HES-SO Valais Wallis

Telemetry for the Formula student

Intermediate report

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1   Introduction

1.1 Formula Student

Formula Student is an international student engineering competition. Teams from all over the world design and build a small-scale Formula-style racing car. During the competitions, the cars are judged on static events: Engineering Design, Cost & Manufacturing, Business Presentation, Lap Time Simulation, and Technical Inspection. The vehicle must comply with the rules [1] for the technical inspection. If the car passes the technical inspection, it can participate in the dynamic events: Skidpad, 1 km autocross/sprint, 75 m acceleration, and 22 km endurance.

Figure 1: Formula Student Endurance race

1.2 Valais-Wallis Racing team

The Valais-Wallis Racing team [2] is the formula student team of the HES-SO Valais Wallis. It was created in the spring of 2022 by a group of students. The team's first car will take part in the races of summer 2023, and the telemetry system developed in this thesis will be used on the next car for the races of summer 2024.

1.3 Objectives

Telemetry is a technology that enables remote measurement and monitoring. This technology is interesting for a race vehicle as it allows live readings from the car's sensors to be read directly from the side of the track. With such a system, the data from all the sensors is easily accessible, and the engineers can adjust the car's parameters during the test sessions to increase the car's performance. A telemetry system is also helpful in improving the driver's skills, providing measurements such as GPS, speed, pedal level, steering angle, Etc. Direct visualization of measurements also allows problems to be identified before they can cause an accident.

This project aims to develop and test a telemetry system for the Formula Student car of the HES-SO Valais-Wallis. This thesis deals with the embedded part of the system and the communication with the PC. This project will be carried out in collaboration with a Business Information Technology student working on the software to display the telemetry system's data.

For this work, the reference race is Formula Student Alpe Adria [3] in Croatia. On this circuit, the maximum distance between the car and the base station will be less than 300 meters. The minimum range of the system must therefore be 300 meters, ideally 500 meters.
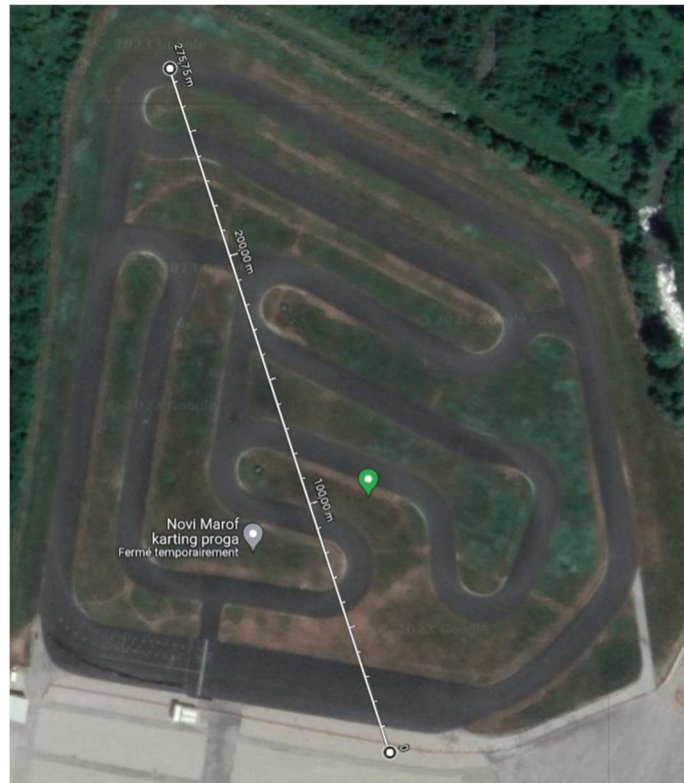

Figure 2: Alpe Adria Circuit

The telemetry device must communicate via the car's CAN bus with the sensors, the BMS, and the Inverter. A GPS must be integrated into the system. A transmission technology must be chosen for the direct visualization of the data, and the system must also store the data on a microSD card.

1.4 State of the art

Telemetry is used in many systems that require real-time remote measurement and monitoring. The telemetry needs to be embedded in a vehicle for this use case. Racing cars often incorporate telemetry systems, but these are proprietary systems unavailable on the market. That's why the Valais-Wallis Racing Team needs its own telemetry system.

Sensors are the fundamental elements of a telemetry system. All sensors must be connected to the telemetry system. The CAN bus is the standard protocol used in the automotive industry for this purpose. CAN bus (Control Area Network Bus) is a communication protocol that enables reliable and efficient data transfer between ECUs (Electronic Control Units) and sensors. It is a multiplexed bus and was introduced to reduce the amount of copper in cars by wiring all the ECUs and sensors on the same bus. It has been standardized with ISO 118987.

The transmission process is the other key point of the telemetry system. Many transmission processes could be used for this purpose. A standard 433 MHz RF transmission can send data through the air at a reasonable range. Many wireless devices use this transmission method with a dedicated protocol. Otherwise, there are many transmission protocols used for remote data transmission. For example, Wi-Fi is one of the most common transmission protocols. Every laptop, smartphone Etc, uses it. LoRaWAN is a protocol used with LoRa technology that enables long-range communication. Many IoT (Internet of Things) applications use this protocol to communicate.

The last component of a Telemetry system is the processing unit. The processing unit on almost every telemetry system is a software on a PC. The processing unit displays for the user and allows him to analyze the measurements made by the sensors and transmitted by the telemetry system. The processing units could also be linked with a database to store the data at the end of every test session or race.

1.5 Planning

week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	15.05.2023	22.05.2023	29.05.2023	05.06.2023	12.06.2023	19.06.2023	26.06.2023	03.07.2023	10.07.2023	17.07.2023	24.07.2023	31.07.2023	07.08.2023	14.08.2023
Transmission technology study														
Hardware														
Software														
Intermetidate presentation														

This schedule shows the project's progress over time. The first two weeks were devoted to the transmission technology study. The next three weeks were devoted to developing the electronic board. The fourth week in the "Hardware" section corresponds to the time to manufacture the electronic board. The remaining time was devoted to programming the telemetry system. A detailed schedule is available in the appendix.

2   Transmission technology

A wireless transmission must be established from the car to the computer. The range of the telemetry system must be greater than 300 meters (ideally 500 meters) with no obstacle between the transmitter and the receiver.

For this transmission, two technologies were studied. A Wi-Fi connection and a 433 MHz RF transmission.

LoRa protocol and 4G/5G cellular networks were not considered, as the bandwidth is not enough for the first, and there is no guarantee of network coverage in the race locations for the second.

2.1 433 MHz RF

The first option is a standard RF transmission. This solution is easy to implement, the range is wide enough, and the bandwidth is sufficient for the small amount of data to be sent. Moreover, there is no need to establish a connection. The transmitter emits the data on a frequency, and the receiver listens to the same frequency. If the transmission is interrupted, the data transmission will instantly work once the signal is recovered. With Wi-Fi communication, the car will need to reconnect to the hotspot, which takes a little time.

However, there will be a lot of teams during the competition, and if other teams use the same transmission method, all systems will disturb each other, and the transmission will not be guaranteed.

For an RF transmission, the RFM69HCW [4] module from HopeRF is one of the best options for this use case. It is available in 433 MHz and 868 MHz.

Figure 3: RFM69HCW module

This module has an output power of +20 dBm and an input sensitivity of -120 dBm at 1.2 kbps. The theoretical range can be calculated with the Friis transmission equation [5] (with omnidirectional antennas → $G_{antenna}$ = 0 dbi):

$$P_r = P_t + 20 * \log\left(\frac{\lambda}{4\pi d}\right)$$

For the 433 MHz module, the received power is -54 dBm at 500m, which is more than enough for the input sensitivity of -120 dBm.

2.2 Wi-Fi

The second option is a Wi-Fi connection. It is a robust protocol that allows the transfer of large amounts of data. With a Wi-Fi connection, a classic router can be used to connect the telemetry system to the computer and directly send IP packets. Moreover, the system will not have to manage interference from other teams because the Wi-Fi protocol uses carrier-sense multiple access with collision avoidance (CSMA/CA). This method shares the band between the stations to avoid collisions between frames.

The only disadvantage of Wi-Fi communication is the range, which will be more difficult to reach.

The best option for Wi-Fi communication is the nRF7002 [6] chip from Nordic Semiconductors. It is a dual-band Wi-Fi module with an SPI/QSPI interface to relate to a host SoC.

Figure 4: nRF7002 chip

On the 2.4 GHz band at 1 Mbps, the maximum output power is 21 dBm, and the input sensitivity is -98.6 dBm.

The theoretical range can be calculated with the Friis transmission equation [5] (with omnidirectional antennas → $G_{antenna}$ = 0 dbi):

$$P_r = P_t + 20 * \log\left(\frac{\lambda}{4\pi d}\right)$$

For the 2.4 GHz band, the received power is -70 dBm at 300 m, which is close to the input sensitivity of a traditional router.

As these equations give theoretical results, tests must be carried out to determine whether the range will be sufficient in practice.

2.2.1 Tests

The aim of this test is to determine if a Wi-Fi connection is suitable for the required range. The tests have been carried out in the 2.4 GHz frequency band.

The router used in this test is an Asus RT-AC68U. The router's technical specifications do not mention the output power, but it does have the CE mark, which means that the output power should not exceed 20 dBm. On the opposite side, a laptop was used. It is equipped with an Intel Wi-Fi 6 AX201 module [7], which has similar performances (in terms of range) as the nRF7002 [6]. The test was realized with the default omnidirectional antennas, so there is room for improvement using sector antennas if needed.

The tests were performed with the iPerf software [8], using the UDP protocol at 1 Mbps.

The laptop and the router could communicate successfully at 400 meters distance.

```
C:\Users\sylve\OneDrive\Bureau\iperf-3.1.3-win64>iperf3.exe -c 192.168.2.35 -u -b1m -i1 -p 6000
Connecting to host 192.168.2.35, port 6000
[  4] local 192.168.2.35 port 52345 connected to 192.168.2.35 port 6000
[ ID] Interval           Transfer     Bandwidth       Total Datagrams
[  4]   0.00-1.01   sec   120 KBytes   970 Kbits/sec  15
[  4]   1.01-2.00   sec   128 KBytes  1.06 Mbits/sec  16
[  4]   2.00-3.01   sec   120 KBytes   976 Kbits/sec  15
[  4]   3.01-4.00   sec   120 KBytes   989 Kbits/sec  15
[  4]   4.00-5.01   sec   120 KBytes   975 Kbits/sec  15
[  4]   5.01-6.00   sec   128 KBytes  1.06 Mbits/sec  16
[  4]   6.00-7.01   sec   120 KBytes   975 Kbits/sec  15
[  4]   7.01-8.01   sec   120 KBytes   989 Kbits/sec  15
[  4]   8.01-9.01   sec   120 KBytes   975 Kbits/sec  15
[  4]   9.01-10.01  sec   128 KBytes  1.06 Mbits/sec  16
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
[  4]   0.00-10.01  sec  1.20 MBytes  1.00 Mbits/sec  0.156 ms  0/152 (0%)
[  4] Sent 152 datagrams
```

Figure 5: iPerf test - Client side

```
------------------------------------------------------------
Server listening on 6000
------------------------------------------------------------
Accepted connection from 192.168.2.35, port 51901
[  5] local 192.168.2.35 port 6000 connected to 192.168.2.35 port 52345
[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
[  5]   0.00-1.01   sec   112 KBytes   904 Kbits/sec  0.057 ms  0/14 (0%)
[  5]   1.01-2.00   sec   128 KBytes  1.06 Mbits/sec  0.105 ms  0/16 (0%)
[  5]   2.00-3.01   sec   120 KBytes   976 Kbits/sec  0.152 ms  0/15 (0%)
[  5]   3.01-4.01   sec   120 KBytes   989 Kbits/sec  0.201 ms  0/15 (0%)
[  5]   4.01-5.01   sec   120 KBytes   976 Kbits/sec  0.208 ms  0/15 (0%)
[  5]   5.01-6.01   sec   128 KBytes  1.06 Mbits/sec  0.193 ms  0/16 (0%)
[  5]   6.01-7.01   sec   120 KBytes   975 Kbits/sec  0.220 ms  0/15 (0%)
[  5]   7.01-8.01   sec   120 KBytes   989 Kbits/sec  0.233 ms  0/15 (0%)
[  5]   8.01-9.00   sec   120 KBytes   990 Kbits/sec  0.222 ms  0/15 (0%)
[  5]   9.00-10.01  sec   128 KBytes  1.04 Mbits/sec  0.156 ms  0/16 (0%)
[  5]  10.01-10.01  sec  0.00 Bytes  0.00 bits/sec  0.156 ms  0/0 (0%)
```

Figure 6: iPerf test - Server side

The same test was also successfully carried out on a smartphone at the same distance.

2.3 Conclusion

The following table shows the differences between a 433 MHz RF transmission and a Wi-Fi communication:

	Wi-Fi	*433 MHz RF*
Bandwidth	More than enough	Just enough
Range	enough	More than enough
Disturbed by interference	No (managed by CSMA/CA)	Yes
Connection to the computer	Wi-Fi / Ethernet	Serial port
Base station module	Wi-Fi Router	To be designed
Protocol	TCP/UDP	To be designed

Table 1: Comparison between Wi-Fi and 433 MHz RF

The critical issues are the range and the ability to operate in an environment with a lot of interference.

The Wi-Fi solution is clearly better regarding its ability to deal with interference. The 433 MHz RF solution should be avoided because there will be many teams during the event, and communication without collision avoidance will likely fail.

For the range, the 433 MHz RF solution is better. However, the tests showed that the range was reachable with a classic Wi-Fi router.

Based on these two criteria, the Wi-Fi solution can already be selected. Moreover, the other points are all the better with this solution.

The system will therefore use Wi-Fi communication with Nordic Semiconductors' nRF7002 [6] module.

3   Hardware development

3.1 SoC

An SoC (System on Chip) needs to be chosen for the project. To start to program the telemetry system before the hardware is manufactured, the SoC must be available on a Dev Kit. The Nordic nRF7002-DK is a development kit that integrates the Wi-Fi chip chosen in the Transmission Technology section. The host SoC of this kit is the nRF5340.

The nRF5340 is a high-performance SoC from Nordic Semiconductors. It integrates two Arm Cortex-M33 processors, Bluetooth, high-speed SPI/QSPI, and more high-performance features. The application processor can be clocked at 64 or 128 MHz and optimized for performance. It has 1 Mbyte Flash and 512 Kbyte RAM. The network processor is clocked at 64 MHz and is optimized for low power and efficiency. It has 256 Kbyte Flash and 64 Kbyte RAM. The nRF5340 can integrate the Zephyr RTOS.

This processor is powerful enough for the system, and its availability in a development kit makes it the perfect choice.

3.2 GPS Module

The telemetry system needs to include a GNSS module. U-Blox is a leading provider of GNSS solutions. They produce high-quality positioning chips, modules, and antennas. Three GNSS solutions were studied.

The first is the SAM-M10Q module. It is an all-in-one module with an internal antenna. It has a UART and an I2C interface. Integrating this module into the design is easy and straightforward.

The second option is the MAX-M10S module. The specifications of this module are similar to the first module. It also has a UART and an I2C interface. It, however, does not have an internal antenna. This makes it less easy to integrate into the design because GNSS external antennas are active, and HF circuitry needs to be designed.

The last considered option is the UBX-M9140. It has two UART interfaces, one SPI, one I2C, and one USB interface. Unlike the two first options, this is not a module but a chip. It is much smaller than the modules, but the integration of this chip in the design is much more complicated.

These solutions are equivalent in terms of precision (standard precision). They all support concurrent reception of four GNSS (GPS, GLONASS, Galileo, and BeiDou). As the system will be placed in a housing in the car, the GNSS module needs to have an external antenna because it needs to be pointed at the sky. The first option is therefore not possible. As the system does not need to be extremely small, the

second option (MAX-M10S) can be chosen to avoid spending too much time on developing the electronic schematics.

To work with this module, the ANN-MB antenna from the same manufacturer is the best option.

3.3 Bloc diagram
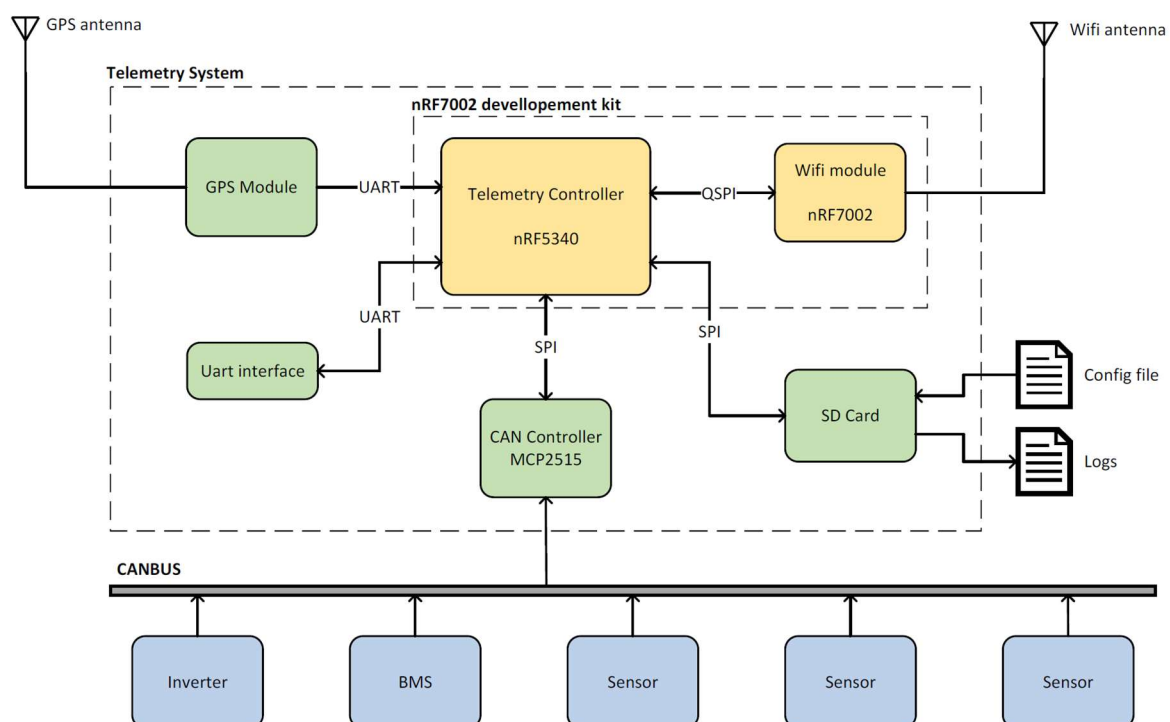
This diagram shows the general architecture of the telemetry system.

The main controller (nRF5340) is the central element of the system.

The CAN controller is connected to the nRF5340 via an SPI bus. On the other side, it is connected to the CAN bus to communicate with the BMS, the inverter, and all the sensors.

Another peripheral is the GPS module. It is connected to the nRF5340 via a UART communication. The GPS module uses an external antenna because it needs to be pointed to the sky, and the telemetry system will be placed in a case in the car.

The microSD card is connected to the nRF5340 via an SPI bus. The microSD card serves to store the measurements of the telemetry system. The memory card also holds a configuration file.

The nRF7002 chip handles Wi-Fi communication. It is connected to the nRF5340 via a QSPI bus. As for the GPS module, the Wi-Fi module uses an external antenna to improve the transmission.

The last peripheral is a UART interface. The telemetry system does not use it. It is just there for debugging purposes and future system improvements (to connect an onboard computer, for example).
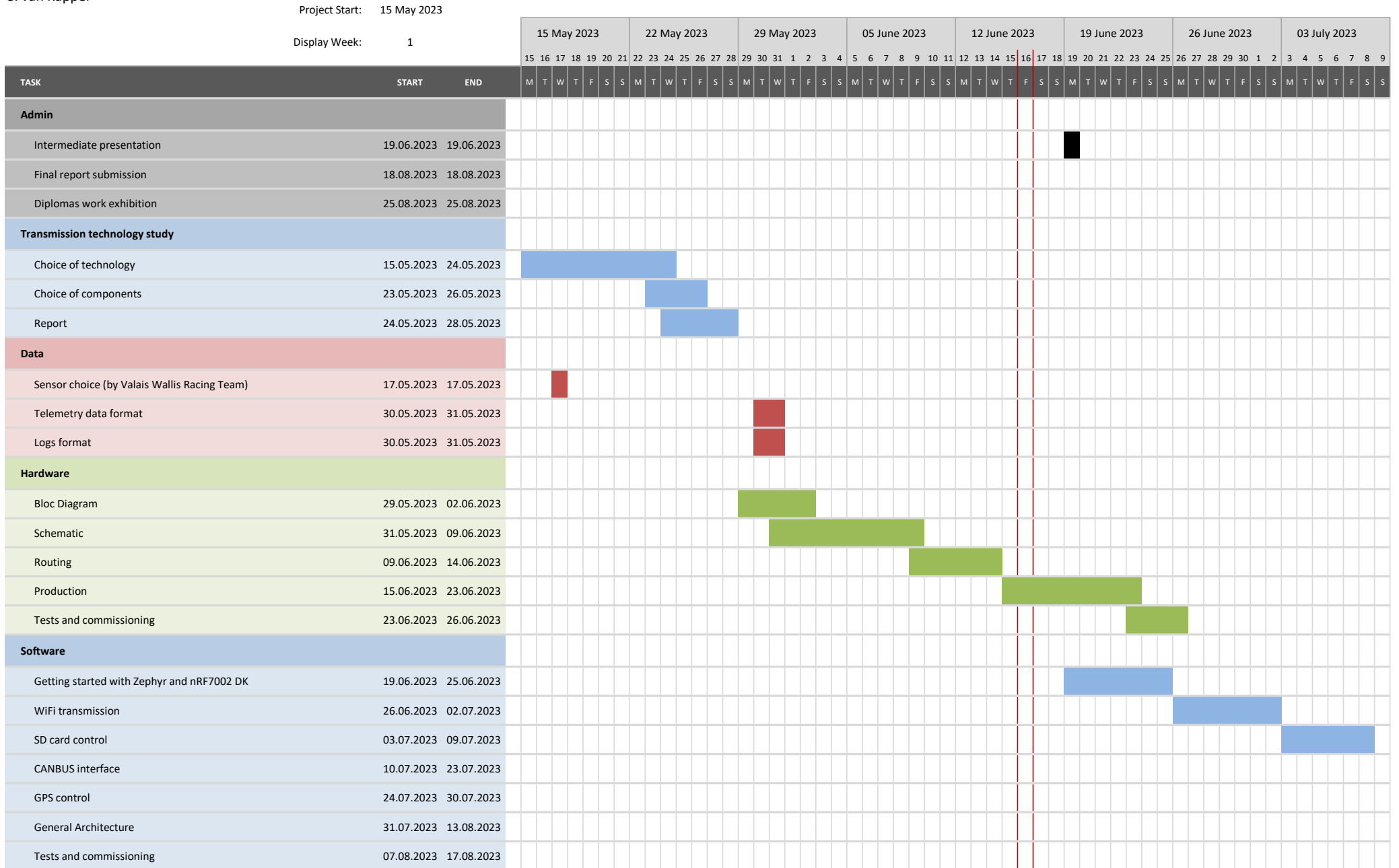
4 Bibliography

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[3] 'FS Alpe Adria - Home'. https://fs-alpeadria.com/ (accessed Jun. 15, 2023).

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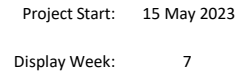
5 Appendix

- Full planning

Telemetry for the Formula Student - Planning

HES-SO Valais Wallis
S. van Kappel

Project Start: 15 May 2023

Display Week: 1

TASK	START	END
Admin		
Intermediate presentation	19.06.2023	19.06.2023
Final report submission	18.08.2023	18.08.2023
Diplomas work exhibition	25.08.2023	25.08.2023
Transmission technology study		
Choice of technology	15.05.2023	24.05.2023
Choice of components	23.05.2023	26.05.2023
Report	24.05.2023	28.05.2023
Data		
Sensor choice (by Valais Wallis Racing Team)	17.05.2023	17.05.2023
Telemetry data format	30.05.2023	31.05.2023
Logs format	30.05.2023	31.05.2023
Hardware		
Bloc Diagram	29.05.2023	02.06.2023
Schematic	31.05.2023	09.06.2023
Routing	09.06.2023	14.06.2023
Production	15.06.2023	23.06.2023
Tests and commissioning	23.06.2023	26.06.2023
Software		
Getting started with Zephyr and nRF7002 DK	19.06.2023	25.06.2023
WiFi transmission	26.06.2023	02.07.2023
SD card control	03.07.2023	09.07.2023
CANBUS interface	10.07.2023	23.07.2023
GPS control	24.07.2023	30.07.2023
General Architecture	31.07.2023	13.08.2023
Tests and commissioning	07.08.2023	17.08.2023

Telemetry for the Formula Student - Planning

HES-SO Valais Wallis
S. van Kappel

Project Start: 15 May 2023

Display Week: 7

TASK	START	END
Admin		
Intermediate presentation	19.06.2023	19.06.2023
Final report submission	18.08.2023	18.08.2023
Diplomas work exhibition	25.08.2023	25.08.2023
Transmission technology study		
Choice of technology	15.05.2023	24.05.2023
Choice of components	23.05.2023	26.05.2023
Report	24.05.2023	28.05.2023
Data		
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Logs format	30.05.2023	31.05.2023
Hardware		
Bloc Diagram	29.05.2023	02.06.2023
Schematic	31.05.2023	09.06.2023
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General Architecture	31.07.2023	13.08.2023
Tests and commissioning	07.08.2023	17.08.2023