

## 0.1 To SKO

Hello Søren

Once again we have a fresh and raw worksheet for you to enjoy. We would first of all love to get feedback on chapter 3 and onwards. The rest has been altered a bit as well, but can be considered recreational reading for you (read: not mandatory).

All the best

Gr512

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## 1.1 Frequency Responses of audio systems

Hi-Fi audio equipment like amplifiers and loudspeakers, are very popular pieces of household electronics. People are seemingly willing to spend a lot of money on sound systems that is able to accurately reproduce sound. Amongst different types of sound-reproducing devices, the transducers<sup>1</sup> are generally the worst at accurately reproducing the actual sound, especially for loudspeakers[11]. Purely electronic devices, like amplifiers, are generally easier to control.

A key feature of high quality sound systems is their frequency response. The frequency response is a term describing the variations in amplitude and phase from the original signal as a function of frequency. It is generally desired to have a "flat" frequency response (i.e. the amplitude- and phase response of the output signal behaves the same way regardless of the frequency of the input signal).

This is hard to achieve in real loudspeakers because of resonances in the physical part of the loudspeaker, which will result in certain frequencies being played louder than others.

The Loudspeaker driver that converts the electric signal to sound waves only has a certain limited range of frequencies where it works optimally and loudspeakers made with only one driver (Full-range drivers) also usually have a hard time reproducing every frequency at a similar amplitude, especially when playing at high levels of power. A lot of loudspeaker systems are therefore made using multiple drivers, that each handles a certain band of frequencies.

There are different design and construction challenges for each type of driver depending on which part of the audio spectrum it should reproduce, but in general drivers for high frequencies are smaller than drivers for lower frequencies. Since drivers for reproducing the lowest part of the frequency spectrum (20 - 200 Hz) are usually quite big and use a lot of power. For this reason, Loudspeaker systems with limited size and power usage (like PC speakers) are usually physically incapable of reproducing these frequencies at the same amplitude as higher frequencies.

## 1.2 Acoustic properties of a room

Even with a perfectly flat frequency response in a sound system, the sound that is actually being perceived by the listener might still be different than the original audio because of the acoustics of the surrounding room.

Room acoustics is a whole subject onto itself, but while this section will not go depth about every physical phenomenon that can influence the sound quality of a room, it will try to briefly cover how the surrounding room can influence the perceived sound quality for a listener.

When a sound wave hits an object in its path, a combination of three things happen. Some of

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<sup>1</sup> Devices that convert one type energy into another.

the wave will be reflected off of the surface of the object. The rest of the wave will travel through the object, where some of the waves energy will be absorbed by the material and transformed into heat. Whatever is left of the wave will be transmitted through the object and continue along its direction of propagation. An illustration of this can be seen on figure 1.1



Figure 1.1: sound interacting with a wall. Illustration from [8] should be remade with vector graphics

How much of the sound wave is reflected, absorbed or transmitted through, is dependent on both the material of the object, the angle of incidence, and the frequency of the sound wave. rule of thumb for different building materials If the object being struck by the sound wave is significantly larger in area than the incoming wave, then the reflected sound wave will be reflected at an angle equal to the angle of the incoming wave. For example, a room with large and bare concrete walls will reflect specific frequencies a lot. If the waves hits a surface that is comparable in size to its wavelength, the waves will diffuse and scatter somewhat evenly across the room.

Acoustic treatment of rooms is often done by fitting rooms with object that will diffuse incoming sound ways, a covering surfaces with sound absorbent materials. This is done to reduce reflected waves in a room.

One problem associated with reflections is the emergence of interference patterns between a sound wave in a direct path to the listener the sound wave reflected off a surface. Since the reflected wave has traveled a longer distance than the direct wave, the to waveforms will likely be out of phase with each other and interference will occur. This can cause the resulting wave to either have a larger or smaller amplitude than the original wave. An example of how this can occur can be seen in figure 1.2

Since a given material absorbs and reflects sound waves differently at different frequencies, and since reflected waves are attenuated a rate given by its frequency according to Stoke's Law of sound attenuation, different frequencies will be affected by interference at the listeners position differently for different frequencies. These phenomena can have a quite significant effect since a wave with a frequency of 50 Hz can behave very differently from one with a frequency of 5000

<sup>2</sup>The lines representing the sound waves can be seen as tangents to the crests of the wave



Figure 1.2: Sound traveling towards a listener along different paths<sup>2</sup>

Hz. And since music in general feature a pretty wide spectrum of frequencies <sup>3</sup>, the frequency response of a given piece of music can change a lot by traveling through a room. Furthermore this behavior can vary a lot based on the position of the speaker, the size of the room, the building materials, and the interior decoration of the room, in ways that might not be obvious to the average listener, who just wants to sit at his/her favorite listening spot.

There is an important phenomenon that provides a general idea about the behaviour of a room and it is independent from the listening point, the reverberation. The reverberation is the greater or the less persistence of the sound when a sound source stops emitting, and it depends on the intensity of the sound source and the threshold of hearing.

### 1.3 Initial problem statement [EARLY DRAFT; please give response]

In the previous sections it has been shown that a piece of audio can often be altered during playback by different frequencies being represented differently. Furthermore, the processes which alters the characteristics of the sound might not be immediately obvious or even fixable for the user of the sound system. Since this is a 5th semester project in Electronics and IT, the project has been is meant to revolve around an electronic system that can interact with its surroundings by measuring some form of signal, processing this data, and generating a new signal based on this processing. For this reason It has been decided to work with a system that can measure the frequency response of a sound system, and correct the frequency response based on these measurements. It is therefore possible to formulate an initial problem statement based on this, as the following:

Which elements are needed to make a system that corrects the frequency response of a sound system?

Which technologies will need to be described to specify a system that corrects the frequency response of a sound system?

<sup>3</sup> 20 Hz to 20 kHz

This chapter will contain the analysis of the theories that make the project possible.

## 2.1 Equalizer

### Citation needed

There are digital and analog equalizers, but in this section the focus will be on analog equalizers.

In the field of audio, an equalizer is a device that modifies the response in frequency of the signal, and adapts it to the user, solving all kinds of problems. These devices are able to either amplify or attenuate one or more frequency bands.

There are different types of equalizers: High-pass and low-pass filters, shelving filters, graphic equalizers and parametric equalizers.

A high-pass filter is an electronic circuit that passes high frequencies and attenuates low ones. The same for the low-pass filters, that allows low frequencies to pass but attenuate the high ones.[15]

On the other hand, shelving filters (figure 2.1) are used as tone controls, as they can attenuate or amplify a signal above or below a certain frequency. [15]



Figure 2.1: Shelving filter. Image from [12]

A graphic equalizer (figure 2.2, however, is composed by some band-pass filters. It takes the name from the physical position that the faders are placed, making possible to see in a easy way the changes made. [15]



Figure 2.2: Graphic equalizer. Image from [13]

Finally, the parametric equalizer (figure 2.3), allows the individual control of three main parameters of the filters that compose the equalizer: amplitude, center frequency and bandwidth. [15]



Figure 2.3: Parametric equalizer. Image from [13]

The analog filter design is mainly limited by the cost of the different elements, so a selection of better components will lead to a better equalizer.

It is well known that most of the signals contain noise, but analog filters have the disadvantage that they add noise to the signal through for example heat and electrostatic noise. [6]

## 2.2 Digital sound

When sound have to be transported over longer distances, or stored for later use, it might be necessary to convert it into a digital signal. This can be done by converting the sound to an analog signal trough a microphone and then converting it to a digital signal trough a analog to ADC (analog to digital converter). The digital signal can then be stored as a string of bits, which can be read by computers and for example be filtered ore shared via the internet. Furthermore it is possible to make calculations based on the digital signal such as equalization or addition of multiple signals.

### Sampling frequency

To ensure that the audio signal can be recreated as an AC-signal, the sampling frequency has to be taken into account. The sampling frequency determines the number of samples, there has to be played pr second. According to the Nyquist sampling theorem[18] the sampling frequency should be above two times the highest frequency of the signal. If this is not the case, some frequencies could be represented as a different frequency, as seen in figure 2.4.

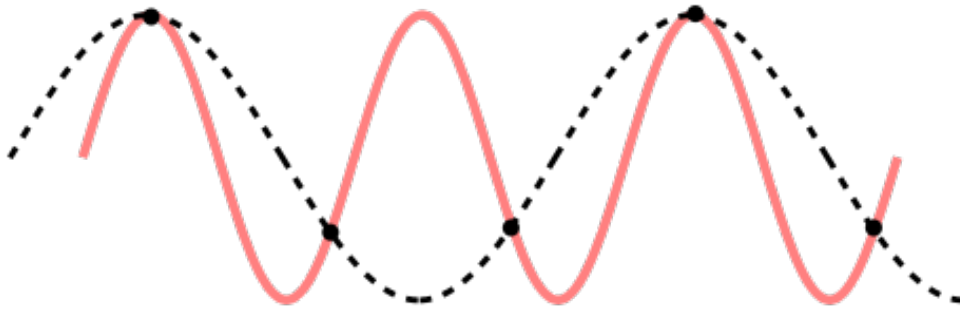


Figure 2.4: Falsely represented signal, due to the sampling frequency being too low. Figure from source [17]

Since the Nyquist sampling theorem states that the sampling frequency should be at least twice the highest frequency of the signal, the sampling frequency should be at least 40 kHz, when sampling audio signals. According to the standard IEC-60908[4] the sampling frequency of sound should be 44,1 kHz. This way audio signals can be recreated up to 22,05 kHz.

### File resolution

When storing audio in a file it is defined by a string of bits that matches the amplitude of a specific sample. Here the amount of bits used to determine the sample, also known as bit depth, is a big factor in the quality of the sound. This means that the amount of bits used per sample determines how well the sound will be when converted to an analog signal. For a 4 bit signal, there would therefore be 16 different values for a sample, and for a 16 bit signal there would be 65536. An illustration of the correlation between an analog signal and its representation in bits, can be seen in figure 2.5.

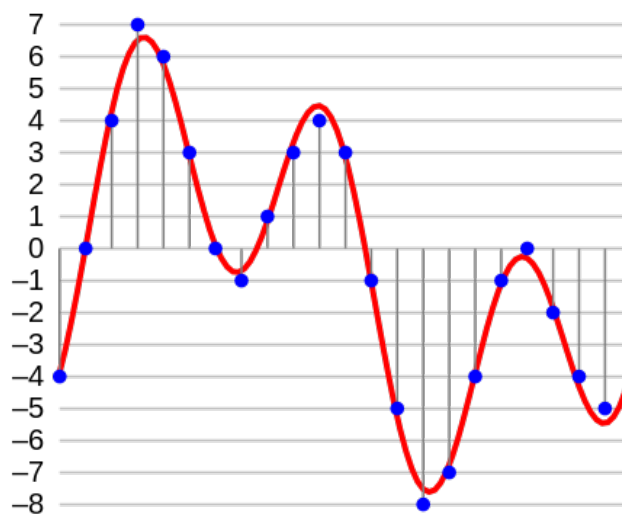


Figure 2.5: Audio signal and its representation in bits. Figure from [16]

CD quality sound is usually stored in a 16 bit resolution. In sound studios they use a bit depth of 24 or above to ensure a proper D/A conversion. If there is a need for adding two 16 bit signals together, 17 bits are needed to avoid clipping.

When audio is converted from analog to digital, there can occur an error in the sampling process. This happens because the digital value might not be exactly the same as the analog value. This



error is referred to as quantization. The quantization error can be  $\pm 0,5$  times the value of the least significant bit (LSB). The signal-to-quantization-noise ratio (SQNR) can be calculated as seen in equation 2.2.1.

$$\text{SQNR} = 20 \cdot \log_{10}(2^Q) \quad [\text{dB}] \quad (2.2.1)$$

where:

$$Q = \text{Signal bit-dept} \quad [.]$$

Using the equation, a 1 bit signal would have an SQNR of 6,02 dB. For every bit added to the bit dept the SQNR goes up another 6,02 dB.

## 2.3 Digital signal processing

Digital signal processing and analog signal processing both is a description of a process to modulate an input. Digital signal processing utilizes digital filters to achieve this modulation. This makes digital signal processing much more versatile than analog signal processing because digital filters can both emulate analog filters, and because it is not limited to passive and active components, but to basic arithmetic, can therefore do a lot more[14]. Additionally there are no outside noise effecting a digital signal, which therefore does not have to be taken into account.

### Digital filters

Finish this when lectures about digital filters are done.

Filters are used to selectively choose some wanted frequencies to be allowed through, and cut out other frequencies. Active filters can also be used to amplify or attenuate the specified frequencies.

A digital filter takes the input sequence of numbers from sampling the signal and computes a new sequence of numbers based on the filters transfer function. However digital filters cannot amplify a signal, only scale it up to the maximum bit value determined by the bit dept. Digital filters can only do basic operations such as: addition, subtraction, multiplication and division, more complex functions must be a combination of these [14] [10].

With digital filters the accuracy of the calculations of the functions can be controlled much more precisely than analog filters. The more complex a function and the closer the more accurate the function needs to be to the ideal, the longer it takes to compute. High computation times limits digital filters usability for real time applications. For real time applications either the filters complexity and accuracy needs to be lowered to decrease the computation time, or a fast digital signal processor is needed [10].

Due to the fact digital filters are calculated in a processor, they can be changed easily compared to analog filters, where the passive or active components would have to be changed.

new stuff, might be changed

There is generally two ways of implementing a digital filter: FIR filters (FIR) and IIR filters (IIR).

IIR Filters have an impulse response that continues forever, just like analog filters made from resistors, capacitors and inductors.

This means that an IIR filter can be designed by taking the transfer function of a known analog filter and transforming it to the Z-domain using Z-transformation and later to the digital domain using reverse Z-transform.

In this way, a digital filter can be given by a difference equation, which is a relatively easy type of equation to solve for a computer to solve given that the computer is able to store a certain number of previous inputs and outputs. In that sense a IIR filter has to have some kind of "feedback".

The other type of filters, FIR filters, on the other hand, have impulse responses that becomes zero after a certain point.

For FIR filter with an order  $n$ , the impulse response will consist of  $n + 1$  samples. the output will be computed as a convolution sum of the impulse response and the last  $n + 1$  input samples.

FIR filters has several advantages over IIR filters. The impulse response of a FIR filter can be based on an ideal impulse response. This means that high order FIR filter can closely resemble ideal filters. FIR filters cannot be unstable since the impulse response will always be zero after a certain point. It is also very easy to design a FIR filter with a linear phase response by making the impulse response symmetric.

However, these advantages comes at a cost. For a FIR filter to have as sharp a cutoff as a IIR filter, the FIR filter needs to be several orders bigger. Because of this it is more computationally expensive to implement a FIR filter than a IIR filter.

## 2.4 The amazing world of sound cards

In order for a computer to play and record audio, it needs a device that can convert analog sound to digital, and vise versa. A sound card also allows the user to perform some degree of digital signal manipulation, where the most common would be to manipulate the audio with an equalizer.

A sound card has a lot of interfaces, depending on the type of sound card. One of these could be a digital input or output from a CD-ROM drive or a MIDI(Musical Instrument Digital Interface). Depending on the type of sound card and the price range, the interfaces of the sound card differs, but the most common is analog input to a microphone or analog outputs to loudspeakers.

Since a sound card performs its operations digitally, all analog signal needs to be converted to digital in order to make recordings, and digital signal must be converted to analog for audio playback. This is done with an ADC(Analog to Digital Converter) and a DAC(Digital to Analog Converter). The resolution of these components depends on the price range, but a resolution of 16 bits is needed for audio in CD quality.[9][19]

For the digital audio processing there are mainly two options. Either use to computers CPU or to use a Digital Signal Processor(DSP).

In order to control and issue commands to the sound card, some form of device driver is needed. The driver handles the data connection between the sound card and an operating system. The driver needed depends mostly on the users OS. For Windows users the drivers will generally be written by the manufactures and will therefore be licensed. Linux users on the other hand,

have a bit more freedom. The most widely used driver is called ALSA (Advanced Linux Sound Architecture). One of the bigger advantages with the ALSA-driver compared to most Windows drivers, is that it allows the user to directly interact with the kernel and therefore the hardware.[2]

## 2.5 Platforms for digital signal processing

In order to correct the soundlevels of the loudspeaker compared to the measured sound, a platform that can process and compare the audio is needed.

For real time digital signal processing the highly specialized digital signal processors (DSP) was created, these had a lot less functionality than normal CPU's but were faster for processing digital signals. Today however CPU's have gotten so fast that they can be used for most real time digital signal processing.

### Microcontroller

A microcontroller is a circuit created for and used to control embedded systems. A microcontroller usually contains a CPU and some random access memory (RAM), besides that it has input output ports, so that it can be used in a embedded system[7].

A microcontroller will typically be set to run a single program indefinitely. This makes it possible to use the CPU<sup>1</sup> quite effectively. It also removes the overhead of trying to effectively schedule the CPU usage between different processes.

A very widely used series of microcontrollers are the Arduinos. The most common Arduinos are equipped with an ARM CPU with a clock speed in the range of about 8-80 MHz.

### Computer

Another option for a platform for digital signal processing, could be a fully fledged computer. Besides a CPU and RAM, a complete computer will often have some form of permanent memory, network capabilities, a dedicated graphical processing unit (GPU), and multiple ports for communication with peripherals. A complete computer is also easily implemented with a operating system, which makes it easier for the CPU to handle multiple simultaneous processes with the help of a kernel.

While you normally think of a desktop PC or a laptop, when you hear the term "computer", There has recently been an emergence of small single board computers, where you have a complete computer implemented on a single PCB. The most well known example of a single board computer is the Raspberry Pi.

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<sup>1</sup> which is often somewhat slow compared to CPU's used in PC's



Figure 2.6: Raspberry Pi model B+. Image from [1]

There are multiple versions of the Raspberry Pi, each version with slightly different hardware. Each type has an ARM processor with a clock speed of at least 700 MHz which is several times faster than even the fastest Arduino. This fact might help with negating the extra overhead associated with running a program in an operating system instead of an embedded system. Another benefit of using a computer, is that it might be possible to use already existing drivers to communicate with a sound card.

## 2.6 Wireless communication

While the system may not necessarily need a wireless connection. Yet do to the curriculum and because it is expected to be of convenience, some useful forms of wireless communication will be studied to a basic level, so that it is possible to make a suitable decision for the design phase of the Self adjusting loudspeaker system.

### Commonly used wireless systems

Because there is lot of different types of communication systems, some which is not relevant for the scope of this project, **we** will try to list some of the more commonly used systems, which is expected to work within the scope of the project.

#### Wireless Local Area Network

In general most of people with wireless access to the internet, are using either cellular or Wireless Local Area Network (WLAN for short). Cellular communication will be discussed later. The most common implementation of WLAN is through WIFI, which is based around the IEEE 802.11 standard. There are many varriations in 802.11 such as

do we want elaboration on frames and CSMA/CA here? or later if we "choose" to use wifi later on in the project

## Wireless Personal Area Netowrk

PersonalArea Netowrk or PAN for short, and the wireless version is call WPAN (wireless PAN). The idea behind WPAN is like that of the WLAN, except the range is typical limited to *personal* space. The range is a lot shorter compared to WLAN, often around 10 meters (but can be wider for industrial purposes), where WLAN often have a range that of a house. WPAN is based on IEEE 802.15 standard. Probably the widest implementation of WPAN is the bluetooth standard (the IEEE 802.15.1 standard).

## Bluetooth

Bluetooth was originally meant as a wireless alternative of the RS-232 standard. The RS-232 is no longer in use by the average person, due to the slow transmission speed, short maximal cable length and large physical connector size. It is still in use in commercial usage. So bluetooth is designed to be a short range wireless communication standard, working in areas with interference. This is done using something frequency hopping spread spectrum (FHSS) in the 2.4 to 2.5 GHz ISM band, sending small packages at up to 79 changing frequency channels. It works in a master slave relation with up to seven slaves. Later on power consumption and bit rate have been improved significantly. It is possible to achieve bit rates up to 2.1 Mb/s [3] and with the use of 802.11 AMP (Alternate MAC/PHY) bit rates of 54 Mb/s is possible. Adaptive frequency hopping spread spectrum (AFH) was also introduced, mainly to avoid interference with WIFI.

## Zigbee

is this worth mentioning??

Another usage of the IEEE 802.15 standard, 802.15.4 to be exact, is the zigbee protocol. This protocol is meant for begin low on price, power consumption, bit rate and low range (though a mesh grid can be a solution to this). So this technology is not useful for this project since the bit rate is about 250 kbit/s using the 2.4 Ghz ISM band. While with the right compression of the sound data, it its possible to achieve a real time system. It would create serious limitations of the system, eg. sampling and transmitting raw sound data at the 44.1 kHz sampling rate with a bit depth of 16 bits is not possible, since this would require 705,6 kb/s. **Do we want to make this delimitation here, or should we wait to the delimitation chapter?**

**Should we mention technologies such as 4G (and cellular in general) and radio broadcasting such as FM-radio?**

# Problem Statement 3

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## 3.1 Project Scope

The preceding analysis, in chapter 2 of potential technologies, it is now possible to outline the project. As mentioned earlier, the goal of the project is to make a system that automatically can correct the frequency response of an audio system. It has been decided that the specific solution that will be described in this project, is a system that can measure audio in a room. The measured audio will then be compared to the original audio signal, and an equalizer will then be used to adjust for an uneven frequency response, and then correct imminent audio signal.

It would be preferable to be able to configure the equalizer for many different kinds of frequency responses. Therefore it has been decided to implement an equalizer using a series of digital band pass filters, that can be automatically adjusted independently. Like the graphic equalizers described in section 2.1.

### delimitations

A big advantage for the imagined system would be if the microphone could be freely moved around the room. Therefore, it has been decided to include some form of wireless communication in the implementation.

It has been decided to use WIFI (one of the IEEE 802.11 standards). The decision is based on the two most reasonable communication standards WIFI and bluetooth, of these WIFI has been chosen. WIFI is chosen because it has the highest bandwidth making the initial design easier, because bandwidth will not be critical and optimization can be made late on.

For this reason it has been chosen to implement the system on two separate devices that can communicate wirelessly: one with a microphone to measure sound system, and another device to do the signal processing.

To save time and money, and to make it easier to implement a prototype it has been decided to to make everything in the project from scratch. It would be more relevant to use already existing hardware. It has been decided to implement both devices on Raspberry Pi single board computers (specifically a Raspberry Pi 3 for the stationary unit, and a Raspberry Pi Zero W for the microphone unit). The conversion from analog signals to digital will also be done using already existing sound cards and drivers. The same goes for microphones and wireless transmitters/receivers.

In general the hardware has been chosen mostly with availability, simplicity and ease of use in mind.

### table over chosen hardware

Since it might not be possible to correct the whole audio spectrum, it has been decided to put a lower limit on the frequencies that will be corrected.

more if necessary

## 3.2 Problem statement

How does?

# Requirements specification 4

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In this chapter the specific requirements for the project will be established. This will include wanted functionality and how this will be divided into subsystems, with there own requirements.

## 4.1 Functional requirements

The system should be able to:

- 1.1 Receive an analog audio input signal.
- 1.2 Output an corrected analog audio signal in CD standard quality.
- 1.3 Correct the frequency response of the signal compared to the input within TBD dB.
- 1.4 Change the frequency response by TBD dB for each alteration guess: 1 dB
- 1.5 Modulate frequencies from TBD Hz to TBD Hz guess: 50 Hz - 20 kHz
- 1.6 Correct the signal within TBD ms.
- 1.7 Run on two separate devices that uses wireless communication.

## 4.2 Division in subsystems

asdf

Based around the functional requirements outlined above, the functionalities of the system have been divided into four different subcategories. These can be seen in figure 4.1.



Figure 4.1: some description

### Audio interface(s)

This module is tasked with converting the analog reference signal and the signal captured by the microphone to digital signals. Furthermore it has to convert the corrected digital signal to an analog output signal. It will also be tasked with storing the sampled input in correctly sized buffers for further use by the system.



## Equalizer

This module is tasked with dividing the input signal into **a number of** frequency bands, using parallel band pass filters. Each band pass filter will need to have an adjustable gain.

## Controller

The controller module is supposed to perform frequency analysis on a buffer of both the measured audio signal and the input signal. The results of these analyses are compared, and the equalizer is configured to try and minimize the differences of the frequency responses of the two signals.

## Wireless channel

The last of the four modules has the job of ensuring that the two raspberry pi's can communicate over WiFi at all times. More specifically it need to make sure that the microphone device is always sending it's measured audio signal to the stationary device.

qwer

- 2.1 Audio interface
- 2.2 Equalizer
- 2.3 Controller
- 2.4 Wireless channel

The requirements for the modules is an early draft

## 4.3 Requirements for audio interface

The audio interface module should be able to:

- 3.1 Convert an analog audio signal to a digital signal.
- 3.2 Convert an digital audio signal to a analog signal.
- 3.3 Sample audio signals with a sampling frequency of 44,1 kHz and a bit debt of **TBD** bits.
- 3.4 Store input and measured data in two buffers of **TBD size**.
- 3.5 Convert the signal within **TBD** ms. **Less then the total delay**

## 4.4 Requirements for equalizer

The equalizer module should be able to:

- 4.1 Capable of dividing a digital signal into **TBD number of** frequency bands.
- 4.2 Adjust the amplitude of the individual frequency bands with **TBD** dB.
- 4.3 Make the frequency adjustments based on input from the controller module.
- 4.4 \*\*\*\*Adjust the signal within **TBD** ms. **Less then the total delay\*\*\*\***
- 4.4 have a group delay lower than **TBD** ms.

## 4.5 Requirements for controller

The control module should be able to:

- 5.1 Analyze frequencies from TBD Hz to TBD Hz guess: 50 Hz - 20 kHz
- 5.2 Change the frequency response by TBD dB for each alteration guess: 1 dB
- 5.3 Correct the frequency response of the signal compared to the input within TBD dB.
- 5.4 Correct the signal within TBD ms. Less then the total delay

## 4.6 Requirements for wireless channel

The wireless channel module should be able to:

- 6.1 Send data between the two raspberry pi's at a constant rate of 300 TB/s.
- 6.2 Communicate using the IEEE 802.11 standard.
- 6.3 Send data with TBD% package loss or below.

## 5.1 Recording with ALSA API

**DISCLAIMER.** This is only general description of how we are recording.

Since it is an USB microphone, the PCM name is hardcoded into the code. It has been decided to record in CD quality (16 bit at 44100 Hz) **why?**.

## 5.2 Equalizer Design

In this section the design of the equalizer module will be described. The equalizer must be designed to live up to the specifications from section 4.4.

From the requirements specification, it is given that the equalizer should be divided into 10 frequency bands. These 10 frequency bands can be implemented using 10 bandpass filters.

### Determination of central frequencies

For all the bands to be equally distinct from each other, the central frequencies of the bandpass filters must be distanced logarithmically from each other **something something how sound works**.

The center frequencies are calculated by starting from 1 kHz and then multiplying or dividing by 2, so that each center frequency is placed an octave apart. This nicely covers the audible frequency range by having the lowest frequency band around  $\omega_{c1} = \frac{1000\text{Hz}}{2^5} = \frac{1000\text{Hz}}{32} = 31,25\text{Hz}$  and the highest frequency range around  $\omega_{c10} = 2^4 \cdot 1000\text{Hz} = 16 \cdot 1000\text{Hz} = 16\text{kHz}$

All the center frequencies can thus be written as  $2^n \cdot 1000\text{Hz}$  where  $n = -5, -4, -3, \dots, 3, 4$ .

$\omega_{c1}$	$\omega_{c2}$	$\omega_{c3}$	$\omega_{c4}$	$\omega_{c5}$	$\omega_{c6}$	$\omega_{c7}$	$\omega_{c8}$	$\omega_{c9}$	$\omega_{c10}$
31,25 Hz	62,5 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz

Table 5.1: Center frequencies spaced one octave apart

These 10 center frequencies are similar to the central frequencies specified in the ISO 266 standard for octave band equalizers [5].

### Design of filter transfer functions

Ideally the passband of the bandpass filters should cover the whole frequency range from **TBD** - **TBD** specified in section 4.4, so that the equalizer will have a flat passband in the neutral configuration.

For each bandpass filter to handle an equally significant amount of frequencies the cutoff frequencies of two filters next to each other should meet at the logarithmic mid point. Thus the edge frequencies of one of the bandpass filters can be formulated as:

$$\omega_{hn} = \sqrt{\omega_{cn} \cdot \omega_{cn+1}} \quad (5.2.1)$$

and

$$\omega_{ln} = \sqrt{\omega_{cn} \cdot \omega_{cn-1}} \quad (5.2.2)$$

Where  $\omega_{hn}$  is the higher edge frequency of bandpass filter number  $n$  and  $\omega_{ln}$  is the lower edge frequency.

Since the central frequencies are spaced exactly one octave apart, the ratio between the edge frequencies can be calculated as:

$$\omega_{hn} = \sqrt{2 \cdot \omega_{cn}^2} \iff \frac{\omega_{hn}}{\omega_{cn}} = \sqrt{2} \quad (5.2.3)$$

and

$$\omega_{ln} = \sqrt{\frac{1}{2} \cdot \omega_{cn}^2} \iff \frac{\omega_{ln}}{\omega_{cn}} = \frac{1}{\sqrt{2}} \quad (5.2.4)$$

Considering this it can also be shown that the passband of any single filter covers exactly an octave.

$$\frac{\frac{\omega_{hn}}{\omega_{cn}}}{\frac{\omega_{ln}}{\omega_{cn}}} = \frac{\omega_{hn}}{\omega_{ln}} = \frac{\sqrt{2}}{\frac{1}{\sqrt{2}}} = 2 \iff \omega_{hn} = 2 \cdot \omega_{ln} \quad (5.2.5)$$

In an ideal world the frequency response of the equalizer should thus look like figure 5.1

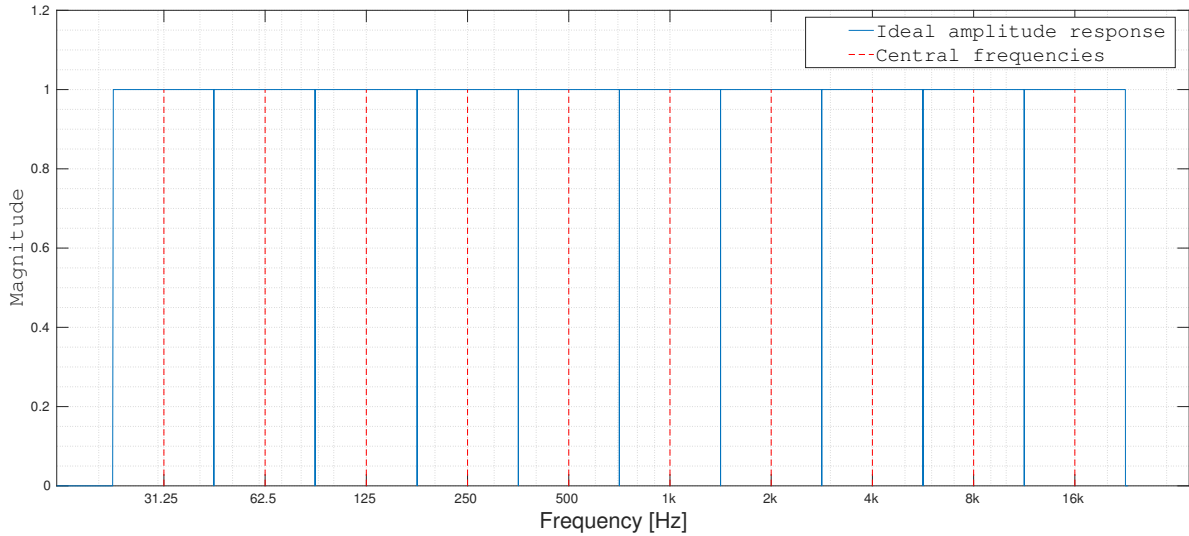


Figure 5.1: Ideal amplitude response of the equalizer.

Since the equalizer is supposed to be implemented on a Raspberry Pi, the bandpass filter will have to be digital filters. There are generally two ways of designing a digital filter as can be seen in section 2.3: FIR and IIR. Since the signal processing of the equalizer will have to be made in approximately real time and since the signal processing will be made on a general purpose CPU, there will be some computational constraints on the filters. Thus the bandpass filters will be made with IIR filters.

To get the desired frequency response given by the requirements in section 4.4, Continuous time filters, that meets these requirements, will be designed initially. They will then afterwards be converted to the digital domain.

Since it is desired to have as flat a passband as possible, it is chosen that the filters will be implemented as Butterworth filters.

calculations of filter order showing that the necessary order is 4

As starting point, let's look at bandpass filters with the same central frequencies and bandwidth as earlier, this time implemented at 4th order bandpass filters.

To see if these filters can fulfill the requirements, all 10 bandpass filters along with the sum of all of them are plotted in a Bode plot in MATLAB.

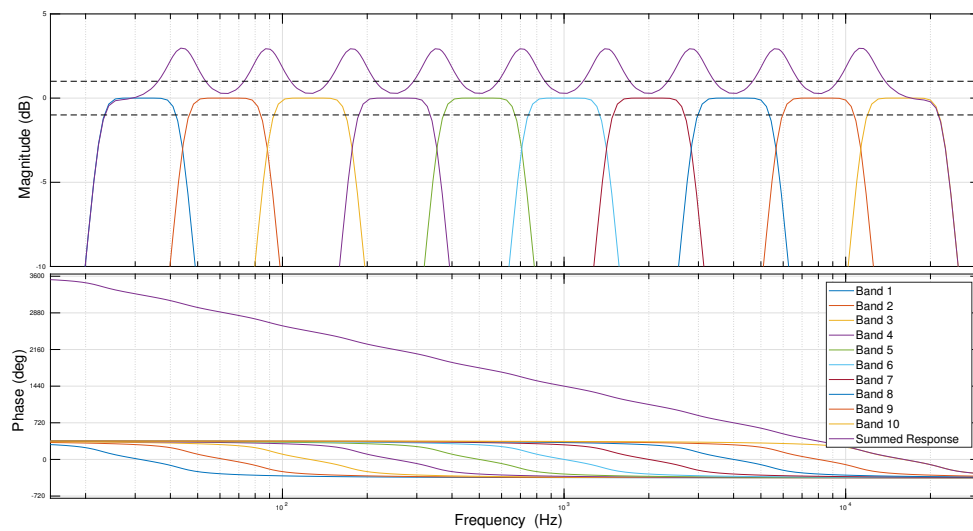


Figure 5.2: Bode plot of bandpass filters as 4th order Butterworth

As can be seen in figure 5.2, these bandpass filters cannot fulfill the requirement of a bandpass ripple at  $\pm 1$  dB. It can be noticed that the gain where the bands meet ( $\omega_{hn} = \omega_{ln+1}$ ), are significantly higher than 1 dB.

# Glossary

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**Equalizer** An electronic device for adjusting the frequency response of a system.. 4

**FIR Filter** Finite impulse response filters. Filters whose impulse responses are zero after a certain point. see. 7

**Frequency response** The way a system output behaves in terms of magnitude and phase, as a function of the frequency of the input. 1

**IIR Filter** Infinite impulse response filters. Filters whose impulse responses continues forever. This property is known from the impulse response of analog filters. see. 7

**Raspberry Pi** Series of single board computers, often used for small projects.. 9

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