4 System Design of the Optogenetic Headstage

4.1 Introduction

In optogenetic stimulation, the light source is usually tuned to a specific wavelength — usually blue at 473 nm [16] [17] [18] . A headstage system requires small size and weight, long life time and physical robustness. High wireless range and high number of stimulation/recording channels are also desirable characteristics as they allow carrying out optogenetic experiments on freely-moving small rodents, conveniently. Having simultaneous optical stimulation and bioelectrical recording at the same headstage would greatly enhance research capability in this area. Also, having the option to support multiple wavelengths would be a plus. However, currently there are no wireless systems available to optically stimulate the brain cells and record the neural response in real-time in multiple independent channels. Thus, the goal of this work is to realize such a research tool.

As research objectives, this project aims to design and fabricate a wireless optogenetic headstage that provides simultaneous optical stimulation and bioelectrical recording inside a wireless device operating in real-time. Moreover, it is desired that a multichannel wireless optogenetic headstage with simultaneous stimulation and neural recording be designed that allows optogenetic experiments on small freely moving animals. It is also highly beneficial that multiple stimulation wavelengths be supported and the size and volume of the device be as small as possible.

In general, wireless headstages are installed on the head of an animal (usually a small rodent) in a surgery procedure and then the headstage will be controlled from a base station where the neuroscientist can determine the stimulation patterns and visualize the acquired signals. In experiment scenarios where animals are freely moving, the animal is usually kept in a cage and its physical behavior is also monitored. Another approach to monitor an animal's neural response to stimulation is to keep the animal still while the experiment is taking place. Wireless headstages are especially useful for experiments on freely-moving animals.

Neural signal acquisition is carried out by placing microelectrodes inside the brain of an animal; then the acquired signal is amplified and filtered using specialized electronics. This analog signal chain, also called the analog front end (AFE), must be as low-noise as possible because the neural signal that is picked up by the electrodes has a low amplitude, comparable to the noise RMS (root mean square) value. The AFE must also be able to separate the high-frequency content of the neural signal (action potentials) from the low-frequency component.

After analog signal processing and digitization, some sort of digital signal processor will process the neural signal samples. This processing can be either 1) directly delivering the digitized samples to the radio transmitter or 2) performing a specific signal processing algorithm on the data prior to transmission. Different types of processing can be performed on the acquired signals, like action potential (spike) detection with or without spike sorting and signal compression.

As discussed in previous chapters, neural stimulation can have either an electrical or an optical nature. For electrical stimulation, microelectrodes can be used while for optical stimulation (including optogenetics), small optical fibers can be placed inside the brain of the animal. The optical fibers or the microelectrodes are connected to their appropriate *drivers* where the stimulation waveforms are generated.

Headstages that perform different tasks, especially signal processing, require some sort of signal processing unit to control the activity of different hardware and software components. This control unit can be a microcontroller, a DSP (digital signal processor), an FPGA (field-programmable gate array) or a combination of these. Low power consumption and real-time responses are necessary for such processing units. Finally, in cooperation with some analog circuitry, the processing unit is also usually responsible for generating the stimulation patterns.

For wireless headstages, there is also a need for wireless data transceivers that are used to transfer acquired neural signals back to a base station where the data can be viewed or analyzed. In recent headstages where multiple neural signal acquisitions are present (refer to Chapter 2), digital modulation schemes such as FSK (frequency-shift keying) or GFSK (Gaussian frequency-shift keying) are very popular for their ease of implementation [17] [69] [84].

Last but not least, the power supply circuitry of the wireless headstage can be a challenge in some scenarios where power is limited. Since headstages are mixed-signal systems, multiple low-noise power rails might be required. On the other hand, depending on the neural stimulation type, some of these power rails might experience heavy current discharge in short time intervals which leads to presence/conduction of noise on other power rails.

4.2 Design Methodology

As mentioned previously, the wireless optogenetic headstage is a research tool that helps neuroscientists to study the brain behavior in different experiments and our goal in this thesis is to design a novel wireless headstage that allows simultaneous real-time multichannel optogenetic stimulation and neural recording, which is not available so far. The focus on real-time and multichannel stimulation and recording comes from the fact that real-time neural recording is required to investigate the effects of millisecond-scale optical stimulation and, multiple channels of recording and stimulation allow simultaneous monitoring of multiple brain regions.

In order to design this research tool, we initially designed a proof-of-concept wireless headstage and based on the experience gained during the design process, we designed the (final) multichannel wireless optogenetic headstage.

In both headstages, we opted for the following innovative approach to design and fabricate the devices:

- Providing means for electrophysiological recording and optical stimulation in the same device: it is necessary that both stimulation and recording be present in the same headstage as it is required to investigate the effects of stimulation using real-time recording (refer to sections 2.2, 2.5.1 and 2.6).
- Using inexpensive, miniature and light-weight COTS components to design a headstage suitable for small rodents: this allows having a low-cost light-weight headstage that can be easily used by neuroscientists.
- Using PCBs as component carrier and chassis for the headstage: this removes the need to have bulky containers to encapsulate the components of the headstage and results in lighter devices suitable for experiments on small rodents (refer to section 1.2).
- Incorporating high-current discrete LEDs as the optogenetic light source: high-current LEDs allow deeper optogenetic stimulation as the optical loss in the brain tissues decreases the received optical power in deeper layers (refer to section 2.6).
- Designing the analog amplifiers based on low-noise COTS to acquire neural signals: as mentioned in previous chapters, neural signals are in order of tens of microvolts and require very low-noise analog recovery (refer to section 2.5). High-quality analog recovery is crucial to further steps of the analysis of neural signals.
- Using wireless transceivers to transfer the acquired neural data to the base station: when a headstage is untethered, it can be easily used in experiments involving freely-moving animals which is the goal of this work (refer to section 1.2).
- Using low-power microcontrollers to control the headstage subsystems.
- Using reliable power sources to supply the stimulation LED and the rest of the system with energy.

In the next two subsections, we will present the proof-of-concept headstage and the final design in more detail.

4.2.1 Proof of Concept

The headstage that has been designed as the proof of concept was based on one stimulation LED and two neural recording channels [17]. This headstage was wirelessly powered using inductive links[†] [85] and required power-delivery chambers to operate. Also, its physical design was based on 3 (rigid) PCBs that were stacked using board-to-board connectors. The following list summarizes the characteristics of this headstage:

- Fabrication based on COTS components
- Light-weight, small and wireless headstage based on three stacked rigid PCBs
- One 100 mA optogenetic stimulation LED
- Two low-noise neural recording channels
- Microcontroller with integrated RF transceiver to control the system and transmit the data to the base station
- Inductive power chamber as power source

Different details about this headstage can be found in [17] and are also summarized in Table 9.

Table 9. Summary of the performance of the first wireless optogenetic headstage.

Parameter	Value
Weight	7.4 grams
Dimensions	15×25×17 mm
Supply Voltage	3.3 V
Readout circuitry Power Consumption	3.73 mW
PMU Power Consumption	16.54 mW
RF Microcontroller Power Consumption	74.25 mW
LED Power Consumption (Constant Mode)	(20 - 380) mW
Total power consumption (Constant Mode)	(114.52 – 474.52) mW
RF Operating Frequency	868 MHz
RF Output Power	0 dBm
Data Rate	320 kb/sec
Power Delivery Architecture	4-Coil Inductive Link
Power carrier Frequency	1 MHz
Power Transmission Range	< 7 cm
Number of Recording Channels	2
Input-Referred Noise	1 µVrms
Sampling Frequency (per Channel)	20,000 Sample/Second
ADC Precision	8 bits
Readout Interface Gain	40 to 60 dB
Readout Interface CMRR	> 100 dB
Readout Interface Bandwidth	100 Hz to 10 KHz

[†] The work on the inductive power delivery link (and some parts of the analog circuitry) has been done by Abdollah Mirbozorgi, PhD student at Laval University, 2013.

Figure 11 and Figure 12 show the physical design of this headstage. It can be seen that the three stacked PCBs are connected together using board-to-board connectors and that the electrodes are wires alongside the optical fiber. The power receiving coil is also sandwiched between two of the PCBs.

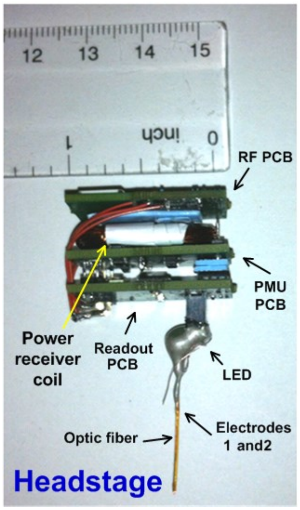

Figure 11. First version of the optogenetic headstage: stacked PCBs, power-receiving coil and the optical fiber.

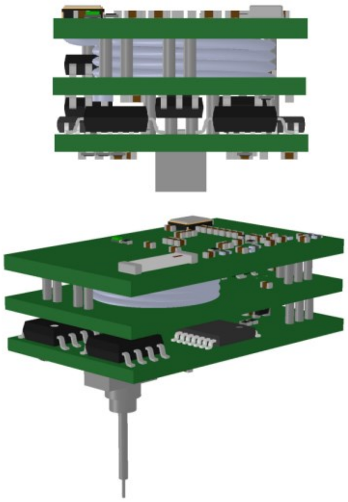

Figure 12. 3D models of the headstage: Side view with the power-receiving coil (top). Complete model with optical fiber (bottom).

4.2.2 Issues, Solutions and Design Approach

Although the proof-of-concept version of the optogenetic headstage satisfied many different requirements of optogenetic experiments, it had shortcomings such as a large size and large weight, and a lack of multichannel capability, which are essential characteristics for conducting practical experiments with freely moving animals. As a result, we have devised an original approach, which will be detailed in the following paragraphs, to design an advanced wireless headstage (detailed in Section 4.3) addressing the mentioned shortcomings. The following list contains different shortcomings and issues of the proof of concept as well as the improvements that were made in the new headstage. The solutions to the mentioned issues comprise our approach to the design of the new headstage:

1) **Issue**: The batteryless nature of the headstage and the fact that the power delivery distance (see [17]) was almost 7 cm resulted in certain limitations in some experiments. For example, if a relatively large rodent decides to stand on its feet it was possible that the headstage did not receive enough power to continue working.

   Solution: In the new design, a battery is used instead of wireless power delivery link. The system is able to work (using the battery) more than 3 hours.

2) **Issue**: The design of the proof-of-concept headstage was based on three stacked PCBs. The non-monolithic design of the first headstage resulted in higher volume and more difficulty in debugging and maintenance.

   Solution: The new design benefits from the rigid-flex PCB fabrication technology. This means that different *rigid* PCBs are connected to each other using *flexible* PCBs. Taking this approach, completely eliminates the need for board-to-board connectors and saves space and results in a robust monolithic PCB design. Also, the new headstage's dimensions will be less than 20×20×20 mm^3 and its weight will be less than 7 grams. The size and the weight of this headstage address the fact that a laboratory mouse (test subject for many different types of experiments) does not usually weigh more than 30 grams [86]. As a result, in order for the mouse to be able to freely move, the headstage weight/size must be as low as possible.

3) **Issue**: There was only one stimulation LED in the proof-of-concept headstage, which resulted in experiments with less degrees of freedom. Furthermore, the maximum current in the LED was limited to 100 mA.

   Solution: The new headstage benefits from two optical stimulation channels where each of these channels is a high-power LED (LB G6SP [87] or LY G6SP [88] by OSRAM Opto Semiconductors [89]) that will be driven by up to 150 milliamps of electrical current. At any given time only one of the LEDs will be active and the optical power generated in the LED will be delivered to neurons via optical fibers.

   Similar to the previous headstage, there will be two neural recording channels where each of these recording channels is connected to a low-noise amplifier and is properly filtered. The filtering that is done in the analog circuitry is bandpass and allows frequency content between almost 300 Hz to 6000 Hz to pass. After amplification and filtering, each channel is digitized at a rate of 20,000 samples/second. The analog front is low-noise enough to be able to extract action potentials with amplitudes as low as 10 microvolts.

   Being equipped with two reading channels as well as two stimulation channels allows simultaneous excitation and monitoring of multiple brain regions. This results in more flexible optogenetic experiments as there will be less need for changing the electrodes and/or optical fiber sites. As mentioned in chapters 0 and 1, different brain regions are dedicated to different tasks so multiple stimulation/reading channels results in more flexibility in studying the brain activity.

   The high current through the LED compensates for the losses of optical fibers and their connections. Depending on the nature of the experiment, this current flow and the resulting optical power might be too much [59]. However, the high irradiance that flows out of the optical fiber allows stimulation of deeper brain areas.

4) **Issue**: The RF center frequency of the transmitter was 868 MHz in the proof-of-concept headstage. Optimum antennas at this frequency are usually much larger than the largest dimensions of the headstage. Since large antennas cannot be used with the headstage, the transmission distance of the headstage decreases.

   Solution: The RF transceiver in the new headstage has a center frequency of 2.4 GHz, which results in much smaller and more efficient antennas compared to the previous headstage. Also, the new RF transceiver is capable of transmitting data up to 720 kb/sec. This bit rate allows transmitting other information as well as the neural data. For example, the outputs of temperature sensors or accelerometers can be sent alongside with the neural data.

5) **Issue**: The proof-of-concept headstage had optical stimulation patterns in the form of PWM (pulse width modulation) waves. However, the transitions between the high and the low states were not fast enough compared to the time scales of the waveforms.

   Solution: The stimulation patterns that were opted for this headstage as well as the previous one are PWM signals. Since the optogenetic stimulations and responses happen in millisecond scales (see chapters 0 and 1), the stimulation and the recording of these events must be real-time enough to capture all information. Particularly for the stimulation, the state transition in the PWM signal must be much faster than the width of the pulse. This requirement is addressed in the new design of the headstage. In essence, the optical stimulation pattern of the LEDs will be a PWM signal with a frequency between 1 Hz to 100 Hz and the duty cycle will be between 0.1 % and 10 %. When the pulse is active, a current of 150 milliamps will flow into the active LED.

As mentioned above, the experience that was gained while designing the proof of concept, was leveraged to implement an advanced multichannel optogenetic headstage. The following list summarizes the approach to design the new multichannel optogenetic headstage being the subject of this project:

- Foldable rigid-flex PCB carrier with light-weight COTS components: the foldable PCB alleviates the need for board-to-board connectors and results in lower weight and size of the system which is necessary for experiments on freely moving small animals.
- Two 150 mA optogenetic stimulation LEDs: having two stimulation LEDs allow neuroscientists to monitor two brain regions simultaneously. This results not only in simultaneous study of two brain

regions but removes the need of performing two surgeries to implant the optical fibers into two brain regions of two different animals.

- Two low-noise neural recording channels: as mentioned previously, very low-noise amplifiers are required to extract the microvolt-scale neural signals from the environment noise and the quality of analog signal acquisitions affects the rest of the signal processing and analysis steps.
- Low power MSP430 microcontroller to control the system: this microcontroller has all the required capabilities to control the system, digitize the neural signals and send the data to the base station. It is also very low-power.
- Separate high-bit-rate RF transceiver capable of using small chip antennas: using an RF transceiver operating at 2.4 GHz results in more flexibility in PCB layout design as smaller antennas are used. Also the higher bit-rate of this transceiver allows transmission of different data from different sensors simultaneously, dynamically changing the stimulation pattern and results in lower power consumption.
- Small Li-Ion battery as power source: this battery allows continuous work for more than three hours without need to change batteries. Also the small form factor of the battery does not add considerable weight to the system.
- Circuitry to generate sharp optical stimulation patterns: as action potentials occur in millisecond time scales, the corresponding stimulation must also have a fine time resolution (refer to section 2.6).

4.3 The Design of the Multichannel Wireless Optogenetic Headstage

In this section, the details of the advanced headstage design are presented. At first, a short overview of the design is presented and then each component of the headstage is discussed in detail. The main novelty of this work is gathering multiple stimulations and recording channels in a small and robust wireless headstage that can be used in optogenetic experiments involving small freely moving rodents. In the next section, we will present the design details of the multichannel optogenetic headstage.

The proposed headstage system includes the following main blocks (subsystems):

1) Analog Front-End (AFE)
2) Optical Stimulation Circuitry
3) Power Management Unit (PMU)
4) Microcontroller Unit (MCU)
5) Digital Wireless Transceiver

In the AFE, bandpass filters keep the useful frequency content between almost 300 Hz to 6600 Hz; this band contains the action potentials and the LFPs. The AFE benefits from high common-mode rejection ratio (CMRR) and power supply rejection ratio (PSRR); both of these characteristics are necessary for the AFE operation in the presence of different types of noise. The high CMRR removes the 50/60 Hz power-line noise and other types of common-mode noise while the high PSRR removes the power supply fluctuations that can be conducted to the AFE inputs.

The optical stimulation circuitry generates the required PWM waveforms that will be applied to the stimulation LED terminals. This subsystem receives a digital PWM signal from the MCU and converts it to electrical current in the LED.

The PMU is responsible for providing other subsystems with appropriate power rails. These power rails are required to be as low-noise as possible because any noise on the power rails directly affects the quality of the acquired signals. In order to remove the high-frequency noise on the power rails, the PMU incorporates a low-pass power supply filter. Details of this filter are provided in the following sections.

The MCU is a low-power microcontroller from the MSP430 family of microcontroller from Texas Instruments. This microcontroller is responsible for delivering the data to the radio transceiver and providing the stimulation LED drivers (optical drivers) with appropriate PWM signals. Furthermore, at the beginning of an experiment, the MCU receives the experiment parameters such as stimulation patterns and the stimulation duration from the base station.

Figure 13 shows the block diagram of the system. It can be seen that the MCU controls all other subsystems of the headstage. Four microelectrode will be connected to the brain tissue; one of them brings the brain tissues to an appropriate common-mode voltage and the three other microelectrodes are the inputs of the AFE.

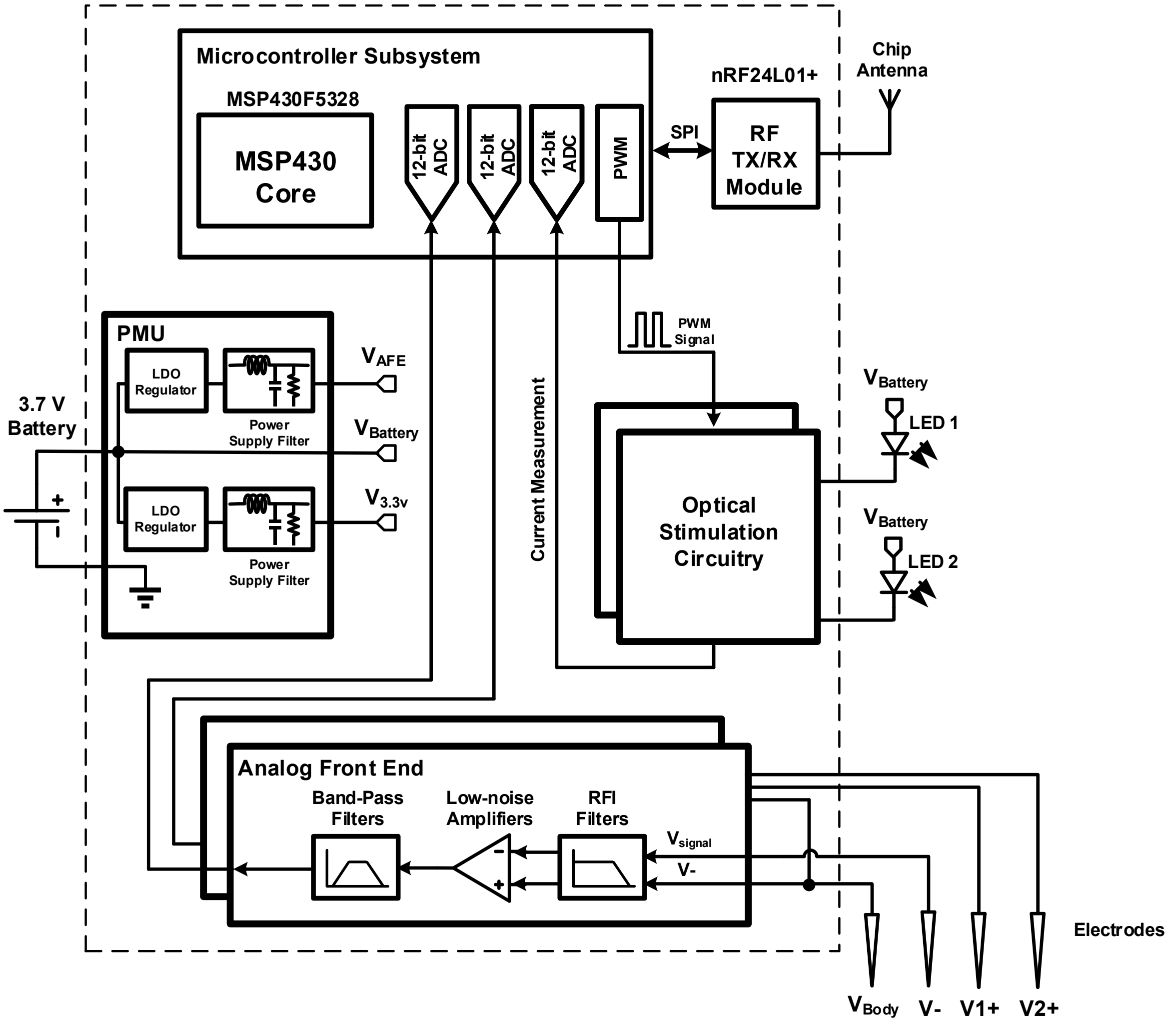

Figure 13. Headstage block diagram.

In the following sections of this chapter we will discuss each subsystem in detail.

4.4 Analog Front-End (AFE)

The AFE, being designed for extracellular signal acquisition, is able to amplify low-amplitude action potentials with minimal distortion. The action potentials are assumed to have worst-case amplitudes between 10 microvolts to 150 microvolts and their frequency content is assumed to be between 300 Hz to 6600 Hz. Changing the lower cut-off frequency can be conveniently done by changing the value of one resistor/capacitor. Figure 14 shows the block diagram of the AFE. The complete schematics of the AFE (and other system components) are available in the appendices.

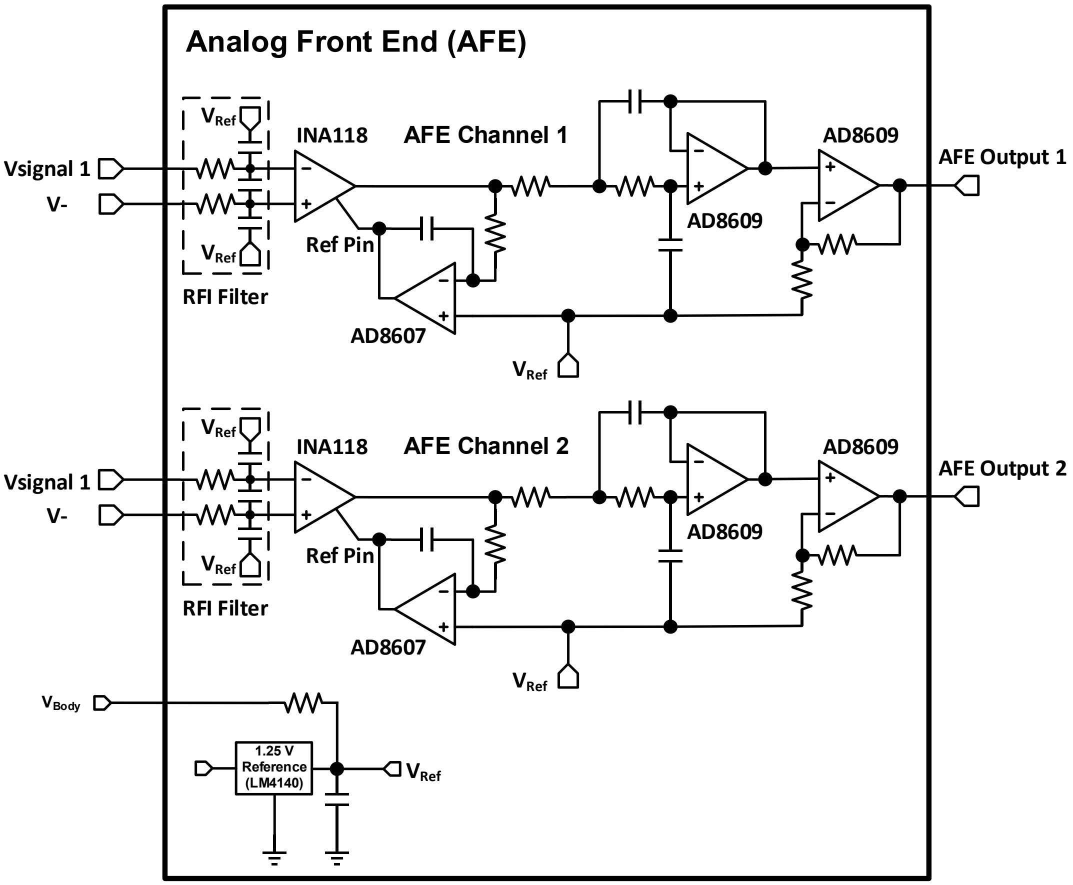

Figure 14. Analog Front End block diagram.

4.4.1 RFI Filter and Preamplifier

The most critical part of the AFE is the preamplifier since it must be as low-noise as possible. In this design, a low-noise low-power instrumentation amplifier from Texas Instruments, INA118 [90], has been used which provides the desired noise characteristics. The INA118 is AC-coupled to the input signals and this is done via another op-amp in a feedback configuration. This feedback adds a high-pass pole to the preamplifier and the cut-off frequency of this pole is determined via the values of one resistor and one capacitor.

This preamplifier is preceded by a passive network, which acts as a radio-frequency interference (RFI) filter [91]. This passive filter is intended to remove the high-frequency signals as the instrumentation amplifiers have very poor CMRR at high frequencies [91].

4.4.2 Mid-Supply Reference

The RFI filter, preamplifier and other parts of the AFE require a stable and low-noise mid-supply reference (a reference voltage equal to almost half the AFE supply voltage). Any noise on this reference voltage will directly affect the low-amplitude signals at the preamplifier terminals. To overcome this issue, a low-noise voltage reference with high PSRR, LM4140 [92], from Texas Instruments has been used. The mid-supply reference is V_{Ref} in the AFE block diagram. The main reason behind choosing a voltage reference rather than a simple but accurate resistive voltage divider is that the resistive voltage dividers tend to have very poor PSRR characteristics.

4.4.3 Low-Pass Filter

After the pre-amplification, the neural signals are passed through a 2nd-order Sallen-Key filter. This filter and the RFI filter, together, provide the AFE with a low-pass cut-off frequency of almost 6000 Hz.

4.4.4 Second Stage Amplifier

The outputs of the low-pass filters are fed to non-inverting op-amp-based amplifiers where these signals are amplified again to a level that is appropriate for the analog-to-digital converter (ADC).

4.4.5 AFE Power Supply Rails and References

The AFE has a 3.0 volt supply voltage that is provided by the PMU and the reference voltage (generated by the LM4140) is 1.25 volts. The 1.25 volt reference voltage biases the input signals at a point where the preamplifier and other op-amps have the best CMRR. The AFE power supply rail has been chosen to be 3.0 volts so a reliable distance between the battery voltage (~3.6 volts) and the LDO (low-dropout regulator) output voltage is kept. As a result, the LDO PSRR is maximized while the *absolute minimum working voltage* of all AFE parts is respected.

4.5 Optical Stimulation Circuitry

The optical stimulation circuitry is responsible for generating stimulation current waveforms in the stimulation LED terminals. This system consists basically of a current source, based on an op-amp. Figure 15 shows the optical stimulation circuitry block diagram.

The PWM waveform, being the stimulation waveform, is provided by the MCU (microcontroller unit) and it has the same voltage level as the MCU logic outputs i.e., 0 volts and +3.3 volts.

The current source is implemented using an op-amp with negative feedback. The LED anode is directly connected to the battery voltage (~3.6 volts) and its cathode is connected to the current course. The feedback mechanism uses a precision ±1% 0.5 Ω resistor to tune the LED current. Since the resistance of 0.5 Ω is comparable to the resistance of a PCB tracks (even short tracks), in the PCB layout of the headstage, the resistor, the op-amp and Q2 are placed as close as possible; also a ground plane provides a low-impedance ground for all the components of the PCB.

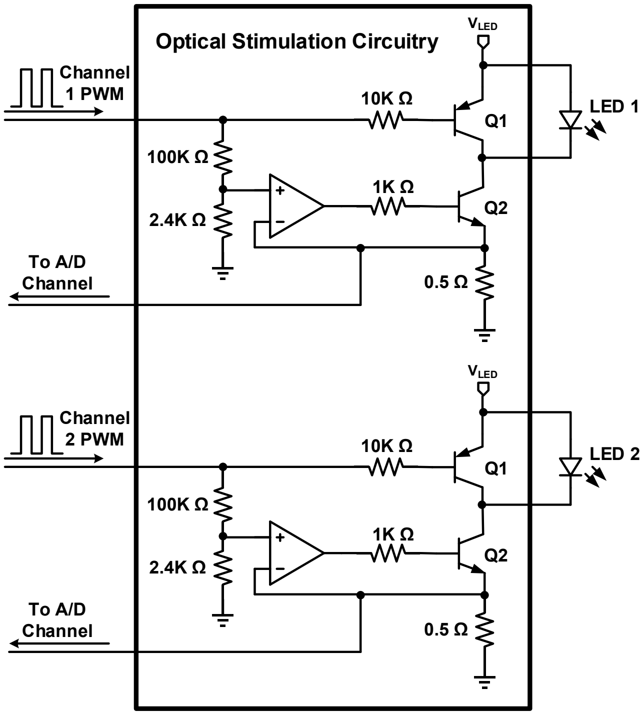

Figure 15. Optical stimulation circuitry block diagram.

In order to control the current and also be informed about the stimulation instances, i.e., when the current is flowing through the LED, the voltage on the 0.5 Ω resistor is monitor by the MCU via one of the A/D (analog-to-digital converter) channels.

4.5.1 LED Current and Sharp Transitions

Since a high amount of current passes though the LED and it needs to be depleted as fast as possible (for the stimulation pattern to have fast rise-/fall-times), Q1 assures that when the PWM is at low state (logical zero), the voltage across the LED is much lower than the conduction voltage (~ 3.3 volts). This allows the LED current waveforms to be sharp i.e., very low rise- and fall-times.

Since the LED current is 150 milliamps when the LED is active, a considerable amount of switching noise can be seen on the battery voltage. This switching noise can be conducted to other components of the headstage. This problem is fully solved by incorporation of high PSRR components and also a power supply filter. More details are available in the PMU section.

4.6 Power Management Unit (PMU)

The PMU is responsible for providing other subsystems of the headstage with stable power supply rails. It consists of two LDOs (Low-Dropout Regulators) with high PSRR and two power supply filters, which remove the high-frequency noise of the power rails. Figure 16 shows the block diagram of the PMU.

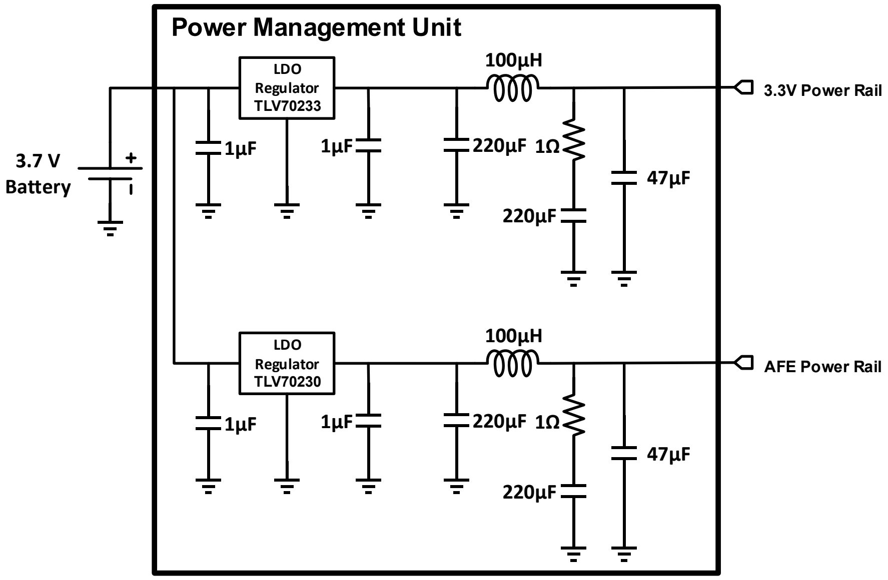

Figure 16. Power management unit block diagram.

The PMU is powered via a 3.7 volt Lithium-Ion rechargeable battery. The battery voltage is high enough so two LDOs can be turned and these two LDOs provide the power for the rest of the components in the headstage system. However, the anodes of the stimulation LEDs are directly connected to the battery's positive terminal rather than any voltage regulator.

It can be seen that one LDO and its power supply filter provides a 3.0 volt power rail for the AFE while the other one provides a 3.3 volt supply for the MCU and the radio transceiver. The reason behind separating the LDOs is 1) minimum noise conduction between the AFE and other components, and 2) a 3.0 volt LDO provides better PSRR than a 3.3 volt LDO when the battery voltage is ~3.6 volts.

4.6.1 Power Supply Filters

The power supply network (Figure 17), being a combination of passive components, provides a very robust removal of high-frequency noise on the LDO outputs. The LDOs that have been chosen (TLV70233 and TLV70230 from Texas Instruments) provide almost 51 dB of PSRR at 100 KHz. The PSRR drops rapidly for higher frequencies. In other words, the PSRR characteristics of these LDOs is very poor at high frequencies. On the other hand, the power supply network is a low-pass network that has a high attenuation at high frequencies. As a result the ensemble PSRR characteristics of the LDOs and the power supply filter provides a high net PSRR at all frequencies. The structure of the power supply filter has been adopted from [93] and its frequency response, after choosing component values, is depicted in Figure 18.

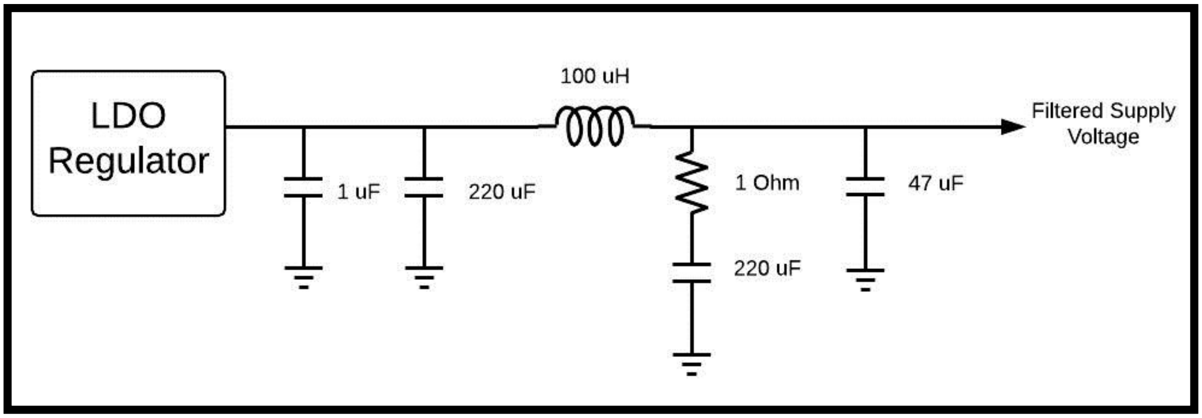

Figure 17. Power supply filter topology.

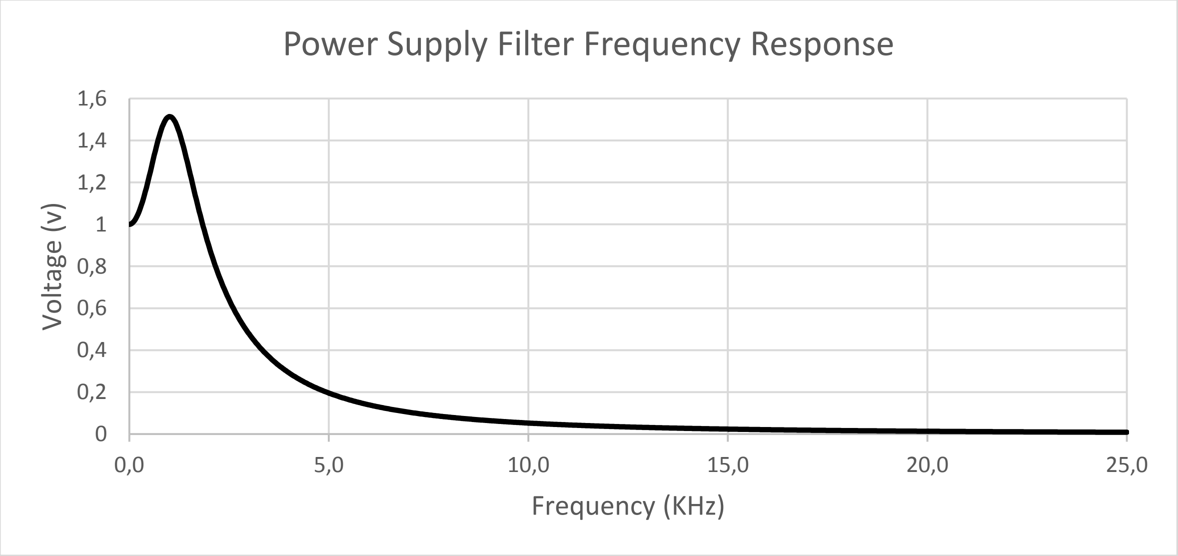

Figure 18. Power supply filter frequency response.

In the headstage system, the noise that the PSRR of LDOs and the power supply filters are targeting to remove is mostly the switching noise of the power supply caused by the LED switching. When incorporating the power supply filters, this noise is significantly reduced and what remains from this noise is taken care of by the high PSRR of the instrumentation amplifiers. This has been proved by measurements and is available in the results in the following chapter.

Finally, it should be mentioned that the power supply filter component values have been chosen for the filter to have the minimum cut-off frequency (the filter has a low-pass behavior). However, lower cut-off frequencies result in bigger electronic components (capacitors, inductors). As a result, there was limitations on the achievable cut-off frequency as the headstage requires small components. The final component values have been chosen as a result of simulations and measurements.

4.7 Microcontroller Unit (MCU)

In this headstage system, a low-power microcontroller, MSP430F5328 from Texas Instruments [94], controls the operation of the headstage. The tasks of this microcontroller include controlling the RF communications, digitizing the output of the AFE and generating the stimulation patterns. This microcontroller, besides occupying a small area on the PCB, has all the necessary peripherals required for the headstage system including the required number of A/D channels and SPI (serial peripheral interface) peripherals. The operating voltage of this microcontroller and its IO (input/output) voltages is 3.3 volts. In order to maximize the power efficiency of this microcontroller an RTOS (real-time operating system) has been used to control the peripherals.

FunkOS [95] has been chosen as the RTOS for its low latency and low memory footprint. Also, FunkOS's programming language, C, its compatibility with MSO430 interrupts and the ease of porting this RTOS to MSP430F5328 have been the driving forces for choosing this RTOS.

During the development phase, the context switching latency of FunkOS has been measured to be almost 35 microseconds, at an operating frequency of 8 MHz, which is the lowest compared to other RTOS like SYS/BIOS, the FreeRTOS and BRTOS. The low context switching latency allows any RTOS task to be interrupted when the A/D buffer is filled. When the A/D buffer is full, the MSP430 DMA (direct memory access) transfers the data to the memory and the microcontroller can send the data to the wireless transceiver.

The firmware running in the MSP430 has the following tasks:

1) One task for receiving commands and configuration from the base station (highest priority).
2) One task for switching the radio transceiver from receiving mode to *idle* mode. This task also synchronizes the beginning of a series of transmission with the base station.
3) One task for transmitting the acquired neural data to the base station when the DMA has finished transferring the data to the pack buffer.
4) One task for putting the microcontroller in sleep mode when no other tasks are being executed.

Figure 19 shows the flowchart of the firmware operation. The complete source code of the firmware is available in the appendices.

When the microcontroller is not executing any task, it is put in sleep mode. In transmitting mode, the microcontroller is awoken every ~800 microseconds, when a 32-byte packet is ready to be transmitted, and the following tasks must be finished before the next packet is ready:

- Context switching (almost 35 microseconds);
- Switching the transceiver mode from Idle to TX (almost 70 microseconds);
- Transferring the 32-byte packet to the transceiver (almost 42 microseconds).

As a result, the MCU can be put to sleep mode for almost 653 microseconds, which equals to 80% of the CPU (central processing unit) time. However, after measuring the sleep time, it has been seen that the MCU is in sleep mode for almost 73% of the time. The reason behind this difference, which translates to less than 7 instructions in MSP430, can be attributed to the overhead added by the execution of some instructions that have not been accounted for.

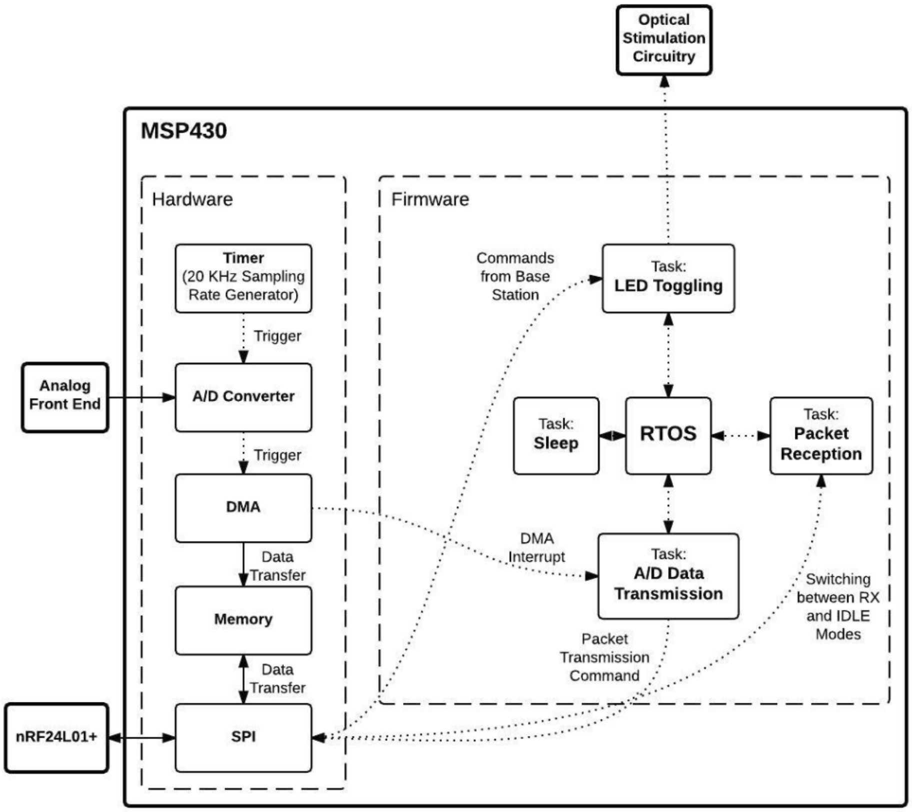

Figure 19. MSP430F5328 firmware flowchart.

4.8 Digital Wireless Transceiver

In order to transmit the received data back to the base station and to receive the stimulation parameters, a modular low-power digital wireless transceiver (nRF24L01+ from Nordic Semiconductor [96]) has been used.

This transceiver is a low-power GFSK radio module operating in the 2.4 GHz ISM (industrial, scientific and medical) band. The raw data of this module can be as high as 2 Mbits per second and the net data rate can be up to almost 700 kbits per second [96]. An SPI interface is available to control the radio and the chip package is QFN (quad flat no-leads) and measures 4×4 mm^2.

This radio module requires an antenna tuned to the 2.4 GHz band and an antenna matching network consisting of capacitors and inductors. In this project, a chip antenna has been used to decrease the system footprint.

Finally, in order to control the radio module, a C library has been developed that is available in the appendices.

4.9 Electromagnetic Compatibility Considerations

Electromagnetic compatibility (EMC) and electromagnetic interference (EMI) problems can happen in almost all electronic systems except for the most trivial ones. Basically, EMC is about the robustness of a system against incoming noise and interference imposed from the environment while EMI focuses on electromagnetic emissions (radiated and conducted) of a system.

In mixed-signal systems where there are fast high-power high-amplitude digital signals in close proximity of low-amplitude analog signals, close attention must be paid to the EMC and EMI of the system. The headstage that is being discussed in this work is a good example of such mixed signal systems. In this headstage, there are microvolt-scale analog signals, fast digital signals, RF signals and also high-current PWM signals.

4.9.1 EMC/EMI and Self-Interference Problems Associated with the Headstage System

The mentioned digital and high-current signals can have a devastating effect on the low-amplitude analog signals in the following ways:

1) First and most importantly, the high-current LED signals can disturb the battery voltage considerably as the anodes of the LEDs are directly connected to the battery. The imposed (switching) disturbance on the battery voltage can be conducted to the outputs of the LDOs, op-amps and instrumentation amplifiers resulting in very poor signal acquisition in the AFE. This type of disturbance on the AFE power rails can totally distort the signal as the fluctuations on the power rails are much larger than the action potentials. This interference can be grouped as conducted emissions.
2) Since the frequency of the stimulation signals (PWM stimulation pattern) is comparable to the frequency content of the action potentials, if the LED stimulation currents and the action potentials share the same ground plane, the return current of the stimulation pattern will heavily distort the action potentials [97]. This type of interference can also be categorized as conducted emission.

3) Any conductor carrying electrical current can be considered as an antenna [97] and the radiated energy can be picked up by other conductors. The amplitude of the radiated energy depends on the different parameters. However two of them are of crucial importance: the frequency and the amplitude. In the headstage, the digital signals have high-speed harmonics and the LED stimulation currents have high amplitudes. As a result, care must be taken when designing the high PCB to minimize the pickup current on the analog signals [97]. This type of interference can be grouped as radiated emissions.
4) Finally, similar to the return currents of the stimulation currents, the return current path of the digital signals may interfere with the analog signals if the current return paths are the same [97].

Besides the mentioned sources of interference, there might be other sources of interference in the environment with potential to affect the operation of the headstage system.

4.9.2 Solutions to EMC/EMI Problems

In the previous subsection, we described different types of interference and their sources. In this subsection, we will present solutions to these problems. These solutions are all PCB design techniques that can be found in different resources talking about EMC/EMI like [97].

The following techniques can alleviate different problems associated with EMC/EMI [97]:

1) The problem of power rails fluctuations can be solved in mainly two different ways: by using components with high power supply rejection ratio and by using proper bypassing [93].
2) The problem of *shared current return path* can arise in PCBs with power/ground planes as well as PCBs without power planes. One way to solve this problem is to separate the power/ground planes of different system components [97] [98].
3) The problem of radiated emissions can be solved by using ground and/or power planes in the PCB design [97]. When a ground plane is available under high-speed PCB traces, most of the return current passes beneath the track in the opposite direction. As a result, the electromagnetic fields created by these currents will cancel out. This means minimum radiation pickup by other traces. In the case of low-frequency but high-current traces, a return path for the current can be drawn (as a PCB trace) beneath the current-carrying trace.
4) Last but not least, PCBs with ground and power planes tend to be much more robust against environment radiations [97] [98].

4.9.3 Headstage PCB Design

In this work, two PCBs have been design for the headstage system. One PCB is a 4-layer PCB with one ground plane, one power plane and two signal layers. This PCB serves as the system prototype. The other PCB is a 6-layer PCB with the required form factor of the headstage. The 6-layer PCB has 4 signal layers, one power plane and one ground plane.

In both PCB designs, the 4 design techniques as well as other PCB design considerations have been used. In the results chapter, we will present the details of the realized PCBs and their performances.