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SUPERACOUSTICS

Development of Android application to measure sound reduction index

KARL BENGTSSON & ELLIOT SANDEFELDT

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MASTER'S DISSERTATION

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Development of Android application to measure sound reduction index

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Supervisors: DELPHINE BARD, Associate Professor, and HANNA AUTIO, MSc, Div. of Engineering Acoustics, LTH, Lund.

Examiner: Professor OLA DAHLBLOM, Div. of Structural Mechanics, LTH.

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For information, address:
Division of Engineering Acoustics,
Faculty of Engineering LTH, Lund University, Box 118, SE-221 00 Lund, Sweden.
Homepage: www.akustik.lth.se

Abstract

Urban dwelling is common in our society today and a considerable portion of the population reside in apartment buildings, making sound insulation an important aspect regarding the comfort of urban living. While using smartphones for acoustic measurements is becoming more and more common, there is an absence of a simple tool for measuring sound reduction index. Sound reduction index is a measurement of the reduction of sound intensity when it passes through a building element. To calculate sound reduction index, sound pressure level, background noise and reverberation time need to be measured. There are various applications available for each individual variable, but none that measure all three to calculate the sound reduction index. The purpose of this thesis is to develop one application that can measure all these quantities and calculate sound reduction index. Furthermore an evaluation is made regarding the use of smartphones as acoustic instruments.

The application is developed on the Android Studio platform for use on all smartphones operating on the Android OS. Measurements were acquired in a laboratory environment and analyzed at the octave band level. To study the validity of the results, measurements were also completed with a sound level meter and compared to those of the smartphones. Results of the measurements show that the smartphone is an efficient tool for measuring sound reduction index but with more restrictions than professional equipment. The smartphones used in this study are able to measure sound pressure level accurately within a span of approximately 55 dB. Within this range the calculated sound reduction index closely resembles that of the sound level meter.

This thesis revealed that a smartphone is a reliable tool for measuring and calculating sound reduction index if the noise levels are within the microphones dynamic range.

To promote further development of this application as well as acoustic applications in general, the source code for SuperAcoustics is free to use and develop further. The code is available on GitHub at the following URL:
`https://github.com/KarlBengtsson/SuperAcoustics`.

Sammanfattning

Urban bosättning är vanligt i dagens samhälle och en övervägande andel av befolkningen bor i lägenheter, där ljudisolering är en viktig aspekt rörande trivseln i bostaden. Användning av smartmobiler för akustiska mätningar blir allt vanligare, men inget enkelt verktyg finns idag för att mäta och räkna ut reduktionstalet.

För att räkna ut reduktionstalet behövs ljudtrycksnivå, bakgrundsljud och efterklangstid mätas. Det finns ett antal applikationer tillgängliga som mäter dessa storheter. Målet med den här uppsatsen är att utveckla en applikation som kan mäta alla kvantiteter och räkna ut reduktionstalet. Vidare har en utvärdering gjorts av smartmobilers förmåga vid akustiska mätningar.

Applikationen utvecklas på plattformen Android Studio för användning på alla telefoner som har operativsystemet Android OS. Mätningarna gjordes i laborationsmiljö och analyserades i oktavband. För att avgöra validiteten av resultaten gjordes även mätningar med en kalibrerad sonometer för att jämföra med smartmobilerna.

Resultaten av mätningarna visar att smartmobiler är effektiva verktyg för att mäta reduktionstalet men vissa restriktioner bör tas hänsyn till. Modellerna på smartmobiler som använts i den här studien kan mäta ljudtrycksnivån bra inom ett spann som är ungefär 55dB. Inom spannet blir uträkningen av reduktionstalet snarlikt resultatet uträknat med sonometern.

Den här uppsatsen visar att smartmobiler är bra verktyg för mätning och uträkning av reduktionstal om ljudtrycksnivån hålls inom spannet som mikrofonen klarar av att mäta.

För att uppmuntra vidare utveckling av applikationen i arbetet samt applikationer för akustiska mätningar i allmänhet, så är koden till SuperAcoustics tillgänlig att använda och vidareutveckla. Koden finns att ladda ned på följande URL:
`https://github.com/KarlBengtsson/SuperAcoustics`.

Acknowledgements

We would like to place our gratitude to the division of engineering acoustics. We would like to thank Delphine Bard and Hanna Autio for their supervision and guidance during our thesis. We would also like to thank Nikolas Vardaxis for helping us with the laboratory setup for performing the measurements.

Notations and Symbols

$\hat{A}$ - *Peak value/amplitude* of wave in air.
$\tilde{A}$ - *Root-mean-square* value of wave in air.
f - *Frequency*, wave cycles per second.
T - *Period time*, time to complete a cycle.
λ - *Wavelength*, the length of the wave.
L_P - *Sound pressure level*, logarithmic measure of sound pressure in relation to reference value.
$\hat{p}$ - *Peak value/amplitude* value of pressure in air.
$\tilde{p}$ - *Root-mean-square* value of pressure in air.
p_{ref} - *Reference value*, human hearing threshold.
A_R - *Absorption area*, area absorbing sound energy in a room.
α - *Absorption coefficient*, dimensionless coefficient stating how effectively a surface absorbs sound energy.
S - *Surface area* of a given wall.
T_{60} - *Reverberation time*, time in seconds it takes for a noise level to decrease by 60 dB.
V - *Volume* of a room.
L_S - *Sound pressure level* in the sending room
L_R - *Sound pressure level* in the receiving room
L_{sb} - *Sound pressure level* of signal and background noise combined
L_b - *Sound pressure level* of background noise
SPL - *Sound pressure level* in general when mentioned in text and figures.

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1 Introduction

In the introduction chapter, smartphones and their use in acoustics measurements as well as the importance of acoustics in our society today will be presented. The objective and workflow of the thesis is also presented.

1.1 Background on smartphones and sound insulation

Today, smartphones and their applications have found a way to influence our lives in almost every aspect of our daily activities. Whether it is social media, contact with friends and relatives, making payments or just pure entertainment, the use of smartphone applications just keeps on growing. Smartphones are becoming more than just a means of communication, as the technology, software and hardware keeps on developing and improving and limitations are becoming fewer. Acoustic measurements is an area where smartphones are becoming an instrument.

In regards to acoustics and acoustic measurements, some research and development has been done using a smartphone for measurements such as reverberation time and sound pressure level measurements, but there is no simple tool for measuring sound insulation. Sound reduction index is a measurement of how much a structure such as a wall, floor or ceiling reduces sound intensity. To calculate sound reduction index, sound pressure level, background noise and reverberation time need to be measured. A limitation for measuring this with a smartphone is the quality of the hardware from an acoustic standpoint. Since the main purpose of a smartphones microphone is for voice communication, a smartphone is not nearly as precise as that of professional acoustics equipment when it comes to acoustic measurements and is more restricted as to which noise levels it can measure. In addition, the hardware may vary depending on the manufacturer of the smartphone, as there are a great variety of smartphones running on the Android operating system.

In 2014, Google released its own integrated development environment (IDE) for development of Android applications known as Android studio. Android Studio is part of the Android open source project, which offers the source code for the Android operating system enabling everyone to contribute to Android development. Android studio has integrated support for github, a web-based hosting service for version control, which allows users to share and use open source projects, promoting Android developers to share and distribute their own code.

Noise generated within a room, will produce vibrations in the air that in turn produce vibrations within walls, floors and ceilings. Some of this energy will be reflected back into the source room and some will pass through the building element, in some cases generating vibrations and producing sound on the other side of the element [13]. As urban dwelling is common in our society today and a considerable portion of the population reside in apartment buildings, sound insulation is an important aspect regarding the comfort of urban living. A smartphone application that can measure sound reduction index would simplify sound insulation measurements. This would make it easy to quantify the quality of sound insulation as it can be completed using only a smartphone for equipment.

1.2 Objective

Today, professional acoustics equipment such as a sound level meter can be used to measure sound insulation. Although a smartphones hardware does not equal that of professional acoustics equipment, it does provide the ability to measure certain acoustic parameters. This may simplify acoustic measurements as there will be no need to carry along a sound level meter as long as you have a smartphone with you. The main goal of this master thesis will be to develop an Android application to measure airborne sound insulation, by calculating sound reduction index and to evaluate the possibility of using smartphones for this purpose. The thesis will evaluate how well a smartphone can measure sound reduction index in different frequency bands and aim to develop an easy to use Android application that provides clear instructions and results. Since this thesis aims to study the possibility of measuring sound reduction index using a smartphone, the application will be designed to work only in a controlled laboratory environment. This ensures that sound will be transmitted only through the building element, eliminating flanking transmission.

1.3 Methodology/Workflow

This Master thesis, carried out at the division of engineering acoustics at Lund institute of technology is divided into the following steps:

1. Literature study of acoustics and earlier acoustic applications developed for Android phones.
2. Introduction to the Android studio platform
3. Development and testing
4. Performance of laboratory testing of application
5. Analysis of results

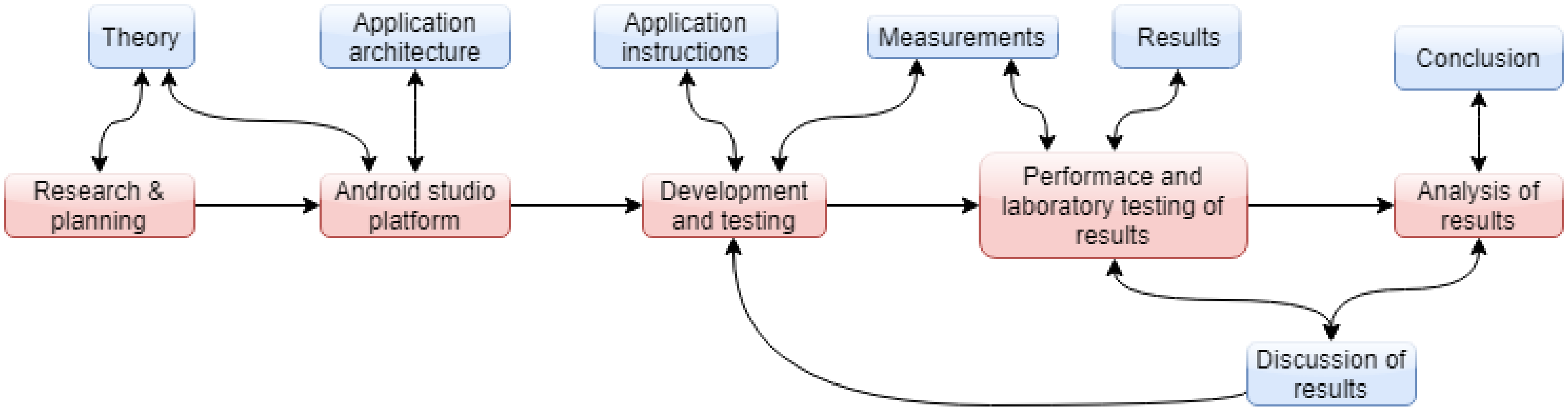

Figure 1.1: Flow chart showing the workflow and report content connected to each process

2 Theory

In this chapter theory discussing sound in air and its importance in room and building acoustics as well as ISO-standards will be presented. Some background on java, Android and smartphones is also introduced.

2.1 Sound in air

2.1.1 Sound Waves

Sound is a wave travelling in a medium. For sound to be able to travel, particles are needed in order to transfer the wave. Sound in air can be interpreted as variations of the density of the air particles, or pressure. Adopting this interpretation states that the wave exhibits interference, either constructive or destructive. The waves oscillate around a static value of air pressure, the atmospheric pressure at a certain time. [13]
The sound wave's propagation can vary greatly in terms of speed and strength if the medium is changed. The quantities describing these properties of the wave are mainly:

- *Peak value/amplitude*, $\hat{A}$ in air (Pa)
- *Frequency*, f wave cycles per second. $(1/s)$
- *Period time*, T time to complete a cycle (s)
- *Wavelength*, λ the length of a wave (m)

These quantities are easily determined for a pure sinusoidal wave.
They can be seen in figure 2.1. Normally, real life sound contains waves with different

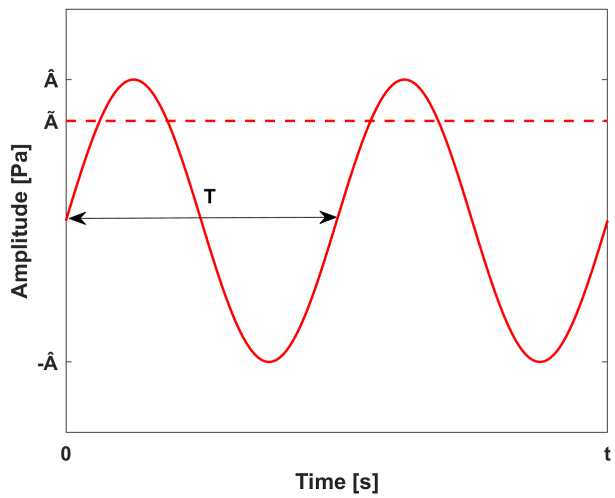

Figure 2.1: Peak value ($\hat{A}$), root-mean-square value ($\tilde{A}$), period time (T) for a pure sinusoidal wave

frequencies and amplitudes that blend together forming something that in the pressure-time domain looks jagged and mixed.[13]
An example of a representative time-signal is presented in figure 2.2.

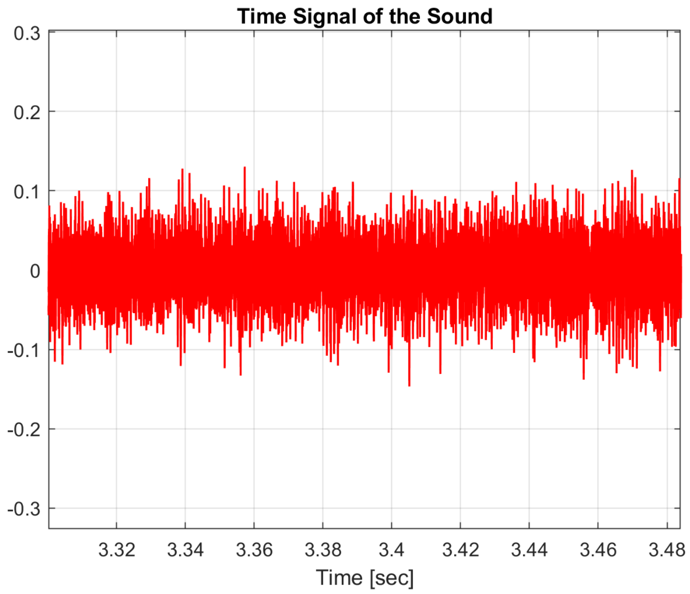

Figure 2.2: Example of real life time-signal containing waves with different frequencies and amplitudes blended together.

2.1.2 Quantifying sound

The pressure variations mentioned in the previous section are small ($\approx 2 \cdot 10^{-5}$ to 20 Pa) compared to the almost static atmospheric pressure ($\approx 10^5$ Pa). The span for the pressure variations is very large and more easily dealt with in a logarithmic scale. Therefore the sound pressure is evaluated in a logarithmic scale using an internationally standardized reference value. The human ear can, according to this reference value, perceive a change in pressure with an amplitude of $2 \cdot 10^{-5}$ Pa. The comparison between the signal pressure and the reference value is then calculated according to 2.1 and is called *sound pressure level*. The unit for the *sound pressure level* is denoted dB, or decibels and calculated using the following equation [16].

$$\mathrm{L}_P = 10 \cdot lg \frac{\tilde{p}^2}{p_{ref}^2} = 20 \cdot lg \frac{\tilde{p}}{p_{ref}}, \tag{2.1}$$

where

- $\tilde{p}$ is the so called *root-mean-square* value. This is a quadratic average of the signal over a sufficient amount of time;
- L_P is the Sound Pressure level;
- p_{ref} is the reference value.

The *root-mean-square* value is calculated according to equation 2.2.

$$\langle p^2 \rangle = \frac{1}{t_0} \int_0^{t_0} p(t)^2 dt = \tilde{p}^2, \tag{2.2}$$

for a harmonic signal the *root-mean-square* value becomes [16]

$$\hat{p}/\sqrt{2} = \tilde{p}. \tag{2.3}$$

Sound waves do not propagate forever in real life. There are a number of ways a sound wave can lose energy. The lost energy is ultimately converted into heat. The process of sound waves losing energy is referred to as attenuation or absorption. For further reading about the different ways of wave attenuation, see (Kuttruff 2006) [16].

The decay of sound pressure in an enclosed volume perceptible to the human ear follows a logarithmic pattern [12]. This observation will be used later on when discussing room acoustics and more specifically, reverberation time.

How humans perceive sound and noise is due to a number of psychological and physiological reasons. The human ear is not uniformly sensitive to all frequencies, several weighting scales for sound pressure level has been developed. The weighting that has been shown to correspond closest to the subjective term of noise is A-weighting. Two sounds judged to the same intensity turns out to have almost the same so-called dB(A)value. A-weighting results in lower sensitivity for lower frequencies and slightly higher between 1kHz-6kHz [13]. A representation of different common weightings is graphically represented in figure 2.3.

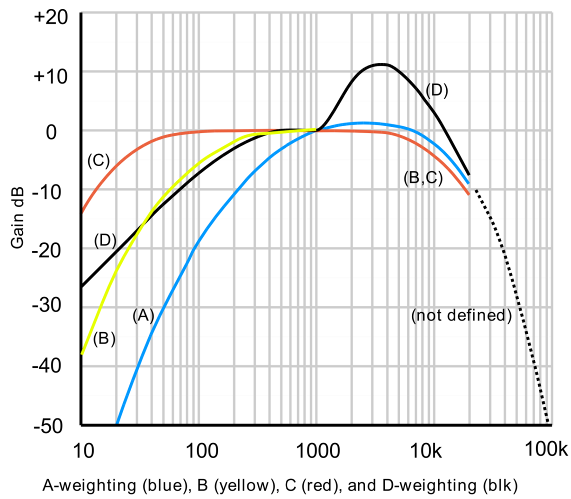

Figure 2.3: Different common weightings of decibel value represented graphically. [25]

2.2 Reverberation Time

Reverberation time is an acoustic parameter evaluated within room acoustics. It defines the time it takes for noise level to decrease by 60 dB. Within a room, noise will repeatedly bounce off surfaces, losing energy with every interaction. This will continue within the room until the sound loses all of its energy. Reverberation time is not dependant on the location within the room, it is a quality of the room as a whole. Reverberation time of a room is affected by the volume of the room as well as the absorption area. Absorption area is a measurement of how much sound energy is absorbed by the boundaries in a room which is dependant on the materials of walls, ceilings floors and other objects present in the room. The absorption area is calculated using the following formula.

$$\mathrm{A}_R = \alpha \mathrm{S}, \tag{2.4}$$

where

- A_R is the calculated absorption area in m^2;
- S is the surface area of a given wall in m^2;
- α the absorption coefficient which is dimensionless.

Absorption area is needed to calculate the sound reduction index of a partition as shown in equation (2.9). In the receiving room, the measured sound pressure level will depend not only on the energy transmitted through the partition, but also how much energy is absorbed in the receiving room. The American physicist Wallace Clement Sabine derived a formula to calculate the reverberation time of a room using the sum of the absorption areas of the walls of a room, better known as Sabine's formula. [3]

$$T_{60} = \frac{0,163\mathrm{V}}{\sum_{n=1}^{\infty} \alpha_n \mathrm{S}_n}, \tag{2.5}$$

where

- T_{60} is the time in seconds it takes for noise level to decrease by 60 dB within a room;
- V is the volume of the room in m^3.

Taking the inverse of Sabine's Formula results in equation (2.8). This is one of the most important applications of Sabine's formula as it is possible to calculate the absorption area by measuring the reverberation time of a room. When measuring airborne sound insulation, the absorption area of the receiving room is needed to calculate the sound reduction index as can be seen in equation (2.9) [3].

For the measurement of the reverberation time, the most important part of the 60 dB sound decay is the first 20-30dB. This part is what the human ear can most easily perceive in terms of sound decay. However the widest decay range possible is preferable. Even so, a decay of 60dB can be hard to achieve in most environments. For the app to be compatible with most environments and testing setups, either T20 or T30 will be used and extrapolated to get the reverberation time. This is a good approximation as the sound pressure level is interpreted as linear in the logarithmic scale during decay. [12]

2.3 Airborne sound insulation

In regards to building acoustics, a wall is considered acoustically effective in its ability to reduce the energy of the sound that travels through it. In other words, reducing the strength of the vibrations in the wall caused by sound is a measure of acoustic efficiency. Ideally, the vibrations would be reduced to almost nothing when travelling through a wall. This is possible but requires a very robust construction that is not ideal for all constructions, for example apartment buildings. Most constructions do transmit sound, with the goal in most cases being to transmit as little as possible. Airborne sound insulation of a wall can be represented by calculating the sound reduction index (R). The sound reduction index of a wall is the difference between two sound power levels and is therefore denoted in dB [13]. It is commonly calculated by measuring the difference in sound pressure level between sending room and receiving room as well as the reverberation time of the receiving room. Equation (2.9) shows how to calculate the sound reduction index from the measured values.

A typical setup for measuring the sound reduction index of a wall is shown in figure 2.4. [13]

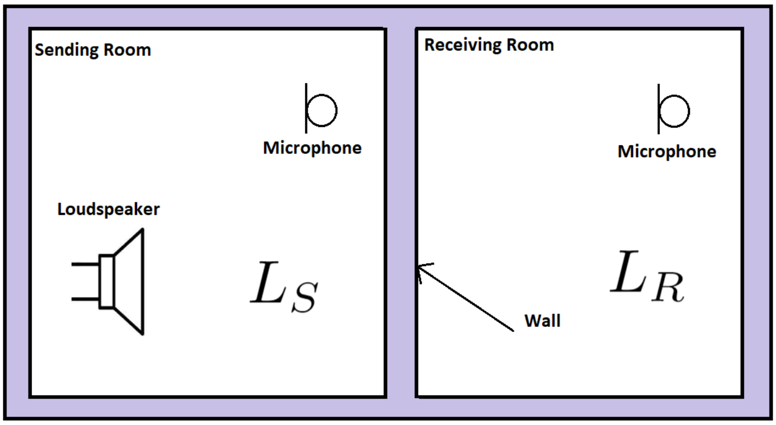

Figure 2.4: Example of a laboratory setup to measure sound reduction index of a wall.

2.4 ISO standards

Measuring the sound reduction index was done according to the ISO standards 140-3, *Laboratory measurement of airborne sound insulation of building elements* [21]. The calculations and measurements needed to determine the sound reduction index are presented in the following section.

2.4.1 Background noise

When calculating sound reduction index, background noise is so-called unwanted noise and can in some cases have an impact on the result. If the background noise is small enough in comparison with the measured sound pressure level in the receiving room, it can be neglected according to the ISO standards [21]. If the background noise is relatively close in sound pressure level, an adjustment has to be made in order to take the background noise into account. When a measurement is taken in the receiving room, the measured sound pressure level is a combination of both background noise and noise generated from the sending room. In the case that the noise produced in the sending room generates a sound pressure level in the receiving room that is too close to the background noise level, the background noise will have an effect on the measurement and needs to be corrected. The ISO standard 140-3 states: *"The background noise level shall be at least 6 dB (and preferably more than 15 dB) below the level of signal and background noise combined. If the difference in levels is smaller than 15 dB but greater than 6 dB, calculate corrections to the signal level according to the following equation"*[21].

$$\mathrm{L} = 10\lg\left(10^{\mathrm{L}_{sb}/10} - 10^{\mathrm{L}_{b}/10}\right)\ \mathrm{dB}, \tag{2.6}$$

where

L is the adjusted signal level, in decibels;

L_{sb} is the level of signal and background noise combined, in decibels;

L_b is the background noise level, in decibels.

If the difference is smaller than 6 dB in any of the frequency bands, use a correction of 1,3 dB. This corresponds to a difference of 6 dB according to equation (2.6)

2.4.2 Sound pressure level

To measure the sound pressure level, a steady sound source with a continuous spectrum is used. The sound source should be loud enough so that the sound pressure level in the receiving room is at least 15 dB higher than the background noise in all frequencies. If the sound pressure level is lower, corrections will be applied in accordance with section 2.4.1. At least five microphone positions shall be used in each room in accordance with the following restrictions [21].

0,7 m between microphone positions;

0,7 m between any microphone position and room boundaries;

1,0 m between any microphone position and the sound source;

1,0 m between any microphone position and the test specimen.

The average sound pressure level from all the measurements is determined by the following equation.

$$\mathrm{L} = 10\lg\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{\mathrm{L}_i}{10}} \text{ dB}, \tag{2.7}$$

where

L is the average sound pressure level in dB, which is used in equation 2.9 to calculate sound reduction index;

L_i are the sound pressure levels L_1 to L_n at n different positions in the room;

n is the number of measurements.

2.4.3 Reverberation Time and sound absorption in the receiving room

To calculate the sound reduction index, the equivalent sound absorption area is needed. This can be determined using Sabine's formula, shown in equation (2.5).

$$\mathrm{A}_R = \frac{0,163V}{T_{60}}, \tag{2.8}$$

where

A_R is the equivalent sound absorption area, in m^2;

V is the receiving room volume, in m^3

T_{60} is the reverberation time of the receiving room, in seconds.

To measure the reverberation time, a minimum of 6 measurements need to be performed, with at least one excitation position and 3 microphone positions [21].

2.4.4 Sound Reduction Index

To calculate Sound reduction index of a partition, the following equation is used.

$$R = \mathrm{L}_S - \mathrm{L}_R + 10\mathrm{lg}\frac{\mathrm{S}}{\mathrm{A}_R}, \tag{2.9}$$

where

> L_S is the measured sound pressure level in the sending room in dB;
>
> L_R is the measured sound pressure level in the receiving room in dB;
>
> S is the surface area of the wall in m^2;
>
> A_R is the absorption area of the receiving room in m^2.

L_S and L_R are the average sound pressure level of the sending and receiving rooms respectively in accordance with equation 2.7.

2.4.5 Test arrangement

The setup in figure 2.4 is that of a controlled lab environment used to calculate the sound reduction index of a wall, floor or other construction. This is done to avoid any flanking transmission. In reality, sound insulation between two rooms will depend on more than just the sound reduction index of the wall between the two rooms as it also depends on the vibrations in the floor, ceiling and junctions of walls. A controlled laboratory setup where flanking transmission is eliminated will be used as this is the simplest way to test the functionality of the app itself. The setup that was used is presented in section 5.3.2. The partition tested in this project is a wooden floor. According to ISO 140-3, the size of the partition shall be between 10 m^2 and 20 m^2 [21].

Three different loudspeaker placements were used. For each loudspeaker placement, five different microphone placements were used. For every microphone placement, ten seconds of sampling was recorded and analyzed.

2.5 Smartphones, signal processing and Java

2.5.1 Java

The programming language used to develop SuperAcoustics is Java. Java is a object oriented programming language that is easy to use and encourages a logical approach, making it one of the most popular programming languages in the world. Java is platform-independent and thus not specifically created for one processor or operating system. Java code itself is written in plain text, which is then compiled into classes, the building blocks of the Java language. Classes contain byte codes which enable them to run on the Java Virtual Machine (JVM). The JVM is available on a number of different operating systems which is what makes classes capable of running on more than one operating system such as Windows, Mac OS and Linux. The JVM together with the Java application programming interface (API) is what makes up the Java Platform. API is a collection of classes, interfaces and other ready-made components that links the android library to the application. The Java Platform is the software environment that runs your own Java program on top of your operating system [22].

2.5.2 Android Studio

To write your own Java program or application, using an integrated development environment (IDE) is convenient. An IDE is a computer program containing a text editor, as well as a compiler and debugger that allows you to write and run Java programs on your computer or Android smartphone. To develop the Android application for this thesis, the IDE Android Studio was used. Android Studio is developed by Google and created for the purpose of developing Android applications. In Android studio, the developer both designs the layout and the functionality of the application. During the development of an Android application, the developer can test it on an Android device or an emulator which is a virtual telephone installed on your computer. This allows the developer to easily test, troubleshoot and debug the application during the development phase [7].

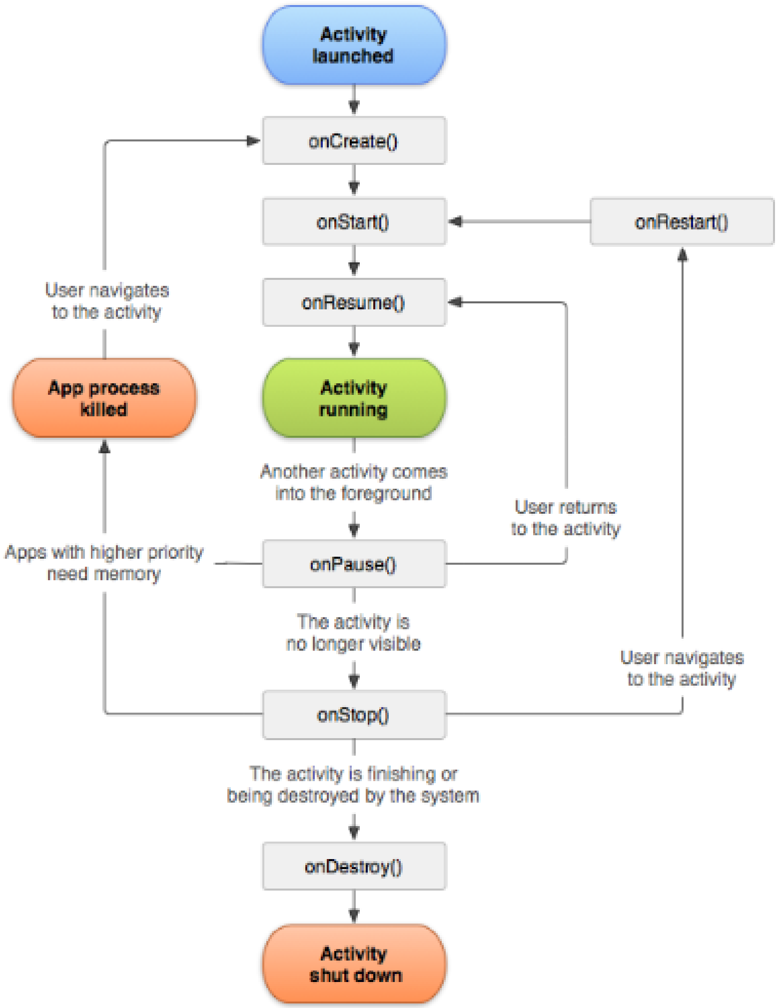

Figure 2.5: Activity life cycle of an Android application [10].

2.5.3 Android Activity Life Cycle

As mentioned earlier, classes are the building blocks of Java. In Android, classes can also be activities. Activities are the classes that communicate with the user interface, control what is displayed on your screen and respond to user inputs. Every Android application has at least one activity that starts when the application is started. A simple application may contain only one class whereas larger and more complex applications will contain many. Each activity transitions through different states of the activity life cycle, whether it is started, paused or terminated, the activity contains a number of callback methods that notify the activity of what state it is in. When an activity is started, the OnCreate() method is called and the activity keeps on running until the onDestroy() method is called upon. For example if more than one application is running on your phone at once, the onStop() method will be called allowing the application to run in the background without shutting down. It is up to the programmer to decide how the activity behaves during these methods and define when data or states of the activity should be saved, discarded or sent to another activity. Understanding the activity life cycle and saving data in the correct methods is essential to developing a well working Android application. A diagram displaying the life cycle of an Android activity is shown in figure 2.5. The methods displayed in this figure, are automatically called upon when an activity enters a certain state. If there are settings or other data that has been changed during an activity and needs to be saved, it is convenient to do so in methods called upon when an activity is paused or stopped. This is discussed in more detail in section 3.5.

In addition to activities, SuperAcoustics also uses fragments. A fragment is viewed as a sub activity that runs on an activity's life cycle. Meaning that the activity is not terminated or paused when a fragment is called. A Fragment, just like an activity, communicates with a user interface to display its own view on your smartphone [5]. In SuperAcoustics , a fragment is used when the user decides to input a reverberation time measurement done in a different application, discussed further in chapter 4.

2.5.4 Using smartphones for acoustics measurements

Over the past few years, using smartphones for acoustic measurements has become more and more common. From measuring sound pressure level to reverberation time to monitoring environmental noise, as smartphones develop and become better, so do acoustic measurements using smartphones. In 2015, a study was conducted at the University of Hartford to asses the capability of using smartphone applications for noise monitoring instead of expensive acoustics equipment such as a sound level meter. The study tested a total of 100 smartphones from six different manufacturers and six different smartphone applications. The study showed that although there is a lot of room for improvement, there is potential and ability for smartphones to measure sound pressure level. It also showed that the variance between measurements done with different smartphones is very large, meaning that an important part of this thesis will be calibration [19]. Since not all smartphone models are equipped with the same acoustic sensor, chances are that 2 smartphones will get different results when measuring sound pressure level and therefore need to be calibrated with professional acoustics equipment before measurements are done.

A microphone is a acoustical-to-electrical transducer that outputs electrical signals proportional to the acoustical signals put in. The transducer can work in a variety of ways. What microphones have in common is the diaphragm. The diaphragm is the component that moves due to variations in pressure, i.e sound. The movements of the diaphragm give rise to variations in electric current, either by position changes in a magnetic field or capacitance. The electric current produced fluctuates, ideally in the same pattern as the pressure and diaphragm, producing a signal. The signal is sent for a device to read, in this case, the smartphone. [24]

There are limits to what a microphone can detect and output, and there may also be limits to the signals the device can perceive. Depending on the type of microphone used, different key factors can vary. The type and size of diaphragms can impact how easily they move back and forth. In today's smartphones a type of microphone commonly used is the MEMS, or *microelectro-mechanical systems* [2]. The dynamic range of a microphone is the difference between upper and the lower limit of input to which the microphone responds linearly to changes in sound pressure level. The upper limit to this point is called the *acoustic overload point*, or AOP. After the AOP non-linear behaviour can occur, such as distortion or microphone clipping. The lower limit is called the *equivalent input noise*, or EIN. Below this point, non-linear behaviour can instead occur with the detection of the input signal. [15]

MEMS typically have good quality of sound recording given the size and the price of production. However, there are limitations in the dynamic range. The range of a modern MEMS microphone is in the order of 60dB. This range is large enough for recording speech but can be problematic when trying to record louder sounds [2].

Gain is the amount of amplification applied to a signal. The amplification can either be done analogously or digitally when analyzing and processing a signal. The amplitude of the signal is the main property used when measuring sound pressure level. Therefore the gain of the signal is important in order for the sound pressure level displayed during analysis to match the true level.

2.5.5 Fast Fourier Transform

The "Fast Fourier Transform", abbreviated *FFT*, is an efficient algorithm for performing transformation of a signal between the time- and the frequency domains. The transformation is possible due to the fact that every signal can be represented as a sum of weighted sinusoidal waves [14]. The algorithm is widely used in signal processing since the computational cost compared to the "Discrete Fourier Transform", abbreviated *DFT* is much less [1].

In order for a signal to be decomposed into the different sinusoidal components accurately, sufficient data points are needed in the signal. In figure 2.6 a harmonic wave sampled with three different frequencies is presented. As can be seen, the result for the different sampling rates vary. The sampling theorem formulated by Nyquist in 1928 and contributed to by Shannon states: The analog signal x(t) can be *uniquely represented* by its discrete samples if the sample rate used is larger than twice the maximum frequency in the signal [1]. When performing an FFT there are numerous parameters to take into account. One of the numerical errors that can occur during transformation is called *spectral leakage*. The effect of spectral leakage can be viewed as a smeared version of the actual content in the frequency domain. This effect can be seen if the studied signal data set is not evenly dividable by the sinusoidal period time. This is almost always the case for real-life signals and the measure taken to minimize the effect of spectral leakage is called *windowing* [14].

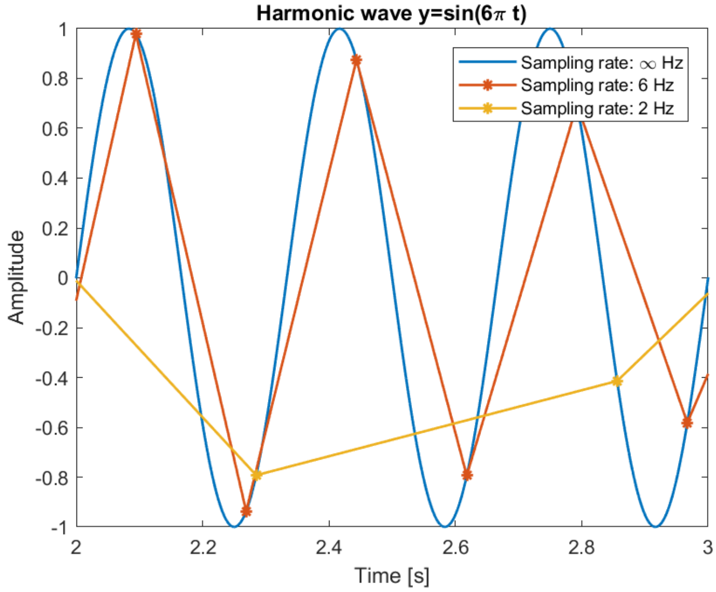

Figure 2.6: A harmonic wave sampled with different sampling rates, justifying the Nyquist frequency. The sinus wave has a frequency of 3 Hz and a sampling rate of 6 Hz is the lowest frequency that can represent the signal uniquely.

Different windows can be applied to the signal by simply multiplying with the window function. If the expected behaviour of the signal is known, a window that fits the purpose can be chosen. If the signal and behaviour is unknown, the so-called *Hann-window* fits the purpose in almost 95% of cases [14].

Three different windows are implemented in the app and available for the user to chose between. If nothing is chosen, the app uses the *Hann-window* as default.

- Hann window - in general satisfactory in 95% of cases
- Uniform/Rectangular window - good for broadband or flat signal
- Flat top window - proposed for single frequency amplitude accuracy

3 App architecture

To measure sound pressure level, SuperAcoustics has used the source code of another acoustics application, Openoise, developed by Arpa Piemonte. Openoise is an open source application protected under GNU v.2 license or later with the code available on GitHub. The current version of GNU license, version 3, states that all users are free to use, share and modify the code and the license exists to ensure that the software remains free for all users [26]. The Fast Fourier Transform used in this application is a discrete Fourier transform developed by Piotr Wendykier at Emory University. This FFT is imported to android studio and not altered or modified in any way. It is an open source code available on GitHub and protected under the Mozilla Public license, stating that the code is open-source, free to use, modify and distribute [18].
Openoise can be found on the following url:
`https://github.com/Bustami/openoise-meter-android`

The FFT used in the thesis can be found on the following url:
`https://sites.google.com/site/piotrwendykier/software/jtransforms`

3.1 AudioRecord

In order to record and analyze audio using the smartphones microphone, SuperAcoustics implements the Java class AudioRecord, which is a part of the Android platform. Audiorecord manages the audiorecording of Java applications using the hardware of the smartphone [11]. When creating an AudioRecord object, the input parameters provided contain information about how the audio signal is to be stored. Parameters such as sample rate, buffer size, channel configuration and input source are chosen and defined in the constructor. The channel configuration in this test is set to mono, since no stereo recording is available for our hardware. The sample rate is chosen according to the so-called Nyquist criteria described in chapter 2. Knowing that only audible sound is to be studied, 44100 Hz sampling rate is sufficient.

In order to record and analyze audio, the data from an audiorecord object is read in real time, processed and overwritten to provide a live update of audio and sound level. In SuperAcoustics , audio data is read into an array of type short. The datatype short is optimal for saving data and is optimal for saving memory in long arrays [23]. The datatype short is a 16-bit integer, meaning that the audio data that is returned from the recording needs to be in 16-bit format. While the audiorecorder is running, the audio data is continuously overwritten. SuperAcoustics calculates the average sound pressure level for the different octave bands each time the audio data is overwritten. The the logarithmic average of all the audio data that is recorded is calculated. This provides the user with an average of the sound pressure level over the measured time. In order for the smartphone to be able to record and analyze audio, the user has to grant SuperAcoustics permission to use the smartphones microphone to record audio.

In the Audiorecord constructor, the defined parameters are shown in table 3.1 [11]. These parameters are what define the instance of audiorecord, how the recorded audio is stored and processed. The different audio sources available and tested in this thesis are presented in table 3.2. This is discussed further in section 5.1.

Table 3.1: Parameters defined in the AudioRecord constructor.

Parameter	**Description**
audioSource	The recording source, see table 3.2 for further description, audiosource is inherited from the Android class mediarecorder.
sampleRateInHz	The sample rate expressed in Hertz, in this case set to 44100 which is the only rate guaranteed to work on all devices.
ChannelConfig	Describes the configuration of the audio channels, in this case set to Mono.
audioformat	Format in which the audiodata is returned, set to 16BIT in order to comply with the data type short.
bufferSizeInBytes	The total size in bytes of the buffer where audio data is written during the recording, in this case set to the minimum buffer size * 2.

Table 3.2: The different audio sources used in audiorecord during this thesis.

Audio source	**Description**
Default	Default audio source.
Mic	Microphone audio source.
Unprocessed	Microphone audio source tuned for unprocessed sound if available, behaves like default otherwise.
Voice Communication	Microphone audio source tuned for voice communication. Takes advantage of echo cancellation and automatic gain if available.
Voice recognition	Microphone audio source tuned for voice recognition.

3.2 Activities and Structure

SuperAcoustics contains 7 activities and 2 fragments that define its user interface, as well as 2 classes to complete the structure of this Java program. To navigate between activities, objects called intents are used. An intent provides binding between two separate components and in this application are used to start one activity from another [9]. When you pass an intent to the Android system, the system uses the intent to identify and start the appropriate app component. Using intents even allows your app to start an activity that is contained in a separate application.Figure 3.1 is a UML class diagram showing how SuperAcoustics classes, activities and fragments interact with each other. A user manual, describing in detail how to navigate and use the application is provided in chapter 4.

In order for SuperAcoustics to be able to record audio, and update the user interface simultaneously, multiple threads need to be used. In Java, a thread is defined as the path a program follows when running and each Java program has at least one thread. When an Android application starts, the main thread starts, defining which operations should run and in which order. This thread is also called the UI-thread as it interacts with the user interface of the application. An Android application can have more than one thread that will run simultaneously on the Java virtual machine [8]. SuperAcoustics has a thread that implements AudioRecord and runs when the application is recording audio, using multiple threads allows SuperAcoustics to record and analyze audio, and update the user interface simultaneously.

3.3 Measuring SPL and background noise

Measuring the sound pressure level is done in the measuredB(A)class of SuperAcoustics. This class measures the sound pressure level in room 1, room 2 as well as the background noise in room 2. The recording is started by pressing the toggle button. When the toggle button is pressed, a new thread starts to record and analyze audio. While the recording thread is running, the application processes data using AudioRecord. Using a Fast Fourier transform, the audio data is processed to provide a live update of the measured dB(A)value. The recorded data is also analyzed to calculate the sound pressure level of different frequency bands. This data along with the average measured sound pressure level in dB(A)is saved to the smartphones external storage for later use.

3.4 Measuring Reverberation Time

SuperAcoustics does not measure reverberation time, instead it uses an external application for this purpose. One of the applications used in this thesis is Acoustic Measurement. Acoustic Measurement was developed as a master thesis at Lund University by two students Yuzhao Cui and Yilin Wang in 2018. In Android you can launch one application from another by using an implicit intent [6]. Since the code for Acoustic Measurement is open source, it was possible to edit the code, start the application with an implicit intent and return the measured results to SuperAcoustics. The result of the reverberation time measurements was returned to SuperAcoustics when the activity is destroyed in Acoustic Measurement.

As later discussed in chapter 5, measurements that were completed using the application Acoustic Measurement proved to be insufficient, a solution to this was to provide the user with the ability to manually input the measured reverberation time. This is done using a dialog fragment which allows the user to input the measured reverberation time for the different frequencies. When the dialog fragment is closed, the entered values are saved to the external storage and later used to calculate the sound reduction index. A separate study of applications that measure reverberation time is presented in section 5.2.

3.5 Saving and loading data

Android provides a variety of different solutions to save and store application data, SuperAcoustics saves data both in the smartphones external storage as well as in shared preferences. Shared preferences is a way to read and write key-value pairs that are stored even if the application is terminated [4]. Settings for audio source and windowing as well as calibration are stored in shared preferences, allowing the user to set these preferences once and then not have to do it again unless desired. Parameters such as room dimensions, surface area and room name are also stored in shared preferences, but are overwritten every time the user starts a new measurement. To make sure that the settings and data are saved to the applictions shared preferences, this is done in the onPause() or onStop() method, before an activity is terminated, as discussed in section 2.5.3.

In order for SuperAcoustics to be able to save data to the smartphones external directory, the user has to grant permission to allow the application to do so. Storing data in the external storage makes it possible for other applications to access the data. There is no specific use for this in the applications current state but it allows for easier interaction with other applications for future development. To save and load data to and from the external storage, a path to the external storage directory is created within the application. Data that is stored in the external storage is the measured sound pressure levels of the sending and receiving room, the background noise, reverberation time and calculated sound reduction index.

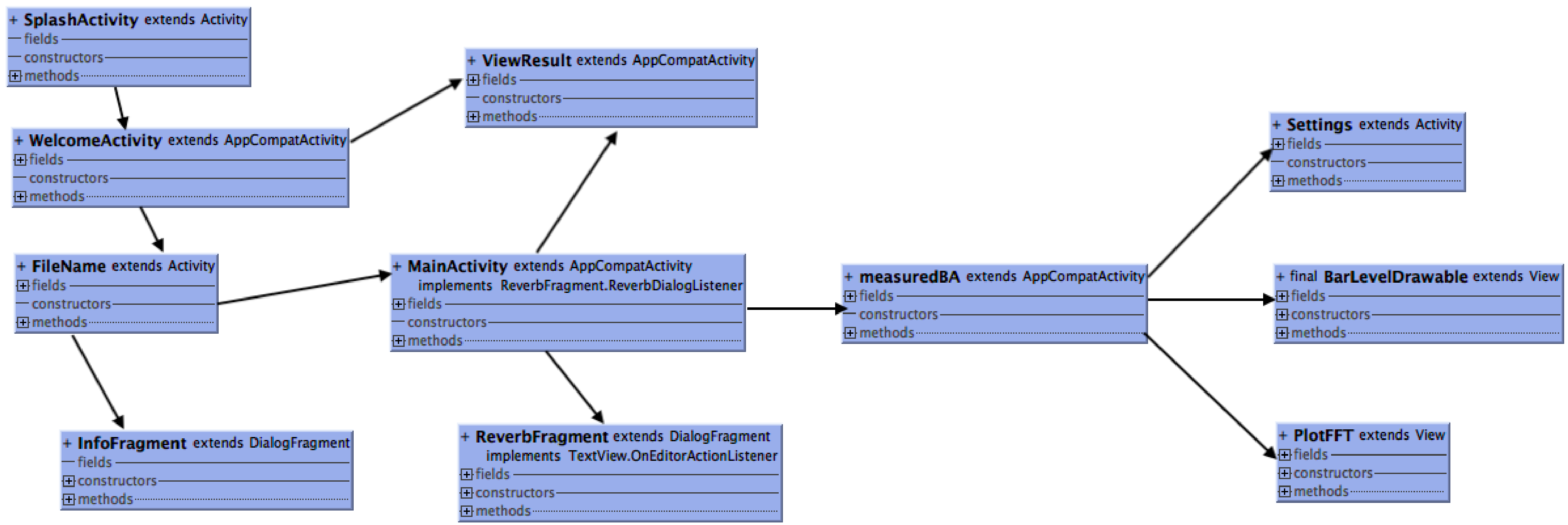

Figure 3.1: UML (Unified Modeling Language) class diagram, showing the structure of SuperAcoustics and how its classes, activities and fragments interact with each other.

4 App instructions

A brief users guide to the SuperAcoustics app.

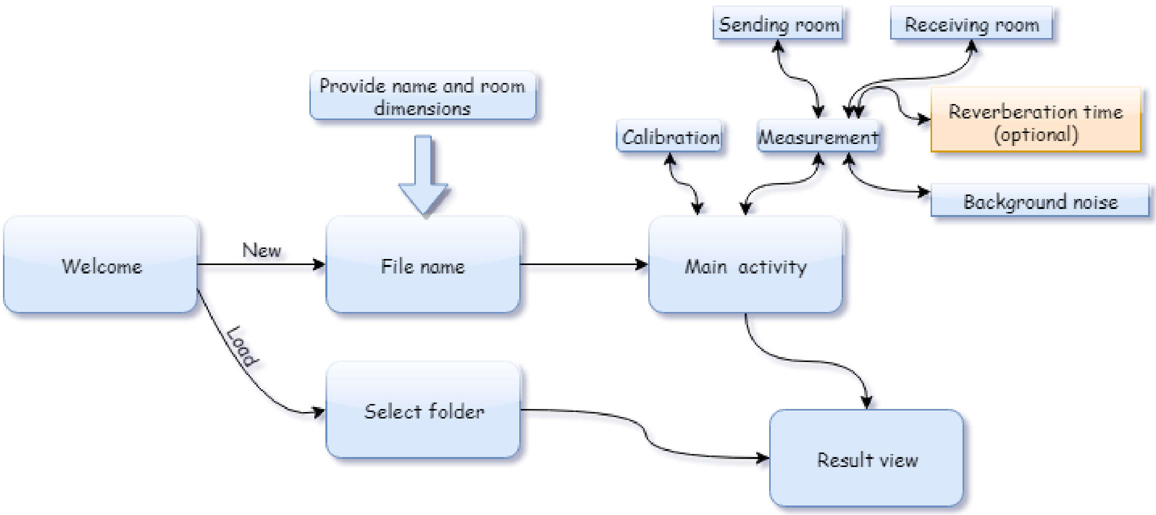

Figure 4.1: Overview of the applications interface, in this section a step by step guide of how the application is used is provided.

4.1 Performing a measurement

When the application is started, the user has the option to either conduct a new measurement or load an old one. The first window for interaction with the user is shown in figure 4.2

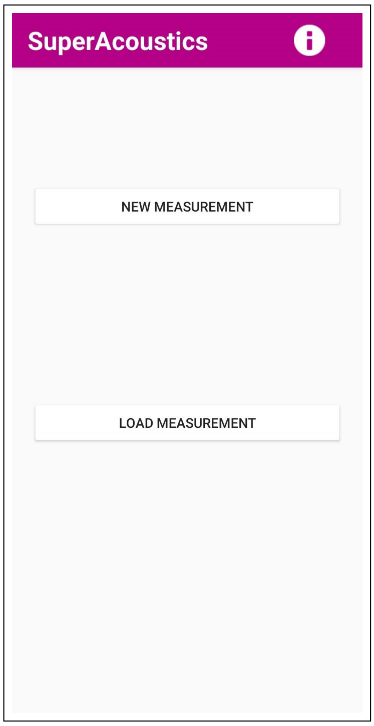

Figure 4.2: The first window, where the user gets to choose between starting a new measurement or loading an old one.

4.1.1 Measurement information

Choosing the button called *"New measurement"* takes the user to a new window shown in figure 4.3. At this stage, the user provides the input needed to calculate the sound reduction index. The name of the measurement and the dimensions of the receiving room need to be provided before the *"OK"* button can be clicked.
If the button is clicked before all the fields are filled in, a prompt will show asking the user "Please fill in all information".
When the *"OK"* button is pressed, the information is stored in the applications shared preferences and the user is taken to the next window.

4.1.2 Main window

Arriving at the "Main window", the user is asked for permission to use both the external storage and the microphone in order to save or load data and record audio. When the user accepts the permissions a button for each of the actions to be taken during the measurement is presented. The "Main window" is shown in figure 4.4.

As the user finishes a measurement, the text-views next to the buttons are updated

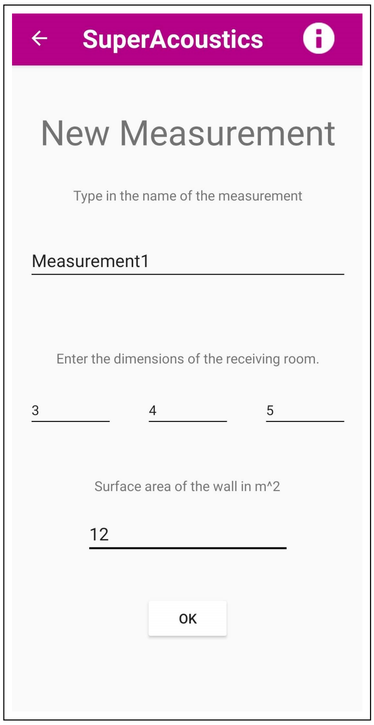

Figure 4.3: Input and dimensions window that lets the user present information about the measurement and the receiving room to be measured.

so that the user is able to see results during the measurement process.

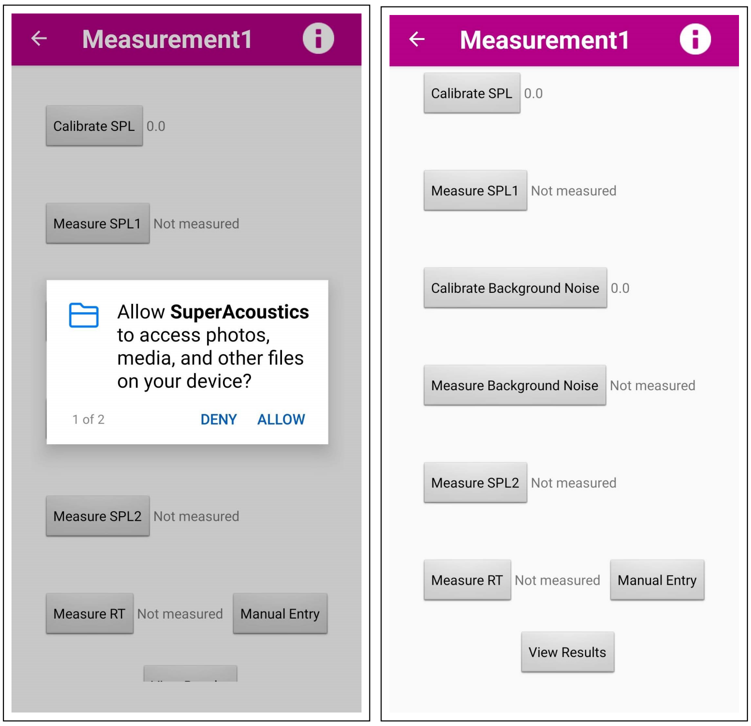

Figure 4.4: The dialog asking for permission to use external storage (left). The main window, containing a button for all the actions to be taken to conduct a measurement (right).

4.1.3 Calibration

Pressing the button called *"Calibrate SPL"* or *"Calibrate Background Noise"* located in the main window takes the user to a new window shown in figure 4.5. In this window the user is able to start the microphone, see a live update of the frequency content, and calibrate the sensitivity of the microphone. To calibrate the sensitivity, a steady sound source and a calibrated sonometer is needed. Once the readings on the phone and the sonometer match for a given amount of sound pressure levels, the user clicks the *"Set calibration"* button and the sensitivity correction is stored in the apps shared preferences until it is changed. When pressing the settings button

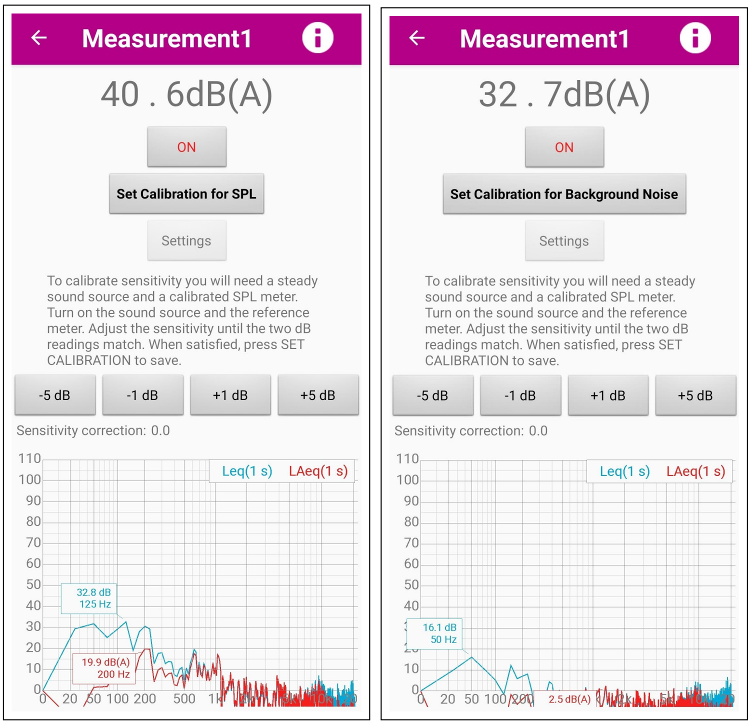

Figure 4.5: The calibration window for SPL(left) and background noise(right), both containing a live display of the frequency content and buttons for sensitivity correction adjustment.

located in the calibration activities, the user is taken to a window with a number of radio buttons. The radio buttons belong to two different radio groups responsible for the audio source and the windowing preferred by the user. Only one radio button per group can be selected. Different settings for background noise and noise measurements can be chosen by entering the settings window from the corresponding activity. The settings window is shown in figure 4.6

4.1.4 Sound pressure level

Pressing one of the upper three buttons starting with the name "Measure" will take the user to a window shown in figure 4.7. The logarithmic average over 10 seconds is measured and calculated once the "START" button is pressed. The button will in the mean time change appearance, letting the user know a measurement is active. If the user wishes to abort the current running measurement, it can be done using the "STOP" button.

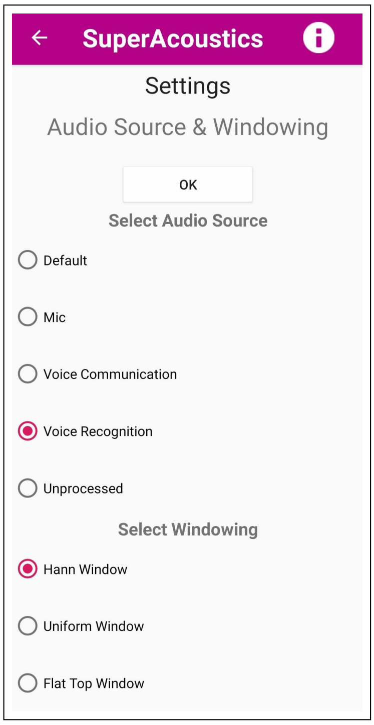

Figure 4.6: The settings window. This window can be entered from both the calibration activities. The settings stored are depending on which activity the user has arrived from.

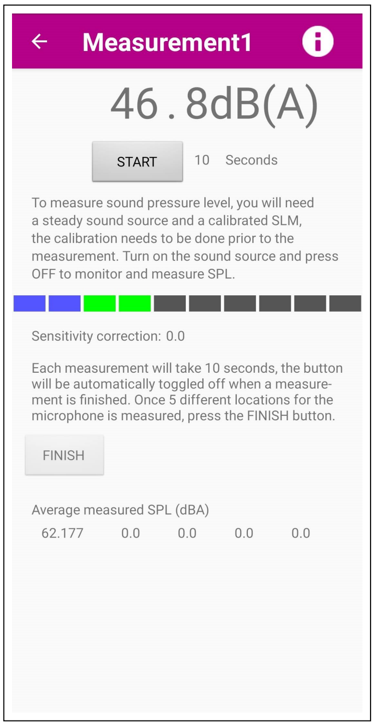

Figure 4.7: The measuring window with a bar for graphically representing SPL. Average SPL updated for each measurement continuously.

4.1.5 Reverberation time

The reverberation time can be measured using the Acoustic Measurement app. Once the measurement is finished for five different locations of the microphone, the data is sent back and stored in the SuperAcoustics app. If the results of this app isn't satisfactory, manual input can be used instead. If the user presses the "Manual Entry" button, a number of text views are presented for manual input of the reverberation time in the corresponding octave bands, as shown in figure 4.8.

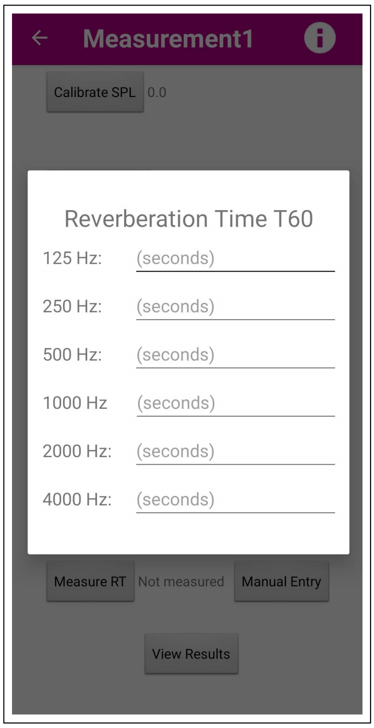

Figure 4.8: The manual entry of the reverberation time looks like this. The user inputs a reverberation time for all the different frequencies presented, known beforehand or measured according to the ISO-standards.

4.2 Loading a measurement and viewing results

If the user chooses to load an old measurement, the user will be taken to the Android built in storage directory. Navigating to the measurement folder and pressing select will instantly load the results of the old measurement. The view is shown in figure 4.9. If the user completes a new measurement and presses the "View Results" button, they will be taken to the same view, displaying the sound reduction index of the performed measurement.

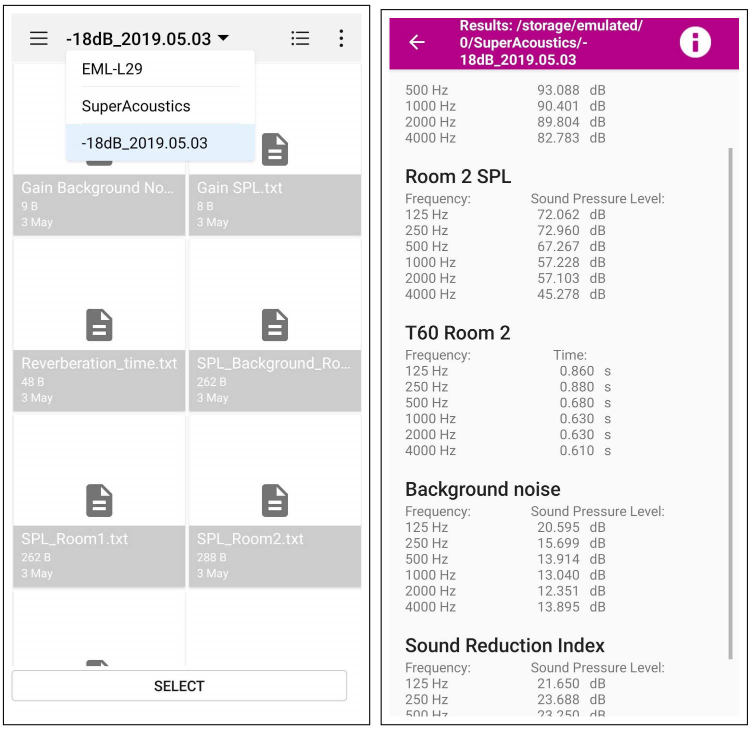

Figure 4.9: The storage navigation window (left) and the loaded results in the results window (right).

5 Calibration of the application and laboratory setup

The calibration process is presented in this chapter. All the calibration parameters implemented in the app are presented as well as some important findings about the parameters. A small study to find an external application for measuring reverberation time is also included in this chapter.

5.1 Calibration

The calibration of SuperAcoustics is set up so that any user shall be able to calibrate their smartphone alongside professional acoustics equipment such as a sound level meter. There are 3 settings that the user is able to modify, the gain which adjusts the measured sound pressure level to equal that of the sound level meter, windowing which adjusts the frequency transformation of the audio signal, and audio source, deciding which audio source of the microphone shall be used for recording. In the calibration phase, the A-weighted sound pressure level is displayed in a live feed along with the dB and dB(A) values in the frequency spectra, allowing the user to find the combination of these 3 settings that best mirror the sound pressure level measured with a sound level meter. This only needs to be done once as the settings are saved in the applications shared preferences. With this setup, the user only needs to have access to a sound level meter or other acoustics equipment during the first measurement to calibrate the smartphone. This is done for both sound pressure level and background noise measurements as the settings for the two measurements may differ from one another.

5.1.1 Gain

For the calibration procedure, a setup was made to measure airborne sound insulation according to the ISO standards [21]. The different sound intensity levels emitted from the hemi-spherical loudspeaker gave rise to different sound pressure levels in both rooms of the lab. For investigation of the different input methods and how the app responds to different amplitudes of signals, data was collected from both rooms.
The A-weighted sound pressure level was compared for each gain set on the amplifier and corresponding L_A value measured by the sonometer. In the range between 46-98 dB(A) the calibration needed is constant for the Samsung phone. In the range between 37-93 dB(A) the calibration needed is constant for the Huawei phone. This is illustrated in table 5.1 and figure 5.1.

The same measurements and calibrations were also done using an external microphone attached to the smartphone. Results displayed in table 5.1 and figure 5.1, show that the external microphone amplifies the measured noise as a much larger gain is needed. However for the loudest level, 110 dB(A), the gain is the same with or without an external microphone, implying that the smartphones may have a maximum noise level it can measure around 100 dB(A).

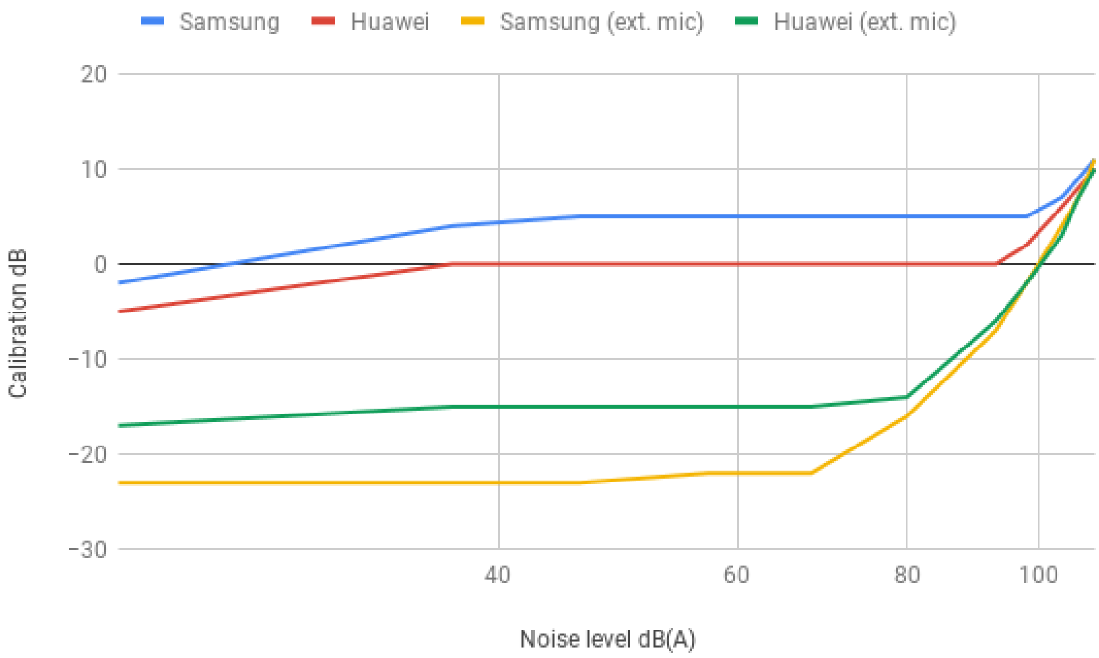

Figure 5.1: Unweighted calibration added to the smartphone measurements for acquiring the A-weighted result recorded by the sonometer. Measurements were taken with and without an external microphone.

Table 5.1: Table showing the unweighted calibration value added in the app for acquiring the same A-weighted result as the sonometer.

Calibration (dB)				
Noise level dB(A)	Samsung	Huawei	Samsung (ext. mic)	Huawei (ext. mic)
21	-2	-5	-23	-17
37	4	0	-23	-15
46	5	0	-23	-15
57	5	0	-22	-15
68	5	0	-22	-15
80	5	0	-16	-14
93	5	0	-7	-6
98	5	2	-2	-2
104	7	6	4	3
107	9	8	7	7
110	11	10	11	10

5.1.2 Windowing

The user is able to chose the windowing used for the FFT. Testing of the windowing settings for the specific smartphones used in the thesis led to the following conclusion. Hann windowing is best used with both the smartphones regarding sound pressure level measurements. The flat top windowing was found best for measuring the background noise when using this approach. When deciding between the different windows, the dB(A) level requiring minimum gain adjustment was preferred. The shape of the live frequency content closely resembled the shape of the corresponding content on the sonometer display when using the chosen settings for the sound pressure level measurements. None of the windows tested for measuring background noise did resemble the shape displayed on the sonometer, therefore the window that required the least gain adjustment was chosen.

5.1.3 Audio Source

Choosing the audio source changes the configuration of the recording and how the audio is processed. The user has the ability to choose between 5 different audio sources. Testing of the different audio sources while observing the live feed proved that the audio source voice recognition gave the best results. This setting was used both for sound pressure level and background noise. On the Huawei smartphone, most of the audio sources tested were accurate in terms of gain adjustment needed. On the Samsung smartphone the voice recognition performed well above the other sources. Since voice recognition worked well on both smartphones, it was chosen as the default for the app.

5.2 External application to measure Reverberation Time

The application Acoustic Measurements was intended for the measurement of reverberation time. Acoustic Measurement was developed as a master thesis by the students Yuzhao Cui and Yilin Wang at Lunds Technical University. After testing, it was concluded that this application did not measure the reverberation time with good enough accuracy, results are presented in chapter 6. Therefore, a study was conducted to find another application that measured reverberation time with greater accuracy.

The smartphone applications that were tested in this study were RT by AppAcoustic, APM Tool Lite by Suonoevita and reverberation time (Nachhallzeit) by Kröber. One similarity of the apps is that they do not require the specifics of the measured room. This means that they will only measure the reverberation time and not base the results depending on the material and dimensions of the room. In this study, two different types of smartphones were used, one Samsung, and one Huawei. In addition measurements were also taken with a Samsung with an external mini microphone attached. The results from these applications were compared to that of a sound level meter, Norsonic 140 to conclude which application is most precise. Measurements were done in 3 different rooms, one reverberation chamber, one anechoic chamber and one classroom of the V-building. For each of the 3 applications, the tests were completed using impact noise and the sound source was a hand clap. Results are presented in figures 5.2, 5.3 and 5.4 below.

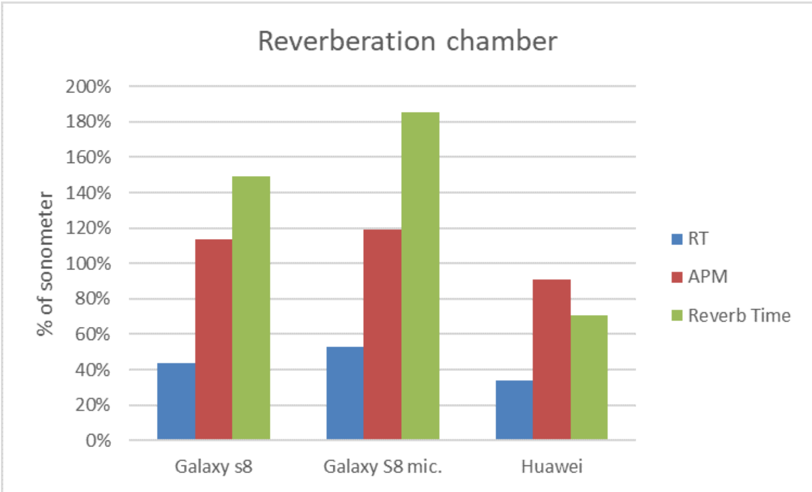

Figure 5.2: Comparison of apps vs. sonometer in the reverberation chamber

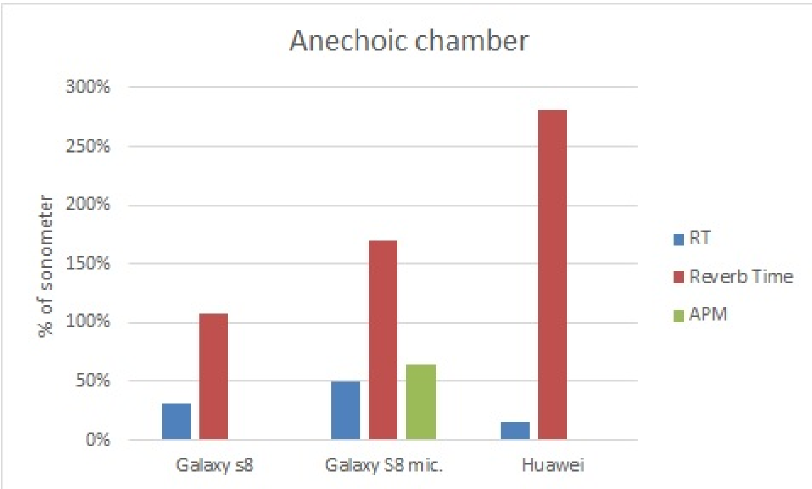

Figure 5.3: Comparison of apps vs. sonometer in the anechoic chamber

The results show that the APM app works best overall, with Reverb Time performing similarly well during the in-situ tests. The RT-app displayed results far off from the true values in all experiments, and is therefore not deemed reliable at all. As measurements were only taken in three different locations, where two of them are extreme environments, it is hard to compare the apps in their intended area.

The APM app description mentions a signal processing commonly used in smartphones, called *AGC (Automatic Gain Control)* [17]. This processing normally allows for different SPL's to be recorded and reproduced in the smartphone as a rather "smooth" recording, even though the SPL may have varied much during the recording. The processing could both increase/decrease the amplitude of the signal in order to get a better recording for listening.

This signal processing might affect the results if not removed since the app gets false

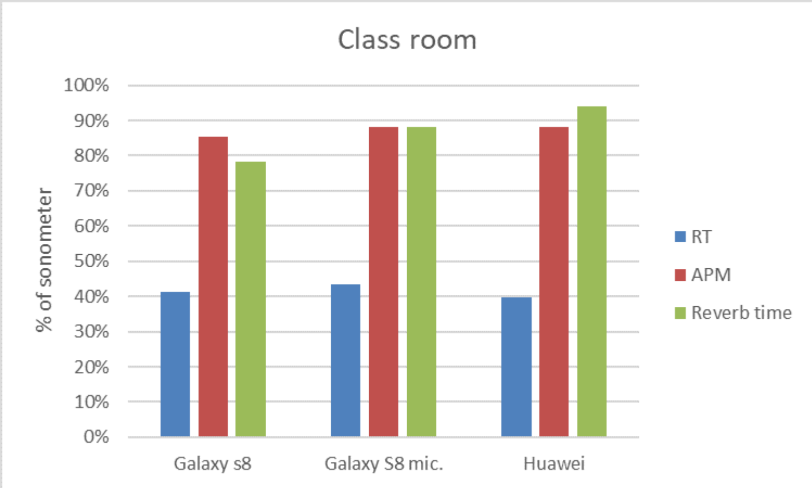

Figure 5.4: Comparison of apps vs. sonometer in a class room

amplitudes from the sensors. This could be the reason why APM delivers results generally closer to the sonometers results. The options available in the app regarding AGC are:

- Disable AGC detection
- Normal
- Advanced.

The default setting for the AGC detection is *Normal* and given our lack of knowledge about signal processing we left the setting to default.

For further analysis of the different frequencies the APM app was used. This was due to the fact that the results produced were more accurate for the previous measurements.

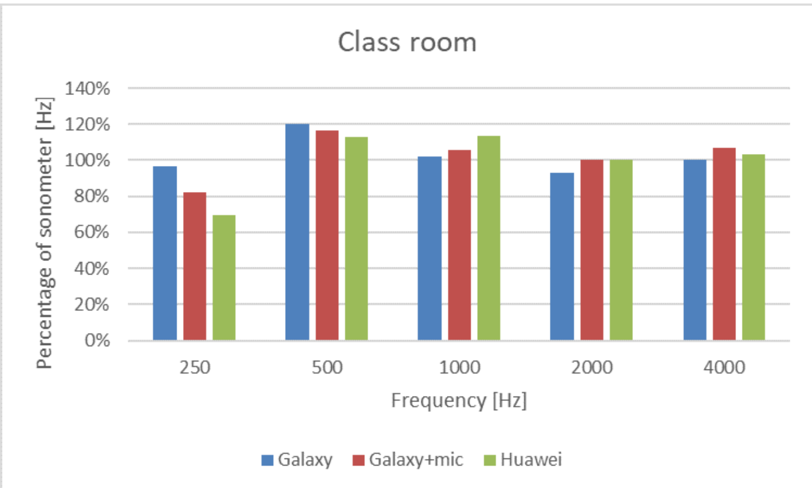

Figure 5.5: Comparison of T_{60} for various frequencies, using *APM* and sonometer in the classroom.

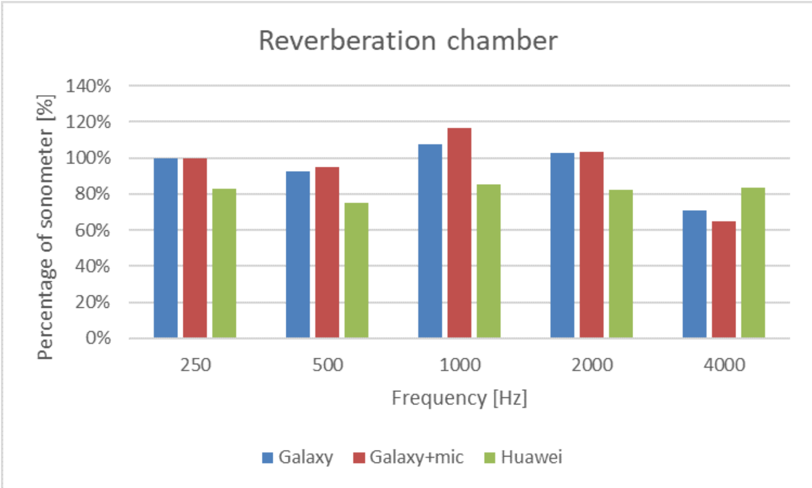

Figure 5.6: Comparison of T_{60} for various frequencies, using *APM* and sonometer in the reverberation chamber.

Figures 5.5 and 5.6 show a comparison of the reverberation time for individual frequencies measured in the reverberation chamber and in the classroom. The results are somewhat mirrored, showing a good accuracy for high frequencies in the classroom and the opposite in the reverberation chamber. In both rooms, the application had a difficulty measuring reverberation time for a frequency of 125 Hz. This is common when using the impulse method for measuring reverberation time, therefore no results are presented for lower than 250 Hz. It is therefore hard to rate the apps concerning results at the frequency level.

The conclusion of this study was that the application APM Tool Lite was the best of the three and was therefore used in this thesis to measure the reverberation time.

5.3 Laboratory setup

5.3.1 Equipment

White noise is the most general of all random noises. However, when performing frequency analysis, due to the effect of energy integration of band filters, white noise will produce sound energy levels for each frequency that increases with the frequencies themselves. After the energy integration effect of band filters, *pink* noise produces a constant sound energy level for each frequency. For this reason, pink noise will be used for testing [20]. The sound source in this case consisted of an amplifier and a hemi-spherical loudspeaker producing pink noise, figure 5.8 shows the setup in the sending room. To carry out the measurements conducted in this thesis, the following equipment was used.

Samsung Galaxy s8;

Huawei P20;

Norsonic Nor140 Sound level meter;

Edutige i-microphone EIM-001 external microphone;

Amplifier;

Hemispherical loudspeaker.

All measurements were done according to ISO standards discussed in section 2.4, and the three different speaker positions used for the measurements are displayed in figure 5.7.

To determine whether the sound amplification affects the results of measurements done with the application, the sonometer or both, different amplification levels were tested.

5.3.2 Rooms and partition

The laboratory used for testing in this thesis is located in the V-building of LTH, John Ericssons väg, 223 63 Lund. The setup consisted of a Sending room below a receiving room seperated by a wooden floor, which is the partition to be evaluated in this study. The dimensions of the receiving room and floor, used to calculate the sound reduction index are displayed in table 5.2. Figures 5.8, 5.9 and 5.10 show the two rooms as well as the wooden floor that separates them.

Table 5.2: Dimensions of floor and receiving room.

	length (m)	**width (m)**	**height (m)**
Floor	2,95	4,05	-
Receiving room	5,85	5,60	2,75

.

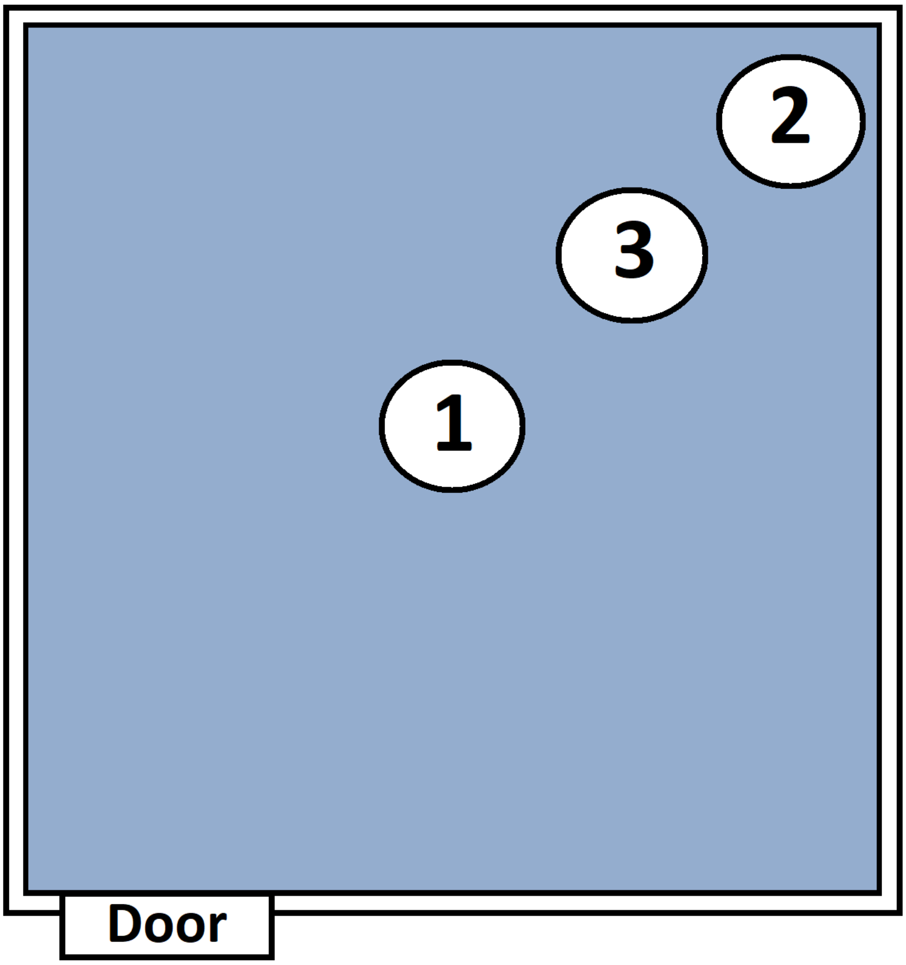

Figure 5.7: The 3 positions used for the loud speaker in the sending room.

Figure 5.8: Sending room setup with amplifier and loudspeaker placed in the center

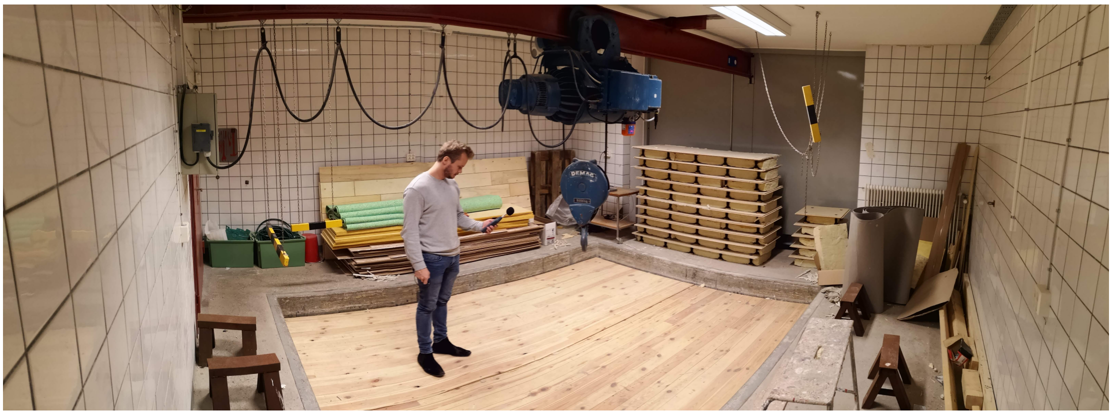

Figure 5.9: Receiving room setup, the wooden floor shown in the picture is the partition tested in the thesis.

Figure 5.10: Floor between sending room and receiving room, as seen from the sending room.

6 Measurement results and calculated sound reduction index

To calculate the sound reduction index of the partition in this thesis, the sound pressure level was measured in the sending room and receiving room along with background noise in the receiving room for 7 different gains set on the amplifier. These levels of the amplifier were measured using A-weighted sound pressure level with the Norsonic 140 sound level meter and used as identifiers for the different measurements. In the legends of the figures, the 7 different A-weighted sound pressure levels are used to separate the measurements. For example Huawei P20 110 dB corresponds to measurements taken when the amplifier generated a sound pressure level that was measured to 110 db(A) with the sound level meter in the sending room. Along with the 7 measurements taken with the 2 smartphones using SuperAcoustics, 3 complete measurements were also taken using the Norsonic sound level meter. In the legends, these are identified using "NOR140".

6.1 Sound Pressure Level

The sound pressure level in both the sending room and receiving room are presented in figures 6.1-6.4 in this section. All the different measurement amplitudes are presented. For the Huawei and Samsung measurements, figures 6.1 and 6.2 show that for the levels between 98 and 110 dB(A)levels, the measured sound pressure levels do not increase according to the sound produced by the amplifier. These results show that there is a limitation in the dynamic ranges of the smartphones and that these levels are too loud for the microphones.

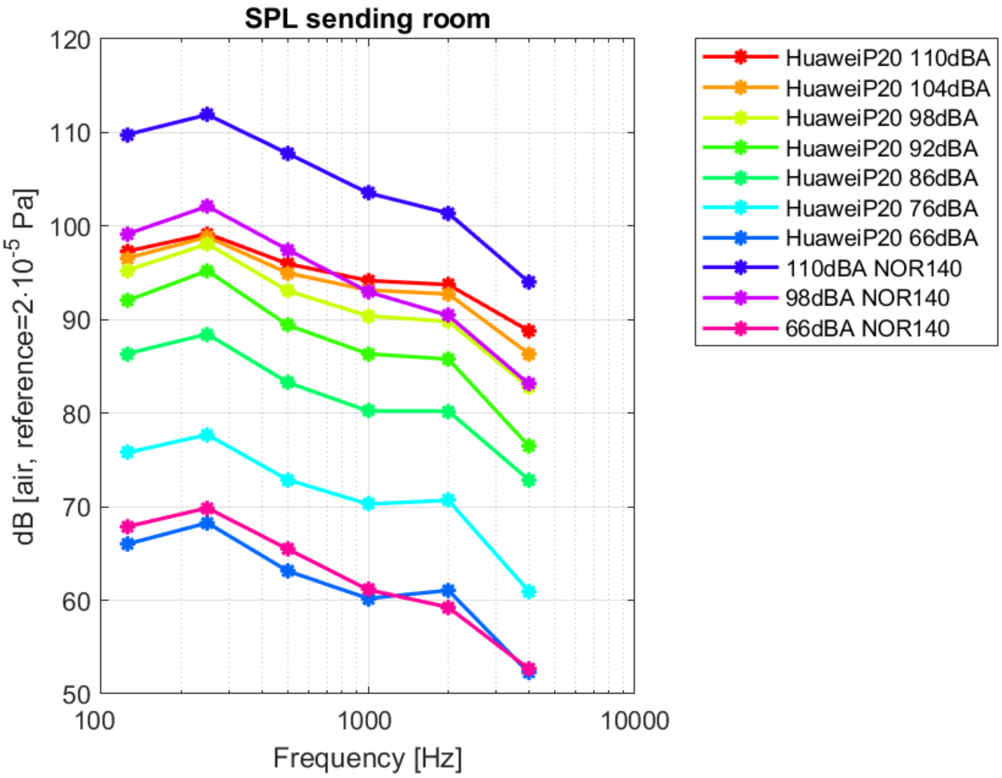

Figure 6.1: Sound pressure levels in the sending room for the Huawei phone for different noise levels.

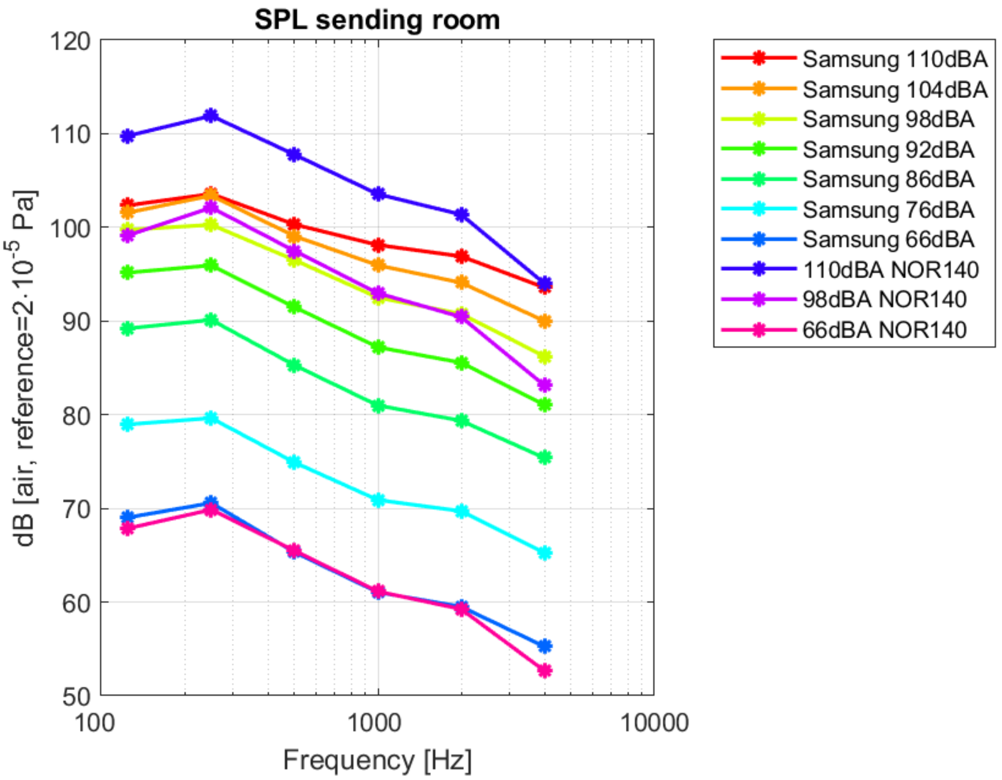

Figure 6.2: Sound pressure levels in the sending room for the Samsung phone for different noise levels.

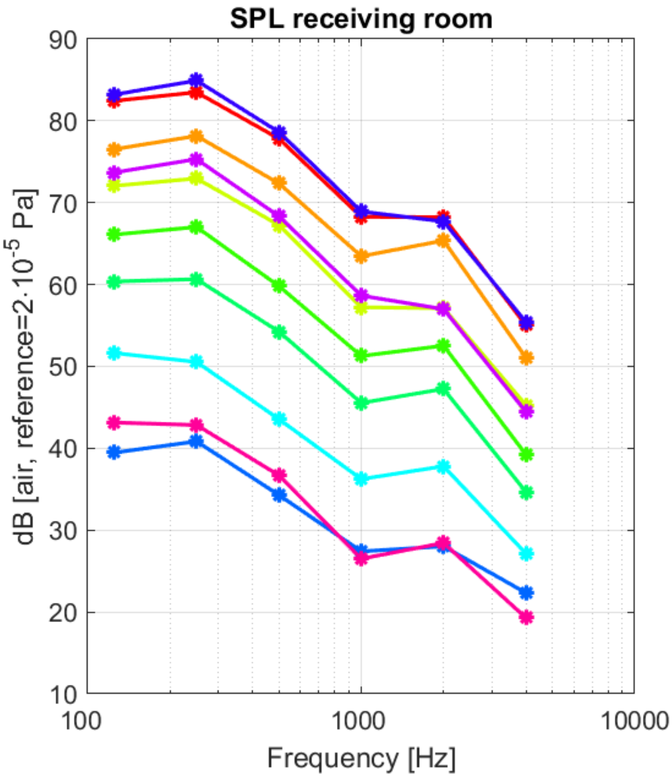

Figure 6.3: Sound pressure levels in the receiving room for the Huawei phone for different noise levels.

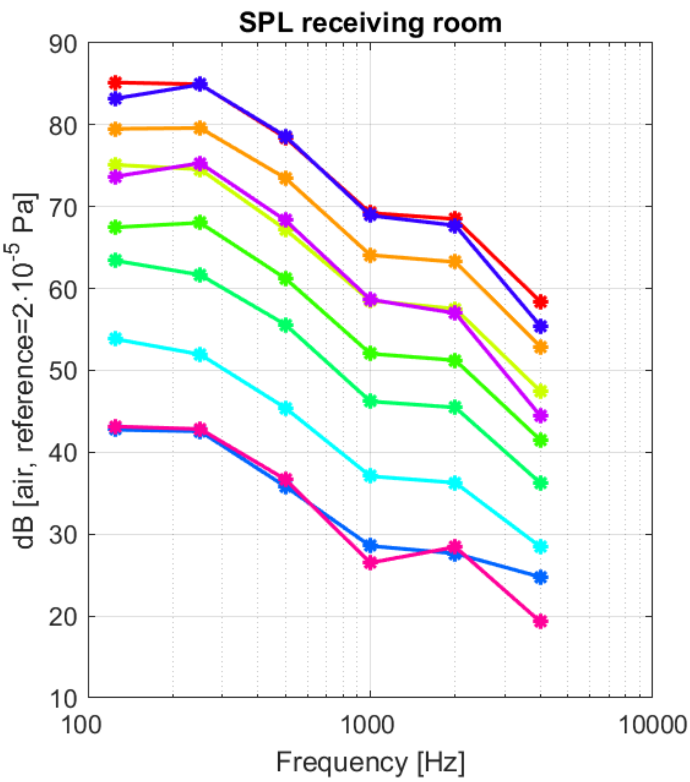

Figure 6.4: Sound pressure levels in the receiving room for the Samsung phone for different noise levels.

6.2 Background noise

For the background noise measurements, seven different results are presented to test the consistency of the measurement. The background noise in the receiving room is presented in figures 6.5 and 6.6. The results show both the precision and the accuracy compared to the sonometer.

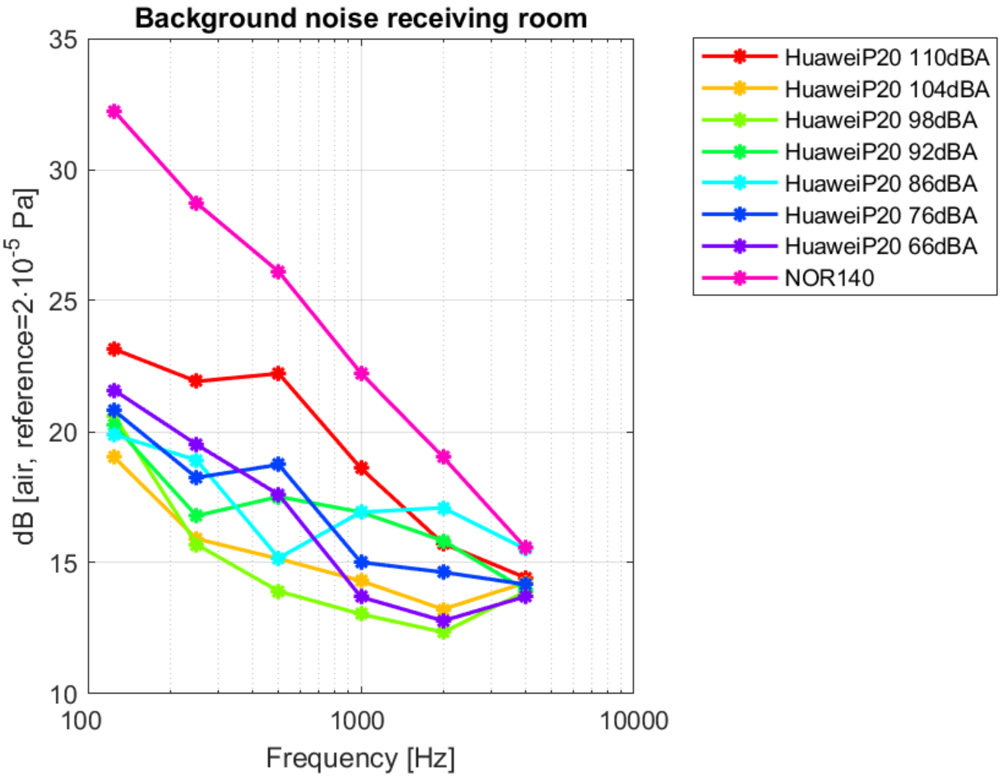

Figure 6.5: Background noise in the receiving room for the Huawei phone for different noise levels.

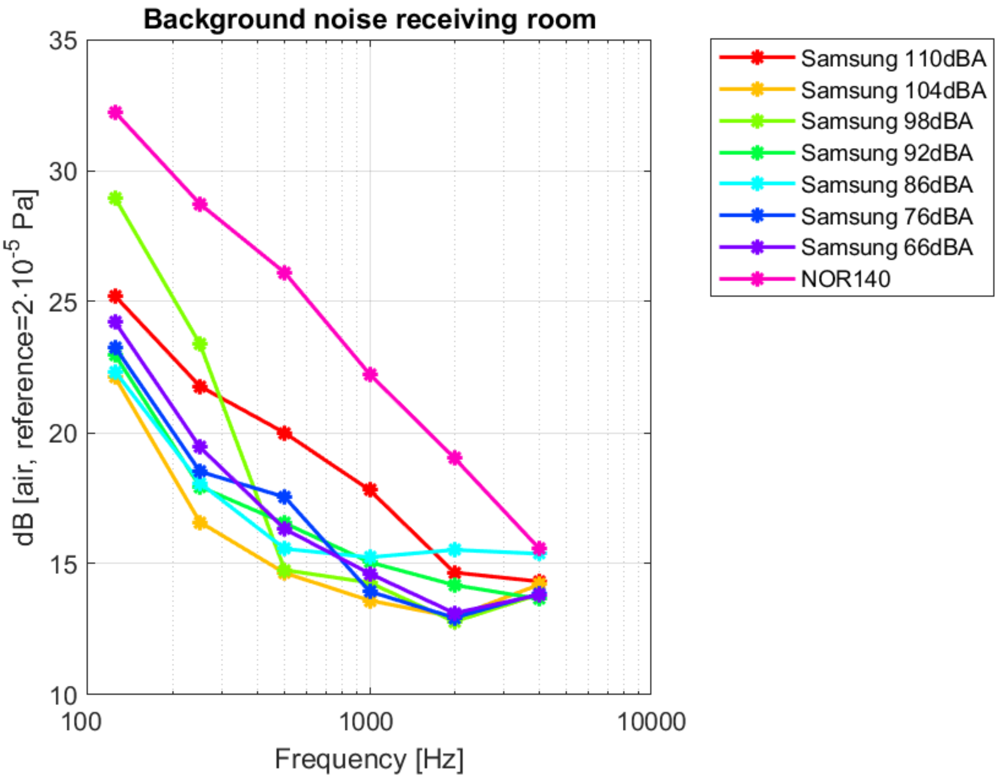

Figure 6.6: Background noise in the receiving room for the Samsung phone for different noise levels.

6.3 Reverberation Time

For reverberation time, all measurements were done using the impulse method with the sound source being a hand clap.

6.3.1 Acoustic Measurement

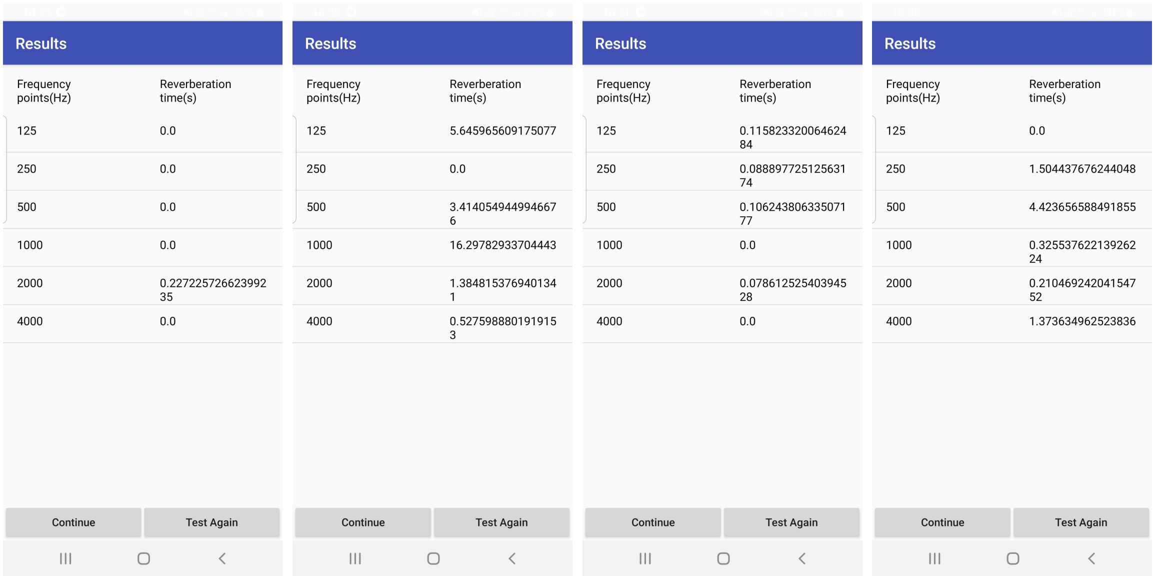

Figure 6.7: Measurements of reverberation time in receiving room taken with the application Acoustic Measurement.

Figure 6.7 shows examples of four measurements of reverberation time done in the receiving room using the application Acoustic Measurement. The results of these measurement proved to be unreliable and incorrect and therefore it was concluded that an external application is needed to measure reverberation time. As discussed in chapter 5, the application APM Tool Lite was used instead, the results of these measurements are presented in section 6.3.2.

6.3.2 APM Tool Lite

For the reverberation time in the receiving room, results were used from measurements taken with the application APM Tool Lite . The average values are presented in table 6.1. Measurements were done in accordance with ISO standards discussed in section 2.4, results from all measurements are presented in appendix A.

Table 6.1: Measured Reverberation time for Receiving room in seconds

	Samsung	**Huawei**	**Norsonic**
125 Hz	0,98	1,19	0,87
250 Hz	0,72	0,77	0,75
500 Hz	0,67	0,66	0,67
1000 Hz	0,63	0,63	0,65
2000 Hz	0,63	0,63	0,63
4000 Hz	0,57	0,57	0,56

6.4 Sound Reduction Index

The results for the calculation of the sound reduction index are presented for three levels, in tables 6.2 and 6.3. The comparison in these results are made as relative difference in equivalent pressure values corresponding to the sound reduction indices. This was achieved with the transformation in equation (6.1) and then the relative difference as in equation (6.2). The energetic averages of the sound reduction index for each interval was used in the calculations. The largest deviations are distinguishable for the smartphone measurements made at 66dB(A)and 104-110dB(A).

$$\tilde{p} = 10^{\frac{\mathrm{R}}{20}} \cdot 2 \cdot 10^5, \tag{6.1}$$

where

$\tilde{p}$ is the equivalent pressure value;

R is the sound reduction index.

$$\epsilon = \frac{\tilde{p}_S - \tilde{p}_N}{\tilde{p}_N} \tag{6.2}$$

$\tilde{p}_S$ is the equivalent pressure value when using the smartphones;

$\tilde{p}_N$ is the equivalent pressure value when using the NOR 140.

Calculated SRI relative difference % (Pa/Pa)			
Samsung	**104-110 dBA**	**76-98 dBA**	**66 dBA**
125 Hz	-49%	12%	27%
250 Hz	-46%	7%	10%
500 Hz	-44%	7%	8%
1000 Hz	-38%	0%	-21%
2000 Hz	-36%	3%	14%
4000 Hz	-24%	0%	-25%

Table 6.2: Deviation of the calculated sound reduction index completed with Samsung Galaxy S8 compared to the sonometer. Energetic averages of the results in each span of dB(A).

The results presented in figures 6.8, 6.9 and 6.10 show different decibel values of the sound reduction index for different nominal A-weighted sound pressure levels plotted against the frequencies studied. The results are a comparison between SuperAcoustics and the sonometer NOR 140. The results show that the accuracy is low for the loudest sound pressure level. For the sound pressure level of 98dB(A)the accuracy is higher. For the 66dB(A)measurements the shape of the plot differ from the sonometer but the overall accuracy is high.

The sound reduction index for each phone as well as the two measurements made with the sonometer NOR 140, plotted against frequencies are presented in figures 6.11 and 6.12. The range of data in the nominal dB(A)level is chosen to the range in which no or little calibration changes were needed, as discussed in chapter 5.1.

Calculated SRI relative difference % (Pa/Pa)			
Huawei	**104-110 dBA**	**76-98 dBA**	**66 dBA**
125 Hz	-56%	10%	44%
250 Hz	-60%	6%	6%
500 Hz	-61%	-6%	0%
1000 Hz	-53%	-2%	-18%
2000 Hz	-56%	-6%	29%
4000 Hz	-36%	-17%	-32%

Table 6.3: Deviation of the calculated sound reduction index completed with Huawei P20 compared to the sonometer. Energetic averages of the results in each span of dB(A).

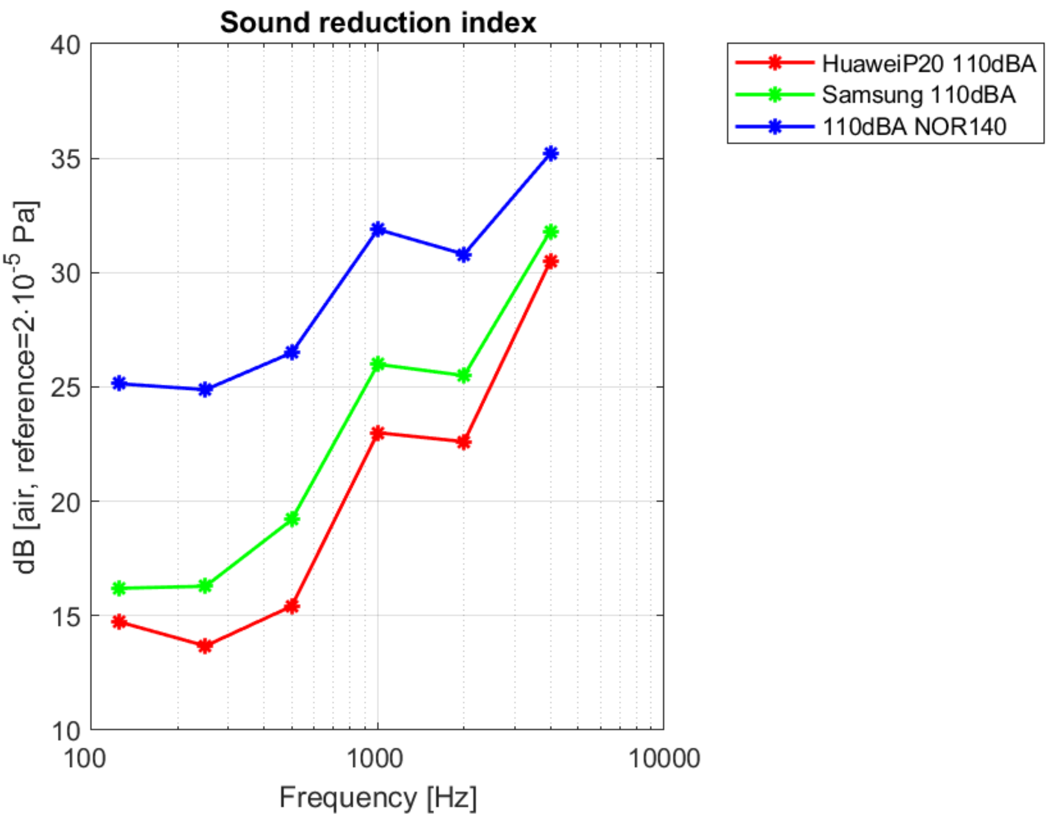

Figure 6.8: Resulting sound reduction index for 110dB(A)for the samsung, Huawaei and Norsonic NOR140.

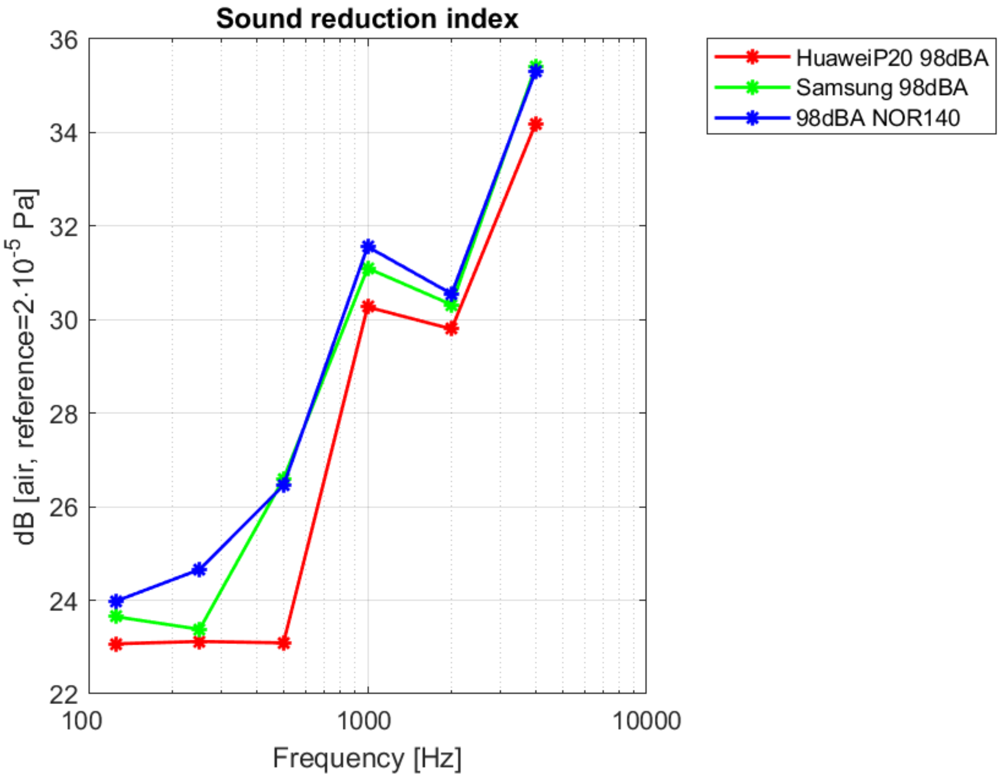

Figure 6.9: Resulting sound reduction index for 98dB(A)for the samsung, Huawaei and Norsonic NOR140.

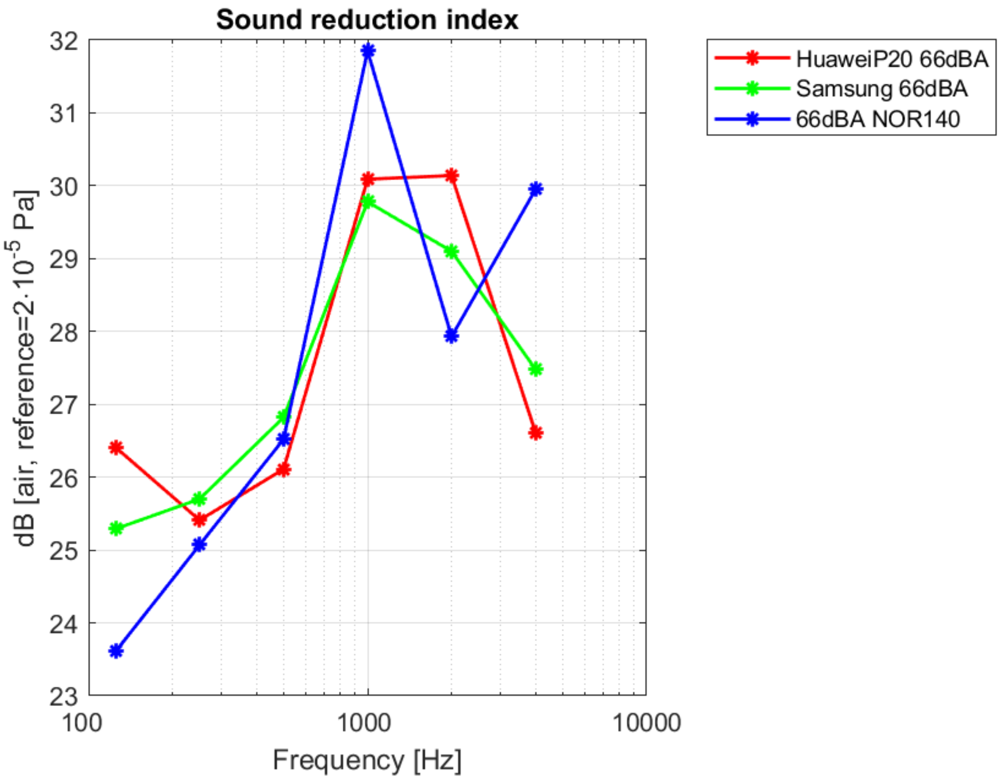

Figure 6.10: Resulting sound reduction index for 66dB(A)for the samsung, Huawaei and Norsonic NOR140.

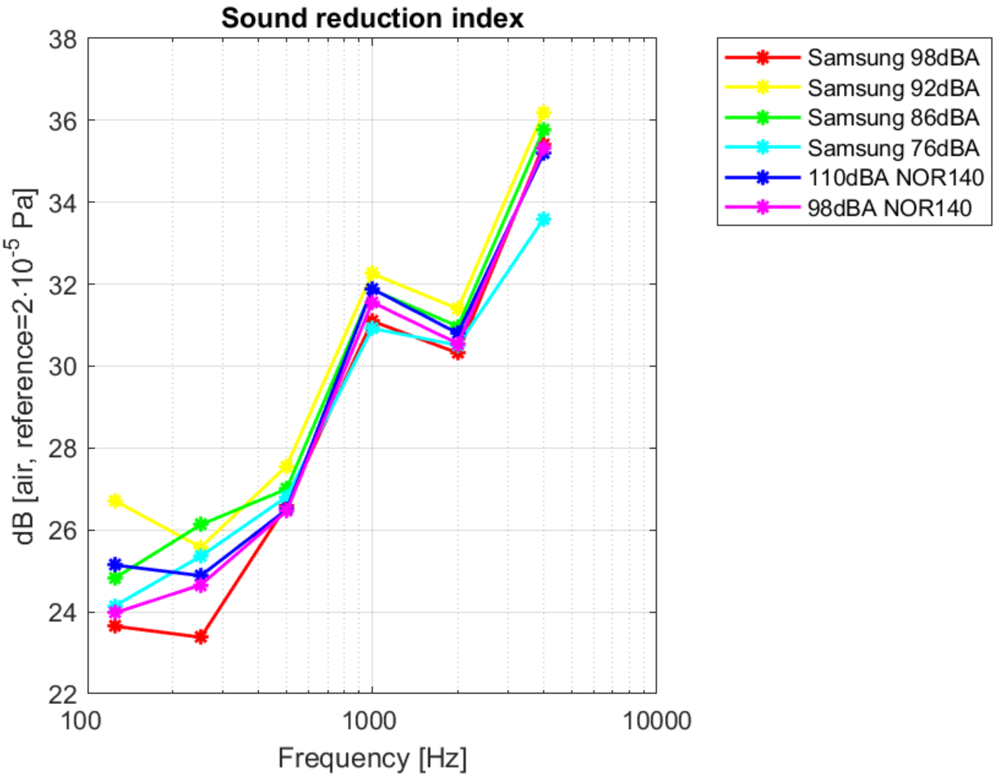

Figure 6.11: SRI for different sound Pressure levels for Samsung Galaxy s8. No or little calibration changes was needed in this range.

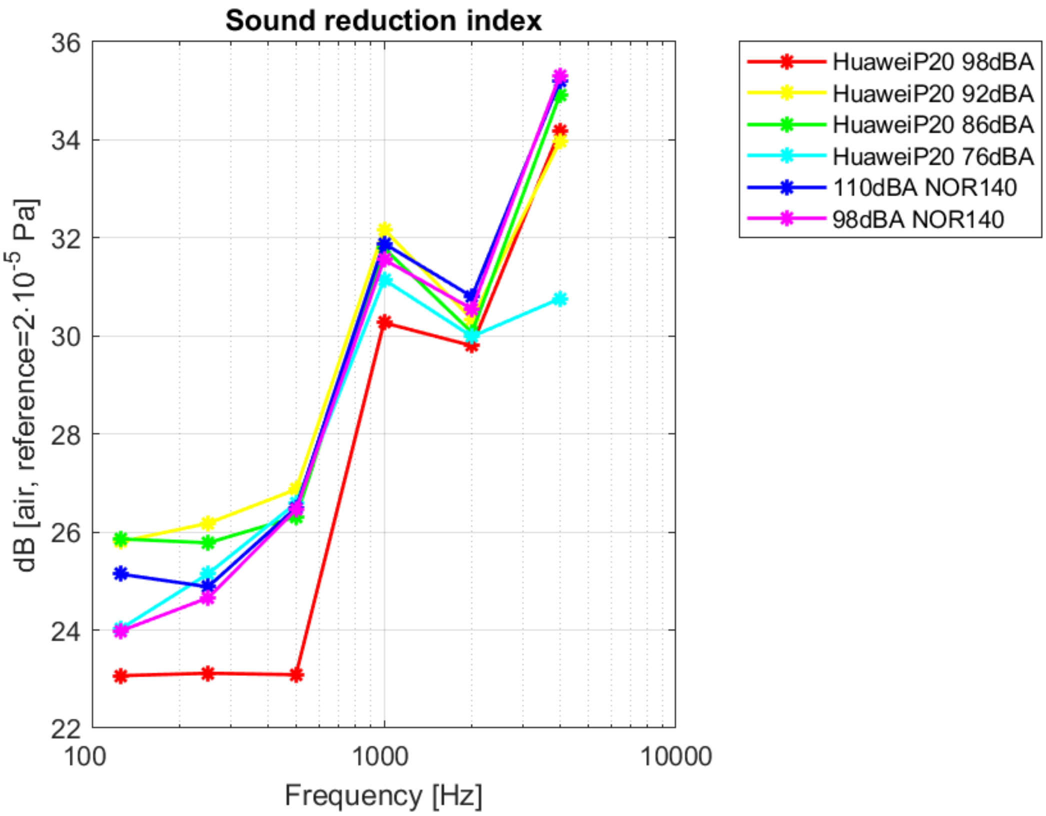

Figure 6.12: SRI for different sound Pressure levels for Huawei P20. No or little calibration changes was needed in this range.

7 Discussion

In this chapter, discussion topics regarding the results are presented. The results obtained when logging the calibration process as well as the results from the individual measurements are discussed. New results regarding the calibration are provided for further discussion.

7.1 Sound Pressure Level

As can be seen in figures 6.1-6.4, the sound pressure levels resemble those of the sonometer for some of the measurements made. The results in the sending room for the loudest levels are off, and look almost capped at a certain level for the smartphones. This could be due to either clipping or saturation of the sensors in the smartphone. The AOP presented in section 2.5.4 could have been reached in these measurements which would mean the signal is outside the dynamic range and no longer behaves linearly in the logarithmic domain. For the lower levels studied in the receiving room, the shape of the curves start to differ slightly from the sonometer curves. This effect can be seen even more clearly in the background noise figures discussed in the next section.

The results of the sound pressure level measurements strengthen the case for the smartphones ability to measure and calculate sound reduction index. Especially in the range this thesis has found to be the dynamic range of the two smartphones, 37 - 93 dB for the Huawei smartphone and 46 - 98 dB for the Samsung smartphone as discussed in section 5.1.

7.2 Background Noise

The results differ every measurement performed with the smartphones. This could be an effect of the EIN discussed in section 2.5.4. The acoustical pressure fluctuations are too small for the microphone to accurately detect them. Figure 6.6 and 6.5 show that background noise measurements taken with the two smartphones differ from that of the sound level meter.

For most measurements, the background noise does not have an impact on the result as the sound pressure level in the receiving room is loud enough so that the background noise does not affect the measurement. However, for the noise level that corresponds to 66 dB(A), the sound pressure level in the receiving room is so low that the background noise does have an effect on the result. This is shown in figure 6.10 and especially for the higher frequencies where the measured sound pressure level is closest to the measured background noise. As is seen in figure 6.5 and 6.6, the shape of the curves vary greatly compared to that of the sonometer. This implies that the sonometer measures background noise or very low sound pressure levels in a different way compared to the smartphones microphone and that the smartphones are not ideally suited for measuring sound reduction index at levels where background noise is a factor.

7.3 Reverberation Time

The results displayed in table 6.1, show that the application used to measure reverberation time, APM Tool Lite , produced results similar to measurements done with the sound level meter. As discussed in section 5.2, the application had a hard time measuring the reverberation time for the frequency band centered around 125 Hz. Looking at figure 6.11 and 6.12 the calculated sound reduction index deviates the most from the correct value at the lower frequencies. For the frequency band centered around 125 Hz, it is probable that the deviation in reverberation time contributes to the error in sound reduction index.

This thesis did not aim to develop a reverberation time measurement for smartphones. However, the results attained with the application APM Tool Lite confirm that the smartphone is suitable to use for reverberation time measurements. For T_{60} measurements, the results of T_{20} or T_{30} were measured and extrapolated to get the reverberation time results on a frequency band level. Comparison with results from measurements with the sound level meter justify that extrapolating the smartphone measurements provides a good and reliable result.

7.4 Calibration

In section 5.1 the calibration procedure proposed for the application is described. This proposed procedure consists of changing the gain, audio source and windowing type so that the weighted dB(A)value measured by the smartphone matches that of a sound level meter. However after reviewing the results for the measured sound pressure level and background noise, it is evident that calibrating for the weighted dB(A)level does not correspond to the best calibration for each octave band. A set of measurements with the amplifier set to a gain corresponding to 98 dB(A), were taken and analyzed for all the different audiosource inputs available to the user. In figures 7.1-7.4 the results from the different input methods, chosen in the AudioRecord class, are presented. In figures 7.1 and 7.3, no adjustments were made to the sound pressure level. In figures 7.2 and 7.4, a gain was added to better match the NOR 140 data but the shape was unchanged. Although the shapes of the curves are similar and all resemble that of the NOR140, these measurements show that there is room for improvement and fine tuning the results with regards to the calibration process. In figure 7.4, voice recognition, the audio source used for the SPL measurements in this thesis, least resembles that of NOR140. This infers that the calibration procedure should be approached in a different manner, taking into account all the octave bands and not simply the weighted dB(A)value.

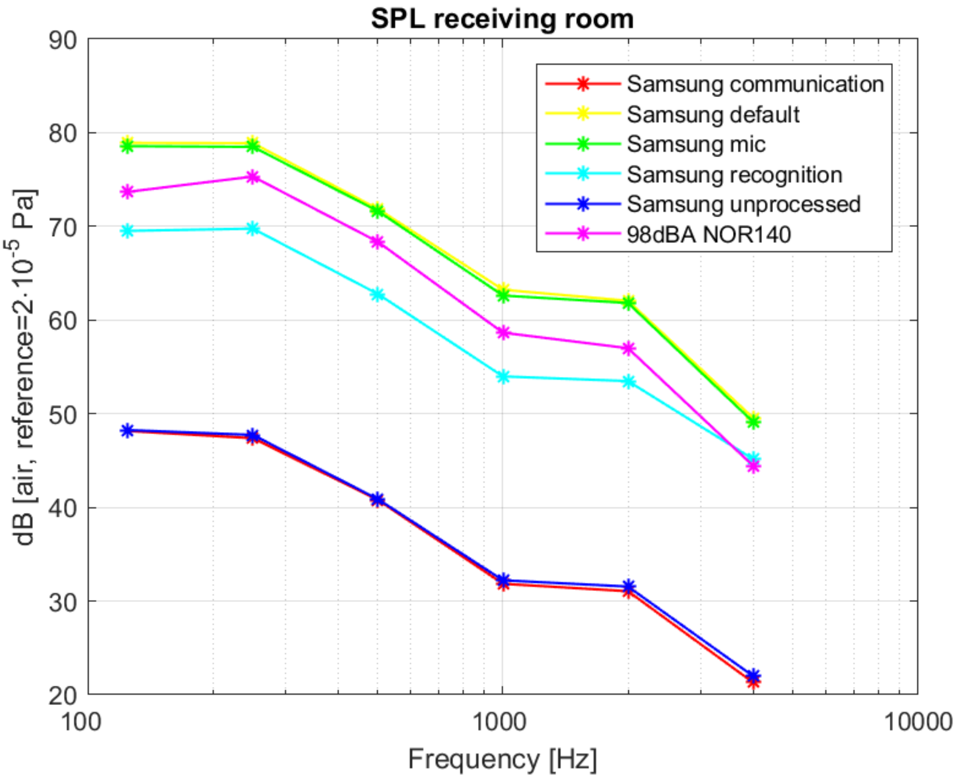

Figure 7.1: SPL of the 5 different audio sources compared to NOR140 using samsung galaxy s8

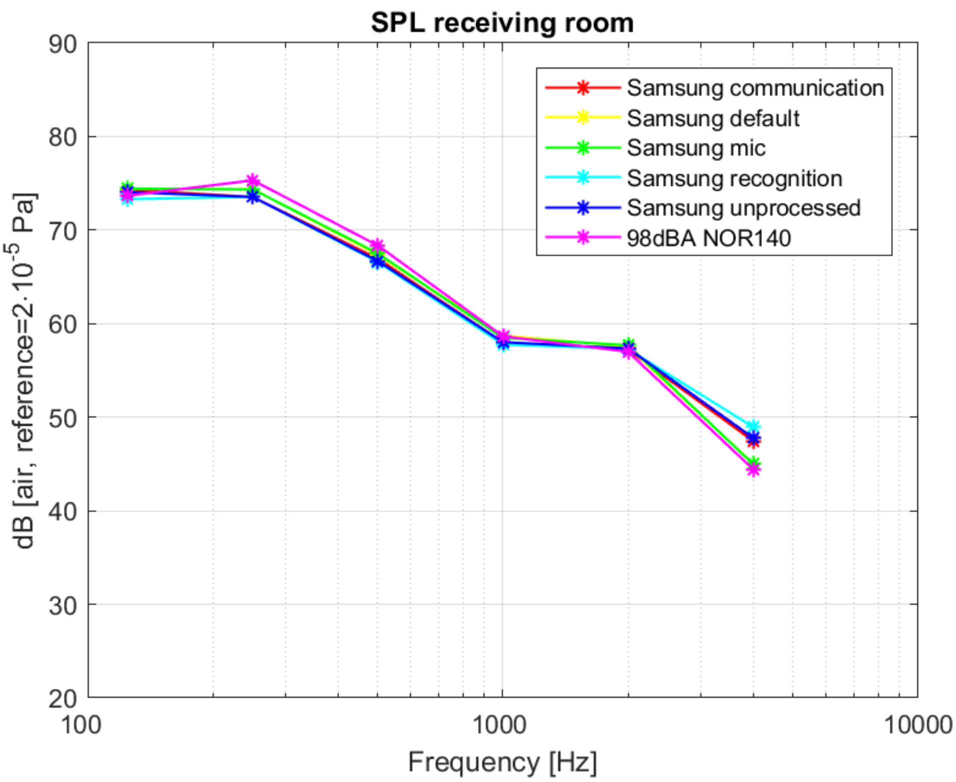

Figure 7.2: Gain added to Samsung measurements to match the SPL of NOR140

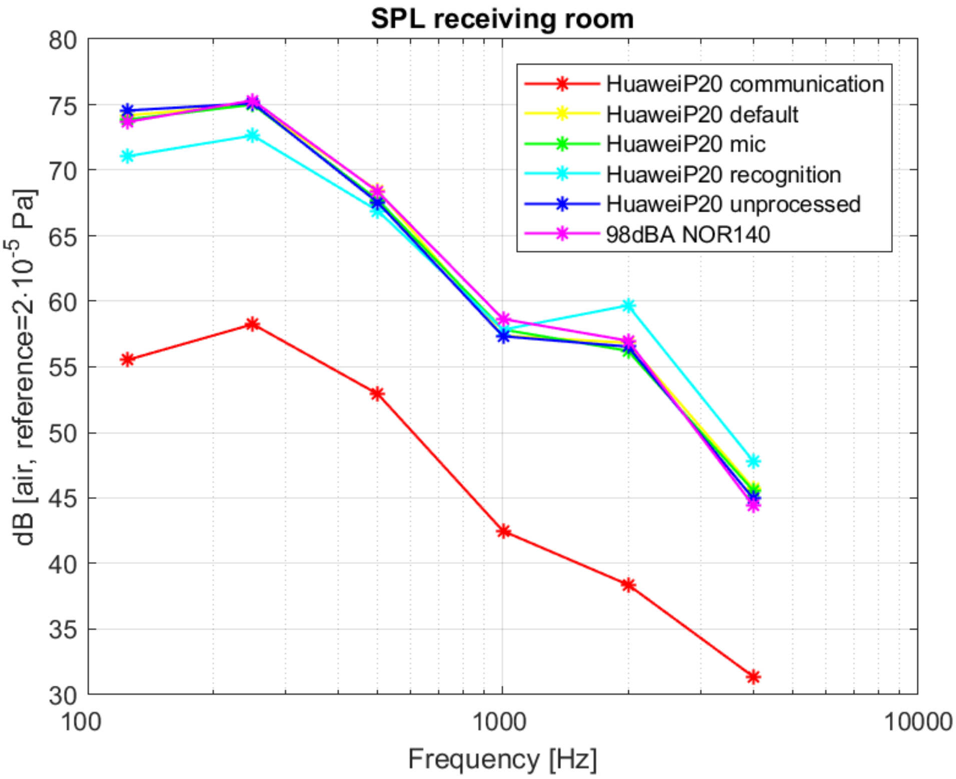

Figure 7.3: SPL of the 5 different audio sources compared to NOR140 using Huawei P20

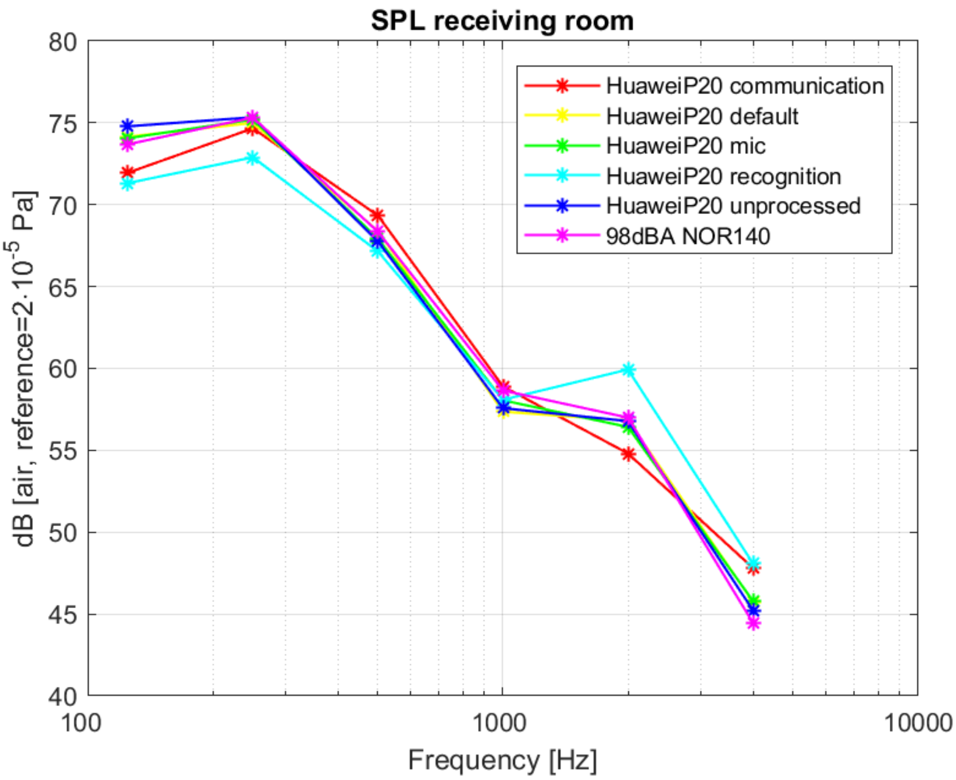

Figure 7.4: Gain added to Huawei measurements to match the SPL of NOR140

7.5 Sound Reduction Index

The results of the sound reduction index measured by the mobile application SuperAcoustics is close to the sonometer results. The discontinuity and reliability vary greatly for extreme volumes produced by the amplifier and loudspeaker.

During the calibration process, it was evident that the smartphone sensors need tweaking for both very loud and very quiet environments. This can be studied in table 5.1 and can be viewed as a limitation in terms of reliance of the app. However, in the sound pressure level range where the calibration remains unchanged, the results are closer. As can be seen in table 6.2 and 6.3 the measurements performed at very loud volumes as well as very low volumes show greater deviation from the results obtained using the sonometer.

In the calibration procedure, the limitations of the smartphones as an acoustic measurement tool became clear. While the sound pressure level is within the dynamic range, the calibration is constant. A proposal for further development reducing the limitations is to alter the signal processing when the sound pressure level is outside the dynamic range. The altering could be done digitally in the application by curve fitting using data points. Data collection on how the signal behaves when reaching the limits in the dynamic range is used to build a model and simulate the behaviour.

As seen in table 6.2 and 6.3, as well as figures 6.11 and 6.12, within the dynamic range, the calculated sound reduction index deviates the most from the correct value at the lowest frequencies. This could be due to a number of different factors. For example the deviation in measured reverberation time as discussed in section 7.3, or the deviation due to calibration errors discussed in section 7.4. The sound reduction index results within the dynamic range provide overall good results, motivating that a smartphone is a reliable tool for measuring sound reduction index.

8 Conclusion

This thesis aimed to develop an Android application to measure airborne sound insulation by calculating the sound reduction index of a partition. The project was designed and carried out within a controlled laboratory environment where flanking transmission was eliminated. This was done since the focal point of the project was to evaluate the credibility of using a smartphone to calculate sound reduction index and determine if it is a reliable tool for this acoustic measurement. The application was developed on the Android Studio platform, where the developer both designs the user interface and the back end functions of the applications. The aim was to create an easy to use user interface with clear instructions and concise results. Functions such as measuring reverberation time with a suggested application or manually entering the parameter are available. A live view of the frequency spectrum using a fast-Fourier transform is available as well.

The results acquired using the app were accurate and resembled the octave analysis shape acquired with the sonometer. The limitations of the app is the dynamic range of the smartphone microphones. Making sure the laboratory environment is setup to stay within each smartphones dynamic range generate satisfactory results. The possible deviations in the results are dealt with by repeating measurements and calculating the energetic average according to the ISO-standards.

As for all reverberation time measurements done using the impulse noise method, low frequency content is harder to analyze. The excitation for low frequencies is often hard to achieve with a single hand clap. The option of using the application Acoustic Measurement to calculate reverberation time proved to be unreliable. An external application should be used for this and APM Tool Lite is recommended as it has been evaluated and proven reliable in this thesis.

The potential of using smartphones for acoustic measurements and the accuracy of the results will improve as the technology develops and improves. As of now, the greatest restriction for these measurements is the hardware of the instrument and more specifically, the dynamic range of the smartphones microphone. Some more work needs to be done regarding the calibration of the app to find the ideal combination of gain and audiosource, something that is presumed to also improve as the hardware improves.

Apple's iPhone cover a large part of the smartphone market today. Future work could include development on a different platform to make this kind of app available for all smartphones.

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Appendix A
Measurement data

* denotes values corrugated for background noise according to ISO standards.

Table A.1: Table showing calculated sound reduction index for Samsung model.

	Calculated SRI in dB						
Samsung	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	16,2	21,08	23,65	26,71	24,83	24,15	25,29
250 Hz	16,29	21,46	23,38	25,58	26,13	25,36	25,7
500 Hz	19,2	22,9	26,6	27,56	27	26,81	26,82
1000 Hz	25,99	28,96	31,1	32,26	31,87	30,92	29,78
2000 Hz	25,5	27,94	30,32	31,4	30,97	30,51	29,1
4000 Hz	31,81	33,72	35,4	36,19	35,77	33,6	27,48

Table A.2: Table showing calculated sound reduction index for Huawei model.

	Calculated SRI in dB						
Huawei	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	14,73	19,9	23,07	25,8	25,86	24,02	26,41
250 Hz	13,68	18,67	23,12	26,18	25,78	25,15	25,41
500 Hz	15,42	19,9	23,09	26,87	26,31	26,59	26,11
1000 Hz	23	26,79	30,27	32,17	31,79	31,15	30,09
2000 Hz	22,61	24,47	29,8	30,34	30,07	29,99	30,14
4000 Hz	30,49	31,98	34,19	33,97	34,92	30,76	26,61

Table A.3: Table showing sound pressure level in the sending for Samsung model.

	Measured SPL Sending Room in dB						
Samsung	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	102,36	101,58	99,74	95,17	89,22	78,97	69,03
250 Hz	103,57	103,39	100,28	95,95	90,12	79,64	70,58
500 Hz	100,31	99,06	96,51	91,48	85,28	74,90	65,32
1000 Hz	98,12	95,95	92,51	87,21	80,99	70,90	61,05
2000 Hz	96,91	94,10	90,77	85,56	79,37	69,71	59,50
4000 Hz	93,58	90,01	86,24	81,06	75,39	65,26	55,26

Table A.4: Table showing sound pressure level in the sending for Huawei model.

	Measured SPL Sending Room in dB						
Huawei	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	97,30	96,57	95,26	92,03	86,37	75,78	66,01
250 Hz	99,19	98,84	98,10	95,23	88,46	77,71	68,28
500 Hz	95,98	94,99	93,09	89,42	83,29	72,88	63,13
1000 Hz	94,17	93,16	90,40	86,34	80,24	70,29	60,20
2000 Hz	93,74	92,74	89,80	85,78	80,22	70,69	61,06
4000 Hz	88,81	86,37	82,78	76,52	72,89	60,98	52,26

Table A.5: Table showing sound pressure level in the receiving for Samsung model.

	Measured SPL Receiving Room in dB						
Samsung	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	85,18	79,52	75,11	67,48	63,41	53,84	42,75
250 Hz	84,96	79,61	74,57	68,04	61,67	51,95	42,56
500 Hz	78,44	73,50	67,24	61,25	55,61	45,43	35,83
1000 Hz	69,23	64,09	58,51	52,05	46,22	37,08	28,37*
2000 Hz	68,50	63,24	57,53	51,24	45,47	36,28	27,48*
4000 Hz	58,40	52,91	47,46	41,49	36,24	28,29*	24,40*

Table A.6: Table showing sound pressure level in the receiving for Huawei model.

	Measured SPL Receiving Room in dB						
Huawei	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	82,44	76,54	72,06	66,10	60,38	51,63	39,47
250 Hz	83,49	78,15	72,96	67,03	60,66	50,54	40,84
500 Hz	77,82	72,36	67,27	59,81	54,25	43,56	34,29
1000 Hz	68,27	63,46	57,23	51,27	45,54	36,24	27,21*
2000 Hz	68,23	65,37	57,10	52,53	47,25	37,80	28,02
4000 Hz	55,01	51,08	45,28	39,23	34,66	26,91*	22,34*

Table A.7: Table showing background noise in the receiving for Samsung model.

	Measured Background Noise Receiving Room in dB						
Samsung	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	25,21	22,11	28,95	22,96	22,34	23,26	24,21
250 Hz	21,77	16,59	23,38	17,94	18,08	18,52	19,45
500 Hz	19,99	14,65	14,76	16,55	15,57	17,54	16,32
1000 Hz	17,81	13,60	14,28	15,06	15,25	13,94	14,63
2000 Hz	14,66	12,97	12,79	14,19	15,53	12,94	13,12
4000 Hz	14,32	14,21	13,83	13,66	15,38	13,86	13,82

Table A.8: Table showing background noise in the receiving for Huawei model.

	Measured Background Noise Receiving Room in dB						
Huawei	**110dBA**	**104dBA**	**98dBA**	**92dBA**	**86dBA**	**76dBA**	**66dBA**
125 Hz	23,15	19,02	20,60	20,24	19,88	20,80	21,58
250 Hz	21,92	15,92	15,70	16,79	18,92	18,25	19,51
500 Hz	22,22	15,15	13,91	17,52	15,18	18,74	17,60
1000 Hz	18,60	14,31	13,04	16,93	16,93	15,02	13,70
2000 Hz	15,73	13,22	12,35	15,84	17,10	14,64	12,78
4000 Hz	14,43	14,24	13,90	13,97	15,52	14,17	13,71

Table A.9: Table showing the results acquired with the sonometer NOR 140 for sound reduction index.

	Calculated SRI in dB		
Norsonic	**110dBA**	**98dBA**	**66dBA**
125 Hz	25,14	23,98	23,24
250 Hz	24,88	24,66	24,90
500 Hz	26,49	26,46	26,12
1000 Hz	31,89	31,56	31,85
2000 Hz	30,80	30,55	27,93
4000 Hz	35,20	35,31	29,95

Table A.10: Table showing the results acquired with the sonometer NOR 140 for sound pressure level in the sending room.

	Measured SPL Sending Room in dB		
Norsonic	**110dBA**	**98dBA**	**66dBA**
125 Hz	109,78	99,15	67,87
250 Hz	111,91	102,11	69,87
500 Hz	107,76	97,48	65,48
1000 Hz	103,55	92,98	61,13
2000 Hz	101,37	90,44	59,25
4000 Hz	94,01	83,13	52,67

Table A.11: Table showing the results acquired with the sonometer NOR 140 for sound pressure level in the receiving room.

	Measured SPL Receiving Room in dB		
Norsonic	**110dBA**	**98dBA**	**66dBA**
125 Hz	83,21	73,69	43,15
250 Hz	84,92	75,32	42,84
500 Hz	78,62	68,35	36,69
1000 Hz	68,92	58,65	26,51
2000 Hz	67,71	57,00	28,43
4000 Hz	55,42	44,45	19,29

Table A.12: Table showing the results acquired with the sonometer NOR 140 for background noise in the sending room.

Measured Background Noise Receiving Room in dB			
Norsonic	**110dBA**	**98dBA**	**66dBA**
125 Hz	N/A	N/A	32,22
250 Hz	N/A	N/A	28,73
500 Hz	N/A	N/A	26,10
1000 Hz	N/A	N/A	22,23
2000 Hz	N/A	N/A	19,03
4000 Hz	N/A	N/A	15,58

Table A.13: Reverberation time measured with the APM tools lite using Samsung model.

Measured Reverberation time Samsung						
Attempt	**1**	**2**	**3**	**4**	**5**	**6**
125 Hz	0,73	1,30	0,93	0,85	0,84	0,79
250 Hz	0,75	0,86	0,77	0,73	0,73	0,65
500 Hz	0,69	0,66	0,68	0,69	0,69	0,6
1000 Hz	0,64	0,64	0,61	0,65	0,65	0,61
2000 Hz	0,66	0,6	0,61	0,64	0,66	0,6
4000 Hz	0,60	0,56	0,55	0,57	0,57	0,57

Table A.14: Reverberation time measured with the APM tools lite using Samsung model.

Measured Reverberation time Huawei						
Attempt	**1**	**2**	**3**	**4**	**5**	**6**
125 Hz	0,86	1,13	1,59	1,12	1,82	0,64
250 Hz	0,88	0,65	0,78	0,75	0,78	0,79
500 Hz	0,68	0,61	0,66	0,67	0,67	0,64
1000 Hz	0,63	0,62	0,65	0,62	0,64	0,62
2000 Hz	0,63	0,63	0,65	0,62	0,63	0,62
4000 Hz	0,61	0,56	0,57	0,57	0,58	0,55