Fourier Analysis of Smartphone Call Quality

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Abstract

In recent decades, the cell phone has provided a convenient form of long-distance communication to the general public. Despite the technological improvements since, cell phones and their smartphone successors have suffered from a lack of clarity over a typical voice call, a result of their limited bandwidth. New phone services, such as HD-Voice and VoLTE, are meant to improve the bandwidth that cell phones can use. This claim was tested in part by performing Fourier analysis on cell phone calls that transmitted white noise from one phone to another, where the receiving phone played the surviving signal to an oscilloscope via microphone. The waveform the oscilloscope records was then Fourier transformed to reveal what frequencies were allowed in transmission. This paper reports on the results of one phone of the conversation having HD-Voice and VoLTE, as well as neither phone having these.

Contents

Chapter I – Introduction

1.1 Purpose

Cell phones have been improving technologically ever since they were introduced in the 1970s, leading to the smartphones we have now. Originally, they were designed solely for allowing a conversation between two distant people. Cell phones now include features not unlike those of contemporary personal computers. However, the quality of the phone call, the device's original purpose, seems to be as poor as ever. That is, until the release of some new services: HD Voice and VoLTE (Voice-over LTE (Long-Term Evolution)). Because we know already why call quality is low without these services (see next section), the purpose of this research is to examine the allowed frequencies—and signal strengths of those frequencies—before and after the addition of the new services.

1.2 Low-Quality Sources

On average, humans can hear a range of frequencies from 20 to 20,000 Hz, and our voices can reach between 200 and 9000 Hz. When cell phones first came into play, though, the full range was deemed superfluous for calling and leaving the voice comprehendible. Therefore, cell phones were designed to transmit frequencies from 300 to 3400 Hz. Cutting out the other frequencies reduced the amount of information that would have to be transmitted and reduced the Nyquist frequency, thus easing the load the cellular networks would have to work with. The Nyquist frequency is the sample rate the phone needs to interpret the correct frequency, and is twice the highest frequency being processed, which Nyquist himself had rounded up to 8000 samples per second [1]. Whether the frequency range of cell phones runs up to 3400 Hz or 4000 Hz varies between sources (most claim 3400, what cell phones were designed for), it is less than the 9000 Hz our voices can reach and far less than the 20,000 Hz our ears can perceive. This is the primary reason why cell phones, including smartphones, have such low quality over voice calls; they are not picking up all the frequencies that make up our voices or that we can hear. Phones with this restriction have already been tested by Horacio Aguilar, and the results, shown in Figure 1, agree with these findings [2]. More details on the methodology can be found in Chapter 2.

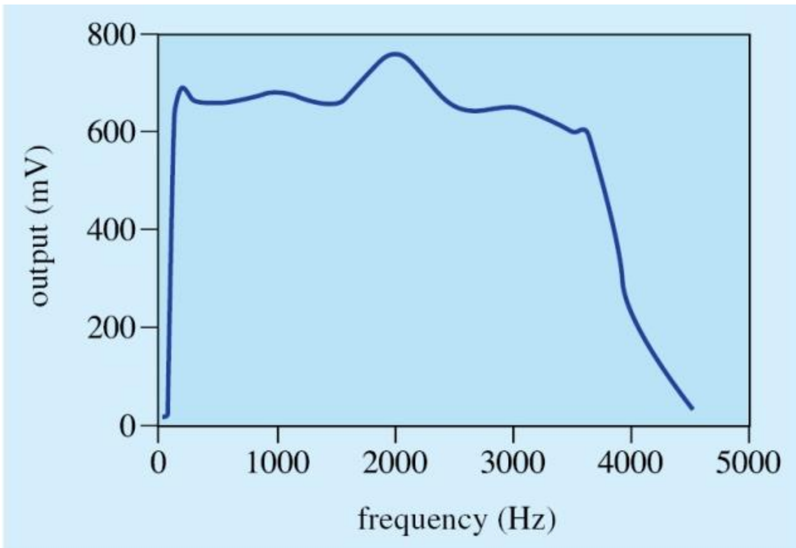

Figure 1: Two Samsung S3s tested, with an oscilloscope measuring the output strength of each frequency out of the receiving phone. [2]

The way the information is transmitted also reduces quality. According to computer and electrical engineering professor Jerry Gibson, the base stations, which cell phone calls are processed by, are limited on how much information they can process at once [3]. This results from the base stations use of circuit-based switching. When phones first came into public use, human operators were needed to literally plug one phone line to another to connect a call. This completed the circuit required to communicate between two calls. The process in the base station is similar, only it is run by computer and uses more modern technology. Despite the improvement in technology, the nature of the system has a limitation on how much information can pass through a station at any given time. So, the stations consider how loaded they and their neighbor base stations are and allocate their bandwidth accordingly. This is done conservatively to prevent ongoing calls from being dropped and incoming calls from being blocked, which results in a decrease in quality, and, depending on how busy the nearby base stations are, the quality of a given phone call may be lowered further still to make room for other calls [3].

Yet another possible reason for poor quality is the hardware, namely the speakers. Despite all the improvements made to cell phones over the decades, no one has taken much time to improve the speakers themselves. This is likely because the rest of the phone was designed for the same quality as the speakers, and so improving the speakers would have resulted in almost no change in voice fidelity. Focus was instead diverted to other features smartphones are more well known for, such as streaming videos, playing games, taking pictures, and texting, to name a few. My own smartphone, for example, has two sets of speakers: one for calling, and one for everything else—and I have always found the media speakers to rival those of my computer, whereas the call speakers, limited to whatever remaining space was allotted to them, seem to be of the same quality as the flip-phone I have had since 8^{th} grade.

1.3 Quality Improving Services

With the advent and continual improvements of smartphones, one would think the quality of the primitive voice calls would also improve. But in recent years, two add-on services—HD Voice and VoLTE—have been introduced that may finally provide the first major improvement in the call quality of smartphones.

1.3.1 HD Voice

HD Voice provides an increase to the bandwidth of audio frequencies the phone will be allowed to send. There are several levels of HD Voice, each varying in how much the bandwidth is improved; wideband speech (WB) covers around 50 to 7000 Hz and super-wideband speech (SWB) includes frequencies up to 14 kHz. These are two considered intermediate steps towards full band speech (FB), which would allow the entire 20-20,000 Hz range to be transmitted [4]. While the improvements this would provide should be obvious, the reality is HD Voice rarely comes into play. Because cell phones still use the same circuit-based switching technology, whether they have HD Voice or not, this service only applies to calls between two HD Voice users, and only those on the same network [5].

1.3.2 VoLTE

The other add-on takes a different approach. Instead of just changing the bandwidth of the transmission, Voice-over LTE (VoLTE) takes the call online, transmitting the data in packets over the Internet, rather than sending it through the circuits and switches used previously. With all the free space available, data need not be reformatted in processing [5]. No loss of data means higher quality. This extra available data space of course would also allow for the bandwidth to incorporate the entire audible spectrum, i.e. VoLTE could aid the implementation of HD Voice, as some networks have exploited (as will be seen later). Like HD-Voice, however, it seems to be limited to calls within networks, except Verizon and AT&T allow VoLTE communication between their networks [6].

1.3.3 HD Voice and VoLTE Reliability

It may seem like, between HD Voice and VoLTE, all problems should be solved, but problems persist nonetheless. First, these add-on services have yet to be fully implemented; only some service providers provide these services, and may not demonstrate they are provided. I have already made mention to how HD Voice only works in special cases. Furthermore, HD

Voice has only been tested in a subjective, qualitative survey based solely on people's personal opinions [4], and VoLTE remains untested entirely. Therefore, testing these services was the focus of this experiment that differentiates it from research past.

Chapter II – Methodology

2.1 Fourier Analysis

Our primary analysis tool is Fourier analysis. Fourier theorem states that any wavelike function can be decomposed into constituent harmonic sinusoidal waves, each with its own unique frequency. The sum of these isolated frequencies make up the Fourier series. By using the fast Fourier transform (FFT)—a computer algorithm that quickly calculates the Fourier series—we can quickly determine what frequencies compose a signal—a voice, for example—that enters or leaves a phone's microphone. In this way, we determine which frequencies make it through even if we send many frequencies at once. For instance, white noise is a superposition of all frequencies with equal amplitudes, and is available on both of our tone generator apps.

To ensure best quality, our setup is similar to that of Aguilar's [2], but with some key differences. In Aguilar's experiment, the test phones were plugged directly into the oscilloscope and a waveform generator, eliminating the error and noise that would be picked up from the surroundings as the sound travels through the air. In this experiment, the sending phone will be playing a frequency or set of frequencies from a tone generator app, and the receiving phone plays whatever comes through to a microphone plugged into the oscilloscope, which displays the signal and FFT. These can be stored on a flash drive for further analysis later. By saving the waveform, we can process an FFT using Mathematica for comparison with the oscilloscope's FFT. Afterwards, we simply compare the relative intensities of the various frequencies to see which frequencies are transmitted well and which are sent poorly—or not at all.

Early equipment tests show, despite any noise present, the tested frequency is detected by the oscilloscope when using one phone's tone generator and one microphone (no calling). In addition to single-frequency tones, we primarily utilized sets of frequencies, like white noise, to observe multiple frequencies simultaneously. Figure 2 shows the FFT from the oscilloscope during a test tone of 10 kHz.

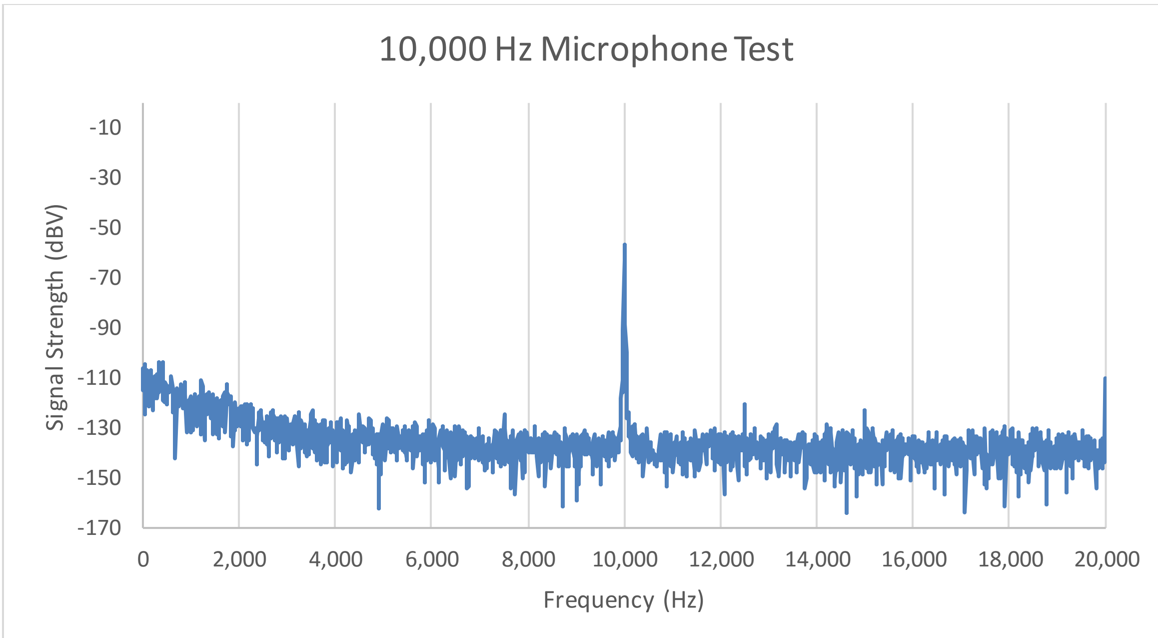

Figure 2: Testing the mircophone, oscilloscope, and tone generator at 10,000 Hz.

2.2 Equipment

The oscilloscope we used is an InfiniiVision DSO-X 2012A by Agilent Technologies, and the microphone is a 33-2001A from Radio Shack. My phone is a Droid Turbo 2 and Dr. McIntyre's is an iPhone 5s, both with Verizon coverage. I also borrowed someone else's phone, a Galaxy S7, and made use of my (Android) Lenovo tablet and McIntyre's iPad. The tone generator on my phone and tablet is Audio Test Tone Generator by Digital Antics and McIntyre's is SimplyNoise by Reactor LLC. Due to technical difficulties on the Galaxy, only my phone has HD-Voice and VoLTE capabilities (these services are coupled for Verizon [7]).

Chapter III – Results and Discussion

3.1 Results

In all following tests, Figures 3-5, the white noise was played off one device into another (either an iPhone or landline) that was in a call with my Android. The Android had HD-Voice and VoLTE enabled. The results are overlaid with the appropriate raw white noise signal(s), though no normalization has taken place.

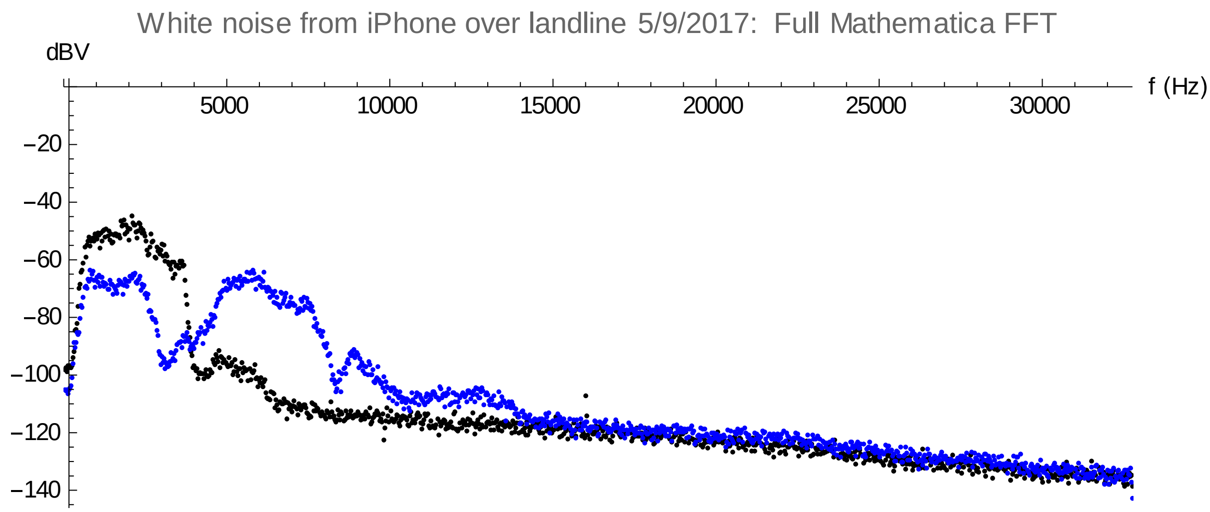

Figure 3: Blue: white noise from iPhone.
Black: the signal after being played into landline calling Android..

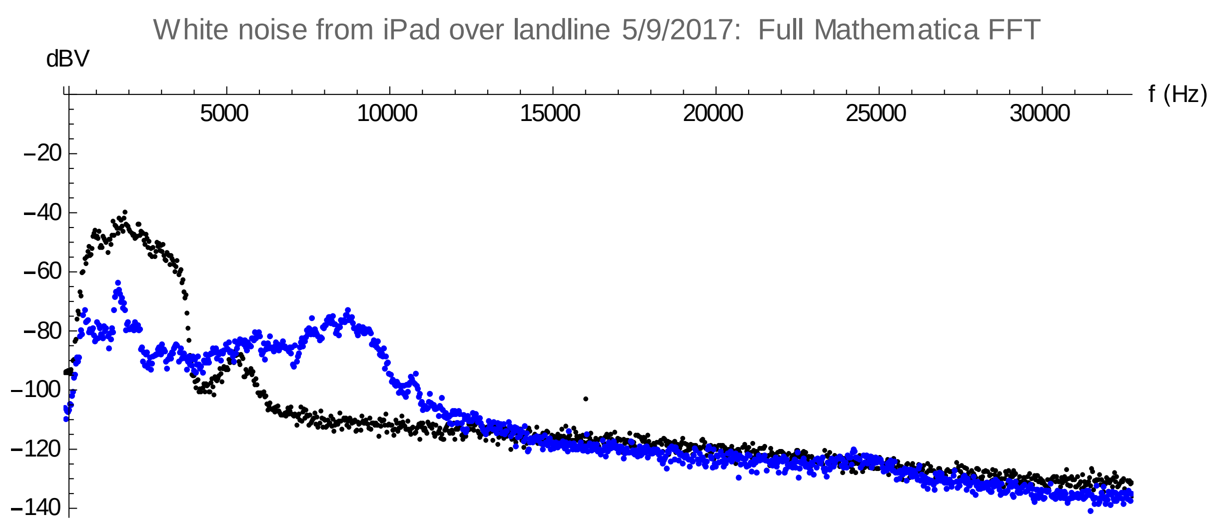

Figure 4: Blue: white noise from iPad.
Black: the signal after being played into landline calling Android..

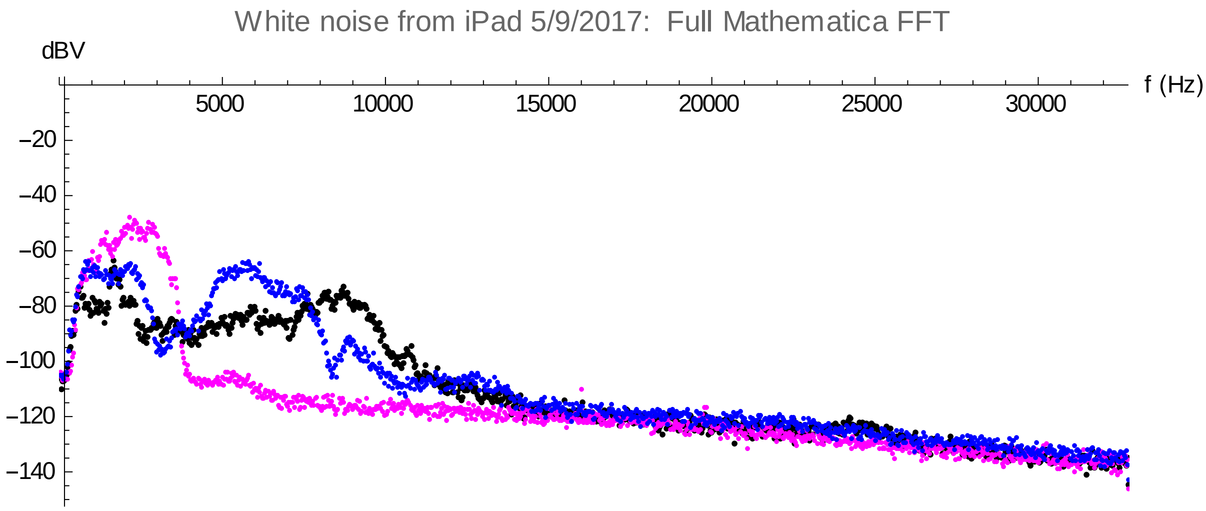

Figure 5: Blue: white noise from iPad. Black: white noise from iPhone.
Magenta: white noise from iPad after being played into iPhone calling Android.

I performed another test wherein I called a test number from my Android smartphone, played white noise from my Android tablet, and had that signal played back over the call. The result is displayed in Figure 6.

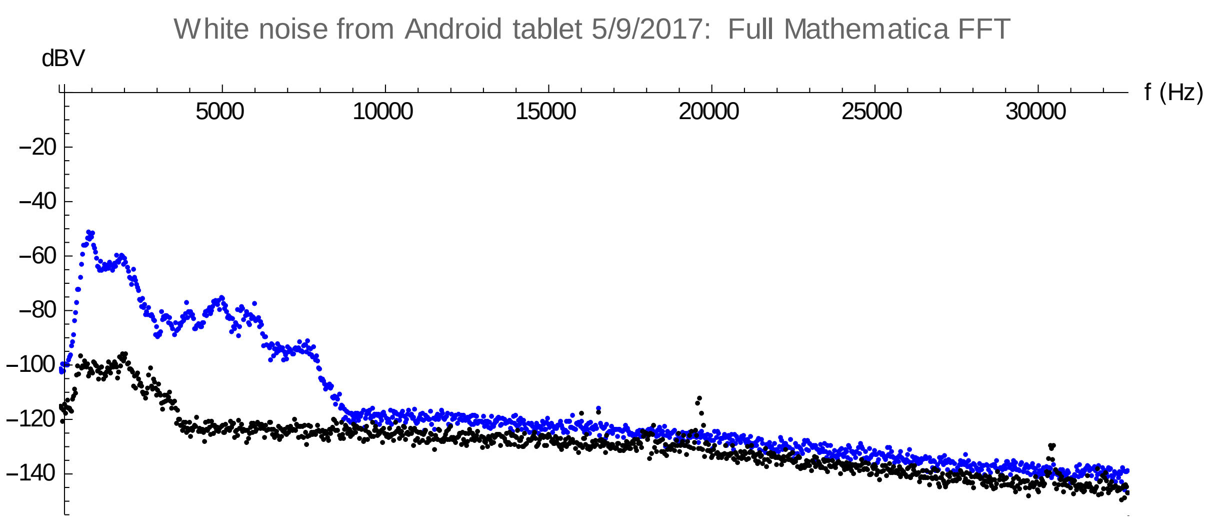

Figure 6: Blue: white noise signal from Android tablet.
Black: the signal played back from a test number.

I also performed this test with my phone and a borrowed Galaxy S7, with my tablet providing the white noise. During testing, I found that, even though the Galaxy S7 has an HD-

Voice/VoLTE option, this particular phone would not enable the feature (24 hours later it was still supposedly updating). The results I could gather are shown in Figures 7-10.

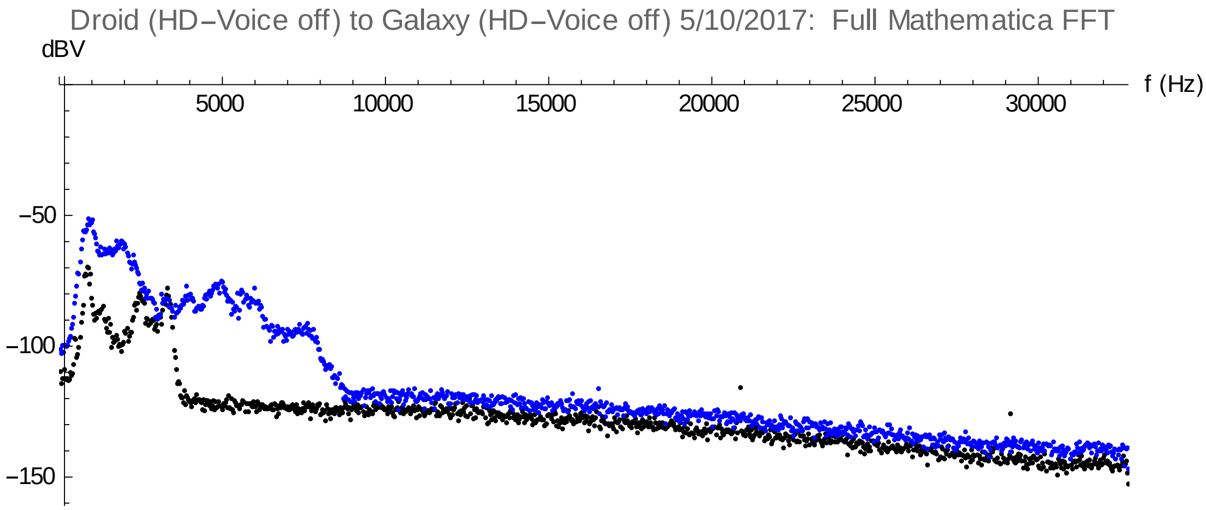

Figure 7: Blue: white noise signal from Android tablet.
Black: the signal after going through the phones.

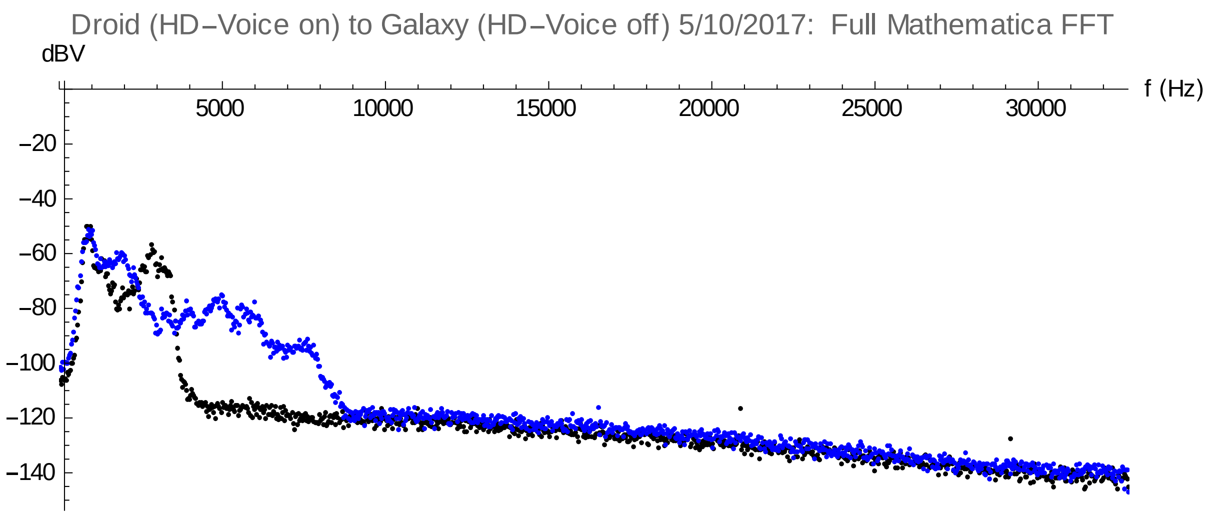

Figure 8: Blue: white noise signal from Android tablet.
Black: the signal after going through the phones.

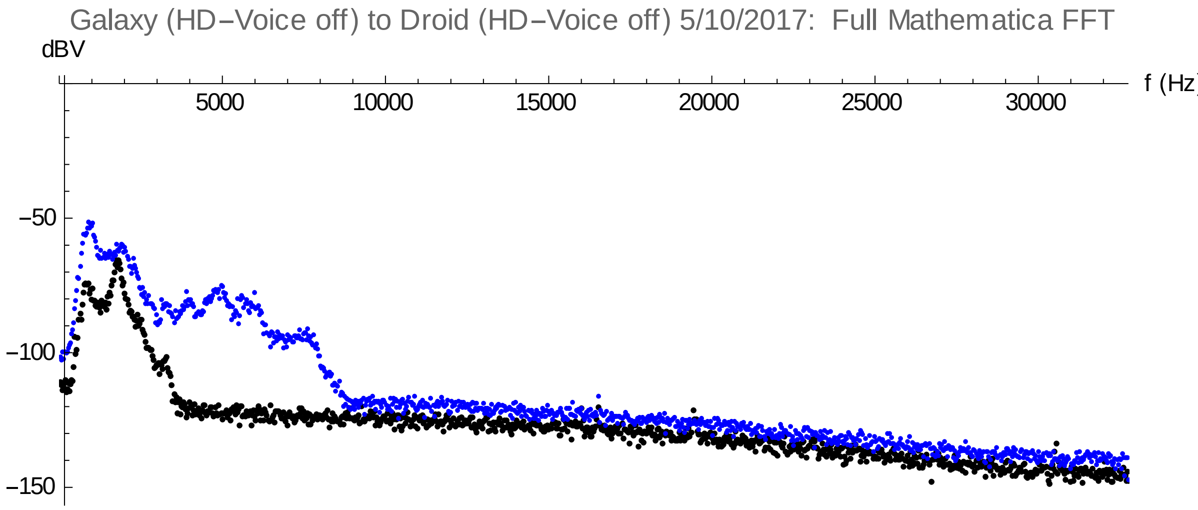

Figure 9: Blue: white noise signal from Android tablet.
Black: the signal after going through the phones.

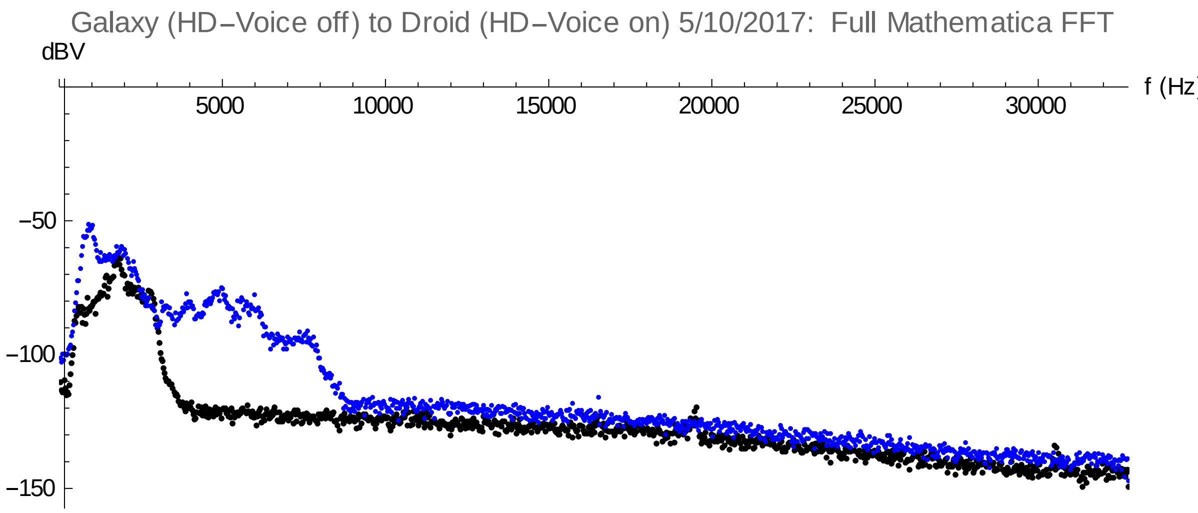

Figure 10: Blue: white noise signal from Android tablet.
Black: the signal after going through the phones.

Because all signals were played out of the Android smartphone, Figure 11 shows the white noise signal from it for reference.

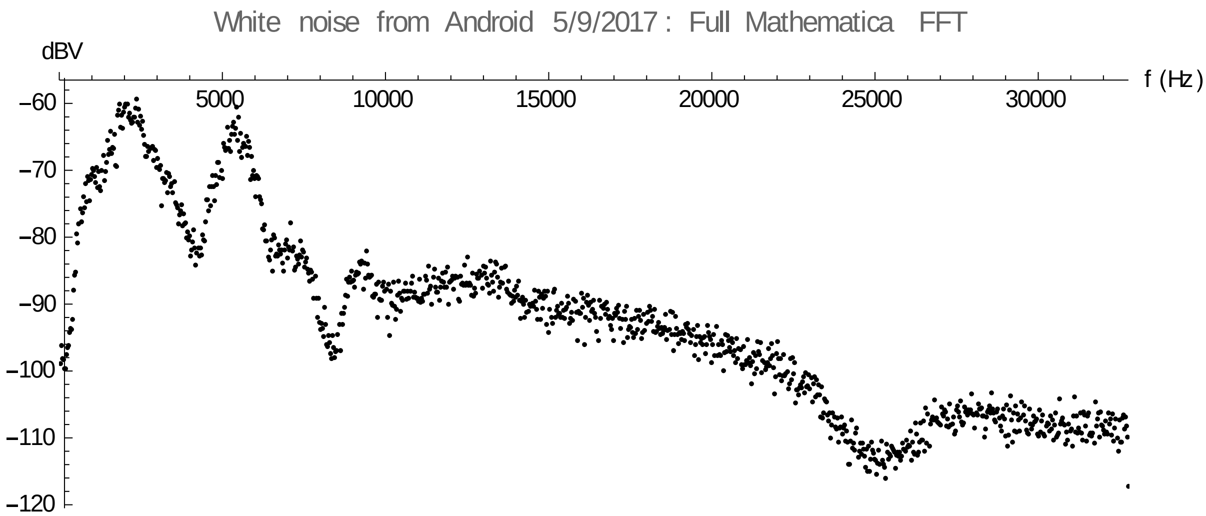

Figure 11: Blue: white noise signal from Android tablet.
Black: the signal played back from a test number.

3.2 Analysis

White noise is a random noise where every frequency has the same intensity. What can be seen from the results is therefore not true white noise. However, it still accomplishes what true white noise would have, by comparing frequencies that go in to frequencies that come out. In every case shown, there is a significant drop in signal strength below 5 kHz, even though the "white noise" signals have no such drop for these frequencies. Without zooming in on this drop-off, it is reasonable to assume this takes place around 3400 to 4000 Hz as predicted. We can therefore not only reaffirm the results of previous experiments, but also confirm that HD-Voice set on a single phone does not improve bandwidth, as expected.

Chapter IV – Conclusions

4.1 Summary

Due to technical difficulties and insufficient resources, this paper does not reveal as much as was intended. However, these results confirm the results of past experiments, and it was found that HD-Voice and VoLTE on a single phone does not improve the bandwidth of a cell phone call, and therefore does not improve call quality. Many different devices and variables (e.g. who is sending and who is receiving) were tested, so our tests should be sufficiently thorough. The exception is my Droid, which was involved in every test; but seeing as how it was the only phone with the improvement services, turning these services on and off had no significant effect on the results, and previous experiments with different phones yielded the same results, it seems unlikely my phone acted as a bottleneck that led to inaccurate results.

4.2 Looking forward

Although expected, this particular test had not been done before, and so, ideally, paves the way for further testing on these services. Furthermore, the results presented here were only conducted with phones connected to Verizon wireless, so any conclusions drawn here cannot necessarily be applied to other services, such as AT&T and T-Mobile. Additionally, HD-Voice was necessarily coupled with VoLTE on my phone, so future experiments may yield different results if these services are tested separately (if possible).

Acknowledgements

I would like to thank Dr. McIntyre for his assistance and guidance throughout this project and his contribution to the results themselves. I also appreciate my brother letting me borrow his phone for a day.

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