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# Sounds of Silence: A Study of Stability and Diversity of Web Audio Fingerprints

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# Sounds of Silence: A Study of Stability and Diversity of Web Audio Fingerprints

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# Table of Contents

# List of Figures

# List of Tables

# Abstract

Browser fingerprinting presents a grave threat to privacy as it allows user tracking even in private browsing modes. Prior measurement studies on HTML5-based fingerprinting have been limited to Canvas and WebGL but not Web Audio APIs. We aim to fill this gap by conducting *the first large-scale systematic study of web audio fingerprints* and studying their *stability* as well as *diversity* properties. Using MTurk and social media platforms, we collected 8 different audio fingerprints from 694 users.

Firstly, we show that the audio fingerprints are unstable unlike other fingerprinting methods with some users having as many as 20 different fingerprints. Despite this, we show that audio fingerprinting can still be used as an effective fingerprinting vector as most fingerprints tend to repeat quite often. We devised a graph-based fingerprint matching mechanism to measure the diversity of audio fingerprints. Our results show that audio fingerprints are much less diverse with only 45 distinct fingerprints among 694 users.

**Keywords**: Web Audio Fingerprints, Browser Fingerprints, Web Audio API, Canvas Fingerprints, Font Fingerprints, User-Agents Fingerprints, Tracking, Web Security

# 1. Introduction

“Browser fingerprinting” is a method of tracking web browsers by their browser configuration and settings information that is visible to the websites, rather than traditional tracking methods such as IP addresses and unique cookies. Browser fingerprinting is both difficult to detect and extremely difficult to thwart. A great example of Browser fingerprinting is Canvas fingerprinting. Canvas fingerprinting is a browser fingerprinting technique that uses HTML5 Canvas feature to draw text or 3D figures on a canvas when a user visits a website. The subtle difference in rendering that varies between users is tokenized to serve as an unique identifier that allows the website to remember the visitor. Another popular browser fingerprinting technique is the WebGL fingerprint. The WebGL hash is generated by rendering a pattern or low high entropy image (Image that does not compress well) and then creating a hash from the resulting rendered pixels. That image is rendered to a frame buffer with a fixed size so changing screen resolution will not affect the resulting hash.

There have been several large scale studies on Canvas Fingerprints and WebGL Fingerprints and the defenses have been proposed as well [1, 2, 3, 4, 5]. However, one area of fingerprinting that has been neglected is audio fingerprinting. Discovered by Englehardt et al. [6] in 2016 while crawling through 1 million websites, audio fingerprinting is fairly new to the browser fingerprinting world. There have been no large scale studies on audio fingerprinting and we aim to fill this gap in our research.

Stability of a browser fingerprint technique plays a pivotal role in its efficiency. The main reason behind browser fingerprinting popularity is its ability to compute a distinct fingerprint for a user when repeated multiple times even in private/incognito browsing mode. A browser fingerprint must be stable, fast and diverse to be used for tracking. First research question we try to answer in our research is that, **RQ1** - *are audio fingerprinting stable enough to be used as a fingerprinting vector?* Computation time of a fingerprinting technique must be attainable to not add any computational overhead to the browser. If a fingerprinting technique takes too much time then it is not effective in a sense that a user might leave the website before the fingerprint computation completes. The second research question we try to find an answer is that, **RQ2** - *do audio fingerprints compute in a reasonable time frame?*

Recent security research has improved the security in the browser and made them less fingerprintable. At the same time, there has been an increasing amount of research on fingerprintability of web browsers [4, 2, 7, 8]. To address this gap for audio fingerprinting we study the effectiveness and diversity of our collected audio fingerprints at large. The third research question we try to answer in this research is **RQ3** - *how diverse are audio fingerprints?* We also compare our audio fingerprinting technique to known fingerprinting methods such as Canvas, Font, User Agent, etc to answer our fourth research question, **RQ4** - *in comparison to known fingerprinting techniques and how serious and effective are our audio fingerprinting techniques?*

Englehardt et al. found two audio fingerprinting techniques being used by the advertising company[6]. They found that the most popular script is from Liverail[1], present on 512 sites and other scripts were present on less than 6 other websites. An additional technique was used on the OpenWPM project [2] which is essentially an additional work by Englehardt et al. However, there can be several approaches to computing the audio fingerprints because of the interfaces provided by the Web Audio API [9]. The fifth question we try to answer in our research is that, **RQ5** - *are there any additional techniques that can be used for audio fingerprinting?* In our research, we use three techniques discovered before and five new audio fingerprinting configurations that we developed to audio fingerprint a user and answer this question.

In the absence of a large scale study, industry has been doing contradictory things. For example, Brave, a privacy concerned browser has been implementing audio fingerprinting protection [10]. This is problematic in a sense that it adds computational overhead and it is also affecting the quality of the audio without actually realising its necessity. On the other hand, the Web Audio API developers from World Wide Web Consortium (W3C) believe - *"This merely allows deduction of information already readily available by easier means (User Agent string), such as "this is browser*

[1]https://www.liverail.com/
[2]https://audiofingerprint.openwpm.com/

*X running on platform Y""* [3] However, both of these issues need a proper research study to pass a judgement on the correctness. Therefore, we raise a final research question, **RQ6** - *are audio fingerprinting defenses necessary?*.

At the heart of our project lies an audio fingerprinting website that collects audio fingerprints as well as uses FingerprintJS [11] to capture canvas and font fingerprints and stores them in a database. The detailed system description is explained in Section 3. Our analysis and results are explained in detail in Section 4. In summary, our contributions are as follows:

1. We conducted the first-large systematic study of Web Audio API-based fingerprinting vectors by employing 633 web users. We measured both the stability and diversity of 8 audio fingerprints by repeating them 30 times for each user.

2. We designed, implemented and analyzed the effectiveness of 5 new audio fingerprinting vectors that made use of FFTs of audio source files and modulated and modified custom waveforms.

3. We designed a graph-based fingerprint matching mechanism to analyze the diversity of partially stable audio fingerprints.

4. We compared the diversity of audio fingerprints with other well-known fingerprinting vectors such as Canvas, font and `User-Agent` headers to allow the browser developers to take informed decisions when developing privacy protection features.

[3] https://www.w3.org/TR/webaudio/#priv-sec

# 2. Literature Review

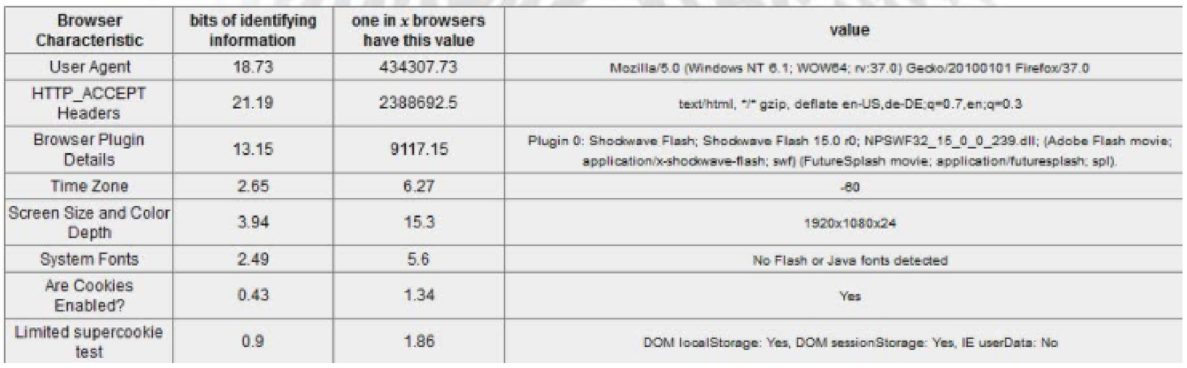
## 2.1 Browser Fingerprinting

In this section, we answer the basic information encompassing the browser fingerprinting history, usages, types, current methods on the web and give an exhaustive overview of the researches led in the area of browser fingerprinting (BF) with a synopsis of current procedures.

### 2.1.1 History

Browser fingerprints were first discovered by Mayer in 2009 [12]. He concluded that the browser features and the plugins are unique to each user and can be used for tracking. He looked at the differences in browsing environments that can be exploited by the remote serve to identify the users. Mayer saw the "quirkiness" that comes with the hardware, operating system and the browser configuration can be used to track users on the internet. In his study 96.23% (1278 of 1328) participants could be uniquely identified.

Following Mayers in 2010, Eckersley conducted the Panopticlick Experiment from Electronic Frontier Foundation (EFF) [13]. The script calculates a uniqueness score based on the data that the web browser reveals during connections. Tests with Google Chrome 5, Opera 10.5 pre-alpha, Internet Explorer 8 and Mozilla Firefox 3.6 revealed that all four web browsers contained unique bits that could be used to identify them. This can be attributed to the web browser fingerprint database of the service as it contains more than 470,000 fingerprints. He also noted that the fingerprints are likely to reduce the uniqueness with the increase in users. The test results are displayed as a table on the screen as shown in Figure 2.1. Each bit of information identified by the test is displayed in its own row in the table revealing the bits of identifying information and how unique it is when compared to the whole database. The higher the number the worse. The experiment was able to identify 84% of the participants.



| Browser Characteristic | bits of identifying information | one in *x* browsers have this value | value |
|---|---|---|---|
| User Agent | 18.73 | 434307.73 | Mozilla/5.0 (Windows NT 6.1; WOW64; rv:37.0) Gecko/20100101 Firefox/37.0 |
| HTTP_ACCEPT Headers | 21.19 | 2388692.5 | text/html, */* gzip, deflate en-US,de-DE;q=0.7,en;q=0.3 |
| Browser Plugin Details | 13.15 | 9117.15 | Plugin 0: Shockwave Flash; Shockwave Flash 15.0 r0; NPSWF32_15_0_0_239.dll; (Adobe Flash movie; application/x-shockwave-flash; swf) (FutureSplash movie; application/futuresplash; spl). |
| Time Zone | 2.65 | 6.27 | -60 |
| Screen Size and Color Depth | 3.94 | 15.3 | 1920x1080x24 |
| System Fonts | 2.49 | 5.6 | No Flash or Java fonts detected |
| Are Cookies Enabled? | 0.43 | 1.34 | Yes |
| Limited supercookie test | 0.9 | 1.86 | DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData: No |

Figure 2.1: Table displayed to the user by the Panopticlick Experiment

### 2.1.2 Fingerprints

The popularity of the web has seen an increase in tracking for statistical, marketing or commercial purposes. User tracking or web tracking allows you to track an Internet user anonymously and by various means while browsing your website. Browser fingerprinting (BFPs) is an incredibly accurate method of identifying unique browsers and tracking online activity. Browser fingerprinting has arrived at a condition of development where it is currently utilized by numerous organizations for various purposes. Several studies have demonstrated the development of this procedure along the years with both the disclosure of new properties and its spread on the web [6, 8, 4, 2]. Unlike cookies and local storage, fingerprint stays the same in incognito/private mode and even when browser data is purged.

**Fingerprint** is formally defined as *a set of information elements defining a device or an instance of an application* and **Fingerprinting** as the *process by which an observer or attacker uniquely identifies a device or instance of an application based on a set of multiple information* by RFC6973 [14]. Browser fingerprints (BFPs) have been defined in many ways on previous research [3, 15, 7]. In general, we can define the Browser Fingerprinting as a powerful method that the website utilizes to extract the device features to generate a single unique identifier which is then used to identify the user with a high probability. Based on the current trend and researches we discuss the primary fingerprinting mechanisms that are wild in the web in the section below.

### 2.1.3 Canvas Fingerprints

The HTML Canvas allows web applications to draw graphics in real time, with functions to support drawing shapes, arcs, and text to a custom canvas element[6]. This was demonstrated on the "Pixel Perfect" project by Mower et. al in 2012 [1]. The minute differences in rendering, smoothing, anti-aliasing and other features of the user devices can contribute to drawing an image differently on each machine allowing the exploitation of these differences to generate a unique fingerprint for a user. Canvas fingerprinting works by exploiting the HTML5 canvas element: when a user visits a website their browser is instructed to “draw” a hidden line of text or 3D graphic that is then rendered into a single digital token, a potentially unique identifier to track users without any actual identifier persistence on the machine. The technique is based on the fact that the same canvas image may be rendered differently on different computers. This happens for several reasons. At the image format level – web browsers use different image processing engines, image export options, compression level, the final images may get different checksum even if they are pixel-identical. At the system level – operating systems have different fonts, they use different algorithms and settings for anti-aliasing and sub-pixel rendering.

In plain English, what this means is that the HTML5 canvas element generates certain data, such as the font size and active background color settings of the visitor’s browser, on a website. This information serves as the unique fingerprint of every visitor. An example of the hidden canvas rendered on a users machine is shown in Figure 2.2

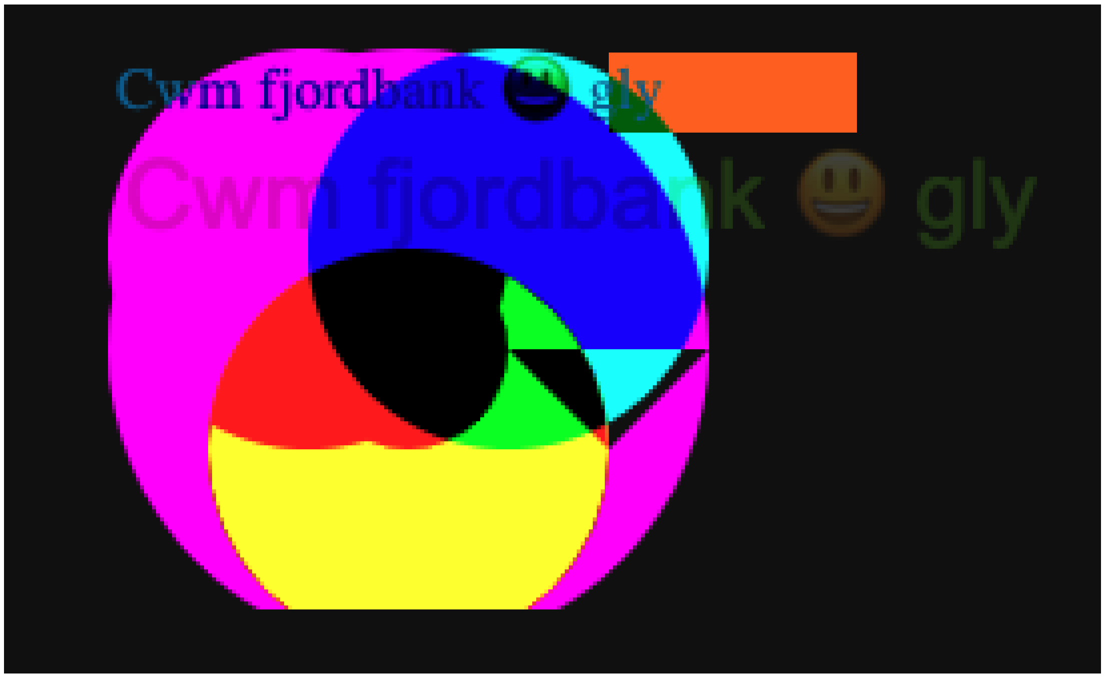


Figure 2.2: Canvas rendering on a user device used for canvas fingerprinting

### 2.1.4 Font Fingerprints

Font list of a browser can also be utilized to fingerprint the users. Font fingerprinting techniques are based on measuring the onscreen dimensions of HTML elements filled with text pieces or single Unicode glyph. Font rendering in web browsers is affected by many factors, and these measurements may vary slightly. Font Enumeration attack is a brute-force method that tries different fonts from a sizable font-family dictionary. If the rendered element's size differs from the default values, it means that the substituted font is present in the system. Shown below in code block 2.1 is an example of the font list of a user that is used to generate a unique identifier for that particular user.

```
["Calibri","PMingLiU","SimHei","Arial","Arial Black","Arial Narrow","Arimo","Calibri","Cambria","Comic Sans MS","Courier","Courier
      New","Garamond","Georgia","Helvetica","Liberation Mono","Liberation Sans","Liberation Serif","Lohit Odia","Lohit Punjabi","
     MS Gothic","MS PGothic","MS PMincho","Monospace","NanumGothic","Noto Color Emoji","Noto Naskh Arabic","Noto Nastaliq Urdu","
     Noto Sans","Noto Sans Armenian","Noto Sans Bengali","Noto Sans Canadian Aboriginal","Noto Sans Cherokee","Noto Sans
     Devanagari","Noto Sans Ethiopic","Noto Sans Georgian","Noto Sans Gujarati","Noto Sans Gurmukhi","Noto Sans Hebrew","Noto
     Sans Kannada","Noto Sans Khmer","Noto Sans Lao","Noto Sans Malayalam","Noto Sans Myanmar","Noto Sans Oriya","Noto Sans
     Sinhala","Noto Sans Symbols","Noto Sans Tamil","Noto Sans Telugu","Noto Sans Thai","Noto Sans Yi","Noto Serif","PMingLiU","
     Roboto","Sans","Serif","SimHei","SimSun","Tahoma","Times","Times New Roman","Trebuchet MS","Verdana","Webdings","Wingdings",
    "Wingdings 2","Wingdings 3"]
```

Listing 2.1: Font list generated for a user used for fingerprinting

### 2.1.5 Audio Fingerprints

Audio fingerprinting (AFPs) is a fingerprinting technique that is moderately new with regards to browser fingerprinting techniques. By using the Web Audio API [9] in modern browsers, one can misuse the subtle differences in the rendering of a fixed audio waveform, for instance a sine or triangle wave, to construct a unique fingerprint of a device. The Web Audio API gives an interface to create/process an audio by linking multiple modules like oscillators, compressor, and filters together to generate a very specific output. A continuous signal is passed through this pipeline to convert the continuous signal to discrete so that the computer can process the audio very easily in the form of a block called frames [8]. Each frame is composed of samples that represent the value of the audio stream at a specific point in time. While utilizing the Web Audio API to generate fingerprints, the code doesn't gather sound played or recorded by your machine rather an identifier is generated by the code based on the frame values that varies based on a machine's sound stack.

## 2.2 Background and Related Work

Audio Fingerprinting (AFPs) technique was first discovered by Englehardt et al. while crawling the web looking for trackers. AudioContext fingerprinting is one of the latest additions in a fingerprinter's toolbox. They found scripts that process an audio signal generated with an `OscillatorNode` to fingerprint devices. The authors add that the fingerprinting process is similar to what is done with canvas fingerprinting as processed signals will present differences due to the software and hardware stack of the device. The relative novelty of this technique explains that scripts using this API were only found on a very small number of websites [6]. Researchers found that the first technique using `AnalyzerNode` to extract FFT to build fingerprints was not consistent and the results were flaky. However, the second technique with `DynamicCompressor` with full buffer was more promising for repeated visitors but they also saw collision between fingerprints and they were not particularly identifying. Their 1M web census saw the prevalence of audio fingerprinting script in 5.6% of the websites. The detailed working mechanism of these methods are explained in Chapter 3

Laperdrix et al. collected 19,467 audio fingerprints from AmIUnique.org to mitigate the risk of audio fingerprinting by 'breaking' the stability of fingerprint over time [8]. They introduced very small noise directly into the audio processing routines of the browser so that tests using any number of AudioContext modules are all impacted. They operate `AudioBuffers` of the `AudioNodeEngine` as they contain the frames of the processed audio and decrease the volume of processed buffers by a factor ranging between 0.000 and 0.001. The changes made it impossible to detect modified sections from unmodified ones and produce a different hash as the audio routine for each browser session.

Queiroz et al. showed that the audio fingerprinting is capable of identifying the device's class, based on features like device's type, web browser's version and rendering engine [16]. They also studied the stability of the two interfaces i.e `AudioContext` and `OfflineAudioContext` and chose to use `OfflineAudioContext` fingerprint users using several audio configurations. The researchers concluded that Web Audio API is capable of providing information about the devices only when employed with other Browser Fingerprinting techniques.

These works have shown how new web technologies such as Canvas API, Web GL API, Font, Audio and browser extensions are increasing the diversity of web browsers and making the users more prone to cookie-less tracking. While these research works have studied the privacy implications of browser fingerprinting, the security implications of these advanced fingerprinting techniques have not been studied well. In particular, no systematic research has been done to see how stable and diverse the audio fingerprinting can be. Our research primarily focuses on addressing this gap.

# 3. System Description

## 3.1 Web Audio API

The Web Audio API provides a powerful and versatile system for controlling audio on the Web, allowing developers to choose audio sources, add effects to audio, create audio visualizations, apply spatial effects (such as panning) and much more [9].

The Web Audio API is based on the concept of modular routing, which has its roots in analog synthesizers. There are audio sources, such as microphones, oscillators, and audio files, which provide some kind of audio signal. This API manages operations inside an Audio Context. Audio operations are performed with audio nodes, which are linked together to form an Audio Routing Graph. Multiple sources are supported within a single Audio Context. This modular design is highly flexible, allowing the creation of complex audio designs. They typically start with one or more sources. Node outputs can be linked to the inputs of others creating chains or webs of audio streams.[17] The APIs have been designed with a wide variety of use cases in mind. Ideally, it should be able to support any use case which could reasonably be implemented with an optimized C++ engine controlled via script and run in a browser. That said, modern desktop audio software can have very advanced capabilities, some of which would be difficult or impossible to build with this system. [18].

Those audio signals can be connected to other audio nodes which perform operations with that signal. These nodes include the Gain Node, which can raise or lower the volume of a signal; Filter Nodes, which changes how the signal sounds; and an Analyser Node, which provides real-time information about a signal which can be used to render a visualization.

Once the sound has been effected and is ready for output, it can be linked to the input of a AudioContext.destination (computer's speakers), which sends the sound to the speakers. Note that this last connection is only required if you need the audio to be heard. [19]

A typical flow for Web Audio could look something like this:

1. Create audio context (AudioContext or OfflineAudioContext)
2. Create sources inside the context (e.g. <audio>, oscillator, streams)
3. Create effects nodes (e.g. reverb, flanger, panner, compression)
4. Choose a destination for the audio (e.g. speakers)
5. Connect the sources to the effects, and the effects to the destination

## 3.2 Main Audio Node Interfaces

In this section we discuss the different audio interfaces provided by the Web Audio API. These audio nodes are very important and are the base of our audio fingerprinting configurations. These nodes are used in combination to generate an audio fingerprinting and each of the nodes have their significance and a role to play in our fingerprinting methods.

### 3.2.1 AudioNode

The `AudioNode` interface is a generic interface for representing an audio processing module. Each AudioNode has inputs and outputs, and multiple audio nodes are connected to build a processing graph. `AudioNode.connect()` method present in the `AudioNode` interface allows to connect the output of this node to be input into another node, either as audio data or as the value of an `AudioParam` [9].

### 3.2.2 BaseAudioContext

The `BaseAudioContext` interface of the Web Audio API acts as a base definition for online and offline audio-processing graphs, as represented by `AudioContext` and `OfflineAudioContext` respectively. `BaseAudioContext` is not used directly, rather its used via one of these two inheriting interfaces.

### 3.2.3 AudioContext

The `AudioContext` interface represents an audio-processing graph built from audio modules linked together, each represented by an `AudioNode`. An audio context controls both the creation of the nodes it contains and the execution of the audio processing, or decoding [9].

### 3.2.4 OfflineAudioContext

The `OfflineAudioContext` interface is an `AudioContext` interface representing an audio-processing graph built from linked together `AudioNodes`. In contrast with a standard `AudioContext`, an `OfflineAudioContext` doesn't render the audio to the device hardware; instead, it generates it, as fast as it can, and outputs the result to an `AudioBuffer` [9].

### 3.2.5 AudioBuffer

The `AudioBuffer` interface represents a short audio asset residing in memory, created from an audio file using the `AudioContext.decodeAudioData()` method, or from raw data using `AudioContext.createBuffer()`. Once put into an `AudioBuffer`, the audio can then be played by being passed into an `AudioBufferSourceNode` [9].

### 3.2.6 OscillatorNode

The `OscillatorNode` interface represents a periodic waveform, such as a sine wave. It is an `AudioScheduledSourceNode` audio-processing module that causes a specified frequency of a given wave to be created—in effect, a constant tone. An `OscillatorNode` is created using the `BaseAudioContext.createOscillator()` method. It always has exactly one output and no inputs [9].

### 3.2.7 DynamicCompressor

The `DynamicsCompressorNode` interface provides a compression effect, which lowers the volume of the loudest parts of the signal in order to help prevent clipping and distortion that can occur when multiple sounds are played and multiplexed together at once. This is often used in musical production and game audio. `DynamicsCompressorNode` is an `AudioNode` that has exactly one input and one output; it is created using the `BaseAudioContext.createDynamicsCompressor()` method [9].

### 3.2.8 AnalyserNode

The `AnalyserNode` interface represents a node able to provide real-time frequency and time-domain analysis information. It is an `AudioNode` that passes the audio stream unchanged from the input to the output, but allows you to take the generated data, process it, and create audio visualizations. An `AnalyserNode` has exactly one input and one output. The node works even if the output is not connected [9].

### 3.2.9 GainNode

The `GainNode` interface represents a change in volume. It is an `AudioNode` audio-processing module that causes a given gain to be applied to the input data before its propagation to the output. A `GainNode` always has exactly one input and one output, both with the same number of channels. The gain is a unit-less value, changing with time, that is multiplied to each corresponding sample of all input channels. If modified, the new gain is instantly applied, causing unaesthetic ’clicks’ in the resulting audio [9].

### 3.2.10 ScriptProcessor

The `createScriptProcessor()` method of the `BaseAudioContext` interface creates a `ScriptProcessorNode` used for direct audio processing using JavaScript. This module is interconnected to two AudioBuffers: 1) Input data 2) Output data. This interface consists of an event handler function; `onaudioprocess` that takes the associated `audioProcessingEvent` and uses it to loop through each channel of the input buffer, and each sample in each channel and is triggered when the incoming `AudioBuffer` is ready to be processed.

### 3.2.11 ChannelMergerNode

The ChannelMergerNode interface, reunites different mono inputs into a single output. Each input is used to fill a channel of the output. This is useful for accessing each channel separately, e.g. for performing channel mixing where gain must be separately controlled on each channel. If `ChannelMergerNode` has one single output, but as many inputs as there are channels to merge; the number of inputs is defined as a parameter of its constructor and the call to `AudioContext.createChannelMerger()`. In the case that no value is given, it will default to 6 [9].

#### 3.2.12 AudioDestinationNode

The destination property of the `BaseAudioContext` interface returns an `AudioDestinationNode` representing the final destination of all audio in the context. It often represents an actual audio-rendering device such as your device's speakers [9].

## 3.3 Digital Signal Processing

In this section we discuss two very popular methods of signal processing in Digital Signal Processing. The knowledge of working mechanisms is vital to understand both of these processes. These methods are used in our research to generate **Amplitude Modulation Hybrid** and **Frequency Modulation Hybrid** Fingerprints. The exact details about the modulating and carrier signals are discussed in the Section 3.4.7 and 3.4.8 respectively.

### 3.3.1 Frequency Modulation

Frequency modulation (FM) is the encoding of information in a carrier wave by varying the instantaneous frequency of the wave. The technology is used in telecommunications, radio broadcasting, signal processing, and computing. Frequency modulation is widely used for FM radio broadcasting. It is also used in telemetry, radar, seismic prospecting, and monitoring newborns for seizure, two-way radio systems, sound synthesis, magnetic tape-recording systems and some video-transmission systems.

To generate a frequency modulated signal, the frequency of the radio carrier is changed in line with the amplitude of the incoming radio signal. When the radio signal is modulated onto the radio frequency carrier, the new radio frequency signal moves up and down in frequency. The amount by which the signal moves up and down is important. It is known as the deviation and is normally quoted as the number of kilohertz deviations. As an example the signal may have a deviation of plus and minus 3 kHz, i.e. ±3 kHz. In this case the carrier is made to move up and down by 3 kHz

[20]. From Figure 3.1, it can be seen that the envelope of the signal follows the frequency of the modulating signal.

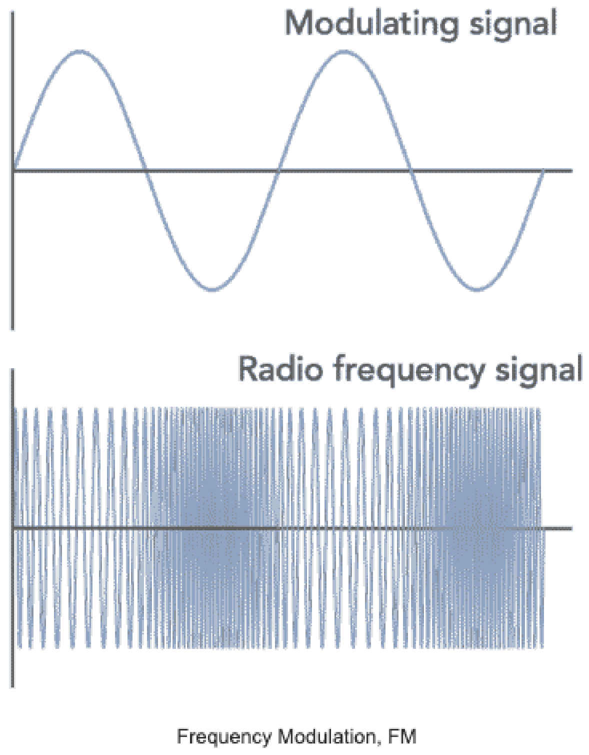
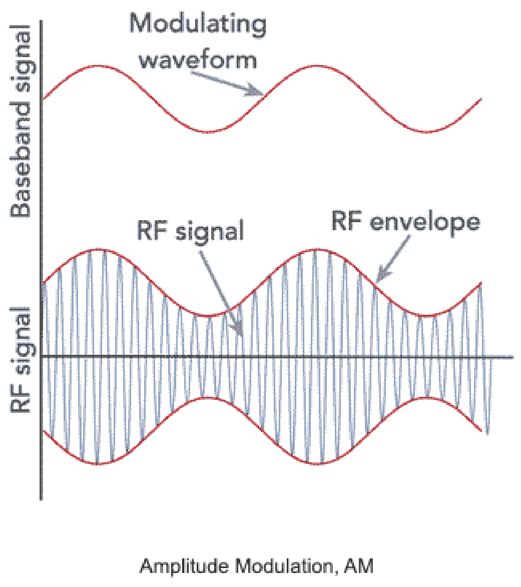


Figure 3.1: Frequency Modulation Example

### 3.3.2 Amplitude Modulation

Amplitude modulation (AM) is a modulation technique used in electronic communication, most commonly for transmitting messages with a radio carrier wave. In amplitude modulation, the amplitude (signal strength) of the carrier wave is varied in proportion to that of the modulating signal, such as a radio signal. Although one of the earliest used forms of modulation it is still used today, mainly for long, medium and short wave broadcasting and for some aeronautical point to point communications.

In order that a radio signal can carry audio or other information for broadcasting or for two way



h

Figure 3.2: Amplitude Modulation Example

radio communication, it must be modulated or changed in some way. Although there are a number of ways in which a radio signal may be modulated, one of the easiest is to change its amplitude in line with variations of the sound. In this way the amplitude of the radio frequency signal varies in line with the instantaneous value of the intensity of the modulation. This means that the radio frequency signal has a representation of the sound wave superimposed in it [21]. From Figure 3.2 , it can be seen that the envelope of the signal follows the contours of the modulating signal.

## 3.4 Fingerprinting Methods

In this section we discuss 8 fingerprinting methods used in this research to get the unique identifier of a user. First, we discuss the two methods namely DynamicCompressor and OscialltorNode that were found by Englehardt et al. during their 1-Million-Site Measurement and Analysis [6]. An additional technique used on the OpenWPM project [1]. Then, we discuss a more advanced methods i.e. **Custom Signal Hybrid, Audio Source Hybrid, Channel Merge Hybrid, Amplitude Modulation Hybrid and Frequency Modulation Hybrid** that we introduced to audio fingerprint the

[1]https://audiofingerprint.openwpm.com/

users and try to answer the research question **RQ5**. The code snippet of all the audio fingerprinting methods are shown in the Appendix A

### 3.4.1 DynamicCompressor Method

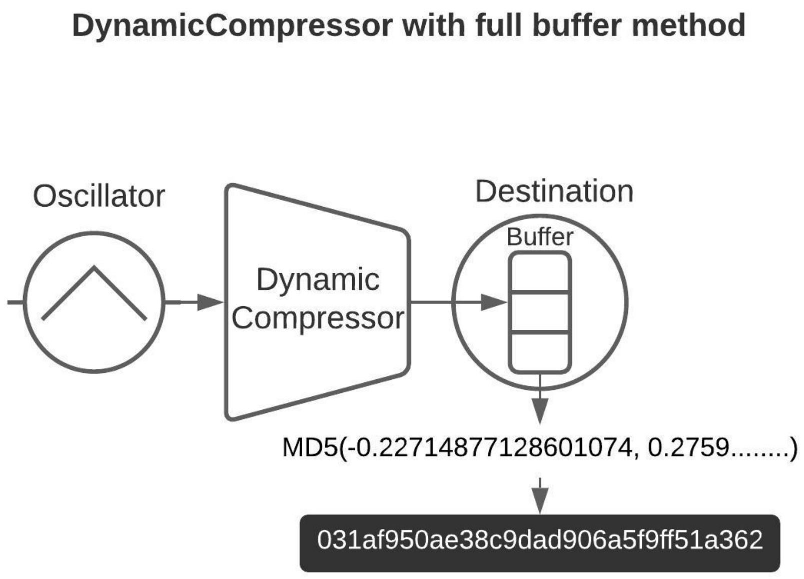

DynamicCompressor with full buffer method
Oscillator
Dynamic Compressor
Destination
Buffer
MD5(-0.22714877128601074, 0.2759........)
031af950ae38c9dad906a5f9ff51a362

Figure 3.3: DynamicCompressor Full Buffer Method

Figure 3.3. shows the utilization of the `OfflineAudioContext` interface to audio fingerprint the sound stack of a device. Initially, a triangle wave is produced as shown in Figure 3.4 utilizing an `OscillatorNode`. The signal is then connected to `DynamicsCompressorNode`, to increment differences in processed audio between devices. The yield of this compressor is passed to the buffer of an `OfflineAudioContext`. Hashes generated from the values from the full buffer is used to audio fingerprint a user. This method was found wild in the web by trackers during their 1-Million-Site Measurement and Analysis [6].

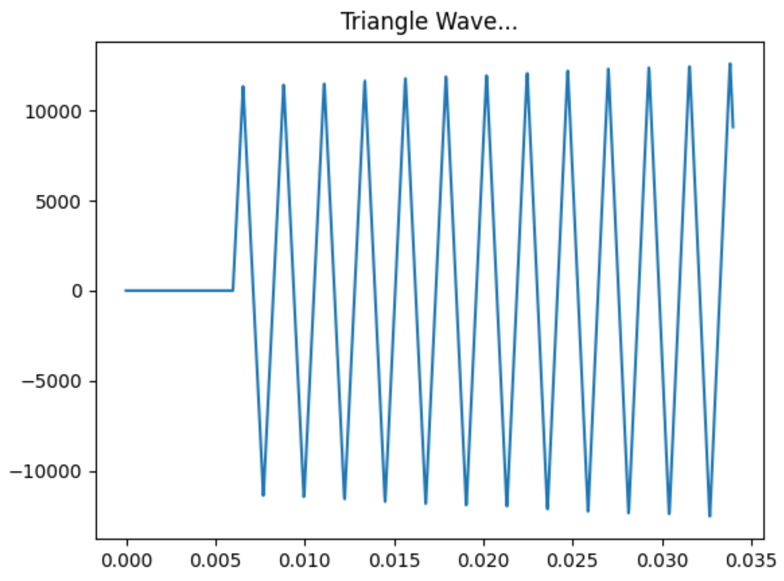


Figure 3.4: Generated Triangle Wave

### 3.4.2 OscillatorNode Method

Figure 3.5. shows the utilization of the `AudioContext` interface to audio fingerprint the sound stack of a device. Initially, a triangle wave is created as shown in Figure 3.4 using an `OscillatorNode`. This signal is then passed to an `AnalyserNode` and a `ScriptProcessorNode`. At last, the single goes through a `GainNode` whose gain is set zero to mute any output to `AudioContext` destination (For example. computer speakers). The `AnalyserNode` gives admittance to a Fast Fourier Transform (FFT) of the audio signal, which is caught utilizing the *onaudioprocess* event handler added by the `ScriptProcessorNode`. The subsequent FFT is taken care of into a hash and utilized as a unique audio fingerprint.

### 3.4.3 Hybrid Method

Figure 3.6. shows the combination of `OscillatorNode` and `DynamicCompressor` methods to generate a unique audio fingerprint of a user using `AudioContext` interface. A triangle wave is generated as shown in Figure 3.4 using `OscillatorNode` which is passed through

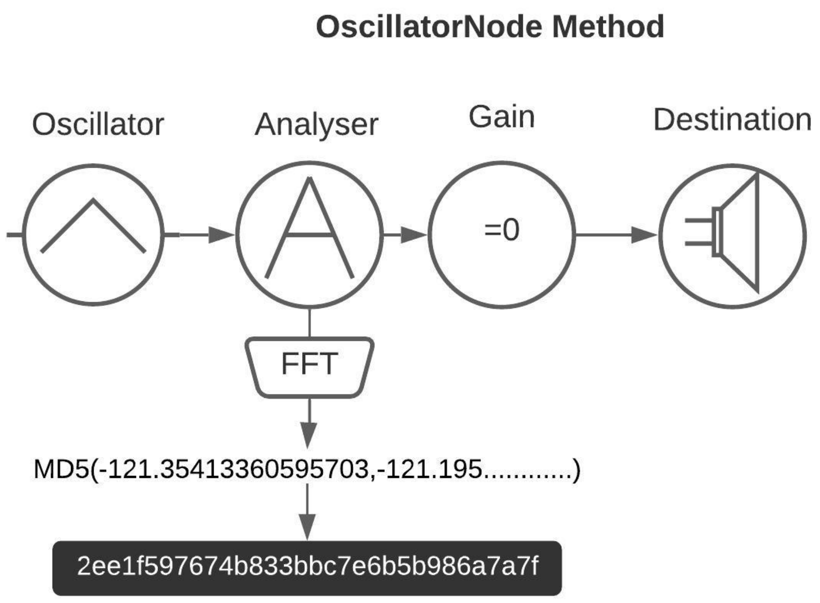

OscillatorNode Method
Oscillator
Analyser
Gain
Destination
=0
FFT
MD5(-121.35413360595703,-121.195...........)
2ee1f597674b833bbc7e6b5b986a7a7f

Figure 3.5: OscillatorNode Method

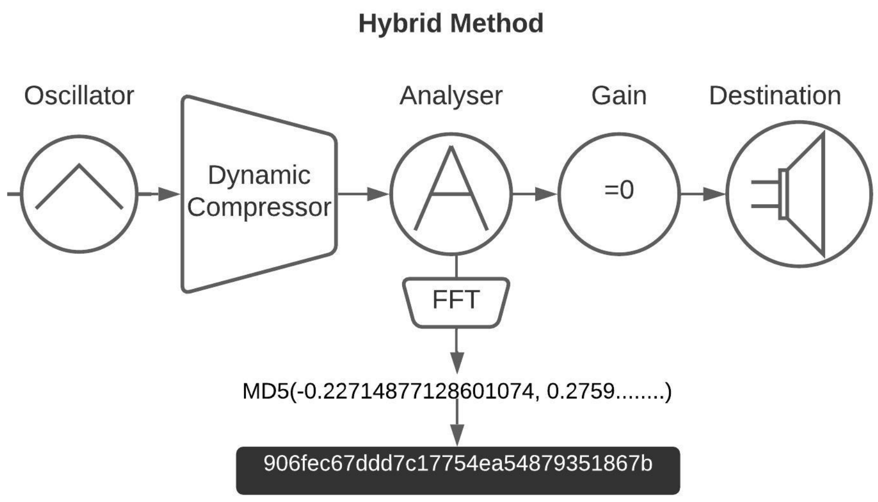

Hybrid Method
Oscillator
Dynamic Compressor
Analyser
Gain
Destination
=0
FFT
MD5(-0.22714877128601074, 0.2759........)
906fec67ddd7c17754ea54879351867b

Figure 3.6: Hybrid (DynamicCompressor + OscillatorNode) Method

the DynamicsCompressorNode. This signal is then passed to an AnalyserNode and a ScriptProcessorNode. Similar to the OscillatorNode method the signal then goes through GainNode that is set to zero. We use AnalyserNode to FFT the audio signal, that is captured by *onaudioprocess* event handler added by the ScriptProcessorNode. The FFT is then hashed using MD5 which acts as an audio fingerprint.

### 3.4.4 Custom Signal Hybrid Method

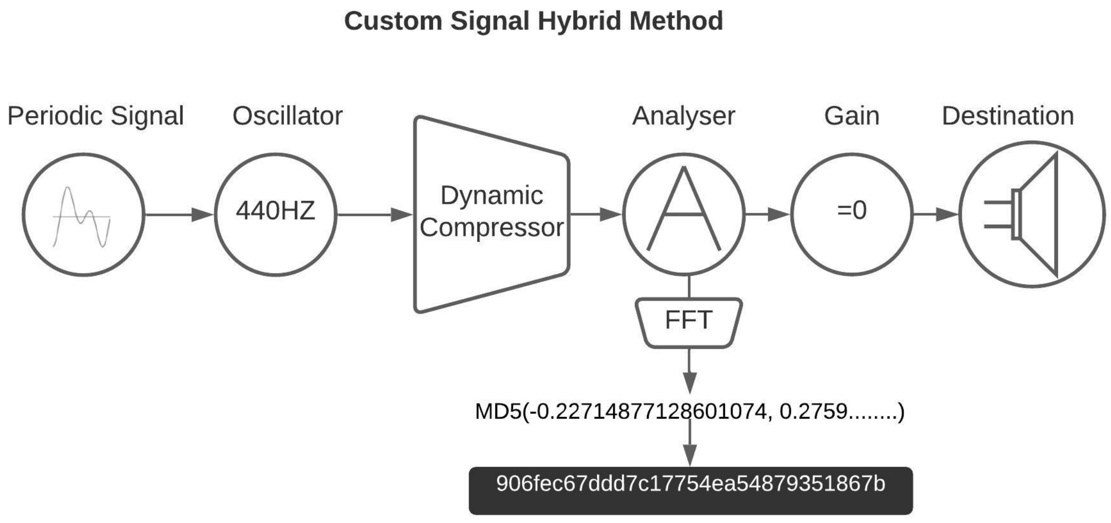

Custom Signal Hybrid Method
Periodic Signal
Oscillator
Analyser
Gain
Destination
440HZ
Dynamic Compressor
=0
FFT
MD5(-0.22714877128601074, 0.2759........)
906fec67ddd7c17754ea54879351867b

Figure 3.7: Custom Signal Hybrid Method

Custom Signal Hybrid Method only differs from Hybrid method in terms of the signal. Instead of using a standard signal (Sine, Triangle, Sawtooth, Square) offered by the Web Audio API, we generate a periodic signal by defining the real and imaginary values as shown in Appendix A.4. Figure 3.7. shows the setup used to generate a unique audio fingerprint of a user using AudioContext interface for custom signal. A custom periodic wave is generated as shown in Figure 3.8 using AudioContext.createPeriodicWave() method which is passed through

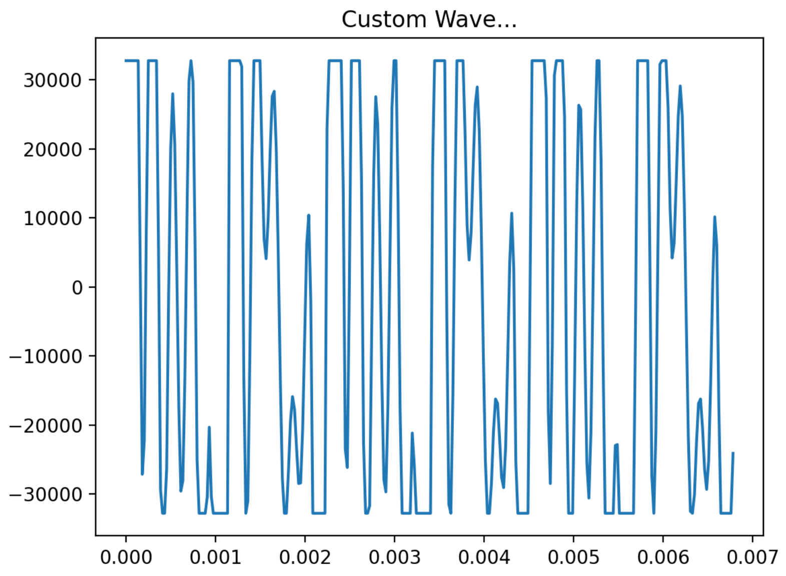


Figure 3.8: Generated Custom Wave

the `DynamicsCompressorNode`. This signal is then passed to an `AnalyserNode` and a `ScriptProcessorNode` as before. Similar as before we use `AnalyserNode` to FFT audio signal, that is captured by *onaudioprocess* event handler added by the `ScriptProcessorNode`. The FFT is then hashed using MD5 which acts as an audio finger-print.

### 3.4.5 Audio Source Hybrid Method

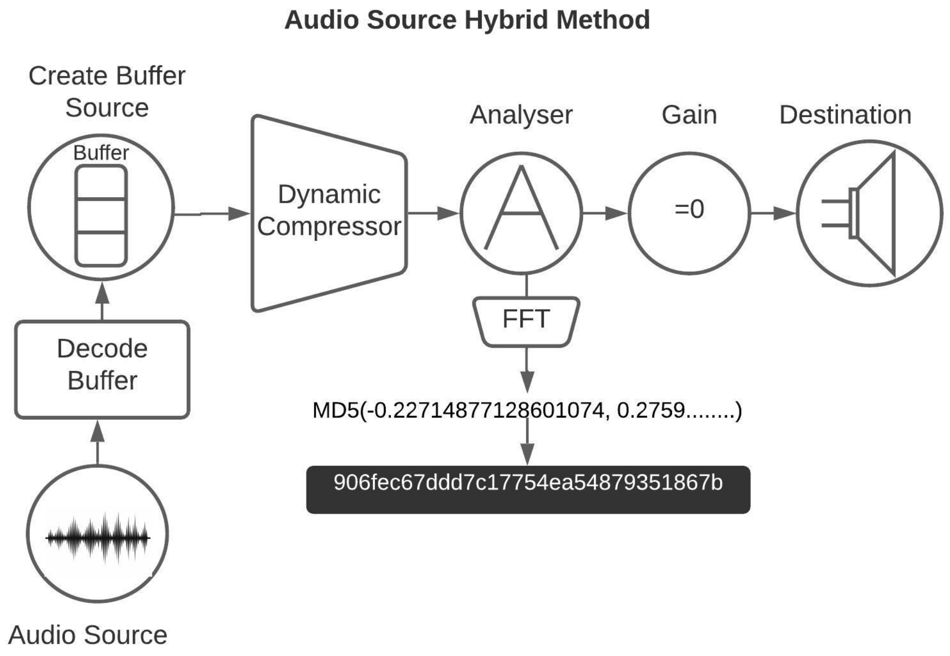

Audio Source Hybrid Method
Create Buffer Source
Buffer
Dynamic Compressor
Analyser
Gain
=0
Destination
FFT
Decode Buffer
MD5(-0.22714877128601074, 0.2759........)
906fec67ddd7c17754ea54879351867b
Audio Source

Figure 3.9: Audio Source Hybrid Method

Audio Source Hybrid is yet another new method that we introduced for audio fingerprinting. This method varies from all of the methods in terms of how the signal is generated. In this method, we used a 40 seconds audio clip [22] that was trimmed down to 5 seconds to make it shorter and suitable for fingerprinting. The audio clip is first decoded using `AudioContext.decodeAudioData()` method to get the audio buffer which is then utilized by `AudioContext.createBufferSource()` to generate the signal as shown in Figure 3.10. This signal is then passed on to the rest of the audio nodes as before. Similarly, the `AnalyserNode` is used to FFT audio signal, that is captured by *onaudioprocess* event handler added by the `ScriptProcessorNode` and then hashed using MD5 to generate an audio finger-

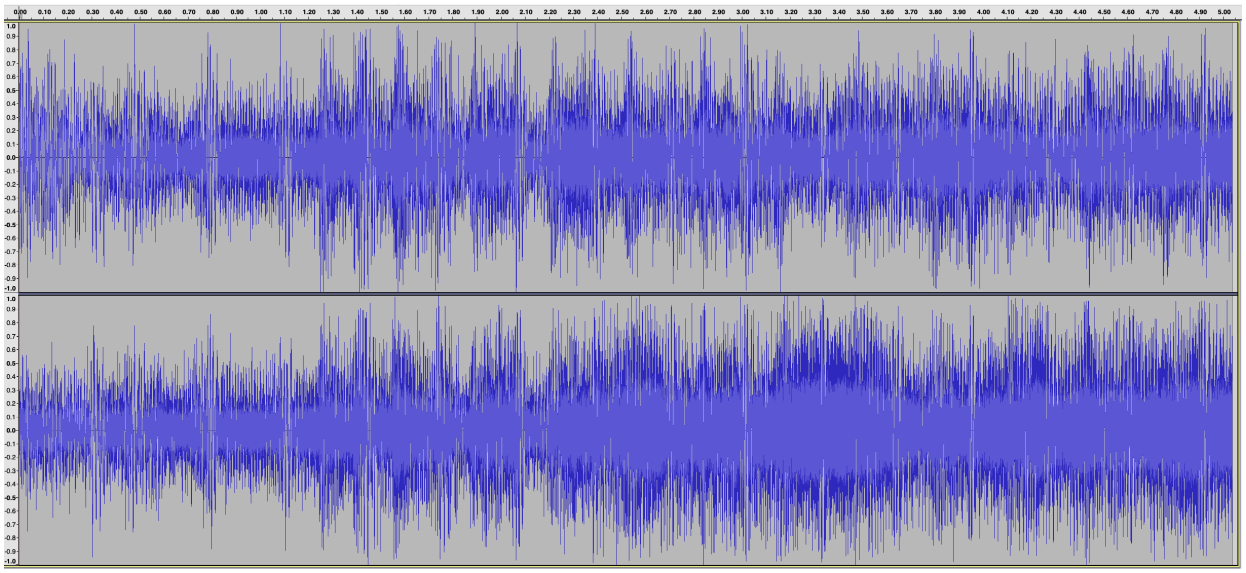


Figure 3.10: Generated Audio Source Wave

print. Figure 3.9 shows the method with different audio nodes used to generate an identifier.

### 3.4.6 Channel Merge Hybrid Method

Channel Merge Hybrid is another addition to audio fingerprinting methods which was created during this research. The idea is to generate multiple signals and merge them using a `ChannelMergeNode`. In this method we create four `OsciallatorNode` with different frequencies and different signal types and merge them together to generate a single waveform. Specifically we create Sine `OsciallatorNode` with frequency 440 HZ, Triangle `OsciallatorNode` with frequency 10000 HZ, Square `OsciallatorNode` with frequency 1880 HZ and Sawtooth `OsciallatorNode` with frequency 22000 HZ. All of these `OscillatorNode` are then connected to the `ChannelMergeNode`. The output of the `ChannelMergeNode` is connected to the `DynamicCompressorNode` as before. The rest of the Audio Nodes remain the same as previous methods with FFT being captured and hashed through the *onaudioprocess* event handler added by the `ScriptProcessorNode`. Figure 3.11 shows the exact implementation of the Channel Merge Hybrid method and Figure 3.12 shows the output of the `ChannelMergeNode`.

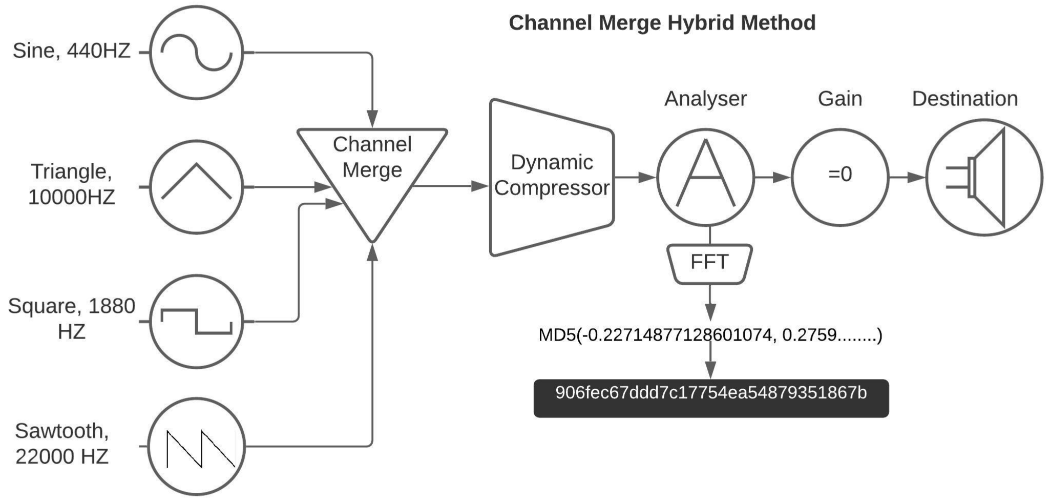


Figure 3.11: Channel Merge Hybrid Method

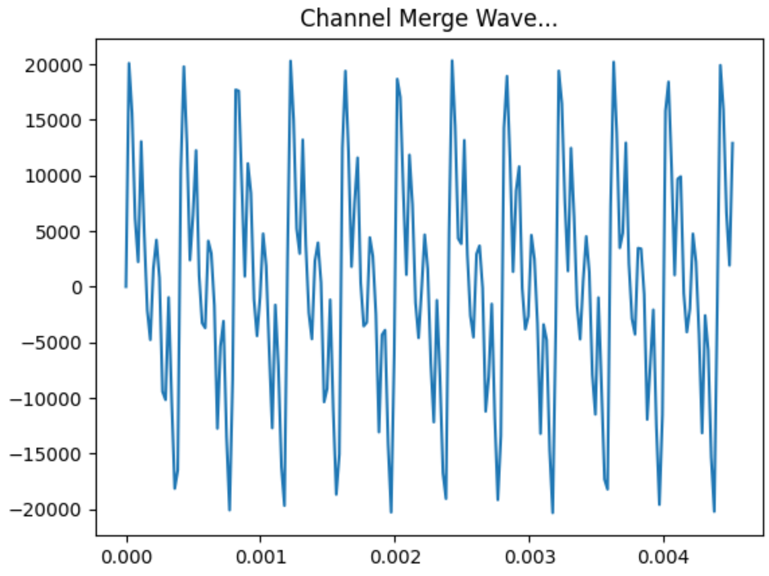


Figure 3.12: Generated Channel Merge Wave

### 3.4.7 Amplitude Modulation Hybrid Method

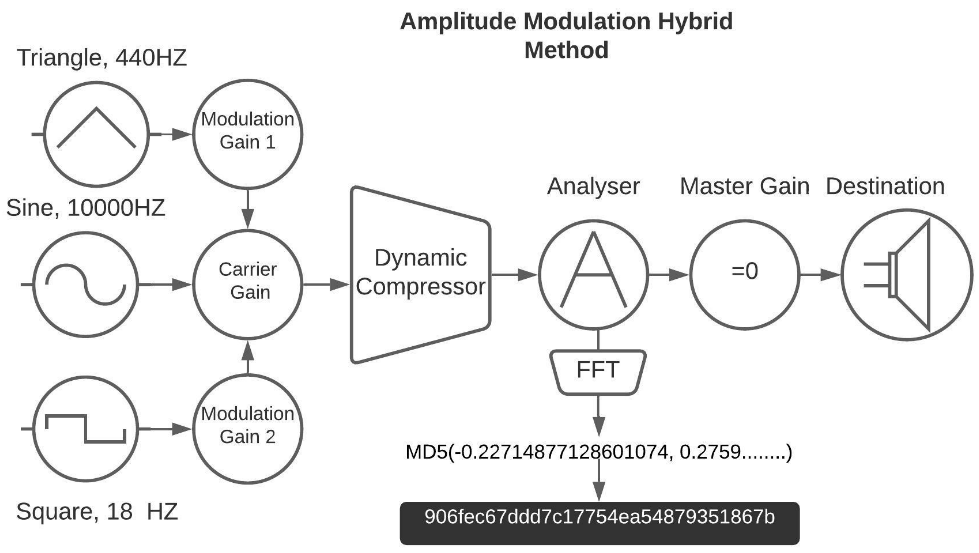


Figure 3.13: Amplitude Modulation Hybrid Method

Amplitude Modulation Hybrid is yet another contribution to the fingerprinting method introduced during this research. The major focus here is also on the signal generation. The rest of the audio nodes remains the same as previous methods where the FFT is being captured and hashed through the *onaudioprocess* event handler added by the `ScriptProcessorNode` to generate an audio fingerprint. We introduce two modulating waves: 1) Triangle, 440HZ 2) Square, 18HZ that are connected to their respective `GainNode`'s. The carrier wave is a Sine wave oscillating at 10000HZ that is connected to its own `GainNode`. The output of the both Modulating `GainNodes` are connected to carrier `GainNode`. This output is then connected to `DynamicCompressor` and the rest of the stack remains the same as well as the process. Figure 3.13 shows the exact implementation of the Amplitude Modulation Hybrid method and Figure 3.14 shows the output of the carrier `GainNode`.

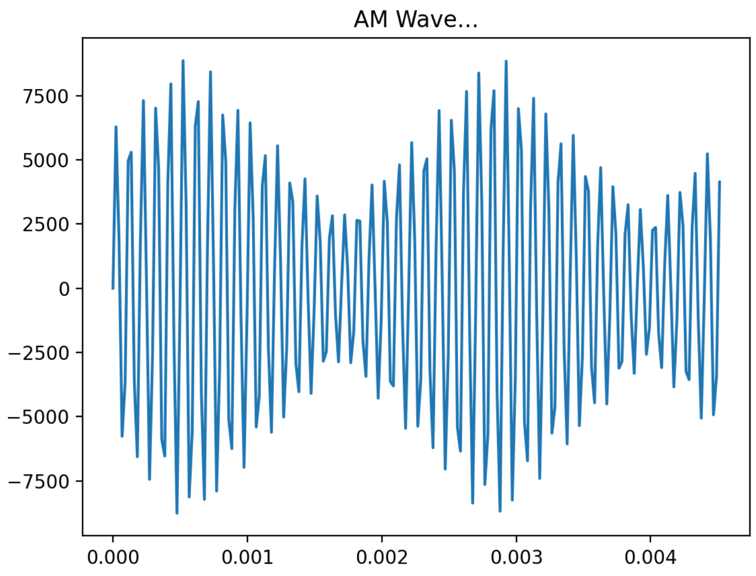


Figure 3.14: Generated Amplitude Modulation Wave

### 3.4.8 Frequency Modulation Hybrid Method

Frequency Modulation Hybrid is another add to fingerprinting method introduced during this research. This method is analogous to Amplitude Modulation Hybrid Method discussed to 3.4.7. Similar to Amplitude Modulation Hybrid Method we introduce two modulating waves: 1) Triangle, 440HZ 2) Square, 18HZ that are connected to their respective `GainNode`'s whose gain is set to 60 and 30 respectively. The carrier wave is a Sine wave oscillating at 10000HZ. The output of the both Modulating `GainNode`'s are connected to carrier frequency. This output is then connected to `DynamicCompressor`. The rest of the audio nodes remains the same as previous methods where the FFT is being captured and hashed through the *onaudioprocess* event handler added by the `ScriptProcessorNode` to generate an audio fingerprint. Figure 3.15 shows the exact implementation of the Frequency Modulation Hybrid method and Figure 3.16 shows the output of the carrier wave.

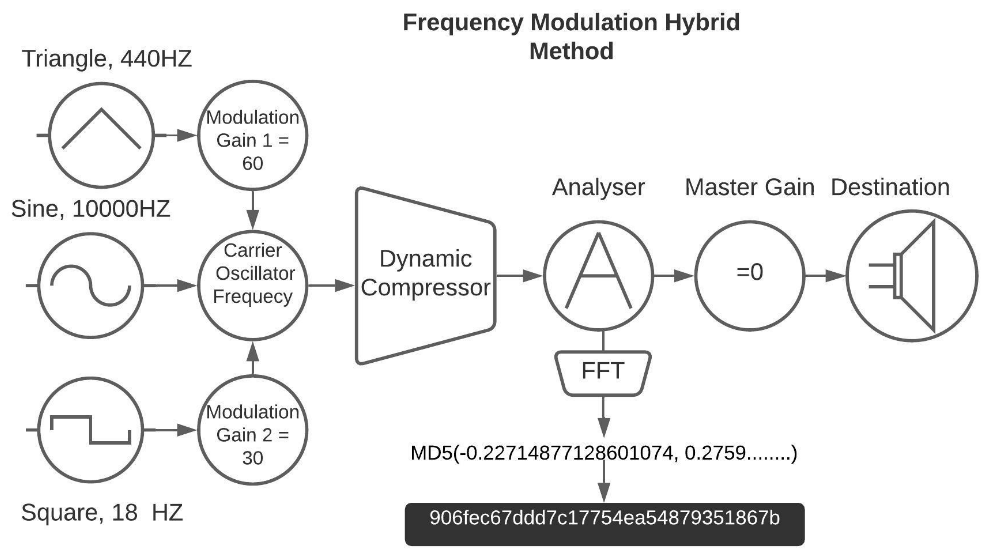


Figure 3.15: Frequency Modulation Hybrid Method

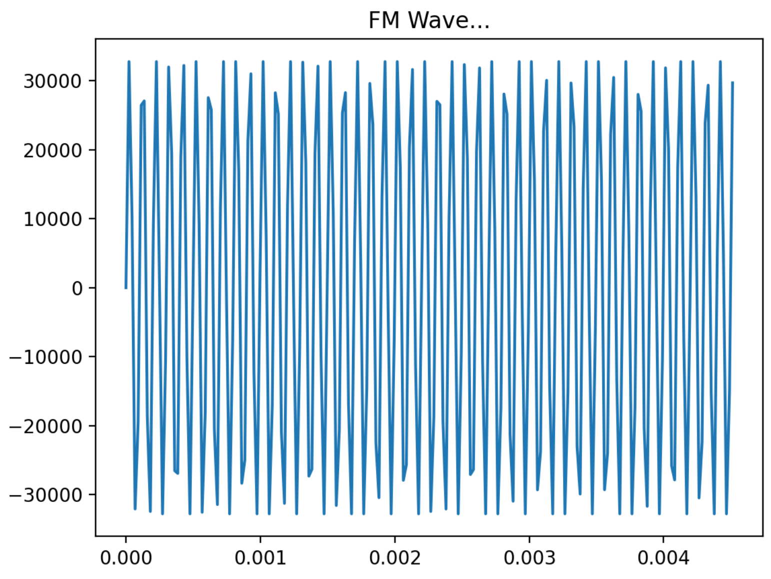


Figure 3.16: Generated Frequency Modulation Wave

## 3.5 FingerprintJS2

FingerprintJS2 is one of the most popular browser fingerprinting library that collects 27 different attributes (at the time of our collection) of browser and hashes them into a single fingerprint called *"vistiorId"* [11]. We primarily used FingprintJS2 to obtain Canvas and Font Fingerprints. We also modified FingerprintJS's font fingerprinting code to expand the list of font from **51 to 1094** [23]. The expanded list of fonts is listed in Appendix A.9.

## 3.6 IP Information

In addition to the FingerprintJS2 fingerprints we also collected IP information of each user that visited our fingerprinting site. We tried several third-party APIs to get user IP information but most of the third-parties were blocked by all of the mainstream browsers and some of the APIs required API-keys and had limits on the number of requests made. However, we were able to successfully get the IP information using a *CloudFlare* API [24]. The *user-agent* collected from this information was used for the further analysis of data in determining the type of device, type of browser and the browser versions used.

## 3.7 User Agent Information

We also used the *Bowser* package to collect the User Agent Information. The library is made to help to detect what browser the user has and gives a convenient API to filter the users depending on their browsers [25].

## 3.8 System Overview

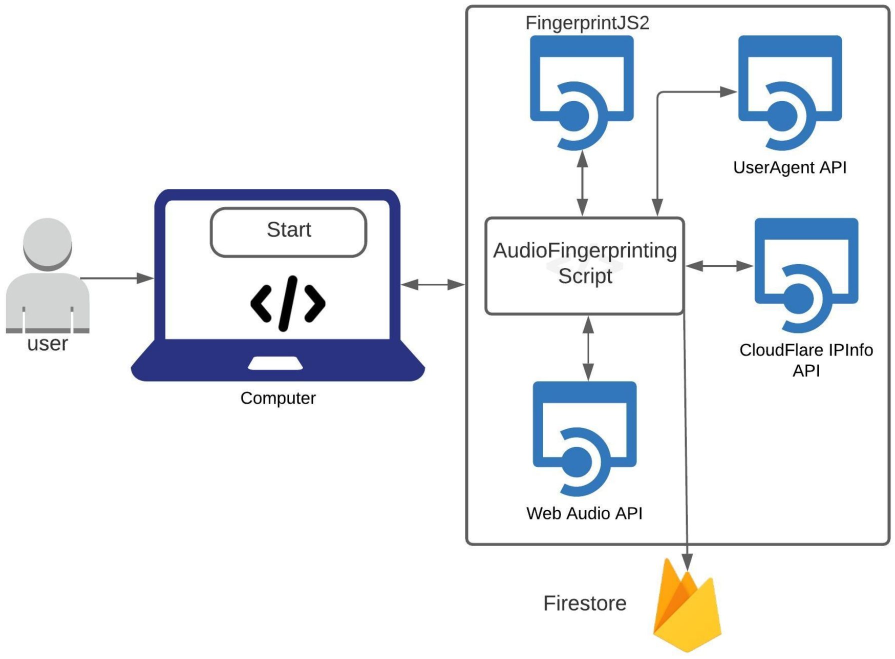


Figure 3.17: System Diagram

Figure 3.17 shows our system overview of our audio fingerprinting project. The center of the system consists of the audio fingerprinting script written in JavaScript (Angular 11.0.4) that utilizes the Web Audio API to generate the fingerprints. The fingerprinting script also uses the popular fingerprinting *FingerprintJS2* to get several components (28) used in browser fingerprinting. The IP information is collected using a *cloudflare* API service [24] and the User Agent is collected using *Bowser* [25]. The collected data is stored in the form of a JSON object in Google Firestore[2]. A cookie is set to each user once the user lands on our fingerprinting page. This cookie acts as an unique identifier in the database.

[2]https://firebase.google.com/docs/firestore

Our script generates 8 different types of audio fingerprints discussed above. For a particular user, all the fingerprints (8) are generated 30 times and saved to the database in each iteration. The code-base resides in GitHub [3] and the project has around 10000 lines of code.

## 3.9 Hosting Stack

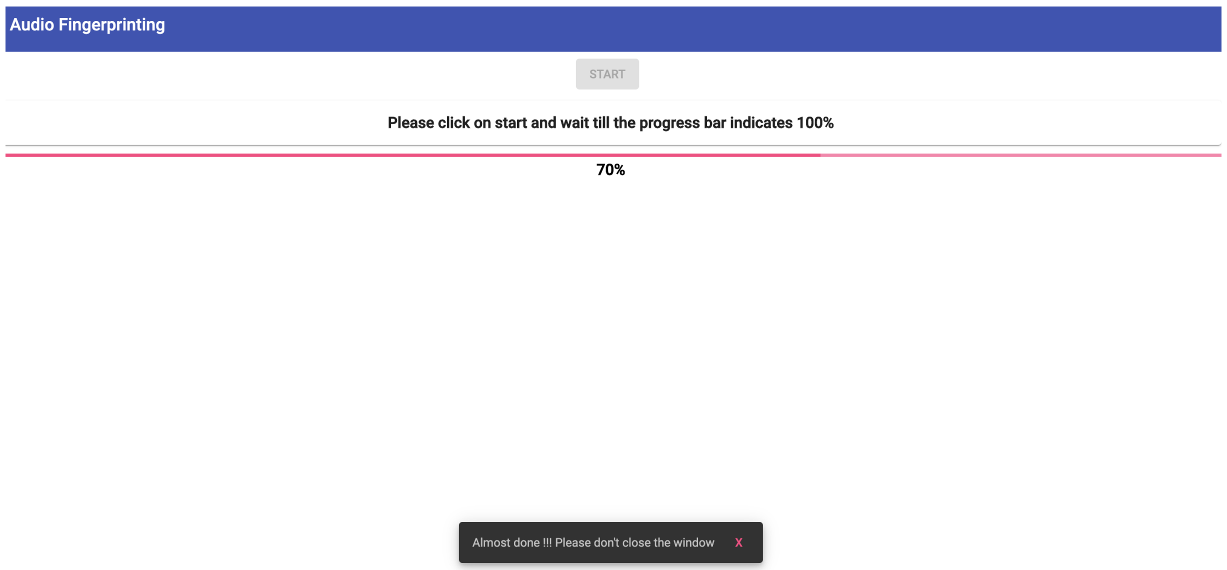
Our entire project is hosted using Firebase Hosting [4]. The web page is hosted as a single page application. The hosting and the firestore is free till 1GiB Stored data, 10 GiB/month Network egress, 20K/day Document writes, 50K/day Document reads and Document deletes 20K/day.

## 3.10 User Study

We conducted our user study using Amazon's Mechanical Turk [26]. Our aim was to get 5000 users for this study. We instructed each user to visit our website [5] and click on the start button and stay on the page until they see a UserID/SurveyID. As soon as the user lands on our website, a unique cookie is set for that user that acts as an identifier in the database. We also instructed each user to submit their UserID/SurveyID once they are done to the MTurk so we can keep a proper track on the progress of our study. For any user the 8 audio fingerprints are generated 30 times and duration of each fingerprinting method is also saved in the database to analyse the average timings.

We had issues with the Apple iOS devices (iPhone, iPad, iPod) not functioning properly with the Web Audio API during testing. These devices were filtered as soon as the user lands on the website and were shown a message saying *"Your iOS device is incompatible. Please try on any other Desktops/Laptops/Android Devices"*. However, the macOS devices(Macbooks/iMACs) had no issues with our setup. Furthermore, the `AudioContext` requires user interaction with the website to instantiate. This restriction made the fingerprinting page unusable without a user clicking on a button to start the fingerprinting. A solution to this problem was to add a "START" button that starts the fingerprinting for that particular user. The website was designed in an interactive way to inform the user of the progress of the fingerprinting with a progress bar and a message

[3]https://github.com/shekharchalise/audio-audiofingerprint
[4]https://firebase.google.com/docs/hosting
[5]https://audiocontextfingerprint.web.app/



Please click on start and wait till the progress bar indicates 100%

70%

Almost done !!! Please don't close the window

Figure 3.18: Fingerprinting Website

saying *"Please click on start and wait till the progress bar indicates 100%"* and *"Almost done!!! Please don't close the window"* to avoid any mid termination of the website by the user that stops our script from running and collecting the data. Figure 3.18 shows the setup of our website that was used for the user study.

# 4. Evaluation

In this section we analyse the data collected during the user study. We also discuss the stability and diversity of the fingerprints. We collected data from 868 users however, after cleaning the data we only used data from 694 users. We discarded the data that were from the same IP address, ones that did not consist of the fingerprints, and the data consisting more than 30 iterations of data which might be caused due to various reasons like browser incompatibility, mid-termination of the fingerprinting website and multiple entry by the same user.

## 4.1 Stability Analysis

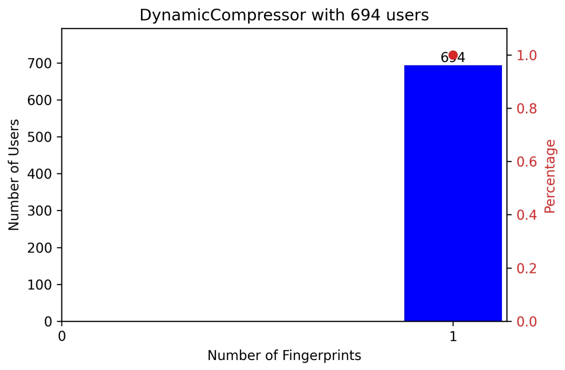
Stability is an important aspect of any fingerprinting method. Once a user fingerprint is collected, it must be reproducible for that user in a subsequent visit. Which means that for any fingerprinting method to increase its effect, it must be stable enough to be generated in a repeated fashion.

### 4.1.1 Statistical Analysis

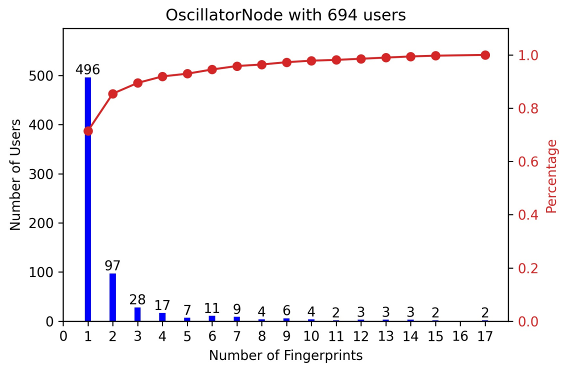
We took a statistical approach to study the stability of the fingerprints. We wanted to run our 8 audio fingerprinting methods under 1 minute for each user. During the testing phase we observed that all of our audio fingerprints could be generated 30 times for each user under 1 minute. This made it possible to study the stability aspect as the fingerprints need to be reproduced in each iteration. To study the stability we grouped fingerprints based on the fingerprinting method used and the total number of fingerprints observed in 30 iterations for a particular user. For instance, a user with 2 different fingerprints in 30 iterations for `OscillatorNode` method falls into group 2, another user with 3 fingerprints in 30 iterations falls into group 3, and so on.

Ideally, a fingerprinting method should only yield one fingerprint even if it is run multiple times. But, the high instability of the computer hardware and software (Web Audio API), makes it not achievable in case of audio fingerprinting. Figure 4.1(a) - Figure 4.1(h) shows the bar graph of the users with respect to the number of fingerprints observed in 30 iterations. The red curve indicates the percentage of users in each group of fingerprints observed. Figure 4.1(a) shows that 100% of the users have a total of one fingerprint in 30 iterations for the `DynamicCompressor` method making it the most stable method. Whereas, Figure 4.1(b) tells a completely different story. Although 71.46% users (496) had a single fingerprint which makes it less stable than `DynamicCompressor`, the remaining users did not generate random fingerprints and the fingerprints were repeating themselves in 30 iterations. For example, there were 9 users with 7 fingerprints in 30 iterations as shown in Figure 4.1(b) which shows the `OscialIatorNode` method was stable to generate audio fingerprints where more than 80% of the users have less than or equal to 7 fingerprints in 30 iterations.

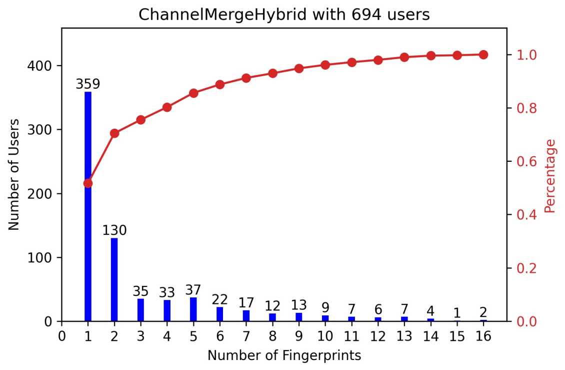
The stability was lowest for Figure 4.1(h), which observed less fingerprints in each group compared to the other methods. However, even for the least stable method, more than 80% of the users have less than or equal to 7 fingerprints in 30 iterations. The extreme number here is 24 for 1 user but not 30 so there is repetition of fingerprints for every user. There exists no column representing a group of size 30 for any audio fingerprinting method; this means that for every user and every fingerprinting vector, there were some fingerprint repetitions thus indicating stability. Results are similar for the reminder of our audio fingerprinting methods. Figure 4.1(f) shows the grouping for 610 users because some of the users were not able to generate the `AudioSourceHybrid` fingerprint due to its complex nature. This clearly answers our first research question on stability **RQ1**.



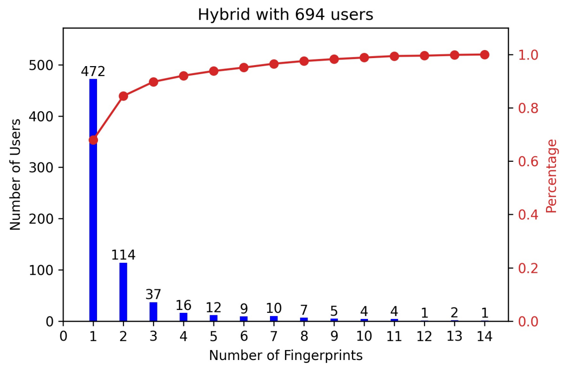
(a) Dynamic Compressor



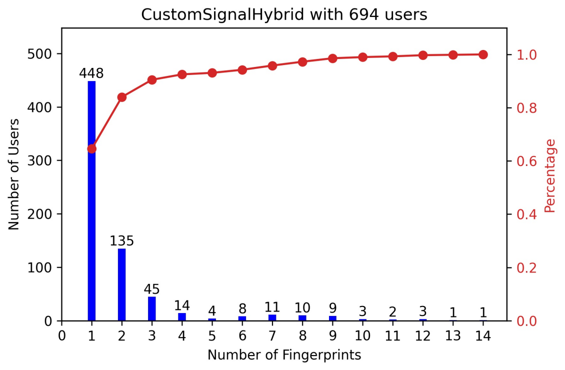
(b) Oscillator Node



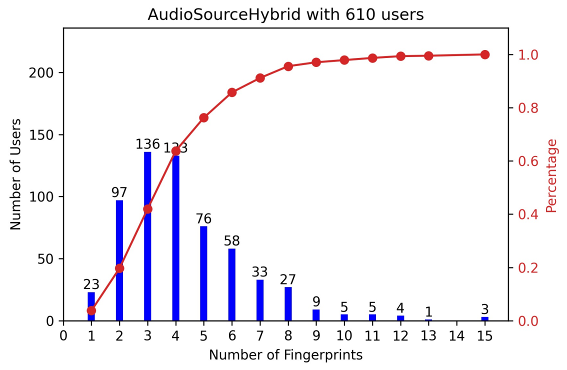
(c) Channel Merge Hybrid



(d) Hybrid

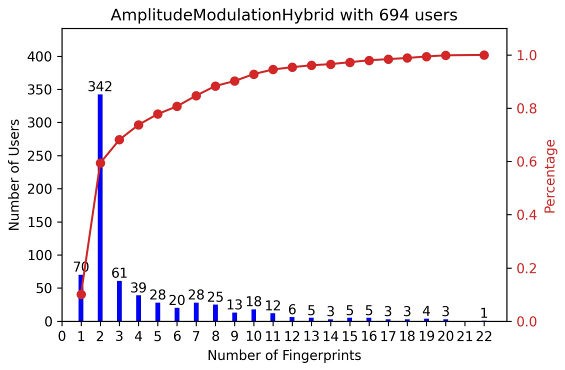


(e) Custom Signal Hybrid

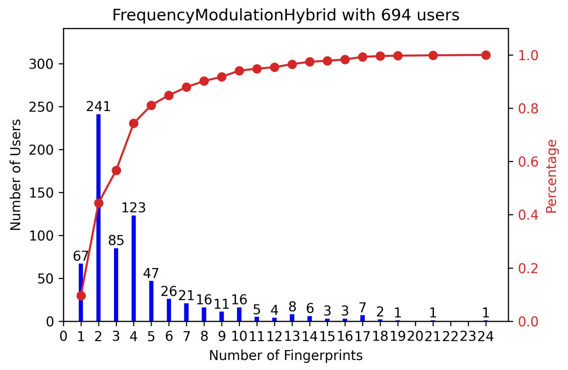


(f) Audio Source Hybrid

Figure 4.1: Bar graphs showing grouping of the number of fingerprints observed for a fingerprinting method cont.



(g) Amplitude Modulation Hybrid



(h) Frequency Modulation Hybrid

Figure 4.1: Bar graphs showing grouping of the number of fingerprints observed for a fingerprinting method

### 4.1.2 Cumulative Distribution Function based approach

We used Cumulative Distribution Function (CDF) [27] to analyse the stability of our fingerprints as shown in Figure 4.2 to solidify our claim on stability. The popularity is the percentage of highest occurring fingerprint value in 30 iterations for each of the fingerprinting methods. Table 4.1 clearly shows that the fingerprints are stable considering the fact that the appearance of the most popular fingerprint occurs at least 2 times in 30 iterations for the `AudioSource` method. This means that even in the worst case the audio fingerprint repeated. Results are more promising for other fingerprinting methods where `DynamicCompressor` shows the best result with the same value occurring 100% of the times in 30 iterations. The graph shows that the `OscillatorNode` method shows that more than 80% of the users observed at least 25 repetitions (83.33%) in 30 iterations indicating stability. Appendix B.1 shows individual CDF plots for all the audio fingerprinting methods.

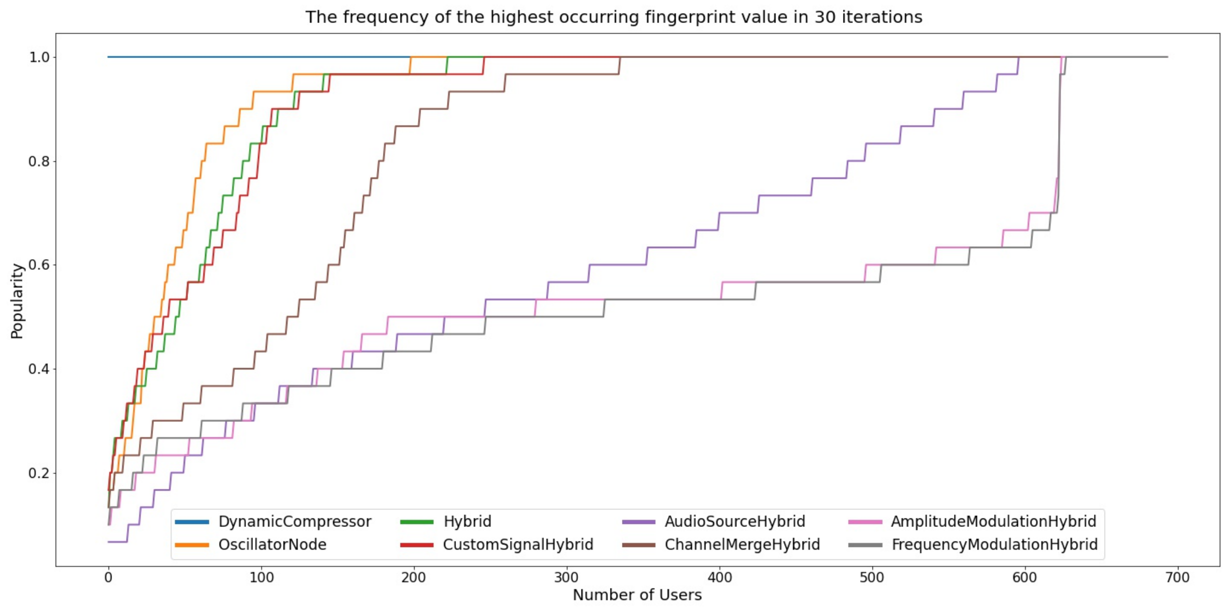


Figure 4.2: The frequency of the highest occurring fingerprint value in 30 iterations

| **Fingerprinting Methods** | **Minimum number of appearances in 30 iterations** |
|---|---|
| DynamicCompressor | 30 |
| OscillatorNode | 5 |
| Hybrid | 4 |
| CustomSignalHybrid | 5 |
| AudioSourceHybrid | 2 |
| ChannelMergeHybrid | 4 |
| AmplitudeModulationHybrid | 3 |
| FrequencyModulationHybrid | 3 |

Table 4.1: Minimum number of appearances of the most popular fingerprint for a user in 30 iterations

## 4.2 Time Analysis

Time and computation is another aspect that is very important for any fingerprinting method. The computational overhead increases the time taken for a fingerprinting method to complete and raise suspicion. Therefore, the fingerprinting method must be computationally efficient to be generated in a certain time frame. In our research we wanted to study the timing stability of our audio fingerprinting methods. Our website collected time taken by each fingerprinting method for each iteration. A particular user running our script will have 30 different timings for each audio fingerprinting method. We first calculated the average time to generate each fingerprint by averaging the time taken to complete 30 iterations for each user for different audio fingerprinting methods. Then that average time is divided by the total users involved in the user study to generate average time to compute each fingerprint once. Table 4.2. shows the average time to generate 8 fingerprints is **1.275** seconds which is analysed with the data from 694 users. The highest time taken is 0.648 seconds by the `DynamicCompressor` method which is probably due its nature of completing the entire buffer rendering that happens in real time. This proves that our entire audio fingerprinting stack is computationally efficient and hence, answers our research question on timing stability **RQ2** and further reinforces our claim on stability.

## 4.3 Diversity Analysis

The first defense to mitigate browser fingerprinting is to decrease the diversity of devices so that real fingerprints are hidden in noise. Diversity that is part of the device fingerprinting, is central to any browser fingerprinting technique. More diverse the fingerprints more easily identifiable the users and more efficient the technique. In this section we compare our audio fingerprinting methods with existing browser fingerprinting methods i.e. Canvas, Font and User-Agent Fingerprinting and try to answer our third research question.

| **Fingerprinting Methods** | **Avg Time (sec)** |
|---|---|
| DynamicCompressor | 0.648 |
| OscillatorNode | 0.106 |
| Hybrid | 0.105 |
| CustomSignalHybrid | 0.106 |
| AudioSourceHybrid | 0.074 |
| ChannelMergeHybrid | 0.103 |
| AmplitudeModulationHybrid | 0.068 |
| FrequencyModulationHybrid | 0.065 |
| **CombinedFingerprint** | **1.275** |

Table 4.2: Average time in seconds to compute each audio fingerprinting method

### 4.3.1 Network Graph based approach

As mentioned in Section 4.1.1 for a particular user there may be more than one fingerprint for a fingerprinting method in 30 iterations. For example for a user running our script can have different `OscillatorNode` fingerprints in different iterations. Unlike Canvas fingerprint where you run a code you get the same result in every iteration, we noticed that although stable, each user would get multiple fingerprints. To account for this instability we choose a network graph based approach using connected nodes to analyse the diversity.

Due to the unstable nature of the audio fingerprints it was not straightforward to do a statistical data analysis to determine the diversity. Our network graph based approach is based on creating a connected node graph between a fingerprint and its associated user for a particular fingerprinting method. To achieve this, we took all the fingerprints for a fingerprinting method and created a map between a fingerprint and a userID. A network graph was created with this data which had two nodes i.e fingerprints and userIDs. Figure 4.3 shows an example of distinct fingerprints group (connected components (CC)) for the collected data. We then calculated the number of distinct, unique, entropy, and normalized entropy of fingerprints for each fingerprinting method using the distinct fingerprint groups of this graph with 694 users as shown in Table 4.3. The number of

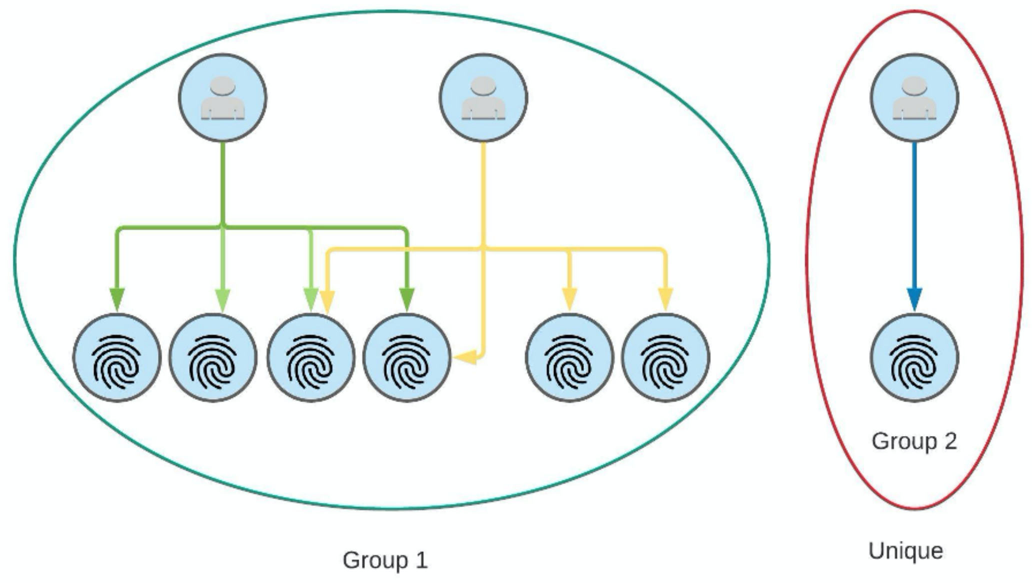


Figure 4.3: An example of distinct fingerprint groups generated with network graph based approach

unique combined fingerprints is calculated by getting the union of all the unique fingerprints for each audio fingerprinting method. In comparison with canvas and font fingerprinting methods that shows 100 unique out of 170 and 232 unique out of 282 distinct users respectively, the best audio fingerprinting method being `Hybrid` shows only 21 unique out of 45 distinct users. If we compare our audio fingerprints with a previous work on Canvas fingerprinting by Gómez-Boix et al., which had 2,067,942 users with 78,037 distinct canvas fingerprints out of which 65,787 were unique [5], it does not yield a very good result in terms of unique and distinct audio fingerprints. Even with 694 users the best fingerprinting method being `Hybrid` could only produce 21 unique fingerprints out of 45 distinct users showing that although stable, audio fingerprints are not diverse enough. This answers our research question number four **RQ4**, only half way through with a comparison with canvas and font fingerprinting. To fully answer our question we compare the audio fingerprints with User-Agent in the Section 4.3.2

| **Fingerprinting Methods** | **# of Users** | **Distinct** | **Unique** | **Entropy** | **Normalized Entropy** |
|---|---|---|---|---|---|
| Canvas | 694 | 170 | 100 | 5.718 | 0.605 |
| Font | 694 | 282 | 232 | 6.553 | 0.694 |
| DynamicCompressor | 694 | 36 | 19 | 2.460 | 0.261 |
| OscillatorNode | 694 | 41 | 20 | 3.712 | 0.393 |
| Hybrid | 694 | 45 | 21 | 3.875 | 0.410 |
| CustomSignalHybrid | 694 | 40 | 19 | 3.558 | 0.377 |
| AudioSourceHybrid | 610 | 36 | 19 | 5.173 | 0.587 |
| ChannelMergeHybrid | 694 | 46 | 21 | 4.327 | 0.458 |
| AmplitudeModulationHybrid | 694 | 46 | 21 | 4.679 | 0.496 |
| FrequencyModulationHybrid | 694 | 46 | 21 | 4.746 | 0.503 |

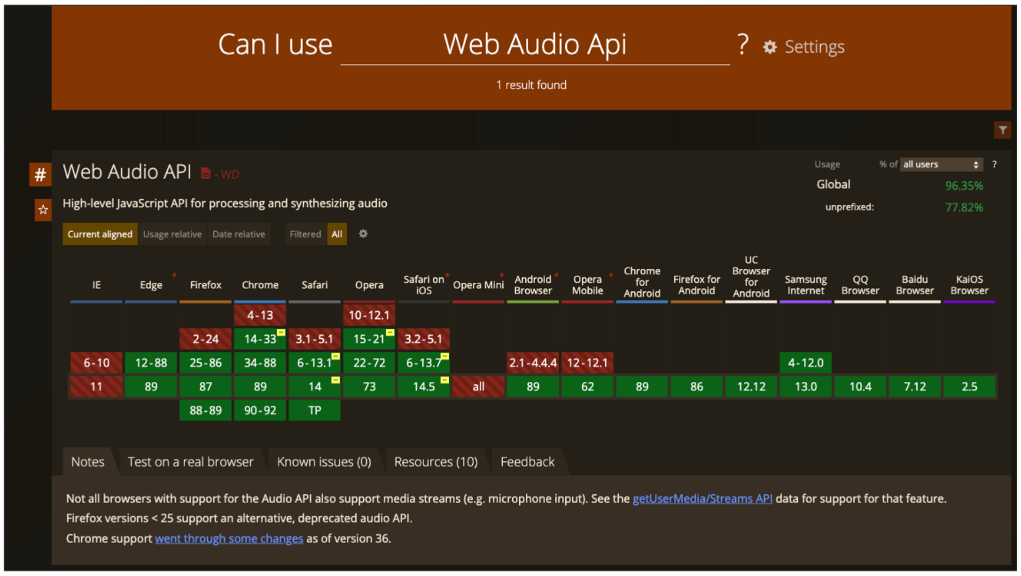
Table 4.3: Number of distinct and unique fingerprints and their entropy and normalized entropy

### 4.3.2 User-Agent Comparison

The User-Agent (UA) request header is a characteristic string that lets servers and network peers identify the application, operating system, vendor, and/or version of the requesting user agent [28]. A User-Agent can be known from the user agent header which is fairly simple, beside that even if a user uses a User-Agent switcher/defense, it is easy to figure out the User-Agent based on what Web API the browser is implementing. Every browser has their own implementation of the Web API and they can decide on the features they want to implement. Browser compatibility[1] can be easily verified and the User-Agent can be easily extracted without any sophisticated technique by getting the differential implementation of Web APIs. Figure 4.4 shows the Web Audio API compatibility across different browsers. With regards to User-Agent we want to know if audio fingerprint diversity was simply an artefact of these implementation differences. In fact, the W3C (World Wide Web Consortium) documentation interestingly makes this exact same point *"This merely allows deduction of information already readily available by easier means (User Agent*

[1]https://caniuse.com/

*string), such as "this is browser X running on platform Y""* [2]. To get an answer to this question as well as to answer the research question **RQ4** and ultimately answer the research question on diversity **RQ3**, we want to compare the audio fingerprints with User-Agent.



High-level JavaScript API for processing and synthesizing audio

Global 96.35%
unprefixed: 77.82%

| IE | Edge | Firefox | Chrome | Safari | Opera | Safari on iOS | Opera Mini | Android Browser | Opera Mobile | Chrome for Android | Firefox for Android | UC Browser for Android | Samsung Internet | QQ Browser | Baidu Browser | KaiOS Browser |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | 4-13 |  | 10-12.1 |  |  |  |  |  |  |  |  |  |  |  |
|  |  | 2-24 | 14-33 | 3.1-5.1 | 15-21 | 3.2-5.1 |  |  |  |  |  |  |  |  |  |  |
| 6-10 | 12-88 | 25-86 | 34-88 | 6-13.1 | 22-72 | 6-13.7 |  | 2.1-4.4.4 | 12-12.1 |  |  |  | 4-12.0 |  |  |  |
| 11 | 89 | 87 | 89 | 14 | 73 | 14.5 | all | 89 | 62 | 89 | 86 | 12.12 | 13.0 | 10.4 | 7.12 | 2.5 |
|  |  | 88-89 | 90-92 | TP |  |  |  |  |  |  |  |  |  |  |  |  |

Notes | Test on a real browser | Known issues (0) | Resources (10) | Feedback

Not all browsers with support for the Audio API also support media streams (e.g. microphone input). See the getUserMedia/Streams API data for support for that feature.
Firefox versions < 25 support an alternative, deprecated audio API.
Chrome support went through some changes as of version 36.

Figure 4.4: Browser compatibility of Web Audio API across different browsers

| Browser/OS | Mapping |
|---|---|
| Samsung Internet for Android | Chrome |
| Yandex Browser | Chrome |
| Microsoft Edge | Chrome |
| Opera | Chrome |

Table 4.4: Browser mapping

[2]https://www.w3.org/TR/webaudio/#priv-sec

We used the diverse fingerprint group (connected components(CC)) discussed in the Section 4.3.1 to further modify our code to find different User-Agent and Browser/Operating System (OS) combinations in one connected component. In order to plot the browser/OS combination in a more manageable way, we considered the browser and OS using the same base as the same entity. We considered Chrome and Firefox as the primary browsers and Windows, Linux, macOS and Linux as the primary OSs. Table 4.4 shows the mapping of different browsers to primary Browser. Figure 4.5 - 4.12 shows a homogeneity in browser and OS combination for all the audio fingerprinting vectors. The top text of each bar indicates the number of users / number of User-Agent associated with that distinct fingerprint group. We see that the majority of the groups either have the same browser or OS configuration. We see that the results are very uniform as we see that every distinct group is associated with only one browser either Firefox or Chrome but not both and at most 2 OSs. There is a lot of uniformity in terms of fingerprint groups and browser OS combination they are manifested in. Although every fingerprint group is associated with one browser, no browser is associated with only one fingerprint. For example Figure 4.5 shows 6 different fingerprint groups of Chrome/Android users with different numbers of users in each group. This means that each browser is associated with more than one fingerprint.

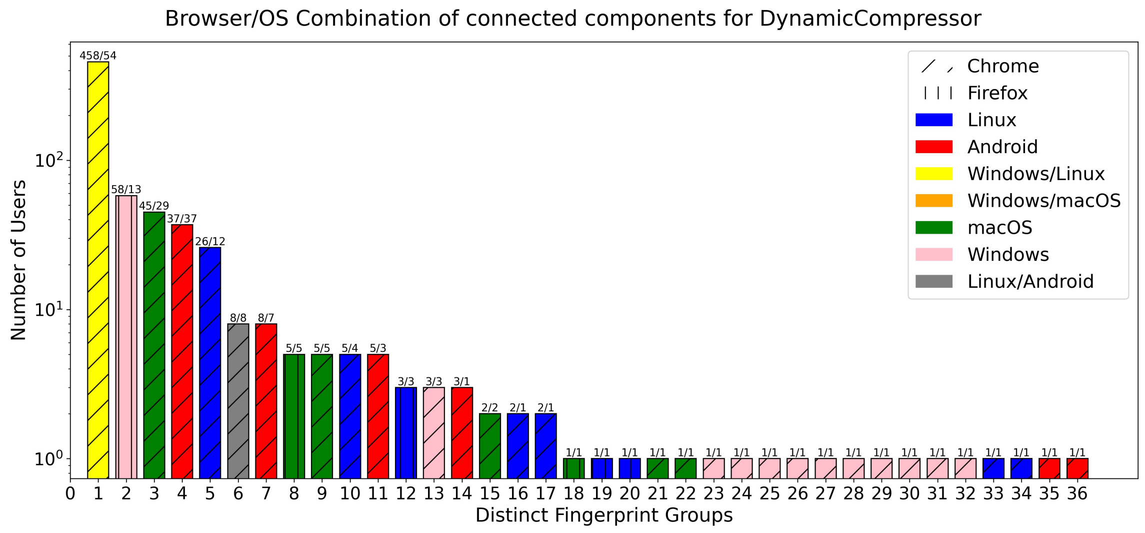


Figure 4.5: Browser/OS combination of distinct fingerprint group for DynamicCompressor

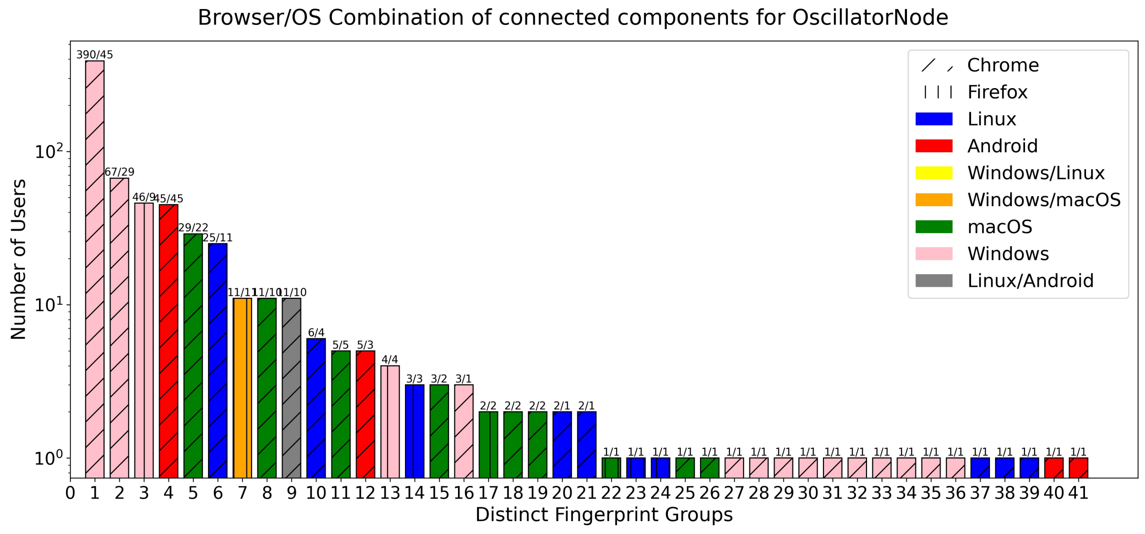


Figure 4.6: Browser/OS combination of distinct fingerprint group for OscillatorNode

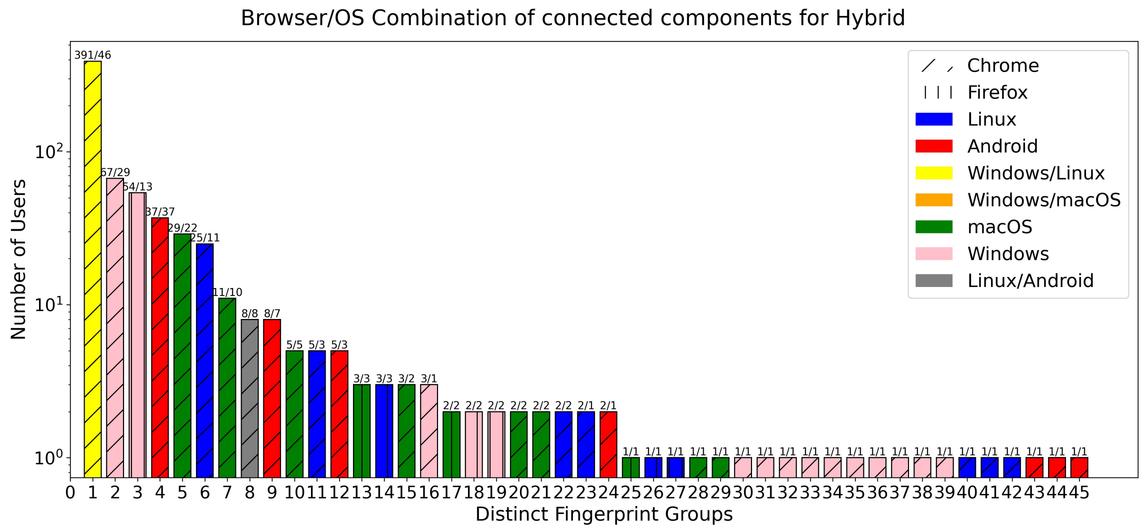


Figure 4.7: Browser/OS combination of distinct fingerprint group for Hybrid

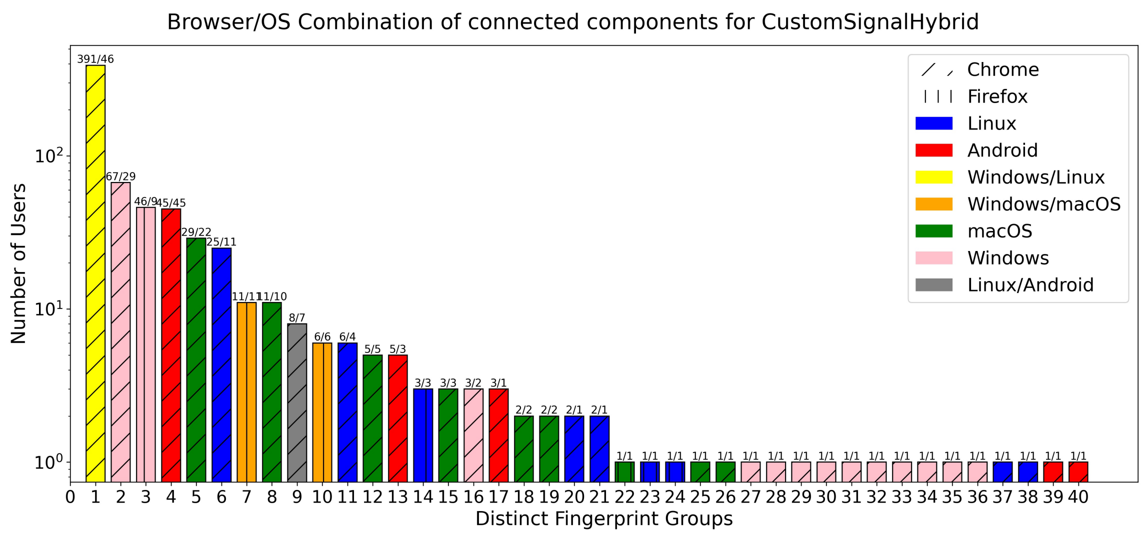


Figure 4.8: Browser/OS combination of distinct fingerprint group for CustomSignalHybrid

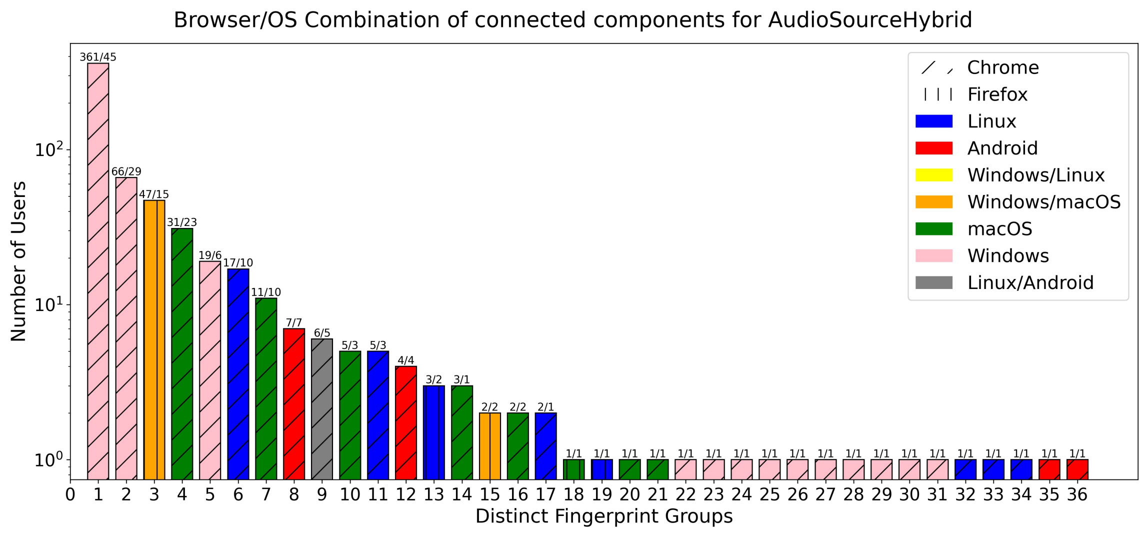


Figure 4.9: Browser/OS combination of distinct fingerprint group for AudioSourceHybrid

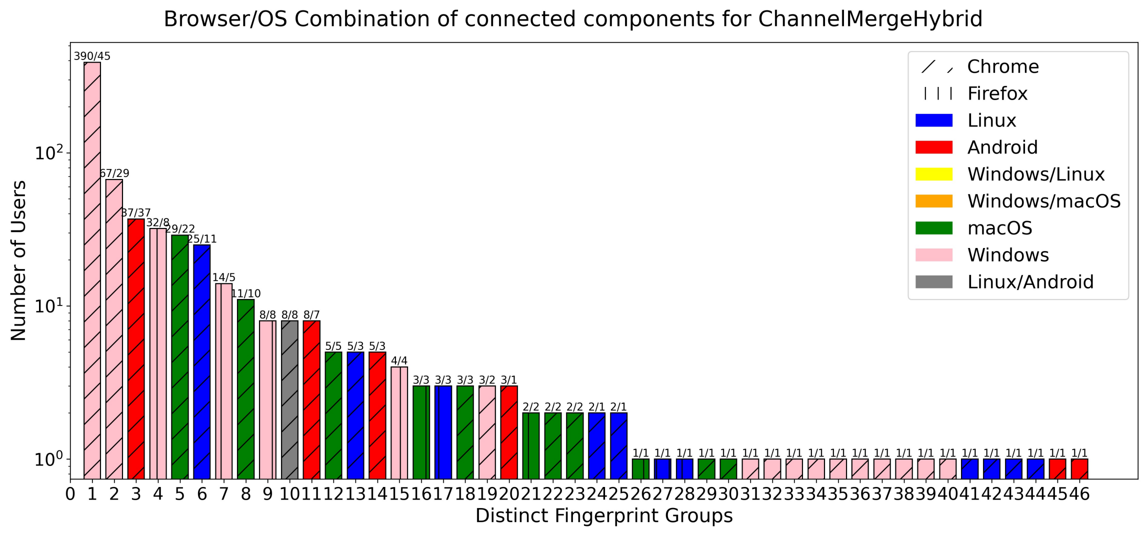


Figure 4.10: Browser/OS combination of distinct fingerprint group for ChannelMergeHybrid

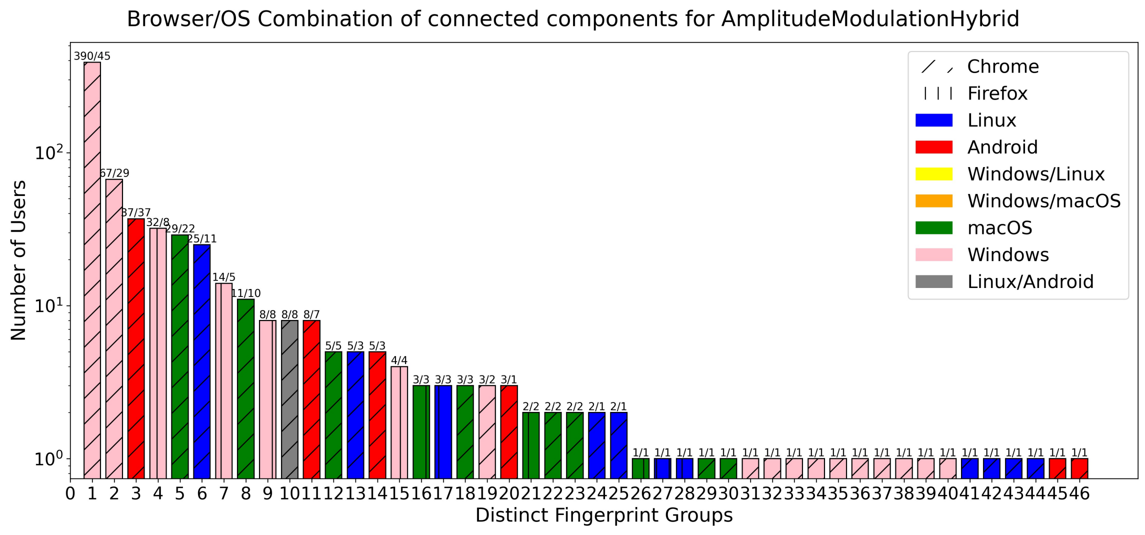


Figure 4.11: Browser/OS combination of distinct fingerprint group for AmplitudeModulationHybrid

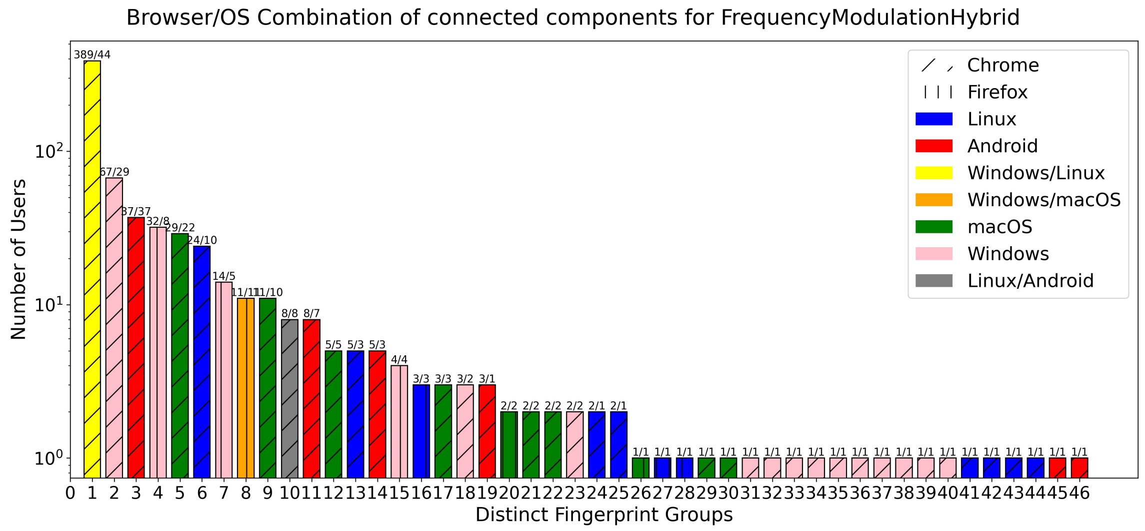


Figure 4.12: Browser/OS combination of distinct fingerprint group for FrequencyModulationHybrid

We also wanted to see if audio fingerprints are a subset of User-Agents. In order to answer that we wanted to see if a single User-Agent is connected to multiple groups. We again utilized the distinct fingerprint group (connected component(CC) from 4.3.1 to find the total distinct and unique User-Agents in the user-study for each fingerprinting method. Then, used the difference between distinct and unique User-Agents to find the non-unique User-Agents for each distinct group to get the association between User-Agent and audio fingerprints. Table 4.5 shows that one User-Agent is spread across multiple groups for each fingerprinting technique. This means that two users having the same User-Agent can have different audio fingerprints. Unlike what the World Wide Web Consortium Document states we found that audio fingerprints can add incremental value to user-agent fingerprinting as there are a number of cases with same user-agent users having multiple audio fingerprints. Although audio fingerprints are better than User-Agents, we see that they do not hold notable value as Canvas and Font fingerprints. Thus, we arrive at a judgement about diversity of audio fingerprints saying that audio fingerprints are better than User-Agent fingerprint, however, they are not adequately diverse to be used as a standalone fingerprinting mechanism and answer our research question **RQ3**.

| **Fingerprinting Methods** | **# of UAs spanning $>$ 1 FP goups** |
|---|---|
| DynamicCompressor | 8 |
| OscillatorNode | 36 |
| Hybrid | 35 |
| CustomSignalHybrid | 36 |
| AudioSourceHybrid | 31 |
| ChannelMergeHybrid | 36 |
| AmplitudeModulationHybrid | 36 |
| FrequencyModulationHybrid | 36 |

Table 4.5: Number of User-Agents spanning on more than 1 diverse fingerprint group

# 5. Discussion

## 5.1 Limitations

The analysis presented in this work has several methodological and measurement limitations. We tested our fingerprinting script using sine wave before settling for triangle wave, which showed similar results. Using other types of single such as square, saw-tooth and even changing the parameters of the `AudioContext` and `OfflineAudioContext` attributes may result in better unique fingerprints. However, we tested 8 different audio fingerprinting methods by obtaining FFTs of audio source files, modulated waves and custom waveforms, where we saw similar results across all the audio fingerprinting vectors. So we think that even if we try different waves and different audio parameters, we will end up with similar results. Secondly, in comparison to popular fingerprinting methods like Canvas and Font Fingerprinting based studies, our study is relatively small. However, even in the small size we see that audio fingerprints are less diverse in comparison to Canvas and Font, so we think that the results are going to hold up even in a bigger study. Thirdly, we had limited financial resources that hindered us to increase the number of users.

## 5.2 Future Work

We focus on the privacy concerned browser like *Brave* and understand their defenses against the audio fingerprinting. We want to understand the defenses proposed and study the robustness of these defenses. We also want to understand the value of audio fingerprints when used in conjunction with the existing browsers fingerprinting techniques like Canvas and Font fingerprinting. In addition, we would also like to conduct a larger user-study to solidify our findings in a more systematic and methodological way.

## 5.3 Conclusion

In this work, we tested the resilience of the mainstream browsers against audio fingerprinting on mobile and desktop. In order to do this, we devised an audio fingerprinting script based on earlier research [6, 8] and added 5 more techniques that collected 694 fingerprints across mobile and desktops. We analysed the stability of the audio fingerprinting methods which shows that the audio fingerprinting methods are stable when repeated multiple times in a timed setting. The diversity analysis, however shows that although the audio fingerprints are stable but they are not diverse enough to be used a single browser fingerprinting method by comparing it with the popular browser fingerprinting methods like Canvas, Font and User-Agent fingerprinting. Audio fingerprinting is important and has a tracking value which is better than User-Agent. Users with the same User-Agent can have different audio fingerprints but it does not have as significant value as Canvas and Font fingerprints. However, if used in conjunction with the more popular fingerprinting mechanism, the audio fingerprints can have an incremental value. Thus, with the statements presented here we finally answer the research question **RQ6** saying that standalone audio fingerprints does not have as much diversity as existing fingerprinting mechanism, however, it does have incremental value, so further studies are needed.

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# Appendix A

# Code snippets

```
getDynamicCompressorFingerprint(): Promise<any> {
  let sumBuffer = 0;
  let sumBufferHash = null;
  return new Promise((resolve, reject) => {
    try {
      let offlineAudioCtx = new ((<any>window).OfflineAudioContext || (<any>window).webkitOfflineAudioContext)(OFFLINEAUDIOCTX.
    numberOfChannels, OFFLINEAUDIOCTX.length, OFFLINEAUDIOCTX.sampleRate);
      if (offlineAudioCtx) {
        let oscillator =  offlineAudioCtx.createOscillator();
        oscillator.type = SIGNAL_TYPE;
        oscillator.frequency.value = FREQUENCY;

        // Create and configure compressor
        let compressor = offlineAudioCtx.createDynamicsCompressor();
        compressor.threshold && (compressor.threshold.value = COMPRESSOR.threshold);
        compressor.knee && (compressor.knee.value = COMPRESSOR.knee);
        compressor.ratio && (compressor.ratio.value = COMPRESSOR.ratio);
        // compressor.reduction && (compressor.reduction.value = -20);
        compressor.attack && (compressor.attack.value = COMPRESSOR.attack);
        compressor.release && (compressor.release.value = COMPRESSOR.release);

        // Connect nodes
        oscillator.connect(compressor);
        compressor.connect(offlineAudioCtx.destination);

        // Start audio processing
        oscillator.start(0);
        offlineAudioCtx.startRendering();
        offlineAudioCtx.oncomplete = ((evnt: any) => {
          sumBuffer = 0;
          let MD5 =  CryptoJS.algo.MD5.create();
          for (let i = 0; i < evnt.renderedBuffer.length; i++) {
            MD5.update(evnt.renderedBuffer.getChannelData(0)[i].toString());
          }
          const hash = MD5.finalize();
          sumBufferHash = hash.toString(CryptoJS.enc.Hex);
          for (let i = 4500; 5e3 > i; i++) {
            sumBuffer += Math.abs(evnt.renderedBuffer.getChannelData(0)[i]);
          }
          oscillator.disconnect();
          //console.log({"dynamicCompressor": sumBufferHash, "sum": sumBuffer});
          //alert("dynamiccompressor " +sumBufferHash)
          resolve({"hash": sumBufferHash, "sum": sumBuffer, "noFingerprint": false});
        });
      } else {
        reject({"hash": sumBufferHash, "sum": sumBuffer, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": sumBufferHash, "sum": sumBuffer, "noFingerprint": true});
    }
  });
}
```

Listing A.1: DynamicCompressor fingerprint generation code

```
getOscillatorNodeFingerprint(): Promise<any> {
  let oscillatorNode = [];
  let hash = null;
  return new Promise((resolve, reject) => {
    try {
      let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioCtx) {
        let oscillator = audioCtx.createOscillator();
        let analyser = audioCtx.createAnalyser();
        let gain = audioCtx.createGain();
        let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);
        gain.gain.value = 1; // Disable volume
        analyser.fftSize = 2048;
        oscillator.type = SIGNAL_TYPE // Set oscillator to output wave
        oscillator.connect(analyser); // Connect oscillator output to analyser input
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(gain); // Connect scriptProcessor output to gain input
        gain.connect(audioCtx.destination); // Connect gain output to audiocontext destination
        scriptProcessor.onaudioprocess = (async (event) => {
            const bins = new Float32Array(analyser.frequencyBinCount);
            analyser.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
              oscillatorNode.push(bins[i]);
            }
            analyser.disconnect();
            scriptProcessor.disconnect();
            gain.disconnect();
            const audioFP = JSON.stringify(oscillatorNode);
            hash = CryptoJS.MD5(audioFP).toString();
            await audioCtx.close();
            resolve({"hash": hash, "values": oscillatorNode, "noFingerprint": false});
        });
        oscillator.start(0);
      } else {
        reject({"hash": hash, "values": oscillatorNode, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": hash, "values": oscillatorNode, "noFingerprint": true});
    }
  });
}
```

Listing A.2: OscillatorNode fingerprint generation code

```
getHybridFingerprintWithAudioCtx(): Promise<any> {
  let hybridOscillatorNode = [];
  let hybridHash = null;
  return new Promise((resolve, reject) => {
    try {
      let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioCtx) {
        let oscillator = audioCtx.createOscillator();
        let analyser = audioCtx.createAnalyser();
        let gain = audioCtx.createGain();
        let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);

        // Create and configure compressor
        let compressor = audioCtx.createDynamicsCompressor();
        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioCtx.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioCtx.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioCtx.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioCtx.currentTime);
        compressor.release.setValueAtTime(COMPRESSOR.release, audioCtx.currentTime);

        gain.gain.value = 0; // Disable volume
        analyser.fftSize = 2048;
        oscillator.type = SIGNAL_TYPE // Set oscillator to output triangle wave
        oscillator.connect(compressor); // Connect oscillator output to dynamic compressor
        compressor.connect(analyser); // Connect compressor to analyser
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(gain); // Connect scriptProcessor output to gain input
        gain.connect(audioCtx.destination); // Connect gain output to audiocontext destination
        scriptProcessor.onaudioprocess = (async (bins: any) => {
            bins = new Float32Array(analyser.frequencyBinCount);
            analyser.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
                hybridOscillatorNode.push(bins[i]);
            }
            analyser.disconnect();
            scriptProcessor.disconnect();
            gain.disconnect();
            const audioFP = JSON.stringify(hybridOscillatorNode);
            hybridHash = CryptoJS.MD5(audioFP).toString();
            await audioCtx.close();
            resolve({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": false});
        });
        oscillator.start(0);
      } else {
        reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
    }
  });
}
```

Listing A.3: Hybrid fingerprint generation code

```
getCustomSignalHybridFingerprintAudioCtx(): Promise<any>  {
  let hybridOscillatorNode = [];
  let hybridHash = null;
  return new Promise(async (resolve, reject) => {
    try {
      let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioCtx) {
        const OFFSET = 0.7;
        const pi = Math.PI;
        // https://medium.com/web-audio/phase-offsets-with-web-audio-wavetables-c7dc85ac3218
        // https://meettechniek.info/additional/additive-synthesis.html
        const real = new Float32Array(11);
        const imag = new Float32Array(11);
        real[0] = 0.360;
        real[1] = 0.760;
        real[2] = 0.120;
        real[3] = 0.745;
        real[4] = 0.235;
        real[5] = 0.145;
        real[6] = 0.545;
        real[7] = 0.675;
        real[8] = 0.585;
        real[9] = 0.685;
        real[10] = 0.115;
        real[11] = 0.660;

        imag[0] = pi/2;
        imag[1] = 0;
        imag[2] = pi/2;
        imag[3] = 0;
        imag[4] = pi/2;
        imag[5] = 0;
        imag[6] = pi/2;
        imag[7] = 0;
        imag[8] = pi/2;
        imag[9] = 0;
        imag[10] = pi/2;
        imag[11] = 0

        const wave = audioCtx.createPeriodicWave(real, imag, { disableNormalization: true });
        let oscillator =  audioCtx.createOscillator();
        oscillator.frequency.value = 440;
        oscillator.setPeriodicWave(wave);
        const offset = audioCtx.createConstantSource();
        offset.offset.value = OFFSET;
        let analyser = audioCtx.createAnalyser();
        let gain = audioCtx.createGain();
        let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);

        let compressor = audioCtx.createDynamicsCompressor();
        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioCtx.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioCtx.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioCtx.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioCtx.currentTime);
        compressor.release.setValueAtTime(COMPRESSOR.release, audioCtx.currentTime);

        gain.gain.value = 0; // Disable volume
        analyser.fftSize = 2048;
        oscillator.connect(compressor); // Connect oscillator output to dynamic compressor
        compressor.connect(analyser); // Connect oscillator output to dynamic compressor
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(gain); // Connect scriptProcessor output to gain input
        gain.connect(audioCtx.destination); // Connect gain output to audiocontext destination

        scriptProcessor.onaudioprocess = (async (bins: any) => {
          bins = new Float32Array(analyser.frequencyBinCount);
          analyser.getFloatFrequencyData(bins);
          for (let i = 0; i < bins.length; i++) {
            hybridOscillatorNode.push(bins[i]);
          }
          analyser.disconnect();
          scriptProcessor.disconnect();
          gain.disconnect();
          const audioFP = JSON.stringify(hybridOscillatorNode);
          hybridHash = CryptoJS.MD5(audioFP).toString();
          await audioCtx.close();
          resolve({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": false});
        });
        oscillator.start(0);
        offset.start();
      } else {
        reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
    }
  });
}
```

Listing A.4: Custom Signal Hybrid fingerprint generation code

```
getAudioSourceHybridFingeprintAudioCtx(): Promise<any> {
  let audioData = null;
  let hash= null;
  let analyserNodeData = [];
  return new Promise((resolve, reject) => {
    try {
      const audioContext = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioContext) {
        const sourceNode = audioContext.createBufferSource();
        const analyserNode = audioContext.createAnalyser();
        const gain = audioContext.createGain();
        const scriptProcessor = audioContext.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.
    numberOfInputChannels, SCRIPT_PROCESSOR.numberOfOutputChannels);
         // Create and configure compressor
        const compressor = audioContext.createDynamicsCompressor();
        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioContext.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioContext.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioContext.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioContext.currentTime);
```

```
          compressor.release.setValueAtTime(COMPRESSOR.release, audioContext.currentTime);
          gain.gain.value = 0; // Disable volume
          analyserNode.fftSize = 2048;

          // Now connect the nodes together
          sourceNode.connect(compressor);
          compressor.connect(analyserNode);
          analyserNode.connect(scriptProcessor);
          scriptProcessor.connect(gain);
          gain.connect(audioContext.destination);

          scriptProcessor.onaudioprocess = (async (event: any) => {
            const bins = new Float32Array(analyserNode.frequencyBinCount);
            analyserNode.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
              analyserNodeData.push(bins[i]);
            }
            const audioFP = JSON.stringify(analyserNodeData);
            hash = CryptoJS.MD5(audioFP).toString();
            gain.disconnect();
            scriptProcessor.disconnect();
            analyserNode.disconnect();
            await audioContext.close();
            resolve({"hash": hash, "values": analyserNodeData, "noFingerprint": false});
          });
          // Load the Audio the first time through, otherwise play it from the buffer
          if(audioData == null) {
            const request = new XMLHttpRequest();
            request.open('GET', '../../../assets/viper-05.ogg', true);
            request.responseType = 'arraybuffer';
            request.onload = (() => {
              audioContext.decodeAudioData(request.response, function(buffer){
                audioData = buffer;
                sourceNode.buffer = buffer;
                sourceNode.start(0);    // Play the sound now
                sourceNode.loop = false;
              },
              function(e){"Error with decoding audio data" + e});
            });
            request.send()
          } else {
            sourceNode.buffer = audioData;
            sourceNode.start(0);    // Play the sound now
            sourceNode.loop = false;
          }
        } else {
          reject({"hash": hash, "values": analyserNodeData, "noFingerprint": true});
        }
      } catch(u) {
        reject({"hash": hash, "values": analyserNodeData, "noFingerprint": true});
      }
    });
  }
```

Listing A.5: Audio Source Hybrid fingerprint generation code

```
getChannelMergeHybridFingerprintAudioCtx(): Promise<any> {
  let hybridHash = null;
  let hybridOscillatorNode = [];
  return new Promise((resolve, reject) => {
    try {
      let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioCtx) {
        let oscillator1 = audioCtx.createOscillator();
        oscillator1.type = "sine";
        oscillator1.frequency.setValueAtTime(440, audioCtx.currentTime);
        let oscillator2 = audioCtx.createOscillator();
        oscillator2.type = "triangle";
        oscillator2.frequency.setValueAtTime(10000,audioCtx.currentTime);
        let oscillator3 = audioCtx.createOscillator();
        oscillator3.type = "square";
        oscillator3.frequency.setValueAtTime(1880,audioCtx.currentTime);
        let oscillator4 = audioCtx.createOscillator();
        oscillator4.type = "sawtooth";
        oscillator4.frequency.setValueAtTime(22000,audioCtx.currentTime);

        let channelMerger = audioCtx.createChannelMerger(4)
        oscillator1.connect(channelMerger, 0, 0);
        oscillator2.connect(channelMerger, 0, 1);
        oscillator3.connect(channelMerger, 0, 2);
        oscillator4.connect(channelMerger, 0, 3);

        let compressor = audioCtx.createDynamicsCompressor();
        let analyser = audioCtx.createAnalyser();
        let gain = audioCtx.createGain();
        let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);

        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioCtx.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioCtx.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioCtx.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioCtx.currentTime);
        compressor.release.setValueAtTime(COMPRESSOR.release, audioCtx.currentTime);

        gain.gain.value = 0; // Disable volume
        analyser.fftSize = 4096;

        channelMerger.connect(compressor); // Connect merger to compressor
        compressor.connect(analyser); // Connect compressor to analyser
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(gain); // Connect scriptProcessor output to gain input
        gain.connect(audioCtx.destination); // Connect gain output to audiocontext destination

        scriptProcessor.onaudioprocess = (async (bins: any) => {
            bins = new Float32Array(analyser.frequencyBinCount);
            analyser.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
              hybridOscillatorNode.push(bins[i]);
            }
            analyser.disconnect();
            scriptProcessor.disconnect();
            gain.disconnect();
            const audioFP = JSON.stringify(hybridOscillatorNode);
            hybridHash = CryptoJS.MD5(audioFP).toString();
            await audioCtx.close();
            resolve({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": false});
        });
        //start source
        oscillator1.start(0);
        oscillator2.start(0);
        oscillator3.start(0);
        oscillator4.start(0);
      } else {
        reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
    }
  });
}
```

Listing A.6: Channel Merge Hybrid fingerprint generation code

```
  getAmplitudeModulationHybridFingerprintAudioCtx(): Promise<any> {
    let hybridOscillatorNode = [];
    let hybridHash = null;
    return new Promise((resolve,reject) => {
      try {
        let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
        if (audioCtx) {
          let mod = audioCtx.createOscillator();
          mod.frequency.setValueAtTime(18, audioCtx.currentTime);
          mod.type = "square"

          let modGain = audioCtx.createGain();
          modGain.gain.value = 30;

          let mod1 = audioCtx.createOscillator();
          mod1.frequency.setValueAtTime(440, audioCtx.currentTime);
          mod1.type = "triangle"

          let modGain1 = audioCtx.createGain();
          modGain1.gain.value = 60;

          let carrier = audioCtx.createOscillator();
          carrier.type = "sine"
          carrier.frequency.setValueAtTime(10000, audioCtx.currentTime);

          let carrierGain = audioCtx.createGain();
          carrierGain.gain.value = 1;

          let analyser = audioCtx.createAnalyser();
          let masterGain = audioCtx.createGain();
          masterGain.gain.value = 0; // Disable volume
          let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);

```

```
        mod.connect(modGain);
        mod1.connect(modGain1);
        mod.connect(carrierGain.gain);
        mod1.connect(carrierGain.gain);
        carrier.connect(carrierGain);
        // Create and configure compressor
        let compressor = audioCtx.createDynamicsCompressor();
        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioCtx.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioCtx.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioCtx.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioCtx.currentTime);
        compressor.release.setValueAtTime(COMPRESSOR.release, audioCtx.currentTime);

        analyser.fftSize = 4096;

        carrierGain.connect(compressor); // Connect carrier oscillator output to dynamic compressor
        compressor.connect(analyser); // Connect compressor to analyser
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(masterGain); // Connect scriptProcessor output to gain input
        masterGain.connect(audioCtx.destination); // Connect gain output to audiocontext destination
        scriptProcessor.onaudioprocess = (async (bins: any) => {
            bins = new Float32Array(analyser.frequencyBinCount);
            analyser.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
                hybridOscillatorNode.push(bins[i]);
            }
            analyser.disconnect();
            scriptProcessor.disconnect();
            masterGain.disconnect();
            const audioFP = JSON.stringify(hybridOscillatorNode);
            hybridHash = CryptoJS.MD5(audioFP).toString();
            await audioCtx.close();
            resolve({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": false});
        });
        carrier.start(0);
        mod.start(0);
        mod1.start(0);
      } else {
        reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
      }
    } catch (u) {
      reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
    }
  });
}
```

Listing A.7: Amplitude Modulation Hybrid fingerprint generation code

```
getFrequencyModulationHybridFingerprintAudioCtx(): Promise<any> {
  let hybridOscillatorNode = [];
  let hybridHash = null;
  return new Promise((resolve, reject) => {
    try {
      let audioCtx = new ((<any>window).AudioContext || (<any>window).webkitAudioContext)();
      if (audioCtx) {
        let mod = audioCtx.createOscillator();
        mod.frequency.setValueAtTime(18, audioCtx.currentTime);
        mod.type = "square"

        let modGain = audioCtx.createGain();
        modGain.gain.value = 30;

        let mod1 = audioCtx.createOscillator();
        mod1.frequency.setValueAtTime(440, audioCtx.currentTime);
        mod1.type = "triangle"

        let modGain1 = audioCtx.createGain();
        modGain1.gain.value = 60;

        let carrier = audioCtx.createOscillator();
        carrier.type = "sine"
        carrier.frequency.setValueAtTime(10000, audioCtx.currentTime);

        let carrierGain = audioCtx.createGain();
        carrierGain.gain.value = 1;

        let analyser = audioCtx.createAnalyser();
        let masterGain = audioCtx.createGain();
        masterGain.gain.value = 0; // Disable volume
        let scriptProcessor = audioCtx.createScriptProcessor(SCRIPT_PROCESSOR.bufferSize, SCRIPT_PROCESSOR.numberOfInputChannels
    , SCRIPT_PROCESSOR.numberOfOutputChannels);

        mod1.connect(modGain1);
        modGain1.connect(carrier.frequency);

        mod.connect(modGain);
        modGain.connect(carrier.frequency);

        // Create and configure compressor
        let compressor = audioCtx.createDynamicsCompressor();
        compressor.threshold.setValueAtTime(COMPRESSOR.threshold, audioCtx.currentTime);
        compressor.knee.setValueAtTime(COMPRESSOR.knee, audioCtx.currentTime);
        compressor.ratio.setValueAtTime(COMPRESSOR.ratio, audioCtx.currentTime);
        compressor.attack.setValueAtTime(COMPRESSOR.attack, audioCtx.currentTime);
        compressor.release.setValueAtTime(COMPRESSOR.release, audioCtx.currentTime);

        carrier.connect(compressor); // Connect carrier output to analyser input
        compressor.connect(analyser); // Connect compressor to analyser
        analyser.connect(scriptProcessor); // Connect analyser output to scriptProcessor input
        scriptProcessor.connect(masterGain); // Connect scriptProcessor output to gain input
        masterGain.connect(audioCtx.destination); // Connect gain output to audiocontext destination
        scriptProcessor.onaudioprocess = (async (bins: any) => {
            bins = new Float32Array(analyser.frequencyBinCount);
            analyser.getFloatFrequencyData(bins);
            for (let i = 0; i < bins.length; i++) {
                hybridOscillatorNode.push(bins[i]);
            }
            analyser.disconnect();
            scriptProcessor.disconnect();
            masterGain.disconnect();
            const audioFP = JSON.stringify(hybridOscillatorNode);
```

```
                hybridHash = CryptoJS.MD5(audioFP).toString();
                await audioCtx.close();
                resolve({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": false});
            });
            carrier.start(0);
            mod.start(0);
            mod1.start(0);
          } else {
            reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
          }
        } catch (u) {
          reject({"hash": hybridHash, "values": hybridOscillatorNode, "noFingerprint": true});
        }
    });
  }
```

Listing A.8: Frequency Modulation Hybrid fingerprint generation code

```
["sans-serif-thin","ARNO PRO","Agency FB","Arabic Typesetting","Arial Unicode MS","AvantGarde Bk BT","BankGothic Md BT","Batang","
     Bitstream Vera Sans Mono","Calibri","Century","Century Gothic","Clarendon","EUROSTILE","Franklin Gothic","Futura Bk BT","
     Futura Md BT","GOTHAM","Gill Sans","HELV","Haettenschweiler","Helvetica Neue","Humanst521 BT","Leelawadee","Letter Gothic","
     Levenim MT","Lucida Bright","Lucida Sans","Menlo","MS Mincho","MS Outlook","MS Reference Specialty","MS UI Gothic","MT Extra
     ","MYRIAD PRO","Marlett","Meiryo UI","Microsoft Uighur","Minion Pro","Monotype Corsiva","PMingLiU","Pristina","SCRIPTINA","
     Segoe UI Light","Serifa","SimHei","Small Fonts","Staccato222 BT","TRAJAN PRO","Univers CE 55 Medium","Vrinda","ZWAdobeF",".
     Aqua Kana",".Helvetica LT MM",".Times LT MM","18thCentury","8514oem","AR BERKLEY","AR JULIAN","AR PL UKai CN","AR PL UMing
     CN","AR PL UMing HK","AR PL UMing TW","AR PL UMing TW MBE","Aakar","Abadi MT Condensed Extra Bold","Abadi MT Condensed Light
     ","Abyssinica SIL","AcmeFont","Adobe Arabic","Agency FB","Aharoni","Aharoni Bold","Al Bayan","Al Bayan Bold","Al Bayan Plain
     ","Al Nile","Al Tarikh","Aldhabi","Alfredo","Algerian","Alien Encounters","Almonte Snow","American Typewriter","American
     Typewriter Bold","American Typewriter Condensed","American Typewriter Light","Amethyst","Andale Mono","Andale Mono Version",
     "Andalus","Angsana New","AngsanaUPC","Ani","AnjaliOldLipi","Aparajita","Apple Braille","Apple Braille Outline 6 Dot","Apple
     Braille Outline 8 Dot","Apple Braille Pinpoint 6 Dot","Apple Braille Pinpoint 8 Dot","Apple Chancery","Apple Color Emoji","
     Apple LiGothic Medium","Apple LiSung Light","Apple SD Gothic Neo","Apple SD Gothic Neo Regular","Apple SD GothicNeo
     ExtraBold","Apple Symbols","AppleGothic","AppleGothic Regular","AppleMyungjo","AppleMyungjo Regular","AquaKana","Arabic
     Transparent","Arabic Typesetting","Arial","Arial Baltic","Arial Black","Arial Bold","Arial Bold Italic","Arial CE","Arial
     CYR","Arial Greek","Arial Hebrew","Arial Hebrew Bold","Arial Italic","Arial Narrow","Arial Narrow Bold","Arial Narrow Bold
     Italic","Arial Narrow Italic","Arial Rounded Bold","Arial Rounded MT Bold","Arial TUR","Arial Unicode MS","ArialHB","Arimo",
     "Asimov","Autumn","Avenir","Avenir Black","Avenir Book","Avenir Next","Avenir Next Bold","Avenir Next Condensed","Avenir
     Next Condensed Bold","Avenir Next Demi Bold","Avenir Next Heavy","Avenir Next Regular","Avenir Roman","Ayuthaya","BN Jinx","
     BN Machine","BOUTON International Symbols","BabyKruffy","Baghdad","Bahnschrift","Balthazar","Bangla MN","Bangla MN Bold","
     Bangla Sangam MN","Bangla Sangam MN Bold","Baskerville","Baskerville Bold","Baskerville Bold Italic","Baskerville Old Face",
     "Baskerville SemiBold","Baskerville SemiBold Italic","Bastion","Batang","BatangChe","Bauhaus 93","Beirut","Bell MT","Bell MT
      Bold","Bell MT Italic","Bellerose","Berlin Sans FB","Berlin Sans FB Demi","Bernard MT Condensed","BiauKai","Big Caslon","
     Big Caslon Medium","Birch Std","Bitstream Charter","Bitstream Vera Sans","Blackadder ITC","Blackoak Std","Bobcat","Bodoni 72
     ","Bodoni MT","Bodoni MT Black","Bodoni MT Poster Compressed","Bodoni Ornaments","BolsterBold","Book Antiqua","Book Antiqua
     Bold","Bookman Old Style","Bookman Old Style Bold","Bookshelf Symbol 7","Borealis","Bradley Hand","Bradley Hand ITC","
     Braggadocio","Brandish","Britannic Bold","Broadway","Browallia New","BrowalliaUPC","Brush Script","Brush Script MT","Brush
     Script MT Italic","Brush Script Std","Brussels","Calibri","Calibri Bold","Calibri Light","Californian FB","Calisto MT","
     Calisto MT Bold","Calligraphic","Calvin","Cambria","Cambria Bold","Cambria Math","Candara","Candara Bold","Candles","Carrois
      Gothic SC","Castellar","Centaur","Century","Century Gothic","Century Gothic Bold","Century Schoolbook","Century Schoolbook
     Bold","Century Schoolbook L","Chalkboard","Chalkboard Bold","Chalkboard SE","Chalkboard SE Bold","ChalkboardBold","
     Chalkduster","Chandas","Chaparral Pro","Chaparral Pro Light","Charlemagne Std","Charter","Chilanka","Chiller","Chinyen","
     Clarendon","Cochin","Cochin Bold","Colbert","Colonna MT","Comic Sans MS","Comic Sans MS Bold","Commons","Consolas","Consolas
      Bold","Constantia","Constantia Bold","Coolsville","Cooper Black","Cooper Std Black","Copperplate","Copperplate Bold","
     Copperplate Gothic Bold","Copperplate Light","Corbel","Corbel Bold","Cordia New","CordiaUPC","Corporate","Corsiva","Corsiva
     Hebrew","Corsiva Hebrew Bold","Courier","Courier 10 Pitch","Courier Bold","Courier New","Courier New Baltic","Courier New
```

```
Bold","Courier New CE","Courier New Italic","Courier Oblique","Cracked Johnnie","Creepygirl","Curlz MT","Cursor","Cutive
Mono","DFKai-SB","DIN Alternate","DIN Condensed","Damascus","Damascus Bold","Dancing Script","DaunPenh","David","Dayton","
DecoType Naskh","Deja Vu","DejaVu LGC Sans","DejaVu Sans","DejaVu Sans Mono","DejaVu Serif","Deneane","Desdemona","Detente",
"Devanagari MT","Devanagari MT Bold","Devanagari Sangam MN","Didot","Didot Bold","Digifit","DilleniaUPC","Dingbats","Distant
 Galaxy","Diwan Kufi","Diwan Kufi Regular","Diwan Thuluth","Diwan Thuluth Regular","DokChampa","Dominican","Dotum","DotumChe
","Droid Sans","Droid Sans Fallback","Droid Sans Mono","Dyuthi","Ebrima","Edwardian Script ITC","Elephant","Emmett","
Engravers MT","Engravers MT Bold","Enliven","Eras Bold ITC","Estrangelo Edessa","Ethnocentric","EucrosiaUPC","Euphemia","
Euphemia UCAS","Euphemia UCAS Bold","Eurostile","Eurostile Bold","Expressway Rg","FangSong","Farah","Farisi","Felix Titling"
,"Fingerpop","Fixedsys","Flubber","Footlight MT Light","Forte","FrankRuehl","Frankfurter Venetian TT","Franklin Gothic Book"
,"Franklin Gothic Book Italic","Franklin Gothic Medium","Franklin Gothic Medium Cond","Franklin Gothic Medium Italic","
FreeMono","FreeSans","FreeSerif","FreesiaUPC","Freestyle Script","French Script MT","Futura","Futura Condensed ExtraBold","
Futura Medium","GB18030 Bitmap","Gabriola","Gadugi","Garamond","Garamond Bold","Gargi","Garuda","Gautami","Gazzarelli","
Geeza Pro","Geeza Pro Bold","Geneva","GenevaCY","Gentium","Gentium Basic","Gentium Book Basic","GentiumAlt","Georgia","
Georgia Bold","Geotype TT","Giddyup Std","Gigi","Gill","Gill Sans","Gill Sans Bold","Gill Sans MT","Gill Sans MT Bold","Gill
 Sans MT Condensed","Gill Sans MT Ext Condensed Bold","Gill Sans MT Italic","Gill Sans Ultra Bold","Gill Sans Ultra Bold
Condensed","Gisha","Glockenspiel","Gloucester MT Extra Condensed","Good Times","Goudy","Goudy Old Style","Goudy Old Style
Bold","Goudy Stout","Greek Diner Inline TT","Gubbi","Gujarati MT","Gujarati MT Bold","Gujarati Sangam MN","Gujarati Sangam
MN Bold","Gulim","GulimChe","GungSeo Regular","Gungseouche","Gungsuh","GungsuhChe","Gurmukhi","Gurmukhi MN","Gurmukhi MN
Bold","Gurmukhi MT","Gurmukhi Sangam MN","Gurmukhi Sangam MN Bold","Haettenschweiler","Hand Me Down S (BRK)","Hansen","
Harlow Solid Italic","Harrington","Harvest","HarvestItal","Haxton Logos TT","HeadLineA Regular","HeadlineA","Heavy Heap","
Hei","Hei Regular","Heiti SC","Heiti SC Light","Heiti SC Medium","Heiti TC","Heiti TC Light","Heiti TC Medium","Helvetica","
Helvetica Bold","Helvetica CY Bold","Helvetica CY Plain","Helvetica LT Std","Helvetica Light","Helvetica Neue","Helvetica
Neue Bold","Helvetica Neue Medium","Helvetica Oblique","HelveticaCY","HelveticaNeueLT Com 107 XBlkCn","Herculanum","High
Tower Text","Highboot","Hiragino Kaku Gothic Pro W3","Hiragino Kaku Gothic Pro W6","Hiragino Kaku Gothic ProN W3","Hiragino
Kaku Gothic ProN W6","Hiragino Kaku Gothic Std W8","Hiragino Kaku Gothic StdN W8","Hiragino Maru Gothic Pro W4","Hiragino
Maru Gothic ProN W4","Hiragino Mincho Pro W3","Hiragino Mincho Pro W6","Hiragino Mincho ProN W3","Hiragino Mincho ProN W6","
Hiragino Sans GB W3","Hiragino Sans GB W6","Hiragino Sans W0","Hiragino Sans W1","Hiragino Sans W2","Hiragino Sans W3","
Hiragino Sans W4","Hiragino Sans W5","Hiragino Sans W6","Hiragino Sans W7","Hiragino Sans W8","Hiragino Sans W9","Hobo Std",
"Hoefler Text","Hoefler Text Black","Hoefler Text Ornaments","Hollywood Hills","Hombre","Huxley Titling","ITC Stone Serif","
ITF Devanagari","ITF Devanagari Marathi","ITF Devanagari Medium","Impact","Imprint MT Shadow","InaiMathi","Induction","
Informal Roman","Ink Free","IrisUPC","Iskoola Pota","Italianate","Jamrul","JasmineUPC","JavaneseText","Jokerman","JuiceITC",
"KacstArt","KacstBook","KacstDecorative","KacstDigital","KacstFarsi","KacstLetter","KacstNaskh","KacstOffice","KacstOne","
KacstPen","KacstPoster","KacstQurn","KacstScreen","KacstTitle","KacstTitleL","Kai","Kai Regular","KaiTi","Kailasa","Kailasa
Regular","Kaiti SC","Kaiti SC Black","Kalapi","Kalimati","Kalinga","Kannada MN","Kannada MN Bold","Kannada Sangam MN","
Kannada Sangam MN Bold","Kartika","Karumbi","Kedage","Kefa","Kefa Bold","Keraleeyam","Keyboard","Khmer MN","Khmer MN Bold","
Khmer OS","Khmer OS System","Khmer Sangam MN","Khmer UI","Kinnari","Kino MT","KodchiangUPC","Kohinoor Bangla","Kohinoor
Devanagari","Kohinoor Telugu","Kokila","Kokonor","Kokonor Regular","Kozuka Gothic Pr6N B","Kristen ITC","Krungthep","
KufiStandardGK","KufiStandardGK Regular","Kunstler Script","Laksaman","Lao MN","Lao Sangam MN","Lao UI","LastResort","Latha"
,"Leelawadee","Letter Gothic Std","LetterOMatic!","Levenim MT","LiHei Pro","LiSong Pro","Liberation Mono","Liberation Sans",
"Liberation Sans Narrow","Liberation Serif","Likhan","LilyUPC","Limousine","Lithos Pro Regular","LittleLordFontleroy","Lohit
 Assamese","Lohit Bengali","Lohit Devanagari","Lohit Gujarati","Lohit Gurmukhi","Lohit Hindi","Lohit Kannada","Lohit
Malayalam","Lohit Odia","Lohit Punjabi","Lohit Tamil","Lohit Tamil Classical","Lohit Telugu","Loma","Lucida Blackletter","
Lucida Bright","Lucida Bright Demibold","Lucida Bright Demibold Italic","Lucida Bright Italic","Lucida Calligraphy","Lucida
Calligraphy Italic","Lucida Console","Lucida Fax","Lucida Fax Demibold","Lucida Fax Regular","Lucida Grande","Lucida Grande
Bold","Lucida Handwriting","Lucida Handwriting Italic","Lucida Sans","Lucida Sans Demibold Italic","Lucida Sans Typewriter",
"Lucida Sans Typewriter Bold","Lucida Sans Unicode","Luminari","Luxi Mono","MS Gothic","MS Mincho","MS Outlook","MS PGothic"
,"MS PMincho","MS Reference Sans Serif","MS Reference Specialty","MS Sans Serif","MS Serif","MS UI Gothic","MT Extra","MV
Boli","Mael","Magneto","Maiandra GD","Malayalam MN","Malayalam MN Bold","Malayalam Sangam MN","Malayalam Sangam MN Bold","
Malgun Gothic","Mallige","Mangal","Manorly","Marion","Marion Bold","Marker Felt","Marker Felt Thin","Marlett","Martina","
Matura MT Script Capitals","Meera","Meiryo","Meiryo Bold","Meiryo UI","MelodBold","Menlo","Menlo Bold","Mesquite Std","
Microsoft","Microsoft Himalaya","Microsoft JhengHei","Microsoft JhengHei UI","Microsoft New Tai Lue","Microsoft PhagsPa","
Microsoft Sans Serif","Microsoft Tai Le","Microsoft Tai Le Bold","Microsoft Uighur","Microsoft YaHei","Microsoft YaHei UI","
Microsoft Yi Baiti","Minerva","MingLiU","MingLiU-ExtB","MingLiU_HKSCS","Minion Pro","Miriam","Mishafi","Mishafi Gold","
Mistral","Modern","Modern No. 20","Monaco","Mongolian Baiti","Monospace","Monotype Corsiva","Monotype Sorts","MoolBoran","
Moonbeam","MotoyaLMaru","Mshtakan","Mshtakan Bold","Mukti Narrow","Muna","Myanmar MN","Myanmar MN Bold","Myanmar Sangam MN",
"Myanmar Text","Mycalc","Myriad Arabic","Myriad Hebrew","Myriad Pro","NISC18030","NSimSun","Nadeem","Nadeem Regular","Nakula
```

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","Nanum Barun Gothic","Nanum Gothic","Nanum Myeongjo","NanumBarunGothic","NanumGothic","NanumGothic Bold","
NanumGothicCoding","NanumMyeongjo","NanumMyeongjo Bold","Narkisim","Nasalization","Navilu","Neon Lights","New Peninim MT","
New Peninim MT Bold","News Gothic MT","News Gothic MT Bold","Niagara Engraved","Niagara Solid","Nimbus Mono L","Nimbus Roman
 No9 L","Nimbus Sans L","Nimbus Sans L Condensed","Nina","Nirmala UI","Nirmala.ttf","Norasi","Noteworthy","Noteworthy Bold",
"Noto Color Emoji","Noto Emoji","Noto Mono","Noto Naskh Arabic","Noto Nastaliq Urdu","Noto Sans","Noto Sans Armenian","Noto
Sans Bengali","Noto Sans CJK","Noto Sans Canadian Aboriginal","Noto Sans Cherokee","Noto Sans Devanagari","Noto Sans
Ethiopic","Noto Sans Georgian","Noto Sans Gujarati","Noto Sans Gurmukhi","Noto Sans Hebrew","Noto Sans JP","Noto Sans KR","
Noto Sans Kannada","Noto Sans Khmer","Noto Sans Lao","Noto Sans Malayalam","Noto Sans Myanmar","Noto Sans Oriya","Noto Sans
SC","Noto Sans Sinhala","Noto Sans Symbols","Noto Sans TC","Noto Sans Tamil","Noto Sans Telugu","Noto Sans Thai","Noto Sans
Yi","Noto Serif","Notram","November","Nueva Std","Nueva Std Cond","Nyala","OCR A Extended","OCR A Std","Old English Text MT"
,"OldeEnglish","Onyx","OpenSymbol","OpineHeavy","Optima","Optima Bold","Optima Regular","Orator Std","Oriya MN","Oriya MN
Bold","Oriya Sangam MN","Oriya Sangam MN Bold","Osaka","Osaka-Mono","OsakaMono","PCMyungjo Regular","PCmyoungjo","PMingLiU",
"PMingLiU-ExtB","PR Celtic Narrow","PT Mono","PT Sans","PT Sans Bold","PT Sans Caption Bold","PT Sans Narrow Bold","PT Serif
","Padauk","Padauk Book","Padmaa","Pagul","Palace Script MT","Palatino","Palatino Bold","Palatino Linotype","Palatino
Linotype Bold","Papyrus","Papyrus Condensed","Parchment","Parry Hotter","PenultimateLight","Perpetua","Perpetua Bold","
Perpetua Titling MT","Perpetua Titling MT Bold","Phetsarath OT","Phosphate","Phosphate Inline","Phosphate Solid","
PhrasticMedium","PilGi Regular","Pilgiche","PingFang HK","PingFang SC","PingFang TC","Pirate","Plantagenet Cherokee","
Playbill","Poor Richard","Poplar Std","Pothana2000","Prestige Elite Std","Pristina","Purisa","QuiverItal","Raanana","Raanana
 Bold","Raavi","Rachana","Rage Italic","RaghuMalayalam","Ravie","Rekha","Roboto","Rockwell","Rockwell Bold","Rockwell
Condensed","Rockwell Extra Bold","Rockwell Italic","Rod","Roland","Rondalo","Rosewood Std Regular","RowdyHeavy","Russel
Write TT","SF Movie Poster","STFangsong","STHeiti","STIXGeneral","STIXGeneral-Bold","STIXGeneral-Regular","STIXIntegralsD","
STIXIntegralsD-Bold","STIXIntegralsSm","STIXIntegralsSm-Bold","STIXIntegralsUp","STIXIntegralsUp-Bold","STIXIntegralsUp-
Regular","STIXIntegralsUpD","STIXIntegralsUpD-Bold","STIXIntegralsUpD-Regular","STIXIntegralsUpSm","STIXIntegralsUpSm-Bold",
"STIXNonUnicode","STIXNonUnicode-Bold","STIXSizeFiveSym","STIXSizeFiveSym-Regular","STIXSizeFourSym","STIXSizeFourSym-Bold",
"STIXSizeOneSym","STIXSizeOneSym-Bold","STIXSizeThreeSym","STIXSizeThreeSym-Bold","STIXSizeTwoSym","STIXSizeTwoSym-Bold","
STIXVariants","STIXVariants-Bold","STKaiti","STSong","STXihei","SWGamekeys MT","Saab","Sahadeva","Sakkal Majalla","Salina","
Samanata","Samyak Devanagari","Samyak Gujarati","Samyak Malayalam","Samyak Tamil","Sana","Sana Regular","Sans","Sarai","
Sathu","Savoye LET Plain:1.0","Sawasdee","Script","Script MT Bold","Segoe MDL2 Assets","Segoe Print","Segoe Pseudo","Segoe
Script","Segoe UI","Segoe UI Emoji","Segoe UI Historic","Segoe UI Semilight","Segoe UI Symbol","Serif","Shonar Bangla","
Showcard Gothic","Shree Devanagari 714","Shruti","SignPainter-HouseScript","Silom","SimHei","SimSun","SimSun-ExtB","
Simplified Arabic","Simplified Arabic Fixed","Sinhala MN","Sinhala MN Bold","Sinhala Sangam MN","Sinhala Sangam MN Bold","
Sitka","Skia","Skia Regular","Skinny","Small Fonts","Snap ITC","Snell Roundhand","Snowdrift","Songti SC","Songti SC Black","
Songti TC","Source Code Pro","Splash","Standard Symbols L","Stencil","Stencil Std","Stephen","Sukhumvit Set","Suruma","
Sylfaen","Symbol","Symbole","System","System Font","TAMu_Kadambri","TAMu_Kalyani","TAMu_Maduram","TSCu_Comic","TSCu_Paranar"
,"TSCu_Times","Tahoma","Tahoma Negreta","TakaoExGothic","TakaoExMincho","TakaoGothic","TakaoMincho","TakaoPGothic","
TakaoPMincho","Tamil MN","Tamil MN Bold","Tamil Sangam MN","Tamil Sangam MN Bold","Tarzan","Tekton Pro","Tekton Pro Cond","
Tekton Pro Ext","Telugu MN","Telugu MN Bold","Telugu Sangam MN","Telugu Sangam MN Bold","Tempus Sans ITC","Terminal","
Terminator Two","Thonburi","Thonburi Bold","Tibetan Machine Uni","Times","Times Bold","Times New Roman","Times New Roman
Baltic","Times New Roman Bold","Times New Roman Italic","Times Roman","Tlwg Mono","Tlwg Typewriter","Tlwg Typist","Tlwg Typo
","TlwgMono","TlwgTypewriter","Toledo","Traditional Arabic","Trajan Pro","Trattatello","Trebuchet MS","Trebuchet MS Bold","
Tunga","Tw Cen MT","Tw Cen MT Bold","Tw Cen MT Italic","URW Bookman L","URW Chancery L","URW Gothic L","URW Palladio L","
Ubuntu","Ubuntu Condensed","Ubuntu Mono","Ukai","Ume Gothic","Ume Mincho","Ume P Gothic","Ume P Mincho","Ume UI Gothic","
Uming","Umpush","UnBatang","UnDinaru","UnDotum","UnGraphic","UnGungseo","UnPilgi","Untitled1","Urdu Typesetting","Uroob","
Utkal","Utopia","Utsaah","Valken","Vani","Vemana2000","Verdana","Verdana Bold","Vijaya","Viner Hand ITC","Vivaldi","Vivian",
"Vladimir Script","Vrinda","Waree","Waseem","Waverly","Webdings","WenQuanYi Bitmap Song","WenQuanYi Micro Hei","WenQuanYi
Micro Hei Mono","WenQuanYi Zen Hei","Whimsy TT","Wide Latin","Wingdings","Wingdings 2","Wingdings 3","Woodcut","X-Files","
Year supply of fairy cakes","Yu Gothic","Yu Mincho","Yuppy SC","Yuppy SC Regular","Yuppy TC","Yuppy TC Regular","Zapf
Dingbats","Zapfino","Zawgyi-One","gargi","lklug","mry_KacstQurn","ori1Uni"]
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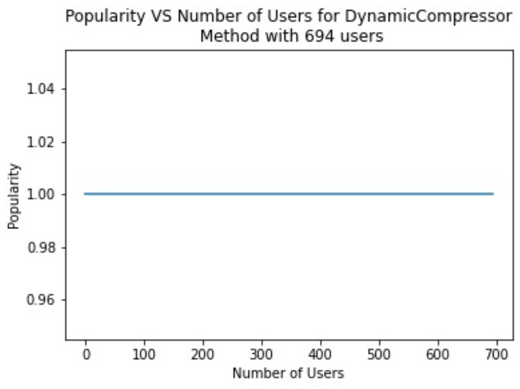
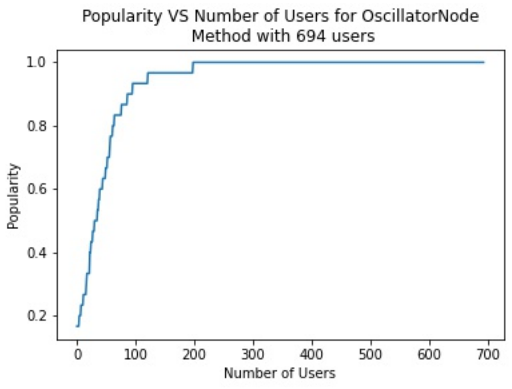
Listing A.9: Expanded Font list

# Appendix B

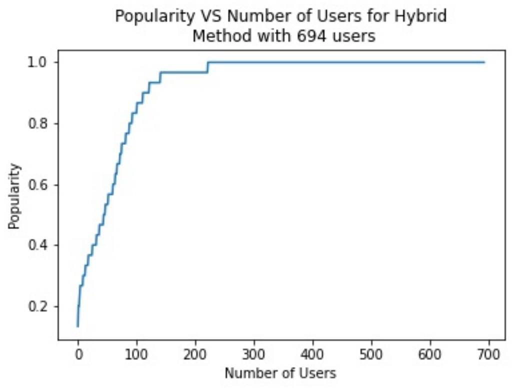
# Figures



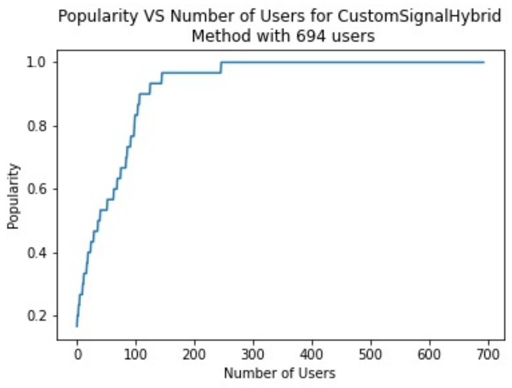
(a) Dynamic Compressor



(b) Oscillator Node

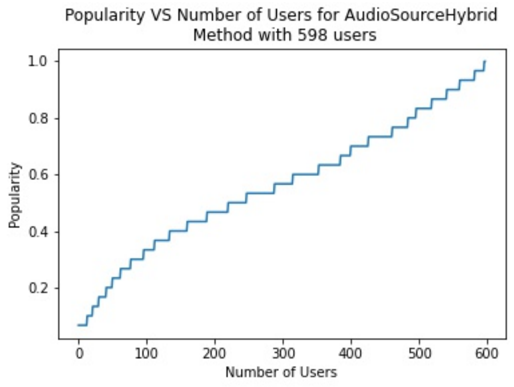


(c) Hybrid

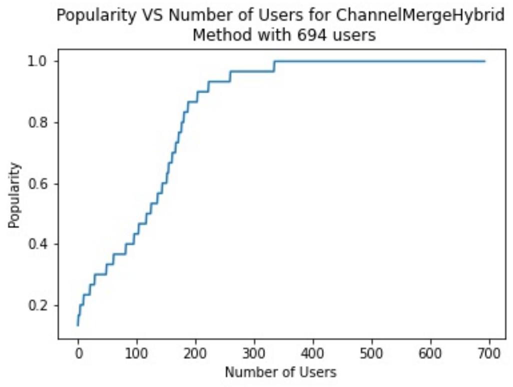


(d) Custom Signal Hybrid

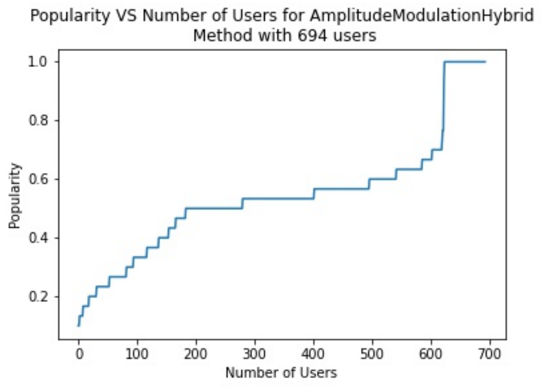
Figure B.1: The frequency of the highest occurring fingerprint value in 30 iterations for individual audio fingerprinting methods contd.



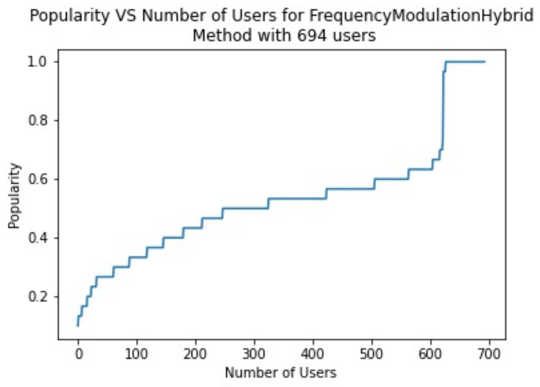
(e) Audio Source Hybrid



(f) Channel Merge Hybrid



(g) Amplitude Modulation Hybrid



(h) Frequency Modulation Hybrid

Figure B.1: The frequency of the highest occurring fingerprint value in 30 iterations for individual audio fingerprinting methods

# Vita

The author, Shekhar Chalise, was born in Kathmandu, Nepal. He obtained his bachelor's degree in Computer Engineering in 2015 from Tribhuvan University, Kathmandu, Nepal. He joined the University of New Orleans Computer Science Master's program in Fall-2019. Shekhar has been working under Dr. Krishna Phani Kumar Vadrevu, in his Cybersecurity lab within the Department of Computer Science, at the University of New Orleans. He is also working as a Software Engineering Intern at LUCID LLC, New Orleans, LA and aspires to be a Software Engineer focusing on privacy and security. He worked on the study of stability and diversity of WebAudio fingerprints as part of his Master thesis in computer science.