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FlockLab 2.0: Hardware Design

Semester Thesis

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Abstract

The FlockLab testbed is used for developing and evaluating wireless sensor network protocols. A testbed helps to reduce the effort of repeatedly deploying test networks when developing protocols for wireless sensor networks. Furthermore, such a testbed improves the reproducibility of experiments and allows to share infrastructure. As there is an interest of extending this platform with more nodes and some of the existing hardware components are not in production anymore the goal was to develop an improved platform, FlockLab 2.0. In addition to all the existing features, new features such as SWD debugging, integrated GPS time synchronization and higher precision in power tracing have been implemented while at the same time reducing the PCB size.

Contents

Chapter 1

Introduction

The development of wireless embedded systems needs means to test and evaluate protocols and applications. Testbeds take this role to provide a controlled, yet realistic distributed environment. Using an node which observes all states of the node under test, allows a precise observation while keeping the overhead on each target minimal and allowing for real-world testing. The existing FlockLab [1] aims to build such a distributed network of observer based testbeds. The observer flashes the software onto the target node, traces all outputs and saves them on a central server as shown in Figure 1.1. The communication to the target is done over input and output pins for timing critical flags and serial messages to log diagnostic information. All observers are precisely time synchronized and can be accessed over a centralized web interface. While FlockLab has served its purpose well, it can be improved. To allow for easier development debugging tools on the target are beneficial. With the rise of ultra low power micro controllers the radio communication is one of the largest contributors to energy consumption and has thus to be optimized to increase battery life. The goal of this thesis is to design a FlockLab 2.0 prototype. This prototype is assembled and tested to verify its functionality and measurement precision and to find possible improvements for the final design.

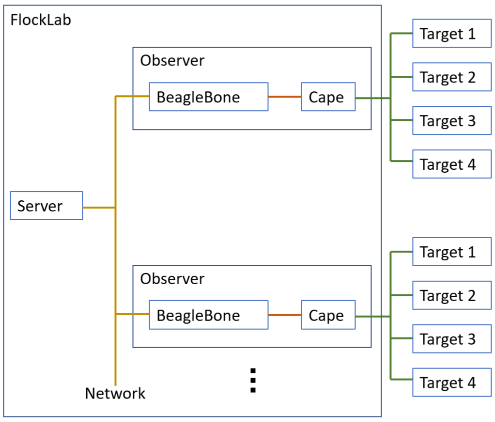

Figure 1.1: Flocklab structure

1.1 Motivation

The existing FlockLab platform is hard to replicate as some of its hardware components are depricated. New features were also asked for such as SWD-debugging which are not supported in the existing Flocklab. This would allow reprogramming of the device without a bootloader. More affordable hardware would aid a widespread adaptation of the FlockLab testbed. With a strong focus on low power networks, a very precise and high dynamic range power tracing is necessary. Ultra low power micro controllers feature low-power modes with a power consumption in the nano ampere range and up to several hundred milliamperes while communicating over a radio. Together with improved target isolation this will greatly improve the power tracing accuracy. All those points lead to a complete redesign of the hardware platform.

1.2 Related work

This section will give a short description of other popular testbeds for wireless sensor networking and compare it to the new FlockLab 2.0 design. D-cube [2] is a tool that allows to accurately measure key dependability metrics such as end-to-end delay, reliability, and power consumption. It is a low cost solution which aims to help developers to benchmark their protocols and compare them under the same conditions. D-Cube uses optocouplers as an isolation layer between target and observer for precise power measurement. It features a single GPIO which can be traced. D-cube is based on an Raspberry Pi 2 with edge-detection hardware for tracing time accurately and analog to digital converter (ADC) to sample voltage and current for power profiling. It has only one target per observer.

Indriya2 [3] is a testbed depolyed over three different floors and with possibly more than 140 nodes. The node is connected over usb and every node transmits the data per USB to a gateway and then to the network.
IoT-Lab [4] is a large scale infrastructure for wireless sensor networks with 2728 nodes and 117 mobile robots distributed at 6 sites. It allows "bare metal" access to the nodes for reprogramming. The additional control nodes allow power measurement, sensor data injection and can be used as network sniffer or inject network packets.
The current FlockLab already features one of the most precise power measurements capabilities which will even improve in the new version. It consists of 27 nodes which is comparably low. With the new hardware this number should increase. Reprogramming is done with the use of a bootloader on the target node and in case of the new FlockLab 2.0 possibly with Serial Wire Debug (SWD). It features time accurate pin actuation and tracing for 5 respective 6 pins and the possibility to connect multiple target to the same observer.

1.3 Background

This work is based on the first version of FlockLab [1] and RocketLogger [5], therefore I briefly introduce them. The existing FlockLab infrastructure at ETH Zürich is already able to measure many key metrics for low power sensor networks. It can measure current samples over a dynamic range which spans six orders of magnitude mainly from 2uA to 100mA with a shunt resistor and amplifier. Some observers are equiped with a GPS for time syncronisation, the others with a custom wireless synchronization protocol using Glossy [6]. This enables sub microsecond precision on tracing and actuation. The data capture is done on an FPGA and a Gumstix verdex pro XL6P [1] running embedded Linux handles the control and networking. Four targets can be connected but only one can be active at the same time. It features programmable target voltages from 1.8 to 3.6V. It programs targets over a serial connection which can also be used for logging data. A web-interface allows uploading of code to all targets and the resulting tracing and measurement data is saved on a central server.
The RocketLogger [5] is a measurement device to log current and voltage. It is designed for applications which use a few nanoamperes in deep sleep and up to several 100mA during radio transmission. This high dynamic range from 5nA to 500mA uses very fast and seamless range-switching to be able to capture short power spikes. The data aquisition is done with a BeagleBone [7] and an analog front-end with two ADCs for two current and four voltage channels. It has a small form factor and is usable for mobile applications.

[1] https://s3.us-west-2.amazonaws.com/media.gumstix.com/datasheets/GUM270B-XL6P.pdf

Chapter 2

Design

In the beginning of this thesis a lot of time was invested on concepts of how to improve the existing platform. Figure 2.1 shows the connections necessary on the cape to bring all the new functionalities together. The following chapters explain which concepts were considered to reach the requirements and which were finally implemented.

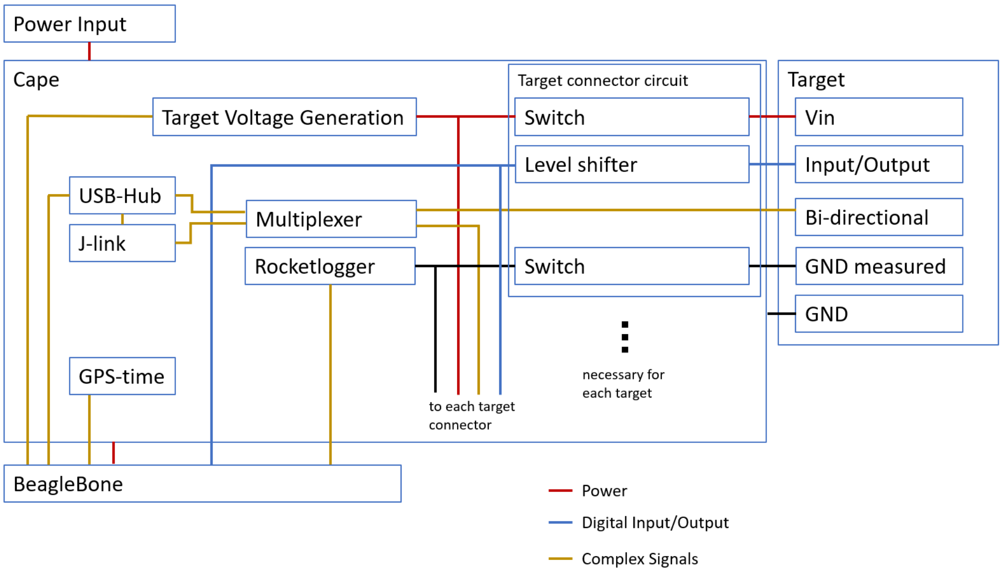

Figure 2.1: Cape Connections

2.1 Requirements

The requirements for the new FlockLab are as follows:

- The target connectors have to be compatible with existing targets.

- The current measurement should be based on the RocketLogger design and have a dynamic range from 5nA to 500mA.
- A BeagleBone Green will be used as the main computing and tracing platform.
- GPIO tracing and actuation has to be done time accurately with 10M Samples/s.
- Serial logging has to be supported.
- The new platform has to support debugging of compatible targets.
- It has to implement means for precise time synchronization such as GPS.
- Up to four targets should be able to connect to the same observer.
- The target voltage has to be controllable in a range from 1.1V to 3.6V.

2.2 Target isolation and target connector

To have a higher precision in the current measurement the target insulation has to be improved compared to the first version of FlockLab. To achieve this, the target connections are divided into three groups which can be controlled individually. Table 2.2 shows all target connections.
The first group consists of the bidirectional connections, such as SWD, SerialID and USB. Only SWD is connected to a target where the current is measured, but as it is a bidirectional high speed connection it is hard to improve the isolation over a direct connection. Also while using SWD certain functions of the processor might be active and consuming additional power and are otherwise powered off. Thus no isolation was used but those connections can be put in an high impedance state where they do not influence the measurement.
The second group are the actuation signals coming from the BeagleBone and goint to the target. Those include the serial RX and the Sig1 and Sig2 signals. As some ultra low power MCUs can be powered trough a single IO which is pulled high from an external source those connections will unavoidably influence the current measurement. To keep the measurement accurate, signals from this group can be switched to a high impedance state where they can not be used anymore but do not influence the measurement.
The last group are the tracing signals from the target to the BeagleBone. Those include Serial TX and the GPIOs to be traced. The power for those signals comes from the target and the current drawn from those connections will reduce the measured current. It is important to keep the steady state input bias current as low as possible. Operational amplifier with no feedback circuit or comparators could be used as a buffer for the signal and achieve a input bias under 1 nA.

pin	name	direction	group	active when	special
1	VCC_3.3V_SW	to target	power	selected	
2	VCC_5V_SW	to target	power	selected	
3	VCC_Target	to target	power	pwr enabled	replaced VCC_sensed
4	VCC_Target	to target	power	pwr enabled	
5	RXD	to target	actuation	act enabled	level shifting
6	TXD	to BeagleBone	tracing	selected	level shifting
7	SIG1	to target	actuation	act enabled	level shifting
8	INT1	to BeagleBone	tracing	selected	level shifting
9	SIG2	to target	actuation	act enabled	level shifting
10	INT2	to BeagleBone	tracing	selected	level shifting
11	PROG	to target	actuation	act enabled	level shifting
12	nRST	to target	actuation	act enabled	level shifting
13	LED1	to BeagleBone	tracing	selected	level shifting
14	USB_P	bidirectional	signal	mux enabled	
15	LED2	to BeagleBone	tracing	selected	level shifting
16	USB_N	bidirectional	signal	mux enabled	
17	LED3	to BeagleBone	tracing	selected	level shifting
18	Serial ID	bidirectional	signal	mux enabled	
19	SWDIO	bidirectional	signal	mux enabled	replaced CTS
20	SWO	to target	signal	mux enabled	replaced RTS
21	SWDCLK	to target	signal	mux enabled	replaced power 3.3
22	Not Connected	-	-	-	replaced interface 3.3
23	GND sensed	to RocketLogger	power	selected	replaced GND
24	GND	GND	power	always	replaced interface

Table 2.1: Target Connector pinout.
pwr: power, act: actuation, mux: multiplexing

The target connector was kept mostly the same as before, unused connections were used for the SWD debugging and new power tracing. Because of the change of high side to low side current measurement the previous GND is now being measured to keep compatibility. An additional GND which is not measured has been added.

2.3 Level shifting

Because Flocklab 2.0 supports different target voltages, all signal lines connected to the target need to be in the target voltage range. This level shifting is done differently for each signal type. Bidirectional signals do not need level shifting as they are independent of the target voltage except for the SWD connections.

Those SWD connections go trough a separate bi-directional high-speed level shifter (TXS0104EPWR).
The actuation signals need level shifting because higher voltage levels than the target voltage would damage the target. At the same time a high impedance state is required for turning off the connection and thus a dual supply, tri-state level shifter is used. The voltage levels of the tracing signals are proportional to the target voltage. To ensure that the BeagleBone captures an high state signal from an target running at 1.1V the signal has to be amplified to 3.3V.

2.4 Signal routing

To support four targets, all signals need to be routed to the target under test. This can also be divided into three parts depending on the signal type.
Bidirectional signals will be routed over a 4-way analog multiplexer to create a direct connection.
Actuation signals are in the existing FlockLab routed over a level shifter with tri-state output. In order to actuate only the selected target, all other level shifters will be put into high impedance mode. All level shifters are connected over a shared bus to the BeagleBone.
Tracing signals use an 4-way or-gate in case operational-amplifiers or comparators are used. By setting the compare value to VCC the output is fixed in a low state and only the currently selected target can set the output to a high state. In case the same level shifter is used as for the actuation signals, they can also be connected over a shared bus and set into high impedance mode if not selected.

2.5 Current measurement

Current measurement is done by including parts of the RocketLogger[5] into the FlockLab 2.0 design. It is already running on the BeagleBone platform and has an current measurement accuracy down to 5nA. The RocketLogger has four voltage channels and two current channels split among two ADCs. Because only one current channel is used, only one of the two ADCs is necessary. The digital tracing circuit is also not used because the tracing is directly done by the BeagleBone to achieve a sampling rate of 10M samples/s. The two remaining voltage channels will be used to measure the voltage over the target. Because the RocketLogger amplifies very small voltage spikes and interference it has to be shielded from the disturbances. High-speed signals such as USB should be as far away as possible and no power for other components should flow trough the analog front-end of the RocketLogger. Thus the ground planes are split around the RocketLogger and only the unfiltered 5V supply is shared between RocketLogger and the remaining circuit.

2.5.1 Measurement setup

Because the RocketLogger measures the current flowing into the common ground, the current measurement can not be done with a high side measurement directly like it was done on the previous version of Flocklab. Different measurement scenarios were looked at.

High side measurement, galvanic isolation between RocketLogger and BeagleBone, Figure: 2.2

+ backwards compatibility
+ no change on the RocketLogger analog front end
- isolating dc/dc converter needed
- splitting of power and ground of the RocketLogger from the BeagleBone
- one directional data signals between RocketLogger and BeagleBone have to be isolated

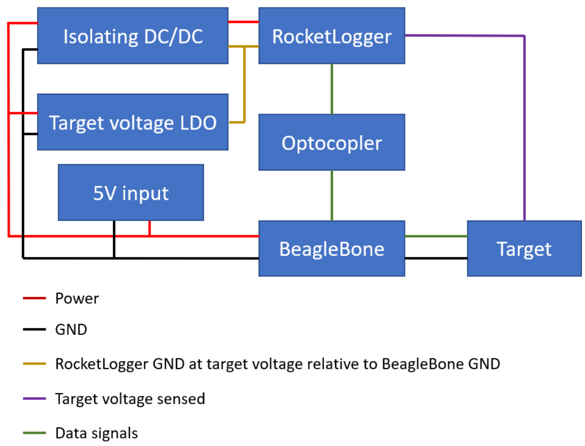

Figure 2.2: High side measurement, galvanic isolation between RocketLogger and BeagleBone

Low side measurement, Figure 2.3

+ no change at all on the RocketLogger
- actuation signals can become negative
- two different grounds at the target, if the target uses components where the power consumption should not be measured they have to be connected to a different ground.

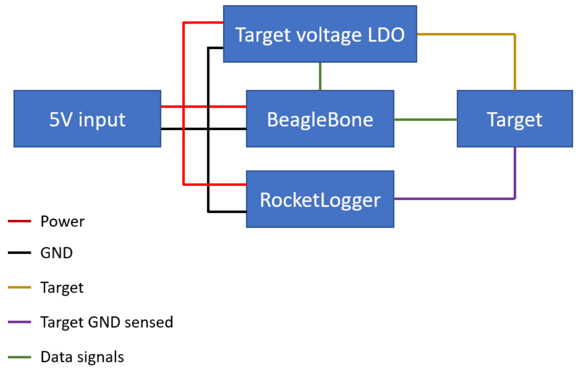

Figure 2.3: Low Side measurement

High side, isolating Target GND and Beaglebone GND, Figure 2.4

+ backwards compatibility
+ no change at all on the RocketLogger
- inverting dc/dc converter needed
- splitting of target ground and Beaglebone ground
- bi-directional high speed signals have to be isolated

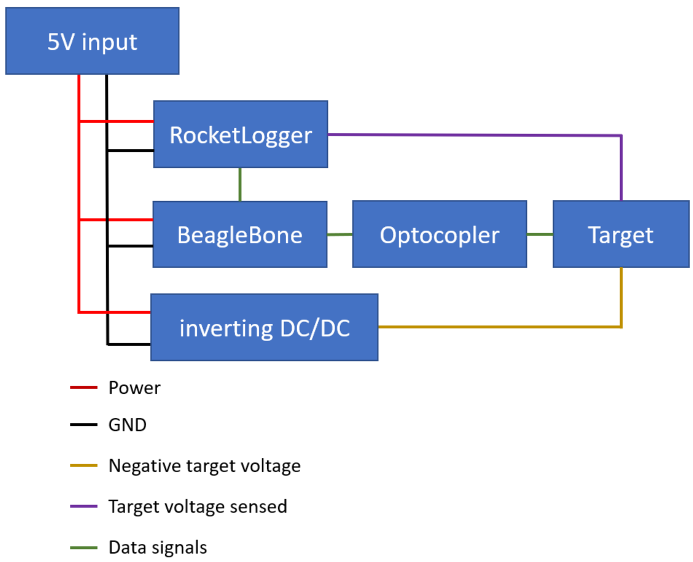

Figure 2.4: High side, isolating Target GND and Beaglebone GND

The decision was made for the low side measurement because none of the existing targets would be affected by the ground measurement. Also no signal isolation and no isolating or inverting dc/dc converters are needed. The voltage drop across the shunt resistor is at most -50mV in static state and most microcontroller support negative GPIO voltages as low as -300mV.

2.5.2 Calibration

The existing RocketLogger calibration procedure should stay the same and thus all channels have to be accessible for calibration. For this reason two connectors for the voltage channels were implemented. The current measurement is done over one of the target connectors. The additional resistance of this path does not affect the measurement as the current is directly regulated by a Source Meter [8]. The target connector where the measurement is done has to be activated so that the power switches are turned on. After calibration the voltage channels can be connected to the hi- and low-side of the target via solder bridges

2.6 Power supply

The FlockLab 2.0 has 10 different voltage levels which need to be supplied. The RocketLogger alone can use up to 1.5A current at 5V. With all the additional hardware and target power supply a direct power input is used to power the observer. The target can use a maximum of 1120mA (500mA V_{Target}, 500mA 5V, 120mA 3.3V) and both USB Ports can each source 500mA. A switching DC/DC converter is used for an output current of 3.5A at 5V. The converter can take any voltage from 6.5V up to 36V which can be applied by a standard barrel connector. The total current draw with everything at the highest current consumption is mor than 3.5A. In this case the converter has an internal over-current protection and shuts off. All external voltages have resettable fuses for short circuit and over-current protection.

name	current
3.3V Target	120mA
5V Target	500mA
V_Target	500mA
USB Port 1	500mA
USB Port 2	500mA
BeagleBone	1500mA
Total	3620mA

Table 2.2: Power Distribution

2.7 Target voltage

To support different microcontroller and also to simulate energy-harvesting to some extent, selectable target voltage is necessary. A low noise low-dropout regulator (LDO) is used with an resistor programmable voltage range of 0.8V to 5V. Using a digital to analog converter (DAC) connected to the feedback resistors, the LDO can be steered to produce any value in between. The resistors can be selected such that the upper bound is exactly 3.6V and the lower bound 1.1V such that no software error can destroy the target. The selected DAC sets the range to half of the maximum on power up which is assumed save for all targets. To make sure the right voltage is produced it can be measured by the RocketLogger prior to turning on the power to the target.

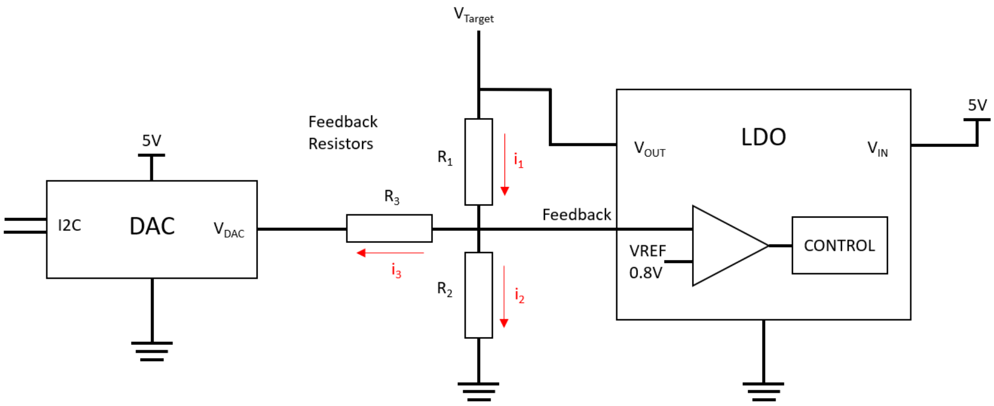

Figure 2.5: voltage controlled LDO.

Calculations

Using a DAC to control the output voltage by an DC/DC converter was described by Maxim [9]. This can be adapted for the setup in Figure 2.5 and the resulting voltages can be calculated as follows:

$$V_{OUT} = V_{REF} + i_1 \cdot R_1 \tag{2.1}$$

$$i_1 = i_2 + i_3 \tag{2.2}$$

$$i_2 = V_{REF}/R_2 \tag{2.3}$$

$$i_3 = \frac{V_{REF} - V_{DAC}}{R_3} \tag{2.4}$$

After substituting Equations 2.2 through 2.4 into Equation 2.1, the higher and lower limits can be specified.

$$V_{OUT(LOW)} = V_{REF}\left(1 + \frac{R_1}{R_2}\right) + \left(V_{REF} - V_{DAC(HIGH)}\right)\frac{R_1}{R_3} \quad (2.5)$$

$$V_{OUT(HIGH)} = V_{REF}\left(1 + \frac{R_1}{R_2}\right) + \left(V_{REF} - V_{DAC(LOW)}\right)\frac{R_1}{R_3} \quad (2.6)$$

Those two equations define the relation between the resistors.
Because there are only two equations and three unknowns they can be selected such that the values meet the requirements of the LDO (TPS7A9001DSKR) for the best performance. See Equation 2.7.

$$\frac{V_{REF}}{R2} > 5\mu A \quad (2.7)$$

V_{REF} is defined by the LDO which is 0.8V in our case.
The selected voltage range from 1.1V to 3.6V is defined by the following resistor values: $R_1 = 25.5k, R_2 = 10k, R_3 = 25.5k$
Because not all resistor values are available in the 1% class the range is only an approximation. This leads to a voltage range from 1.1V to 3.64V. The equation for the target voltage becomes:

$$V_{Target} = 2.84 + (0.8 - V_{DAC}) \quad (2.8)$$

The DAC has a resolution of 8bit which leads to a voltage step of 9mV.

2.8 Serial wire debugging

Debugging will be done using the J-Link on board (OB) [10] as it allows a direct integration on the PCB and is essentially the same hardware as the J-Link EDU mini [11]. The three signal lanes which are used for debugging are routed through a bidirectional level shifter and then through a multiplexer. This allows multiple target voltages as the J-Link OB only works with 3.3V and also allows to connect the debugger to different targets.
The debugger features a network client mode where it exposes the standard interface on the network. This is included in the J-link software. [12]

2.9 Data capture

The BeagleBone has different ways to access the GPIOs. By using the one chip peripheral (OCP) every pin on the BeagleBone can be accessed but this interface is shared with other parts of the system and thus there can be some jitter in the read or write time. There is also an enhanced GPIO module which is directly connected to one of the PRUs as visible in Figure 2.6. They connect some pins directly to the PRU registers and can be accessed in just one clock cycle. The

register R31 is used to read the pins and R30 to write them. Each PRU has different pins connected to those registers. The pins were selected in a manner that all timing critical pins of the RocketLogger are directly connected to PRU0 and all signals used for target tracing and actuation are connected to PRU1. Synchronisation of RocketLogger measurements with target tracing is done over the ADC data ready signal which is routed to both PRUs and can be traced on PRU1 simultaneously to the target signals.
The GPS time-sync signal is routed to the PRU1 as well as to timer four to allow for synchronization of the internal clock.

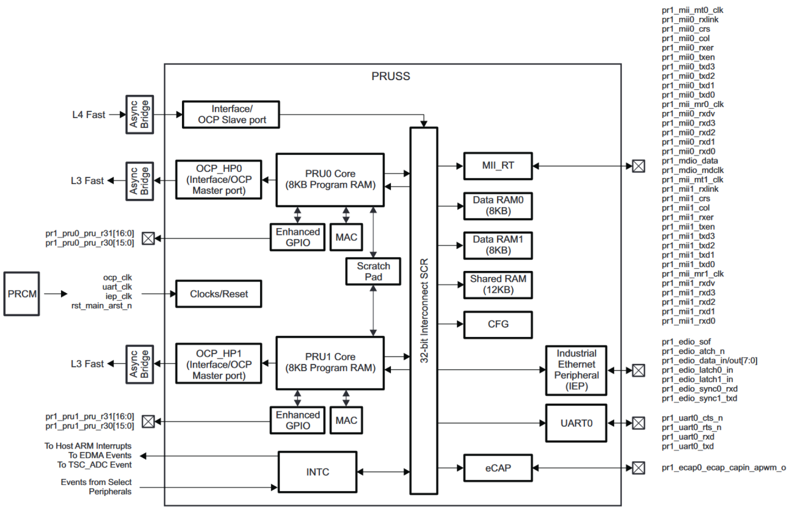

Figure 2.6: PRUSS Integration. Source: [13]

2.10 Modularity

To allow the highest functionality but also to offer a cheaper solution, the FlockLab 2.0 hardware is built with two versions in mind. The high functionality version, Figure 2.7, allows the connection of four targets and the usage of a GPS module for time-sync and SWD debugging. Two target connectors use the length of the BeagleBone and the two additional ones just extend further outside but can be omitted if not needed as shown in Figure 2.8. Also GPS has a connector for an external active antenna but if it is not needed, it does not have to be assembled. The time-sync pin is broken out so any other time source can be used. Another option is to rely on network time synchronization via NTP or PTP only. Similarly, the J-Link OB debugger does not have to be assembled, the FlockLab 2.0 features a standard 10-pin JTAG header for connecting any debugger.
The FlockLab 2.0 also features two extra USB 2.0 ports in case additional hard-

ware needs to be connected.

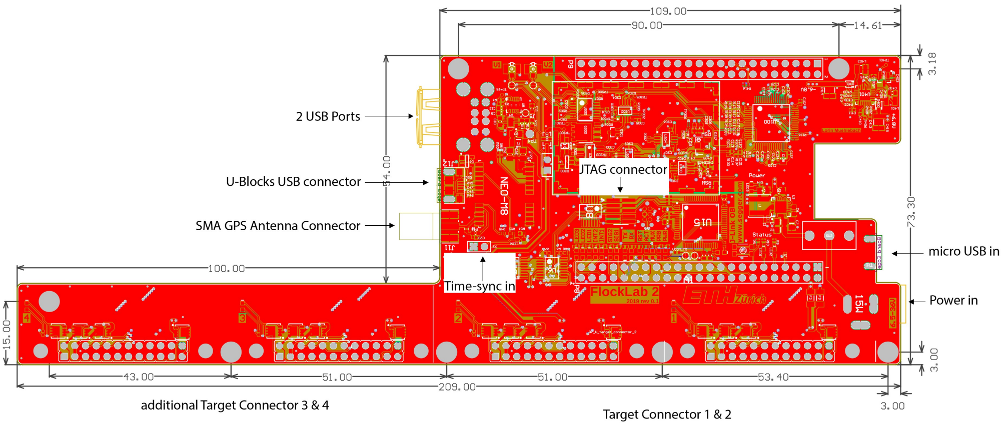

Figure 2.7: The full version with markings for external connectors.

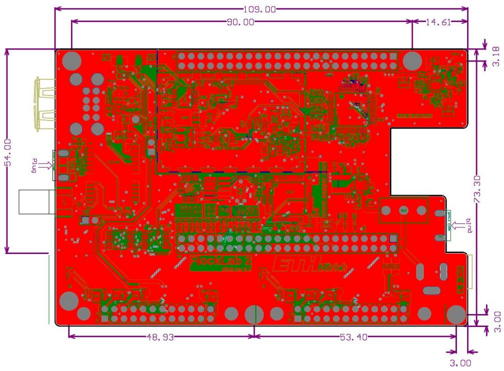

Figure 2.8: The smaller version with just two target connectors.

2.11 Testing of components

Because of the high accuracy in current measurement and the high data-rate on some signals it had to be verified that the proposed solutions actually work before the design is started. The core components which had to be tested were:

- Multiplexing of SWD signals
- Current measurement setup
- Target power switching
- Target tracing speed and influence on current measurement

2.11.1 Measurement setup

The selected power switches were tested in a setup visible in Figure 2.9. The signal block was changed between comparator, operational amplifier, multiplexer and level shifter. For the multiplexer, comparators and level shifter the input current was also separately measured with a Keithley 2450 SourceMeter. Active input bias current and the current flow in the disabled states were measured. In those measurements the low side switch is not connected because it was only implemented afterwards.

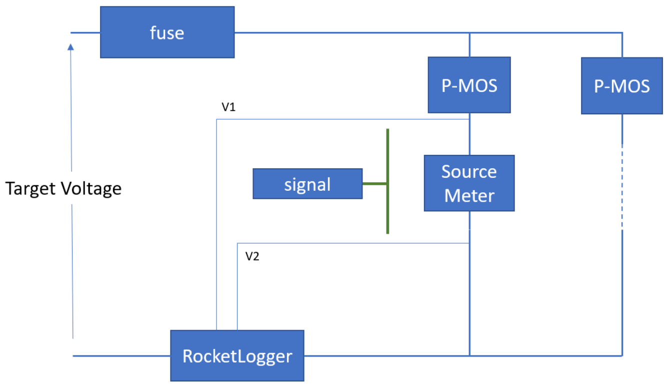

Figure 2.9: Measurement Setup

The devices under test were:

- Analog multiplexer: 74CB3Q3253PWJ
- Fuse: 0ZCG0030FF2C
- High side switch: SI7615CDN-T1-GE3
- Low side switch: CSD17579Q5A
- Level shifter: SN74AXCH8T245PWR
- Operation amplifier: ADA4891-4ARZ-R7
- Comparator: TC75W57FU,LF

2.11.2 Results

Multiplexing of the target signals worked at the highest speed settings. Only for USB high speed, which sends signals at 480 Mbps, a special multiplexing chip is necessary. When the multiplexer was disabled all inputs and outputs where high impedance and no measurable current would flow through them with an input

voltage of 3.3V.
The power switching also worked but introduced additional resistances in the current path. Those where up to 1 but are due to resistances in the cable and breadboard. In case of a low target voltage, less than 1V, the resistance in the high-side P-MOS got large or it turned off. This is due to the low gate voltage as it is 0V minus target-voltage. Because such low target voltages (<1V) are not required the circuit was kept the same, otherwise the p-mosfet could be driven with a negative voltage to increase the gate voltage. Figure 2.10 shows the relative measurement error at different current ratings. The setup was first measured directly without the fuse, P-MOS and the parallel path for additional targets. Figure 2.9 shows the setup with the switches and parallel target.
An additional low side N-MOS will be in the final design to make sure no leakage current from any other target influences the measurement. This N-MOS will is optimized for low $R_{ds}on$

$$\text{Relative Error} = \frac{\text{Current}_{SourceMeter} - \text{Current}_{RocketLogger}}{\text{Current}_{SourceMeter}} \tag{2.9}$$

The comparator has a input bias current of $< 1nA$ but it has changing propagation delays from 40ns to 160ns and could not keep up at 10MHz switching speed. The operational amplifier also uses less than 1nA but could keep up with high frequencies with a propagation delay of 20ns. The testing of the high frequency response is done on a breadboard and thus has a lot of oscillations in the measurement. Those oscillation would reduce on the actual PCB.

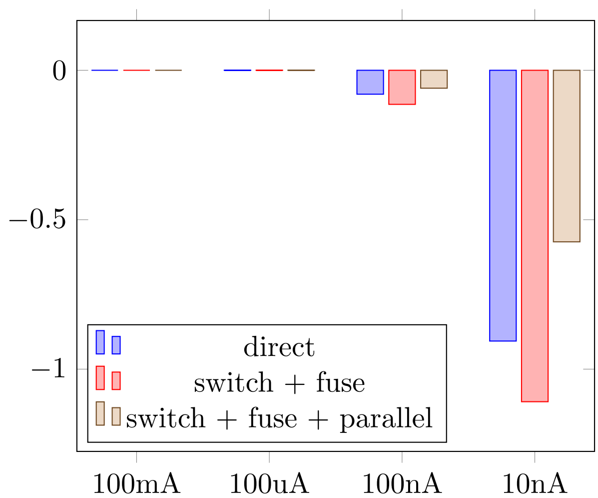

Figure 2.10: relative measurement error

The selected level shifter (SN74AXCH8T245PWR) did not have the expected high impedance output instead it just disconnected the input signal from the output but kept sourcing the high/low side of the target. This behaviour is unsuitable for the FlockLab and the level shifter (FXL4245MPX) of the existing

FlockLab was tested again. This one had a proper high impedance output and out of interest the input-bias current was measured. It was below 1nA in steady state and thus acceptable even for target tracing without disturbing the current measurement. With a 10MHz squarewave signal the propagation delay was just 10ns which was consistently the same. The decision was made to use this level shifter in the same manner as in the existing FlockLab because no improvements with operational amplifiers or comparators could be made.

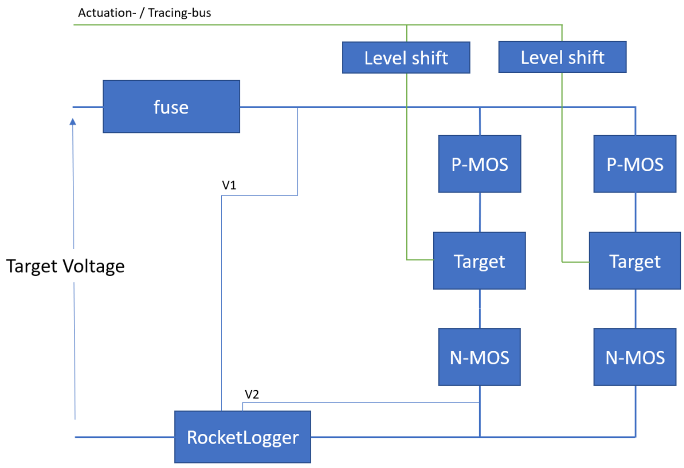

Figure 2.11: FlockLab 2.0 target power connection

Chapter 3

Implementation

The results from the concept and testing phase were implemented in a new PCB design in Altium Nexus 2.

3.0.1 Schematic

The schema is divided into nine main sheets to have a better functionality overview. The "cape" is the central connector to the BeagleBone and shows the pin-out as well as user controllable LEDs and a button. The RocketLogger page is the top page of all five sheets adapted from the RocketLogger with a removed second current channel as well as no digital tracing and EEPROM. "Power" contains the DC input and target voltage generation. As the name suggests "target signal splitting" splits all signals which are routed individually to each target. "Target connector" contains all components which are necessary for each target such as the power switches and level shifter. This sheet is the same for all four target connectors. The "USB hub" contains the micro USB-in, protection diodes as well as the 4-port USB hub controller and accessories. USB-in has to be connected by an external USB cable from the BeagleBone to the cape as no USB connection is on the GPIO headers. The "J-link debugger" contains the MK22FN128VLH10 which is programmed over the Segger needle adapter with the J-link OB firmware. The standard 10pin JTAG connector is also on this sheet. "GPS" contains the NEO-M8 module as well as the drive circuit for the active antenna and an external USB-port which is not connected to the internal USB hub. This USB port is only used for updating the firmware. The last page, "indicator", just contains all indicator LEDs for the current target control as well as actuation and tracing. Signals which belong together are routed in a "Harness" such that for example all tracing signals can be kept together but the signal name and not just a bus number is kept, unlike with a bus connection.

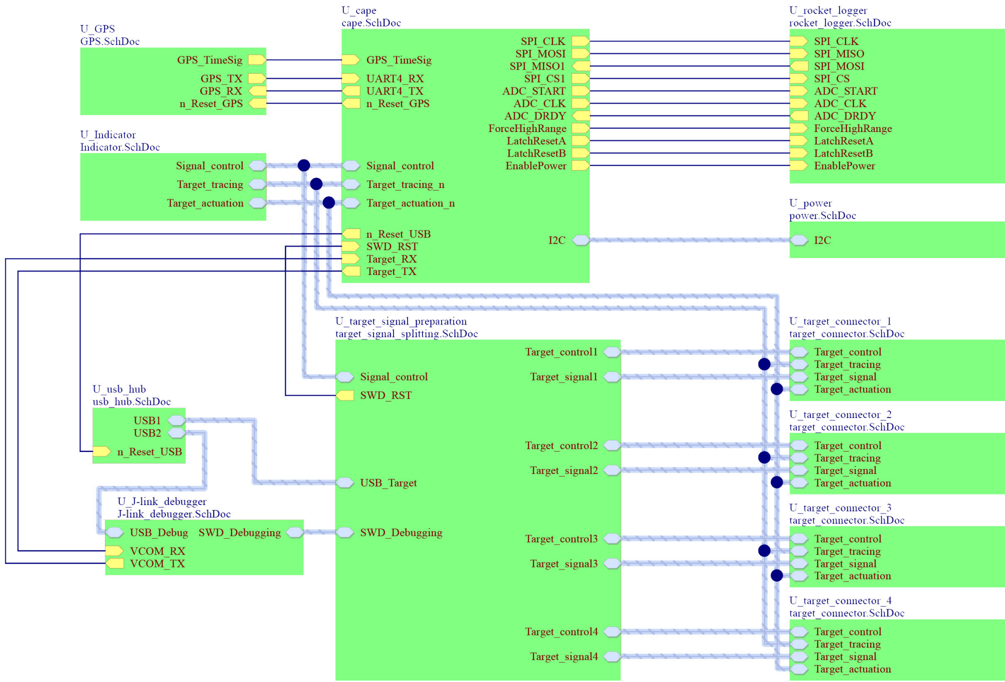

Figure 3.1: FlockLab 2.0 Schema Overview

3.0.2 PCB

The key aspects while designing the PCB was to incorporate the existing RocketLogger, keep interference as small as possible and also to reduce the size of the board.
RocketLogger circuit was kept as close as possible to the existing design to have a tested and trusted design. Channel two was left on the board at the same place as before with only a few component and trace movements to fit it under the new, smaller EMI shield. One of the precision LDOs and range switching was moved under the ADC where previously the tracing circuit of the RocketLogger was. The ground of the RocketLogger is divided by a gap under the Shield so that spikes in the current consumption of other parts of the board do not get amplified. Also no other signal lines where routed trough the analog part of the RocketLogger and USB lines were kept away as far as possible. To keep the measurements precise, guard-traces were routed for the voltage lines and the current line insulated with ground traces. Because the RocketLogger uses 6 layers the new FlockLab design uses a 6 layer design as well. All digital switching is preferably positioned on the bottom and all analog parts on top.
The power distribution is directly under the power switches as a bus connected to each target. Also all tracing and actuation signals are routed as a bus to all targets. Target number four could thus experience higher signal deformation as

it has the longest trace. The bi-directional signals are routed one layer above except for target USB which is even one layer higher. The USB hub is placed in the center and close to the debugger and multiplexer such that not many long USB signal lines are routed trough the PCB. Additional connections such as GPS-antenna and USB ports are on the left side with the cut out such that it can be fitted better into an enclosure. The two USB connectors had to be moved upwards to keep the SD-card of the BeagleBone accessible. Because of place constraints there could not be a connector for the serial interface of the BeagleBone (UART0) on the FlockLab. This UART would be used in case SSH over network is not working. The BeagleBone provides Ethernet via USB which can be used to debug issues without network access. Figure 3.2 gives an insight into the final PCB design.

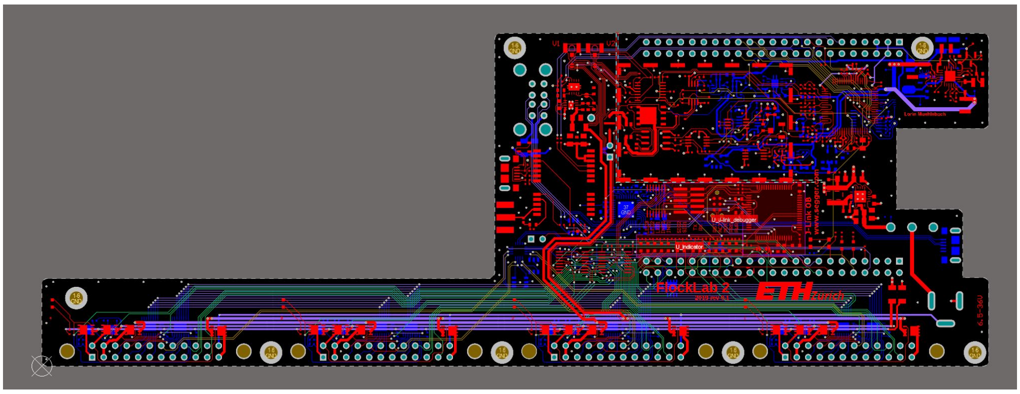

Figure 3.2: FlockLab 2.0 PCB

Chapter 4

Testing of implementation

4.1 Assembly

The assembly by hand was difficult because of the tight component placing and components down to a package size of 0402. The solder stencil helped a lot so that not all pads had to be filled with solder individually. For the prototype more than 400 components had to be assembled by hand. Figure 4.1 shows the prototype connected to a BeagleBone running the standard RocketLogger software. Because the pinout has changed the connection had to be made by jumper cables.

In the design PowerPack N-MOS (SISA72DN-T-GE3) have the wrong footprint as well as the level shifter. Both footprints are mirrored which made it impossible to assemble. For the top side n-mosfets, which switch the sensed ground, the footprint was modified by hand on target one and four to allow testing under real conditions.
Level shifting was tested by using an external PCB with the correct pin-out of the level shifter which was then manually connected to one tracing and one actuation line of target four possible to see on the left of Figure 4.1.
The DC/DC step down converter for the input was not available and thus was not assembled. The board is powered directly trough the 5V pins. One of the operational amplifiers, U304 (AD8421ARMZ), for the RocketLogger was not available and was replaced by AD8421TRMZ which has the same pin-out and is acceptably similar.

4.2 Power

The target power generation was in the beginning only able to produce voltages upwards from 2.6V. This was on one side due to a short in target two and three. Target two is fixed but target connector three still can not be used with target power enabled. The second error was that the ADC was supposed to produce

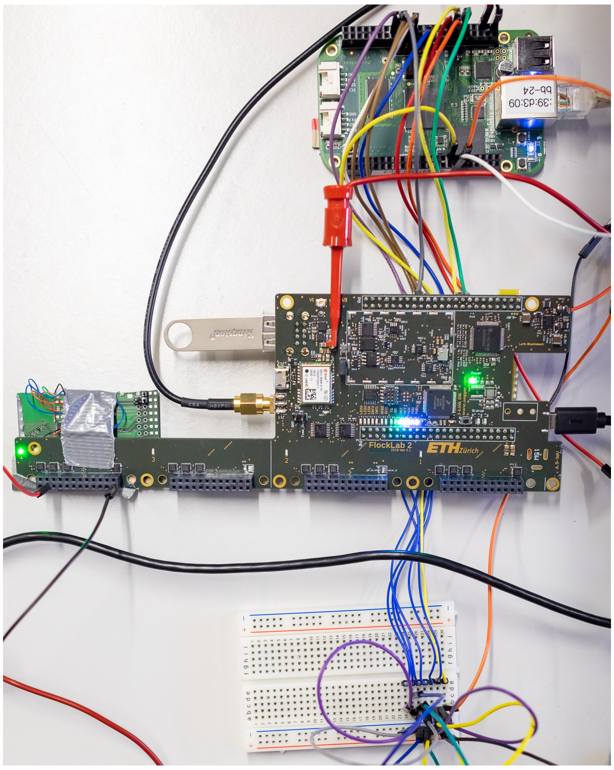

Figure 4.1: Fully assembled and working prototype.
top: BeagleBone, middle: FlockLab 2.0, bottom: control breadboard.

values in the range from 0V to 2.54V and is inversely proportional to the target voltage. If the target voltage is below the ADC voltage a current would flow from the ADC over the resistors to the LDO. The LDO has no means to control this current resulting in a higher output voltage. The DAC has different amplification settings and with a gain of one instead of two the highest voltage would be 1.227V. The resistor values were changed again so that the highest necessary DAC voltage at 1V is still below the lowest target voltage. Because the resistors which were chosen had to be available in the laboratory (R_1 = 10k, R_2 = 10k, R_3 = 3.4k) the range was now 1V to 3.9V. By changing R_3 to 4.02k the range would be exactly 1.1V to 3.6V resulting in the following relationship:

$$V_{Target} = 1.6 + (0.8 - V_{DAC}) \cdot 2.48 \tag{4.1}$$

Because not the full range of the DAC is used, only from 0-1V, the voltage step increased to 12mV which is still acceptable.
Because of an error in testing, the 3.3V and 5V supplies were switched and all chips on the 3.3V potentially damaged. The debugging MCU, USB hub and the U-Blox module were replaced afterwards. The ADC was also connected to the 3.3V line but appeared to be working. For the later tests a power board was

built to prevent further errors. A dedicated LDO for 3.3V could or a protection diode could be included to prevent this error.
The idle current draw on the 3.3V rail is 60mA but can rise to up to 130mA with high-speed data transfer through the USB hub. The remaining 120mA can be used for the Target 3.3V and the total stays below the avaiable 250mA. If it was exceeded the BeagleBone would be damaged as it supplies the 3.3V.

4.3 Signal

4.3.1 Actuation and tracing

Tracing and actuation have to produce good flanks for up to 10Mhz. It was tested on target connector four because it has the longest traces and thus all other connectors are expected to yield better results. Both directions were tested at 1, 5 and 10Mhz. The scope was a Tectonix MSB4104B and for signal generation a HP 33120A was used. The flanks were even improved by the level shifter. All measurements were done at 1Mhz, 5Mhz and 10Mhz with Square wave input, displayed in Figure 4.2 and 4.3. The propagation delay is negligable at 10nS. The oscillations at the flanks have a frequency of 23.3 Mhz and are coming from the measurement setup as they were still visible with the probes directly connected to the function generator.

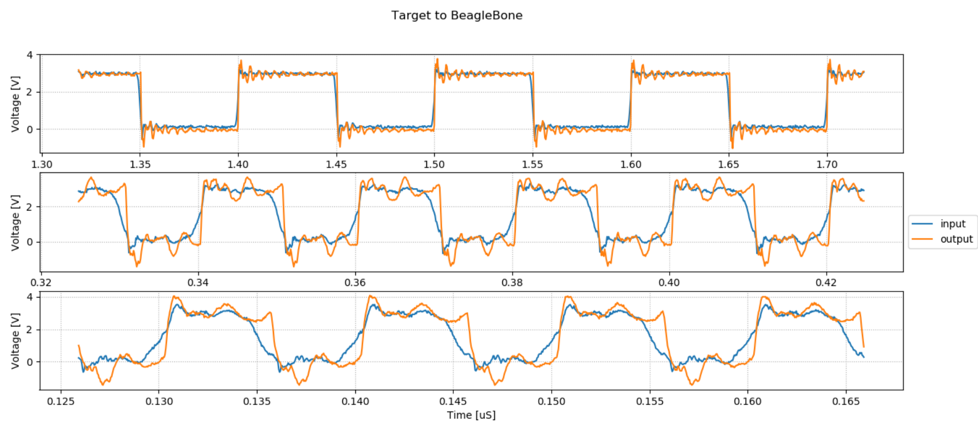

Figure 4.2: Target 2.8V to BeagleBone 3.3V at 1Mhz, 5Mhz and 10Mhz

4.3.2 Debugging

Debugging was tested on target four by connecting an external debugger [11] on the debugging connector and target voltage set to 3.3V. The highest speed setting of 12000kHz worked repeatedly without any problems. With an 10MHz

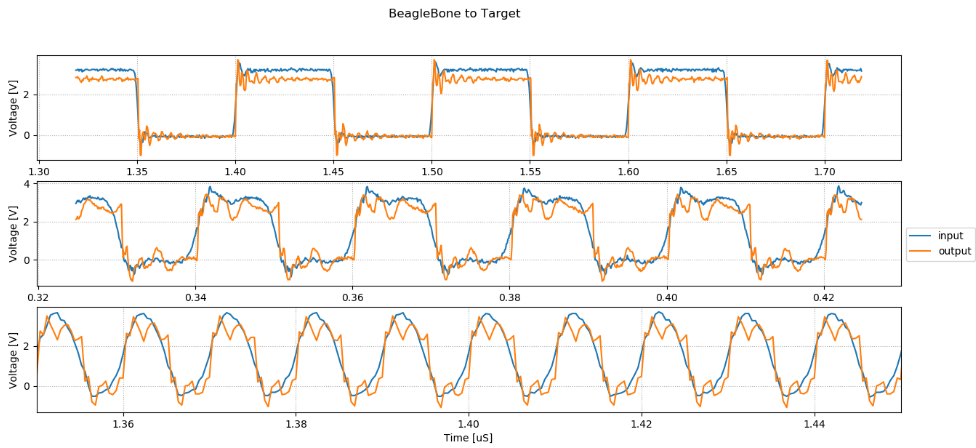

Figure 4.3: BeagleBone 3.3V to Target 2.8V at 1Mhz, 5Mhz and 10Mhz

disturbance signal on the TXD line there were no problems debugging at the highest speed.
The onboard debugging MCU was not programmed and tested as the reset would have to be manually connected to the target. This is caused by the error in the level shifter footprint.

4.3.3 USB

The USB hub was in the beginning tested with an faulty USB cable. After replacement it worked flawlessly. After a power cycle the reset pin was pulled low to reset the hub but it was not tested if it was really necessary. Switching of targets while an active USB connection to one target is established could lead to problems. For this case the reset pin of the USB hub is avaiable for the BeagleBone.

4.3.4 GPS

The GPS timesync signal worked after replacing the damaged U-Blox module. The USB connection for uploading firmware update did initially not work. The U-Blox module uses the V_{Bus} from the USB connection to detect if a cable is plugged in. Because the detection circuit uses 1mA the voltage divider with 100k resistors did not produce the required 3V but 0.7V instead. By switching to 1k resistors this problem should be solved.

4.4 Measurement

The hardware initial operation was done the same way as described in the RocketLogger wiki [1]. The only abnormality was +513mV and -556mV instead of +/-400mV (+/-50mV) on the Offset-compensation rail. A possible cause for this could be the replacement of the op-amp.
The calibration can be done the same way described in the RocketLogger repository [2]. The measurements for the second current channel can be skipped. The sampling of the channels V3,V4 and I2 has to be turned off at any time. The calibration files can be loaded by the "rl_do_cal.m" file but the "rl_cal.m" file had to be edited to compensate for the missing measurements from the second ADC. Lines 199 to 204 were changed to:

```
i1l = i1l_rld.get_data({'I1L'});
i1h = i1h_rld.get_data({'I1H'});
i2l = i1l;
i2h = i1h;

v = v_rld.get_data({'V1', 'V2', 'V1', 'V2'});
```

After calibration, the solder bridges J2 and J3 can be closed if measurement of the target voltage and GND_{sensed} is required.

4.4.1 Influences on measurement

It was measured whether other functionalities of the FlockLab would influence the current measurement by the RocketLogger. For this the SourceMeter was connected to target four with a constant current draw of 100nA and the target voltage set to 3.3V. Target four was chosen because it has the longest signal lines and is therefore expected to cause the biggest interferences. The metal cage over the RocketLogger circuit was not assembled to facilitate debugging. Thus higher noise levels can be expected. All graphs have additionally to the raw a filtered signal with a lowpass at 30Hz.
A 10MHz square wave signal was applied to the target TXD pin but no change on the RocketLogger was measurable. Also no additional noise was visible.
USB was also connected to the target four and an 400MB file transfer was done at 14MByte/s. This produced a constant offset of about 20nA and some additional spikes of about 30nA in the current measurement as visible in Figure 4.4. USB connected to the two peripheral USB ports had the same influence. The cause of the constant offset was further investigated by connecting a 400mA load on the peripheral or the target four port. The offset was now bigger, 41nA on the target four port and 60nA on the peripheral port. The power for the target adapters

[1] https://gitlab.ethz.ch/tec/public/rocketlogger/wikis/hardware-initial-operation/
[2] https://gitlab.ethz.ch/tec/public/rocketlogger/wikis/calibration

is supplied from the right side of the PCB and cannot flow trough any of the RocketLoggers analog front-end circuit and thus if the error was the current flow trough the PCB it should not be visible in the measurement with the load connected to target four. It is most likely caused by the higher current draw and the voltage drop in the small jumper wires which were used to power the whole board. This has to be tested with the DC/DC assembled to eliminate this factor.

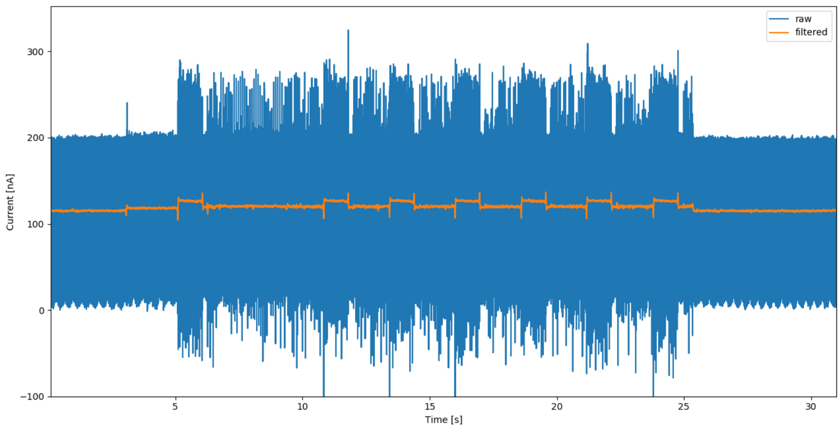

Figure 4.4: USB highspeed data transfer to Target 4 from 5s to 26s

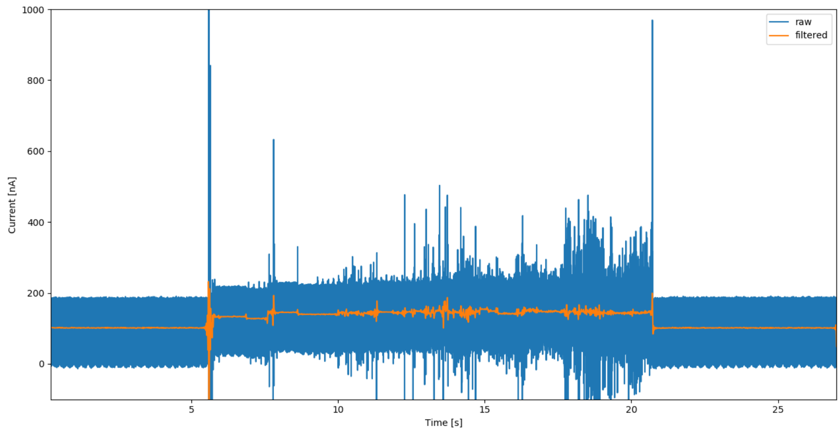

Figure 4.5: plug and unplug of a 400mA load at 5V on the target 4 connector

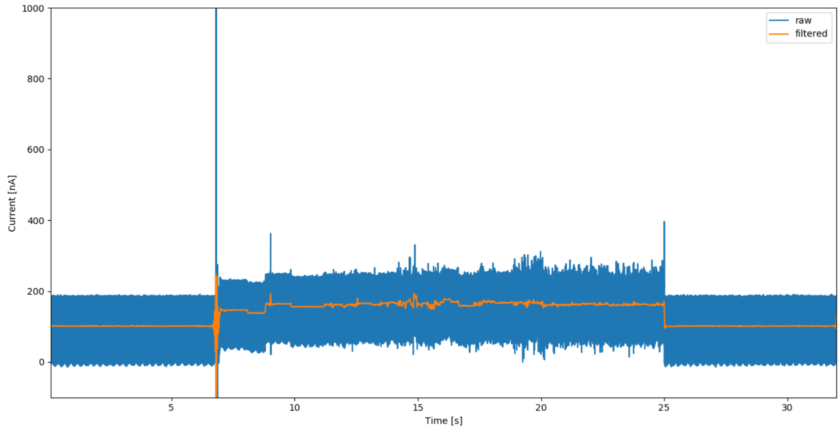

Figure 4.6: plug and unplug of a 400mA load at 5V on USB peripheral connectors

4.4.2 Further notes

If the current draw changed from 1mA to 100mA the RocketLogger sometimes crashed directly and sometimes the displayed samples and seconds of measurement started to count up very rapidly before it crashed. This only happened if the "calibration measurement" button was not checked and thus the calibration files were loaded. By using "force high range" it was sometimes possible to make correct measurements for 100mA. The cause for this could be an error in the assembly of the range switching circuit, damage from 5V on the ADC or a software problem because only a single ADC is connected and the unmodified RocketLogger software expects two ADCs.

Chapter 5

Conclusion

All requirements have been tested and were reached. The new target adapter is directly compatible to existing targets even tough some pin functionality was changed.
The current measurement with the circuit from the RocketLogger works directly even without changing the software and adapting for a single ADC. The measurements were accurate and the target switching as well disturbance signals did not change the result by more than 60nA. Further testing for the influence of power draw on the 5V rail has to be done.
Tracing and actuation can be done with 10Mhz and minimal constant propagation delay.
SWD debugging was tested using an external debugger and worked as expected.
The U-Blox Module was able to receive data from the external antenna and blinked the LED with the one second time synchronization signal.
Up to four targets are supported and with two select bits all signals are routed to the correct target. If only two targets are used, the PCB design can be easily reduced in size by just removing target connector three and four. No change to the circuit has to be made.
The target voltage can be selected over I2C and has a resistor defined range of 1.1V to 3.6V.
The DC/DC input converter as well as the on-board debugger still have to be tested.
The new FlockLab has a smaller area by a factor more than 2.5 compared to the existing FlockLab. This makes the new version easier to deploy and cheaper to produce. Component cost including the BeagleBone is approximately 230CHF.

Chapter 6

Appendix

6.1 Furter work

The measurements lead to conclusions what has to be improved for the next version:

- Remove the pull down resistors R27,R29,R31 and R32 from the USB-hub.
- Fix the footprint for the level shifter U12 and U13.
- Fix the footprint for the Q3, Q5 and Q7.
- Maby repace Q3 and Q5 by a small signal N-MOS.
- Fix placement of reverse current protection diode D1 and replace it by a different diode with higher current rating.
- Change LDO resistance values to R11 = 10k, R13 = 10k and R12 = 3.4k
- Change R46 and R48 to 1k for the U-Blox USB detection circuit.
- Make the vias tinted to prevent shorts on the target connectors.
- Remove jumper connection on GND sensed bevore the RocketLogger.
- Optional separate 3.3V LDO or protection diode, to protect the 3.3V supply from user errors.
- Optional use only one pin for SerialID or replace Q1 by a standard small signal N-MOS
- Change that ADC_START is traced by PRU1 instead of ADC_DRDY. because ADC_START is the timing critical signal.

Some measurements still have to be done:

- Test input DC/DC converter.
- Test the on board debugger.
- Test the DAC
- Investigate range switching error.

6.2 Notes to current prototype

Because of changes were made on the prototype, to get it working even with design errors, it might not behave as expected in some cases. The exceptions are as follows:

- Target power works only with target 1 and 4, turning on power while target 3 is selected could damage the LDO.
- Only target 4 has one tracing and one actuation line working. Those are TXD and RXD. The target actuation has to be enabled and it is not possible to use tracing alone without actuation enabled.
- Problems occur with the range switching circuit in the RocketLogger design.
- The USB V_{BUS} divider resistors have to be replaced by 1k resistors. to get it working.
- The SerialID N-MOS (Q1) is not assembled.
- The ADC might be damaged because of 5V input instead of 3.3V.

6.3 Time schedule

In the begining of this thesis a time estimation was made which can be seen in Table 6.1.

6.4 Project tasks

- Formulate a time schedule and milestones for the project. Discuss and approve this time schedule with your supervisors.

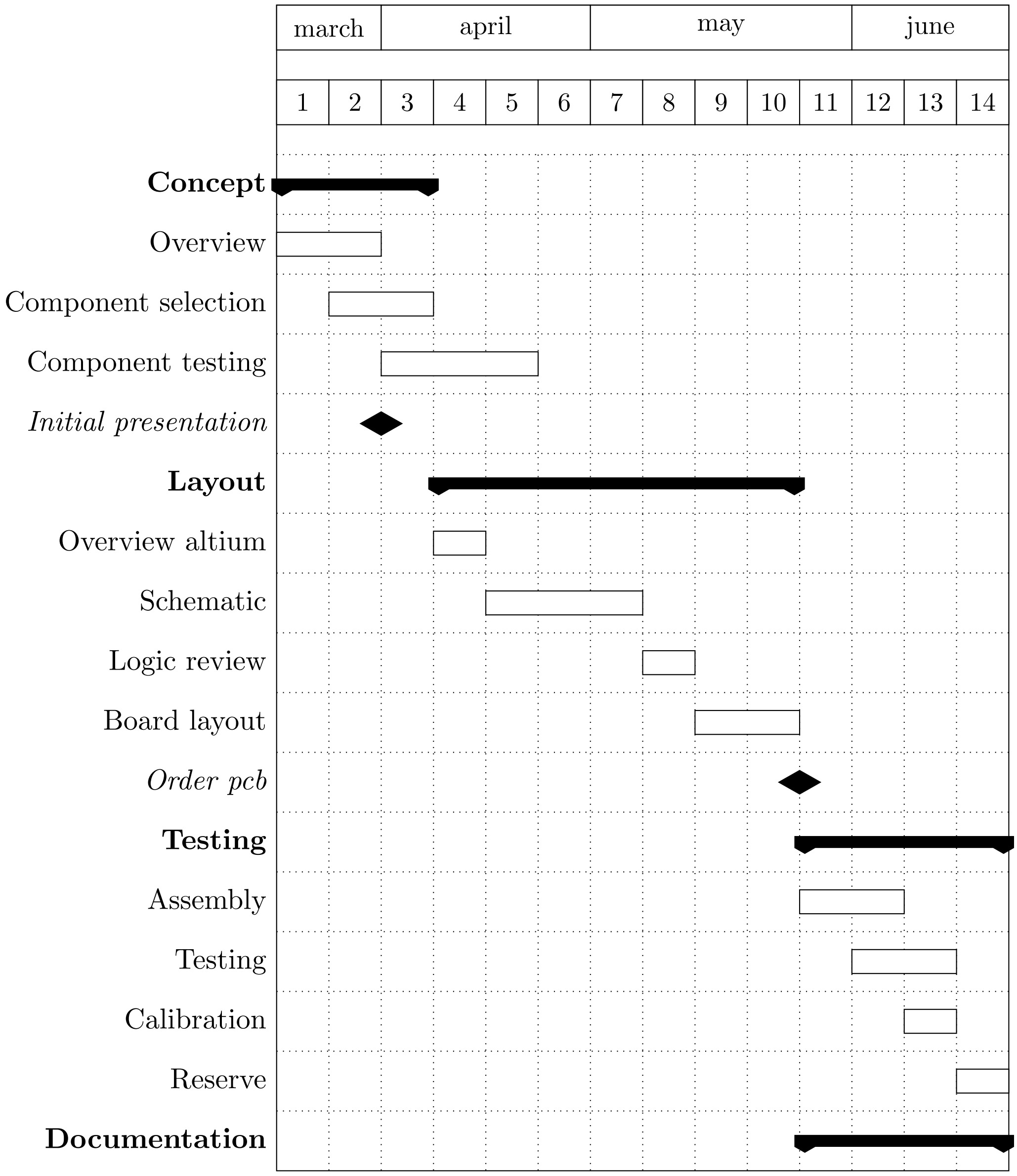

Table 6.1: Time Management

- Familiarize yourself with the existing FlockLab platform and its hardware design.
- Define the interfaces between the observer and the targets in collaboration with WB2.
- Explore the different options how to integrate the dierent components (RocketLogger, debugger, serial communciation, power delivery). Pay spe-

cial attention to the proper isoliation of the target.

- Select the best option and implement the hardware design with the Altium Designer.
- Document your project with a written report. As a guideline, your documentation should be as thorough to allow a follow-up project to build upon your work, understand your design decisions taken as well as recreate the experimental results.

6.5 Files

The following files are handed in with this thesis:

- FlockLab 2.0 Schematic and PCB output files
- Results from the component tests.
- Results from current measurements.
- Results from actuation/tracing measurements.

Bibliography

[1] R. Lim, F. Ferrari, M. Zimmerling, C. Walser, P. Sommer, and J. Beutel, "Flocklab: A testbed for distributed, synchronized tracing and profiling of wireless embedded systems," May 2013.

[2] R. Lim, F. Ferrari, M. Zimmerling, C. Walser, P. Sommer, and J. Beutel, "A competition to push the dependability of low-powerwireless protocols to the edge," 2013.

[3] P. Appavoo, E. K. William, M. C. Chan, and M. Mohammad, "Indriya2: A heterogeneous wirelesssensor network (wsn) testbed," 2019.

[4] C. Adjih, E. Baccelli, E. Fleuryt, G. Harter, N. Mitton, T. Noel, R. Pissard-Gibollet, F. Saint-Marcel, G. Schreiner, J. Vandaele, and T. Watteyne, "Fit lot-lab: A large scale open experimental lot testbed," 2019.

[5] L. Sigrist, A. Gomez, R. Lim, S. Lippuner, M. Leubin, and L. Thiele, "Rocketlogger - mobile power logger for prototyping iot devices," in *14th ACM Conference on Embedded Networked Sensor Systems (SenSys 2016)*, Stanford, CA, USA, Nov 2016.

[6] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with glossy," in *Proceedings of the 10th International Conference on Information Processing in Sensor Networks (IPSN 2011)*. Chicago, IL, USA: ACM/IEEE, Apr 2011.

[7] BeagleBoard.org, "Beaglebone," 2019. [Online]. Available: https://beagleboard.org/bone

[8] Keithley, "2450 sourcemeter," 2019. [Online]. Available: https://www.tek.com/sites/default/files/media/media/resources/1KW-60904-0_2450_DataSheet_0.pdf

[9] M. Integrated, "Digital adjustment of dc-dc converter output voltage in portable applications," 2019. [Online]. Available: https://www.maximintegrated.com/en/app-notes/index.mvp/id/818

[10] Segger, "Onboard debugger probe," 2019. [Online]. Available: https://www.segger.com/products/debug-probes/j-link/models/j-link-ob/

[11] Segger, "J-link edu mini," 2019. [Online]. Available: https://www.segger.com/products/debug-probes/j-link/models/j-link-edu-mini/

[12] Segger, "J-link remote server," 2019. [Online]. Available: https://www.segger.com/products/debug-probes/j-link/tools/j-link-remote-server/

[13] T. Instruments, "Am335x arm® cortex™-a8 and the integrated pru," 2019. [Online]. Available: https://elinux.org/images/6/65/Spruh73c.pdf#page=231