Ada on the ST SensorTile

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Abstract

This project is a submission for the Make with Ada contest. Ada is shown in three activities, one as a server connected to ST's BLE app, then as a server to a Raspberry Pi3 and finally as client and server SensorTiles. All communication is done using ST's BLE chip via Ada coded drivers. Numerous sensors are present and almost all are used/initialized. For the client/server demo, a musical instrument, *AdaTheremin* is created. This is in the spirit of Léon Theremin's eponymous creation but in no way is it to be a betterment. It is realized by using a fixed magnet and its proximity to and motion of the SensorTile server. This proximity and motion is beamed to the client node where audio may be heard that is derived from the incoming data. This project paves the way for Ada+BLE on ST's new STM32WB SoC (CM4F + CM0(BLE)) coming in March.

1 Introduction

To describe the effort for this project I visualize a cartoon where a hapless fool has a teaspoon to move a mound of sand, as the frame pans back, the mound turns out to be larger and then impossibly larger. This is the feeling you may experience if you are to try a port of Ada to a SensorTile using just weekends and holidays to do it. Here is a cartoon from my sister Felicity that captures this:

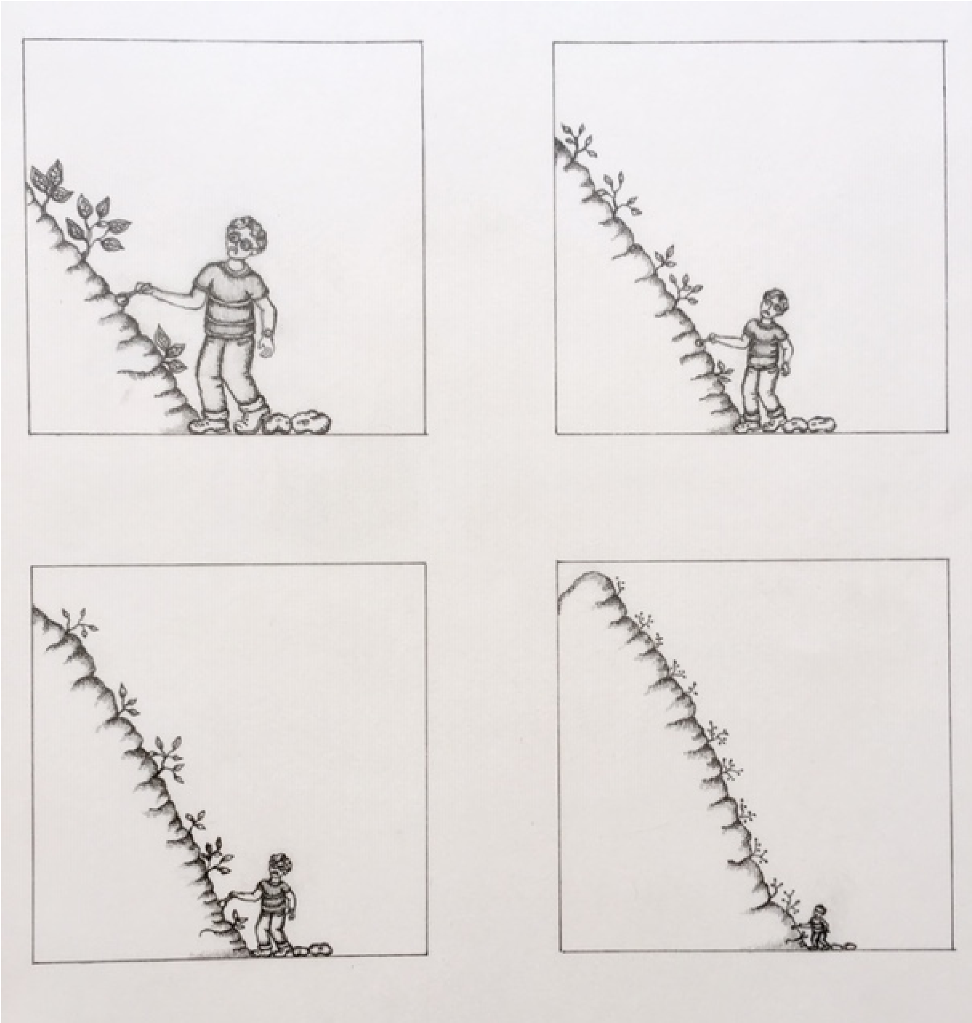


Figure 1.1: by Felicity Rainnie depicting the impossible task

Like all such tasks though, just stay focused and keep working away little by little at the problem. Slowly but surely items that seem intractable become tractable and progress gets made. I bought a SensorTile a year ago and then added another. They are not cheap, 80$ each. Out of the package you can run a SensorTile on one of two cradles, a small one which fits in a plastic holder and can be a wearable as it is powered by either external connections or the cradle $105\,\mathrm{mA\,h}$ battery. The other cradle is has Arduino headers and sports a USB connector plus a 3.5mm audio jack. The smaller cradle has two off SensorTile sensors shown in the table below as S1 & S2, the larger cradle, just one I2C peripheral, the PCM1774 audio codec (from TI no less, I guess ST doesn't have that one).

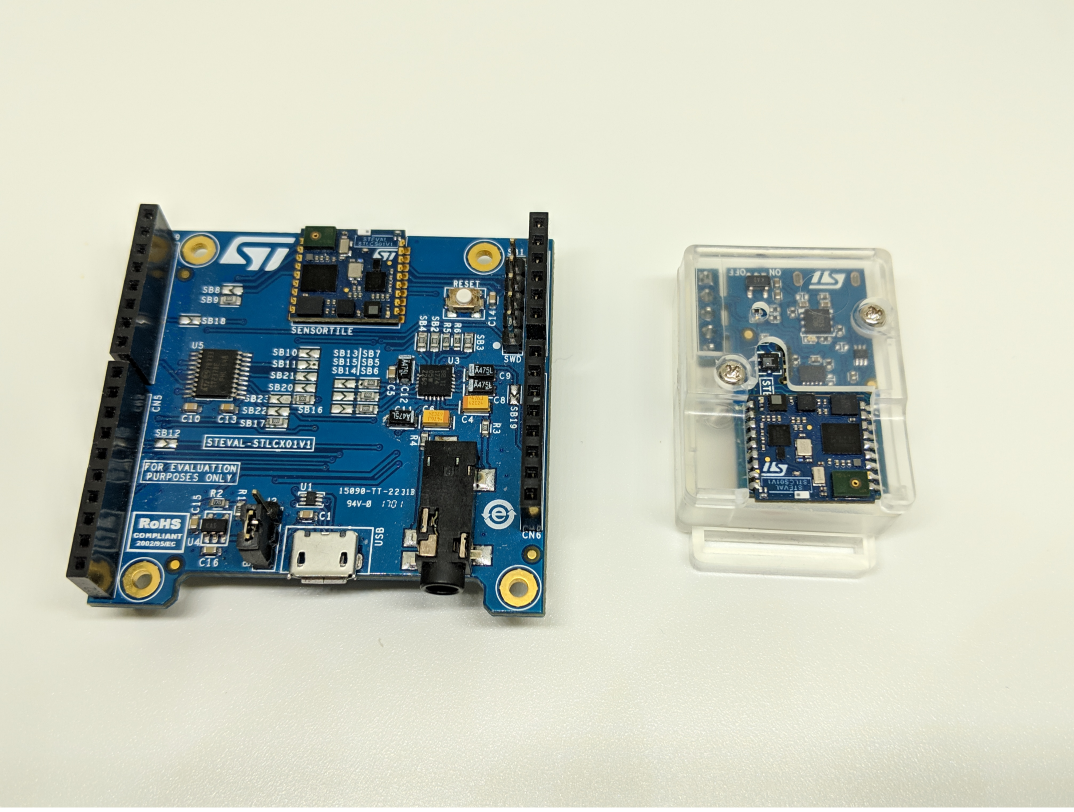


Figure 1.2: SensorTiles and cradles shown as Client on left, Server on right

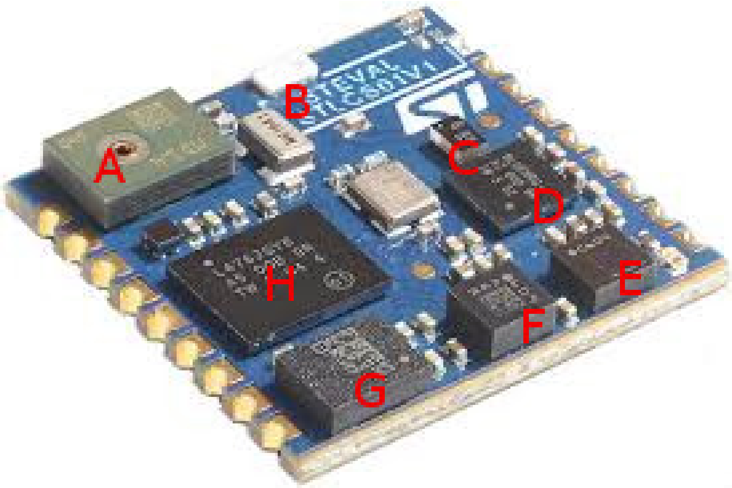


Figure 1.3: The ST SensorTile. 13.5mm square

Reference	Device	Description	Interface
A	MP34DT04	MEMS audio sensor digital microphone	DFSDM
B	ANT1	BT Antenna	-
C	BALF	50 Ω BT Balun	-
D	BlueNRG-MS	BLE network processor	SPI1 4 wire
E	LPS22HB	MEMS pressure sensor	SPI2 3 wire
F	LSM303AGR	eCompass, 3D accelerometer & 3D magnetometer	SPI2 3 wire
G	LSM6DSM	3D accelerometer & 3D gyroscope	SPI2 3 wire
H	STM32L476	ARM Cortex-M4F 32-bit microcontroller	-
Server/Client	Device	Description	Interface
S1	STC3115	Battery monitor	I2C3
S2	HTS221	Humidity sensor	I2C3
C1	PCM1774	Audio codec	I2C3

2 First steps

The first item of business was to assess the target. For the past Make with Ada project, I had ported the Ada_Drivers_Library to the STM32L432 this is a relatively small SoC and has a reduced amount of almost everything. Same CPU though, the CM4F. This SensorTile SoC however had lots of peripherals but they were all connected quite specifically to perform the SensorTile function. So the SensorTile schematics were invaluable. From the schematic, its easy to see what pins are used for sensor interfacing. ST also provides SVD files for each STM32 SoC they produce. This file is **gold** and without it, I doubt this project could have been done (at least using the methodology I like to use).

One word of caution here, a SensorTile is only 13.5mm square, it is 100% composed of high density BGA parts. There are **no** exposed traces between the packages. This means that no-one is going to be connecting up a Saleae analyzer to probe traffic to and from the SoC to the sensors. The upshot is, everything useful in the bringup of this target in Ada must be obtained over the SWD port. Which makes SWD debug and tools associated with that absolutely critical to project success.

2.1 SWD

The SensorTile uses SWD for its debug communication. Out of the box, there is no way to immediately connect to it unless you have a donor STM32 series with its STLinkV2.1 (don't we all?). So, pop off two jumpers on a STM32F401 Nucleo board and the SWD connector is no longer connected to the STM32F4 part but to whatever you have on the end of the connector. Helpfully, in the SensorTile blister pack is a 5 pin cable for just this bridge. Once this is connected up, OpenOCD (with some small mods to understand the parts flash layout) can now be connected to the target. Here we see the cfg file. The first two lines allow selection of STLinkV2.1 or STLinkV2 the former is for the board to board bridge, the latter for use with an inexpensive STLink that can be had on eBay for about $2.50. I like the inexpensive one as its small and can be transported easily, see it pictured below after the cfg file.

```
#source [find interface/stlink-v2-1.cfg]
source [find interface/stlink-v2.cfg]
transport select hla_swd
source [find target/stm32l4x.cfg]
reset_config srst_nogate
adapter_khz 1000
```

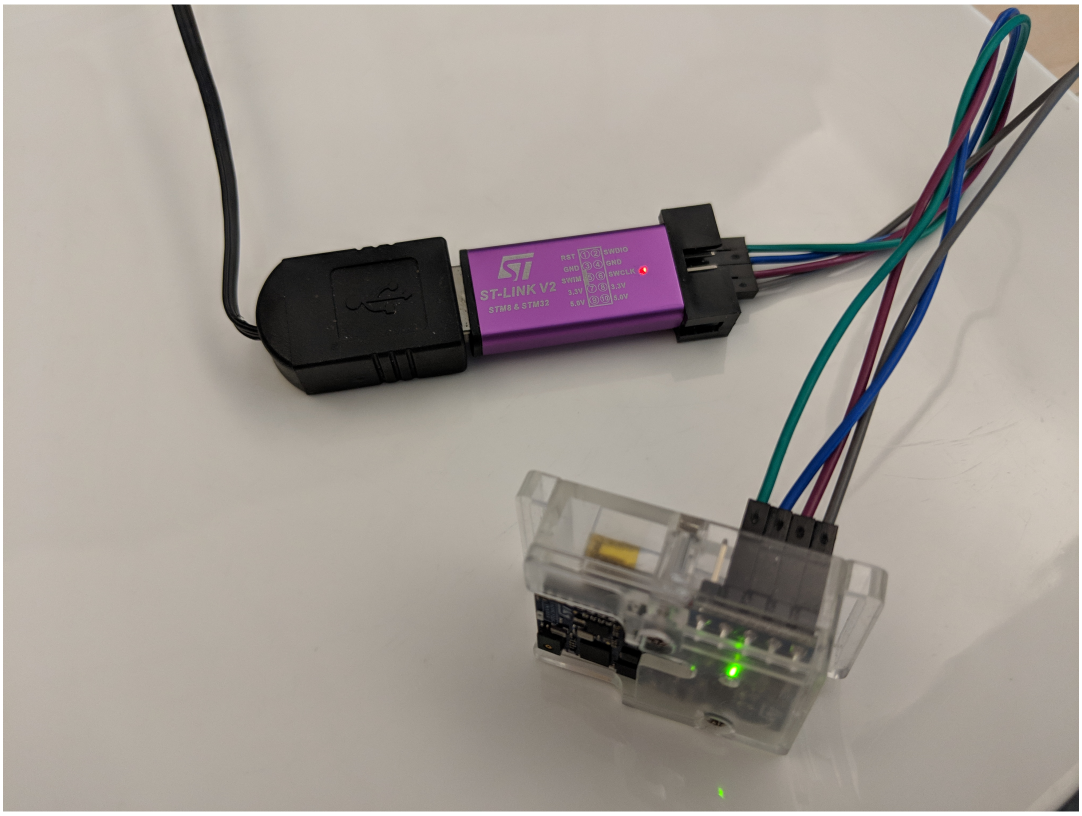


Figure 2.1: STLinkV2 connected to a SensorTile

2.2 Examination phase one

I had written some Ruby scripts a year or so ago that parse SVD files. The SVD file contains all blocks, all the registers and all the fields in the SoC in XML format. This includes symbolic names for all the above and their numerical offsets, fields widths and base addresses. AdaCore themselves uses the SVD files with a clever tool svd2ada that emits a bunch of critical .ads files that are used by the Ada_Drivers_Library to control the SoCs. Again, without SVD files, I am sure even AdaCore would not have approached targets without such automatic mapping. An SVD file entry for an L476's DAC block might look like this:

```
<peripheral>
  <name>DAC</name>
  <description>Digital-to-analog converter</description>
  <groupName>DAC</groupName>
  <baseAddress>0x40007400</baseAddress>
  <addressBlock>
    <offset>0x0</offset>
```

```
        <size>0x400</size>
        <usage>registers</usage>
      </addressBlock>
      <registers>
        <register>
          <name>CR</name>
          <displayName>CR</displayName>
          <description>control register</description>
          <addressOffset>0x0</addressOffset>
          <size>0x20</size>
          <access>read-write</access>
          <resetValue>0x00000000</resetValue>
          <fields>
            <field>
              <name>EN1</name>
              <description>DAC channel1 enable</description>
              <bitOffset>0</bitOffset>
              <bitWidth>1</bitWidth>
            </field>
            <field>
              <name>TEN1</name>
              <description>DAC channel1 trigger
              enable</description>
              <bitOffset>2</bitOffset>
              <bitWidth>1</bitWidth>
            </field>
```

My Ruby tools, svd2gdb and logs2dump both take an SVD file as an argument, the first tool emits scripts that GDB uses to dump all SoC blocks, the second takes the dumps and composes them into human readable info. Lets see partial output of svd2gdb first for the DAC:

```
set logging overwrite on
set logging file DAC.log
set logging redirect on
set logging on
x/256x 0x40007400
```

The partial resultant output from GDB after you run that script is:

```
0x40007400:     0x00000000      0x00000000      0x00000000      0x00000000
0x40007410:     0x00000000      0x00000000      0x00000000      0x00000000
0x40007420:     0x00000000      0x00000000      0x00000000      0x00000000
0x40007430:     0x00000000      0x00000000      0x000c0012      0x00000000
0x40007440:     0x00000000      0x00000000      0x00010001      0x00010001
0x40007450:     0x00000000      0x00000000      0x00000000      0x00000000
```

And the partial interpretation of the dump via log2dump:

```
DAC.CR.EN1: 0
DAC.CR.TEN1: 0
DAC.CR.TSEL1[2:0]: 0
DAC.CR.WAVE1[1:0]: 0
DAC.CR.MAMP1[3:0]: 0
DAC.CR.DMAEN1: 0
DAC.CR.DMAUDRIE1: 0
DAC.CR.CEN1: 0
DAC.CR.EN2: 0
DAC.CR.TEN2: 0
DAC.CR.TSEL2[2:0]: 0
DAC.CR.WAVE2[1:0]: 0
DAC.CR.MAMP2[3:0]: 0
DAC.CR.DMAEN2: 0
DAC.CR.DMAUDRIE2: 0
DAC.CR.CEN2: 0
DAC.SWTRIGR.SWTRIG1: 0
DAC.SWTRIGR.SWTRIG2: 0
DAC.DHR12R1.DACC1DHR[11:0]: 0
DAC.DHR12L1.DACC1DHR[11:0]: 0
DAC.DHR8R1.DACC1DHR[7:0]: 0
DAC.DHR12R2.DACC2DHR[11:0]: 0
DAC.DHR12L2.DACC2DHR[11:0]: 0
DAC.DHR8R2.DACC2DHR[7:0]: 0
DAC.DHR12RD.DACC1DHR[11:0]: 0
DAC.DHR12RD.DACC2DHR[11:0]: 0
DAC.DHR12LD.DACC1DHR[11:0]: 0
DAC.DHR12LD.DACC2DHR[11:0]: 0
DAC.DHR8RD.DACC1DHR[7:0]: 0
DAC.DHR8RD.DACC2DHR[7:0]: 0
DAC.DOR1.DACC1DOR[11:0]: 0
DAC.DOR2.DACC2DOR[11:0]: 0
DAC.SR.DMAUDR1: 0
DAC.SR.CAL_FLAG1: 0
DAC.SR.BWST1: 0
DAC.SR.DMAUDR2: 0
DAC.SR.CAL_FLAG2: 0
DAC.SR.BWST2: 0
DAC.CCR.OTRIM1[4:0]: 0x12
DAC.CCR.OTRIM2[4:0]: 0xc
DAC.MCR.MODE1[2:0]: 0
DAC.MCR.MODE2[2:0]: 0
DAC.SHSR1.TSAMPLE1[9:0]: 0
DAC.SHSR2.TSAMPLE2[9:0]: 0
```

```
DAC.SHHR.THOLD1[9:0]: 1
DAC.SHHR.THOLD2[9:0]: 1
DAC.SHRR.TREFRESH1[7:0]: 1
DAC.SHRR.TREFRESH2[7:0]: 1
```

The scripts are on my GitHub. You can use them on any SVD file, they are not ST specific so that makes them quite useful for the future I feel.

https://github.com/morbos/ruby/tree/master/svd2gdb and https://github.com/morbos/ruby/tree/master/logs2dump

2.3 Examination phase two

So this then allows us a window into a target SoC to see what registers are set at the moment we halt the SoC in GDB. All we need do is to source the GDB script and we then get 76 log files generated for each of the blocks in the STM32L476. We then recompose those logs with the benefit of the SVD file to put human readable structure back onto the raw register reads. In this way, we now have a human readable story on the state of the SoC at that moment. A small leap ahead allows us to see that we can take a working SoC FW, stop it, dump its state and then take the state of a non-working SoC FW, perform the same state dump and then diff the two human readable output files, where there are differences could be clues as to why the non-working FW is indeed not working. I have used this technique on STM32s to great effect accross a whole range of parts. I do encounter SVD file bugs from time to time as I delve deeper into the designs. I repair these errors always with the central tenet that the datasheet is the arbiter for correct specifcation. Indeed as I have done these repairs, that has always borne out. As I repair the SVD file, I refold it back into the svd2ada .ads build. Now at the end of January, I now see ST has updated their SVD files to v1.2. v1.2 adds much more detail to the CPU. (MPU, systick etc). I believe I am still on v1.1 but still I did not see some of the fixes I made so I think I will stay with v1.1 for this project. Bringing this back to the examination phase, ST provides the ALLMEMS FW for SensorTile evaluation. Its a download from ST's website and can be compiled with the free eclipse gcc based toolchain. ST calls the toolchain, System Workbench. Projects associated with that toolchain are in the SW4STM32 dirs. Once the ALLMEMS elf file is built, it can be flashed on the SensorTile. Using gdb as I mention, we can stop the target and take a state dump of it. This is becomes the gold standard for what I needed to achieve in my Ada bringup. For more advanced study, some mods were made to the ALLMEMS FW to make a ring buffer. At certain points in the FW, bytes are logged into the ring and they get saved to the disk in a similar fashion as the raw register dumps. This particular ring is used for outgoing BLE packet data and incoming interrupt data. Another Ruby script was crafted, this one has initimate knowledge of the BLE API call structure and can reassemble the packets sent to and fro. Another important tool is the ST CubeMX Windows software. It will allow creation of a project that is tied to a particular SoC or board. The SensorTile is not one of the boards selectable but the SoC, the STM32L476 is. We create a project using that SoC and begin to setup the clocks. Also we can use the CubeMX to examine pin alternate functions. It can also generate C code but I did not use that option for this target.

2.4 Preliminaries

Armed with the tools some steps can be taken. First is to begin an Ada_Drivers_Library for the L476. To begin, we copy over the L432. The L432, whilst complete enough last year for a simple challenge is not robust enough for SensorTile work as will be discovered. So we have a library, change the flash and ram specs, modify OpenOCD to for the L476, we can build a small program, tryL476. Failing to reach main, we begin the task of asymptoting to the init seq ALLMEMS uses. We start to narrow down PLL differences and back patch those into the setup_pll function. This continues until we finally reach main as by then slowly but surely the diffs were ironed out. SensorTile RCC clocking is different from a lot of STM32 platforms I have used. It uses the on chip oscillator. That on chip oscillator (MSI) can reach 48Mhz via factory tuned constants that are loaded up at PoR. Actually, I had a bug in my code that assumed the MSI was 4Mhz (factory default) for the SensorTile. A close examination of the diffs however showed that the ALLMEMS FW bumped that MSI clock to 48Mhz. Anyway, with the diffs, its all pretty straightforwards to catch these types of discrepancies.

2.5 CM4F Memory Protection Unit (MPU)

I should also mention I run the CM4F on the STM32L476 like a police state. That means I have numerous code/data and device regions set in the MPU. I set all ram to eXecute Never (XN). Each region is sized only as big as it needs to be to allow normal access.

Region #	Address	Size	Attributes	Comment
0	16#00000000#	4GB	No access	Lowest pri faultall region
1	16#08000000#	1M	Read Only	Flash memory
2	16#20000000#	128K	Full access, XN	SRAM1 (its physically 96K)
3	16#10000000#	32K	Full access, XN	SRAM2 (used by logger curr)
4	16#40000000#	256M	Device space	STM32 periphs
5	16#50000000#	512K	Device space	STM32 periphs cont
6	16#E0000000#	64K	Device space	ARM periphs
7	16#1FFF0000#	64K	Device space	STM32 system space

Wandering outside of the MPU regions denoted above will place you in the fault handler. To Ada's great credit, you have to try very hard to get a compiling program to enter an ARM fault handler, normally you will be in the 'last chance handler' long before a bad access has a chance to present itself. Not so with C, I routinely enter fault handlers during development when the MPU is hardened as I have done here (which is where the fault handler shown below came from). The fault handler has been modified to give a little more colour to the nature of the fault. Observe only r0-r3 are used as the real r0-r3 are stacked at fault time. There is also another function 'hang' that has the same treatment.

```
        .thumb_func
fault:
        ldr     r0,=0xe000ed00
        ldr     r1,[r0,#0x28]   /* Configurable Fault SR */
        ldr     r2,[r0,#0x2C]   /* Hard Fault SR */
        ldr     r3,[r0,#0x38]   /* Bus Fault Addr Reg*/
        ldr     r0,[r0,#0x24]   /* System Handler ctl state reg */
fault_spin:
        b fault_spin
```

2.6 First FW

So we have a library and we can get to main. The first order of the day was to talk to a sensor. I decided to start with the LPS22HB pressure sensor. The work began with a generic driver for it. Seems all pretty straightforwards. One difference was that ST was using SPI 3-wire mode. All the previous SPI sensors I have used were 4-wire. 3-wire is a bit like I2C in that, like the SDA line, one of the communication wires needs to be turned around on a read. So the Ada setup for this is a bit different:

```
   procedure Initialize_Sensor_Hardware
     (Port      : access SPI_Port;
      SPI_AF    : GPIO_Alternate_Function;
      SCL       : GPIO_Point;
      MOSI      : GPIO_Point
     )
   is
      GPIO_Conf     : GPIO_Port_Configuration;
      SPI_Points    : constant GPIO_Points := SCL & MOSI;
      Config        : SPI_Configuration;
```

```
begin
   Enable_Clock (SPI_Points);
   Enable_Clock (Port.all);
   Enable (Port.all);

   STM32.Device.Reset (Port.all);

   GPIO_Conf.Output_Type := Push_Pull;
   GPIO_Conf.Resistors   := Pull_Up;
   GPIO_Conf.Speed       := Speed_100MHz;
   GPIO_Conf.Mode        := Mode_AF;
   Configure_IO (SPI_Points,  GPIO_Conf);

   Configure_Alternate_Function (SPI_Points, SPI_AF);

   Config.Mode := Master;
   Config.Baud_Rate_Prescaler := BRP_16;
   Config.Clock_Polarity := High;
   Config.Clock_Phase := P2Edge;
   Config.First_Bit := MSB;
   Config.CRC_Poly := 7;
   Config.Slave_Management := Software_Managed;  --  essential!!
   Config.Direction := D1Line_Tx;
   Config.Data_Size := HAL.SPI.Data_Size_8b;
   Config.Fifo_Level := True;

   Disable (Port.all);
   Configure (Port.all, Config);
   Enable (Port.all);

end Initialize_Sensor_Hardware;
```

So now, with suitable initialization we can try to talk to the sensor. Perhaps not surprisingly, it did not work. As I mentioned earlier in this document, no probing is possible on this SensorTile. Thus we are presented with a puzzle, how to diagnose balky communication on this new (to me) 3-wire SPI connection? So now, I will reveal another method I used. I have a webpage Bluepill+, where I show how I performed a brain transplant on a sub-$2 Bluepill board by replacing its STM32F103C8 (a 10yo CM3 design btw) with a modern pin compatible STM32L443CC SoC. (**Massive** hat tip to ST Microelectronics for supporting a 10yo footprint!). Now, the STM32L443CC is a close cousin of the STM32L476 and shares a great deal of commonality. A Bluepill board is the opposite of a SensorTile, 1) its large (relative to a SensorTile) 2) all the SoC pads come out to easy to connect 0.1" centre pins.

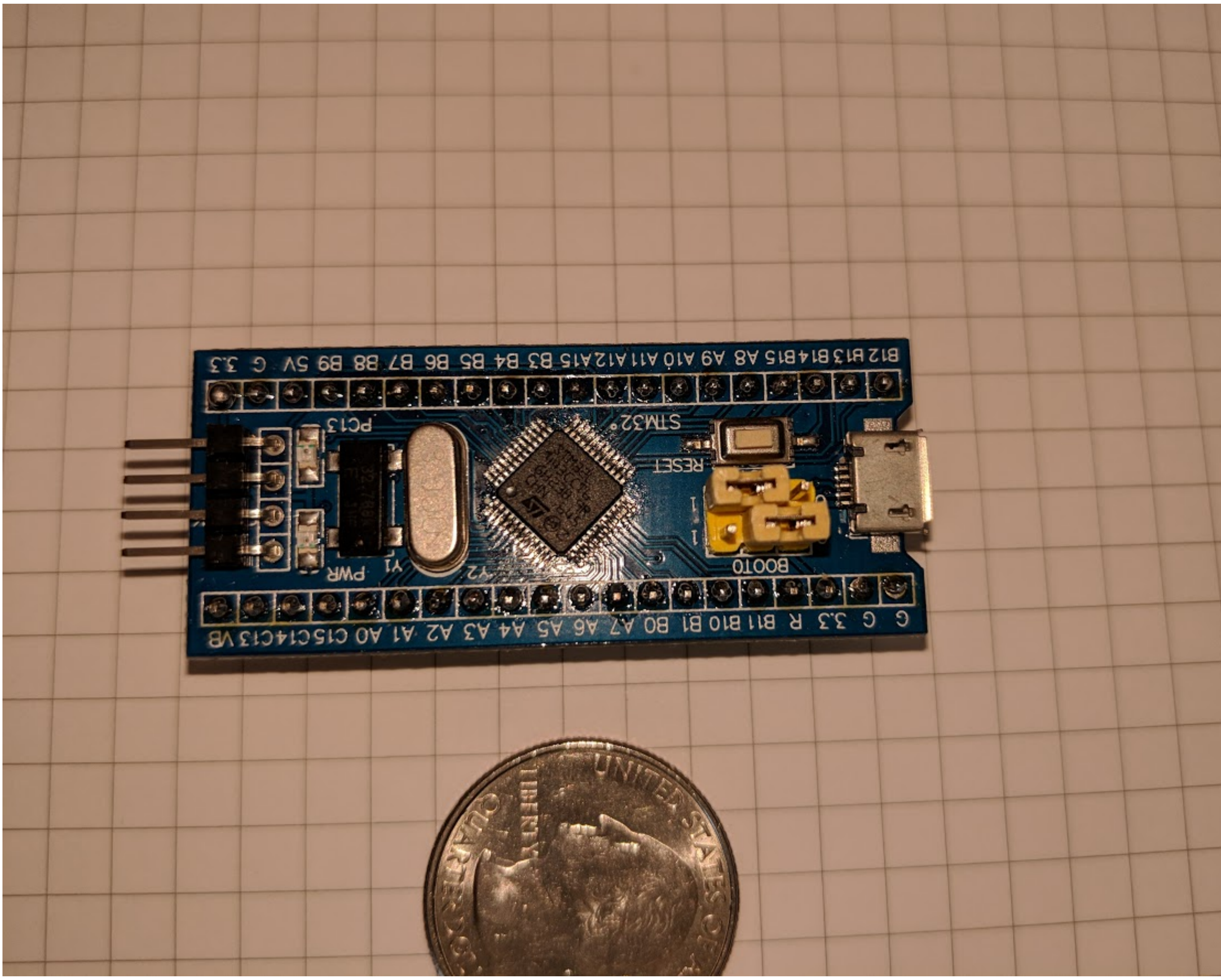


Figure 2.2: A Bluepill+, created via an SoC swap

Perhaps you see where I am going with this? We can take an ST sensor (like the LIS3DSH) and connect it to the STM32L443 using wires, then we can try the 3-wire SPI code with that sensor and shake down where in the library the issue is. Since its a bare wired physical connection, a Saleae analyzer can be used to diagnose the protocol. Once the issue with the library is sorted out for the L443 we move the change to the L476 library. Via a rebuild, we retry the pressure sensor and magically, it now works. Subsequently, pressure readings were pulled out and the numbers seemed OK.

Much later I had another bug with 3-wire that was a lot harder to find. Basically, the accelerometer/gyroscope and magnetometer readings would become erroneous. First step was to compare a diff of ST's ALLMEMS FW vs mine. After giving that a good study, I noticed the overrun bit was set in my dump of the SPI2 status reg. This was a good clue and I followed up using the Bluepill+ technique, I was able to analyze that at the fast baud rate that the SensorTile was using, it was possible to get an overrun. 3-wire SPI is a bit odd, all is good for writes to the slave, its when reads happen that the fun begins. The write is a bit like 4-wire SPI then, you disable the SPI and restart it in 3-wire mode. Once you do that, the SPI block will emit a **continuous** stream of clocks out to the slave, the slave, also configured as a 3-wire device accepts this and dutifully begins to emit bytes on the wire, because the stream of clocks is continuous, you have to shut the valve off once you get your data. Unfortunately the timing of that can be tricky and invariably once in a while another byte is clocked into the fifo. Subsequent reads, not expecting, this can go out of sync. The fix in the library was as so:

```
if This.Periph.CR1.BIDIMODE then  --  One wire mode TX only
   Disable (This);
   This.Periph.CR1.BIDIOE := True;
   Enable (This);

   --  vvvv this loop cleans up the runon in BIDIR mode. Because
   --  the clock is automatically generated, it bursts at the BR and
   --  the SoC samples the input. There is no clean way to say, burst only
   --  for N clocks, its continuous. So for an 8bit xfer as this is, any stragglers
   --  coming in can subsequently fill the fifo and mess up the next read.
   --  To address this, we just drain the input at the end of the xfer.
   declare
      Dummy : UInt8;
      Data_8bit : UInt8 with Volatile, Address => This.Periph.DR'Address;
   begin
      while not This.Rx_Is_Empty loop
         Dummy := Data_8bit;
      end loop;
   end;
end if;
```

2.7 Moving on

Now that we can talk to one SPI 3-wire sensor, we can talk to more. There are 3 SPI sensors in a SensorTile. Each has its own chip select. So the next FW was one to enumerate all the sensors by checking their ID's. Register 16#0F# in most ST sensors is call a WHO_AM_I register and returns a unique code for that sensor family. Once that FW was ready, we could verify that all the sensors were present.

3 BLE (or the elephant in the room)

Well, one can keep probing sensors all you like but ultimately, to be useful and perhaps the raison d'etre for this project entry was to get ST's BLE chip working with Ada as a pure Ada driver, not a hybrid. By the way, I tried a hybid for a week or so, basically linking Ada vs ALLMEMS C FW. I got some OK results but the entire structure of that was impure and not at all where I wanted to go. You see, ST's BLE, as a single chip peripheral, is just a stepping stone. In March of 2019, ST will world release the STM32WB. Basically its an STM32L4 + BlueNRG-MS, some slight changes since both IPs are on the WBs SoC they don't use SPI but an interprocessor communication channel. So if we can overcome the elephant in the room, we will have a BLE stack that can move easily over to the new single chip design next year. That is the ultimate goal. The SensorTile is a method to get us there.

3.1 BLE first steps

Its pretty straightforwards to get the BlueNRG-MS plumbed over to the STM32L476 we have all been connecting 4-wire SPIs to STM32s for a while now, this one is no different, initially. Relatively quickly, one finds that the BlueNRG-MS uses the interrupt line to alert the STM32L476 that packet data is waiting. So, we need to plumb over the interrupt line and get a handler in place at the correct EXTI9_5_Interrupt. Once again, the diff technique worked wonders as its easy to make sure all the GPIO's are right and the NVIC is set to take the interrupt. Now, a BlueNRG-MS will not spontaneously begin interrupt transmission, you need to get it initialised to start that. I figured the first command I would go with was the one that interrogates the revision and manufacturer info from the BlueNRG-MS. This is officially where the rabbit hole begins. Just to transmit that revision request and handle its reply requires BLE outbound command processing, inbound command parsing, data structures and a lot of other procedures and functions. Then the record is sent with a reply pointer set to where the reply goes. Now the call to the send is a blocking call and after the comand is sent, an interrupt comes back with indication of a packet waiting (the response). How packets are passed around in ST's BLE is via a doubly linked list. They have a structure like this:

```
typedef struct _tListNode {
        struct _tListNode * next;
        struct _tListNode * prev;
}tListNode, *pListNode;

/* structure used to read received data */
typedef struct _tHciDataPacket
{
  tListNode currentNode;
  uint8_t dataBuff[HCI_READ_PACKET_SIZE];
  uint8_t data_len;
} tHciDataPacket;

void list_insert_node_before (tListNode * node, tListNode * ref_node)
{
  uint32_t uwPRIMASK_Bit;

  uwPRIMASK_Bit = __get_PRIMASK();  /**< backup PRIMASK bit */
  __disable_irq();                  /**< Disable all interrupts by setting PRIMASK bit on Cort

  node->next = ref_node;
  node->prev = ref_node->prev;
  ref_node->prev = node;
  (node->prev)->next = node;

  __set_PRIMASK(uwPRIMASK_Bit);     /**< Restore PRIMASK bit*/
}
```

That structure relies on the fact that they can process the linked list separate from the payload. They tack the payload after the currentNode declaration above. This allows them to have arbitrary elements after the linked list record and write the linked list code without any knowledge of the dataBuff element for example.

In Ada, we cannot partially specify a record and then promise to fill it in later when we know what will follow. So in my implementation of the doubly linked list I made it a generic where the element that follows the linked list record is a type that is passed in. In this way, we cleanly pass the payload when we instantiate the generic as so:

```
generic
   type Payload is private;
   Limit : Natural;
package Gen_List is
   type ListNode;
   type ListNodePtr is access all ListNode;
   type ListNode is record
      Next : ListNodePtr;
      Prev : ListNodePtr;
      Elem : Payload;
   end record;
   type ListNode_Array is array (1 .. Limit) of aliased ListNode;
   procedure List_Init_Head (ListHead : in out ListNodePtr);
```

```
   function List_Is_Empty (ListHead : ListNodePtr) return Boolean;
   procedure List_Insert_Head (ListHead : ListNodePtr; Node : ListNodePtr);
   procedure List_Insert_Tail (ListHead : ListNodePtr; Node : ListNodePtr);
   procedure List_Remove_Node (Node : in out ListNodePtr);
   procedure List_Remove_Head (ListHead : in out ListNodePtr; Node : in out ListNodePtr);
   procedure List_Remove_Tail (ListHead : ListNodePtr; Node : in out ListNodePtr);
   procedure List_Insert_Node_After (Node : in out ListNodePtr; Ref_Node : in out ListNodePtr)
   procedure List_Insert_Node_Before (Node : in out ListNodePtr; Ref_Node : in out ListNodePtr
   function List_Get_Size (ListHead : ListNodePtr) return Natural;
   procedure List_Get_Next_Node (Ref_Node : ListNodePtr; Node : out ListNodePtr);
   procedure List_Get_Prev_Node (Ref_Node : ListNodePtr; Node : out ListNodePtr);
end Gen_List;
```

I am embarrassed to reveal it took a few weekends to get that doubly linked generic to a point where it was usable. After a rather nasty deletion bug it was finally ready for use. You need only five 128byte packet buffers to make this BLE stack work. The linked list data structure is critical to all phases of packet processing in the stack. I feel the time was well spent as once it was created, we now had a solid data structure that was 100% Ada and able to handle the packet flow.

Now back to the revision query. So after we climb out of data structure prep, next is composing the query. There is a certain format that BLE (and perhaps BT itself) use comprising ogf and ocf codes, these two fields end up being composed into a 16bit field. The two numbers seem to be the division of the API request and the actual code within the division. The divisions are formed by a 6 bit OGF value and a 10bit OCF code. For the revision number you end up with this:

```
OGF_INFO_PARAM                  : constant UInt6  := 16#04#;

OCF_READ_LOCAL_VERSION          : constant UInt10 := 16#001#;
```

Which makes a req of 16#1001# after sliding the OGF value up to the top 6 bits.

Here is a partial output from the Ruby script analyze.rb that I mentioned further up that helped to parse the raw gdb ring buffer memory to recreate the sequence of calls to and from the BlueNRG-MS. Observe the results at the top to the revision query. Note that 0030 is ST's hex Bluetooth manufacturer id.

```
ISR @0 6
"proprietary_event"
SENDCMD @8 4 0 ogf 4 ocf 1 OGF_INFO_PARAM OCF_READ_LOCAL_VERSION plen 0
ISR @15 15
"EVT_CMD_COMPLETE_CODE"
[04,001]
status 00
hci_version 07
hci_revision 3107
lmp_pal_version 07
manufacturer name 0030
lmp_pal_subversion 2323
ISR @32 6
"proprietary_event"
SENDCMD @40 4 0 ogf 3f ocf 101 OGF_VENDOR_CMD OCF_GATT_INIT plen 0
ISR @47 7
"EVT_CMD_COMPLETE_CODE"
[3f,101]
status 00
SENDCMD @56 4 3 ogf 3f ocf 8a OGF_VENDOR_CMD OCF_GAP_INIT plen 3
ISR @66 13
"EVT_CMD_COMPLETE_CODE"
```

```
[3f,08a]
status 00
service_handle 0005
dev_name_char_handle 0006
appearance_char_handle 0008
SENDCMD @81 4 6 ogf 8 ocf 5 OGF_LE_CTL OCF_LE_SET_RANDOM_ADDRESS plen 6
ISR @94 7
"EVT_CMD_COMPLETE_CODE"
[08,005]
status 00
SENDCMD @103 4 13 ogf 3f ocf 106 OGF_VENDOR_CMD OCF_GATT_UPD_CHAR_VAL plen 13
ts 614d: servh 0005 charh 0006 cvo 0 cvl 7
6b 65 41 64 61
ISR @123 7
"EVT_CMD_COMPLETE_CODE"
[3f,106]
status 00
SENDCMD @132 4 26 ogf 3f ocf 86 OGF_VENDOR_CMD OCF_GAP_SET_AUTH_REQUIREMENT plen 26
ISR @165 7
"EVT_CMD_COMPLETE_CODE"
[3f,086]
status 00
SENDCMD @174 4 2 ogf 3f ocf f OGF_VENDOR_CMD OCF_HAL_SET_TX_POWER_LEVEL plen 2
ISR @183 7
"EVT_CMD_COMPLETE_CODE"
[3f,00f]
status 00
SENDCMD @192 4 19 ogf 3f ocf 102 OGF_VENDOR_CMD OCF_GATT_ADD_SERV plen 19
ISR @218 9
"EVT_CMD_COMPLETE_CODE"
[3f,102]
status 00
handle 000c
```

The analyze.rb script is also on my GitHub: https://github.com/morbos/ruby/tree/master/analyze

Just issuing a packet is not a sure thing. ST has an odd SPI retry that continuously keeps transmitting the pkt until the reply back is correct. One thing to note here on SPI communication to the BlueNRG-MS is that its transmit_receive, so we expect a reply the moment we send data. Sometimes the BlueNRG-MS will push back with a not ready code so a retransmit is required.

```ada
procedure Hal_Write_Serial (Data1    : DataBuffT;
                            Data2    : DataBuffT;
                            N_Bytes1 : UInt8;
                            N_Bytes2 : UInt8)
is
begin
   loop
      exit when 0 = BLE.BlueNRG_SPI_Write (Data1, Data2, N_Bytes1, N_Bytes2);
   end loop;
end Hal_Write_Serial;
```

3.2 HCI_Isr

To get the replies back, a routine HCI_Isr is used. This is the procedure that gets called once the EXTI line for the BlueNRG-MS device asserts. Below I attach the handler. It is a critical item for getting BLE going. When the EXTI asserts it loops whilst BLE data is ready. There is a read packet pool, its full when there are N packets ready to be allocated and empty when all packets are busy. In the case its busy, the handler just acks the interrupt but doesn't take the packet. In the other case, it takes the packet and makes some decisions about what queue to attach it to based on validity and len of the payload, if all is ok, it goes on the RxQueue otherwise, length zero or invalid, the buffer gets recycled back into the free pool. HCI_Isr also is called from a number of non-interrupt contexts. In each case, its to move along a blocking call by clearing out BLE traffic from the BlueNRG-MS. At some point in the future, I would like to revisit this software architecture and restructure it with threads. Ideally, HCI_SendReq could be linked with a thread who sleeps on a suspension object which is set when a suitable BLE packet arrives. In this way, the HCI_Isr can be just that and not a general purpose function to be called almost in a polled fashion.

```
procedure HCI_Isr
is
   use HciDataPacketT;
   HciReadPacket : ListNodePtr;
   Len           : UInt16;
   BLE           : BlueNRG_Radio   (BlueNRG_Port'Access);
begin
   Clear_External_Interrupt (EXTI_Line_5);

   while BlueNRG_DataPresent loop
      if not List_Is_Empty (HciReadPktPoolPtr) then
         List_Remove_Head (HciReadPktPoolPtr, HciReadPacket);
         Len := BLE.BlueNRG_SPI_Read_All (HciReadPacket.Elem.DataBuff);
         if Len > 0 then
            HciReadPacket.Elem.Data_Len := UInt8 (Len and 16#FF#);
            if HCI_Verify (HciReadPacket) = 0 then
               List_Insert_Tail (HciReadPktRxQueuePtr, HciReadPacket);
            else
               List_Insert_Head (HciReadPktPoolPtr, HciReadPacket);
            end if;
         else
            List_Insert_Head (HciReadPktPoolPtr, HciReadPacket);
         end if;
      else
         --  HCI Read Packet Pool is empty, wait for a free packet.
         Clear_External_Interrupt (EXTI_Line_5);
         exit;
      end if;
   end loop;
end HCI_Isr;
```

3.3 BLE setup

Intialization of the BlueNRG-MS after the revision query finishes follows. There are some messages that need to be sent to get the radio up and able to transmit with a specified power etc. Also, one main activity is the setup of the characteristics. You first need to create a server handle. Off of that server handle, you then prepare as many characteristics as your application needs. These char APIs have

UIDs that uniquely identify the service being requested or provided to the other side. For example, when ALLMEMS creates its UIDs to communicate with the iOS or Android app, there is an agreement between both sides as to what those UIDs are as they identify the functionality on that char channel. Let's take the accelometer/gyroscope/magnetometer as an example. We want to send 3D data from each sensor. Each data element is 16bits. So this means we need to send at least 18 bytes. Each characteristic over to the mobile app also prepends 2 byte timestamp in milliseconds to the packet. So 20 bytes makes for the full size.

```
--  The UUID
AccGyroMag_UUid : constant UUidT :=
  (16#00#, 16#E0#, 16#00#, 16#00#,
   16#00#, 16#01#, 16#11#, 16#e1#,
   16#ac#, 16#36#, 16#00#, 16#02#,
   16#a5#, 16#d5#, 16#c5#, 16#1b#);

--  State for the characteristic
AccGyroMagCharHandle      : UInt16;
AccGyroMagCharSize        : UInt8 := 2 + 3 * 3 * 2;


   --  Acc+Gyro+Mag declare to stack
   UUid_Copy (UUid, AccGyroMag_UUid);
   Status :=  Aci_Gatt_Add_Char
     (ServiceHandle  => HWServW2STHandle,
      CharUuidType   => UUID_TYPE_128,
      CharUuid       => UUid,
      CharValueLen   => AccGyroMagCharSize,
      CharProperties => CHAR_PROP_NOTIFY,
      SecPermissions => ATTR_PERMISSION_NONE,
      GattEvtMask    => GATT_NOTIFY_READ_REQ_AND_WAIT_FOR_APPL_RESP,
      EncryKeySize   => 16,
      IsVariable     => False,
      CharHandle     => AccGyroMagCharHandle);


   --  sending of the sensor data
   Status := Aci_Gatt_Update_Char_Value
     (ServHandle    => HWServW2STHandle,
      CharHandle    => AccGyroMagCharHandle,
      CharValOffset => 0,
      CharValueLen  => AccGyroMagCharSize,
      CharValue     => Buff);
```

So that is the declaration for just one characteristic. Fully, there are 16 characteristics declared. For our Ada port of BLE, only environmental, AccGyroMag and Battery are supported. There are others like AccEvent that use the special features of the MEMs sensors to report things like gestures etc. Also we don't handle the sensor fusion code. ST has a binary blob in ALLMEMS that is full of vector dsp code to do sensor fusion. My goal was not a perfect workalike for all these characteristics but to get a useful working subset over BLE and to demonstrate that. Using the code stack built, it will be possible to tailor all types of characteristics to host requirements. As an example, I was able to get a Raspberry Pi3 via its on board BLE stack to communicate with a SensorTile and extract the acc/gyro/mag data.

```
#! /usr/bin/python
import sys
import struct
```

```
from bluepy import btle
from bluepy.btle import UUID, Peripheral,DefaultDelegate
from bluepy.btle import Scanner

server_name = "MkAda␣S"

# 2 delegates, one for scan one for characteristic data
class ScanDelegate(DefaultDelegate):
    def __init__(self):
        DefaultDelegate.__init__(self)

class MyDelegate(DefaultDelegate):
    def __init__(self, params):
        DefaultDelegate.__init__(self)

    #func is caled on notifications
    def handleNotification(self, cHandle, data):
         print struct.unpack(’Hhhhhhhhhh’, data)

# First we scan for the server
scanner = Scanner().withDelegate(ScanDelegate())
devices = scanner.scan(1.0)

BDaddr = 0
for dev in devices:
    for (adtype, desc, value) in dev.getScanData():
        if (desc == "Complete␣Local␣Name") and (value == server_name):
            print "Scan␣finds:␣’%s’␣addr:␣%s" % (server_name,dev.addr)
            BDaddr = dev.addr

if BDaddr == 0:
    print "Not␣found!"
    exit()

# Scan was successful, now connect
dev_name_uuid = UUID(0x2A00)

print "Connecting..."
dev = btle.Peripheral(BDaddr)

ch = dev.getCharacteristics(uuid=dev_name_uuid)[0]
if (ch.supportsRead()):
        print ch.read()

dev.setDelegate( MyDelegate(dev) )

accgyromag_char_uuid = UUID("00e00000-0001-11e1-ac36-0002a5d5c51b")
sensortile_service_uuid = UUID("00000000-0001-11e1-9ab4-0002a5d5c51b")
sensortile_service=dev.getServiceByUUID(sensortile_service_uuid)

ch = sensortile_service.getCharacteristics(accgyromag_char_uuid)[0]
h=ch.getHandle()
first = 1
```

```
for descriptor in dev.getDescriptors(h):  # The handle range should be read from the services
        if first == 1 and descriptor.uuid == 0x2902:
                hccc = descriptor.handle
                first = 0

# Now tell server to send accgyromag data
dev.writeCharacteristic(hccc, struct.pack('<bb', 0x01, 0x00))

# Notification Replies (accgyromag...) are handled by the delegate up top ^^^^
while True:
    if dev.waitForNotifications(1.0):
            continue

    print "Waiting...␣Waited␣more␣than␣one␣sec␣for␣notification"


dev.disconnect()
```

When run on my RPi3 you see the results below. Observe in the data shown, Az is ~1000, this is 1000mg or 1g. The first field is the timestamp in 8ms per tick. I tipped the sensor to show changing data.

```
root@pi3:/backup/ada/STM32/L/L476/sensortile/doc# /SShare/scan.py
Scan finds: 'MkAda␣S' addr: fa:ce:fe:ed:27:24
Connecting...
MkAda S
(41530, 8, -4, 1003, -7, -30, 9, -54, -126, 6)
(41536, 7, -3, 1004, -7, -31, 9, -62, -132, -5)
(41542, 8, -5, 1004, -7, -31, 8, -54, -125, -3)
(41548, 6, -4, 1005, -7, -30, 9, -53, -126, 2)
(41555, 8, -4, 1004, -7, -31, 9, -60, -128, 6)
(41561, 7, -3, 1003, -7, -31, 9, -54, -122, 5)
(41567, 7, -3, 1003, -7, -30, 9, -51, -122, 5)
(41573, 6, -3, 1002, -7, -30, 9, -50, -123, 6)
(41580, 24, 4, 1000, -7, -30, 9, -42, -120, -3)
(41586, 50, -45, 1002, 18, 5, 1162, -63, -123, 8)
(41592, 119, 78, 1012, -183, 278, -515, -56, -113, -5)
(41598, -23, -47, 1012, -14, 123, -173, -56, -101, 2)
(41605, 45, 13, 1026, -30, 1337, -224, -53, -95, 8)
(41611, -220, -184, 777, 297, 9269, -1511, -56, 24, 56)
(41617, -596, 114, 803, 93, 4944, -261, -60, 146, 164)
(41623, -853, -7, 509, -111, 2392, 12, -56, 192, 234)
(41630, -871, -43, 351, -422, 2040, 151, -63, 216, 296)
(41636, -782, -194, -161, 395, 5200, -158, -68, 228, 404)
(41642, -1067, 123, 161, 965, 1915, 357, -62, 216, 476)
(41648, -1028, 3, 35, 422, -1960, 3, -53, 221, 452)
(41655, -992, -86, 89, 348, 244, 0, -68, 218, 423)
(41661, -1026, 61, 95, 76, 125, -19, -63, 222, 419)
(41667, -997, -25, 64, -8, -30, 10, -62, 225, 423)
(41673, -995, -25, 62, -8, -30, 9, -57, 218, 423)
(41680, -997, -25, 60, -8, -31, 9, -71, 218, 425)
...
```

So this shows we are device agnostic and are not bound to communicating only with ST BLE solutions. Lots of possibilities for sensor and data connection are possible here. Now we have Ada running the communication its really a blank slate to be filled however you like.

4 Source tree

```
sensortile
├── src
│   ├── comm
│   │   └── bt
│   │       ├── hci
│   │       │   └── controller
│   │       └── utils
│   ├── sensors
│   │   └── components
│   └── audio
├── doc
├── openocd
└── SVD
```

All the BLE related hw and sw setup is in comm and below. The sensors dir has the sensors.adx files which instantiate all the sensors in the directory. Audio is exclusively for the client board which has the PCM1774 codec + 3.5mm jack.

4.1 Two board flavors from one source tree

So an interesting question arises as to how the same source tree can support server BLE and client BLE. Given the SensorTiles are identical and only the carrier boards differ with respect to the complement of on board sensors. All carrier board sensing is done via I2C3. If you interrogate an I2C sensor and no-one is there to pick up the phone, Ada_Drivers_Library will summarily raise a Program_Error. So we can use this to find out what board we are talking to. HTS and GG point to the humidity/temp and gas gauge (battery) sensors respectively. Those two parts are only on the client. The client board has the PCM1774 codec part and no need for battery monitoring etc:

```ada
LPS22.Configure;
Acc.Configure;
Mag.Configure;
AccGyro.Configure;
begin
   HTS.Configure;
   GG.Configure;
exception
   when Program_Error =>
      Main.Set_Master;
      PCM1774.Configure;
end;
```

The beauty of that solution I feel is it captures precisely what I want between the server and the client board differences.

4.2 Ada tasking

Part of the source is a task. ST's ALLMEMS FW has an **elaborate** use of TIM1's capture and compare regs to produce timing ranges for the sensor packets. There is periodicity for each characteristic to the host, they select this via having each of the characteristics derated to the correct time they want via CC channels. There are four CC channels and they are tricky to setup and serve from interrupt context. Rather than descend down that rabbit hole I took a different way. For each characteristic you enable, it sets one timer up with the periodicity that char needs. Once the interrupt arrives on the timer, a suspension object is set that triggers a task that serves the activity. A bitvector reflects which char is active.

```
task body Main_Event
is
begin
   loop
      Suspend_Until_True (Main_Go);
      if Connected then
         if (Event_List and Environmental_Event) /= 0 then
            Update_Environmental;
         elsif (Event_List and AccGyroMag_Event) /= 0 then
            Update_AccGyroMag;
         elsif (Event_List and Battery_Event) /= 0 then
            if Is_Client then
               Update_Battery;
            end if;
         end if;
      end if;
   end loop;
end Main_Event;
```

That task is triggered by incoming Timer_4 ticks as so (Timer_2 is used for the millisecond count (prob could have dipped into the raw SYSTICK value for that but that seemed a bit too hacky even for me)).

```
   procedure IRQ_Handler is
   begin
      if Status (Timer_2, Timer_Update_Indicated) then
         if Interrupt_Enabled (Timer_2, Timer_Update_Interrupt) then
            Clear_Pending_Interrupt (Timer_2, Timer_Update_Interrupt);
            Tick := Tick + 1;
         end if;
      end if;
      if Status (Timer_4, Timer_Update_Indicated) then
         if Interrupt_Enabled (Timer_4, Timer_Update_Interrupt) then
            Clear_Pending_Interrupt (Timer_4, Timer_Update_Interrupt);
            if not Current_State (Main_Go) then
               Set_True (Main_Go);
            end if;
         end if;
      end if;
   end IRQ_Handler;
end Handler;
```

There is also another task used only by the client. Its for scanning. I have two server SensorTiles and each has a different addr. Rather than hackily continue to change the src whenever I wanted to use one or the other its possible to scan for the server. There is a call Aci_Gap_Start_General_Discovery_Proc that will begin scanning for a programmed interval. The results come in via interrupt callbacks. The task has a state machine that waits for the scan to finish and then to parse the result. If there was a match, then a connection is made. The name the client looks for is: **MkAda S** for Make with Ada Server. There is some interesting filtration in the isr callback that has to dig into the advertising results and search for an AD_TYPE_COMPLETE_LOCAL_NAME and once we see that, we check the name for the previously mentioned string. If a match was seen, the task is apprised and it then starts up the connection.

5 The demos

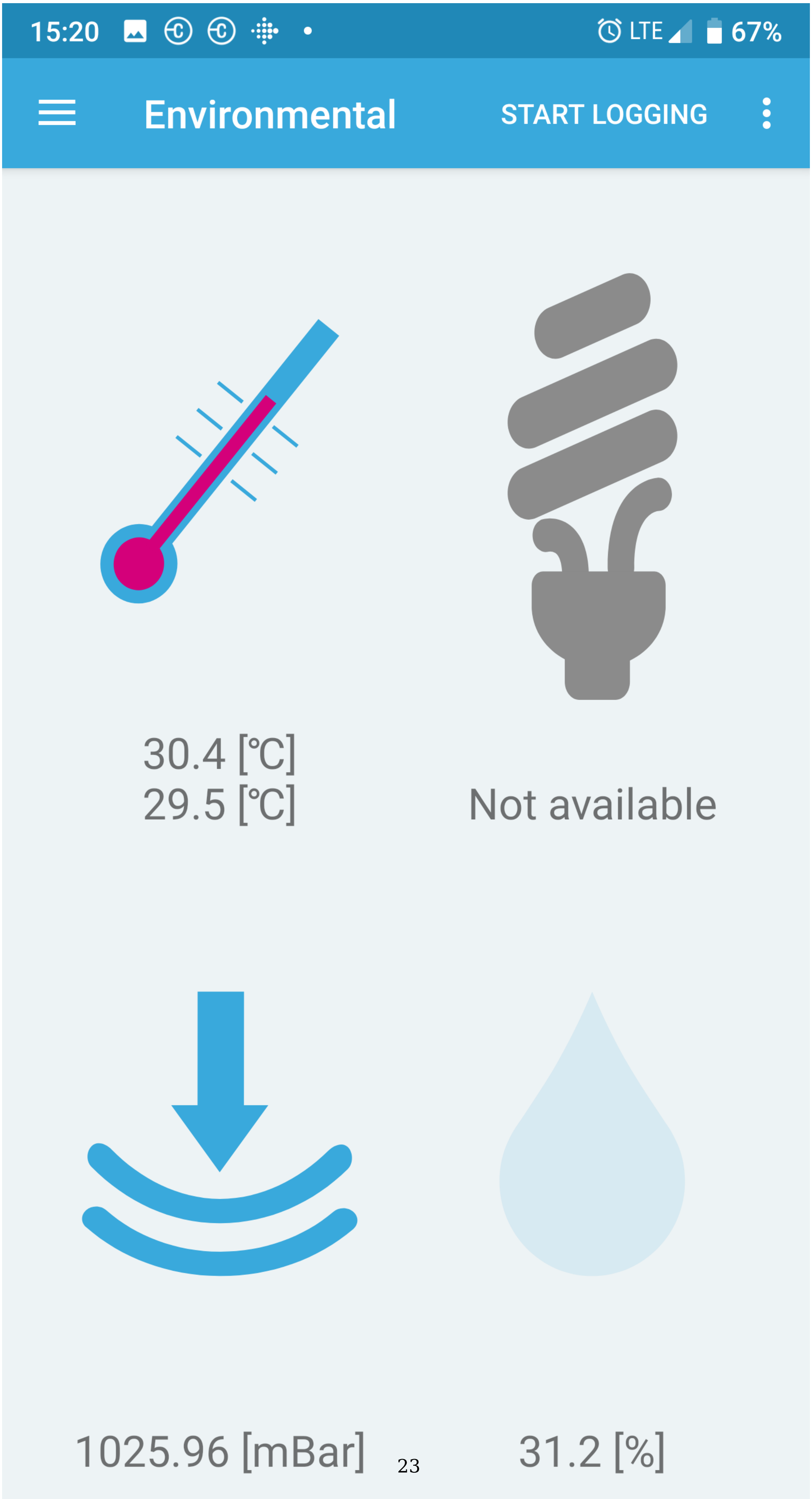
Its a bit of a challenge to demo a networking stack. A network is just one of those things that we all know needs to exist but seldom need to peer inside to see a bunch of cables or antennas 'doing their thing'. At my day job, making wifi SoCs, to demo wifi, invariably there are 4k streams being transmitted and received over wifi. At least there you see a tangible result from the smooth delivery of packets through the air. For this case, the SensorTile, I have chosen two demos.

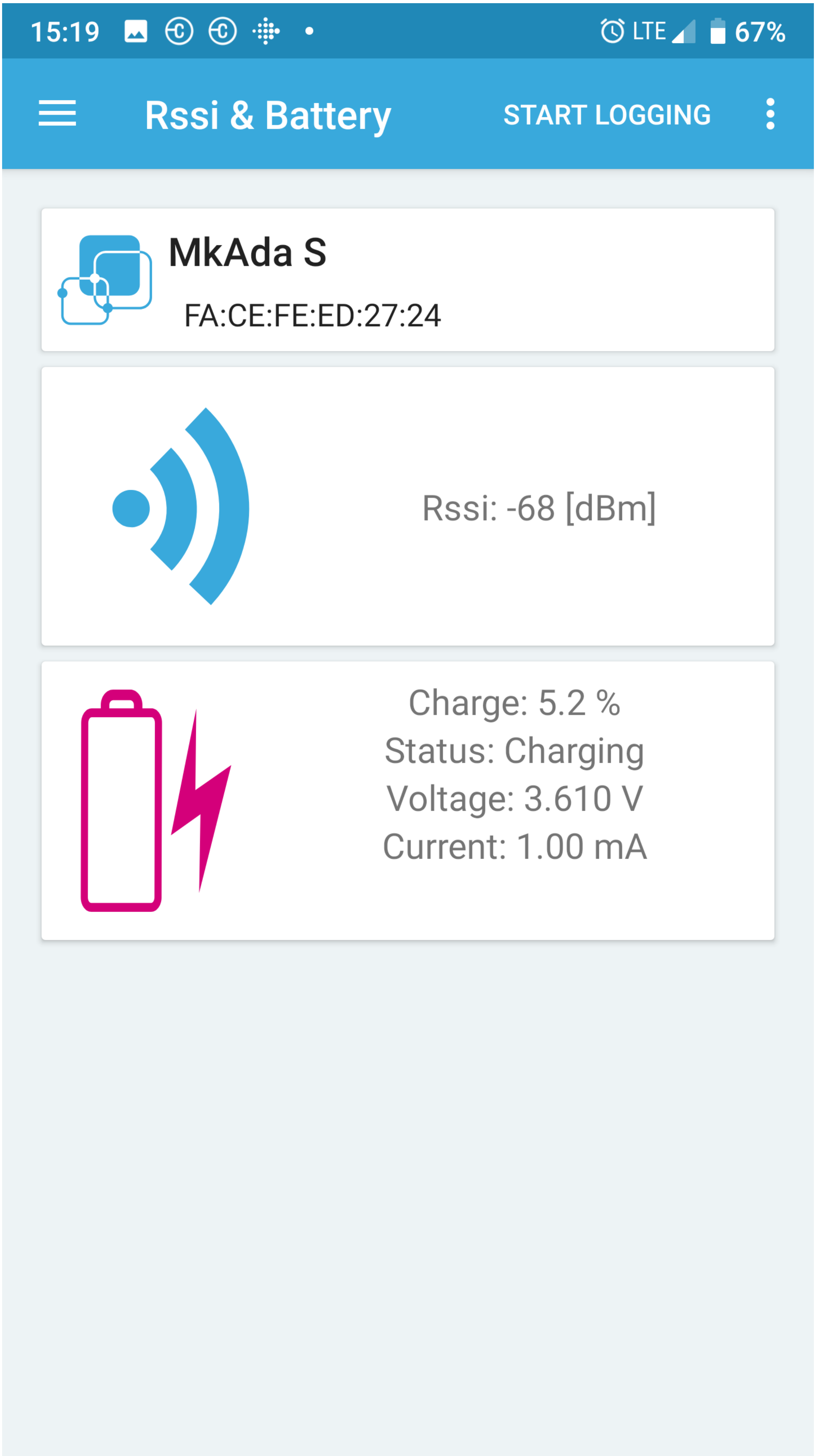
5.1 App: ST BLE

ST provides a free downloadable app 'ST BLE Sensor' for iOS and Android. This app is a one stop for ST's BLE offerings and as such has more features than we need to demo BLE connectivity. For my server SensorTile I present 3 main activities.

Activity	Description
Environment	Temp1&2, pressure, humidity
Battery	State of charge with current & voltage
MEMS	Acceleration Gyroscope & Magnetometer

Here are some screen captures of the activities via the ST BLE app on the authors phone.


15:20
LTE
67%
Environmental
START LOGGING
30.4 [℃]
29.5 [℃]
Not available
1025.96 [mBar]
31.2 [%]


15:19
LTE
67%
Rssi & Battery
START LOGGING
MkAda S
FA:CE:FE:ED:27:24
Rssi: -68 [dBm]
Charge: 5.2 %
Status: Charging
Voltage: 3.610 V
Current: 1.00 mA


15:21
LTE
67%
Plo...
PLOT LENGTH
START LOGGING
Accelerometer
Accelerometer:
Timestamp: 20763
Data: (X: -998 Y: -29 Z: 49)
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
-200.0
-400.0
-600.0
-800.0
-1000.0
-1200.0
-1400.0
-1600.0
-1800.0
-2000.0
mg
7000
7556
8111
8667
9222
9778
10333
10889
11444
120
Time (ms)
X
Y
Z

Also there is a video that shows how these activities interact with the server SensorTile.

5.2 AdaTheremin

This was a slog. First, someone told me that BLE chips could not be both a client and server. That is wrong but it conditioned my thoughts for a time. I had an idea that it would be cool if a SensorTile server could send its data to a RaspberryPi and via its 3.5mm jack, emit tones in sympathy to the motion of the users hand, all transmitted over a BLE connection. This idea sat there whilst I worked on the server and network bringup. At some point, looking at the larger cradle, I was thinking it would be great if the SensorTile there could act as a client to the server since there already is an audio dac with 3.5mm connector on the cradle. I pulled down some BlueNRG-MS demoes from ST and one of them was a client-server example. It took some work as like all things embeddded, nothing usually works right away. The trick to get it to work was the goto strategy I use for debug, log the BLE messages on client and server, filter via the Ruby analyze script and try to isolate where issues appear. Actually another very useful method is, the LED! First let me say that unlike other SoCs and associated hookups, the one on the SensorTile is obscure. Yes, like others a GPIO controls it, but to get the GPIO to work means enabling another power domain in the SoC as its normally off. Once that was out of the way, I had the client and server enable the LED when they were connected. Finally, I had them both on once the comm bugs were worked out and new functions needed for client operation were in. Unfortunately, that told me something but not everything, namely that they were connected but the server was not sending anything. Finally, I assymetrically assigned the LEDs, when connected the client would enable it but on the server, only when data was being sent. This permitted me to locate a power up sequencing issue between client and server. An LED is a valuable debugging tool, some folks nowadays even PCM them to wiggle state out optically. Just after saying this, I now have a port conflict once audio is introduced into the picture. Audio on SD_A also is on the LED pin (PG13), so if you want audio out, you lose a GPIO that controls the LED. I should mention at this stage that another relatively common occurance has happened with my experience of embedded Ada development, namely that the audio out worked almost first time. That meant, channel DMA (vs streams used in F4, F7), SAI ported over from the Ada_Drivers_Library for F7 and all the attendant RCC PLL enables for SAI1 (and routing to SAI2). Plus the PCM1774 inititialization. I expected to lose a week of debug on this to get it going. I had a good bug that has a characteristic sign (no pun intended). Namely, use of UInt16 for the samples when Integer_16 was needed:

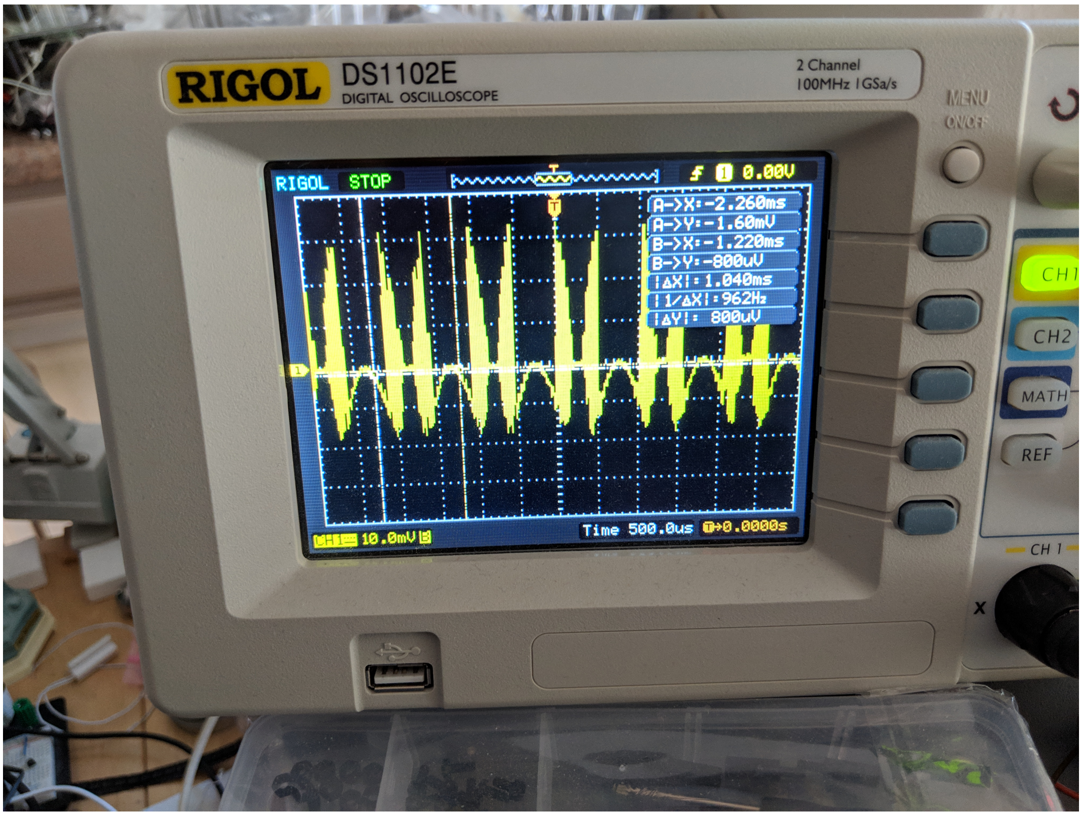


Figure 5.4: Unsigned 16 bit output when Integer was needed

5.3 Magnetic fields

To achieve the AdaTheremin, some magnet work needs to take place. The basic idea is a disc magnet from K-J Magnetics, the D83-N52, is used to emit a field wherein the SensorTile can be used to detect it and deduce its position in the field from the XYZ vector returned. Per KJ's website, here is the field:

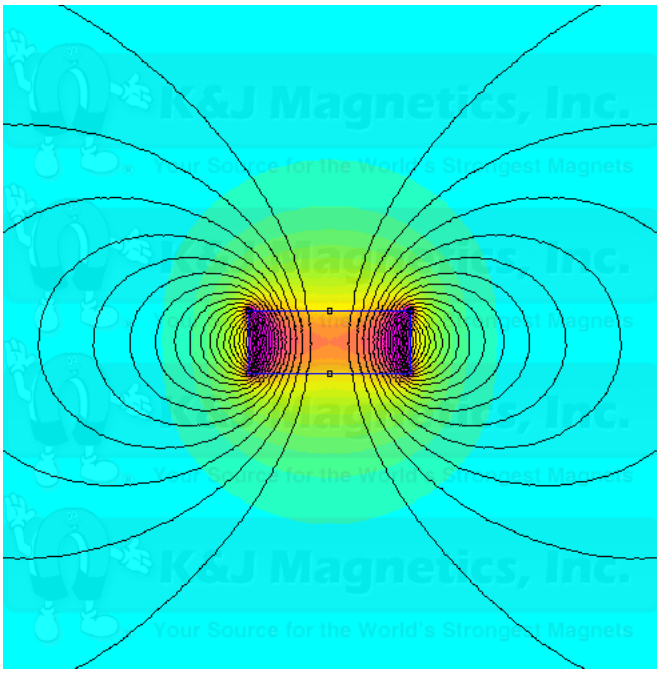


Figure 5.5: KJ Magnetics 2 dimensional field from a D83-N52 disc magnet

If you look at how a real Theremin works, there are two antennas. The tall one on the right is for pitch. As your hand approaches that antenna, the pitch rises. The flat loop antenna on the left is controlled by the left hand to control amplitude. Touching the loop produces zero amplitude going to progressively higher amplitude in proportion to the players hand distance from the loop. For the AdaTheremin a distance is computed from the magnetometer's Y axis. The force seen by the MEMs magnetometer is proportional to $1/distance^2$ so we map that force change as a pitch change. The force range change is translated to this frequency band: 100hz to 3hkz. In lieu of a left hand amplitude computation the angle of the sensor to the horizontal plane in front of the magnet is translated into the PCM1774 amplitude. If the sensor is tipped to the left the amplitude is reduced and if tipped to the right, it advances to the maximum amplitude. This angle is deduced from the Y axis accelerometer g value.

5.4 Audio generation

This was another **major** diversion. At first blush, audio is a slam dunk, a gimme. How hard could it be? Well, lets take a look at the STM32L4 and the setup of the client board:

(a) Codec chip? ✓

(b) Dedicated SoC audio circuit? ✓

(c) DMA to SAI audio circuit? ✓

So what's not to like there? If it were that you just wanted to stream an audio file out to the DAC that would work fine. But in our case, the AdaTheremin, we want adjust the freq real time, so constant buffer updates. So that should be a no brainer, just use double buffered DMA and you would be done right? Well, no, there is no double buffer support in the STM32L4 series. Uh, oh. OK, well we can try having 2 DMA's pointing at SAI Block A and just enable each one at individuallly? No, that produced no audio at all. It seems the HW does not allow any audio to pass if the DMA1&2 point at the same SAI block. (I can sort of see the logic there afterwards). Alright then. What can we do to get this promised demo done before the deadline? We can get an interrupt at the end of the DMA transfer. This interrupt however is quite nasty, regardless of how many cycles of the tone you want to ship out, its a lot of interrupts, up to 3000ps. How are we going to get BLE still being useful with its own interrupt load plus timers, systick, the Ada runtime. This is where I start to wander into the darkside. To get this to work smoothly I had to undertake some draconian measures. One, I moved the entire Ada system's interrupt priority up by one Group, from group 1 to group 2. Next, I set the DMA1 interupt priority to group 1. Also SYSTICK was at group0 and was moved up to be lower priority than DMA1. Next I crafted a C binding for the DMA1 channel 6 IRQ handler that went into an Ada procedure to handle the IRQ, rather than go through __gnat_irq_trap (the default landing spot for all IRQs since normally you want the Ada runtime to help manage your IRQ. In this case, I absolutely don't want the IRQ wandering off into the Ada runtime. Time is too tight. The final piece was reworking the code that was liberally using PRIMASK and cpsie cpsid to change the global interrupt priority stance to use BASEPRI. With BASEPRI, interrupt nesting is possible. I have not had to use interrupt nesting since the 90's where at IIT, my Mips-X isr handler was nested 4 deep with, audio(!) as the highest priority (above video, bitstream interrupts etc). Audio is the tail that wags the dog once again as these designs (and ours earlier) have small fifo's that are prone to underrun with the slightest bubble in service latency. The SAI has an 8word FIFO and I during the development of this demo, I had many underruns until I could smooth this service out. There are still some imperfections in the audio, especially as the volume changes. Maybe a ramp to the new volume level might work better. Overall, a nightmare but I learned a great deal about CMx exception priorities and for that I am quite happy.

6 Deficiencies and Improvements

Any reasonably complex project will have some failings and some room for improvement. This one is no exeception. Let me enumerate some:

(a) Not enough Ada typing in BLE stack. Too many oversized elements. UInt8 for shorter fields etc.

(b) The Ada API to the BLE stack is no where near complete.

(c) Still some audio impurity.

(d) Startup sequencing between client and server. Could be better. Seems issue is with this client than others (i.e. ST app is fine).

7 Final thoughts

This was a fascinating project. I had never attempted to reverse engineer such a small physical target before where all the interesting stuff is on the other side of one SWD wire. Also, its now programmed fully in Ada, this gives the Ada community a good head start on the new STM32WB coming soon as I mentioned. For me, Ada has been a breath of fresh air having been a C/Asm programmer for 30+ years. After such a long time, you get tired of C's shenanigans despite having a good radar for them. Ada has forced me to code better via its strong typing and package system. Its actually quite thrilling programming in Ada as it is such a contrast from what I have become used to, there is a similar feeling of joy as when I first started programming. Probably that thrill comes from the discipline that the enviroment and language instill in the user. C can devolve rapidly into an unsupportable, unstructured mess, so one must be eternally vigilant. Ada on the other hand will not let you devolve in your development like that so straight away your foundation is rock solid. I am still an Ada toddler but I sure do like the path it offers and I certainly feel going forwards it will always be my embedded language choice.

Acknowledgement

Thanks to my long suffering wife who, as a captive audience on our walks, received potentially unwanted verbal project updates. She is an engineer but one mustn't go out of ones way to try others patience.

To AdaCore for:

(a) Literally offering **aerospace quality** tools to the community.

(b) Ada_Drivers_Library without which none of these projects can happen.

(c) Ravenscar profiles, a mix and match for your task.

(d) Their engineers who have created a calm, professional community wherein these projects can be nurtured and encouraged!

(e) Lastly to my NYU CS profs, Ed Schonberg & the late Robert Dewar. We are always learning from you.

Appendix

ST's Document UM1865 - BlueNRG-MS BluetoothÂő LE stack application command interface (ACI) may be of help to anyone carrying on this work where gaps are noted. UM1865 All the cited sensors have PDFs describing their functions. Also the microprocessor.