Tampere University

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RAILWAY MICROPHONE SWITCH ELECTRONICS AND DEVICE DESIGN

Master of Science Thesis
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ABSTRACT

Niko Nuutinen: Railway microphone switch electronics and device design
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The aim of this thesis work was to design a microphone switch to be used in rolling stock announcement applications. The device allows to connect up to three microphones into one microphone input one at the time being active.

The base of the design is from a previous project where the similar functionality was achieved using discrete relays. This project has been the starting point for this thesis work and the aim has been to improve this design, add some features and make it into one compact device.

The main functionality of the device is to connect one microphone to the output based on the tangent information from the microphones. The microphone inputs have priorities, one being higher and two being lower. The higher priority is also bypassable to enable more possible applications. In addition to microphone switching, other features are phantom power switching and additional buttons potential-free routing through the device.

The main emphasis of the work was on schematic and layout design. The mechanical design was done by a colleague. The scope of the project was from design phase to first prototype validation. The prototype was validated according to the validation plan to ensure the desired functionality and to find out any design flaws or other areas of improvement.

Since the enclosure did not arrive in time for the testing, ESD-test and mechanical validation could not be performed yet. Other than that the design was proved to work as intended and it met all the requirements. Only minor component value changes are needed which was known beforehand as the values were designed to be fine-tuned with the prototype. In addition, one text label needs to be changed from the enclosure.

As a result the design was successful. After the enclosure arrives the final validation tests can be finished and the prototype is ready for the next phase in productization.

Keywords: microphone switch, PCB design, microphone, relay

TIIVISTELMÄ

Niko Nuutinen: Junan mikrofonivalitsinkytkimen elektroniikka- ja laitesuunnittelu
Diplomityö
Tampereen yliopisto
Sähkötekniikka, DI
Marraskuu 2020

Työn tavoitteena oli suunnitella mikrofonikytkin junien kuulutusjärjestelmäkäyttöön. Laite mahdollistaa enintään kolmen mikrofonin kytkemisen yhteen mikrofonituloon, joista yksi kerrallaan on aktiivinen.

Suunnittelun pohjana toimi aikaisempi projekti, jossa vastaava toiminnallisuus oli toteutettu diskreeteillä releillä. Projekti toimi tämän työn lähtökohtana ja tavoitteena oli parantaa tätä toteutusta, lisätä siihen ominaisuuksia ja suunnitella siitä kompakti laite.

Laitteen päätoiminnallisuus on mikrofonin kytkeminen sen ulostuloon mikrofonien tangenttitiedon perusteella. Mikrofonituloilla on prioriteetit niin, että yksi tuloista on korkeamman prioriteetin ja kaksi matalamman. Korkeampi prioriteetti on mahdollista kytkeä pois, joka mahdollistaa enemmän käyttökohteita. Mikrofonilinjojen kytkemisen lisäksi laitteen muita ominaisuuksia ovat phantom-jännitteen kytkeminen sekä lisäpainonappien potentiaalivapaa ohjaus laitteen kautta.

Työn pääpaino oli piirikaavio ja -levysuunnittelussa. Mekaniikan suunnitteli kollega. Työn laajuus oli suunnitteluvaiheesta ensimmäiseen prototyyppiin. Prototyyppi validoitiin validointisuunnitelman mukaisesti, jotta haluttu toiminnallisuus pystyttiin todentamaan ja löytämään mahdolliset suunnitteluvirheet tai muut parannuskohteet.

Mekaniikka ei saapunut ajoissa testaamista varten, joten ESD-testejä ja mekaniikan validointia ei voitu tehdä vielä. Näitä lukuun ottamatta laite toimi suunnitellusti ja täytti kaikki vaatimukset. Vain pieniä komponenttiarvojen muutoksia pitää tehdä, joka oli tiedossa jo etukäteen, sillä arvot oli suunniteltu hienosäädettäväksi prototyyppivaiheessa. Lisäksi yksi tekstimerkintä kotelon kannesta täytyy muuttaa.

Kaiken kaikkiaan toteutus oli onnistunut. Kotelon saapumisen jälkeen viimeiset validointitestit voidaan toteuttaa ja prototyyppi on valmis seuraavaan vaiheeseen tuotteistamisessa.

Avainsanat: mikrofonikytkin, piirilevysuunnittelu, mikrofoni, rele

PREFACE

I'd like to thank Seppo Saukko and Teleste for giving me the opportunity to do do this thesis work at Teleste. I'm grateful for all the tips and help from the colleagues during the work. Especially Saku Jaurimo and Vesa Ahtiainen kindly offered their knowledge and time countless times during the project. I want to also thank my instructors professor Karri Palovuori and university lecturer Erja Sipilä for helping me with all the practical questions. Last but definitely not least I want to thank my family and friends for continuously supporting me through this from time to time stressful project.

Tampereella, 23rd November 2020

Niko Nuutinen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternative current
ADP	Ammonium dihydrogen phosphate
AlN	Aluminium nitride
DC	Direct current
DIP	Dual in-line package
DKT	Dipotassium tartrate
DPDT	Dual-pole-dual-throw
EMC	Electromagnetic compatibility
ESD	Electrostatic discharge
HF	High frequency
IC	Integrated circuit
IPAMP	IP audio amplifier
KDP	Potassium dihydrogen phosphate
LF	Low frequency
MEMS	Microelectromechanical systems
NC	Normally closed
NO	Normally open
PCB	Printed circuit board
PTT	Push-to-talk
PVDF	Polyvinylidene fluoride
PZT	Lead titanate
RF	Radio frequency
SMD	Surface-mount device
SNR	Signal-to-noise ratio
SPDT	Single-pole-dual-throw
SPST	Single-pole-single-throw
TVS	Transient-voltage-suppression

ZnO	Zinc oxide

1 INTRODUCTION

The objective of this thesis was to design a microphone switch allowing to connect up to three microphones into one microphone input. The device is intended to be used with the Teleste IPAMP (IP audio amplifier), an IP audio amplifier for rolling stock announcement applications, when additional microphone inputs are needed which are not required to be active simultaneously.

There are several different use cases where multiple microphone inputs are needed but only one being active at the time. One possibility is to have the drivers microphone with higher priority and two side microphones for both sides of the train with lower priority. Another possible use case would be to connect background noise measuring ambient microphone to lower priority input and then have two other microphones with higher priority. Naturally there are many more possible configurations and the aim was to design the device to be as flexible as possible while keeping it simple and reliable. Illustration of general device application is shown in figure 1.1.

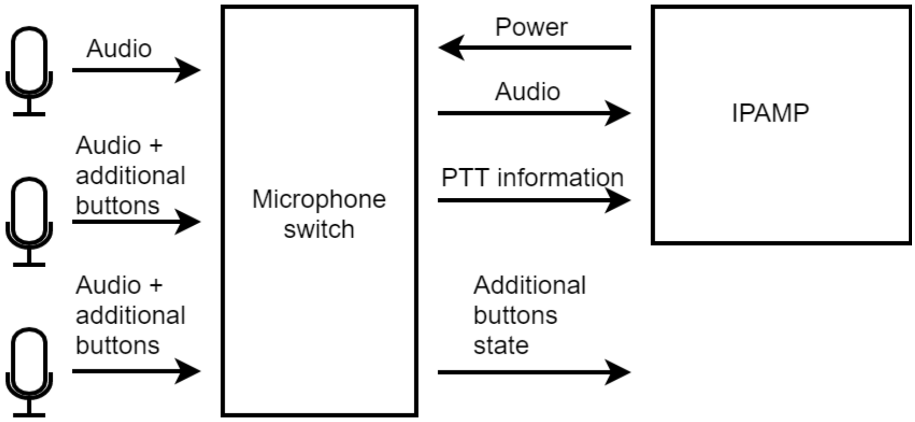

Figure 1.1. *Illustration of general device application.*

The base of the design was from previous project where similar functionality was implemented using discrete relays. Some initial design for the device was done earlier based on that project. The aim of this thesis work was to improve this implementation by designing one compact product with more universal compatibility and added features. These added features include microphone input priorities, phantom power switching, and additional buttons potential-free routing through the device.

Main emphasis of the thesis was on electronics design including schematic and layout design. Also the functionality requirements developed through the design process. Mechanics were designed by a colleague. The thesis was done at Teleste information solutions Oy which provides video security, passenger information and display solutions.

Chapters 2, 3 and 4 discuss about the theoretical background related to the thesis. In chapter 2 microphones are discussed in general and different microphone types are presented including pickup patterns and transducer types. Also newer MEMS (microelectromehanical systems) microphones are briefly introduced. Major part of the thesis is PCB (printed circuit board) design and guidelines for PCB design are discussed including grounding, layout and layer stackup. These are covered in chapter 3. In chapter 4 are covered relays and relay transient suppression methods.

Chapter 5 concentrates on the design of the device. First the design process of the functionality is presented. After functionality design schematic and layout designs are discussed. Chapter 6 covers prototype testing and validation. Finally the conclusions are in chapter 7.

2 MICROPHONES

Microphones are used to convert acoustical energy into electrical energy. To accomplish this all microphones have either a diaphragm or a moving surface. This diaphragm or moving surface is excited by an acoustical wave creating electrical signal representing the acoustical input. [1, p. 5] General microphone operating principle is shown in figure 2.1.

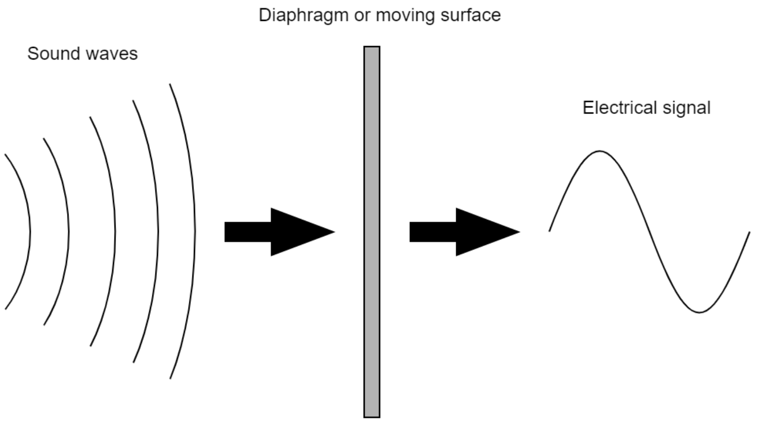

Figure 2.1. *General microphone operating principle*

Microphones can be classified based on different qualities. Sound sources vary significantly by their characteristics. Different sound sources have different waveforms, dynamic ranges and so on. To be able to reproduce individual sound sources characteristics well, different qualities are required. [1, p. 4]

In this text qualities used for classification are pickup patterns and types of transducers. Different types of pickup patterns include omnidirectional, bidirectional and unidirectional microphones. A microphone can have one or multiple different selectable pickup patterns. Transducer types covered are carbon, crystal and ceramic, dynamic, capacitor and electret microphones. There are some other types of pickup patterns and transducers as well which are not covered here. In addition, MEMS microphones are shortly introduced.

2.1 Pickup patterns

Omnidirectional microphones have spherical polar response. This is achieved by exposing only the front side of diaphragm with the acoustic wave. As the acoustic wave is only hitting the front of the diaphragm, there are no cancellations. Therefore all the signals from sides, rear and front have the same pickup sensitivity. Although this is true only as long as the signal wavelength is longer than the diameter of the microphone. As the wavelength reaches diameter of the microphone, sound waves coming from off axis are no longer able to bend to the microphone diaphragm. This makes omnidirectional microphones increasingly directional as the frequencies increase. [1, p. 5] Omnidirectional pickup pattern is shown in figure 2.2.

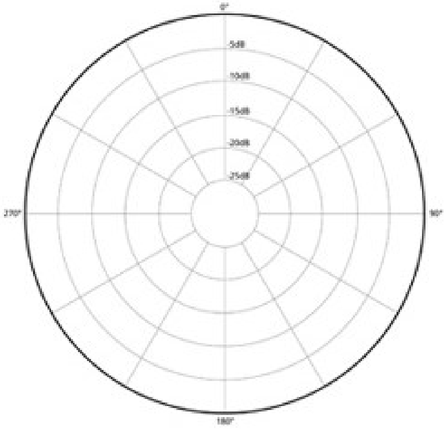

Figure 2.2. *Omnidirectional pickup pattern. Adapted from [2].*

To have a flat frequency response at higher frequencies, smallest possible microphone diameter is preferred. As downside decreasing size of the microphone lowers SNR (signal-to-noise ratio) as it lowers the microphone sensitivity. This leads to balancing between flat and smooth frequency response opposed to good SNR. Spherical pickup pattern makes omnidirectional microphones ideal for capturing sounds from different directions. Drawback is picking up also the unwanted noise in a noisy environment. [1, pp. 8-9]

Bidirectional microphones pickup sound equally well from the front and back while cancelling most of the sound coming from the sides. This lowers the background noise compared to omnidirectioanl microphone. Bidirectional microphone is useful when two sound sources from opposite directions are wanted to be captured. Increased directivity also enables 1.7 times greater pickup distance before feedback in direct field compared to omnidirectional microphone. [1, p. 9] Bidirectional pickup pattern is shown in figure 2.3.

Unidirectional microphones have highest sensitivity to acoustic waves coming from front while cancelling most of the sound from any other direction. Normal front-to-back

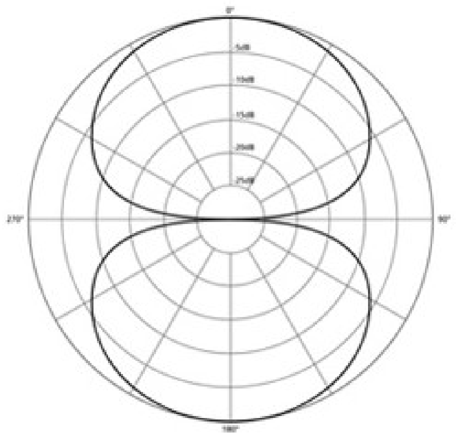

Figure 2.3. *Bidirectional pickup pattern. Adapted from [2].*

ratio of an average unidirectional microphone is 20-30 dB. This makes unidirectional microphones more resistant to background noise enabling more gain before feedback. Directionality also helps to discriminate different sound sources which is useful in many cases. [1, p. 10]

Unidirectional microphones have different type of cardioid patterns like cardioid, supercardioid and hypercardioid. The cardioid pattern is usually produced using one diaphragm and acoustically delaying the sound wave before it reaches the rear of the diaphragm. Phase difference between sound waves hitting the front and rear is something between 0° and 180°. Ideally the phase difference is 180° which doubles the output as it adds the rear input to the front input. Sound waves coming from the rear cancel the output as they hit both the rear and front at the same time with the same phase 0°. [1, p. 12] Cardioid pickup pattern is shown in figure 2.4.

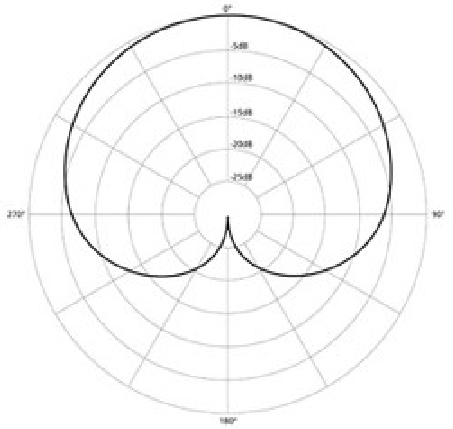

Figure 2.4. *Cardioid pickup pattern. Adapted from [2].*

2.2 Transducer types

Some of the earliest microphones were manufactured using carbon granules. Carbon microphones were commonly used with telephones for many decades. Its limited bandwidth and dynamic range were not a problem in telephony. [3, pp. 2-3] Carbon microphone consists of a loose pack of carbon granules and a diaphragm connected to the pack. Constant bias current flows through the carbon granules. The resistance of the carbon granules is altered when the sound waves move the diaphragm. Alternating resistance causes changes in potential over the pack inversely proportional to the sound pressure. [4, p. 204] Simplified diagram of a carbon microphone is shown in figure 2.5.

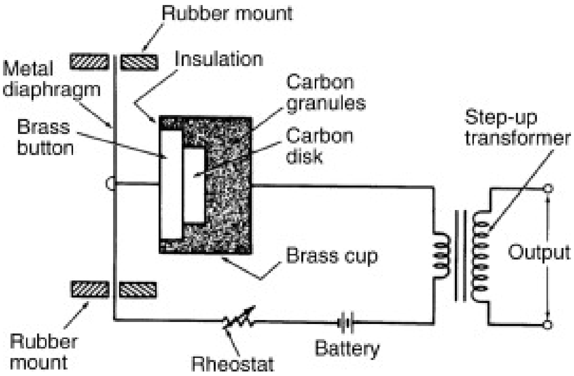

Figure 2.5. *Simplified diagram of carbon microphone [1].*

Advantages of carbon microphones are their simplicity and high sensitivity. Other than those, there are several downsides. Non-linearity of the carbon pack causes distortion. There is also a large amount of self-noise and eroding of the carbon granules causes decrease of sensitivity over time. [4, pp. 206-211]

Other previously popular transducer types are crystal and ceramic. They are cheap and have high-impedance high-level output. This allowed them to be connected directly to the input of a tube amplifier. Especially popular they were with home tape recorders as they had high input impedance and short microphone cables. [1, p. 24-25] Shunt capacitance causes HF (high frequency) losses in the cable which limits the cable length between the microphone and amplifier [3, p. 60]. Simplified diagram of crystal microphone is shown in figure 2.6.

Crystal and ceramic microphones are based on piezoelectric effect. These materials produce voltage proportional to applied pressure. [1, p. 25] Earliest materials used were Rochelle salt, ammonium dihydrogen phosphate (ADP) and lithium sulfate crystals [4, p. 233]. Ammonium dihydrogen phosphate and lithium sulfate are still used but new materials are also utilized such as dipotassium tartrate (DKT), potassium dihydrogen phosphate (KDP), lead zirconate and lead titanate (PZT). Ceramic materials require polarization process to have piezoelectric properties. [1, p. 25]

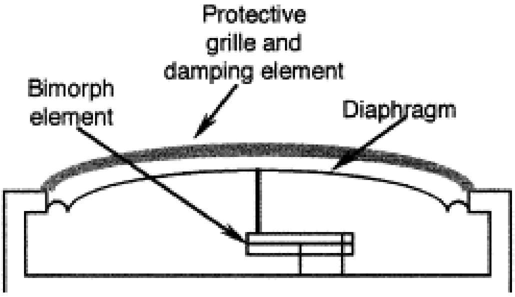

Figure 2.6. *Simplified diagram of crystal microphone. Adapted from [3].*

Typical frequency response for crystal and ceramic microphones is from 80 to 6500 Hz, but it can be extended to 16 kHz. Their output impedance is high, around 100 kΩ, so high load impedance in megaohm range is required. [1, p. 26]

Dynamic microphone operation is based on magnetic induction. Small diaphragm connected to a voice coil moves in a permanent magnetic field causing an output proportional to the sound waves hitting the diaphragm. [1, p. 26] Simplified diagram of the dynamic microphone is shown in figure 2.7.

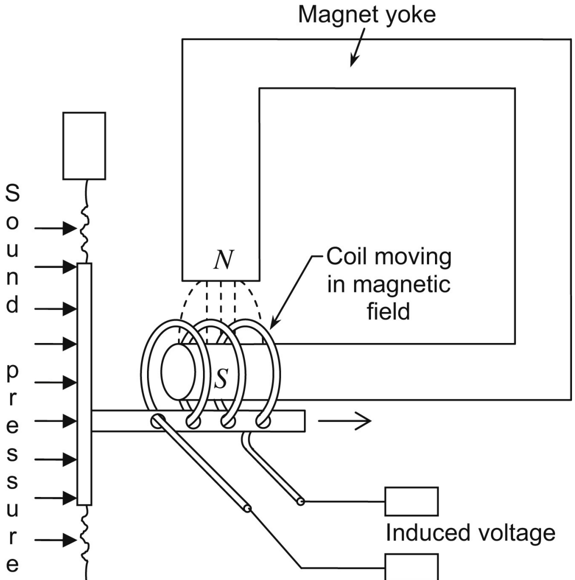

Figure 2.7. *Simplified diagram of dynamic microphone [5].*

The mechanical mass and compliance of the coil and diaphragm will have mechanical resonance. The resonance is usually designed close to the geometric mean of the frequency response. This resonance peak is damped with an acoustic resistor, typically layers of silk or a thin felt between the coil and the back of the air chamber. The drawback of dampening resonance peak is decreased sensitivity in midband. Typically resonance peak is reduced about 25-35 dB. [3, pp. 53-54]

In addition to resonance peak dampening, additional LF (low frequency) and HF compensation is needed. The LF response falloff is compensated by adding a tube inside the microphone housing coupling from the microphone housing cavity to the outside. Dimensions of the tube will determine the self resonance frequency extending the LF response. HF response falloff is compensated with a small resonant chamber inside the diaphragm extending HF response. [3, p. 54]

Capacitor microphone also called condenser microphone operation is based on a capacitor, the diaphragm of the microphone acting as one capacitor plate and the back electrode as the other. The capacitor is polarized with bias voltage through large resistor which keeps the charge of the capacitor constant apart from low frequencies. [4, pp. 211-212] These frequencies are below audio frequency range thus in audio frequency range the charge stays constant [1, p. 31].

According to the relation $Q = CE$ as the diaphragm moves with sound waves and charge Q stays fixed, capacitance C changes causing output voltage E proportional to the displacement of the diaphragm. [4, pp. 211-212] Simplified version of a capacitor microphone electrical circuit is shown in figure 2.8.

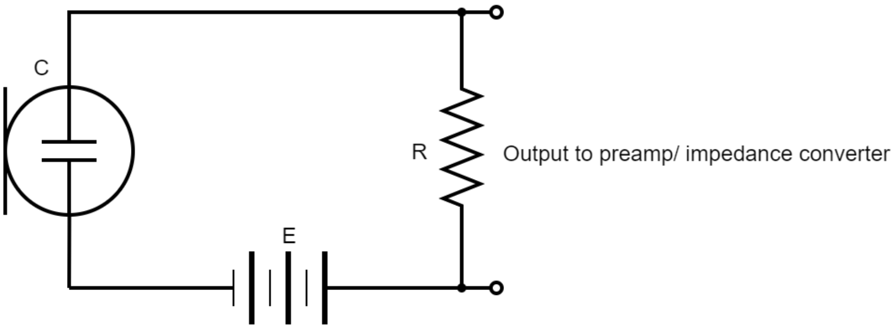

Figure 2.8. *Simplified electrical circuit of capacitor microphone. Adapted from [3].*

The large value resistor across the circuit causes the output impedance to be high. Internal preamplifier is needed to remove the loading from the circuit preserving the frequency response characteristics. [6]

The bias voltage is called phantom power. Typical bias voltage for studio-grade condenser microphones is 48-65 volts. For instrumentation microphones it can be in range of 200 V. [1, p. 32] Condenser microphones are typically balanced, so they have two signal connectors and one connector acting as a ground and shield. Balanced audio signal is differential and therefore as the bias voltage is applied to the both conductors, it cancels out in balanced microphone input. The most common bias voltage is 48 V. It should be distributed through 1/4 W ±1 $\%$ 6.8 kΩ resistors. [6]

Condenser microphones have several advantages. Due to their rigid small and low-mass diaphragms the vibration pickup is lowered. The frequency response is wide and smooth. Their robust structure allows measurement of high sound pressure levels. [1, p. 35] Long continuous operation at high humidity might increase the noise because of the leakage current across the insulators. Though it is not permanent and desiccation restores the quiet operation. [7, p. 216] Also the need for external bias voltage can be considered as a disadvantage.

Electret microphone is a type of a capacitor microphone with permanent charging in transducer capacitor. This removes the need for the external bias voltage. The electret is prepolarized with a strong electric field under heat. After removing the heat, the electric charge is remained. Electret can be thought as an electrostatic equivalent of permanent magnet [3, p. 46] and to be exact, the name electret comes from the electrostatic magnet [7, p. 397]. Modern electret materials make it possible to achieve performance characteristics of a standard condenser capsule [3, p. 46].

2.3 MEMS microphones

MEMS microphones typically use mainly traditional microphone transducer principles but they differ in the size and materials used. In MEMS, semiconductor microelectronics and the micromachining technology are combined. Main principles used in MEMS microphones are piezoresistive, piezoelectric, capacitive and optical membrane vibration detection. [8] MEMS microhpones are widely used in smartphones, laptops, tablets and so on [9]. Some new rolling stock devices are also utilizing MEMS microphones.

MEMS microphones have several advantages over existing conventional devices improving their cost/performance factor. These are such as possibility to manufacture large quantities reducing costs, device miniaturizing and possibility to integrate acoustic transducers with ICs (integrated circuit). [8]

Piezoresistivity is similar to piezoelectricity discussed earlier but instead of electrical charge, resistivity changes as an effect of deformation or mechanical stress. Piezoresistive MEMS microphones are robust, easy to manufacture and because of the low output impedance no integrated electronics are needed. Downsides are high noise floor and power consumption. Piezoresistive materials also have thermal degradation. [8]

Piezoelectric MEMS microphone has the same operating principle as the traditional piezoelectric microphone. The difference comes in size and manufacturing techniques. Piezoelectric microphone implementations differ based on used materials. Common materials used are zinc oxide (ZnO), aluminium nitride (AlN), aromatic polyurea, polyvinylidene fluoride (PVDF) and lead zirconate titanate. As opposed to piezoresistive microphones piezoelectric microphones have low power consumption and no need for an additional power supply. At the same time the high noise floor is still present as with piezoresistive microphones. Heat and humidity also cause aging of piezoelectric crystal. [8]

Capacitive MEMS microphone has the same operating principle as traditional capacitor microphone, it is just smaller. The airgap between the capacitor plates is really narrow so to maximize the response the diaphragm should be as thin as possible. Capacitive MEMS microphones can also be implemented with an electret to remove the need for external biasing voltage allowing portable applications. Advantages of capacitive MEMS microphones are relatively high sensitivity, extensive bandwidth, low power consumption and noise. There are certain disadvantages such as instability caused by electrostatic pull and attenuation of the output because of parasitic capacitance. [8]

Another MEMS microphone technique is optical MEMS microphone. Instead of converting audio signal directly to electrical signal, it first converts audio signal to optical signal which is then converted to electrical signal. The conversion is based on modulating light. More detailed analysis of the working principle is not covered here. Advantages of optical MEMS microphones are higher immunity to electromagnetic interference and temperature. Disadvantage is generally need for complex circuits to perform the conversion from optical signal to electrical signal and precise alignment of all the system components. [8]

3 PCB DESIGN GUIDELINES

PCB is the foundation of most electrical devices. It serves several purposes main function being creating connections between components. The PCB substrate also serves as a mechanical base and a thermal connection to the components. In more advanced cases electronic characteristics of the PCB such as controlled impedance, inductance, capacitance and resistance can be designed according the needs. [10]

3.1 Grounding

Grounding is an essential part of any electrical circuit. Proper grounding is needed to have a noise-free and safe system. Although having safe system doesn't mean it is noise-free and vice versa. Grounding is easily taken for granted which can lead to time consuming and costly noise problems after the device is built and tested. This is why careful attention to grounding should be paid at the design phase as it will eventually save time and money. [11, p. 106]

Term "ground" can be a little confusing as it is used to refer several things. It can mean the safety earth to protect in faulty operation, a ground plane on high frequency PCB or a thin trace for analog signal return path on PCB. They all have different requirements yet they are all still commonly referred as ground. [11, pp. 106-107]

Technically grounds can be divided into two categories, safety grounds and signal grounds. Safety grounds do not carry current in normal operation, only in case of fault. They are used to protect the user and surroundings in case of fault from electric shock or fire. In opposite to safety ground, signal ground carries current in normal operation and therefore should be rather called as returns. They could be further subdivided to signal and power returns based on the current they carry. To separate them from safety ground, if term ground is used, they should be called "signal ground" and "power ground". Nevertheless, they all are typically referenced as ground. [11, p. 107] In this text greater attention is put on signal ground.

To have a properly working ground, there are three basic rules to follow. Ground return path should not be interrupted, current loops for the return currents should be smallest possible and possible common impedance coupling needs to be acknowledged. [11]

The crucial factor of grounding is the ground conductor impedance Z which is defined as

$$Z_g = R_g + j\omega L_g$$

where R_g is the ground resistance and L_g the ground inductance. Equation shows the frequency dependency of ground impedance. At the low frequencies resistance is dominant and at the high frequencies inductance. [11, p. 121]

Ground conductor behaves as any connector meaning it will have voltage drop, if current flows through it according to Ohm's law

$$V_g = I_g \times Z_g$$

To minimize the ground noise, ground impedance Z_g and ground current I_g need to be as low as possible. Lowering the ground impedance is usually applied with high frequency and digital circuits using low inductance ground plane or grid. In analog circuits I_g can be lowered by using individual ground return paths. [11, p. 122]

There are three ways to implement signal ground which are single-point, multipoint and hybrid ground. They are suitable for different type of circuits and all have their advantages and disadvantages. Knowledge of the circuit, like the frequencies present, is needed to choose the right method. [11, p. 123]

Single-point grounding is suited for low-frequency signals, from DC (direct current) to up to around 20 kHz. Using single-point grounding it is possible to determine the return current path. It lowers the ground noise as the current I_g decreases and also helps preventing ground loops. [11, pp. 124-125]

Single-point grounding can be done either in series or in parallel. Series is the simplest one but also the most undesirable method. Series connection adds common impedance as all the return currents add up in the return path. [11, pp. 124-125] Series single point ground is shown in figure 3.1.

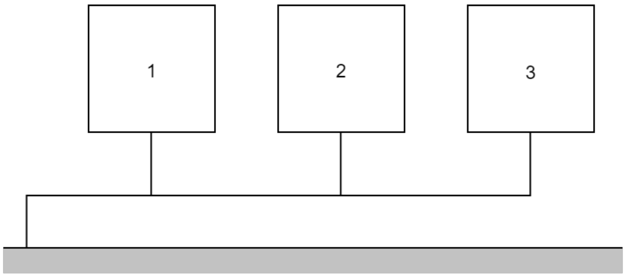

Figure 3.1. *Series single point ground. Adapted from [11].*

More recommended method is parallel connection where all the return paths connect in one point removing the cross coupling between different circuits. This method however will become easily complicated in a larger system because of the high number of ground return conductors. The combination of both series and parallel connections is often the practical compromise. [11, pp. 124-125] Parallel single point ground is shown in figure 3.2.

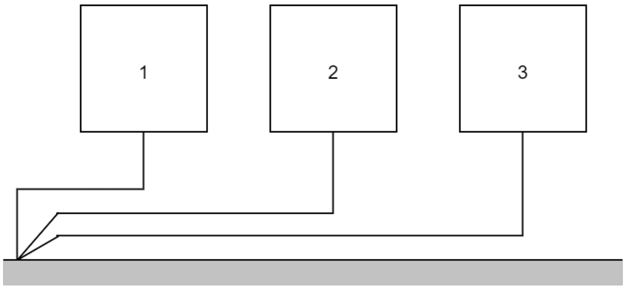

Figure 3.2. *Parallel single point ground. Adapted from [11].*

For high frequencies, above 100 kHz, and for digital circuits single-point grounding is not an option and multipoint grounding is used instead. To minimize the ground noise, the ground impedance needs to be minimized. With the high frequencies the inductance is the dominant character. Low inductance is achieved the best by using a ground plane which allows short low inductance connections to the ground. To lower the inductance even more, multiple connections between the circuit and ground plane are preferred. If there is no possibility of having a ground plane, similar results can be achieved with a ground grid. [11, pp. 126-128] Multipoint ground is shown in figure 3.3.

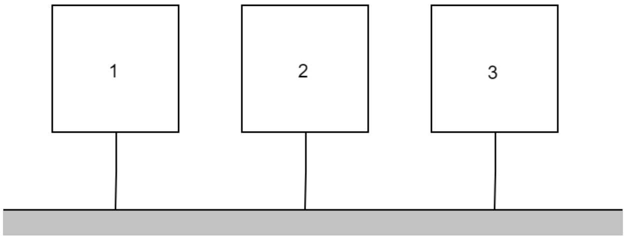

Figure 3.3. *Multipoint ground. Adapted from [11].*

Third option is using a hybrid ground. This might be useful when there is wide frequency range covered. In hybrid ground low frequency signals are connected with the single point grounding and higher frequencies are connected with the multipoint grounding via capacitors. [11, p. 130] Hybrid ground is shown in figure 3.4

In analog or digital circuits with mixed package sizes where ground connections are made in random fashion, the ground plane is advantageous. This usually requires a multilayer board as the ground plane should be continuous with as little interference as possible. All the cuts or tracks in the ground plane decrease its effectiveness and should be avoided. [12]

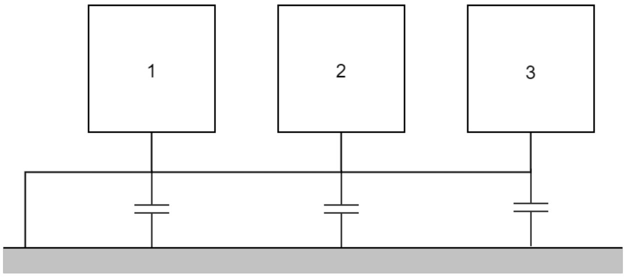

Figure 3.4. *Hybrid ground. Adapted from [11].*

3.2 Layout

Designing the layout there are typically two aims. First is manufacturability of the bare board. Second one is ease of assembly, test, inspection and repair of the finished system. These both lead in to lower cost and better reliability. [12] In addition to ease of manufacture and assembly, layout plays critical role in functionality and EMC (electromagnetic compatibility) performance [11, p. 622].

The design rules that should be considered when starting to design the board include track width and spacing, hole and pad diameter, track routing, ground distribution, solder mask, component identification and surface finish, terminations and connections. These depend both on requirements of the design and capabilities of manufacturing techniques. [12]

Track width and spacing are the major factors determining the obtainable packing density of the board. For low current tracks the limiting factor of the minimum track width is the controllability of the etching process and the layer registration with multilayer boards. Different manufacturers have different processing capabilities but the current narrowest tracks and spacing can be down to 0.1 mm wide. With critical signals the resistance of the conductor needs to be considered as narrowing the track width will naturally increase its resistance. [12]

Voltage breakdown and cross talk needs to be taken into account in determining the spacing. In dry and non conductive particles containing environment spacing of 1 mm per 200 V is sufficient to prevent voltage breakdown. In low-voltage applications voltage breakdown is not likely to cause any concerns. [12]

Cross talk is more likely to cause some limitations on low-voltage digital or high-speed analogue boards. Cross talk occurs because of the mutual coupling between tracks. If connections are electrically short they can be spaced closer without too much concern. Also routing ground conductor between susceptible signals decreases cross talk. [12]

The primary rule of track routing is minimizing the track length. Short track lengths improve their EMC performance as they are less susceptible to interference and cross talk, the parasitic reactance is lower and they radiate less. [12] Track routing goes hand in hand with the component placement. Components should be placed in functional groups. Groups should be positioned on the board so that critical signals like high frequency or sensitive analog signals have minimal interference. Properly positioned functional groups allow shorter track lengths and improve signal quality. [11, p. 622] If possible, all the components should be oriented the same way, particularly the polarized ones. This helps with the inspection and component insertion in production phase. [12]

Track angles should be 45 degrees allowing modest increment in signal density. With right and acute angles there is a risk of etchant traps which might lead to track corrosion and therefore should be avoided. [12]

Empty areas of the top and bottom sides of board can be filled with copper connected to ground. This is called a ground fill or a copper pour and the aim is to decrease emissions and susceptibility by decreasing the signal traces field fringing and by providing extra shielding on the board. The fill must be connected tightly to the existing ground from multiple points. Otherwise it will have an opposite effect and can cause an ESD (electrostatic discharge) problem. Ungrounded copper areas will also increase cross talk. [11, p. 634]

Testabilitiy needs to be addressed in the layout design phase. Testing is essential to ensure that the final PCBs are working as intended. Making sure that all the important signals and test points are easily accessible makes testing efficient. [12]

3.3 Layer stackup

Number of layers and how they are stacked has great impact on EMC properties of the PCB. It also affects the routing and component placement. There are options from single and double layer boards to multilayer boards depending on the requirements and budget. [11, p. 635]

Single and double layer boards are suited for the low frequency circuits. They are problematic with higher frequency signals and require careful attention in design. Dedicated power and ground planes are not possible with single and double sided boards. Their only advantage is low cost. [11, p. 636]

Raising the layer number to four allows having dedicated ground and power planes between the top and bottom layers. This lowers the radiated emissions significantly. It also gives more flexibility and signal integrity in routing as the power and ground are not on the signal layers and they are accessible through vias at every point of the board. [11, pp. 637-638]

Adding even more than four layers allows having multiple ground and power planes as well as internal track layers. This is necessary with more complex boards with high frequency signals. With multiple layers the layer order has great impact on EMC properties. Having multiple ground planes allows shielding high-frequncy signals by burying them between the ground planes. [11, pp. 637-642]

4 RELAYS

Electromechanical relay is a switch which state is operated by energizing or de-energizing it. Typically it consists of wire coils and a moving iron armature held back with a spring. The control current flowing through wire coils causes magnetic force which moves the iron armature changing the state of the relay. There are also solid state relays which have no moving parts but they are not covered here. [13, pp. 1007-1009] Typical relay structure is shown in figure 4.1.

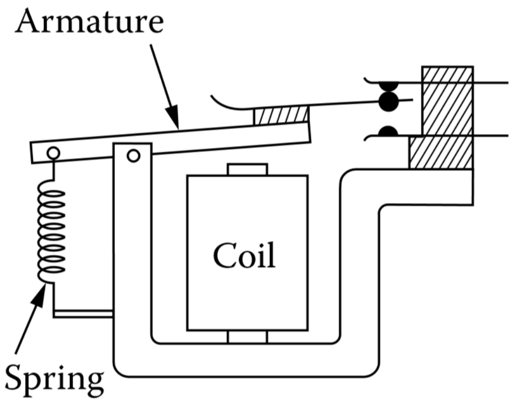

Figure 4.1. *Typical relay structure. Adapted from [13, p. 1009].*

The relay contacts are typically referred as NO (normally open) and NC (normally closed). They indicate the state of the relay contacts in de-energized condition. Relays can be also referred by the number of contacts they have. Common options are SPST (single-pole-single-throw), SPDT (single-pole-double-throw) and DPDT (dual-pole-dual-throw) shown in figure 4.2. [13, p. 1008]

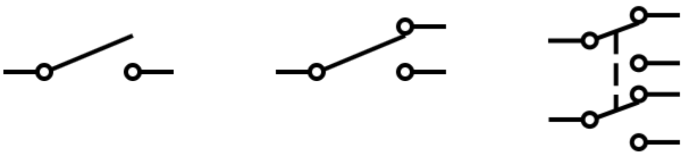

Figure 4.2. *SPST, SPDT and DPTD switches in respective order.*

Relays have different features and the contact capacities and coil energies vary significantly. Relays can be used to control both AC (alternative current) and DC potentials up to thousands of volts and frequencies from DC to all the way to RF (radio frequency).

Switching times and power handling capacities are often contrary. Fast switching means typically lower power handling and high power handling lower switching speed. [13, pp. 1007-1008]

Electromechanical relays are prone to cause EMC problems if left unconsidered due to their operation principle. Mechanical motion created with electrical signal usually results to creating a magnetic field moving permanent magnet or magnetising a metal actuator. In addition to this intentional electromagnetic field, moving magnetic and metallic objects can cause electromagnetic interference. [14, pp. 107-108]

To have properly functioning device when using relays, attention must be paid to EMC design point of view. With relays there are two potential EMC problem sources. First one being the inductive character of the coil and the second one being the bouncing of the switch contacts. [14, p. 109]

Transient protection is needed to protect other circuits from transients caused by de-energising the relay coil. To reduce possible radiation to surroundings, the transient protection circuit needs to be placed at the relay coil terminals. [14, p. 109]

There are several options to implement the transient protection. Common alternatives for DC relays are zener diodes, reverse biased rectifier diodes, resistors or combinations of those and varistors (voltage variable resistors). [15] For switch contact bouncing general suppression methods can be applied. From the EMC point of view the solid state relays are better as the drive element is low or non-inductive and there is no mechanical switch action. [14, p. 109]

The simplest transient suppression method is a resistor parallel to the coil shown in figure 4.3 A. As the switch closes the steady state current continues to flow through the resistor. Therefore the transient voltage peak will be equal to steady state current times resistor resistance. The voltage across coil will be operating voltage plus the induced voltage. Since there is a current flowing through the resistor in steady state as well, there will be constant power loss. [11, pp. 315-316]

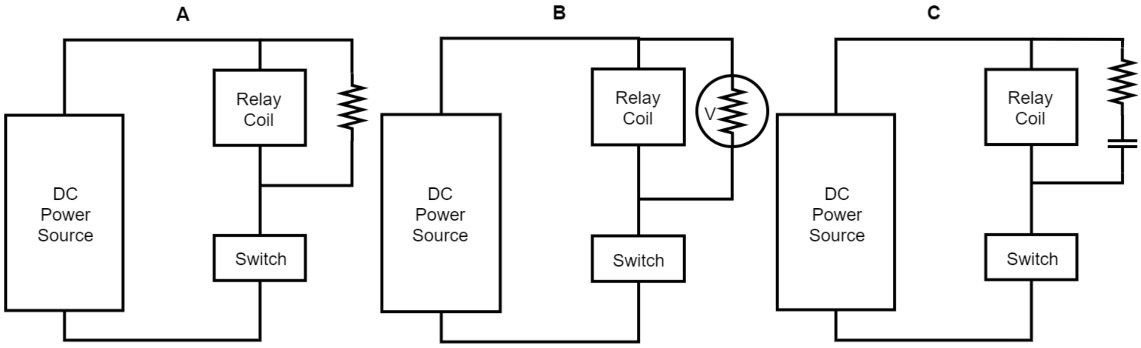

Figure 4.3. *Relay transient suppression with resistor, varistor and resistor and capacitor in series.*

Resistor power dissipation can be reduced by switching the resistor to a varistor shown in figure 4.3 B. With low voltage across it, the resistance is high and vice versa. Transient suppression operates as with the resistor but the power dissipation is decreased in energized state of the relay. [11, pp. 315-316]

Placing a capacitor in series with resistor shown in figure 4.3 C no power is dissipated when the relay coil is energized. As the coil is de-energized, the capacitor will initially act as a short circuit. The induced current then drives through the resistor. [11, p. 316] However, according to [15] this is generally the least economical solution and no longer recommended.

Reverse biased diode shown in figure 4.4 A does not conduct current when relay coil is energized. When the coil is de-energized the voltage across the coil is opposite of supply voltage. As a result the diode is forward biased and transient voltage is limited to the diode forward voltage drop and IR drop in the diode which are really low. Therefore the voltage across the coil will be close to the operating voltage and the reverse biased diode is really efficient transient suppression method. [11, p. 316]

The disadvantage of diode transient suppression is increased opening time for relay due to longer decay time of the coil current. In some cases this may cause operational problems. [11, p. 316] On the other hand as the normally-open operation is degraded the normally-closed operation is typically improved. This is because of less contact bouncing due to the slower armature motion. [15]

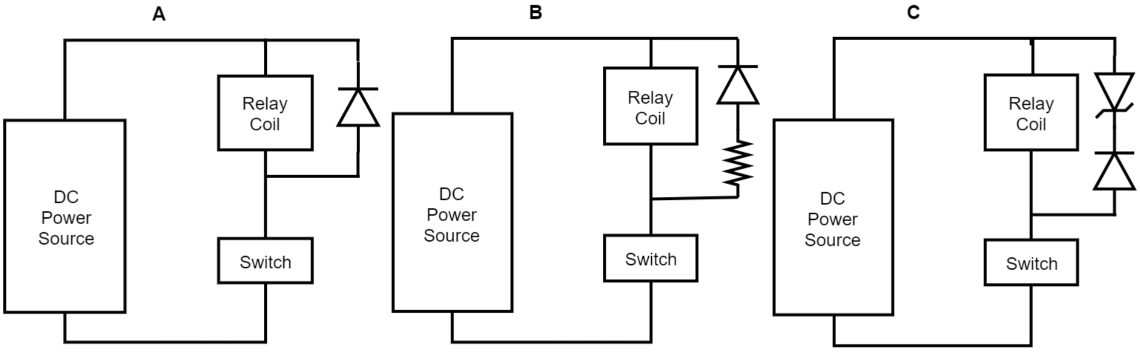

Figure 4.4. Relay transient suppression with reverse biased diode, with added resistor and with added zener diode.

There are two options to decrease the increased relay time resulted from the diode transient suppression. First one is adding a small resistor in series with the diode shown in figure 4.4 C. The drawback is higher transient voltage. Another option to decrease the coil current decaying time is adding a zener diode in series with the diode shown in figure 4.4 C. It also increases the generated transient voltage by the zener voltage. Both of the options add an extra component to the circuit and the protection is not as good as with only a diode. [11, p. 316]

5 DESIGN

Designing the device consists of three sections: functional, schematic and layout designs. Designing also includes mechanical design which was in this case done by a colleague and therefore is not covered in this text.

5.1 Functionality

The main function of the device is to be able to connect up to three microphones into single microphone input. Block diagram is shown in figure 5.1. Base of the design is from a previous project implemented using discrete components. Objective of this project was to take this design into one compact device and to make it more universally compatible with different microphones and applications. The final functionality is outcome of iterative process thinking of different options and requirements of possible applications.

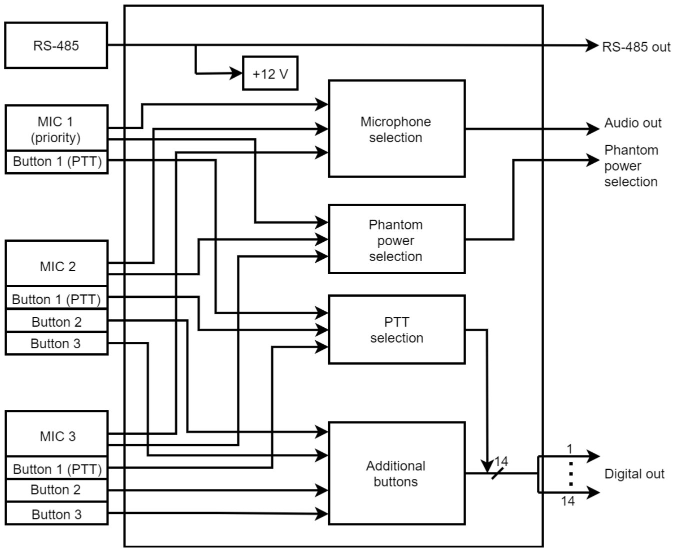

Figure 5.1. *Block diagram of the device.*

Active microphone is selected with PTT (push-to-talk) buttons information from each microphone. Each microphone input PTT signal is transmitted separately to digital inputs of the IPAMP. Only one PTT signal is transmitted to IPAMP at the time. Input 1 has higher priority and inputs 2 and 3 are lower priority excluding each other. Input 1 priority can be removed with a DIP (dual in-line package) switch bypassing the PTT signal. In inactive state with no PTT buttons pressed input 1 is connected to output.

Input 1 can be used for ambient microphone measuring the background noise. This information is used for controlling the audio output volume of IPAMP. When ambient microphone is used, input 1 PTT line must be bypassed with DIP switch, removing the priority. Thus in inactive state ambient microphone is connected to output and inputs 2 and 3 have priority over it.

Some microphones require phantom power. Since there is a possibility of using simultaneously microphones requiring phantom power and not requiring it, phantom power needs to be configurable individually per input. There were two options of providing the phantom power. First one was to implement the phantom power circuit into the device. Second one was to use the phantom power from the IPAMP.

Internal phantom power built into the device would allow constant phantom power individually for each input. This is beneficial as switching phantom power on and off can easily cause loud pops. The disadvantage is the added complexity. The DC-DC step up converter needed for creating the phantom power has high switching frequency which can potentially cause noise problems and requires careful layout design.

Using the phantom power from the IPAMP, phantom power is only available for the active microphone. This requires that the microphone's need for phantom power is always transmitted from the active microphone to the IPAMP. Since the phantom power is already available from IPAMP and only one microphone is active at the time, it is more convenient to use the phantom power from IPAMP than have separate phantom power in the device.

Phantom power is engaged from the microphone end by connecting pin 5 to ground. In addition, there are parallel DIP switches connected to ground for each input to engage phantom power directly from the device. Only the active microphone phantom power information is transmitted to the IPAMP.

The device is powered from IPAMP's RS-485 connection providing 12 V DC voltage and 300 mA current. RS-485 is used only for powering the device. To be able to connect other devices using RS-485, it is transmitted through the device.

Some microphones have additional buttons besides the PTT which operate with the same common pin as the PTT. These buttons are also routed through the device. States of the buttons are transmitted using normally open relays to make them potential-free.

One consideration during the functionality design was adding a unity gain preamplifier to the device. This could have allowed longer cable runs from the device providing high impedance input for the microphone signal. Downside is the added complexity to the circuit and potential increased noise. The preamplifier would also prevent the phantom power use from IPAMP. As there is no proof of the preamplifier having more advantages than disadvantages and it is not necessary for the device functionality it was decided to be left out.

5.2 Schematic design

The basic functionality of the device is implemented using unlatching DPDT relays. There are four different signals in total that are controlled with relays: audio signals, PTT information, phantom power information and additional buttons information.

Audio signal controlling is implemented with two relays in series. Two lower priority microphone inputs are connected to the first relay selecting between those inputs. Microphone input 2 is connected to normally open and microphone input 3 to normally closed contacts of the first relay. PTT of the microphone input 2 operates the relay to change its state. The output of the first relay is connected to the normally open contacts of the second relay which selects between the higher priority microphone and the lower priority microphones. Both inputs 2 and 3 operate second relay to switch between the higher and lower priority inputs. Diodes are added to isolate the PTT signals allowing multiple PTT signals to control single relay. Microphone input selection logic is shown in figure 5.2.

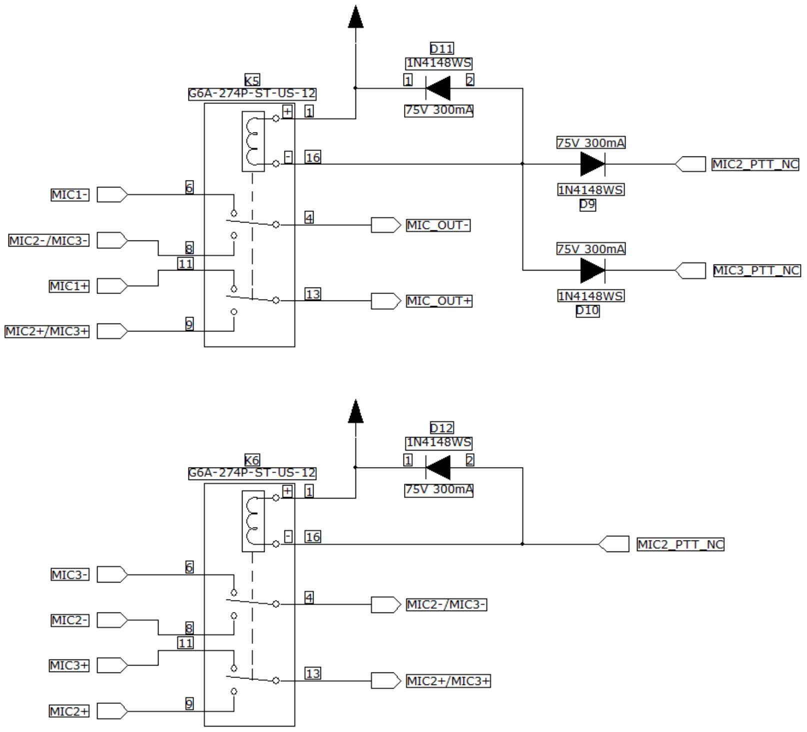

Figure 5.2. *Microphone selection logic.*

Lower priority microphones' PTT signals are each routed through separate relays normally closed contacts controlled by the complementary PTT signal. This excludes the other lower priority microphone while the other is active. Also microphone input 1 PTT signal is controlling these relays to prevent them changing the state while input 1 is active. Microphone input 1 PTT can be bypassed with a DIP switch which removes the PTT priority. PTT selection logic is shown in figure 5.3.

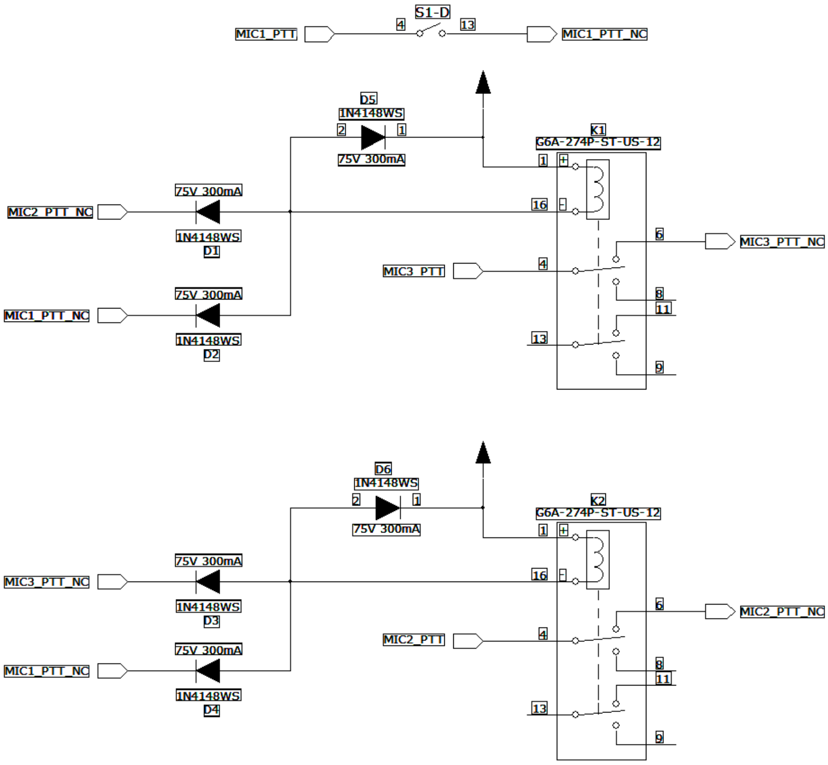

__Figure 5.3.__ PTT selection logic.

Phantom power is switched on in IPAMP by connecting microphone connector pin 5 to ground. This information needs to be transmitted to the IPAMP based on the selected microphone. Microphone inputs 2 and 3 pin 5 are connected to individual relays. Microphone input 1 pin 5 is routed through both relays normally closed contacts making it connected as default. As microphone input 2 or 3 is selected, microphone input 1 pin 5 becomes unconnected. Since microphone input 1 PTT signal unconnects microphone input 2 and 3 PTT signal and inputs 2 and 3 PTT signals are excluding, only one phantom power information is transmitted at the time. Phantom power selection logic is shown in figure 5.4

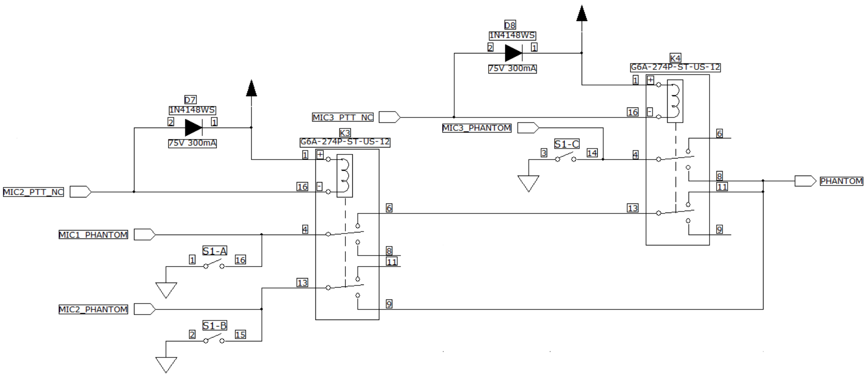

__Figure 5.4.__ Phantom power selection logic.

Relay transient suppression is implemented using reverse biased diode parallel to the relay coil. This is the recommended method of EN 50155 standard [16]. It limits the transient voltage to lowest value compared to other suppression methods.

When phantom power is switched on, DC blocking capacitors in IPAMP's microphone input are charged. Phantom power is connected through 6.8 kΩ resistor. This is in series with audio inputs 1 kΩ current limiting resistor and 220 nF DC blocking capacitor. Time constant $\tau = RC$ can be calculated using those values $\tau = (6.8\ k\Omega + 1.0\ k\Omega) \times 220\ nF = 1.7\ ms$ [17, p. 343]. Charging of DC blocking capacitor after switching on phantom power measured with oscilloscope is shown in figure 5.5.

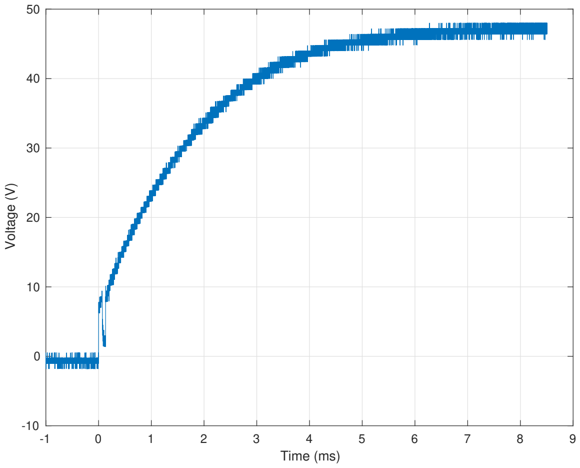

Figure 5.5. *IPAMP DC blocking capacitor charging measured with oscilloscope.*

Charging of the capacitor results in audible popping noise. To prevent this, a small delay needs to be added before PTT signal is transmitted to the IPAMP. This allows the capacitors to charge before the IPAMP opens the audio line based on the received PTT information. The relays have finite set time which needs to be taken into account in delay time. Maximum set time for the relay according the datasheet is 5 ms [18]. This added to time constant sets the delay to be at minimum 6.7 ms.

Delay is implemented using a comparator based non-inverting schmitt trigger and a RC high pass filter. The advantage of using schmitt trigger instead of just comparator circuit is the hysteresis introduced by positive feedback. Hysteresis prevents small changes like noise in signal around the reference to cause undesired transitions in the output state [19, p. 802].

Each PTT signal has its own identical delay circuits. Delay circuit of microphone input 1 is shown in figure 5.6. Pressing the PTT button discharges capacitor $C2$ through resistor $R6$. As the delay time needs to be adjusted with the prototype, additional capacitor spot is added in parallel with the low pass filter capacitor allowing more capacitor value combinations. This additional component is not placed in manufacturing. When the voltage over capacitor $C2$ goes below the lower threshold value, schmitt trigger changes its state and PTT signal is transmitted to IPAMP's digital input.

The initial component values were chosen using simulator. With $R6$ being 100 kΩ and $C2$ 100 nF simulated switching time from high to low is 7.4 ms. The final delay time needs to be adjusted with the prototype to have the optimal functionality.

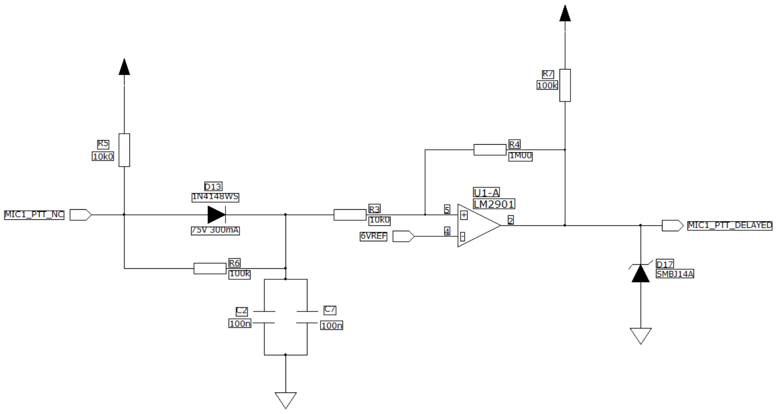

Figure 5.6. *Delay circuit.*

Resistor $R5$ is in parallel with the relay coils controlled by the PTT signals. In switch release capacitor $C2$ is charged through the parallel connection of relay coils and resistor $R5$ as diode $D13$ bypasses resistor R2. When the voltage crosses upper threshold value, schmitt trigger changes its state and PTT signal is no longer transmitted to the IPAMP.

Relay coil resistance is 720 Ω [18] which is significantly less than resistor $R5$ value. Thus relay coil resistance will be the dominant factor determining the switch release time. The resistor $R5$ value is negligible and it is set to be 10 kΩ. Also PTT 1 and 3 signals are controlling 2 relays and PTT 2 signal is controlling 3 relays so the parallel resistance of relay coils is different between PTT signals causing different release times. As the switch release time is not critical and should be rather short, small differences are not a problem. Simulated release times with coil resistances in parallel are close to 20 us for all the PTT signals. Exact release time is hard to estimate since the transient protection affects the release time. The actual release time can be measured with the prototype.

Schmitt trigger hysteresis is defined by resistors $R4$ and $R3$ as

$$\Delta V_T = \frac{R3}{R4}(V_{OH} - V_{OL})$$

Output voltage V_{OH} is the operating voltage 12 V and output voltage V_{OL} is ground. Resistors $R4$ and $R3$ have values 1 MΩ and 10 kΩ respectively resulting in 120 mV hysteresis.

Negative input reference voltage is set to 6 V with a voltage divider of two 10 kΩ resistors. One 100 nF decoupling capacitor is added in between 6 V and ground. The same 6 V reference is used for all comparator circuits.

The used comparator is LM2901 quad differential comparator [20] having four comparator circuits in one package. As only three comparators are needed, one is left unused. According to the manufacturers application notes the unused input pins should be connected in a way that the comparator stays in normal operation range and there is no direct connection to low impedance nodes. Output must be left open and unconnected. [21] Positive input pin is connected to ground through 10 kΩ resistor and negative input pin to 6 V reference setting the output to low state which fulfils the application notes requirements.

Because the comparator output is open collector, it requires a pull-up resistor for the output to go high. The pull-up resistor size affects the rise time larger resistor values having higher rise times. Manufacturers application notes [21] recommends the current in low state to be in the range of 100 uA to 1 mA. Pull-up resistors used for the circuit are 100 kΩ resulting in 120 uA current in low state which is in the recommended range.

According to the application notes, if the output is run off-board the output must be protected from transient voltages [21]. The maximum output voltage of comparator is 36 V [20]. Therefore possible transients need to be limited under that. TVS (Transient-voltage-suppression) diodes are used to limit the possible transient voltages to 14 V keeping them below the output maximum value. 100 nF ceramic bypass capacitor is added to positive supply voltage input to protect from noise and transients in the supply voltage [21].

The need to make the device compatible with multiple different microphones sets certain requirements for the connectors. Microphone inputs 2 and 3 have an option to have microphones with two additional buttons which need to be connected to same connector with the microphone signal. This sets the minimum number of pins to 6 on inputs 2 and 3. Typically used microphone connector is 5 pin A-coded M12. In case of microphone inputs 2 and 3 it is not an option since it has only 5 connector pins. There is an 8 pin version of M12 connector available but the A-coded version has voltage rated at 30 V [22, p. 30] which makes it not compatible with the 48 V phantom power.

The best option is to use a 9 pin D-sub connector. It has enough pins and high enough voltage rating. For microphone input 1 A-coded 5 pin M12 is used as there is no need for additional buttons and therefore 5 pins are enough. Same connectors are also used for audio output and RS-485 input and output.

The D-sub connectors have mounting screws which are connected to the chassis ground. Also the PCB mounting screws are connected to chassis ground. These are not connected to signal ground as it could potentially cause noise problems. If there is a voltage difference between the microphone switch and the device it is connected to, current will flow through the ground connector causing unwanted noise.

Digital signals are all routed out through one 14 pin PCB connector. Both PTT and additional buttons information output are routed through this connector.

EN 50155 standard [16] applied in designing electronic devices for on board rolling stock sets certain limitations and rules for the components. Derating should be applied to certain components. For thick film resistors used in this device it requires that the maximum values present do not exceed 25 % of power rating at 70 ℃ and 80 % of voltage rating. For ceramic capacitors EN 50155 states the maximum working voltage to be 50 % of the rated working voltage and maximum working current to be 70 % of the specified working current at 70 ℃.

Currently commonly used SMD (surface-mount device) component size is 0402. All the resistors used in device are 0402 size which are rated for 1/16 W at 70 ℃ and 50 V [23] meaning the maximum power dissipation is $0.25 \times 1/16$ W = 15.6 mW and maximum voltage is 0.8×50 V = 40 V. These are not limiting factors other than with operating power indicator led ballast resistor. For capacitors the only limiting factor in the context of this device is the voltage rating. The operating voltage is 12 V so all the capacitors need to be rated at least 24 V. All the capacitors used are rated for 50 V.

Leds are typically driven with a few milliamperes. As the operating voltage is 12 V and typical forward voltage for the green led used for operating power indicator is 2 V [24], voltage drop over ballast resistor is 10 V. For 2 mA current the power dissipation over ballast resistor would be 2 mA × 10 V = 20 mW which is more than stated in the standard. Power dissipation requirements can be met by connecting several resistors in parallel. As 10 kΩ resistors are used widely in other parts of the circuit, six 10 kΩ resistors are connected in parallel resulting in total resistance of 1.67 kΩ and 10 V / 1.67 kΩ = 6 mA current. Power dissipation in one resistor is 10 mW, which is well below the maximum power dissipation.

As the power is provided from the IPAMP, there is no need for advanced power filtering. One 10 uF decoupling capacitor is added to the input. Also the same TVS diodes used for protecting the comparator outputs is added to input to protect the device from voltage transients.

5.3 PCB layout design

The PCB is implemented using a four layer board. This allows having separate power and ground planes. It simplifies the layout design significantly as the power and ground connections can be made directly to the planes at any point of the board. Also the microphone audio signal is sensitive to noise and interference, so having dedicated ground plane helps preventing unwanted coupling. Layer stackup is shown in figure 5.7.

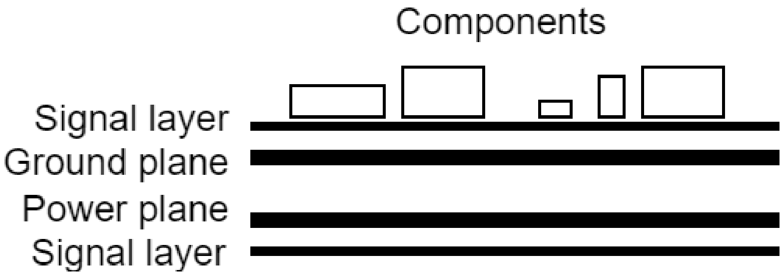

Figure 5.7. *PCB layer stackup. Adapted from [11, p. 641]*

Connectors were placed first as they need to be located at the edge of the board. All the connectors are wanted to the same side to ease the installation. Therefore they are the defining factor of the board width. Spacing between the connectors must be wide enough to allow the incoming and outgoing cables to be connected. The operating power indicator led is also located on the same side with the connectors.

After connector placing rest of the components were grouped into functional subgroups. There are relays for four different purposes which are grouped together based on the function. All the relays have transient suppression diode which needs to be located as close to the coil terminals as possible. In addition to transient suppression, some relays have additional diodes to enable connection of multiple PTT signals which are located next to the relays.

Delay circuit has basically three identical subcircuits. All the subcircuit components were first placed in groups around the comparator chip which was then placed on the board. The bypass capacitor needs to be as close to the comparator supply voltage pin as possible. It is located right next to the power supply pin with other end connected to +12 V plane and other end to ground plane directly.

TVS diodes protecting comparator are placed right next to the digital IO-connector to prevent voltage transients reaching comparator outputs breaking the comparator chip. Relay transient suppression diodes need to be also as close to the relay coils as possible so they are positioned right on top of each relay with the other end connected to the +12 V plane directly.

All the components were placed to be accessible afterwards. No components were placed too tight or between larger components like relays preventing later modifications or fixes.

All the same type components were also oriented the same way unless it caused more complicated signal routing to the ease component placement and visual inspection.

In the initial routing phase second audio relay signals were crossing. Swapping the signals from input and output allowed shorter and cleaner routing without changing the circuit functionality.

Default trace width for the whole board is 0.2 mm. All the signal traces are routed with the default width using 45 degree corners and in some unavoidable cases 90 degree angles are used. Exceptions in line width are made with the power input decoupling capacitor and TVS diodes which are routed with 0.5 mm trace width. Also the comparator output protection TVS diodes are routed with 0.5 mm trace width. Relay transient protection diodes are routed with 0.4 mm trace width.

Microphone signal is the most sensitive signal on the whole PCB. It is routed with 0.3 mm trace width. Microphone signal is differential making it more robust to noise and interference. To prevent common mode interference, differential pairs are routed with minimum spacing between traces.

Extra protection is added by routing the microphone signals between relays and connectors in third layer +12 V plane. The plane is partitioned so that ground plane is added to the area of the microphone signal traces. No traces are running across microphone signal traces on adjacent layers and there are continuous ground planes above and below. Ground planes are connected tightly together by adding stitching vias at approximately 10 mm intervals. This creates a Faraday cage for the microphone signals [11, p. 641]. Only the short signal pair between two relays is routed on the top layer of the PCB since it is crossing the other microphone trace. Routing the short traces on third layer would have required more effort than the gained profit had been.

The PCB is connected to chassis with six screws. Copper strip around the periphery of the board connects the screws together. The copper strip is added to all four layers and connected together with multiple vias around the board. Since one of the screws is located closer to the center of the board, it is not connected to the copper strip. Extending the copper strip to this screw would have prevented connections from the edge of the board. Unconnected screw is still connected to the same potential with the rest of the screws via the chassis connection.

All the empty areas on top and bottom sides of the PCB are filled with copper. The copper is connected to the ground through vias at 10 mm intervals. The smallest copper areas are limited to 1 mm^2 size because smaller areas are not advantageous and they are problematic to manufacture. Traces are routed in a way to maximise the ground fill area and to make it as continuous as possible.

The device must be able to be tested after manufacturing. Test points are added to PTT signals before and after the delay circuit allowing the measurement of the delay time. All the other signals are accessible from the input and output connectors. Therefore no test points are added for those. In addition to test points, one plated hole connected to the ground is added to allow easy ground connection for test measurements.

6 PROTOTYPE VALIDATION

The prototype is validated to ensure the desired functionality and to find out further improvements. Validation includes PTT delay time fine-tuning, functionality tests, power consumption, thermal testing, audio testing, mechanics validation and ESD test.

The prototype was ordered as assembled PCB from the factory. PCB is shown in figure 6.1. The mechanics were ordered at the same time with the PCB but the delivery time is longer and the mechanics had not arrived at the time of testing. Therefore mechanics validation and ESD test could not be performed yet. The designed tests for mechanics validation and ESD are still presented below.

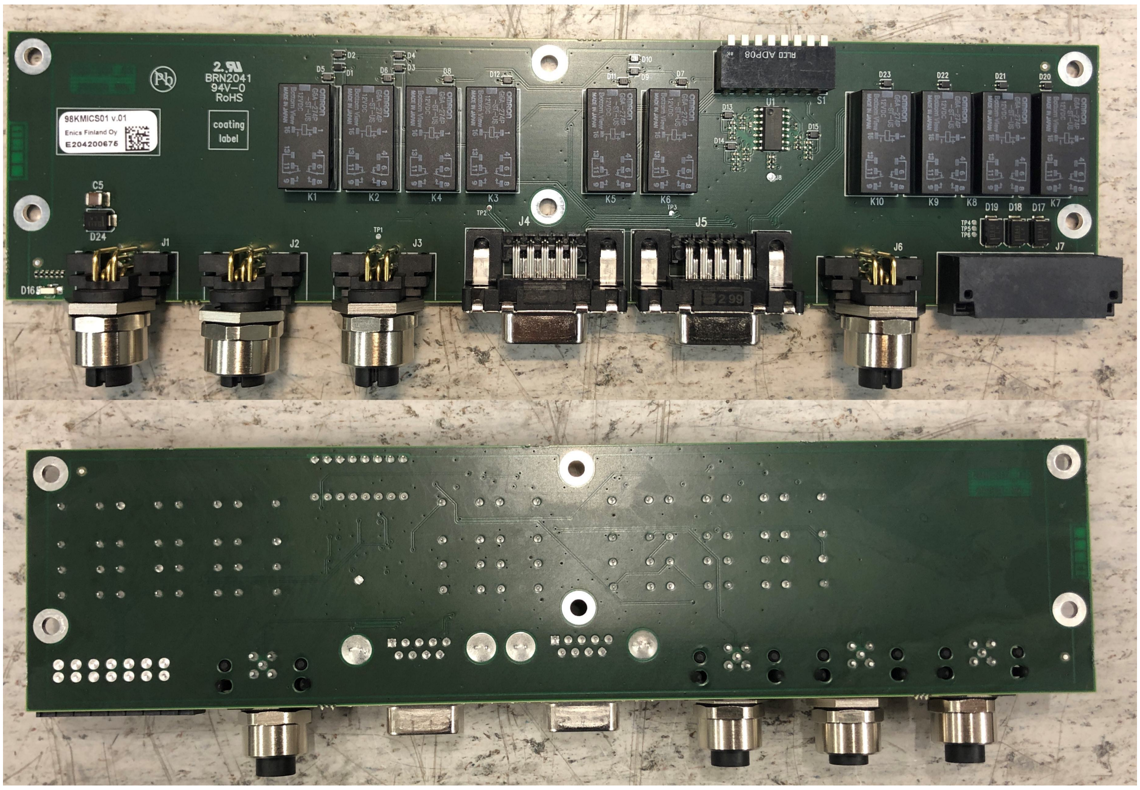

Figure 6.1. *Prototype pictured from top and bottom.*

6.1 PTT delay fine-tuning

The initial delay time for the PTT signal to reach the IPAMP digital input was based on simulations and the actual optimal delay time needs to be measured and fine-tuned by hand. Since the components connected to the relay coil terminals affect the relay operation time it is hard to evaluate the actual operation exactly beforehand. Therefore the final delay time is adjusted by measuring the delay time with oscilloscope and observing the silent operation point without popping noise by ear. The component values are fine-tuned for optimal operation to set the delay time for long enough to have silent operation without being unnecessary long.

The delay was measured from the prototype with oscilloscope probes connected to test points before and after the comparator circuit. Measured delay when PTT is pressed was 5.8 ms for all three PTT signals which is slightly less than the simulated value 7.4 ms. The difference is probably due to differences in actual components and simulated component models. Actual and simulated values are still the same magnitude and as the actual delay time is adjusted by hand in any case the simulated value was good enough.

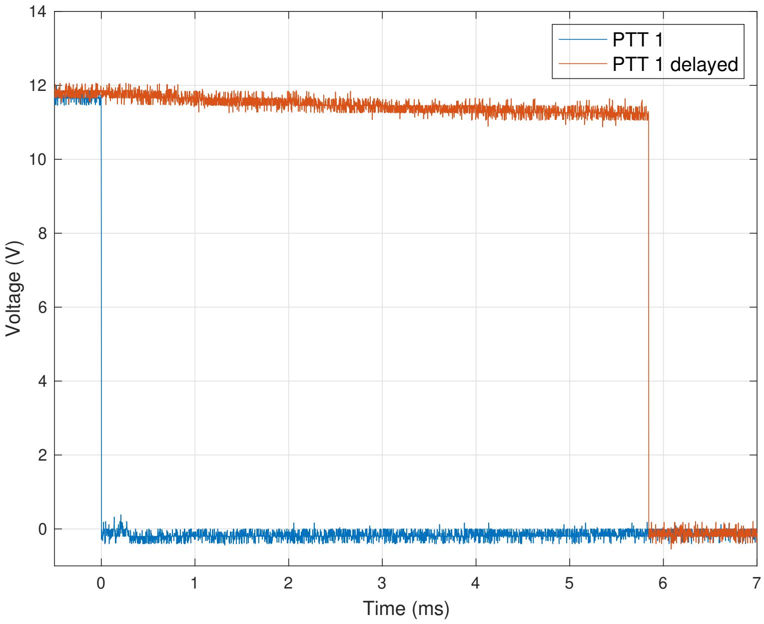

Figure 6.2. *PTT 1 delay time when PTT is pressed.*

The delay when PTT is released has small variations due to different number of relay coils in parallel to the resistor. These variations are only a few microseconds so the difference between different release times is irrelevant. The release time is between 9 to 21 us. The release time measured with oscilloscope for PTT 1 is shown in figure 6.3. More gentle rise of the delayed signal is due to the comparator chip limitations. The factors affecting the rise time are load capacitance and pull-up resistance.

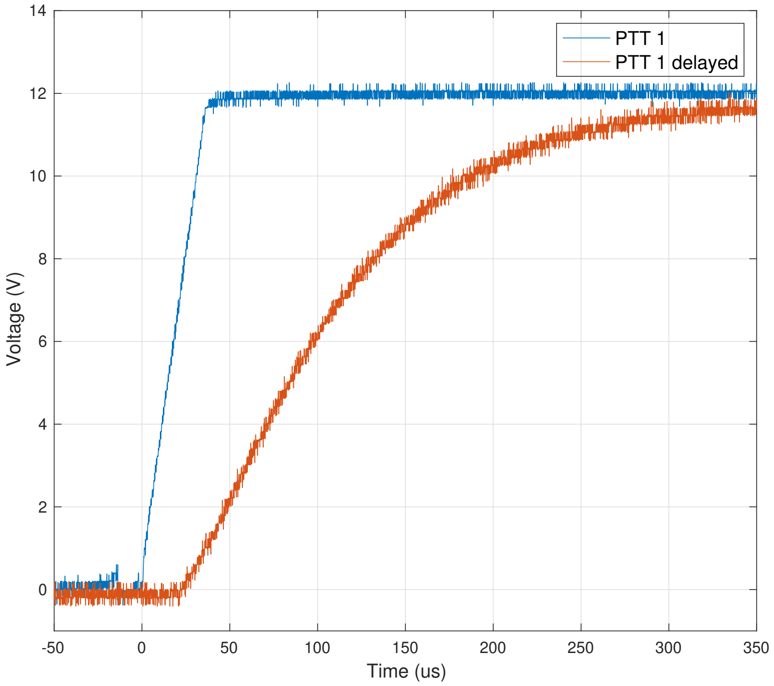

Figure 6.3. *PTT 1 delay time when PTT is released.*

With 5.8 ms delay there is an audible popping noise when phantom power is activated as the audio output is activated before the DC blocking capacitors in IPAMP's microphone input are charged. The delay time was fine-tuned by changing the comparator circuit component values until the long enough delay time was achieved. Since the delay circuits are identical in all the microphone inputs only one input was modified to find out the optimal component values.

Delay time component modifications are listed in table 6.1. First change was adding second 100 nF capacitor parallel to the first capacitor. This raised the delay time to 11.3 ms which was still too little. Next modification was changing the 100 kΩ resistor to 330 kΩ. This resulted in 39.8 ms delay which was long enough to reduce the popping noise to a silent enough level.

The 330 kΩ resistor is bypassed with diode when PTT is released and therefore only the added parallel capacitor is affecting the release time. After the modifications the release time was increased to about 23 us.

Table 6.1. *Delay time fine-tuning.*

Component change	**Delay time (ms)**	**Outcome**
Initial values	5.8	Loud audible pop
Parallel 100 nF capacitor	11.3	Pop reduced but too loud
100 kΩ resistor changed to 330 kΩ	39.8	Pop reduced enough

6.2 Functionality testing

To ensure the device functions as desired, all the possible functionalities need to be tested including:

- Priorities
- Different microphone combinations with and without phantom power requirement
- Ambient microphone use
- Parallel phantom power DIP switches
- Additional buttons

The test setup is illustrated in figure 6.4 and the actual test setup is shown in figure 6.5. In addition to the figure 6.4, the additional buttons testing is observed using multimeter measuring the relay closing. Also the RS-485 output is tested by connecting a device using RS-485 to ensure it is operating as wanted. The testing was implemented according to the test plan shown in table 6.2.

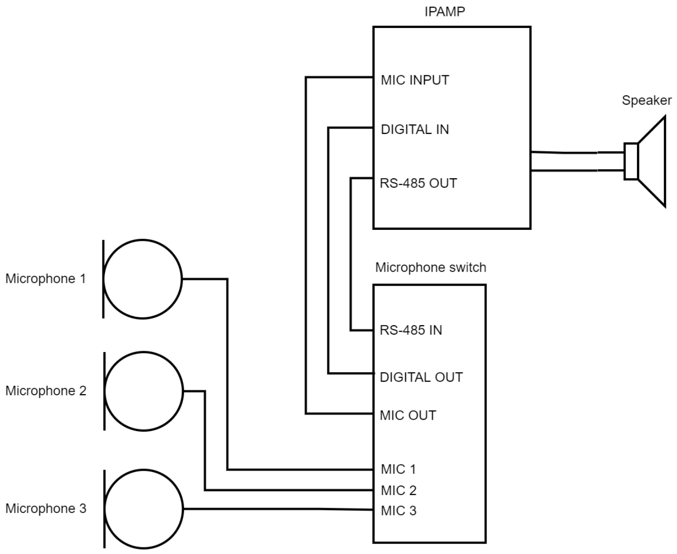

Figure 6.4. *Test setup illustration.*

The outcome of all the test cases in functional testing were as desired. Only observation was that the DIP switch used for microphone input 1 priority bypassing needs to be in off position to bypass the priority. This is due to thinking the DIP switch operation in reverse in design phase. Luckily only the text on the label on top of the device enclosure needs to be changed and there is no need for any other modifications.

6.3 Power consumption

The power consumption of the device depends greatly of the number of active relays and therefore typical power consumption is hard to define exactly. The maximum power

Table 6.2. *Functionality test plan.*

Test ID	Microphone configuration	Phantom power configuration	Test case	Expected result
1	-	-	Power on	Power indicator led turned on
2	Input 1	off	Microphone 1 PTT activated	Microphone 1 connected to output Phantom power off
3	Input 2	off	Microphone 2 PTT activated	Microphone 2 connected to output Phantom power off
4	Input 3	off	Microphone 3 PTT activated	Microphone 3 connected to output Phantom power off
5	Input 1	on from microphone	Microphone 1 PTT activated	Microphone 1 connected to output Phantom power on
6	Input 2	on from microphone	Microphone 2 PTT activated	Microphone 2 connected to output Phantom power on
7	Input 3	on from microphone	Microphone 3 PTT activated	Microphone 3 connected to output Phantom power on
8	Input 1	on from device	Microphone 1 PTT activated	Microphone 1 connected to output Phantom power on
9	Input 2	on from device	Microphone 2 PTT activated	Microphone 2 connected to output Phantom power on
10	Input 3	on from device	Microphone 3 PTT activated	Microphone 3 connected to output Phantom power on
11	Inputs 1 & 2	Input 1: on Input 2: off	Microphone 1 PTT activated while microphone 2 is active	Microphone 2 disconnected and microphone 1 connected to output Phantom power turned on
12	Inputs 1 & 3	Input 1: on Input 3: off	Microphone 1 PTT activated while microphone 3 is active	Microphone 3 disconnected and microphone 1 connected to output Phantom power turned on
13	Inputs 1 & 2	off	Microphone 2 PTT activated while microphone 1 is active	Microphone 1 stays connected to output
14	Inputs 1 & 3	off	Microphone 3 PTT activated while microphone 1 is active	Microphone 1 stays connected to output
15	Inputs 2 & 3	off	Microphone 3 PTT activated while microphone 2 is active	Microphone 2 stays connected to output
16	Inputs 2 & 3	off	Microphone 2 PTT activated while microphone 3 is active	Microphone 3 stays connected to output
17	Input 1: Ambient microphone priority bypassed	on	Ambient microphone connected	Ambient microphone connected to output Phantom power on
18	Input 1: Ambient microphone priority bypassed Input 2	Input 1: on Input 2: off	Microphone 2 PTT activated while using ambient microphone	Ambient microphone disconnected and microphone 2 connected to output Phantom power turned off
19	Input 1: Ambient microphone priority bypassed Input 3	Input 1: on Input 3: off	Microphone 3 PTT activated while using ambient microphone	Ambient microphone disconnected and microphone 3 connected to output Phantom power turned off
20	Input 2	-	Pressing microphone 2 button 2	Microphone 2 button 2 relay closed
21	Input 2	-	Pressing microphone 2 button 3	Microphone 2 button 3 relay closed
22	Input 3	-	Pressing microphone 3 button 2	Microphone 3 button 2 relay closed
23	Input 3	-	Pressing microphone 3 button 3	Microphone 3 button 3 relay closed
24	-	-	RS-485 output connection	RS-485 signal is passed through to output

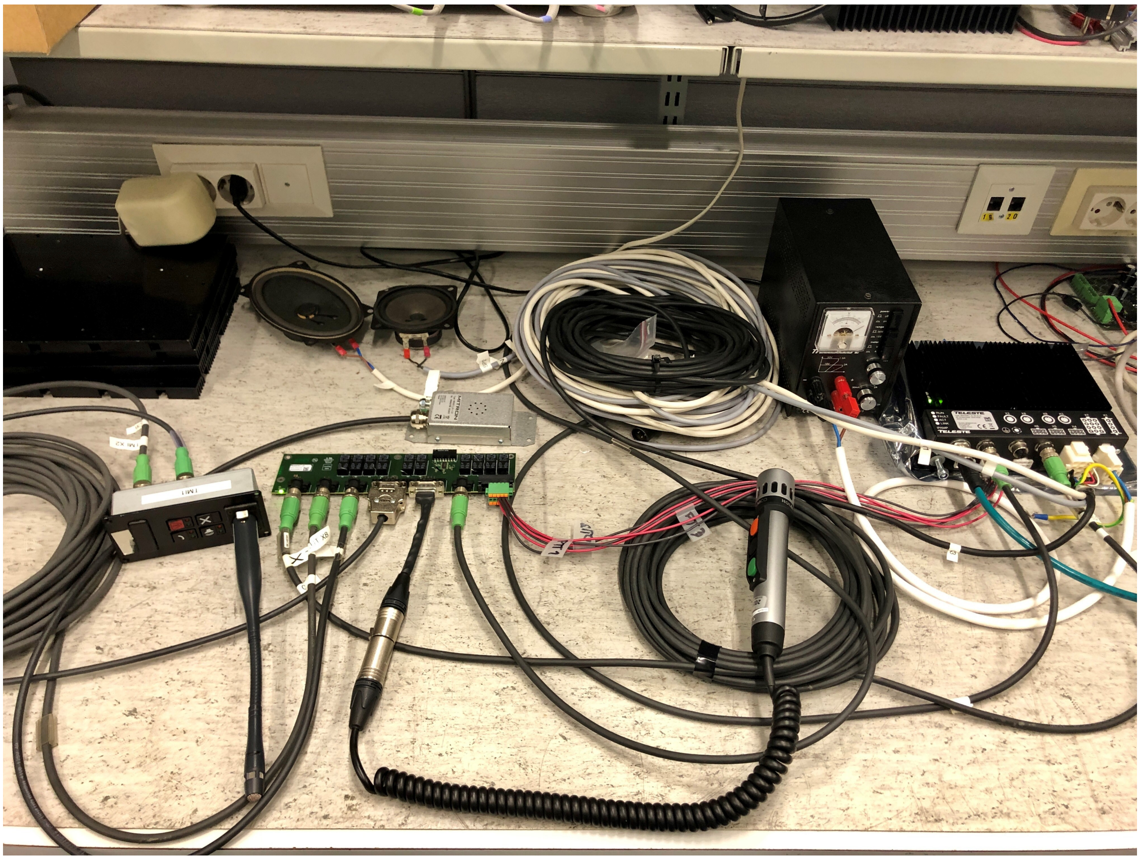

Figure 6.5. *Test setup.*

consumption is achieved when microphone input 2 is active and all the additional buttons are pressed which means 8 active relays in total.

According to the relay datasheet [18] the rated current for used relay is 16.7 mA. Therefore in total with 8 relays active the relays should draw around 133.6 mA. In addition to relays, other active parts of the circuit drawing current are the power indicator led and the comparator circuit. These added to the current draw of relays the maximum current draw should be around 140 mA. This means with 12 VDC operating power the maximum power consumption should be about 1.68 W.

The current draw was measured by powering the device using a laboratory power supply and measuring the current with a multimeter. Both the idle and maximum current were measured. The measurement results are shown in table 6.3.

Table 6.3. *Current draw.*

Measurement	Current draw (mA)	Power (W)
Idle current	7.3	0.08
Maximum current	139.1	1.7

The measured maximum current draw matches well with the estimated maximum current draw. The idle current draw is 7.3 mA which consists mainly of the power indicator led current draw. The maximum current the IPAMP RS-485 output is 300 mA and the maximum current draw stays well below that.

6.4 Audio testing

The minimum -3dB audio bandwidth for the device is required to be from 100 Hz to 12 kHz. It is measured by feeding a sine wave with a signal generator to all the microphone inputs individually and then measuring the ratio between the input and output.

The audio frequency response was measured using NTI audio MR Pro Minirator signal generator and XL2 audio analyser both shown in figure 6.6. The signal generator was sending -20dBu sine wave sweep signal from 20 Hz to 20 kHz to each microphone input of the device at the time. The audio was measured with the audio analyser from the audio output of the device.

The audio frequency response is shown in figure 6.7. The frequency response is completely flat from 20 Hz to 20 kHz which was expected as there are only copper traces and relay contacts in the audio path.

Figure 6.6. *NTI audio MR Pro Minirator signal generator and XL2 audio analyser.*

6.5 Temperature testing

Temperature testing was done by placing the device in to a heating chamber shown in figure 6.8 and testing the functionality in minimum and maximum temperatures defined in the requirements specification. The minimum operating temperature is -40 ℃ and maximum 70 ℃.

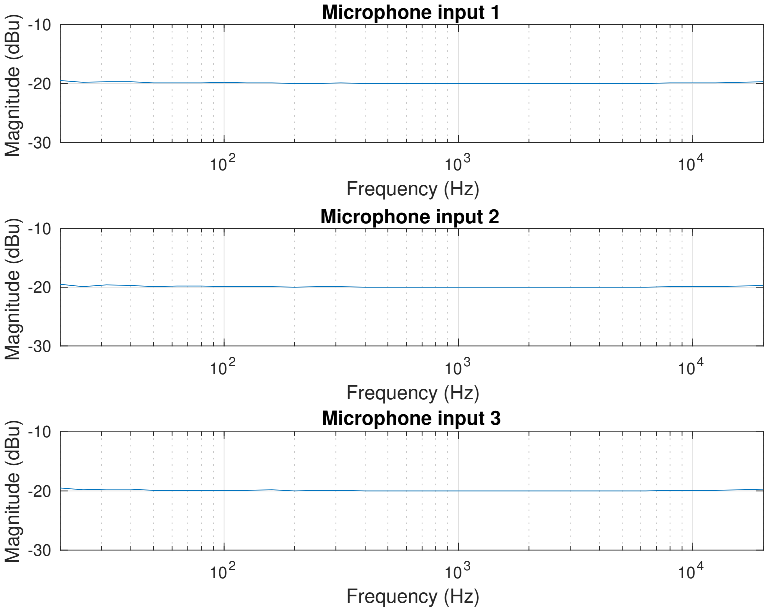

Figure 6.7. *Audio measurement results.*

The device is using really basic components which are not quite temperature sensitive. All the components are specified to operate from −40 ℃ to 70 ℃. The only part of the device which can have temperature dependent effects is the comparator circuit used for the PTT delay. Therefore the delay time is measured in minimum and maximum operating temperatures.

The delay time is measured from each input in minimum and maximum temperatures and also in room temperature for reference value. All the values are shown in table 6.8. In PTT delay fine-tuning the microphone input 3 PTT delay was modified to find out the optimum delay time. Therefore it has longer delay time than the other two which are still set to default value. The slightly longer delay time in PTT 2 compared to PTT 1 is due to the different microphones used. The microphone PTT button in microphone used for input 2 had a little bit of bouncing when pressed which leads to longer delay. Despite the bouncing, the comparator circuit works as intended.

Table 6.4. *Delay time temperature measurements.*

PTT number	**PTT state**	**Delay** (21.5 ℃)	**Delay** (70 ℃)	**Delay** (−40 ℃)
1	press	5.7 ms	4.7 ms	5.8 ms
1	release	21.0 us	19.6 us	15.6 us
2	press	6.9 ms	5.5 ms	6.8 ms
2	release	9.4 us	10.4 us	7.6 us
3	press	36.8 ms	30.0 ms	35.7 ms
3	release	22.8 us	24.4 us	17.4 us

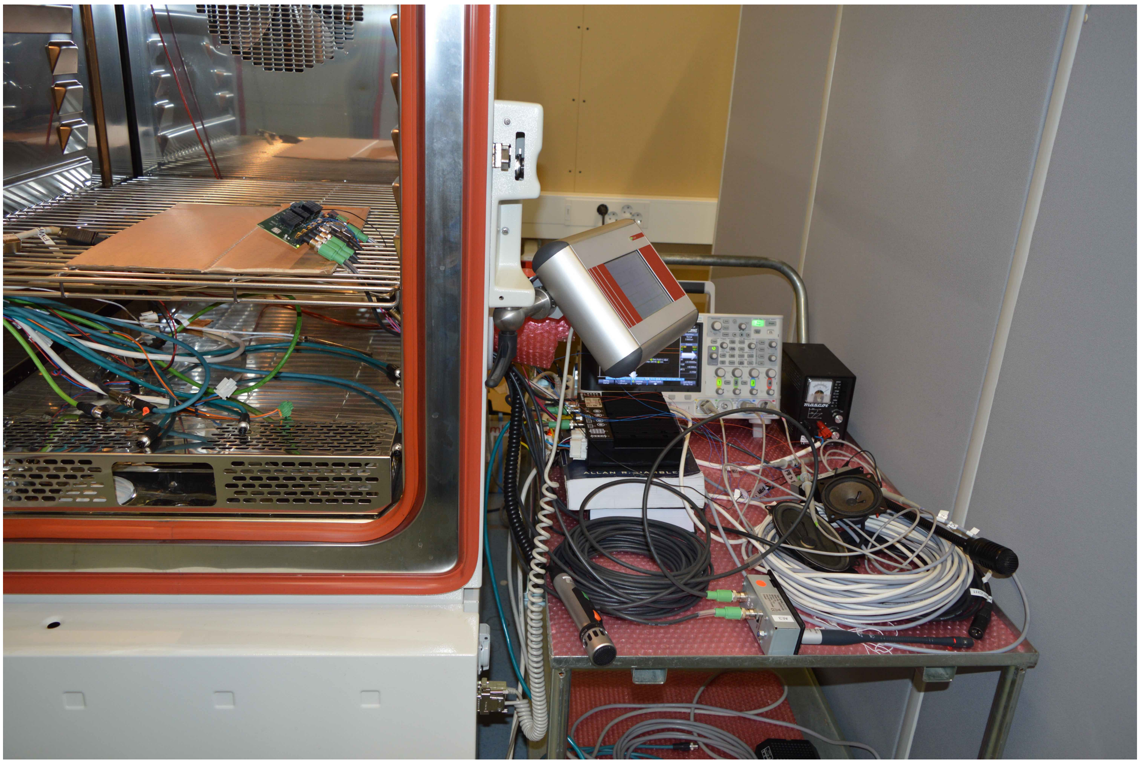

Figure 6.8. *Temperature test setup.*

The delay time is noticeably lower in 70 ℃ temperature. In -40 ℃ there are small differences but nothing drastic. The difference in higher temperature can be mainly explained with the capacitor capacitance temperature reliant behavior. The used capacitors are X7R rated ceramic multilayer capacitors which capacitance drops in 70 ℃ about 7 percent according to the general X7R capacitor datasheet [25]. This explains the lower delay time in higher temperature. In -40 ℃ the capacitance drops only a few percent and the effect is much more subtle. The absolute capacitance change is hard to evaluate since there is not exact information which particular capacitors the PCB manufacturers use. In any case the capacitor temperature behavior is something similar.

Other components should not have any significant effect in delay time. The used resistors temperature coefficient is $\pm$ 100 ppm℃. This means only a few hundred ohm difference in maximum and minimum temperatures which is insignificant compared to 100 kΩ or 330 kΩ resistor values used. The comparator chip has also slight changes in input bias and supply currents but the capacitor value change is the most significant factor in delay time temperature dependency.

Although there are small differences in delay times at the minimum and maximum operating temperatures there is nothing too drastic. The device works as intended at both extremes and the delay time has still a reasonable value.

Another temperature test could have been measuring the temperature rise of the components with a thermal imaging camera during the operation. The only components in the device that heat up are the relays. Since they are switched on only momentarily for a short period of time, the temperature rise is insignificant and there is no need for such measurements.

6.6 Mechanics validation and ESD testing

The mechanics are validated in two parts. The first part is to validate the mechanics against the manufacturing drawings making sure they correspond to the designed drawings. Second part is to validate the mechanics against the assembled device with all the cables connected making sure the mechanics fit with the PCB, all the cables are connectable and the DIP switches at the back are accessible. The mechanics drawings are shown from front and back in respective order in figures 6.9 and 6.10.

Figure 6.9. *Mechanics pictured from front.*

Figure 6.10. *Mechanics pictured from back.*

ESD effects can be divided in to three categories, which are hard errors, soft errors and transient upset. Hard errors include physical damage to the system hardware such as destruction of an IC. Soft errors do not cause physical damage but still affect the system operation, such as program lockup. Transient upset does not cause permanent damage but the effect is observable during the test. [11]

Preliminary ESD testing for the prototype is done according to the EN 61000-4-2 standard [26]. EN 61000-4-2 defines that the only allowed ESD effect is transient upset. This means that degradation of performance is allowed during the test but after the test the device must continue to operate as intended. [11]

The enclosure is made of two peaces of aluminium, top and bottom, and there are holes for the IO connectors and the power indicator led. The enclosure is grounded but the potential ESD problems can occur in the seams and holes. Therefore attention must be paid for these parts in the ESD testing.

7 CONCLUSIONS

The aim of the thesis was to design a microphone switch allowing to connect up to three microphones in to one IPAMP microphone input. As a starting point for the design was used previous project where the similar functionality was implemented using discrete relays. Based on that project were also made some initial design for the actual product. In this thesis work that design was improved and completed to a prototype phase.

7.1 Areas of improvements and further steps

Mainly the prototype worked as designed and no major design flaws were found. The only slight observation was the reverse functionality of the microphone input 1 priority bypass switch. It is easily corrected by changing the text label on top of the enclosure to match the functionality. Also the delay circuit components need to be modified for the next revision. This was known already in the design phase as the components were chosen only based on simulations and the actual fine-tuning was done with the prototype validation.

Ordering the prototype PCB and mechanics took longer than originally planned. Due to this the mechanics did not arrive on time for the testing. Therefore ESD tests and mechanics validation could not be done yet and needs to be done after the mechanics arrive. After the prototype validation is finished and all the needed corrections are made the device needs to be type tested for the actual productization.

7.2 Accomplishments

The final design came out as neat and simple while meeting all the requirements. As the circuit is kept as simple as possible the device is reliable and easy to use. All the designed features including priorities, PTT delay and additional buttons worked as desired. Also the device functions in whole required temperature range, the power consumption is reasonable and the audio frequency response is flat.

Although some PCB designing is done during the university studies, getting to do the schematic and layout design for a complete device expanded the understanding and knowledge greatly. Also the factory manufactured PCB gave an opportunity to use four layers which is not possible when PCB is manufactured by hand. This made the layout design more flexible and gave an opportunity to try different routing techniques such as routing the microphone signals between two ground layers.

As a whole the design process was successful. The thesis work project was educational and interesting process. It gave an opportunity to get hands on experience on actual electronics design process from requirements to prototype phase which will be highly beneficial in the future.

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