Examensarbete

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Jämförelse av Bluetooth codecs med fokus på batteriladdning, CPU användning och räckvidd

Comparison of Bluetooth codecs with focus on battery drainage, CPU usage and range

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Abstract

With the constant advances in technology, people are using more wireless products, such as earphones or speakers whereas many of them use Bluetooth. With the current advances in Bluetooth technology, consumers and manufacturers have a hard time keeping up with the pace. Thus, when it comes to factors such as battery drainage, CPU usage, and range there is missing knowledge. This study is conducted to find out what effect the different codecs have on these factors, by comparing the two most commonly used codecs SBC and AAC. Using a codec that has lower battery drainage whilst still having a good enough audio quality can have a positive impact on our society and environment. Needing less electricity, lessens the overall energy consumption and directly lowers the energy production. Our results indicate that there is a significant difference in CPU usage but not in battery drainage or range.

Keywords: Bluetooth codec, Battery drainage, CPU usage, Range, Experiment, Advanced Audio Coding, Low-Complexity Subband Codec

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1 Introduction

In the modern era, more and more people are getting used to using wireless products, such as earphones or speakers. All such devices share a common point, Bluetooth (Blackman, 2022). With this fast growth pace, people are more reliant on Bluetooth technology. Yet there is a lack of proper knowledge regarding potentially important factors depending on the intended use case. The lack of knowledge makes it harder for the users and manufacturers to make informed decisions. Current studies regarding Bluetooth and codecs focus on factors such as RSSI, line-of-sight, and environmental effects on the connection between the devices (Qureshi et al., 2018; Hidayab, Ali & Abas Azmi, 2009).

When it comes to the codecs' effect on battery drainage and range, there is almost no publicly available data even though they are important for both the users and manufacturers. In areas such as bird monitoring, battery size is limited (Magno et al., 2017). A Bluetooth codec with lower specifications regarding audio quality, such as bitrate and sample rate, may have less effect on battery drainage and thus be more suitable for limited battery size. Similarly, the connection quality and its range are important as well. Quershi et al. (2018) discuss how connection quality and range are affected by environment and transmission power. If the codec can mitigate the environmental effect or requires less transmission power, it might be preferable in certain use cases.

In our study, by conducting two sets of experiments, one focusing on battery and CPU, and the other solely on the range, the aim is to determine if different codecs are more suitable in scenarios where battery time and range are of higher importance. Two True Wireless Earphones (TWS) were connected to a smartphone and measured how long it took for the battery to deplete whilst playing music. At the same time, the CPU usage was monitored. For the range experiment, while using the same setup but by walking away from the smartphone while wearing the TWS until the connection was lost, the range could be measured. For both experiments, the TWS devices were tested using two common codecs, Advanced Audio Coding (AAC) and low-complexity subband codec (SBC).

2 Background

Bluetooth is a widely used wireless technology and is constantly growing and evolving. The common user might not be able to keep up with the fast pace of constant changes and new terms. Finding information regarding less known and popular factors may be an issue for the users and manufacturers when choosing what properties are best for their needs or situation.

Previous research is almost entirely focused on audio quality on the real-life effects of different codecs. Therefore, it might be hard for the users and manufacturers to choose the proper codec for a given use case, such as when battery drainage or range is the most important factor.

This study aims to complement the already existing knowledge out there and encourage further and more in-depth studies on a larger scale.

2.1 Personal Area Network

Much of today's technologies use different types of networks to communicate with each other. Devices such as True Wireless Earphones (TWS), smartwatches, and wireless speakers make use of a smaller network called Personal Area Network.

A PAN (Personal Area Network) is a short-range network involving the connections centered around an individual's space. There are two categories involved in PANs, Wired Pan and Wireless Pan. Wired PAN is when the network is set up by using USB (Universal Serial Bus), Firewire, or other cable types. Wireless PAN is when the network is connected by using signals from infrared, ZigBee, Bluetooth, ultrawideband, and others ('Overview of Personal Area Network (PAN)', 2020).

2.2 RSSI

RSSI, "received signal strength indicator", is a measurement of the signal strength in percentage as indicated by the receiver. A higher number means that the signal is stronger, while a lower number means that the signal is weaker. Thus, the implication is that the value can estimate the distance between the source and the receiver (Gao, 2015). A crowded environment can have a significant impact on the RSSI measurement (S. Humaid & I. Moustafa, 2021).

2.3 Propagation

Propagation is when the signal that gets sent out interacts with the environment and gets affected by them, either negatively or positively, by factors such as reflection, scattering, and diffraction:

- Reflection is when the medium's surface absorbs some of the energy and reflects the remaining energy depending on the surface material.
- Scattering is when the transmitted signal gets reflected from colliding with small objects and splitting in every direction before it reaches the receiver.
- Diffraction is when the signal bends depending on the obstructed object's surface. A diffracted signal may be strong enough for the receiver if the sender is obstructed (Hidayab, Ali & Abas Azmi, 2009).

A positive effect can occur when for example, the signals get reflected and concentrated towards the receiving part. This results in a stronger connection since more signals are received compared to them being sent in a direction that is not towards the receiver (Hidayab, Ali & Abas Azmi, 2009). This is the basic principle behind a TV parabola.

The weather is a factor that can negatively affect the signals. In a snowy environment, the signals may hit a snowflake on its way to the receiving part which will scatter the signal making it split and weaken. Depending on the weather this may mean that barely any signals reach the receiving part, resulting in a weak connection (Hidayab, Ali & Abas Azmi, 2009).

Another factor to consider is if there is a line of sight between the sender and receiver, where a line of sight means that there is no major obstruction in the way and no visual impairment. A non-line-of-sight could mean a wall in the way or a heavily crowded group of people. In that case, the material and dimensions of the obstruction will have different propagation effects (Eridani, Rochim & Cesara, 2021).

2.4 Bluetooth

Bluetooth is a well-known and used technology for sending data wirelessly between a sender and receiver. There are two standards used for Bluetooth technology, Bluetooth classic and BLE (Bluetooth Low Energy). Both standards are operating on the 2.4 GHz frequency band. To keep the interference to a minimum, BLE jumps between different channels, referred to as frequency-hopping, to mitigate interference (Marcel, 2020).

BLE works on many devices, such as smartphones, audio-, tracking- and hearing aid devices. Additionally, Bluetooth classic and BLE can coexist, focusing on different features such as low energy factors and physical layer (Treurniet et al., 2015).

The main focus of BLE is the optimization for using less power by sending the data in short bursts spaced out with periods of no sending in between. This optimization lessens the power consumed by the application on smartphones (Czurak et al., 2018).

2.5 Bluetooth Codecs

When Bluetooth is transmitting audio, the digital audio data needs to be encoded before sending and then decoded after receiving. The codecs are responsible for determining the method for doing that. The different codecs have their specified transfer rate of bit rate, bit depth, and sample rate.

By compressing the data, and lowering the bit rate, the sound quality might be reduced but less data needs to be sent. On the contrary, while being less compressed, the sound quality may be higher, but it will require a higher transfer bandwidth for playback and larger file size (Katz, 2021), thus it could increase the CPU usage to process them.

SBC (low-complexity subband codec) is available on all music streaming devices due to its mandatory availability on any Bluetooth device capable of audio transmission. It has a low computational power as well as power consumption but has a bad reputation due to its low bit rate and compression algorithm (He et al., 2010).

AAC (Advanced Audio Coding) is the standard for digital audio compression, and it is the license-free standard for YouTube and Apple devices (Katz, 2021). Contrary to SBC it is capable of having higher bit depth, although with a lower sample rate and bit rate, as well as higher power consumption and computing power. While the AAC codec enables more complexity than SBC, AAC performance relies on the implementation quality of the manufacturer. It is a clear step up compared to SBC on Apple devices, whereas AAC's performance fluctuates more on Android devices (Gleeson, 2022).

2.6 Specification

There can be a difference in range and battery drainage with the different codecs, which might have varying importance depending on the intended use area.

While looking at specifications on TWS, features such as wireless charging, color, and estimated battery time are stated, but other potentially helpful information is often neglected. Many TWS can use several different Bluetooth codecs but no information on the codecs´ effect on factors such as range and battery consumption for the connected devices.

Studies have shown a connection between different codecs when it comes to battery consumption (Yadav & Ramasubramanian, 2014). A higher transmission power affects the range factor with a range increase (Qureshi et al., 2018). A codec that is transmitting more data will also increase the transmission power.

3 Problem

3.1 Related Works

One constant challenge while developing small technology devices is to keep the batteries small without a distinct reduction to the battery time for the device. A smaller battery is crucial for applications such as small bird monitoring since a larger tracking device might affect the birds' behavior.

If the behavior changes too much, the collected data might be useless since it no longer is an actual representation of the behavior (Magno et al., 2017). To make the monitoring devices smaller Magno et al. (2007) developed a lightweight lower power sensor node that uses BLE in combination with low-power technologies to achieve a run time of 24 hours while still retaining good sound quality.

Achieving better battery duration is not only beneficial for tracking animals. It can be vital in emergency systems and hearing aids (Yedukondalu et al., 2016). These systems must have low battery drainage, so they stay active for long periods. The less interaction needed, the better, especially in fields related to health and eldercare.

While designing emergency systems and hearing aids, power and size are the most challenging factors. Yedoukondalu et al. (2016) designed a physical codec that encodes and decodes VHDL (VHSIC Hardware Description Language) code level data with ultra-low power and minimum area.

In a study from 2014, four video codecs were compared regarding CPU usage and battery consumption, and a noticeable difference was found between the codecs (Yadav & Ramasubramanian, 2014). According to their results, one of the codecs consumed less battery and had a lower CPU usage. The results indicate that if a codec uses the CPU more efficiently or uses it less, it is preferable when choosing what codec to use. The study had a limitation, as audio and video quality were not measured and possibly, controlled as part of the study.

Quershi et al. (2018) studied the range effects of Bluetooth communication. They measured how different transmission power levels affect RSSI and distance in an indoor environment, both with and without line-of-sight. The conclusion was that a higher transmission power results in a more stable RSSI at a long distance.

Eridani, Rochim, & Cesara (2021) experimented on Bluetooth, Wi-Fi, and ESP-NOW, where they conducted multiple experiments on an ESP32 development board. Using Bluetooth v.4.2, they managed to get a range of 15 meters using the built-in antenna and 25 meters with an external antenna. The authors also experimented on the effects of being blocked by materials in a non-line-of-sight condition, with results aligned with Quershi et al. (2018).

Hidayab, Ali & Abas Azmi (2009) studied the effect of propagation, both indoor and outdoor, to see the difference between the different environments. They found that the propagation in an outdoor environment results in a better RSSI value. Although factors such as wind, drizzle, and rain may give a more inconsistent reading which in turn can affect the RSSI.

Other studies have been conducted to predict the distance between a Bluetooth sending device and a Bluetooth receiving device using RSSI. A stronger value implies that the distance is closer between the sender and receiver, which is useful in indoor localization and GPS technology where connection range and stability are essential (Soewito, Ritonga & Gunawan, 2016; Qureshi et al., 2018; Yoon et al., 2018).

3.2 Problem & Hypothesis

Studies conducted in the past have focused on the following:

- improving battery life via Bluetooth and BLE
- how to predict distance using RSSI
- how the environment affects the signals

Concerning range, studies have focused on how to predict the distance between a sender and a receiver by utilizing the fact that a stronger RSSI value implies that the distance is closer between them. Additionally, previous studies have been done on the environmental factor and how it affects the Bluetooth signal's performance. Therefore, there is a need for more studies to be conducted concerning battery drainage, CPU usage, and range.

Currently, many devices use Bluetooth with many different codecs. It is, therefore, difficult to choose the right device for the right purpose since the different codecs themselves all have their strengths and weaknesses. With use cases such as bird monitoring and music listening, they are both different, but they still share the factor of requiring a small battery and wanting to have as a long battery life as possible. One possibility would be to reduce CPU usage, which could increase the runtime of the devices. Bluetooth range is important for both GPS technology and TWS devices because having a longer range would make them more effective and usable in more scenarios. Therefore, more research is needed concerning the battery drainage and range of Bluetooth codecs. The focus will be on TWS, although the fruits of this study should be beneficial for other areas concerning Bluetooth.

The aim: To compare and contrast a selected set of Bluetooth codecs concerning battery drainage, CPU usage, and range. To achieve our aim, the following objectives need to be fulfilled.

1. Research relevant literature
2. Identify possible TWS codecs and how they can be compared and contrasted with a focus on experiment location, measuring software, and tools
3. Measure the codecs' effect on battery drainage
4. Measure the codecs' effect on CPU usage
5. Measure the codecs' effect on range
6. Analyze and present the results

Due to the lack of proper information on the TWS from the manufacturer, the intent is to look into how codecs such as AAC and SBC might affect range and drainage.

Research questions:

RQ1: How do the different Bluetooth codecs compare to each other regarding battery drainage?

- H1.0: The different codecs have no significant difference in battery drainage.
- H1.1: There is a significant difference in battery drainage between different codecs.

RQ2: How do the different Bluetooth codecs compare to each other regarding CPU usage?

- H2.0: The different codecs have no significant difference in CPU usage.
- H2.1: There is a significant difference in CPU usage between different codecs.

RQ3: How do the different Bluetooth codecs compare to each other regarding the range?

- H3.0: The different codecs have no significant difference in range.
- H3.1: There is a significant difference in range between different codecs.

3.3 Method

An experiment is used as a method to carry out this study. With a controlled experiment, the cause-effect relationship can be observed. Therefore, the relation between the used codecs, battery drainage, and the range can be studied. In addition, it makes the experiment easier to control and more replicable. The experiment only focuses on a set of selected use cases as all possible Bluetooth use-cases cannot be covered during a single experiment.

Case studies could have given more information by monitoring and analyzing real-life scenarios. It has the chance to provide a more accurate depiction of how the codecs affect the TWS and smartphone. The accuracy it might add would be positive, but it would make the scope too large for this study and there is no control over the environmental context.

Interviews would have been possible to do with the manufacturers and developers of Bluetooth devices since they most likely have information on the performance of the different Bluetooth codecs. Interviews are, however, not feasible to reach the aim of this study as it would require personal contact with Bluetooth developers to which we do not have access. Additionally, there would be a need to formulate proper questions, reach out, and conduct the interviews. While manufacturers and developers should know this area, they might skew the data to benefit their agenda.

Surveys and literature samples could have given more information from a larger sample and more in line with real-life scenarios. However, for a survey to be effective, it needs to reach a larger sample that has some knowledge about the field. Otherwise, it will not yield any useful information. While introducing more people into the experiment might increase the likelihood of additional bias. With a literature study, there would be a need for a large number of articles on the topic.

Another option, if the aim was to measure sound quality, is to use frequency response-, waterfall-, impulse-graphs, or spectrograms. Although, sound quality is not looked at since it is highly subjective. Every single person has their individual preferences for what they like in terms of tonality and library. It is affected by the fact that we all have different shaped heads and ears, and hearing health which makes measuring sound quality overall hard (Olive, 2021). These factors make it not feasible for this study since it requires a larger study in terms of time and scope.

3.4 Approach

3.4.1 Literature search

Most of the research was done during January 2022, with a preliminary search performed at the end of 2021. Most of the articles were found on The IEEE Xplore (Institute of Electrical and Electronics Engineers), but other sites such as ScienceDirect, Springer, ACM (Association for Computing Machinery), and Google Scholar were also used. The search terms used were a combination of words such as Bluetooth, battery, range, accuracy, and others (see appendix B for full list). Many articles were collected and gathered under the selection criteria of them having a fitting title and abstract. Previously selected articles were later looked through thoroughly, and only the relevant articles were chosen for this study.

3.4.2 Experiment

Important independent variables are the devices, namely the different TWS, codecs, and smartphones. Because of the different ways of collecting and measuring the data, the two experiments used different methods. A measuring wheel was used to measure range while Google's Android Debug Bridge (2007), often referred to as ADB, was used for measuring CPU usage, and the application Simple Battery Graph (2019) for measuring the battery.

The dependent variables for the battery drainage experiment are the CPU usage for the smartphone and the battery drainage for both the sending and the receiving device, whereas the smartphone is the sender and the TWS is the receiver. For the range experiment, the dependent variable is the distance between the sender and receiver, similarly to the drainage test. Quantitative data was gathered during the experiments.

Since interference from the environment may affect the results (Hidayab, Ali & Abas Azmi, 2009), location is an important independent variable for these tests. Therefore, the range experiment was done on the campus, whereas the battery drainage and CPU usage were done in the countryside. By conducting the range experiment in an outdoor environment, the number of affecting variables was reduced, and therefore, the signal strength was more consistent. Similarly, by doing the battery drainage and CPU usage experiment in the countryside there would be less outside interference from other devices and signals, thus resulting in a more consistent test.

3.4.3 ANOVA

For evaluating the results, either ANOVA or T-test could be used.

Both ANOVA and T-test consider multiple components of data, one of them being the P-value. P-value indicates how believable the null hypothesis is, whereas a higher value indicates higher believability. A 95% confidence was used, resulting in an alpha value of 0,05. 95% of that mean would fall in the same range for a replication study as for this experiment. Comparing the P-value with the alpha value shows if the difference is significantly different or not. To reject a null hypothesis, the P-value needs to be less than the alpha.

A T-test is only suited for two groups of factors since having more than two groups would mean the necessity of conducting multiple T-tests and, therefore, the error rate for Type I errors would increase.

Because of these factors, the ANOVA test was chosen and used for all results.

4 Implementation

For all experiments, the following TWS were used: Sony WF-1000XM3 and the Samsung Galaxy Buds pro referred to as XM3 and Galaxy BP. While two different smartphones were used, the Oneplus 8T for the range experiment and the Huawei P20 Pro for the battery drainage and CPU usage. The usage of two different smartphones may affect how generalizable the results might be. The effect should not affect the credibility since the smartphone is consistent during each experiment. By using two smartphones, the credibility should not be affected since the smartphone is consistent for all experiments. Furthermore, since the focus is on the codecs' general effect, the interest is in if they differ no matter the smartphone. More on this under chapter 7.

Two TWS devices were used to minimize the possible impact of codec implementations on the devices. If both devices show similar results for the same codec, then it is most likely caused by the codec itself. The battery drainage and CPU usage experiment were using a factory reset smartphone, whilst the range one did not. More about this in the respective sections. Therefore, two different smartphones were used, one for battery drainage and CPU usage measurement while the other one was used for range.

4.1 Preliminary Experiments

As there are three hypotheses, there is a need to divide the experiments into two separate parts. One focuses on both the battery drainage and CPU usage while the other solely on the range. Dividing the experiments prevents them to affect each other in unpredictable ways, while the battery drainage and the CPU usage can be conducted at the same time.

If the experiments are conducted at the same time, the range one would negatively affect the other factors since it involves the disconnection from the TWS, which requires the smartphone to pause the music. Pausing the music will affect the battery factor since the TWS would no longer be playing until the battery dies and affect the CPU usage, which in the end makes it significantly harder to see if there is any potential difference. Alternatively, the TWS could be reconnected with the smartphone, and the music resumed. Reconnecting the TWS could become a confounding variable and negatively affect the measurements' validity concerning CPU usage.

4.1.1 Battery drainage and CPU usage

Some weeks before the experiments, some smaller tests were conducted to ensure that the software and equipment worked as intended. For monitoring the CPU, a smartphone was connected to a laptop running ADB via USB-C cable, and the debug option was activated on the smartphone. By using the command “adb shell top -m 20 -d 1200”, ADB (2007) displays the top 20 running processes on the smartphone, sorted ascending by CPU usage. The displayed CPU usage is an average over the specified time, where “-d 1200” specifies how long it should measure in seconds. After ADB was launched and set to measure for 20 minutes, whilst music was playing from a Spotify (2006) playlist.

The smartphone was not factory reset at this point. After 20 minutes, the CPU percentage was noted, and the same test was done for the other codec using the same songs.

This initial test shows two things:

- The software can be used to get an average CPU usage from the process during the set amount of time, and there is a difference between codecs.
- There is no option for disabling charging the smartphone while connected to the computer. Therefore, the charging needs to be resolved somehow, possibly by conducting two tests, one where the battery is monitored and one where the CPU usage is monitored. As a solution, the smartphone was connected to the laptop wirelessly to allow capturing of the CPU usage.

4.1.2 Range

As with the battery and CPU experiment, there was a preliminary test conducted for the range experiment as well to ensure that the experimental setup was working.

During the test, the smartphone was connected to the TWS, and the first codec was used. The smartphone was personal and was not factory reset to make the experiment more realistic but was using airplane mode.

After connecting the devices, a local music file was played, with a music player on the smartphone. Then one person held the smartphone in the starting area and the other person with the TWS in their ears started to walk away in a straight line of sight until the TWS stopped playing music and noted down the distance.

The weather during the preliminary test was poor with snow and wind. Thus, the propagation was most likely affected by this. As a result, for the actual experiments, we ensured to perform all measurements during better weather conditions and consistent throughout all measurements.

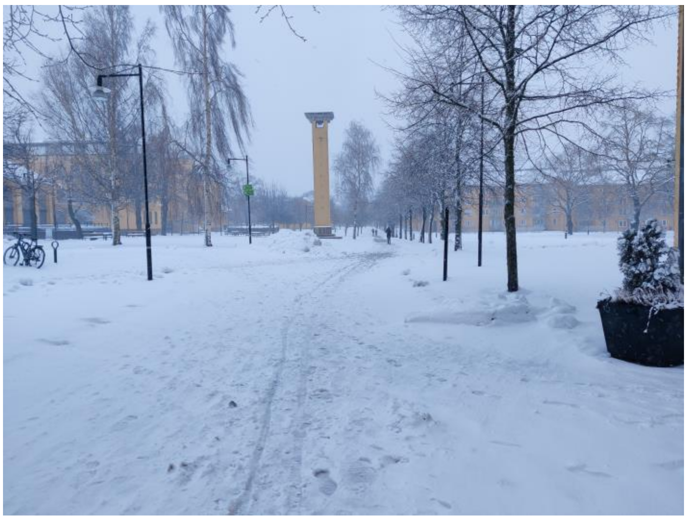

Figure 1 Preliminary test weather condition

4.2 Updates to the experimental setup

4.2.1 Battery drainage and CPU usage

The original idea was to do one-hour sessions in two separate locations when measuring the battery drainage and CPU usage. Experimenting with two locations would minimize how much interference would affect the experiment. While doing an entire test run of the setup, a problem with one TWS setting was found. One could no longer disable the option to pause the music while they were outside of the ear. The problem with the setting meant that the execution had to be changed, and the experiment had to be redone. At the same time, the idea of doing experiments at two locations was also scrapped since there was a lack of access to the testing location. Instead, the experiment would only be done in the countryside, with the benefit that the interference would be lower and less fluctuating.

After redoing the first half of the experiment, when changing to the other TWS device, a new problem occurred. The device no longer showed the exact battery value but instead showed in steps of 100%, 70%, 50%, 20%, and 0%. To counter the imprecise battery value, the whole planned procedure had to be revised since there was no possibility of monitoring the TWS's exact battery level. The alternative was to run each session until the TWS device completely ran out of battery and compare how long they lasted. This, however, introduced new problems as it would take significantly more time since the expected battery time for both TWS devices was at least five hours. Firstly, it meant that the experiment would take at least 80-hours, which is a bit much for a thesis like this. Secondly, it would require the tester to stay at the location with the TWS device in their ear during the whole session.

To solve the first problem, it was, therefore, opted to measure a part of the runtime since ADB (2007) works by collecting the average CPU usage for a given period. It would be impossible to predict the exact time, but by measuring a majority of the TWS device's expected battery time, it represents the whole runtime. Even if the values will not be exactly as they would've been, the important factor is not the values themselves but rather the difference between them. Both TWS had an expected battery time of at least five hours which means four hours covers the majority of that time, and still leaves room for variation in runtime between different codecs.

The second problem got solved by a software update which further opened up the possibility of automating the measuring process with ADB (2007). The update also mostly fixed the problem of disabling the option to pause the music while they were outside of the ear. Most of the time, it allows the music to play while the TWS is placed on the table, but in some cases, it would still pause. The TWS devices were placed on a piece of cloth to trick it into thinking it was constantly in an ear.

4.2.2 Range

For the range experiment, there were not as many changes that had to be done to it as with the battery drainage & CPU usage experiment.

Although the intended implementation initially was to experiment indoors, it was assumed that the range would be within the capacity of the test building. The assumption, however, was quickly changed, as, during the preliminary testing, it was shown that the indoor building would not have the size required as the building was too small. Changing the environment from indoor to outdoor also meant that there were fewer propagation effects due to the building, as mentioned by Hidayab, Ali & Abas Azmi (2009).

While the other change was that the samples for each codec needed to be increased from one to three to increase the reliability of the conclusion from a statistical standpoint such as having a statistical significance. Therein there was a need to gather more samples.

5 Data acquisition

To ensure that the gathered data holds a high quality as well as is representative of a larger audience, some aspects need to be considered.

5.1 Battery & Drainage

The exact amount of interference a person will be subjected to is subject to multiple factors, such as where the person is located and what time of the day it is (Hidayab, Ali & Abas Azmi, 2009), which makes it hard to create an ideal test scenario. Therefore, the experiment was conducted at a private residence in the countryside. Experimenting at the private residence made it easier to control factors. Furthermore, it gives the possibility to conduct experiments around the clock because of the constant access to the equipment and location.

To further mitigate variation, the experiment started with a fully charged, factory reset smartphone in airplane mode, with a few functions and applications running as possible. By factory resetting the smartphone, the aim is to minimize other background applications and functions' effects on the battery drainage and CPU usage, which will make it clearer how much is used by the Bluetooth and codec. On the same note, both TWS devices had their applications installed on the smartphone and set up in a way that they would have as similar settings and volume as possible.

In an attempt to generalize the sound, an offline playlist based on It’s Hits Sweden (Spotify 2022) was played without shuffle, and to make the results more consistent, the playlist was downloaded. Since there is no single-use case for Bluetooth, it is impossible to create a tracklist that accurately represents every user's listening habits. Using the playlist causes the test situation to be more applicable to a large number of Bluetooth users since the playlist is based on what users listen to.

After connecting the TWS to the smartphone, the music was started, and the measuring software was enabled and set to collect data for four hours straight. When four hours had passed, the CPU usage was noted, the collection stopped, but the TWS was left to play until the battery died. To monitor when the TWS ran out of battery, the inbuilt HCI (Host Controller Interface) snoop log in the smartphone was used. It tells the exact moment the smartphone loses connection with a Bluetooth device, i.e. when the TWS runs out of battery. The disconnection time was then used to measure how long the battery lasted, mitigating the need to see the TWS battery level. All devices were then charged, and the experiment restarted.

This was repeated three times for each codec followed by repeated in whole for the other TWS, resulting in twelve measurements total. Since time was limited, there was only time to run two to three experiments each day.

5.2 Range

Eltahir (2007) and Pu, Pu & Lee (2011) have shown that RSSI is linear in an outdoor environment due to propagation effects, thus making the experiment easier to conduct and more consistent. Therefore, the experiment was conducted outdoors, specifically on the school grounds. During the experiment, the procedure was done in the same way as the preliminary test, the smartphone was connected to the TWS with the SBC codec activated. To make the experiment realistic, a non-factory reset smartphone was used. It was, however, done in airplane mode to prevent sudden calls or disturbances. The respective TWS applications were installed on the smartphone, and both TWS had active noise cancellation and ambient mode turned off while other settings were mirrored as closely as possible.

After connecting the devices, a local music file on the smartphone was played using the music player called UAPP (USB Audio Player Pro). The specific track was Avid (Sawano, 2021) from the album single Avid and was in FLAC format at a 993 Kbps bit rate. The reason for using a single track was to make the experiment more consistent.

The experiment was then conducted by having one person holding the smartphone while the other person walked away in a straight line of sight, with the TWS in their ears, using a measuring wheel to measure the distance. Once the music stopped playing, the person with the TWS noted the distance measured by the measuring wheel. The steps were repeated two more times on the same TWS and SBC codec to gather more data. After gathering three samples of the same configuration, the codecs were changed to AAC and three new experiments were done. After collecting the results for AAC the TWS was swapped, and the procedures were repeated three times with SBC active and three with AAC.

Lastly, the collected data was organized into tables for easier display and were compared based on the distance between the different experiments.

The weather during the experiment was clear without rain, wind, or snow thus, the results should have been more consistent than for the preliminary test due to less propagation, but since the preliminary test was conducted with only one sample for each codec, we cannot say for sure.

Figure 2 Range experiment location

6 Results

6.1 Battery & CPU

When it comes to codecs' effect on battery consumption, there are two areas to consider:

- How much battery is drained on the TWS
- How much is drained on the smartphone

Some problems occurred while reading the CPU usage for two samples since the average used by the Spotify app did not show. Since there were at least two more hours left before the battery would run out, a new measure was done, focusing only on Spotify. The results were marked down and looked at after all samples had been finished. They were found to be in line with readings from the other samples as well as the potential difference was small enough that it would not affect the final result.

By combining and grouping the samples by codec, seen in Figure 4, SBC still has a longer runtime but the big difference in deviation for the Galaxy BP is not as noticeable.

TWS Runtime		
TWS + Codec	Mean (HH:MM:SS)	Deviation (HH:MM:SS)
XM3 AAC	06:02:40	00:22:43
XM3 SBC	06:10:20	00:24:40
Galaxy BP AAC	07:27:40	00:30:08
Galaxy BP SBC	07:41:00	00:06:33

Figure 3 Runtime results

TWS Runtime		
Codec	Mean (HH:MM:SS)	Deviation (HH:MM:SS)
AAC	06:45:10	00:52:19
SBC	07:00:30	00:44:35

Figure 4 Codec-wise runtime results

From the results in the mean column in figure 3, SBC lasted slightly longer in general than AAC. The average runtime differs by roughly 3 minutes for the Galaxy BP and 7 minutes for the XM3, depending on the codec. Similarly, while looking at the deviation column, SBC has a lower deviation value which means that SBC is more consistent between the different samples. This is especially true for the Galaxy BP, where the difference in variation is roughly 24 minutes between SBC and AAC.

While only looking at the results for the codecs, seen in figure 4, SBC still has a longer runtime but the big difference in deviation for the Galaxy BP is not as noticeable.

Smartphone Battery Drain		
TWS + Codec	Mean (%)	Deviation (%)
XM3 AAC	14.67	1.15
XM3 SBC	13.67	0.58
Galaxy BP AAC	17.33	1.53
Galaxy BP SBC	17	3.46

Figure 5 Smartphone battery drainage

Smartphone Battery Drain		
Codec	Mean (%)	Deviation (%)
AAC	16.00	1.90
SBC	15.33	2.88

Figure 6 Codec-wise battery drainage

When it comes to the battery drainage for the smartphone, it follows the same pattern where SBC is the codec that consumes the least amount of battery, see figure 6. But contrary to the TWS, the AAC codec is now the more consistent one. Similar to the runtime experiments, there is a greater difference in a deviation between the two codecs for the Galaxy BP, see column 3 in figure 5, where SBC had a larger difference than AAC.

Smartphone CPU Usage		
TWS + Codec	Mean (%)	Deviation (%)
XM3 AAC	8.72	0.91
XM3 SBC	8.42	1.17
Galaxy BP AAC	8.08	0.20
Galaxy BP SBC	7.10	0.21

Figure 7 Smartphone CPU usage

Smartphone CPU Usage		
Codec	Mean (%)	Deviation (%)
AAC	8.40	0.68
SBC	7.26	0.35

Figure 8 Codec-wise CPU usage

The CPU usage was more consistent regarding deviation for the Galaxy BP where there was only a 0.01 unit difference between them, as seen in column 3, figure 7. Contrary to the small difference in deviation for the Galaxy BP, there is a bigger difference in mean compared to the XM3. In this case, the mean for the XM3 is more consistent between the two codecs with, a difference of 0.3 compared to the Galaxy BP´s 0.98.

When only looking at the codecs, figure 8 shows that SBC uses slightly less CPU compared to AAC. Furthermore, it gets emphasized that SBC is more consistent in its CPU usage than AAC, where SBC had a standard deviation, see column 3, of 0.35 compared to AAC's 0.68.

6.2 Range

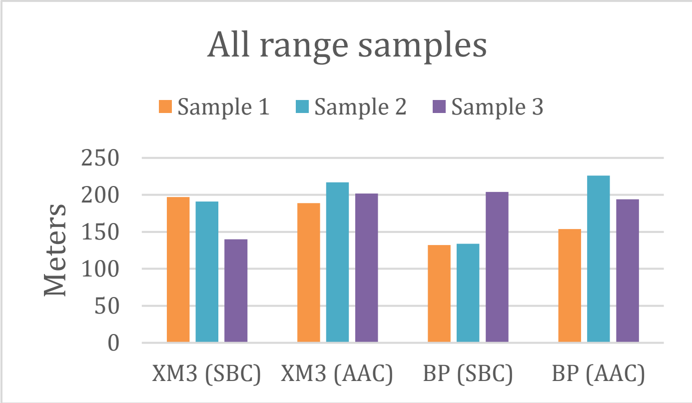

Figure 9 All range samples

All samples have been collected and grouped by codec and TWS combination, as seen in figure 9. Samples 1, 2, and 3 respectively reached 197, 191, and 140 meters on the XM3 using the SBC codec, while on the AAC codec, they were 189, 217, and 202 meters. For the Galaxy BP, samples 1, 2, and 3 on the SBC codec reached 132, 134, and 204 meters while on the AAC codec they reached 154, 226, and 194 meters.

The individual samples in figure 9 do not have much consistency within the same TWS and codec combination. When averaged into a single column, based on codec, with mean values for each, the results in figure 10, show that SBC's mean is 166 meters while the AAC mean is 197 meters. The standard deviation shows that the SBC codec deviates by 34 meters compared to AAC at 25 meters for this experiment. This is why the samples in figure 9 show a lack of consistency, especially with the SBC codec.

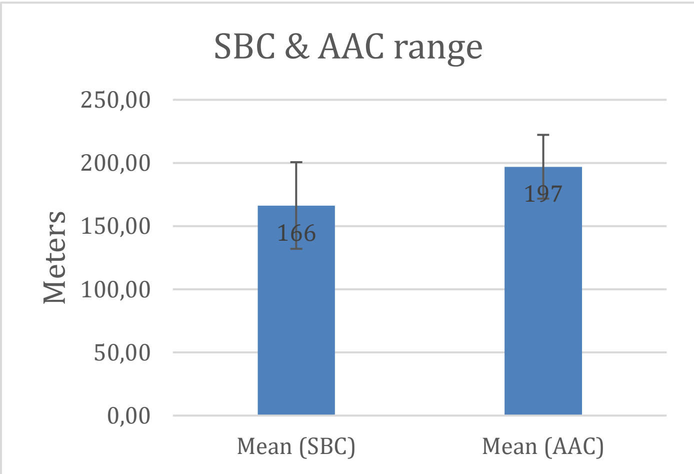

Figure 10 SBC & AAC with standard deviation

6.3 Analysis

6.3.1 Battery & CPU

Codec	TWS runtime (H:M)	Smartphone Battery Drain (%)	CPU usage (%)
AAC	06:45:10	16.00	8.40
SBC	07:00:30	15.33	7.26

Figure 11 Battery drainage & CPU usage

When looking at the battery drainage in conjunction with the CPU usage for the Galaxy BP figure 11, shows that SBC uses less CPU in general and has the least battery drainage. While comparing the two codecs against each a correlation between the AAC's higher CPU usage and higher battery drainage seems clearer. The AAC uses a bit over 1 percentage unit more than SBC, as well as being more inconsistent. The difference in CPU usage goes in line with Yadav & Ramasubramanian's (2014) conclusion that there is a difference between different codecs. The codex with higher resolution playback will use more CPU and therefore drain more battery from the connected devices.

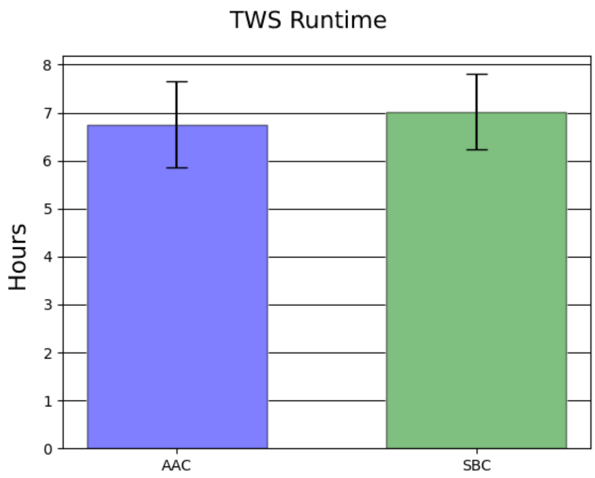

Figure 12 TWS runtime with a confidence interval

SBC has the better runtime lasting roughly 15 minutes longer but seeing there is an overlap between the confidence intervals, in figure 12, where SBC has an interval of ±0.89 and AAC ±0.79. There is uncertainty about whether the difference is significant enough.

According to the ANOVA test with 95% confidence, there was no significant difference between the two codecs. As seen in Appendix B-1, the p-value is 0.58 which is a fair bit larger than 0.05, meaning that there is no significant difference between the two codecs when it comes to battery drainage on the TWS devices.

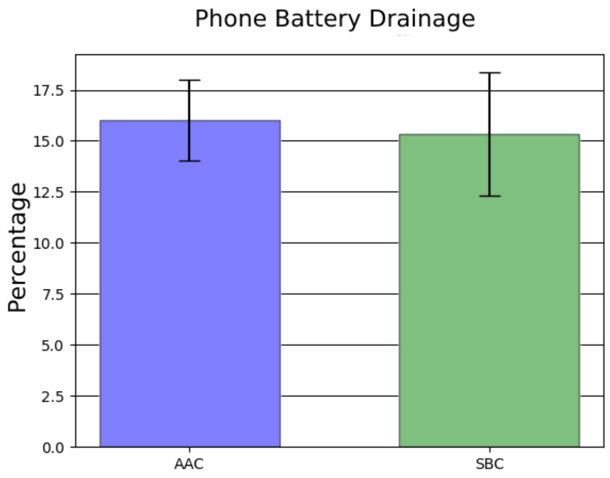

Figure 13 Phone battery drain with a confidence interval

Similar to the battery drainage on the TWS, the overlap in confidence interval for the smartphone's battery drainage calls for an ANOVA test, see figure 13. SBC has an interval of ±1.99 and AAC ±3.02.

As a result of the ANOVA test, we can conclude that there is no significant difference between the two codecs regarding battery drainage on the smartphone. The P-value of 0.65 is again a fair bit larger than the breakpoint of 0.05 as seen in Appendix B-2.

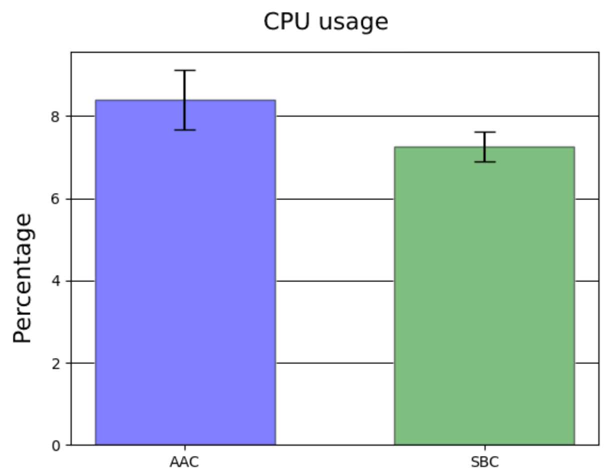

Figure 14 CPU usage with a confidence interval

When it comes to the CPU usage on the smartphone, there is a relatively big difference, visually speaking, see figure 14. Still, there is some overlap between the two's confidence intervals, SBC has an interval of ±0.72 and AAC ±0.36, which calls for another ANOVA test.

This time the p-value of 0.0045 is smaller than the breakpoint of 0.05, which indicates that there is a significant difference between the two codecs, Appendix B-3. Even though there is no direct proof that the SBC had a lower battery consumption, the gathered results for SBC were lower than AAC. This would be logical considering the difference in CPU usage.

6.3.2 Range

During the experiment, the weather was clear, without much wind, and no rain or snow. Thus, the weather should not have been a factor for inconsistencies due to little propagation effects, as shown by Hidayab, Ali & Abas Azmi (2009).

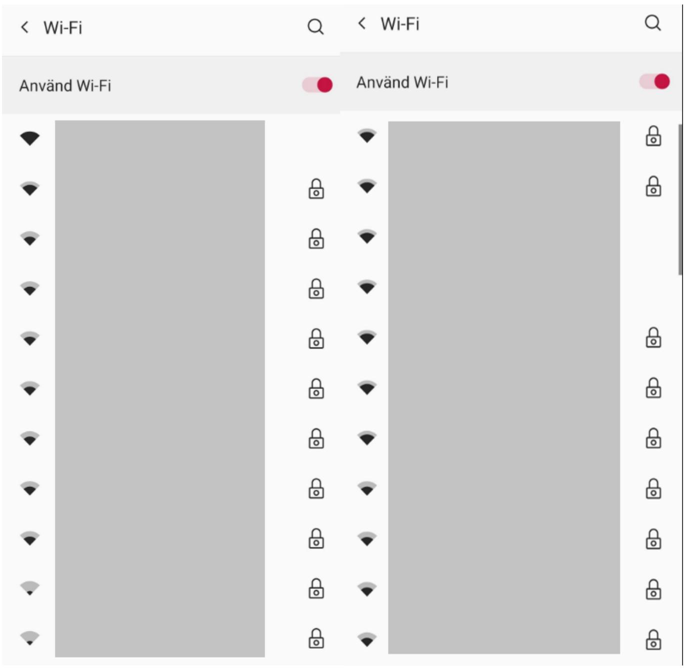

Figure 15 Available Wi-Fi at the starting point & propagation point

There was a specific area, around 80-90 meters from the starting point where nearly all of the TWS encountered problems. This will be referred to as the propagation point and is located close to a residential area. As can be seen in figure 15, the left side shows the 11 Wi-Fi connections that the Oneplus 8T smartphone could find at the starting point of the test area. The right side shows more than 11 networks. Note the scrollbar on the right side, that the smartphone could find at the propagation point. The difference in the length of the list, shows a clear difference in the available networks and the connection strength, with the propagation point having more networks available. The sudden increase in Wi-Fi signals from the residential area at the propagation point implies more interference there than at the starting point. Increasing Wi-Fi signals is most likely the cause of why the TWS devices encountered problems when in the proximity of the propagation point as the interference from the Wi-Fi signals could have interfered with the smartphone to TWS connection.

The XM3 on the SBC codec had a max distance of 197, 191, and 140 meters for the respective samples. Sample three was the one with the lowest distance. While it is hard to say if it is just an outlier based on such a small sample size, it is likely that the reason for this particular value is due to there being more people around the testing area. Thus, with more people around serving as an additional factor for interference, it is likely to be the cause as mentioned by Satan & Toth (2018).

While using the AAC codec, the XM3 had a more consistent reading between the samples, at 189, 202, and 217 meters, while it also did not face any issues at the propagation point.

The Galaxy BP on the SBC measured at 132, 134, and 204 meters, respectively. Sample three had a much longer distance than the other two samples, and it could have been due to sample three not encountering any issues at the propagation point while the first two samples had apparent issues like stuttering and an aftereffect of the sound beginning to distort and sounding like a robot.

Using the AAC codec on the Galaxy BP, the respective measurements were at 154, 194, and 226 meters. While the results were more consistent than on the SBC codec, all of the three samples ran into similar issues at the propagation point, being brief stuttering. In contrast at the max distance, none of the three samples managed to reconnect back to the smartphone.

The samples with propagation point issues had a lower distance than the ones that did not encounter any problems, what this implies is that due to the effect of the propagation point the Bluetooth signals could have been interfered with and thus resulted in the worse performance. The AAC codec also seems to have a consistently better range than the SBC codec and it can be seen in the mean and standard deviation values where the mean is higher than the SBC as well as having a lower standard deviation.

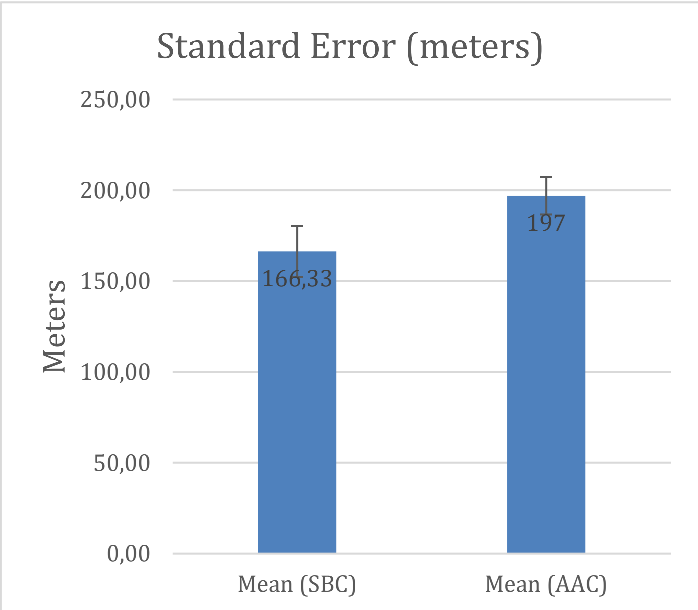

Figure 16 Range with standard error

The small sample size is justified by the standard error interval as seen in figure 16, which shows that the sample mean is a good representation of the population mean as the standard error is small.

The confidence interval of the mean values can be seen in the figure below, where the SBC has a confidence interval of ±36 meters while the AAC has a confidence interval of ±26 meters.

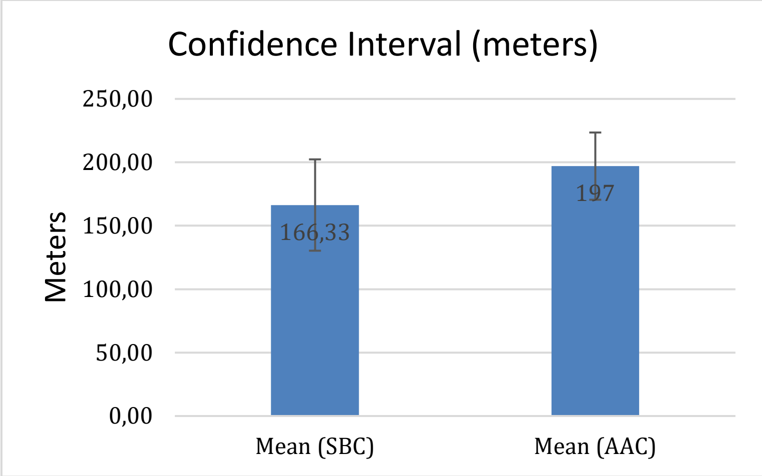

Figure 17 Range with a confidence interval

Since there is an overlap between the confidence interval for SBC & AAC, see figure 17, there is a need to determine if the difference is large enough. An ANOVA test was conducted to see if the difference is statistically significant or if the difference is caused by chance.

When comparing the p-value of 0.11 from the test with the alpha, there is a difference since the p-value is larger, see Appendix B-4. Therefore, there is no statistically significant difference between the two codecs, and the H3.0 hypothesis is accepted.

Judging from the gathered results presented in chapter 6, we keep the null hypothesis for all research questions except for H2. A significant difference cannot be observed for factors such as battery drainage or range. However, there is a significant difference in CPU usage between different codecs.

7 Discussion

7.1 Conclusion

The results after the experiments are that there was no significant difference in either battery drainage or range. But there was a difference in the CPU usage. Therefore, the conclusion is that the null hypotheses for H1 and H3 are kept but the null hypothesis for H2 is rejected.

It would seem that a significantly lower CPU usage would result in lower battery drainage since less power would be needed to power the CPU. However, no significant difference was found in the battery drainage or the range. It can be so that today's equipment is better suited to handle the different codecs more efficiently.

Even though there is no significant difference in the battery drainage, looking purely at the raw data shows that the AAC does consume more battery. The higher battery consumption goes in line with the statistical difference in CPU usage. There might be a statistical Type II error due to the low sample size which caused the sampling error. By increasing the sample size, a significant difference might be observed.

The range experiment was conducted outdoors. The reason for experimenting outdoors was that Hidayab, Ali & Abas Azmi (2009) claimed that the RSSI value was better than in an indoor environment due to propagation. However, during the experiment, the encountered propagation point showed that there is more to consider other than the weather when it comes to disturbances caused by propagation. The people present in the area and the trees have different propagation characteristics than cars or residential buildings. Additionally, residential buildings house people who use Wi-Fi and other technologies that bring another source of propagation (Hidayab, Ali & Abas Azmi, 2009).

The range experiment also resulted in all samples having over 100 meters in range. Our results show a much longer range than the results Eridani, Rochim & Cesara (2021) got. However, the hardware that they conducted the experiments with performs significantly worse than the smartphones used in this paper. Another possible cause for the difference could be the Bluetooth version v.4.2. Our study used at least v.5.0.

As supported by Quershi et. al. (2018) study, more transmission power is needed to transfer more data. Therefore, the range should have been longer for the AAC, considering that it had higher CPU usage. This should mean that the battery factor is also affected, as transferring more data, more power should be needed by the smartphone. This was shown in the results where the CPU usage was higher. Based on the tools we used, we cannot see if CPU usage is related to the transmission or the encoding process. It could mean that the range will not increase even though the CPU usage is higher, since the focus is on the encoding process.

7.2 Ethical considerations

Since the experiment measures the differences that the codecs have, there is a need to measure on different TWS to assure that the experiment will reflect the codec and not just the different hardware. The same could be said for the smartphone since it may be better suited for handling different codecs. A higher-performing smartphone might have better performance and make up for the difference between two codecs, while the different codecs have a bigger effect on cheap smartphones with weaker Bluetooth chips. However, to keep this study to a suitable level, it was opted only to use one smartphone and encourage others to use more devices to see the impact of using different smartphones in a future study.

As the range experiment was conducted at the school, the resulting data from the experiment might vary depending on how many people were present at each experiment (S. Humaid & I. Moustafa 2021). To minimize the casual ambiguity two TWS was used to ensure that it is not the hardware or software that is being measured instead of the codecs. Although, since other factors such as weather, propagation, and other present people are not controllable factors, it is uncertain if they will have an effect or not. Additionally, the smartphone implementation and optimization of the Bluetooth codecs are not something that can be changed and it is uncertain what effect they had on the results.

For both the experiments, due to the lack of TWS devices, it is hard to say if the results are representative of the majority of devices, especially since the experiments only focus on the Android. One might think that the results would stay the same if done with Apple devices, but this might not be the case since their structure and design differ. Subsequently, all smartphones have their different states, whether they are new or have years of use, it is hard to test for every scenario, and thus the results might be less generalizable.

Concerning the range experiment, since it was done in only one type of weather, the results might not apply to other weather scenarios. Furthermore, it is not possible to walk in a straight line every time consistently. Even though this may add an extra meter or so for the measurement, it would only be a problem if the aim were to compare more precisely. For there to be a difference in results, there has to be several meters difference between the codecs for the experiment to say one codec is better than the other. This is further proven by the ANOVA tests, which say that even though there is a numerical difference between the codecs, there is no significant statistical difference.

For the battery drainage and CPU usage experiment, there might be some minor variations in how long it took from starting the smartphone until starting the monitoring. All settings and commands had to be set and entered manually for each run. The setup process might differ a couple of seconds. The minor variations should not affect the results on the whole since the experiment spanned such a long period.

By having lower battery drainage and less CPU usage in hearing aids, the quality of life for the user may increase by extending the runtime of the device, for example, in cases where the user has trouble changing or remembering to charge the battery (Yedukondalu et al., 2016). A longer runtime means less interaction required and reduced stress and impact on the user's daily life. Alternatively, a more battery-efficient codec allows for the production of smaller devices. Depending on the user's ear shape and size, a smaller device might fit better and be more comfortable, leading to less physical stress on the ear. Furthermore, depending on the size of the devices, they might be more appealing to use for individuals since the device itself will be less noticeable or intrusive.

The arguments hold for bird monitoring as well, where a smaller size can be vital for the quality of the monitoring and well-being of the birds. A more battery-efficient codec allows for smaller bird monitoring devices. Smaller devices mean less physical stress on birds, especially smaller ones. If the physical stress is too much on the bird, it will render the monitoring useless as it is no longer an actual representation of its behavior (Magno et al., 2017). A more battery-efficient codec will enhance our ability to monitor birds to increase our knowledge and lessen our impact on the animals around us.

Furthermore, utilizing a codec with lower battery drainage, less electricity is needed to power and charge all devices with Bluetooth. It would not only be beneficial economically wise but also ecologically by lowering electricity consumption. A lower power consumption means less power production, which allows for a more sustainable society.

There are no previous studies in this specific area and all the data gathered for this project was done by the authors or were attributed. There was no need to consider factors such as confidentiality or informed consent since there were no human participants or subjects in either experiment.

7.3 Future work

The results found in this study show that the choice of Bluetooth codec does matter regarding CPU usage. The findings of this study concerning CPU usage go in line with Yadav & Ramasubramanian's (2014) conclusion that there is a difference between different codecs both in regards to battery drainage and CPU usage. However, the results collected in this paper show no significant difference in battery drainage. More research on other codecs is needed to determine this.

As this experiment is limited in both time and resources, several factors can be added to future studies. More codecs need to be included to understand its effect since different codes have different compressions and focus on different factors. Newer codecs may show bigger variations between each other since technologies have advanced since AAC and SBC were introduced. Comparing more codecs will increase the certainty of if the different codecs affect the CPU usage. More data is needed to prove if the observed difference in battery drainage and range is significant.

Similarly, more TWS devices are needed to further determine how much the actual codecs affect battery drainage, CPU usage, and range compared to the hardware and software in the devices themselves. Additionally, including smartphones of different brands and models, from the low-end to the flagships, may give a better overview of the field, as well as including Apple devices.

The quality of the audio is an important factor to consider. A codec that scores well on battery drainage, CPU usage, or range is only actually useful if the audio is of good quality. For example, measuring the frequency response of different codecs to see if there is any difference.

More environments need to be included to further generalize the results, especially for the range experiment. Location with more and less interference and different propagation characteristics should affect the connection, which in turn may affect how well the codecs function, as well as performing them under different weather scenarios.

The addition of using other data gathering methods, such as interviews or case studies, would complement the main experiment. They could bring more data from different perspectives such as real-life scenarios which would create a richer overview.

With all these added factors, there is a greater need of conducting the experiments on a bigger scale to achieve more generalizable results, both in terms of the number of samples but also due to the exponential increase in permutations. In addition, by increasing the sample size, the certainty of our findings will increase since more data is acquired as well as the risk of making a Type II error will decrease. The result would be that manufacturers and consumers can make better-informed decisions when it comes to which codec to use in their products or intended use case.

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Appendix A - Search terms

- Accuracy
- Audio
- Battery
- Bluetooth
- Codec
- Coder
- Consumption
- Distance
- Drainage
- Energy
- Localisation
- Localization
- Network
- Positioning
- Power
- Propagation
- Signal
- Sound
- Wifi

Appendix B - ANOVA

Anova: Single Factor						
Alpha	0,05					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
AAC	6	40,50	6,75	0,73		
SBC	6	42,10	7,02	0,57		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0,21	1,00	0,21	0,33	0,58	4,96
Within Groups	6,46	10,00	0,65			
Total	6,68	11,00				

Figure B-1 ANOVA runtime

Anova: Single Factor						
Alpha	0,05					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
AAC	6	96	16	3,6		
SBC	6	92	15,33	8,27		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1,33	1,00	1,33	0,22	0,65	4,96
Within Groups	59,33	10,00	5,93			
Total	60,67	11				

Figure B-2 ANOVA phone battery

Anova: Single Factor						
Alpha	0,05					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
AAC	6	50,42	8,40	0,47		
SBC	6	43,57	7,26	0,12		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3,91	1,00	3,91	13,33	0,0045	4,96
Within Groups	2,93	10,00	0,29			
Total	6,84	11				

Figure B-3 ANOVA CPU usage

Anova: Single Factor						
Alpha	0,05					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SBC	6	998	166,33	1177,07		
AAC	6	1182	197,00	637,60		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2821,33	1,00	2821,33	3,11	0,11	4,96
Within Groups	9073,33	10,00	907,33			
Total	11894,67	11,00				

Figure B-4 ANOVA range

Appendix C - Range – Wi-Fi

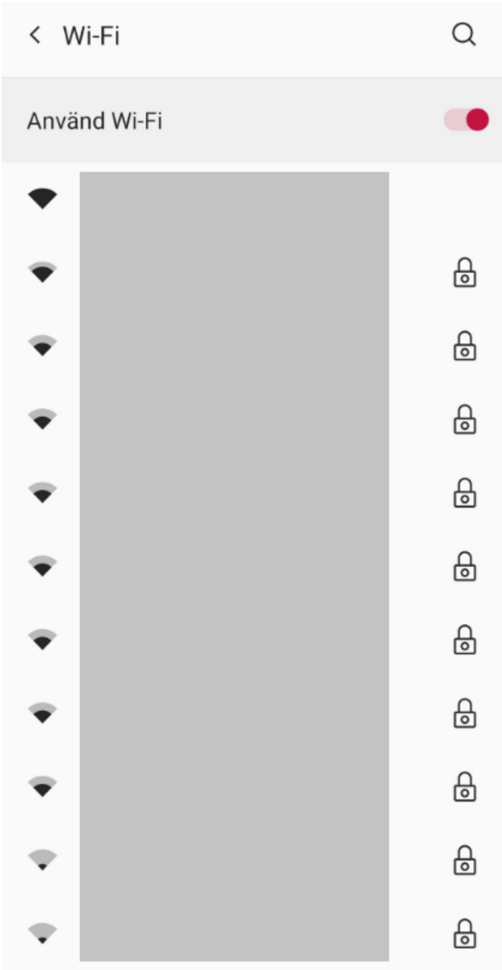

Figure C-1 Starting point Wi-Fi screenshot

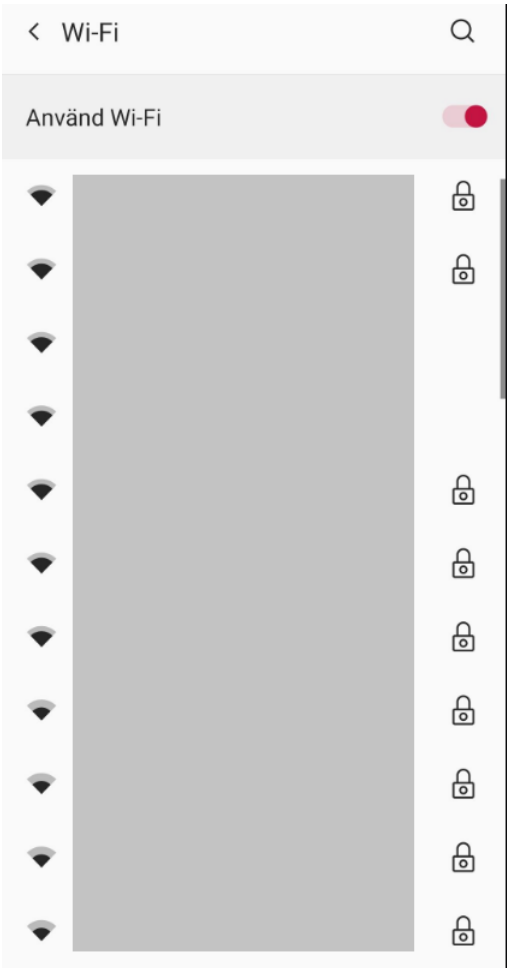

Figure C-2 Propagation point Wi-Fi screenshot