# PROPOSED METHOD FOR RECORDING AND ANALYZING CELL PHONE

# ADAPTIVE NOISE REDUCTION FILTERS

by

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Proposed Method for Recording and Analyzing Cell Phone Adaptive Noise Reduction Filters Thesis directed by Associate Professor Catalin Grigoras

# ABSTRACT

During cell phone conversations, the noises from the world around us can interfere with call clarity; noise being an unwanted sound that ruins the quality of the signal. One solution to minimize the noise is to utilize adaptive noise cancellation filters. The majority of cell phone manufacturers have implemented this technology [1][2] into their products, aiming to increase caller intelligibility by reducing ambient background noise. Many aspects of a cell phone's noise filtering features are proprietary, [3] which is unfortunate from a forensic standpoint. The algorithms used in many cell phone adaptive noise cancellation systems are kept private from the public.

There is a void in forensic audio analysis of cell phones [4]. Very little forensic research has been devoted to the experimentation of adaptive noise filters, especially in regards to their use in cell phones. Since a large number of cell phones utilize such filtering, it is important that the forensic community considers this key attribute offered in cell phones today. The adaptive filters' unique qualities could prove to be an asset to forensic sciences. This thesis provides indepth research into the performance of adaptive noise cancellation filters in cell phones and proposes methods to test and analyze them. A method to capture the adaptive noise filters via audio recording was tested and proven to be successful. In addition to this, signal to noise ratio (SNR) values were recorded and categorized by cell phone maker and model.

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# DEDICATION

I would like to dedicate this thesis to my friends and family.

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# LIST OF TERMS

# TERM

SNR - Signal to Noise Ratio

ANC - Adaptive Noise Cancellation

FFT - Fast Fourier Transform

Hz - Hertz

PCM - Pulse Code Modulation

SPL - Sound Pressure Level

#### **CHAPTER I**

## **INTRODUCTION**

The first active noise control system was patented in 1936 by developer Paul Lueg. Lueg's system [5] was known as the "Process of Silencing Sound Oscillation." Since then, active noise control systems have made their way into a variety of devices, most notably headphones, automobiles, and cell phones. In 2008, Audience introduced a development in cell phones that enabled them to utilize adaptive noise control in voice calls. The feature was aimed at improving caller intelligibility and reducing background noise [6]. Soon after the market began to change and adopted the feature for their products.

Noise cancellation is a feature that can be found in most cell phones. Depending on the manufacturer, the active noise cancellation can be referred to as "noise cancellation" or "noise suppression." Since this feature is so common, it is imperative to study the abilities and unique qualities of noise cancellation for forensic research purposes. This thesis considers seven different cell phones, as follows:

iPhone 6 iPhone 7 iPhone8 LG Stylo3 LG K20 Samsung S6 Samsung S9

## Background

The purpose of noise cancellation in a cell phone conversation is to increase caller clarity and reduce background noise. Cell phone conversations occur in a multitude of acoustic noise environments and as a result, cell phone conversation can be plagued with unwanted background noise that can deteriorate the call quality.

The solution is to use adaptive noise cancellation. For noise cancellation to be possible a cell phone needs to have multiple microphones to access the incoming signals. The first cell phones to offer adaptive noise cancellation did not have an additional microphone. Headphones were needed to activate the feature by providing a second microphone. Later designs in the early 2010's provided a microphone array for filtering. Often times, a cell phone manufacturer will license through a third party to develop the active noise canceling application. Like how Apple used the company Cirrus Logic to develop audio chips for their product [7].

Since cell phone manufacturers, such as Apple and Samsung, use a proprietary algorithm [6] for their products noise cancellation feature, this could indicate that different cell phone manufacturers adaptive noise cancellation filters would hinder different results in caller quality. An analysis of the speech quality could help identify cell phone brand or manufacture. SNR can be used as a mathematical measurement of filter quality. This could offer a way to identify a cell phone by brand or model. Recording SNR values in how they pertain to cell phone brand and model is beneficial for forensic research, since the data could later be used in a database for further forensic research.

Some notable third-party companies that produce adaptive noise cancellation technologies for cell phone manufacturers and their chipsets include:

Qualcomm Snapdragon

Audience A1010 Voice Processor

#### Cirrus Logic

A large number of cell phone's utilize Qualcomm Snapdragon chips. which offers an adaptive noise cancellation feature [8]. However, it appears that the cell phones user interface might be responsible for the features and quality of the adaptive noise filter. For instance, Sony offers an adaptive noise cancellation filter that allows the user to change the setting based on the type of noisy environment they are in [9]. This feature seems to be unique to the Sony Xperia user interface. The Samsung's user interface no longer allows the user to turn on or off the adaptive noise cancellation filter. Cell phone manufacturers develop their own user interfaces to control and change how the Operating System performs certain tasks [10].

#### **Scope and Limitations**

The scope of the proposed methods has been limited to three individual cell phone manufacturers. LG, Apple, and Samsung. The limitation of this study is that it has not yet categorized cell phone brand by the chipsets. In addition, this thesis does not actively assume which algorithm for adaptive filter a manufacturer uses. It does attempt to interpret and record key attributes in a cell phone manufacturers' use of adaptive noise cancellation filters.

#### **CHAPTER II**

# ADAPTIVE NOISE REDUCTION FILTER

#### **Introduction Into Filters**

The term "filter" is a derivative of the electrical engineering world, where a filter performs a transformation of an electrical signal into something different [11]. The point of using a filter is to remove unwanted parts of a signal. The unwanted signal could be noise or a certain frequency range. For this paper, we can separate filters into two different categories known as fixed and adaptive filters. A fixed filter estimates the input signal and removes the unwanted noise and is dependent on prior knowledge of the input signals. Since prior knowledge of the noise characteristics is vital in the design of a fixed filter, it limits the filters used in a real-life scenario. For instance, a fixed filter would yield minimal results in filtering out the noise of a busy city, since the noisy environment of a city generally has constantly changing noise. However, adaptive filters require minimal or no prior knowledge of the input signals' noisy characteristics. This makes adaptive filters perfect for noise cancellation applications. [12]

#### **How Adaptive Filters Work**

Figure 1 shows a general layout for an adaptive filter, with x(k) being the input signal, d(k) being the desired response, h(k) being the impulse response of the filter, and y(k) being the filtered output. If filter x(k) filtered we get y(k), we subtract y(k) from the desired input d(k). This would result in e(k)[13]. From there, we pass the signal into a coefficient adjustment algorithm, labeled in figure 1 "Adaptive Algorithm." After the signal passes through the adaptive algorithm, it is fed back into the adaptive filter to make an adjustment to the signal coefficients. In essence, it changes how the filter is filtering the signal. The coefficients in an adaptive filter are the various impulse responses from the signal, the most common algorithms being least mean square, recursive least square and normalized least mean square.



Figure 2.1 Adaptive Filter Signal Flow

# **Adaptive Noise Cancellation Filters In Cell Phones**

Adaptive noise cancellation filters acclimate to the noise of the changing environment and filter out unwanted sounds. Adaptive noise cancellation works by utilizing two inputs, which are the primary and references inputs [13]. An adaptive noise cancellation filter application on a cell phone can be demonstrated in figure 2 - ANC Signal Flow. The primary signal in a cell phone conversation should be comprised of the caller's voice, and the background noise would be comprised of a noisy city street. The background noise is decreasing the intelligibility of the caller's voice. The reference input is now comprised of the source of the noise. It is important to note that the reference input noise source has no relation to the caller's voice; the noise source is associated with the noisy city street. The noise source is passed through an adaptive filter where it produces a filtered output noise. The filtered output noise is then subtracted from the primary signal and creates a desired output signal.



Figure 2.2 ANC Signal Flow

# **Adaptive Filter Algorithms**

There are many different types of algorithms used for adaptive filters. The most common types consist of LMS (least mean square), NLMS (normalized least mean square), and RLS (recursive least square) [14]. The implementation of the algorithm is used to generate desired results. Different algorithms poses both wanted and unwanted outcomes. In the study *Analysis of Adaptive Filter Approach for Speech Enhancement Using Simulink, International Journal of Advance Research, Ideas and Innovations in Technology* [15], the authors found that the RLS algorithm provides a faster and smaller error rate when processing coefficients in an unknown setting. The RLS algorithm was recommended for adaptive filtering. The study *Comparison between Adaptive filter Algorithms* (LMS, NLMS and RLS) [16], also found the same results involving the RLS algorithm, and recommended this algorithm for speech enhancement adaptive

filters. It is important to understand the attributes of these algorithms due to the fact that they play a crucial role in the adaptive filter design.

# **CHAPTER III**

# **CELL PHONE LAYOUT**

## **General Cell Phone Microphone Layout**

Most cell phones contain an array of microphones in order to record the multiple signals involved in a phone call and active noise reduction. Figure 3 demonstrates a general layout for a cell phone's microphone array. The microphone on the bottom is used to record the voice signal while the microphone at the top of the phone near the camera is used to record the noise signal source. In figures 4-10 we can see the general microphone array layout for iPhones, LG, and Samsung cell phones. This appears to be the optimal layout for a cell phone microphone array.



Figure 3.1 General Cell Phone Microphone Array

# **Apple iPhone**

Apple first introduced the noise cancellation feature on the iPhone 4. Since then, various brands have implemented the noise cancellation or reduction feature in their devices. Apple licensed the company Audience A1010 Voice Processor [17]. However, as of 2010, Apple has employed the company Cirrus Logic to develop their noise reduction chips. This thesis examines the adaptive noise cancellation filter for the iPhone 6, iPhone 7 and iPhone 8. The microphone layout in figures 4, 5 and 6 shows the basic layout used. One microphone is located at the bottom of the phone and the other two microphones are located on the top of the phone.



Figure 3.2 iPhone 6 Microphone Array. By <u>https://www.att.com/devicehowto/index.html#!/devicediagram?make=Apple&model=iPhone6</u>







Figure 3.4 iPhone 8 Microphone Array. by https://www.apple.com/iphone-8/specs/

LG cell phones utilize Qualcomm Snapdragon processor chips for active noise cancellation filtering. For this study, an LG Stylo 3 and K20 phone were examined. Their microphone arrays are shown in figures 7 and 8. In LG cell phones, the noise cancellation filter is referred to as "noise suppression." Please note that the microphone array in figure 3.5 dictates that the LG Stylo 3 only has one microphone. This could indicate that only one microphone records both the voice signal and the background noise signal.



Figure 3.5 LG Stylo 3 Microphone Array by LG Stylo 3 manual

# Top and Bottom Views Wicrophone Headset jack Microphone Microphone Microphone

Figure 3.6 LG K20 Microphone Array by LG K20 manual

## Samsung

Samsung deploys Qualcomm Snapdragon chips into their devices, is responsible for the adaptive noise cancellation. Previous Samsung Galaxy phones used to allow the user to specify if they would like to use noise suppression or not. This was provided by a toggle switch in the call setting menu. With the introduction of the Samsung Galaxy S6, this option is no longer available. All Samsung cellular products now have the noise suppression turned on by default. This information was provided by Samsung customer support. The noise suppression features were tested on Samsung Galaxy S9 and Samsung Galaxy S9. Figure 9 demonstrates the microphone layout for Samsung Galaxy S6, and figure 10 demonstrates the microphone layout for Samsung Galaxy S9. Both phones utilize a microphone on the bottom and the top.





Figure 3.8 Samsung Galaxy S9 Microphone Array by Samsung Galaxy S6 manual

#### **CHAPTER IV**

## TESTING

It is imperative to implement and test a cell phone's adaptive noise cancellation feature in different environments. Two tests were conducted for the purpose of this thesis. Both Test 1 and Test 2 were replicated three different times with the adaptive noise cancellation feature on and off. This was done for comparison reasons. Two cell phones were needed to conduct the test. Cell Phone A represents the caller's cell phone. Cell phone B represents the receivers signal cell phone. To acquire the recordings the application an named Another Call Recorder by the company NLL APPS was installed on the receiver signal cell phone. To mitigate, bias both tests were deployed in different locations and studios. It is important to note that cell phone noise cancellation feature needs to signal to have both sources active at the same time. The first signal was the caller's voice and the second signal was the noise. In addition, it is important to note that Samsung cell phones models from Galaxy S4 to Galaxy S5 allow the consumer to turn the active noise cancellation on and off. However, turning adaptive noise cancellation off for Samsung Galaxy S to S9 was not an option due to the fact that the noise suppression feature is built into the phone. Without the option to turn it off. This was confirmed by Samsung Technical Support.

Both tests were modeled after the tests found in the studies *Dual-microphone noise reduction for mobile phone application* [18], and *Background Noise Reduction Design for Dual Microphone Cellular Phones: Robust Approach* [19]. Both studies aimed to test the adaptive noise filter of a cell phone and its enhancement quality of a caller's speech. *In Dual-microphone noise reduction for mobile phone application*, the approach to testing was to record and compare the adaptive noise filter of a cell phone in three different live scenarios. The first scenario was recorded in an office space, the second was recorded in a cafeteria, and the third scenario was recorded in a bus. In *Background Noise Reduction Design for Dual Microphone Cellular Phones: Robust Approach*, the approach for testing was to examine different cell phones' adaptive filters in a lab scenario. Noise generators were introduced in different locations while the source cell phone recorded the noise and filtered it out. These two tests provided a fantastic approach to produce and examine a cell phone's adaptive noise filter. The live and lab testing influenced the approach in the following test; Lab testing and Live Scenario Testing.

# Lab Testing

The laboratory test consisted of playing a broadband noise labeled as "Master Waveform" over loudspeakers, while a human spoke into cell phone A. Cell phone A transmitted the signals to Cell phone B, where the application Another Call Recorder recorded the signals. Each sample recording consisted of 20 seconds. Seven different cell phones were used in Test 1. Each cell phone was recorded 3 times with the noise cancellation filter and 3 times without. In addition, the source cell phone was recorded at two different volume levels. The first volume level for the Master Waveform was set at 70 dBa. 70 dBa fs would be the average volume level for a noisy environment [20], such as traffic and that of everyday life. The second volume level for Master Waveform was set at 80 dBa. 80 dBa fs would be the above average volume level for a noisy environment like a vacuum cleaner or garbage disposal. Please note that a volume threshold is needed to trigger the noise cancellation filter. All volume dB limits were measured with an SPL meter at A weighted scaled.

The Master Waveform was needed to simulate a controlled noisy signal. White noise was used as the noise due to the fact that it disperses noise evenly across the frequency spectrum [21.] In addition to this, impulses were added at the 1-second and 19-second mark to help create a reference for future synchronization.

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lms 1.0		1.0 ·				0.0 1				8.0 1 <sup>.</sup>	
$\rightarrow$											_

Figure 4.1 Master Signal

ARC recorded all test recordings at 16bit, 44100 kHz, WAV PCM. Cell phone communication only transmits at the frequency range of 8bit 8 kHz. This reaction then caused all sample recordings to be downsampled to 8bit, Wav PCM, and all redundant data above 8 kHz to be removed. Comparison of the difference between the noise cancelation filter being turned on or off and by manufacture model can be seen in Chapter 5. To mitigate bias, Test 1 was performed at different labs in different parts of the country. The main location for lab testing was performed in Denver, CO Other locations included Colorado Springs, CO, Davis, CA and Berkeley, CA. The replication of Test 1 in different environments hindered similar results.

## Live Scenario Testing

The implementation of the live scenario testing was performed to replicate the methods of the lab test in a real-life scenario. The caller's cell phone was operated by an individual providing the speech signal. The noise signal is the natural acoustical environment of the marketplace. Implementation of a real-life scenario was performed at a marketplace during rush hour, which can result in a volume level of 70 dBa. The same method of recording between the caller's cell phone and the receiving cell phone from the lab test was replicated in the live scenario. Each cell phone recorded three 20-second test recordings with the noise cancellation filter off. Since playing broadband noise is not possible in a public location, a twenty-second sample was recorded as an exemplary

reference noise sample. In addition to this, clicks by a finger-snap were implemented into the background at the 1-second and 19-second mark of test sample recordings. This was done to mimic the impulses in the Master Waveform from the lab test for synchronization in later analysis. Results for the real-life scenario can be seen in chapter 5.

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#### **CHAPTER V**

## ANALYSIS AND RESULTS

All sample recordings from the lab test were imported into Adobe Audition, where each sample recording was synced in the timeline by utilizing the impulses at the 1-second and 19-second mark. After syncing, all test recordings were trimmed to 20-second increments. All recordings from the Live Test were also imported into Adobe Audition. The Live Test recordings do not have impulses at the 1- and 19-seconds marks. They were synchronized by the snaps at the beginning of the live test recordings.

In addition to trimming, all test recordings underwent a speech signal removal process. Figure 12 demonstrates the test recording in its full form. Figure 13 represents the test recording after the speech signal was removed. Removing the speech signal from the sample recording allowed further analysis of the effects of adaptive filter on the noise signal in the original sample recordings.



Figure 5.1 Sample Recording Before Speech Removal



Figure 5.2 Sample Recording After Speech Removal

# Spectrogram

A spectrogram is a great way to capture and visualize the adaptive noise filter at work. The spectrograms in figures 5.3 and 5.4 are from two recordings made by an LG Stylo by utilizing test/method 1. The recording in figure 5.3 is with noise cancellation and the recording in figure 5.4 is without. In figure 14, we can see that the noise is evenly reduced as indicated by the breaks in the red color. This tells us that the noise is filtering out the noise signal and allowing the voice signal to pass through. We can also see these results for the test recordings in figures 5.5 and 5.6.



Figure 5.3 LG Stylo3 With Noise Suppression



Figure 5.4 LG Stylo3 No Noise Suppression



Figure 5.5 LG K20 With Noise Suppression



Figure 5.6 LG K20 No Noise Suppression

## **SNR Results**

SNR or Signal to Noise Ratio was used to plot every test cell phone with and without the adaptive noise filter on and off. Similarly, in the paper *Dual-microphone noise reduction for mobile phone application* [18], the authors used SNR to analyze the SNR relationship between their test cell phone's adaptive noise filtering. For the SNR analysis, it was important to compare an SNR relationship between a cell phones noise-canceling feature turned on and off. In addition, the SNR was compared between different cell phone brands. The SNR helps to apply a calculated representation of the ANC filter in use over time.

Figures 16 to 45 plots signal to noise over time against the originally recorded sample. SNR averages between cell phones and volume threshold, in relation to the adaptive noise filter on vs off can be seen in figures 18 through 23. In addition to this SNR average values of the sample, recording can be seen in tables 5.1 through 5.6. The error bar in the following figures 5.1 through 5.6 represents the standard deviation.



Figure 5.7 SNR Averages at 70 dB



Figure 5.8 SNR Averages at 80 dB



# Figure 5.9 SNR Averages Live



Figure 5.10 SNR Averages of Noise at 70 dB



Figure 5.11 SNR Averages of Noise at 80 dB





# Tables

Table 5.1	Average	SNR	Values	at	70	dB
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	ANC_on_SNR	ANC_off_SNR
iPhone б	33.1707	35.0946
iPhone 7	25.3598	32.0819
iPhone 8	32.9037	33.1431
LG Stylo3	18.9703	31.9403
LGK20	36.6622	34.3940
Samsung Galaxy S6	34.9594	N/A
Samsung Galaxy S9	21.9771	N/A

# Table 5.2 Average SNR Values at 80 dB

	ANC_on_SNR	ANC_off_SNR
iPhone б	33.1707	35.0946
iPhone 7	25.3598	32.0819
iPhone 8	32.9037	33.1431
LG Stylo3	18.9703	31.9403
LGK20	36.6622	34.3940
Samsung Galaxy S6	34.9594	N/A
Samsung Galaxy S9	21.9771	N/A

# Table 5.3 Average SNR Values Live

	ANC_on_SNR	ANC_off_SNR
iPhone 7	25.1318	26.1005
LG Stylo3	38.2109	41.2942
LGK20	49.2333	51.2349

	ANC_on_SNR	ANC_off_SNR
iPhone б	10.9489	11.3862
iPhone 7	6.2233	7.7634
iPhone 8	7.3209	9.3229
LG Style	5.2909	4.1179
LGK20	5.0634	6.5641
Samsung Galaxy S6	6.0795	<b>N/A</b>
Samsung Galaxy S9	6.3012	N/A

Table 5.4 Average SNR Values Noise of 70 dB

Table 5.5 Average SNR Values Noise of 80 dB

	ANC_on_SNR	ANC_off_SNR
iPhone 6	9.1001	11.4825
iPhone 7	6.5654	9.2167
iPhone 8	6.7051	11.7282
LG Stylo3	1.5742	2.8837
LGK20	5.0634	19.6365
Samsung Galaxy S6	10.3680	N/A
Samsung Galaxy S9	8.1867	N/A

Table 5.6 Average SNR Values Live Noise

	ANC_on_SNR	ANC_off_SNR
iPhone 7	6.9273	7.0534
LG Stylo3	6.5650	9.2167
LGK20	16.4150	16.0683

#### **FFT Analysis**

The Fast Fourier transform (FFT) is a mathematical expression that can be used to convert an audio signal from the time domain to the frequency domain [22]. This allows us to visualize an audio signal through frequency (Hz) over gain (dB). Where frequency utilizes the x-axis and gain(dB) utilizes the Y-axis, as displayed in figure 5.14.

All background noise samples discussed previously in this chapter were processed through FFT analysis. Each recording was classed into categories by phone, adaptive noise filter setting and volume threshold of the noise. For instance, iPhone test samples that were recordings at 70 dB were compared between the adaptive noise filter being on and off. The blue frequency in figures 5.14 through 5.19 represents the FFT frequency analysis with the adaptive noise filter on, where all red frequencies in figures 5.14 through 5.19 represent the FFT frequency analysis with the adaptive filter off.



Figure 5.13 FFT iPhone 6 80 dB ANC On vs Off



Figure 5.14 FFT iPhone 7 80 dB ANC On vs Off



Figure 5.15 FFT iPhone 8 80 dB ANC On vs Off



Figure 5.16 FFT iPhone 7 Live ANC On vs Off



Figure 5.17 FFT LG K20 80 dB ANC On vs Off



Figure 5.18 FFT LG K20 Live ANC On vs Off

#### **CHAPTER VI**

#### CONCLUSION

With the lab test, it is apparent that after analyzing the SNR average values and viewing a spectrogram that one could detect if a cell phone has the adaptive noise filter or noise cancellation on or off. For instance, the LG Stylo3, at 80 dB, has an increase in its SNR when noise reduction is off. This would indicate that the noise is bleeding into the desired signal of the sample recording. One can see similar results with the plotted SNR in figures and tables listed in Chapter 5. The lab test hindered similar SNR average differences between filter being on and off across all test cell phones. The increase in SNR average when the adaptive noise filters off makes sense, due to the fact that more of the noise signal is not being suppressed.

The FFT analysis of the noise signals also yielded some interesting results. All iPhone cell phones' noise samples performed a consistent dip at 4,000 Hz and remained at a volume level of around 120 dB. We can see this consistency between all iPhones in figures 5.15, 5.16, 5.17 and 5.7. All other phones veered inconsistently around different volume levels, except for the LG K20. The LG K20's FFT analysis proposed some interesting results. A spike in volume around 12000 HZ and 20000 HZ can be seen in figures 5.18 and 5.19. Figure 5.18 was from a noise sample that was recorded in the lab testing. Where figure 5.19 was from a noise sample that was recorded in the live testing. No other phones created these unique spikes.

In addition, spectrogram analysis of the LG Stylo3 in figures 5.3 and 5.4 clearly demonstrated a visual representation of the adaptive noise filter in action. We can also see this in the LG K20 in figures 5.6 and 5.7. The noise-only samples from the test recording further demonstrated that the method was successful in indicating whether the adaptive noise filter was

on or off. The SNR averages showed a clear increase in dB when the filter was switched off, as seen in tables 5.1 and 5.2.

It should be noted that the LG Stylo3's SNR performance was poor and inconsistent at times. It seemed that the higher the simulated background noise the worse the filter performed. The SNR average values in figures 5.4 and 5.3 were drastically different than the other six phones. This may be due to the fact that the LG Stylo3 does not possess a second microphone to attain the noise signal. Intense noise reduction is needed in a single microphone system, which can result in lower speech quality [23].

The method discussed in the live scenario tests yielded mixed results. Live recordings were tested on an iPhone 7, LG Stylo3 and LG K20. With the live testing of the LG K20, very little differences in SNR averages were recorded. Unfortunately, spectrogram analysis was unsuccessful in detecting differences in adaptive noise reduction filter being turned on or off.

The iPhone 7's noise sample generated similar results in the FFT analysis, however, the FFT analysis of the Live Scenarios iPhone 7 noise sample generated similar results to the lab test's iPhones. The Live Test scenario of the iPhone 7 demonstrated a frequency dip at for 4000 HZ and a consistent volume level of around 120 dB.

After finalizing all testing, it would appear that in order to fully detect whether adaptive noise canceling is on or off, the dB level would have to be at a high level. The higher the volume threshold, the more active the noise filter. Test recordings in the lab test with volume levels of 70 dB were concluded with very little results. However, when volume levels were increased to 80 dB, the effects of the adaptive noise filter could be seen and recorded.

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Since the proposed method of capturing the adaptive noise cancellation filter in action is obtainable, further research into categorizing cell phone SNR values by manufacturer and model is possible for forensic use.

#### **CHAPTER VII**

# **FURTHER RESEARCH**

Since adaptive noise cancellation filters are prevalent in most cell phone brand and models. It would be neglectful of the forensic scientific community to ignore such a key attribute. The proposed methods from chapter 4 could be utilized to test other cell phone manufacturers. For instance, cell phones from manufacturers like Sony, Google and HTC, Asus and Huawei were not tested for this thesis. All of these brands offer a noise reduction feature and need to be analyzed in similar manners listed in chapter Five. It seems that SNR values of the noise reduction filters exhibits unique qualities in relation to cell phone models and brands. FFT analysis of the noise signal also provided some unique characteristics. Further forensic research of this subject is needed. A creation of a database that recorded SNR and FFT results could lead to advancements in cell phone forensic audio analysis. A subject in forensic science that is vastly overlooked.

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