1-D Round-Trip Time application for Indoor positioning-based adaptive Audio

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***Abstract*—Wi-Fi RTT is the most recent Wi-Fi based protocol to be added to the arsenal of indoor positioning methodologies. However, the availability and application of FTM still remains mostly in research and commercial use. This proposed IoT system aims to explore the viability and effectiveness of Wi-Fi RTT application through an audio use-case in a real-world residential setting that is typical of an urban single household living space. The implementation and evaluation of the system has shown that Wi-Fi RTT indoor positioning with a singular reference point is contextually viable. Within the limits of realistic procurement of relevant resources and practicality, the resulting indoor positioning is useful and has benefits to be leveraged. Though with notable margin or errors, most consumer-level application with the use of singular reference access point should be viable for target users and use cases.**

***Index Terms*—RTT, round trip time, audio, indoor positioning, fine time measurement, FTM, 802.11mc, 802.11-2016, IEEE, internet of things, IoT**

I. Introduction

With the onset of the necessity to work from home and the end nowhere in sight, there is a noticeable increase in the average noise level during the day. Noise complaints have reportedly increased by 22% in certain areas of the USA [24] and even increased by 50% in some areas of the UK in the later months of 2020 [19].

In multiple-occupant households, family members may need to share nearby open spaces to perform their daily school activities and work commitments, which further increases the effects of noise pollution inside each household. In more urban settings, household sizes are smaller, and living units are even more compact. In crowded residential areas, especially for living spaces with shared walls, noise pollution is a rising intra-household and inter-household problem that affects residents' physical and mental health alike.

Regardless of preference towards headphones or speakers, prolonged exposure to sound has been linked to hearing loss and ear damage [17]. The higher the volume, the shorter duration of exposure a person needs to be affected. In a setting where remote school and work commitments have replaced its in-person counterparts entirely, we are faced with 7-9 hours of required sound exposure each day. Furthermore, the people who have access to work or study remotely are more likely to find entertainment using the same means. This results in a higher likelihood that an average person with working access to internet after working hours would be exposed to an audio source for longer than the average working hours.

More so than relaying audio, speakers may serve as a better alternative to headphones in terms of comfort and safety as well. The audio source is further away than in-ear or on-ear headphones, so any potential damages are not as amplified. Important audio signals such as fire alarms and car horns are easier to hear when the ear canals are not sealed by headphones. Nevertheless, a downside of stationary speakers is the limiting range. As the listener moves away from the audio source, the perceived volume decreases, in comparison to headphones where perceived volume remains constant.

With the incorporation of Wi-Fi Round-Trip Time (RTT) into the IEEE 802.11-2016 Standard, also known as IEEE 802.11mc, many recent studies have been focusing on substituting RSSI-based multilateration approach with the newly introduced Fine-Time Measurement [5]. Most published studies are focused on the robustness of a positioning system more representative of commercial settings, where supported devices of higher specifications are available and abundant; and where high accuracy is crucial with only small margin of errors accepted.

In common household settings, accessibility to cutting-edge technology is limited in quantity in lieu of practicality and frugality. Often, most consumers gradually replace electronic devices as they become obsolete or when enough improvements have been made since the previous model to warrant a purchase. Despite the Wi-Fi RTT feature becoming more available in recent years, the use and application of FTM is not as widespread in consumer-grade electronics [22].

The need for alternate indoor audio consumption and the availability of a finer indoor positioning option has incited the combination of an audio speaker that leverages the user's location to deliver the same experience as a headphone while minimizing noise pollution when not needed.

This IoT system seeks to explore the viability and effectiveness of Wi-Fi RTT application through an audio use-case in a real-world residential setting that is typical of an urban single household living space.

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II. Related Work

Wi-Fi-based positioning is not a novel approach in the network field. As wireless network has become the new base standard of network connection and internet access, and even arguably a necessity; its existence has become a common commodity. Prior Wi-Fi-based methodologies used for indoor positioning can be categorized into two main approaches: multilateration and fingerprinting [5].

The long-standing multilateration approach to indoor positioning is the superset to the Fine-Timing Measurement (FTM) method. As the name suggests, the multilateration method leverages the geometric properties of the resulting "shape" formed by the placement of the signal transmitters and receivers, or the access points and the mobile device in this case. The two-dimensional position of the mobile device can be estimated using at least three measured ranges from the mobile device to each access point. This approach was historically executed using RSSI, however, the attenuation pattern of RSSI is dependent on each indoor spatial topology, and thus is not applicable without calibration to specific spaces.

A case study on a volume control interface was conducted by Takahashi et al. in 2015 to study the use case for automatic volume control for a telepresence system [2]. This previous work offers the speaker agency over their speech volume to adapt to their desired context even through remote communication.

This IoT system focuses on the user as the audio recipient and aims to provide agency over how the user wants to experience their audio as a receiving subject.

III. Problem Statement

Even though speakers are commonly available alternatives to headphones, the lack of effortless mobility and its effects on perceived audio quality deters headphone-preferred users from switching and creates inconveniences for users who already use them. Current users of audio speakers may face annoyances throughout the workday as their occasional trips to the grab a forgotten item or a visit to a nearby room meant that they might miss unplanned communication or ongoing ones when users are out of the effective hearing range. A manual solution would be to pre-adjust the volume before the user temporarily relocates, however, that implies that users must already know the target level to set the volume to. Often, this might result in an intentional loud burst of audio if the volume level is not returned to the original value.

The solution components are purposely limited to utilize only commercially available consumer-grade electronic devices to better represent a universally applicable solution while remaining practical in residential-settings.

IV. System Model

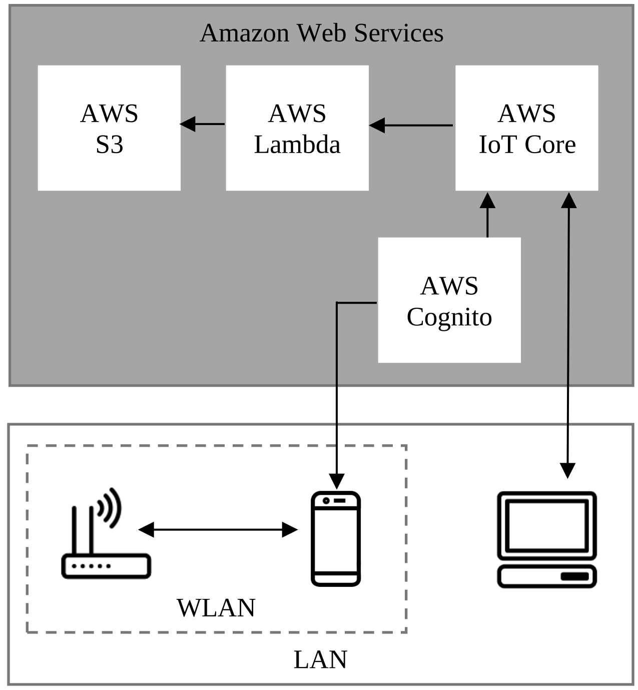

Fig. 1. System overview

A. Project description

This IoT system is set to constantly measure and update the distance between the mobile android device and the access point to the desktop or laptop device; or the RTT initiator, RTT responder, and the audio output device, respectively. The audio output device then converts distance readings into scaled volume percentages and sets its the master volume level to the resulting value.

B. System Modules

The system is comprised of three main components: the local devices component, the cloud services component, and the application component.

The local component of the system consists of a local area network with an android device, an access point, and a computing device to output audio via speakers; all of which are located in close to moderate proximity of each other. The mobile device and desktop are not required but advised to connect to the same access point or the reference access point at all, but the system must be able to discover and identify the access point by its BSSID. Wireless components must support Fine Time Measurement (FTM) to measure round-trip time, and the local area network must have access to the internet. Relative indoor locations of all three devices are also needed for distance calibration. The specific devices used in this IoT system are Google Wifi Router, Google Pixel 3 XL and a Windows desktop computer.

The cloud services component involves AWS IoT Core's Message Queuing Telemetry Transport (MQTT) protocol for communications between the mobile device and the desktop client device, AWS Lambda and S3 for data processing and storage, and AWS Cognito for authenticating mobile device connection with AWS resources. The local audio output device should be registered to AWS IoT Core as an IoT device.

The application component encompasses the android application and the desktop application working in conjunction. The android application communicates with the desktop application via the IoT Core and also offers front-end elements for the user to interface with the back-end without making changes to the source code on either client device.

C. Variables

The system's dependent variable is the master volume in percentage of the desktop device. The independent variables are the measured distance between the android device and the access point, minimum distance allowed, maximum distance allowed, minimum volume percentage allowed, and the maximum volume percentage allowed. The volume levels are represented as percentages and therefore are relative measurements. The distances are measured and represented in millimeters.

Notably. users can configure the minimum and maximum values to influence the conversion scale using the android application user interface.

D. Assumptions

An ideal execution of this system expects that the user has uninterrupted access to internet in addition to access to all physical devices and cloud services necessary. The cloud resources are available for implementation within the Free Tier.

The Round-Trip Time request initiator (mobile device) and responder (access point) must both support the IEEE 802.11mc protocol, which specifically limits the mobile device to operate on at least Android Pie (9.0) or at API level 28 or higher. The audio output device is assumed to be a computer running on any variant of Windows 10.

The physical devices' locations are assumed to be placed with relatively obstacle-free line of sight within reasonable local area network proximity. For best possible RTT ranging request results, the access point should be located as close to the audio output device as possible or within a generally linear alignment with all three physical devices.

V. Mathematical Model

The output volume level is derived from the android device's position with reference to the access point and is bound by the values set by the user. The conversion of distance to volume level is represented by the formula below.

P = input position (mm)
$\mathrm{D_{min}}$ = minimum distance (mm)
$\mathrm{D_{max}}$ = maximum distance (mm)
$\mathrm{D_{range}} = \mathrm{D_{max}} - \mathrm{D_{min}}$
$\mathrm{V_{min}}$ = minimum volume level (%)
$\mathrm{V_{max}}$ = maximum volume level (%)
$\mathrm{V_{range}} = \mathrm{V_{max}} - \mathrm{V_{min}}$
**Distance is measured from the access point to the android device

$$V_{output} = \begin{cases} V_{min}\,, & P < D_{min} \\ \left(\frac{P - D_{min}}{D_{range}} \times V_{range}\right) + V_{min}\,, & D_{min} \le P \le D_{max} \\ V_{max}\,, & P > D_{max} \end{cases}$$

where $0 \le V_{min} \le V_{output} \le V_{max} \le 100$
$0 \le D_{min} \le P \le D_{max} \le 5000$

If the input value falls in between the minimum distance and maximum distance allowed, the volume will be proportionally scaled to the volume level range. If the P is less than D_{min}, the volume level output will be bounded by V_{min}. If the P exceeds the D_{max}, the volume level output will be bounded by V_{max} . The output volume level will always be a percentage between V_{min} and V_{max} inclusively.

VI. Analysis

The distance of the user from the computer device can be used as the function of the audio volume level to achieve a location-responsive speaker. The solution to this specific problem can be automated as an IoT system. In order to achieve this effect, Wi-Fi RTT can be incorporated into a system for the volume to respond to the relative location of the user. Even though a Wi-Fi RTT enabled router is currently available on the market, there is no commercially available Wi-Fi Network card or API support for iOS and Windows computer [22]. To simulate this effect without a Wi-Fi RTT enabled computer, the access point will be placed in proximity of the computer and the ranging results processed in reference to the access point.

An urban single household may occupy from 20 m^2 to 80 m^2 of living space. This estimation is well within the effective range an average singular access point Wi-Fi router supports. This system has been designed with one RTT supported access point and one RTT supported mobile device taken into consideration as key limitations, which has shown to be viable by the proposed and implemented designed.

VII. Design and Implementation

A. Distance measurement

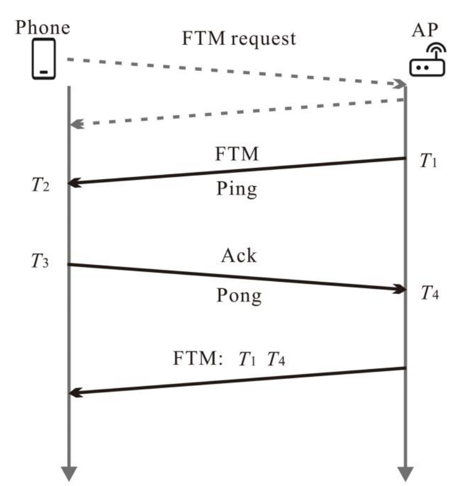

Figure 2. IEEE 802.11mc Fine Time Measurement protocol

The distance between the two client devices is determined using Fine-Time Measurement (FTM) requests between a request initiator and a request responder, the android mobile device and the desktop computer respectively, to retrieve the round-trip time. The distance measurement is part of the ranging request result returned from the request responder as an object.

The distance is returned in millimeters, along with a standard deviation of typically seven successful bursts of signals achieved within a single ranging request [11].

The Google Wifi router was chosen as the access point device since it is fairly representative of a consumer-grade commercially available device with plausible accessibility.

B. Android application

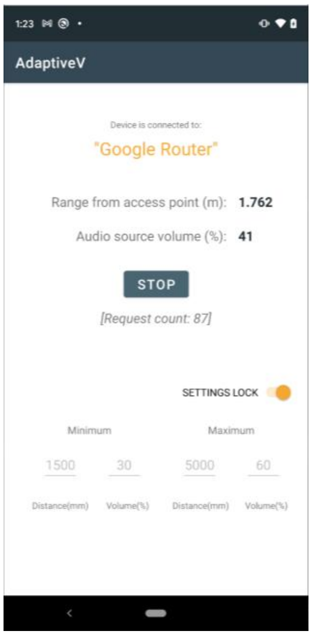

Figure 3. Screenshots of the developed android application.

Android was chosen as the mobile development platform due to the Android API's capability to utilize the Wi-Fi RTT feature. The android application was specifically developed on Android Studio due to React Native's limitations in using Wi-Fi RTT functionality.

The android application is intended to be the user input gateway for this IoT system. Since the system utilizes the android mobile device as the locator, the design decision was made to host the user interface on the android device rather than the desktop computer. The android device is more likely to be accessible to the user for the most amount of time during usage.

The application has two interactable interface components. The core component displays live distance readings as the measurements are relayed from the access point and the most recent master volume level of the desktop computer. The SSID of the connected wireless network and the number of ranging requests made since the start of the session is also displayed. In this component, the user can initiate and terminate the ranging requests from the android device and the publishing of the distance readings to IoT Core's MQTT broker.

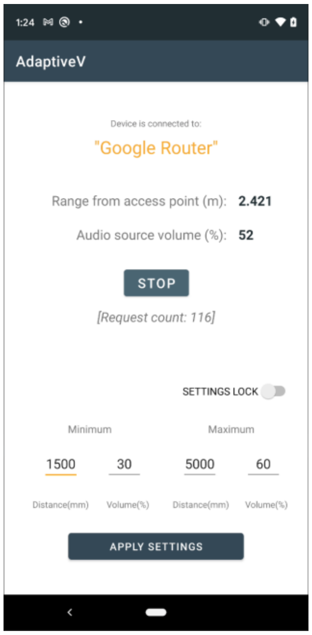

Figure 4. This screenshot variation shows the variables settings option when enabled.

The secondary user interface component is the user-configurable variables. The user is able to input numerical values for the minimum and maximum variables to adjust the conversion scale of the distance to volume percentage. The editable interface is hidden behind a toggle button to avoid users from making unintentional changes. The variable values are locally stored and persists as part of the application preferences.

C. Desktop application

The desktop application is executed with a Python script with no user interface. The script subscribes to the MQTT topic specific for retrieving distance readings. The distance measurement is then converted to scale based on the minimum and maximum variables configured by the user. The output value is used to update the master volume level of the desktop device and then published to another MQTT topic for the android application to retrieve and display. The desktop application also publishes a JSON object containing the input and output data to the IoT Core as well. This processing of data is completed at the desktop computer application to prioritize lowest resource consumption at the mobile client device, where memory and energy capacity are more limiting.

D. MQTT protocol

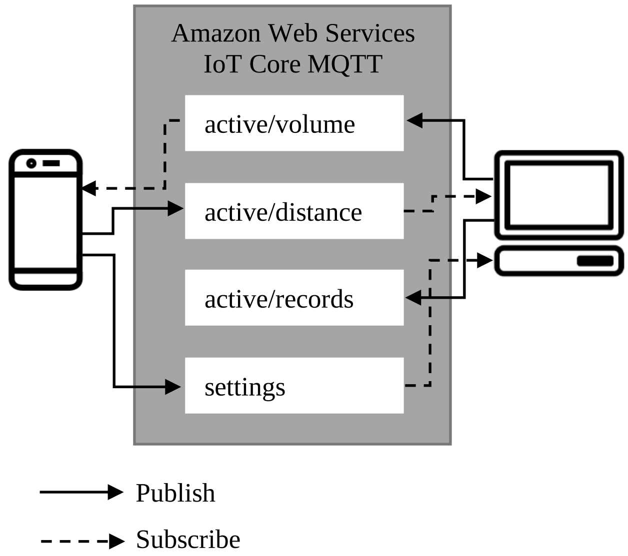

Figure 5. MQTT topics publication and subscription.

Amazon Web Services IoT Core serves as the MQTT broker between the two MQTT client devices. The MQTT broker handles four topics in total for this IoT system. In addition to the ranging results and the volume levels. The user configurable-values and data records are each handled by a separate topic. The quality of service (QoS) used is 'at most once' due to the responsiveness of the system. Each distance measurement has a brief time to live. Any messages missed should be ignored, as the most recent measurement has the highest priority.

E. Data processing and storage

Amazon Web Services S3 and Amazon Web Services Lambda will be used to process and store the output data. The lambda function adds metadata to the message from the desktop application and puts the record into a storage container. The Amazon Web Services features were chosen as they share the same platform and ecosystem as the MQTT broker.

F. Local to Cloud connection

As the platform used is hosted by Amazon Web Services, both the desktop client and the android client needed some form of authentication to access the services offered. The desktop application is authenticated using the private and public key certificates, and the android application is authenticated using credentials provided by Amazon Web Services Cognito.

G. System setup

The system is set to operate over a single-level small area of up to 5 meters from the reference access point, which can approximately cover 20-80 m^2 or the size of a typical nano-apartment up to a one-bedroom apartment. The desktop client and the access point should be placed at the same location and the android mobile client should accompany the user as they move around inside the coverage area. If the access point and desktop computer cannot be placed together, the desktop device should be placed in the area in between the access point and where the mobile client device will be. Line of sight is preferred.

VIII. Evaluation

Data collection is made indoors with similar environment setup as the real use-case. A controlled factor is the height of the ranging request initiator and responder. This translate to both the mobile device and the access point is place at the same height to eliminate factors influencing y-coordinates in a 3D space. The other controller factor is a persistent line of sight. The mobile device is place at a location where it has an unobstructed line of sight to the access point. The mobile device is moved linearly as the reference range is changed.

Actual ranges are compared to collected results from FTM ranging requests of a stationary mobile phone. Ten data points are collected at each range. The collected data includes the ranging request result distance and each data point's standard deviation.

The standard deviation retrieved from the FTM ranging request results are calculated from multiple bursts of request signal contained within one ranging request attempt. The usual number of successful bursts per each ranging request attempt is 7, hence the standard deviation is usually derived from a sample size of 7 [22].

The following figure is a scatterplot of the collected data points. The x-coordinate represents the actual range between the access point and the mobile device, and the y-coordinate represents the measured range returned by the ranging requests.

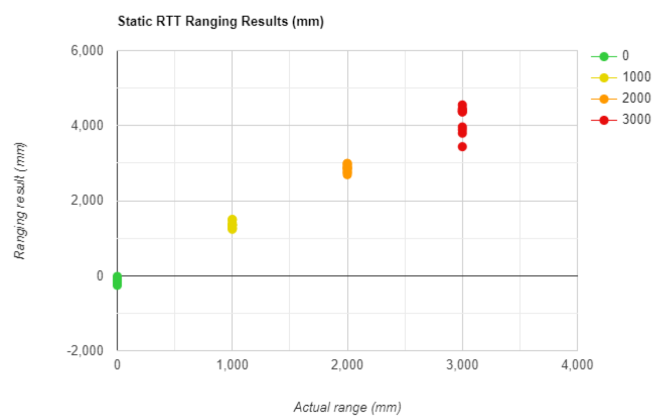

Figure 6. RTT ranging results as a function of actual range

Each cluster of data points decreases in precision as the actual range increases, as illustrated by the spread of the data points. The spread of the data points at smaller ranges is notably smaller, but the accuracy of the measured range is still lacking. The average accuracy of data points in each cluster also decreases as the actual range increases as well.

Actual range (mm)	Average RTT ranging results (mm)	Average RTT ranging results Std. Dev. (mm)
0	135	368
1000	1356	279
2000	3356	380
3000	4279	330

Table 1. RTT ranging averages and RTT ranging standard deviation averages compared to actual ranges with one reference access point

Table 1 shows the averages of the collected measured range and the averages of the standard deviations. The average RTT ranging results offset increases as the actual range increases, which is also illustrated in the graph, but based on the graphical representation, some data points within the same range are closer to the actual range. For instance, the lowest ranging result at the actual range of 3000 mm has a smaller difference to coordinate (3000, 3000) than the difference between the lowest ranging result at the actual range of 2000 mm and coordinate (2000, 2000). This may suggest that larger range measurements requires longer duration to stabilize or that some other factors may be affecting the resulting RTT at greater ranges from the access point.

With decreasing accuracy, the precision confidence is remarkably persistent at approximately 300-350 mm, indicating that each ranging result has approximately 66% confident. The standard deviation value is contextually acceptable as it is comparable to 1-2 strides of an average adult.

After the system has been running for a while, it was clear that a constantly responsive system will consume a constant amount of resources. This revelation brought forth an additional implementation into consideration. As the standard deviation remains fairly consistent in a small range increase, a condition to publish the ranging result was added to the application. The condition allows the ranging result to be published when the previous distance reading is within a standard deviation away from the most recent distance. After the condition was applied, the number of MQTT messages published was reduced by 95%; from 300 messages in five minutes to 14 messages with the same duration.

IX. Conclusion

The implemented IoT system has responded well under the target environment. Wi-Fi RTT has shown to be a viable method for indoor positioning at a consumer level, when the typical measured range is small and when moderate margin of errors is acceptable or tolerable.

The moderate precision and low accuracy take away from the robustness of the system, however, this is to be expected from a singular reference point. All the system limitations were adhered to, which suggests that similar small-scale IoT system would be viable and effective enough for consumer use. In larger households where multiple access points are more commonplace, these small-scaled indoor-positioning based systems would be even more effective.

X. Future Work

Prior studies have shown that using Received Signal Strength Indication (RSSI) values to estimate indoor positioning does not produce reliably accurate results, especially with increasing range from the signal transmitter to the receiver. However, there is a correlation to be leveraged when used in conjunction with other indicators. The introduction of Fine-Time Measurement has added another layer of measurement to what can be achieved with a single wireless access point. Ranging distance calibration can be improved by incorporating findings from a prior study on a hybrid Wi-Fi RTT-RSS approach. RSS or RSSI values can be used to weigh clusters of distance measurements for more precise and tighter groupings of measurements in ranging requests results when stationary.

A future rendition of this IoT system should also consider the responsiveness of the RTT ranging results when the android device is in motion. Due to the observed high fluctuations in ranging results when stationary, an actuation point has been applied to evaluate the system. Unless a new ranging results has exceeded the actuation point, the ranging results will not be relayed to the MQTT broker. The result of this evaluation has stabilized stationary ranging results. However, the system is slower to respond to motion due to the delay caused by the threshold. Further balance between responsiveness to motion and fluctuation threshold should be pursued.

As an IoT system, the system should aim to provide users with more agency and control when preferred. Even though there are major configurations in place, minor configurations left much to be desired. Addition of request delays, request frequency, and custom threshold could all be included, and existing settings expanded for individual usage fine tuning and better user experience.

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