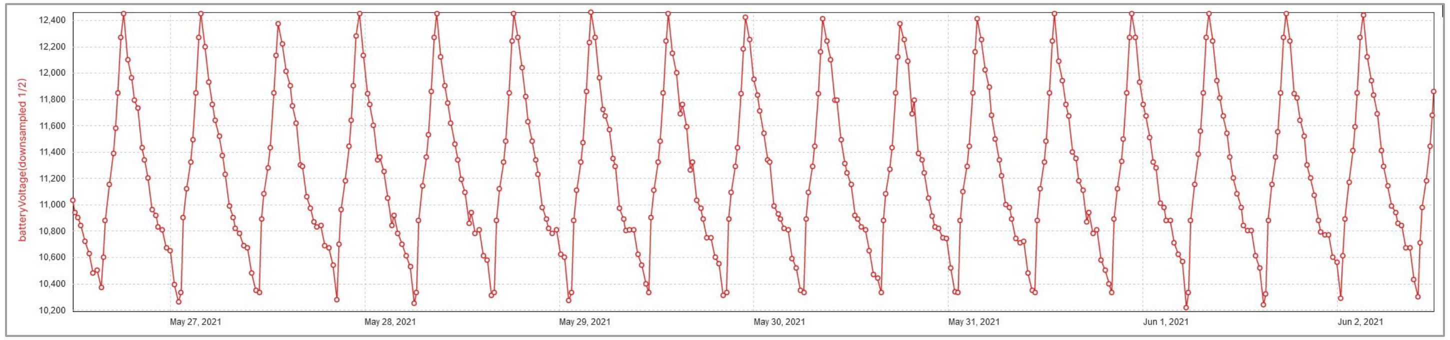




- Track automated tests progress
- On-device metrics: battery, runtime, number of inputs/output...
- Test-jig metrics: test pass/fail count, number of requested inputs...
  - via REST API from jig
- Compare on-device and test system results to track issues

About IRNAS

At Institute IRNAS, we strive to apply the vast **scientific knowledge to everyday reality,** by creating **hardware products and IoT systems** that are:

- *effective,*
- *affordable,*
- *well-tailored,*
- *future-proof.*

We believe in an open-source world and sharing.

We aim to empower the world with technologies that improve lives, let that be an advanced communication system, an open, affordable medical device, 3D bioprinting or a simple everyday utensil.

6-in-One Complete Service

irnas

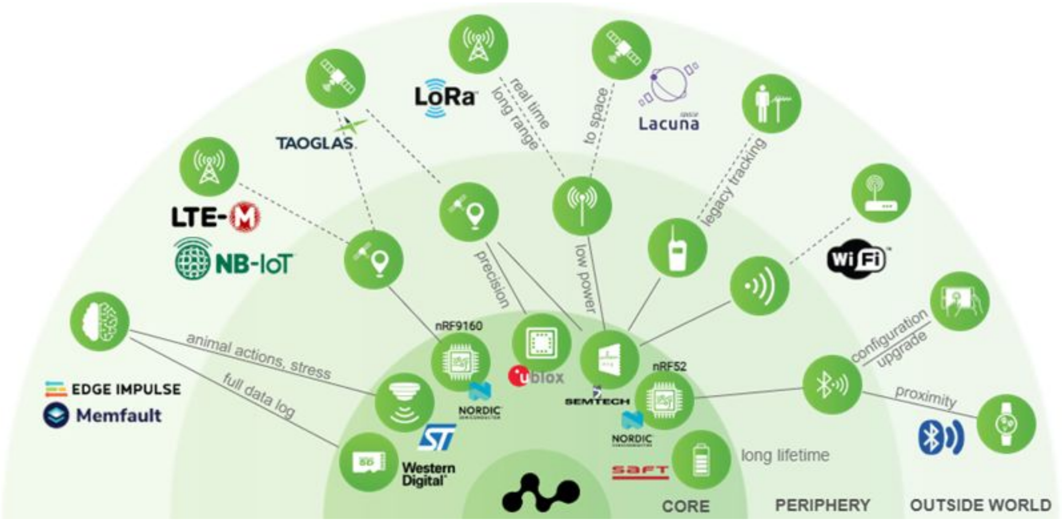
- **Electronics Engineering**
- **Software Engineering**
- **Mechanical Engineering**
- **Rapid Prototyping**
- **Small to medium-size series manufacturing**
- **Experimental testing for scientific applications**

Why IRNAS for Zephyr Devices

- **Product Development** - Offer a complete development service, taking your project from the idea to the finished product. Focusing on industrial IoT applications primarily on BLE, NB-IoT/LTE-M, LoRaWAN based on Nordic Semiconductor solution and running Zephyr.

- **In-house Manufacturing -** In-house fabrication lab is fully equipped for prototyping & manufacturing, and it includes an electronics PnP line, 3D printers, a laser cutter, a CNC workstation, a CNC mill, and more.

- **Cross-Disciplinary Team -** Highly-skilled team of scientists and engineers with expertise in mechanical, electronic and software engineering, data analysis and numerical control, acoustical, medical and bio-engineering.



IRNAS technology map 2021

Why Memfault for Zephyr Devices

Memfault

Fault Debugging

- Zephyr integrations for 1.14 LTS - 2.6
- Automatic Issue Deduplication
- Zephyr RTOS Task Awareness
- Fault handler provided as part of C-SDK
- Full stacktrace and variable recovery

Device Monitoring

- Easily scale up or down
- Add custom metrics with 2 lines of code (battery level, connectivity stats, RTOS Statistics, etc)
- Device and fleet-level metrics in one dashboard

OTA Firmware Updates

- Send bug fixes from the same platform
- Deploy and schedule cohort-based and staged rollouts
- Stop faulty updates with one click

Extra Reading & Resources

Zephyr™ Project
Developer Summit

IRNAS

- IRNAS Website
- IRNAS Blog: ElephantEdge tracker: Designing the firmware and first prototype solution
- IRNAS Blog: RAM-1: Remote monitoring of smart power grids with cellular IoT- and Bluetooth LE-powered device

Memfault

- Memfault Free Trial
- Interrupt Blog: How to debug a HardFault on an ARM Cortex-M MCU
- Interrupt Blog: Fix Bugs and Secure Firmware with the MPU
- Interrupt Blog: A Practical guide to ARM Cortex-M Exception Handling
- Interrupt Blog: A Guide to Watchdog Timers for Embedded Systems

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Questions?

Zephyr™ Project

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June 8-10, 2021 ▪ @ZephyrIoT