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eight million dollar Michigan Mobility Challenge

Indoor Wayfinding for Veterans including the Visually Impaired

Final Report

Michigan Mobility Challenge Contract No. 2019-0061

for Michigan Department of Transportation

Massachusetts Institute of Technology

Western Michigan University

Kevadiya Inc. Ingenious Computing

MMCG Progress Report

TO: Fred Featherly, MDOT Project Manager

FROM: Mark Schwartz

DATE: 20 August 2021

SUBJECT: Final Report for Contract No. 2019-0061

Indoor Wayfinding System (IWS) Overview

The overall project goal has been to improve **indoor wayfinding process** for the general population by enhancing accessibility of some of the best indoor navigation technology. In particular, this project is intended to solve ***"the last mile problem"*** by providing guidance for Veterans to find their way from the building entrance to their appointment. Addition of universal design features is geared to improve usability of navigation aids for the **Blind and Visually Impaired (BVI)**.

As detailed below, this project successfully developed a **proof-of-feasibility prototype** which provides indoor navigation capabilities using latest and innovative technologies.

The key areas for project development have been:

- **Optimized Controls** - screen reader with natural speech solicit inputs and provides directions
- **Audio Feedback** - turn-by-turn audio instructions
- **High Accuracy** < 2 meter accuracy has become available on Android Smartphones. This enabled our developing real-time directions.

Indoor Wayfinding Team

The project team consisted of personnel from a complementary group of organizations:

Kevadiya Inc. (KVD)

Baseline Software
Dr. Mark Schwartz - Project Lead
Dr. Nilesh Patel – Engineering Lead
Michael Flynn – Senior Software Engineer
Tejpal Singh – Senior Programmer / App development
Travis Thayer – Software Engineer live navigation testing

Keith Ferriols – UI / UX Designer

Massachusetts Institute of Technology (MIT)

Prof. Berthold Horn – Advanced Localization Algorithms

Western Michigan University (WMU)

Department of Blindness and Low Vision Studies (BVI)

Prof. Robert Wall Emerson – App testing and evaluation

Prof. Dae Kim - App testing and evaluation

Indoor Wayfinding System (IWS) Final Report

This final report reviews the current status of developments on the IWS which is the ultimate culmination for the pilot program Kevadiya developed for the **2019 Michigan Mobility Challenge Grant (MMCG)**. In the last several months, from February through August 2021, Kevadiya made significant progress on the IWS project in order to complete the final tasks:

Indoor Navigation Algorithms

The complete algorithmic approach that KVD developed to provide accurate indoor navigational guidance is shown in Figure 1.

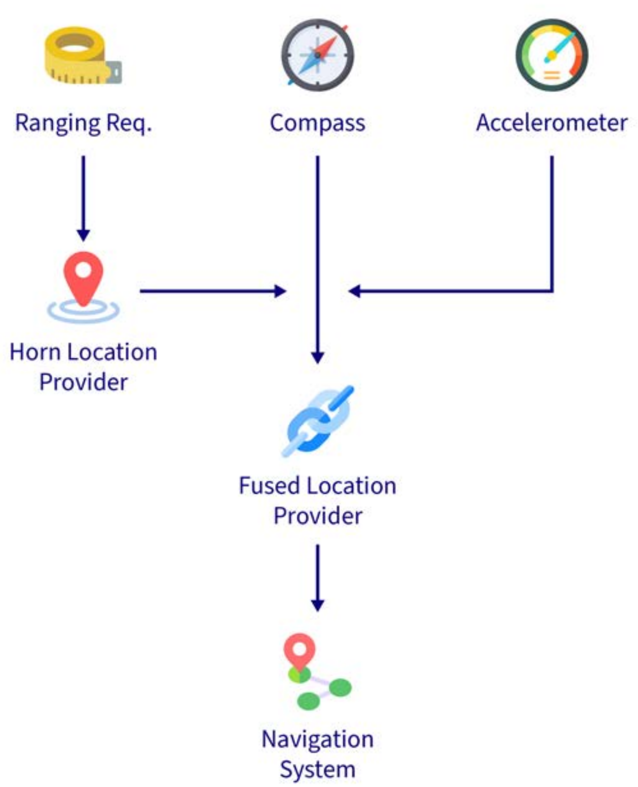


Fig. 1. IWS Algorithm Modules Flow

Prof. Horn recently published in March 2020 a paper entitled, *"Doubling the Accuracy of Indoor Location: Frequency Diversity."* Appendix A attached gives full academic journal publication in which was explained his scientific research and results. (**Sensors** 2020, 20(5), 1489) https://doi.org/10.3390/s20051489).

Doubling the Accuracy of Indoor Location: Frequency Diversity

Berthold K.P. Horn[a]

Abstract—Determination of indoor location based on fine time measurement (FTM) of the round trip time (RTT) of a signal between an initiator (smartphone) and a responder (Wi-Fi access point) enables a number of applications. However, the accuracy currently attainable — standard deviations of 1–2 meter in distance measurement under favorable circumstances — limits the range of possible application. A first responder, for example, may not be able to unequivocally determine on which floor someone in need of help is in a multi-story building.

The error in location depends on several factors, including the bandwidth of the RF signal, delay of the signal due to the high relative permittivity of construction materials, and the geometry-dependent "noise gain" of location determination. Errors in distance measurements have unusal properties that are exposed here for the first time. Improvements in accuracy depend on understanding all of these error sources.

This paper introduces "frequency diversity," a method for doubling the accuracy of indoor location determination using weighted averages of measurements with uncorrelated errors obtained in different channels. The properties of this method are verified experimentally with a range of responders. Finally, different ways of using the distance measurements to determine indoor location are discussed and the Bayesian grid update method shown to be more useful than others, given the non-Gaussian nature of the measurement errors.

to the task given the unusual nature of the error in distance measurement.

II. Introduction

The contributions of the research presented here are as follows: This paper introduces: (1) "frequency diversity" — a method for doubling the accuracy of FTM RTT distance measurements; (2) the "position-dependent error" texture surface — a new way of understanding the nature of the errors in FTM RTT distance measurement; (3) analysis of the unusual properties of the errors in distance measurement in terms of properties of super-resolution algorithms; (4) recognition of the serious impact of signal delay in common building materials resulting from their high relative permittivity — arguably more important than possible multi-path effects;

III. Background

A number of different methods for indoor location have been explored, some of which make use of properties of existing radio frequency signals emitted by Wi-Fi access points and

Fig. 2. Prof. Horn Algorithm Journal Abstract

The enabling technologies which motivated this project are the improved accuracies promised from Google WiFi RTT (Round-Trip-Time). Kevadiya thereupon deployed, from our staff, additional engineers to finalize our algorithm development. We worked in partnership with Prof Horn's MIT lab in order to implement, as best possible, the advances made in the above referenced paper. As disclosed in his publication, Prof. Horn demonstrates the possibility of achieving accuracies within potentially one meter with a precision of roughly 90%.

Kevadiya fully integrated this advanced accuracy MIT location provider approach into KVD's Indoor Navigation application. After further discussion with Prof. Horn, we worked out some details to improve our implementation of his algorithms.

We incorporated these into the algorithms for the Android App compensations:

Wall thickness - for buildings with rectangular structural organization, we found it expedient to add a "preferred direction" (long axis) so that the Bayesian grid will be more efficient. Then, lat / long was found to have enough resolution to represent wall thickness reasonably well.

Geographic vs Cartesian – in terms of coordinate systems we adopted the use of geographical coordinates instead of Cartesian coordinates this allowed us to reduce the number of conversions necessary and overall computing steps necessary to calculate in real-time the App users actual position.

Access Point Hardware - after adoption for this project of the Google WiFi hardware, KVD tested location accuracy using these new Google WiFi APs. We adopted 80 MHz bandwidth and with this higher quality hardware did show notable improvements in location findings.

KVD then tested various alternatives for adjusting offset settings for the Responders. With proper setting of offsets, we were able to achieve the actual path being close to the expected path walked (within roughly 1-1.5 meters margin of error).

Hardware Installation – while we previously had used CompuLab Access Points (APs), by switching to Google WiFi devices KVD increased the coverage and processing speed for positional calculations. This change also allows us to use more than 10 APs at a time. This capability will certainly be needed when we move from this proof-of-feasibility project to actual deployments in the much larger facilities of major VA Medical Centers and hospitals.

Wayfinding Calculations Efficiency – the project engineering team worked to select how to avoid frequent costly (computational wise) and slowly performing WiFi scans. Experimentation using the new APs, allowed us to determine the procedures to decrease inefficiencies in computing costs that are associated with probing APs that do not respond (out of range).

Then, based on prior testing, the accuracy of IWS software that relied upon regular floating point variables was shown to not be acceptable. KVD rewrote all that code to employ higher double digits variables for precision purposes. In order to represent walls reasonably well, the program needs 0.01-meter accuracy (otherwise, lines on opposite sides of wall may end up crossing over).

Hardware Calibration - Prof. Horn determined that it is useful to individually calibrate the APs to get their offsets. KVD performed this indoors in an unobstructed environment. A single measurement will not do, because of the "position-dependent" error. Determined best is to take a dozen or so measurements along a line with say 0.5-meter increments starting a meter or two away from the AP. Then do a linear least squares fit. Or more easily, just subtract the average of the actual distances from the average of the reported distances. In terms of hardware devices Prof Horn found that Qualcomm and Google have done a lot to improve the quality of results from Google WiFi (original) versus Google Pixel (or other phones using Qualcomm). This may be useful in the future since Google WiFi is now below $100 a device and since WILD will no longer be offered in the near future.

Architectural Adjustments – when designing the building map and laying out the structural designs, a lot of the areas represented by the grid could be considered by the software to be outside the building and thereby "wasted". Also, the "pixelation" of the walls for the grid worked more reliably in a coordinate system aligned with the building. The walls help curtail the spread of the probability distribution. KVD team engineers found it useful to include the azimuth of the dominant direction in a rectangular building so that the Bayesian grid could be better aligned with it.

Gait Compensations - during actual live testing, KVD found that when a pedestrian walks too fast the calculated location lags slightly behind the pedestrian's actually positioning. This is not a significant issue given the present case of our target audience. However, the faster the calculations can be processed, the better. In communications, Prof. Horn suggested fixes which could be made to speed up the location calculations. An improvement we implemented for example, is eliminating all of the UI and visual location rendering that is not needed for our use case. Removing that logic did speed up the locating services.

Workplan Modifications

The primary reason this project's workplan ended up being significantly modified is because we had designed the project for a partnership with a company which was to supply the complete accurate indoor navigation algorithms. Originally our project would have been based on magnetic signatures which seemed a very promising idea at the time. Kevadiya agreed to integrate our software with their accurate location determination and then we would concentrate almost entirely on the audio and speech based user interface for the visually impaired. However, that collaboration reached several technological impasses as the proposed partner company became very protective of what they considered their proprietary technology. Their lack of free and open cooperation reached the point where it was impossible to work efficiently together.

Therefore, based on publications and representations in the engineering literature that Kevadiya decided that we could develop our own technology for accurate positioning based on the latest advancements in WiFi standards being pioneered by Google. Prof. Horn at MIT had published some encouraging results achieving high accuracy based on the Google technology. To best work with

Prof. Horn, Kevadiya has developed our own platform for mapping out indoor of buildings. This platform was completely unforeseen effort that we undertook so as not to be dependent on any other companies so that we could develop our own indoor navigation tools. However, when KVD began working with the MIT algorithms we could not achieve submeter but approximately 2-5 meter accuracy. Also, the location signal was jumping around a lot. These problems required our engineers to modify the algorithms. This entailed our team needing to work at Oakland University in order to have a realistic test site environment.

It took over 4 months working with Professor Horn's program code to get accuracy to a manageable level. KVD lost a lot of time that could have been spent working on user interface to developing the navigation part. But this tradeoff had to be made because without location information and localization accuracy it would be premature to improve the program's user interface. KVD was up against the timeline for completion by July 2020 and had to focus efforts on location accuracy so that the system was able to be assessed in any meaningful way. KVD expended its main efforts for 4 months working with Prof Horn at MIT to refine the navigation and get the user's position with sufficient accuracy.

Therefore, there were changes in our workplan firstly because Kevadiya had to spend so much time developing advanced navigation algorithms based on the new Google WiFi standards, The second largest factor for changes in original workplan was due to the lack of ability to work more closely with the VA hospitals and their staff. Rather than rely upon the VA building and architecture departments to provide electronic blueprints to work off, It was necessitated to develop floor plans for our own offices and then for Oakland University Engineering Building.

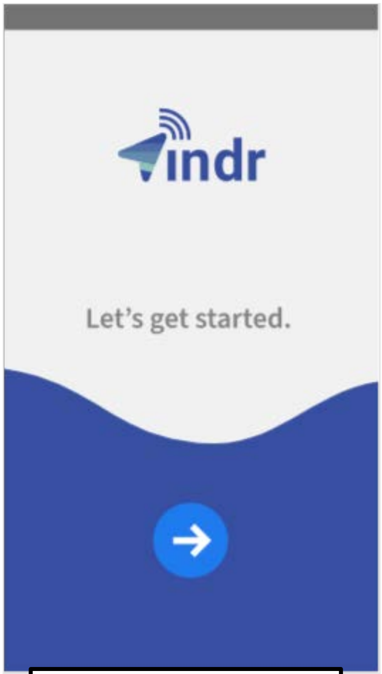
Audio was implemented for prompting the user and giving canned directions. However, free form voice input was not accommodated due to development efforts being expended in other directions as explained above. Crucial to indoor navigation is not just efficiently worded interface but accuracy of navigation.

App Development

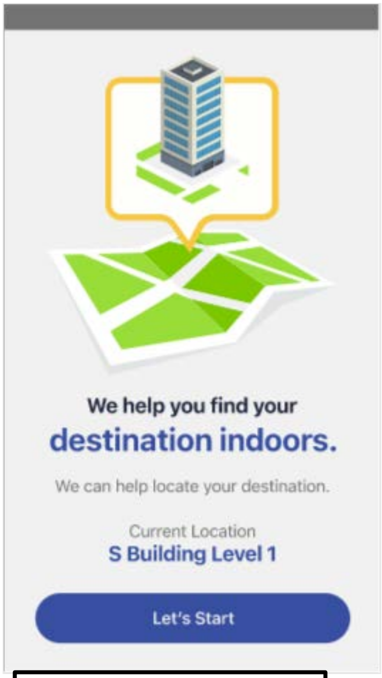
Navigating through a menu, for the blind and visually impaired, typically takes on the order of 1 minute. While the use of audio commands can be expected to reduce the time to merely take a few seconds. KVD designed an Android App to try to incorporate user interface principles which could optimize the process for the BVI population. Next generations of this App will be available in the Google Play Store.

Fig. 3 Play Store Logo for indr

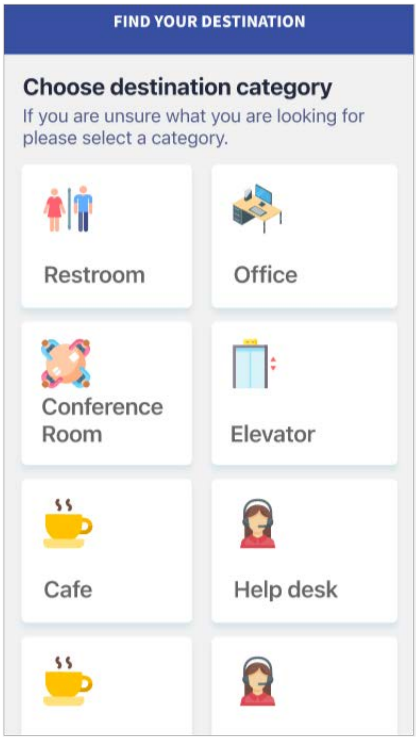
indr App Flow



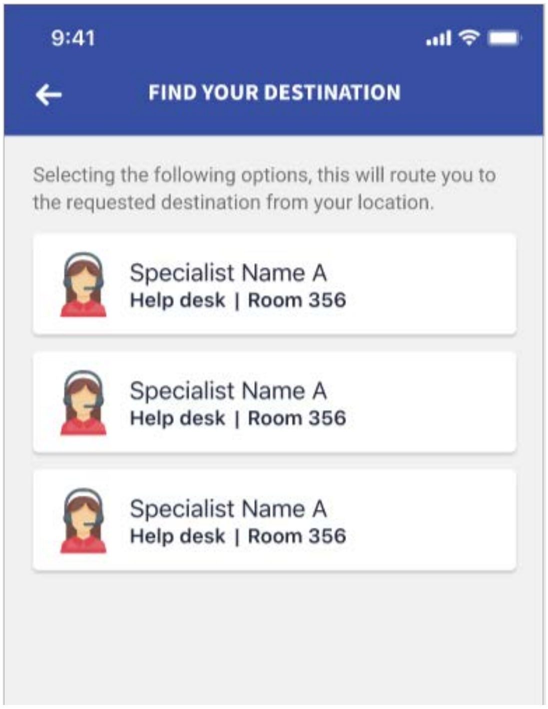
1 App startup



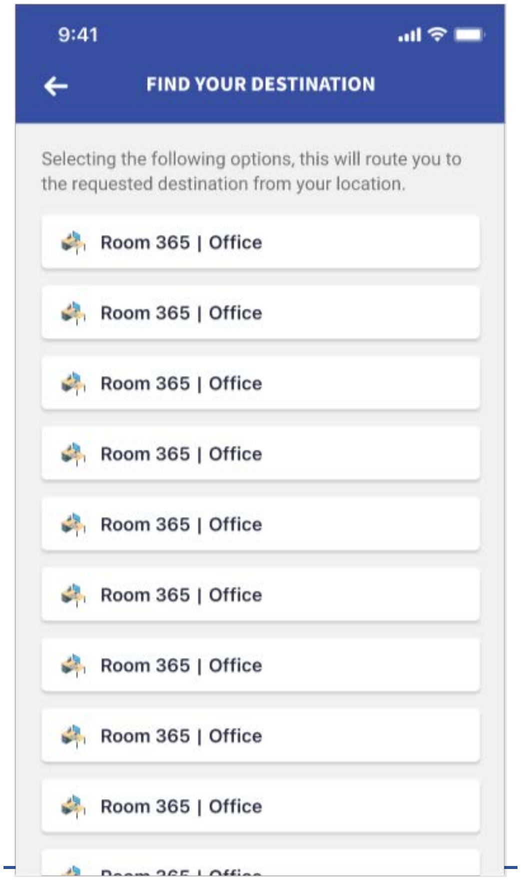
2 Current location



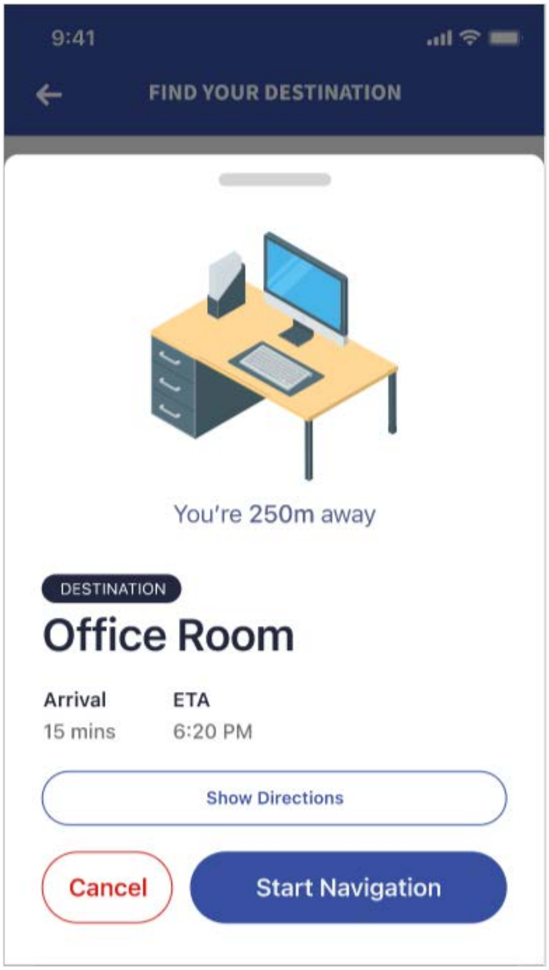
3 Destination Category



4 Destination by Person



5 Destination by Room



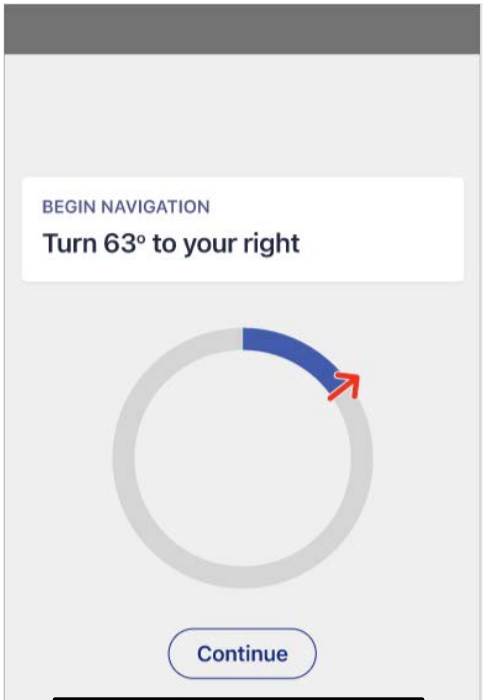
6 Estimated Arrival Time

Screen 1 - 2 – App logo. BVI users verify what facility at which they are currently located.

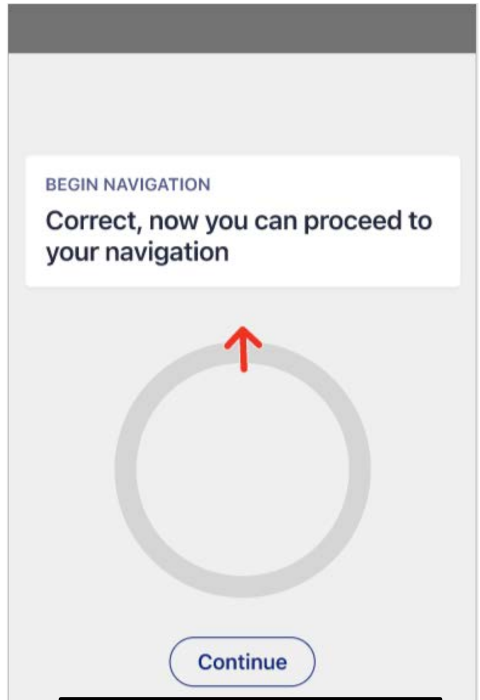
Screen 3 –When they enter their destination location, then they are presented with turn-by-turn directions from their present position. User verifies their current location

Screen 3 - 5 - User has several options for picking desired destination

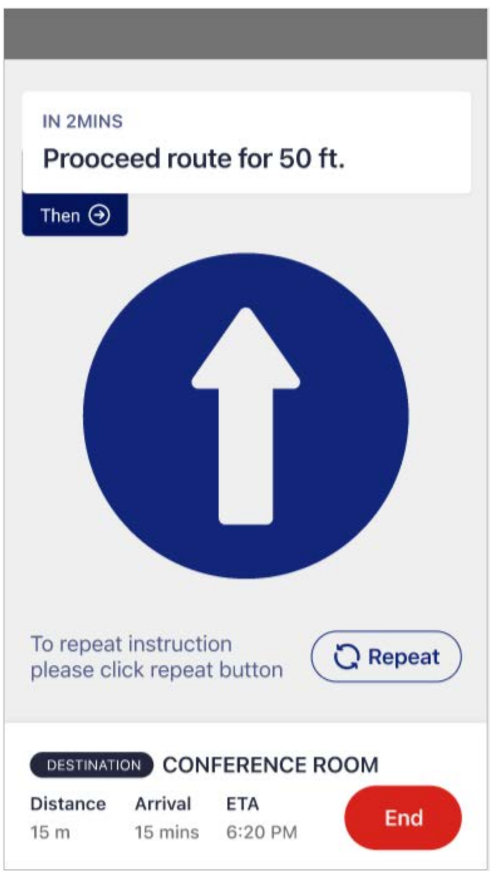
Screen 6 - User presented estimated ETA to selected destination



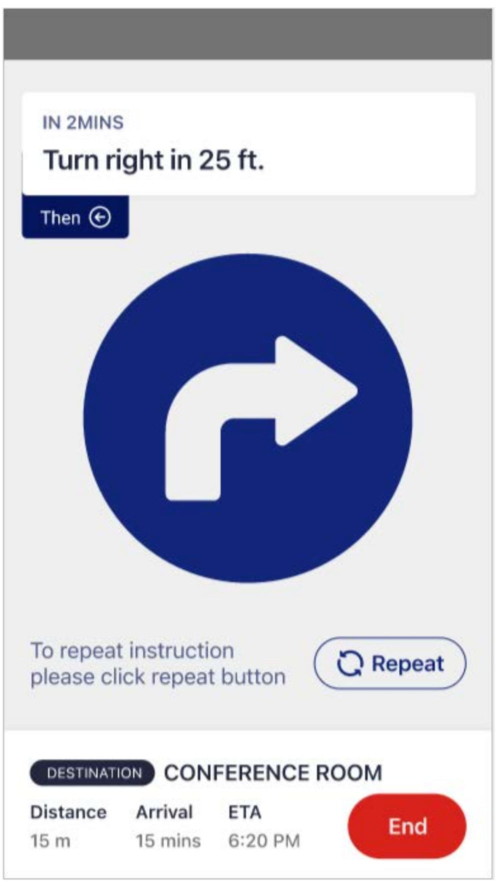
7 Adjust Orientation



8 Orientation Complete

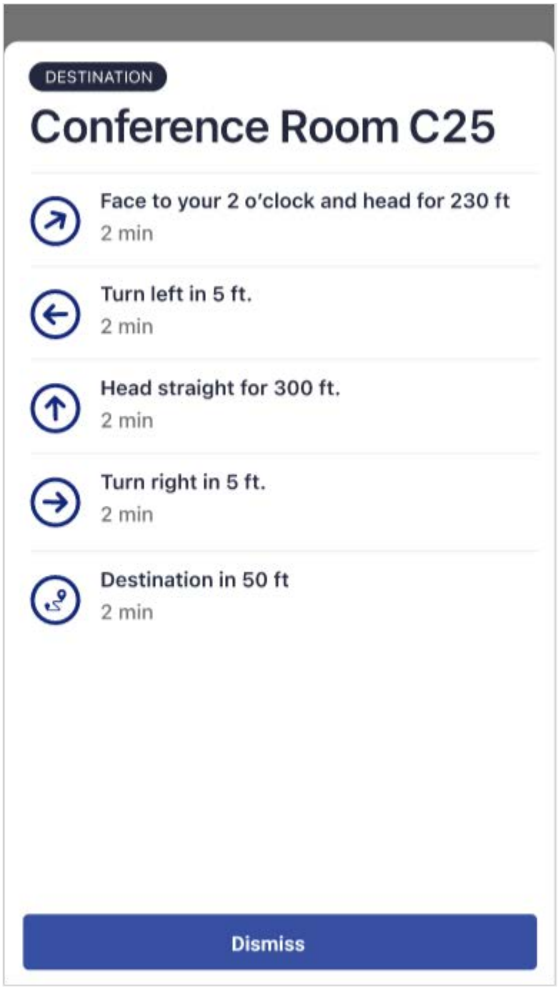


9 Forward Instruction



10 Turn Instruction

11 Arrival Success



12 Route Summary

Screen 7 - 8 - User adjusts their orientation and heading before start of walking

Screen 9 - 10 – Sample instruction screens for App giving walk directions

Screen 11 - User informed they have reached their selected destination

Screen 12 – Summary screen presents user with trip summary once start and end locations are determined

System Test and Evaluation

Once the system was completed and tested internally at Kevadiya offices it was ready to be turned over to Prof. Robert Emerson Wall and Prof. Dae Kim. Our team spent over a week at their Department of Blindness and Low Vision Studies located in the College of Health & Human Services Building at Western Michigan University. Based on their recommendations we mapped out alternative navigation scenarios on the building first floor (see Fig. 4) to be tried with their test subjects.

Fig. 4 First Floor - College of Health & Human Services Building

Following setup of APs on the First Floor, Team Kevadiya trained Prof. Wall in the App operation to do the system evaluation with BVI test subjects.

IWS Testing Participants

Subjects - 10 men 4 women
Age average - 37.4 range 21 - 58
Wide ranging

- All - legally blind >= 8 years average ~ 26 years
- All - users of long cane
- mobility skills
- technological sophistication

VA Medical Center Test Sites

The initial project, as proposed, provided for prototype testing while onsite at the Battle Creek VA Medical Center. This site was selected because Battle Creek VAMC has a Blind Rehabilitation Facility which is a Center of Excellence for visually impaired Veterans. This location was intended to avail us with access to a constantly renewing supply of onsite patient visually impaired. This population then would have conveniently tested the system with normally sighted Veterans as control subjects.

It became clear, however, from the first public recognition of the Covid-19 outbreak that federal agencies were to be taking a hardline and setting strict rules for permissible social interactions. Therefore, when Kevadiya tried from mid 2020 to schedule meetings with Battle Creek VA management to make plan which would establish our medical center test locations, there was reversal of the prior VA agreement to support our project.

Unfortunately, making of arrangements occurred simultaneously with the time the virus initiated the first lockdowns of hospitals. New Battle Creek policies put a halt on any outsiders coming onto their campus. Kevadiya pursued the issue to the Assistant Director and even the Battle Creek Director level. Compounding the pushback from the Director was the fact that he had just transferred to Michigan from a California VA Hospital and was new to this higher seniority level position and the new environment.

What with shutdowns, our pilot project was regarded as a potential source of increased close interpersonal physical interactions. Kevadiya was told that only when things settled down, the Battle Creek VA could reexamine the idea of onsite testing (i.e. once the pandemic was over).

Once it was clear that Battle Creek was ruled out as a pilot test site, Kevadiya attempted to substitute that location with the Ann Arbor VA Medical Center. We got early encouraging signs but with time it evolved into a similar situation to Battle Creek VA in terms of delays. Participant recruitment could not be started until a test site was finalized. VA reaction to visitors with highly tightened security forced our team to find a new test site.

Western Michigan University Test Site

With the end of the project nearing, it was decided that Dr. Wall Emerson would conduct testing at Western Michigan University (WMU). Luckily, Prof. Emerson Wall was able to secure us the ability to do testing on the Western Michigan University (WMU) campus in their building which houses the Department of Blindness and Low Vision Studies.

However, WMU like other universities was being placed on virtual shutdown, It became impossible to us to achieve the performance testing of 20 blind users and 20 sighted users as well as follow up satisfaction surveys. Toward the end of the project period, with the system not yet in a final state and with planned testing locations not available, Dr. Wall Emerson and Dr. Schwartz decided that it was necessary to adopt a more formative assessment approach.

The initial plan to test both blind and sighted participant was to illustrate not only the benefit of the system for participants who are blind (using versus not using the system) but also demonstrate that sighted users might benefit from such guidance in a complex environment (and to compare relative benefits). Again, with the end of the project looming, and the University campus in virtual shutdown, there was not time to recruit and test sighted participants (which was deemed to be the least important aspect of the testing). Instead, focus was shifted to testing only blind participants, to reduce the number from 20 to 14, and to focus more on formative feedback through interviews since the navigation system was not yet in a finalized state.

To this end, a smaller set of blind participants was to be assessed on use of the navigation system to the extent that it was operational within a limited setting. Performance measures were taken on specified routes within a limited travel setting and satisfaction surveys were replaced with an interview format to allow for richer collection of participant feedback on good and bad features of the navigation system. A summary of both performance and interview data was created. Appendix B (see attached) gives the Final Test Report from our WMU BVI evaluation team.

Location

College of Health and Human Services first floor, WMU (Kalamazoo, MI)

Test routes

2 routes using IWS App
2 routes using verbal route directions

Test Procedure

Experimenter gave redirections when improper functioning of the App or due to the participant travelling too far off route without realizing it.

Evaluation Plan

Our original planned use of the KPIs (key performance indicators) was predicated on the expectation that system testing would be performed at Battle Creek Medical Center. Scheduling originally was based on this assumption that we would be able to recruit high numbers of subjects for the evaluation of our pilot app with a balanced mix of user types naturally occurring by recruitment from VAMC visitors.

The automated collection of Key Performance Indicators (KPI) directly from the Kevadiya created prototype **indr App** was not feasible with the campus populations of both normally sighted and visually impaired being so diminished. It was also impossible to offer the volunteers to have extended training in the **indr App**.

IWS App UI Interactions

Because each subject became crucial in terms of test numbers, it was necessary for Prof. Emerson Wall to step each individual through the evaluation processes to ensure their proper understanding of the test questions. As explained above, the strict campus CV policies for visitors and social distancing made it impossible to achieve the population test size that we desired or had expected. The compressed testing period and the fact that it became harder to recruit controls made it clear that we had to make do with a much smaller set of test subjects.

Therefore, the formal survey was replaced with a structured interview format to allow for a deeper and broader range of feedback to Kevadiya in order to facilitate further development of the navigation system.

- All participants were to be able to interact with the App with minimal instruction
- UI operated in a manner that participants experienced as logical and appropriate
- Participants generally did not travel routes long enough to request repeated directions

IWS App Test Results Summary

As demonstrated in the attached Appendix B, KVD learned that a successful IWS (indoor wayfinding system) requires a multitude of elements. Traditional roadway approaches to navigation are segment based and do not work indoors. These traditional navigation algorithms, which are based on segmenting walk segments, are only good for users without visual disabilities.

Outdoor navigation typically has a user steer towards their first destination point and the system waits to determine where the user is located. In road navigation the user knows where the road is located. Those users can visualize the hallway segments and start walking on them once the navigation system displays the first maneuver. Contrary to that, visually impaired users require a very precise mechanism to snap to the first segment and put them on the right course. Indoors, with BVI users, the expectation that a user will keep to an identified path cannot be assumed. Because of this, a system intended to be used with blind users must be able to handle users that will travel “off path” and in typically unexpected ways.

For indoor route segments, hallways have overlap at junction points. But when a user begins a trip, the initial location is a source of potential error. When a user is in a stationary situation beginning at a junction, the system snaps users to one of the intersecting segments. Our approach was based on the expectation that we would get sub-meter positional accuracy. But when this is not achieved, the location calculated jumps around and it is harder for blind individuals to reliably use the information they get from the system. Improved location accuracy and more refined indoor mapping should address these issues.

A number of issues in accuracy of destination have to do with the initial segment being properly determined. When this segment is snapped to by the user the system is highly accurate. In fact, our experiments found that when visually impaired users were properly oriented on a segment as their starting position, our system worked flawlessly and guided the user with 100% accuracy. It was when we allowed users to start at random locations, the system accuracy dropped to 61%. This was due to the fact that the user was not able to make it to the first segment effectively. In summary, when the initial segment is correctly snapped to by the user, i.e. when on correct start segment, the navigation guides users to correct destination with 100% accuracy.

The first maneuver performed by the user is critical and system failure in finding destination only occurs if the initial error is high. The system is 100% accurate when BVI users get snapped to the proper segment. But when the user starts in a larger hallway (ex. at WMU hallways are much larger) then the initial segment calculation takes longer and has potential errors. Therefore, KVD is looking at new approach for how to snap user onto proper segment for first maneuver in larger hallway environment settings.

KVD is working on an alternate approach that can snap a user onto the correct segment more reliably. The system also needs higher accuracy beacons to better set the point of origin better.

Generally positive impression of the IWS

- All participants were to be able to interact with the App with minimal instruction
- Any assistance in wayfinding is seen as positive
- Even when the system did not work well or was not accurate, these events were discounted

Conclusions

- People who are blind are so often faced with technology that is not available
- Any system that is designed to be accessible is seen as a positive

Indoor Navigation Lessons Learned

Below are listed key lessons learned by Kevadiya in performance of this grant.

1. For buildings on rectangular organization, it found it preferable to add a "preferred direction" (long axis) so that the Bayesian grid locating will be more efficient. Then, latitude/longitude was found to have enough resolution to represent wall thickness reasonably well.

2. Investigated for the Google WiFi Access Points, the significant costs associated with probing APs that do not respond (out of range). For the future, Kevadiya is working in future to figure out how to avoid frequent costly and slow WiFi scans.

3. Kevadiya found for our algorithm input, for measurement it is necessary to go to 7 digits of precision - and hence using floats is not acceptable. We needed to use double precision - because, to represent walls reasonably well, we need 0.01 meter accuracy (otherwise, lines on opposite sides of wall may end up crossing over).

4. Kevadiya found it most useful to include the azimuth of the dominant direction in a rectangular building so that the Bayesian grid could be aligned with it. Otherwise, a lot of the area represented by the grid could be outside the building and "wasted". Also, the "pixelation" of the walls for the grid worked more reliably in a coordinate system aligned with the building. The walls help curtail the spread of the probability distribution.

5. Kevadiya investigated alternatives for setting offsets for Responders. We were able to get the actual path close to the expected path walked (within roughly 1-1.5 meters margin of error).

6. Kevadiya found that in terms of actual live testing the location lags slightly behind from where you actually are - if you walk fast (not a significant issue given our target audience, but the faster the better). An approach we are considering for

example, after discussion with Prof Horn, is for all of the UI and visual location rendering that is not needed for our use case, and removing that logic could speed up the location service.

7. Prof. Horn determined that it is useful to individually calibrate the Access Points individually to get their offsets. Kevadiya found it best to do this outdoors in an unobstructed environment. A single measurement will not do, because of the "position-dependent" error. Determined best is to take a dozen or so measurements along a line with say 0.5 meter increments starting a meter or two away from the AP. Then do a linear least squares fit. Or more easily, just subtract the average of the actual distances from the average of the reported distances.

8. In terms of hardware devices, Kevadiya and Prof Horn found that Google has done a lot to improve the quality of results from Google WiFi (original) versus Google Pixel (or other phones using Qualcomm). This may be useful in the future since Google WiFi is now below $100 a piece.

9. Results from live testing taught that:

    a. Voice input is an important feature for BVI users

    b. Audio feedback should be in steps rather than feet

    c. Audio directions should be different for BVI users than what is useful for sighted users.

WMU Test Result Recommendations

Results from App testing identified a number of features which will improve Indoor Wayfinding System (IWS) accessibility by both the Blind and Visually Impaired (BVI) and general public.

- Provide overview of route before beginning travel
- Create ability to put the phone in a pocket and just listen via Bluetooth headpiece
- More voice activation to interact with the system
- Eliminate inconvenience of having to hold a phone in your free hand while using a cane
- Verbosity level settings
- Preference settings (more or less)r
- Environmental information (water fountains, stairs, benches, bathrooms etc)
- Route information

Future Directions – Funding

Team KVD is continuing our dedication to performing research in the navigation area to improve wayfinding for blind and visually impaired individuals. However, it is expedient for us to also develop for all users the ability to perform convenient and accurate indoor navigation which will be useful for all users especially in buildings such as large hospitals where patients typically get lost without guidance.

Work on this project complements the **Vets to Wellness MMCG project** that Kevadiya performed with **MTA-Flint.** This present IWS project expands on the MTA results as it will aid Visitors/Patients in navigating through hospitals. Also, by virtue of aiding all Veterans including the Blind and Visually Impaired (BVI).

Originally plan for this project was to pilot at the **Battle Creek VA Medical Center** rather than WMU. But the pandemic put an end to those plans. As distancing restrictions lessen, KVD intends to work with our Dept. of Veterans Affairs contacts to try to get Phase 2 of this project to pilot at **VA Ann Arbor Healthcare System**.

In order to extend the present MDOT funded project we intend to apply for other grant funding sources including those from non-profit foundations and especially government agencies such as the National Institutes of Health and specifically the National Eye Institute.
Our transportation software is deployed in all 50 states and even US territories. Therefore, based on our solid track record, we have begun discussions with our contacts in **Veterans Transportation Services** to deploy IWS at all major

Veterans Health Administration Medical Facilities after successful deployment in Ann Arbor VAMC. The Office of Innovation of the Department of Veterans Affairs Has provided moral support and encouragement for our work in the past. Based on our progress to date we believe we will be able to apply to them for funding Phase 2.

Future Directions - Technology

Long-term a combination of better instructional approach with improved location accuracy is desired to achieve 100% useful navigation performance. Kevadiya is confident that this can be achieved. However, such experimentation is not just time intensive but also very expensive. Our team is committed to continue to improve this and other areas of navigational tools. We will employ emerging technologies to enable making platform enhancements. Some potential directions for new technologies that this pilot project and our evaluation results have inspired in KVD personnel for future Phase 2 development are:

- Tracking of others in user's group
- Blue dot tracking of user's position
- Artificial intelligence (AI) chatbots that recognize natural language queries. We may develop the audio input based upon a AI chatbot such as Google's DialogFlow which supports easy creation of Chatbots with natural language interfaces
- Chatbot will be further utilized to improve the user interface by enabling voice commands
- Make use of www.wayfindr.net established guidelines for creating directions for the visually impaired
- Investigate use of Apple UWB Phone technology for greater location accuracy
- Plan for incremental testing with end users throughout project development
- Develop a system for integrating building maps in a quick, reliable manner so that mapping by the navigation system is quick

Project Budget

KVD Milestones 1-10	$149,435

Other Direct Costs

WMU Subcontract IWS Mobile App testing	$35,290
Total Subs	$83,365

Total KVD due:	**$232,800**

Details are in Appendix C.

Please note that a number of the tasks in the original budget were for products to be purchased from outside companies. Kevadiya developed equivalent items internally or through our Subcontractors for identical overall pricing. This gives Kevadiya the advantage of keeping all technological advances and products within

Agreement

Michigan Department of Transportation		KEVADIYA, INC.	
By:	______________________________	By:	______________________________
Name:	______________________________	Name:	Mark Schwartz, PhD
Title:	______________________________	Title:	Proposal Manager
Date:	______________________________	Date:	08/20/2021

It is agreed by the party signing above on behalf of MDOT that the Michigan Mobility Challenge Contract No. 2019-0061 Final Report is the complete and accurate description of the work which was performed by Kevadiya and its Subcontractors. This Agreement may not be amended in any way except through a written agreement by authorized representatives of each party.

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Appendix A

MIT IWS Accuracy Report

Doubling the Accuracy of Indoor Location: Frequency Diversity

Berthold K.P. Horn[a]

Abstract—**Determination of indoor location based on fine time measurement (FTM) of the round trip time (RTT) of a signal between an initiator (smartphone) and a responder (Wi-Fi access point) enables a number of applications. However, the accuracy currently attainable — standard deviations of 1–2 meter in distance measurement under favorable circumstances — limits the range of possible application. A first responder, for example, may not be able to unequivocally determine on which floor someone in need of help is in a multi-story building.**

The error in location depends on several factors, including the bandwidth of the RF signal, delay of the signal due to the high relative permittivity of construction materials, and the geometry-dependent "noise gain" of location determination. Errors in distance measurements have unusal properties that are exposed here for the first time. Improvements in accuracy depend on understanding all of these error sources.

This paper introduces "frequency diversity," a method for doubling the accuracy of indoor location determination using weighted averages of measurements with uncorrelated errors obtained in different channels. The properties of this method are verified experimentally with a range of responders. Finally, different ways of using the distance measurements to determine indoor location are discussed and the Bayesian grid update method shown to be more useful than others, given the non-Gaussian nature of the measurement errors.

Index Terms—**indoor location, fine time measurement, round trip time, FTM, RTT, IEEE 802.11mc, IEEE 802.11-2016, time diversity, spatial diversity, bandwidth diversity, frequency diversity, Bayesian grid, observation model, transition model**

I. Overview

Determining location accurately indoors, where GPS is not reliable, has many potential applications and has been of interest for some time [1], [2], [3], [4], [5]. One of the latest entries in this effort is fine time measurement (FTM) of round trip time (RTT) as specified in the 2016 update of the IEEE 802.11 Wi-Fi standard (also referred to as IEEE 802.11mc) [6].

We start by briefly discussing alternative methods for indoor location determination. This is followed by an exploration of the error sources in indoor location determination, particularly those for FTM RTT. Then, different attempts at getting more accurate distance measurements using uncorrelated error contributions are discussed and the frequency diversity method introduced. Experimental results confirm the prediction that frequency diversity can double the accuracy of indoor location, given that there are six non-overlapping 80 MHz channels available in the 5 GHz band [7]. Finally, various methods for turning distance measurements into locations are explored and the Bayesian grid update method shown to be well suited to the task given the unusual nature of the error in distance measurement.

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II. Introduction

The contributions of the research presented here are as follows: This paper introduces: (1) "frequency diversity" — a method for doubling the accuracy of FTM RTT distance measurements; (2) the "position-dependent error" texture surface — a new way of understanding the nature of the errors in FTM RTT distance measurement; (3) analysis of the unusual properties of the errors in distance measurement in terms of properties of super-resolution algorithms; (4) recognition of the serious impact of signal delay in common building materials resulting from their high relative permittivity — arguably more important than possible multi-path effects;

III. Background

A number of different methods for indoor location have been explored, some of which make use of properties of existing radio frequency signals emitted by Wi-Fi access points and Bluetooth beacons (For a quick review see first few chapters of [8]).

A. Signal Strength

Perhaps the simplest approach is to measure the signal strength (RSSI) of a Wi-Fi access point (AP) at a hand-held device such as a smartphone (STA).

Unfortunately, the inverse square law causes the accuracy to drop off inversely with distance and so the measurements are at best only useful close to the AP. Furthermore, signal strength is affected by many factors other than distance. This includes the current power level of the AP and standing waves resulting from interference between signals reflected from material outside the line of sight (LOS) between the transmitter and the receiver. As a result, the relationship between distance and signal strength is not monotonic and not invertible (Fig. 1).

B. Fingerprinting

In light of this, another way of using signal strengths has been explored. So-called "finger printing" methods depend on careful mapping signal strengths from *several* sources in the volume of interest. Signal strengths do not vary much with time as long as objects (and people) are not moved. When they *are* moved, the finger-print data may have to be remeasured. Measuring signal strengths of multiple sources at many points in a volume is tedious and does not scale well.

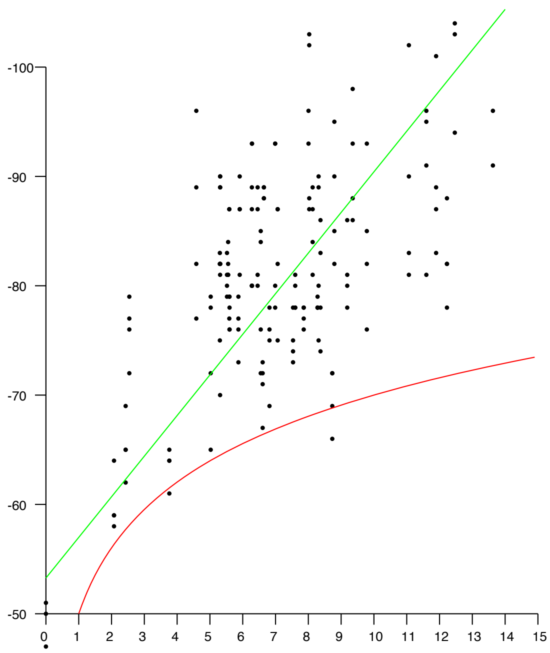

Fig. 1. Scattergram of Signal Strength (RSSI) versus distance in typical three-level wooden building. Horizontal axis: distance between smartphone and APs (in meters). Vertical axis: Signal Strength (in dBm). Red curve: expected inverse square law dependence ($-50 - 20\log(R)$ dBm). Green line: linear fit ($-53 - 3.7R$ dBm). Because of the large scatter, it should be clear that RSSI is not very useful for estimating distance.

C. Channel State Information

A simple model of the transfer function of the channel from transmitter to receiver is a weighted sum of impulses, each representing a signal that travelled along a different path. If there is a clear line of sight (LOS), the first impulse in that sum is due to the LOS path. So, if the response function can be determined, the first impulse can be isolated and used to determine the time of flight. A network analyzer can be used to measure the frequency response of a communication channel, which is the Fourier transform of the impulse response. It is, however, not practical to deploy network analyzers, in part because they require physical access to both the transmitter and the receiver.

D. Orthogonal Frequency-Division Multiplexing

In the case of orthogonal frequency-division multiplexing (OFDM) signaling — used in all but the earliest IEEE 802.11 physical layer (PHY) standards [6] — the channel is divided into many equi-spaced narrow subchannels. In operation, the response of each subchannel needs to be known and consequently is estimated continuously. This channel state information (CSI) is potentially available (at least since IEEE 802.11n using e.g. Intel 5300). It is a low-resolution approximation to what a network analyzer would measure. Unfortunately, at this point no widely used platform provides access to the CSI.

E. Angle of Arrival

With many antennas, a base station can estimate the direction of arrival of the signal from user equipment (smartphone). High angular resolution is required since the position error is the product of the distance and the angular resolution. Thus unless distances are very small, base stations with many antennas (and perhaps many radio chains) are needed, since angular resolution varies inversely with the number of antennas. There are also some privacy issues, since here a critical part of the location determination is done by the base stations, not the smartphone.

F. FTM RTT IEEE 802.11-2016

Finally, we come to fine time measurement (FTM) of round trip time (RTT) as specified in IEEE 802.11-2016 (also referred to as 802.11mc) [6]. One might expect this to overcome the limitations of other methods, since time of arrival is based on the *first* signal component, and so should be immune to multi-path problems, such as interference and standing waves.

Access to FTM RTT measurements has been provided on the Android platform since 2018 (Android 9 / Pie), although initially few smartphones and Wi-Fi APs supported the protocol (see also Appendix B).

Experimentally one finds that the distance measurements provided by FTM RTT may have standard deviations of 1–2 meter under favorable circumstances. This is fine for some applications but not others. It is important to understand the underlying causes of the observed errors in distance.

IV. Nature of the Error

In FTM RTT, the error — difference between measurement and the actual distance — can be thought of as having several components, which behave very differently. It is important to understand these contributions to the overall error e, since they need to be dealt with in different ways.

$$e = m(c; \ldots) + E(\mathbf{r}, c; \ldots) + o(c; \ldots) \qquad (1)$$

Here $m(c; \ldots)$ is "measurement noise" (see below) which depends on the channel c (i.e.frequency) and other factors, while $E(\mathbf{r}; c \ldots)$ is the "position-dependent error" (see below) which depends on position $\mathbf{r}$, the channel c and other factors, while $o(c; \ldots)$ is the offset (see below) which depends on the channel c, type of initiator, type of responder etc.

All of the above also depend on the bandwidth, but, except where noted below, we'll assume use of the highest bandwidth at which FTM RTT is supported by both the initiator and the responder (currently 80 MHz) because that normally leads to the highest accuracy.

Further, where there is a dependence on position as indicated above, there is also dependence on orientation, which we will not continue to refer to explicitly from here on.

A. "Measurement Error"

Remarkably small spreads in results are observed when measurements are repeated without changes in position (or orientation) of initiator and responder, in a fixed environment. In this case, the standard deviation (e.g. 0.1–0.2 meter under favorable circumstances) is considerably smaller than the actual error in distance measurement (which is typically greater

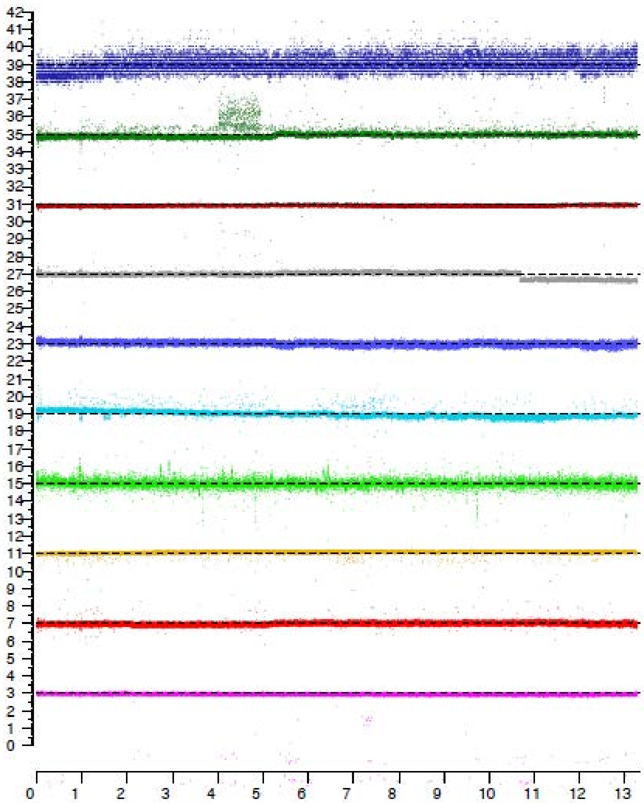

Fig. 2. Sample measurements using ten different responders in fixed positions. (Top plot is for an access point operating in the 2.4 GHz band, the rest in the 5 GHz band). Horizontal axis: time in hours. Vertical axis: distances in meters (individual plots are offset vertically to avoid overlap).

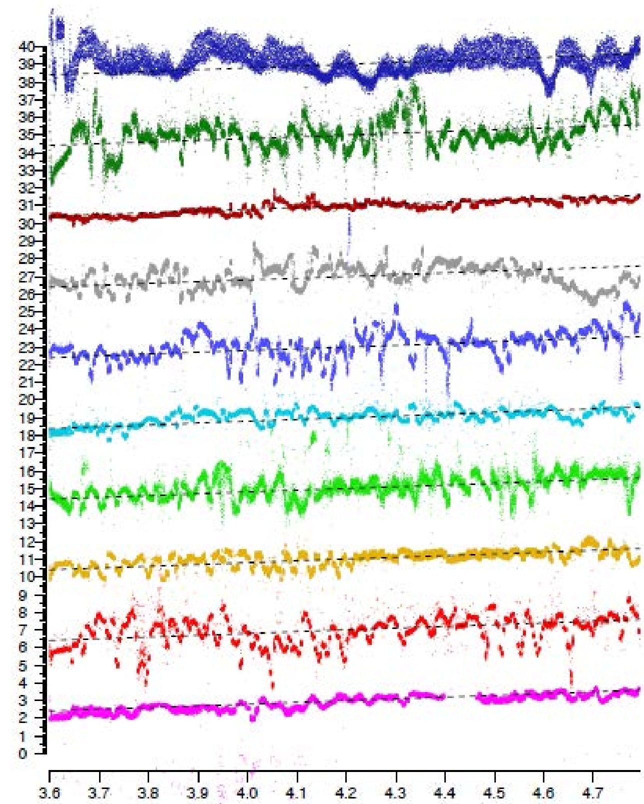

Fig. 3. Sample measurements using ten responders in a range of positions (Top plot is for an access point operating in the 2.4 GHz band, the rest in the 5 GHz band). Horizontal axis: actual position in meter. Vertical axis: reported distances in meters (individual plots are offset vertically to avoid overlap).

than 1–2 meter). As a consequence, perhaps surprisingly, results are *not* significantly improved by averaging repeated measurements.

While this error component looks a lot like typical measurement error resulting from additive random noise, it should be noted that: (i) its distribution is *not* Gaussian; (ii) there are distant outliers in many cases; and (iii) the distribution is not always even unimodal. Importantly, small changes in position (or orientation) can cause large changes in the distribution. As a result repeated measurement in fixed positions can lead one to grossly underestimate the error in distance. We'll say that repeated measurements obtained in fixed positions exploit "time diversity," and note that time diversity does *not* provide a path to improved accuracy.

B. "Position-Dependent Error"

Perhaps somewhat surprisingly, small movements (millimeters) of the initiator (or the responder) induce large changes (meters) in reported distance measurements. This error component is a function of 3-D position (and orientation). It is difficult to explore and visualize the error dependence fully in 3-D, but much can be learned by simply scanning along lines.

It is clear that the "position-dependent" error in Fig. 3 is much larger than the "measurement noise" in Fig. 2. Careful measurements along lines surprisingly shows fluctuations in the error surface that have "texture element" size comparable to the wavelength of the radio frequency signal (which ranges from 58 mm for 5210 MHz to 52 mm at 5775 MHz). This is confirmed by inspection of the spatial power spectrum, which has much of its energy at and below the frequency corresponding to about two cycles per wavelength.

Measurements taken at positions separated by more than say a wavelength are fairly uncorrelated. This suggests one way of improving accuracy: average several measurements taken (far enough apart) along points spaced out along a line (or on a regular grid). This indeed leads to a result with considerably higher accuracy than averaging repeated measurements taken in a fixed location. We'll say that repeated measurements obtained on a line (or on a grid of locations) exploit "spatial diversity" and note that spatial diversity *can* improve accuracy significantly.

It is, however, not clear how this observation can be used in practice since it requires either a set of regularly spaced antennas in an array larger than the typical smartphone, or perhaps some mechanism for moving a single antenna into a set of positions in some regular pattern.

For experiments requiring high accuracy, however, such as measurements of the relative permittivities of building materials like concrete, brick and wood, the extra effort in making measurements in several positions is well justified, since for these types of measurements the raw accuracy of FTM RTT is not adequate.

C. Offset

Over a large range of distances, with a clear line of site, the reported distance varies linearly with the actual distance. The slope of the linear fit is 1 (see e.g. Fig. 4) but there typically is a significant offset, which depends on the type of initiator, the type of responder, the channel in use, bandwidth, and the preamble.

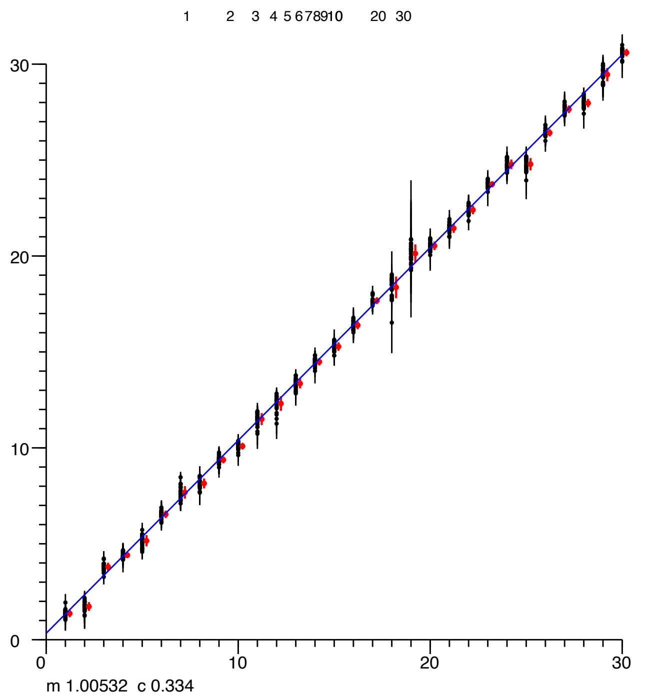

Fig. 4. Linear fit of reported distance to actual distance (outdoors, clear LOS, no obstructions in the first Fresnel zone). The offset in the well calibrated setup tested here happens to be small (less than half a meter), but can be five meters or more in other situations. Horizontal axis: actual position in meter. Vertical axis: FTM RTT reported distances in meters.

Ideally, all initiator/responder combinations would come calibrated to yield zero offset. Presently this is not the case, and different responders will yield different offsets with different initiators (sometimes differing by five or more meter). Even a particular combination of initiator and responder has different offsets when operating in different channels (which can lead to hard-to-track errors when the AP decides to switch channels for some reason!). Presently one must calibrate for the particular combination of initiator and responders to be used in order to eliminate these offsets.

D. Noise Gain

The accuracy of the final location estimate is not the same as the accuracy of the raw measurement of distance between the initiator and the responder. The error in location may be considerably larger than the error in distance measurement, depending on the geometry of the layout of responders and initiator. The ratio of the error in location to the error in the distance measurement is the "noise gain" — euphemistically referred to as "dilution of precision" (DOP) in GPS terminology. This suggests that there is some benefit to carefully planning the distribution of responders so as to minimize the error in the worst-case position of the initiator (see also Appendix C).

E. Dependence on Bandwidth

The expected accuracy is inversely proportional to the bandwidth of the Wi-Fi signal. Currently the highest bandwidth of initiators and responders that support the IEEE 802.11 FTM RTT protocol is 80 MHz (there are some access points and some Wi-Fi adapters that support 160 MHz but, as of this writing, do not support FTM RTT).

One may consider "bandwidth diversity" as another possible measure to improve accuracy, but the results at 40 MHz and 20 MHz tend to be noticeably worse than those at 80 MHz. As a result, there is only a small gain in accuracy using a best fit weighted average of the three results (aside from that, the offsets are different for different bandwidths and need to be calibrated out).

V. Where does the large position-dependent error come from?

The main component of the error is the position-dependent error. Given the size of the "texture element" of this type of error, it appears to be related to some sort of interference pattern resulting from reflections off objects that are not in the line of sight. This is quite unexpected since the first arriving component of the signal should *not* be affected by any such reflections.

In contrast to this, signal strength (RSSI), being a steady state measurement, *is* subject to large fluctuations ("fast fading") over relatively small distances due to just such interference. (see upper plot in Fig. 5)

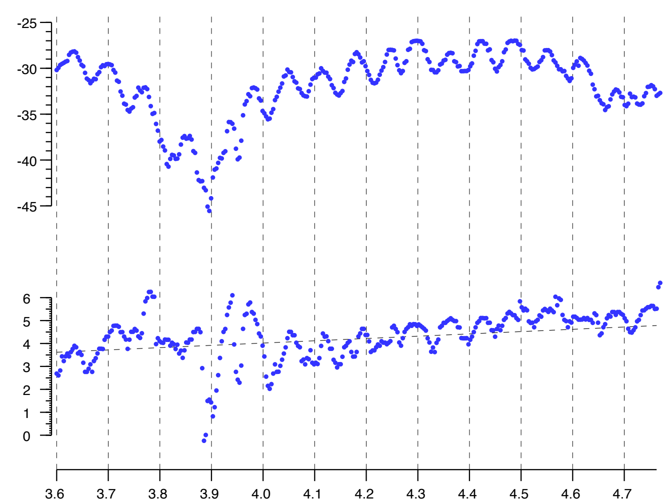

Fig. 5. Upper plot: signal strength (RSSI) in dBm, Lower plot: reported distance in meter. Horizontal axis: actual position in meter. Note undulations with wavelength somewhere between about half the wavelength and the full wavelength of the electromagnetic wave.

Again, at least with a clear line of sight, the first arrival should *not* be affected by later arriving signals reflected from objects in the environment. Thus, it comes as a surprise that FTM RTT distance measurements seem to be affected by some sort of interference patterns or stationary waves (see lower plot in Fig. 5) To understand how this can be, we must know more about how these measurements are made.

A. Super Resolution

With OFDM modulation, demodulation is done by inverse Fourier transform of samples of the signal. For 80 MHz bandwidth, these samples are taken at 80 Msps (actually, both Q (real part) and I (imaginary part) are sampled at that rate, but that does not affect the argument here). That means that samples are taken every 12.5 nsec, which corresponds to 3.75 meter round trip travel of the radio-frequency (RF) wave. So, if first arrival was based merely on which sample exhibits the first sign of a rising waveform, then the (one-way) resolution would be 1.875 m. The measurement actually provided to the user has much finer resolution (RTT, for example, may be given in units of 0.1 nsec, very much smaller than the 12.5 nsec sampling interval). Super-resolution methods are used to "interpolate" between known samples of the signal.

Several super-resolution methods are used, such as MUSIC, ESPRIT, and pencil matrix [9], [10], [11], [12], [13], [14], [15], [16]. These are based on specific assumptions about the transfer function of the communication channel. In particular, it is assumed that the impulse response of the channel is a weighted sum of shifted impulses, corresponding to different components of a multi-path signal.

While the aim is to provide the user with finer resolution, such methods also have limitations. They are highly non-linear and can exhibit discontinuities and non-monotonicity. Further, information on what actual algorithms are used in the Wi-Fi initiator and in the Wi-Fi access points is not available to the user.

To illustrate the potential problem, consider first an over-simplification. A simple algorithm has arrival time estimated based on when a sample of the signal amplitude exceeds some threshold. However, one cannot use a fixed threshold for deciding when the signal arrives, since the signal can vary over several orders of magnitude (e.g. -100 dBm to -40 dBm — i.e. a ratio of a million to one in power) The threshold to determine whether the "toe" of a signal has arrived must be scaled based on the strength of the signal. But that "signal strength" can only be ascertained later when it has reached a peak. While the "toe" is not affected by multi-path reflections, the amplitude used for normalization *is* subject to the interference pattern. So even though the first arrival is not contaminated by interference, the threshold against which it is compared *is*. This sort of effect can give rise to the wildly fluctuating position-dependent error surface described above (see lower plot in Fig. 5).

VI. Frequency Diversity — six channels

Since the position-dependent error surface has "texture" the order of the wavelength of the radio frequency signal, it stands to reason that operating at different frequencies would produce different position-dependent errors. There are six non-overlapping 80 MHz channels in the 5 GHz band [7]. This provides for up to six measurements with uncorrelated error contributions, potentially leading to a multiplication of the error by $1/\sqrt{6} \approx 0.408\ldots$. (Note that there may be some restrictions on some channels in some parts of the world. The highest channel, for example, is not available in Japan, Israel, Turkey and South Africa [7]).

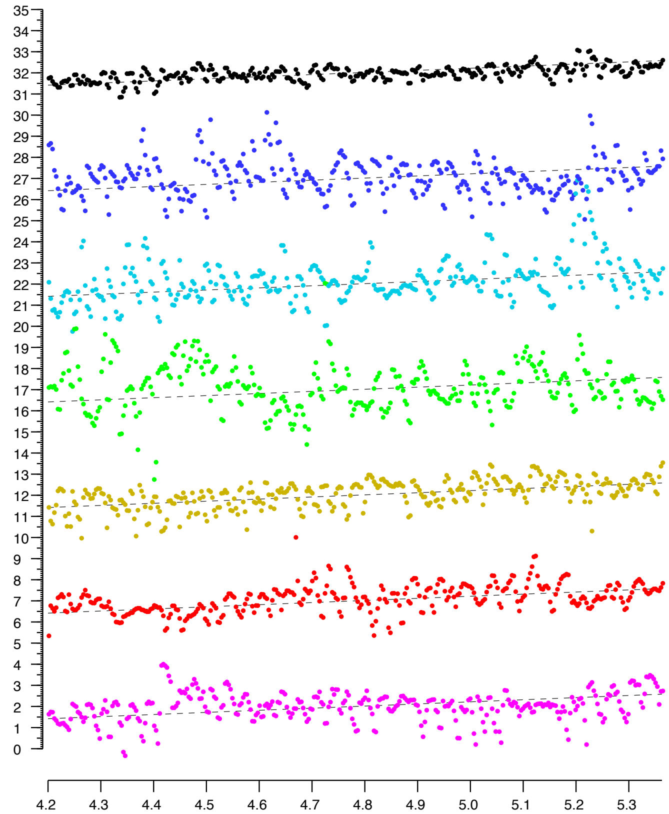

Fig. 6. Sample plots (colored) of reported distances in six 80 MHz wide channels in the 5 GHz band. The top (black) plot is a simple average, which has less than half the error of the individual measurements. Horizontal axis: actual distance in meter. Vertical axis: reported distance in meters (offset to prevent overlap)

Fig. 6 shows plots of distance measurements in six channels as a function of actual position. The channels have center frequencies 5210 MHz (magenta), 5290 MHz (red), 5530 MHz (brown), 5610 MHz (green), 5690 MHz (cyan), and 5775 MHz (blue). The correlation matrix (eq. 2) shows that the position-dependent errors in the different channels are essentially uncorrelated.

$$\begin{bmatrix} 1 & -0.05 & -0.19 & 0.21 & -0.03 & 0.12 \\ -0.05 & 1 & 0.13 & -0.04 & -0.14 & -0.09 \\ -0.19 & 0.13 & 1 & -0.19 & -0.09 & 0.00 \\ 0.21 & -0.04 & -0.19 & 1 & -0.07 & -0.11 \\ -0.03 & -0.14 & -0.09 & -0.07 & 1 & -0.04 \\ 0.12 & -0.09 & 0.00 & -0.11 & -0.04 & 1 \end{bmatrix} \quad (2)$$

The st. dev. of position-dependent errors from the six channels are 0.710 m, 0.578 m, 0.540 m, 1.163 m, 0.944 m, and 0.909 m respectively (average 0.808 m). A simple average of the six distances has st. dev. 0.309 m, which is significantly better than the best channel on its own, and more than twice as accurate as the average.

A weighted sum — rather than a plain average — can do even better. In this particular case, with weights 0.155, 0.234, 0.301, 0.080, 0.130, and 0.100, the st. dev. comes to 0.264 m (which is only about a third of the average st. dev. of the six channels). With six channels, the added refinement of least-squares weighting may not always be worth the effort since the relative quality of the channels depends on the environment and will be different in different situations.

By the way, averaging FTM RTT measurements from six 80 MHz channels does *not* produce the same results as if one were to perform a single FTM RTT measurement in a channel of 480 MHz bandwidth. In the case of a single ultra-wide channel, the error would be multiplied by $1/6$, not $1/\sqrt{6}$.

VII. Frequency Diversity — Three channels

It may not always be practical or convenient to use all six 80 MHz channels for FTM RTT distance measurements. In some situations a smaller number may be more easily accessible. Several "tri-band" mesh Wi-Fi APs (e.g. Eero Pro, Netgear Orbi and Linksys Velop). have two radios which make it easy to get measurements for at least two channels in the 5 GHz band (e.g. 5210 MHz in U-NII-1 and 5775 MHz in U-NII-3). Often also, one of the radio chains is shared between the 2.4 GHz and 5 GHz bands and if the device happens to respond to FTM RTT requests in both bands (e.g. Linksys Velop) then this opens up the possibility of taking three measurement with uncorrelated error contributions.

Taking a simple average potentially multiplies the error by $1/\sqrt{3} \approx 0.577\ldots$ (assuming similar distributions for the three channels and with uncorrelated noise). Not as good as with six channels, but still a useful improvement. Actually, this may be a bit optimistic, since the 2.4 GHz channels is not as good as the other two, but suitable weighting of the three contributions can get one close to the ideal.

In Fig. 7, the bottom three plots are for channels with center frequency (i) 5210 MHz (red), (ii) 5775 MHz (green), and (iii) 2442 MHz (blue). The correlation matrix (eq. 3) shows that the position-dependent errors in the different channels are, once again, uncorrelated.

$$\begin{bmatrix} 1 & -0.00 & 0.03 \\ -0.00 & 1 & -0.13 \\ 0.03 & -0.13 & 1 \end{bmatrix} \tag{3}$$

The top plot (black) in Fig. 7 is for a weighted average (weights 0.48, 0.35, and 0.17 respectively). The st. dev. of the position-dependent error in the lower three plots are 0.382 m, 0.480 m, and 0.721 m, for an average st. dev. of 0.528 m. The st. dev. of a simple average is 0.302 m (which is better than any of the individual channel st. dev.). and the st. dev. of the weighted average is 0.270 m (which is almost twice as accurate as the average channel).

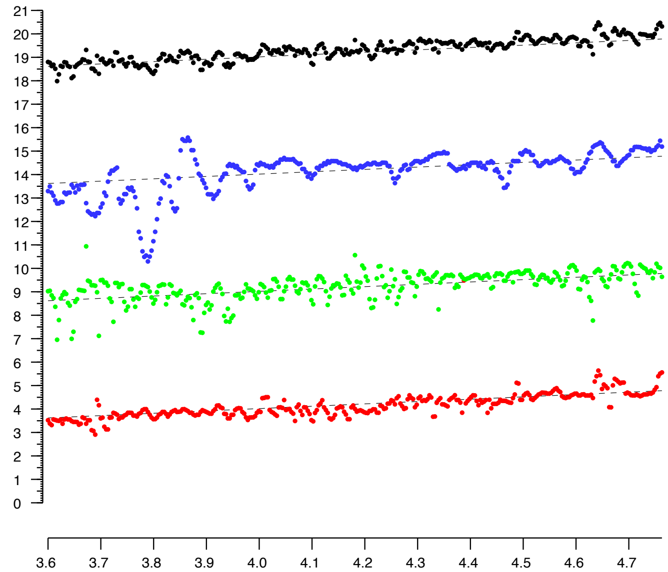

Fig. 7. Sample plots (colored) of reported distances in three channels. The top (black) plot is a weighted average, which has only a bit over half of the average error in the individual plots. Horizontal axis: actual distance in meter. Vertical axis: reported distance in meters (offset to prevent overlap)

Typically different chips are used for the two radio chains. In the case of Eero Pro, for example, the first 5GHz radio (and the 2.4 GHz radio) uses the Qualcomm IPQ4019 chip, while the second 5Ghz radio uses the Qualcomm QCA9886 SoC. These have somewhat different measurement qualities and thus weighting their contributions differently (as above) helps improve the overall result.

Finally, if three channels are not available, using two channels can already bring some improvement in accuracy relative to relying on a single channel.

VIII. High relative permittivity of common building materials

Inside buildings, signals often have to travel through walls and floors of concrete, wood, brick, drywall or glass. These materials have high relative permittivity which slows down the signal significantly. Careful measurement of thick layers of various materials show relative permittivities, in the 8–10 range for wood, and 5–7 range for concrete, depending on moisture content and composition (The signal also is attenuated significantly, but this does not directly affect the time-of-arrival) [17], [18], [19], [20]. Time-of-flight times the speed of light is the equivalent distance travelled in vacuum — which may be considerably larger than the actual distance. A 0.5 meter thick concrete wall can, for example, add 3 or 4 meters to the reported FTM RTT "distance." This needs to be taken into account somehow in the estimation of position from distance measurements. The effect of thick walls and floors should also be a concern when planning the placements of responders.

Arguably, the effect of high relative permitivitties of building materials on distance measurements is more important than that of multi-path. Particularly reminding ourselves again that

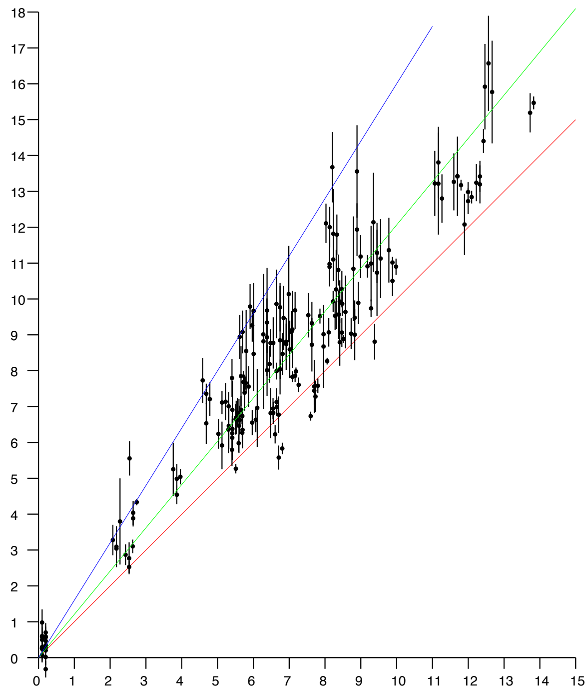

Fig. 8. Scattergram of measured distances versus actual distance in wooden three-story house. Vertical axis: measured distance (meter). Horizontal axis: actual distance (meter). Red line (slope 1) is the ideal relationship; Green line (slope 1.2) is the best linear fit; Blue line (slope 1.6) is an upper extreme. The high permittivity of building materials biases the distances measured by FTM RTT.

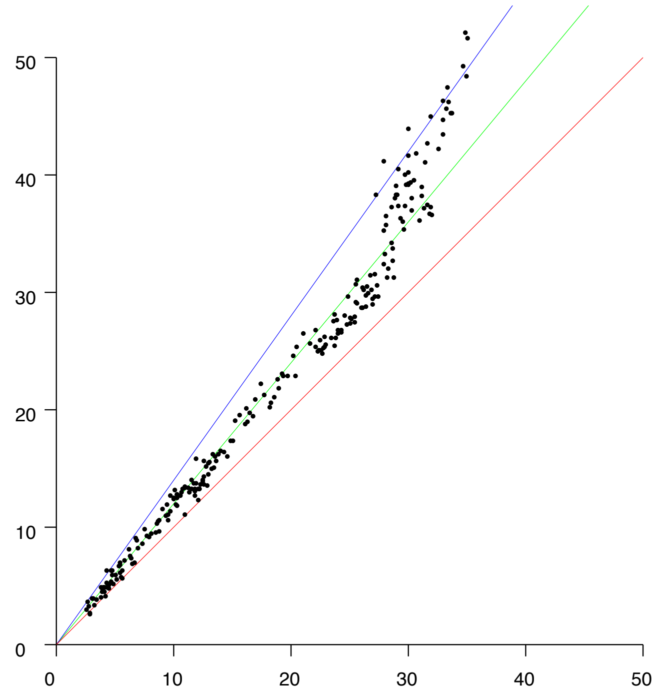

Fig. 9. Scattergram of measured distances versus actual distance in a large open plan office building. Vertical axis: measured distance (meter). Horizontal axis: actual distance (meter). Red line (slope 1) is the ideal relationship. Green line (slope 1.2) is the best linear fit. Blue line (slope 1.4) is an upper extreme. The high permittivity of building materials biases the distances measured by FTM RTT.

the time of first arrival should *not* be affected by reflections that arrive later.

Fig. 8 shows how building materials affect measurements in a three-story wooden house. Fig. 9 show how building materials affect measurements in a large open plan office building. The effect there is less extreme, although over long enough distances just as significant.

IX. Recovering location from distance measurements

Once we have estimated distances from a number of AP responders in known locations we can try and determine where the initiator is.

A. Multi-lateration

If we are dealing with a single level building, we can treat this problem in 2-D. In this case each measurement confines the possible location of the initiator to points on a circle with an AP at the center, — or a circular annulus if we take into account uncertainty in the measurement. Two measurements lead to the intersection of two circles, which typically is two points (These two points lie on a line that is perpendicular to the line connecting the centers of the circles). A third measurement can disambiguate if needed. Three or more measurements are typically inconsistent but can be used in a least squares fashion to reduce the error in location estimation.

This is quite analogous to finding a cellular base station from multiple LTE Timing Advance (TA) measurements — just with much finer resolution [21].

In the more general full 3-D case, each measurement confines the location of the initiator to points on the surface of a sphere with an AP at its center — or a spherical shell if we take into account uncertainty in the measurements. Two measurements restrict the solution to the intersection of two spheres, which typically is a circle (This circle lies in a plane that is perpendicular to the line connecting the centers of the spheres). A third measurement reduces the possibilities to the intersection of a circle and a sphere, which typically occurs in two places. A fourth measurement can disambiguate if needed. Four or more measurements are typically inconsistent but can be used in a least squares fashion to reduce the error in location estimation.

B. Linear multi-lateration?

The equations for the circles — or spheres — are second order, but all with the same higher order terms. Thus it is tempting to subtract them pairwise to obtain linear equations, since sets of linear equations are easy to solve. This is a mistake. While the resulting equations yield the correct solution if the measurements are perfect, the “noise gain” is very high. That is, small errors in distance measurements translate into large errors in position. One way to understand why this happens is that we are throwing away some of the constraint provided by the measurements. For convenience, here we consider the solution to be confined to the planes containing the circles of intersection, *not* to the actual circles, which is a much tighter constraint. (For mathematical details of the argument see [22]).

An aside: this is quite analogous to the infamous "8-point method" in machine vision for solving the relative orientation problem. While it is very appealing because of the linear form of the equations, minimization of errors in those equations does not minimize the sum of errors in image positions [23], [24]. As a result, this method cannot be recommended (other than perhaps in the hope of finding plausible starting values for methods that do the right thing).

C. Least Squares minimization and brute force grid search

For a given hypothesized location for the initiator, the distance from each AP can be computed and compared with the measured distance. One can then find the location that minimizes the sum of squares of the differences between computed and measured distances. Gradient-descent may not work reliably to find the global minimum of this error sum, since the shape of the error surface can be complex. We can, however, divide the space into pixels (2-D) or voxels (3-D) and simply compute the error for each cell. This is, after all, not computationally expensive, since, given the limited accuracy of FTM RTT measurements, the cells need not be very small (e.g. perhaps 0.5 m on a side). So even a typical building with side lengths of tens of meters would be represented by just a few thousand cells.

D. Kalman filtering

Kalman filtering [25], [26] provides a way to update an estimate of the position along with an estimate of the covariance matrix of uncertainty in the estimated position ever time a measurement is made. It is based on assumptions of Gaussian noise independent of the measurement, Gaussian transition probabilities and linearity.

Unfortunately the measurement error is not Gaussian nor is it independent of the measurement itself. Further, when near one of the responders, the area of likely positions is shaped more like a kidney (i.e. part of a circular arc) — or even bimodal — rather than something that can be well approximated by a linearly stretched out Gaussian distribution (Fig. 13). As a consequence, Kalman filtering does not provide the best way to use the available informatiom.

E. Particle filter

If a probability distribution is not easily modeled in some parameterized way (such as a multi-dimensional Gaussian), then other means may be used to represent it. One such method is that of particle filters which uses weighted samples to represent a distribution [27]. The distribution is in effect approximated by the sum of weighted impulses. At each step, the position of the particles is updated based on a transition model. The weights of the particles are adjusted based on the measurements. Particles with low weight are then discarded, while new particles are sampled to keep the overall number of particles at a desired value.

F. Bayesian grid update

Another way of dealing with a probability distribution that can't be easily parameterized is to represent it with values on a regular grid. Sequential Bayesian updates can be applied to such a grid of probabilities [28]. This method starts with a prior distribution (perhaps uniform). A transition model is invoked at each step which modifies the distribution based on likely movement of the initiator (e.g. a random walk). If a floor plan is available, impenetrable walls can be taken into account in the transition model if desired. This is followed by Bayesian update based on distance measurements, which uses an observation model which estimates the probability of seeing a measurement given the actual geometric distance between a voxel and the responder.

If a single location is required as output, rather than a distribution, one can, for example, use the mode (maximum likelihood) or the centroid (expected value) of the distribution.

As with other forms of "filtering," there can be a lag in the response when the initiator moves more rapidly than the transition model expects. Also, a bad solution may get "trapped" behind walls, when a floor plan is used to prevent "tunneling" through walls in the transition model.

G. Observation Model

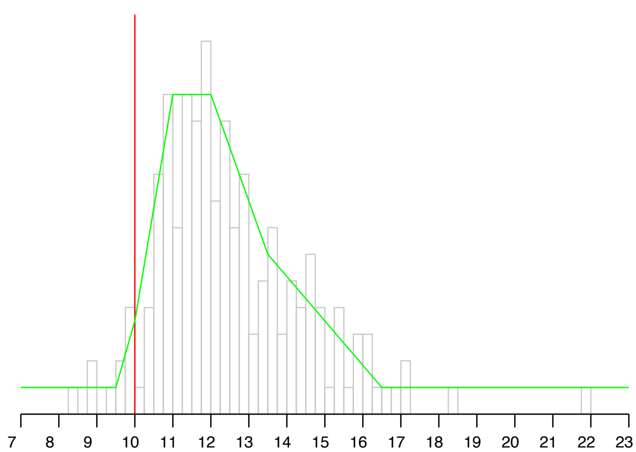

Fig. 10. A slice through an observation model. Horizontal axis: measured distance (when actual distance is 10 m) Grey histogram: measurements from typical three-level residence. Green curve: observation model — probabilty of measuring the specified distance (piece-wise linear fit to grey histogram).

Fig. 10 shows a section of an observation model. It shows the probability of various measured "distances" on the horizontal axis in meter) given that the actual distance between initiator and responder is 10 meter (i.e. the vertical red line). The actual distance is a lower bound on the measurement. It can be considerably larger since the signal may pass through building materials with large relative permittivity. In the figure, the observation model (green curve) is a piece-wise linear fit to experimental data from a three-level residence (grey histogram).

The observation model is used to update the probability at each grid cell. For each cell on the grid, the distance from the AP is known and so the appropriate slice of the observation model can be accessed. The observed FTM RTT distance is then used to look up the probability that this observation would occur, given the known actual distance for this grid point. This value is then used to multiply the current value in that cell. Optionally, the resulting grid of values can than be normalized so it once again adds up to one.

H. Transition Model

We use a simple transition model of a random walk of a step size based on comfortable walking speed of 1.4 m/sec[29]). In a simple implementation this just "pushes" probabilities into neighboring cells (exept for cells on the edge of the grid). If more information is available from inertial measurement (IMU) and magnetic compass, then this can be used to refine the transition model. But the simple model appears to be adequate for location determination. A floor plan can be used to limit "forbidden transitions" such as walking through a wall. This can further improve the tracking of a location solution as the user progresses through the environment.

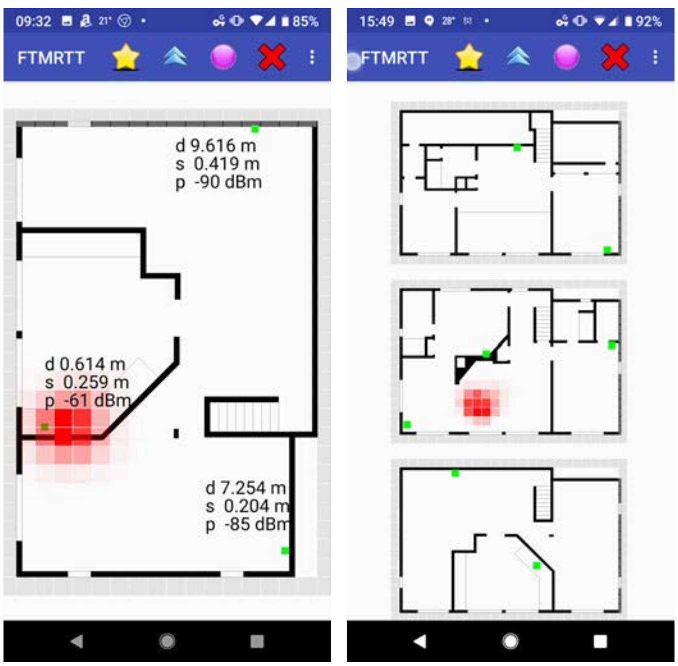

Fig. 11. Sample "heat maps" of Bayesian grids. Left: 2-D case (single level) with 3 responders (green dots). Text shows current FTM RTT distance, st. dev. and signal strength. Right: 3-D case (three levels) with 7 responders. Voxels in each floor were collapsed into a single layer for display purposes.

Fig. 11 shows probability distributions on grids with cells 0.5 meter on a side. The green dots mark the positions of the responders (In this case, the floor plan was not utilized to limit the transition model). For an MP4 movie showing the Bayesian grid evolve as someone moves on one level, see [30]. For an MP4 movie showing the Bayesian grid evolve as someone moves through a three-story building, see [31].

X. Noise Gain (a.k.a. Dilution of Precision — DOP)

The geometric arrangement of responders determines the "dilution of precision" (DOP, or "noise gain"), that one can expect in various parts of the volume of interest.

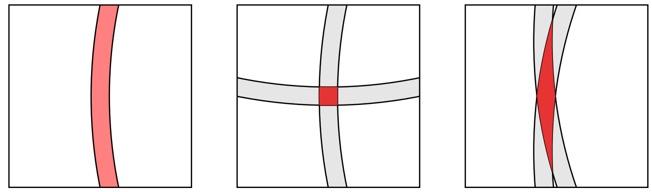

Fig. 12. Dilution of Precision. Left: constraint from single distance measurement; Middle: favorable combination of constraints; Right: unfavorable combination of constraints. The area of the overlap grows as $1/\sin(\theta)$, where θ is the angle between the directions to the APs.

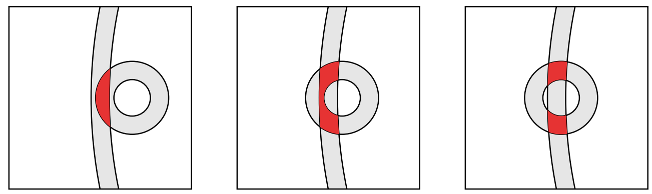

Fig. 13. Dilution of Precision when close to responder. Left: Intersection is more or less an oblong oval; Middle: Intersection is sort of kidney shaped; Right: Intersection is bimodal Such distributions cannot reasonably be approximated by multi-variate Gaussians.

On the left in Fig. 12, is shown the annulus within which the initiator position is constrained when a single, noisy distance measurement is available. In the middle is the situation when two measurements are available from responders that are more or less at right angles in directions as seen from the initiator. Plausible solutions in this favorable case are confined to a small area. On the right is the less fortunate situation where the directions to the responders are similar, and not much new information is provided by the second measurement. Correspondngly, the likely position of the initiator is not as well confined.

When close to one of the responders, the geometry becomes more intricate, and, counter-intuitively, the solution may be less well determined. This is illustrated in Fig. 13.

It is generally not a good idea to have the responders close together, since then the distance measurements will be correlated and redundant. The effect of errors typically not isotropic, but is stronger in some directions than others (as, for example, in the case of GPS, where the vertical DOP is considerably larger than the horizontal DOP, as a result of the fact that the "visible" satellites are not distributed evenly over a sphere of possible directions). In some cases curves of constant error may be quite elongated, meaning that while the position may be well defined in some directions, it is not in others. Finding the "best" layout of responders in a given 3-D volume is an open research problem.

For additional detail see Appendix D.

XI. Conclusions

The accuracy of FTM RTT distance determination can be doubled using frequency diversity. The error in FTM RTT distance has peculiar properties (for a start, it is non-Gaussian) that derive from the super-resolution algorithms used. Common building materials can introduce large errors in FTM RTT distance estimates because of their high relative permittivity. Bayesian grid estimation is well suited to the task of recovering location from distance measurements given the unusual nature of the errors. The "noise gain" in location determination can be kept low by carefully planning the geometric arrangement of access points.

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References

[1] (2017, February) Wi-Fi CERTIFIED location brings Wi-Fi indoor positioning capabilities. Wi-Fi Alliance. [Online]. Available: https://wi-fi.org/news-events/newsroom/wi-fi-certified-location-brings-wi-fi-indoor-positioning-capabilities
[2] F. V. Diggelen, R. Want, and W. Wang. (2018, July) How to achieve 1-meter accuracy in Android. [Online]. Available: https://www.gpsworld.com/how-to-achieve-1-meter-accuracy-in-android/
[3] J. Cobb. (2018, September) Testing WiFi RTT on Android P for indoor positioning. [Online]. Available: https://www.crowdconnected.com/blog/testing-wifi-rtt-on-android-p-for-indoor-positioning/
[4] M. Ibrahim, H. Liu, M. Jawahar, V. Nguyen, M. Gruteser, R. Howard, B. Yu, and F. Bai, "Verification: Accuracy evaluation of WiFi fine time measurements on an open platform," in *MobiCom-18*, New Delhi, India, October 2018.
[5] (2019, September) Indoor positioning with WiFi RTT and Google WiFi. [Online]. Available: http://www.darryncampbell.co.uk/2019/09/27/indoor-positioning-with-wifi-rtt-and-google-wifi/
[6] *IEEE 802.11 - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std., 2016. [Online]. Available: https://standards.IEEE.org/standard/802_11-2016.html
[7] List of WLAN channels. [Online]. Available: https://en.wikipedia.org/wiki/List_of_WLAN_channels
[8] J. Xiong, "Pushing the limits of indoor localization in today's Wi-Fi networks," Ph.D. dissertation, University College of London, September 2015.
[9] X. Li and K. Pahlavan, "Super-resolution toa estimation with diversity for indoor geolocation," *IEEE Transactions on Wireless Communications*, vol. 3, no. 1, pp. 224–234, June 2004.
[10] A. A. Ali and A. S. Omar, "Time of arrival estimation for WLAN indoor positioning systems using matrix pencil super resolution algorithms," in *Proc. 2nd Workshop on Positioning, Navigation and Communications (WPNC)*, 2005.
[11] F. X. Ge, D. Shen, Y. Peng, and V. O. K. Li, "Super-resolution time delay estimation in multipath environments," *IEEE Transactions on Circuits and Systems I*, vol. 54, no. 9, pp. 1977–1986, September 2007.
[12] D. Humphrey and M. Hedley, "Prior models for indoor super-resolution time of arrival estimation," in *Proc. IEEE 69th Conference: Vehicular Technology Conference (VTC)*, May 2009.
[13] C. Morhart and E. M. Biebl, "High resolution time of arrival estimation for a cooperative sensor system," *Advances in Radio Science*, vol. 8, pp. 61–66, 2010.
[14] T. J. S. Khanzada, A. R. Ali, and S. A. Napoleon, "Use of super resolution algorithms for indoor positioning keeping novel designed wlan signal structure," *ACM IWDE*, 2010.
[15] M. Noto, F. Shang, S. Kidera, and T. Kirimiti, "Super-resolution time of arrival estimation using random resampling in compressed sensing," *IEICE Trans. Commun.*, vol. E101-B, no. 6, June 2018.
[16] J. A. Bhatti, B. M. Ledvina, R. W. Brumley, W. Zhang, N. Wong, and E. Chiu, "Time of arrival estimation," U.S. Patent 10 361 887, July, 2019.
[17] R. Wilson. (2002, August) Propagation losses through common building materials - 2.4 ghz vs 5 ghz. [Online]. Available: http://www.am1.us/Papers/E10589PropagationLosses2and5GHz.pdf
[18] B. Davis, C. Grosvenor, R. Johnk, D. Novotny, J. Baker-Jarvis, and M. Janezic, "Complex permittivity of planar building materials measured with an ultra-wideband free-field antenna measurement system," *Journal of Research of the National Institute of Standards and Technology*, vol. 112, no. 1, January/February 2007.
[19] B. Kapilevich, M. Einat, A. Yahalom, M. Kanter, B. Litvak, and A. Gover, "Millimeter waves sensing behind walls - feasibility study with FEL," in *Proceedings of FEL 2007*, Novosibirsk, Russia, 2007.
[20] R. Rudd, K. Craid, M. Ganley, and R. Hartless. (2014, September) Building materials and propagation final report - fcom. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0034/55879/ihp_final_report.pdf
[21] B. K. P. Horn. (2017) Timing advance and Android smartphones. [Online]. Available: https://people.csail.mit.edu/bkph/cellular_repeater_TA
[22] ——. (2018) Reduction to linear equations and the pseudo inverse. [Online]. Available: https://people.csail.mit.edu/bkph/ftmrtt_location#Linear_Equations
[23] ——. (1999) What is wrong with so-called 'linear' photogrammetric methods? [Online]. Available: https://people.csail.mit.edu/bkph/articles/Orientation_2D_Illustration.pdf
[24] ——. (1999) Projective geometry considered harmful. [Online]. Available: https://people.csail.mit.edu/bkph/articles/Harmful.pdf
[25] Kalman filter. [Online]. Available: https://en.wikipedia.org/wiki/Kalman_filter
[26] Thorvald N. Thiele. [Online]. Available: https://en.wikipedia.org/wiki/Thorvald_N._Thiele
[27] Particle filter. [Online]. Available: https://en.wikipedia.org/wiki/Particle_filter
[28] Bayesian inference. [Online]. Available: https://en.wikipedia.org/wiki/Bayesian_inference
[29] Preferred walking speed. [Online]. Available: https://en.wikipedia.org/wiki/Preferred_walking_speed
[30] B. K. P. Horn. (2019) FTM RTT locations while moving around on one level. MP4. [Online]. Available: https://people.csail.mit.edu/bkph/images/FTM_RTT_2D-2019-01-03-170903.mp4
[31] ——. (2019) FTM RTT locations while moving through a three-story home. MP4. [Online]. Available: https://people.csail.mit.edu/bkph/moviesFTM_RTT_Bayesian-2018-12-20-164419.mp4
[32] Java reflection. [Online]. Available: https://docs.oracle.com/javase/tutorial/reflect/

Appendix A
Current state of support for FTM RTT

The ability to perform FTM RTT measurements is announced by an access point in the beacon it emits at regular intervals (typically every 100 msec). Presently only Compulab's "Wi-Fi Indoor Location Device" (WILD) (with a modified Intel AC-8260 Wi-Fi adapter) and Google Wifi (with Qualcomm IPQ4019) do this. Importantly, however, quite a number access points do *respond* to FTM RTT requests even though they do not announce this capability. This includes several of the recent "mesh" APs (e.g. Eero Pro, Netgear Orbi, Linksys Velop) — as well as some older APs such as ASUS RT-ACRH13.

APs that support FTM RTT, but do not advertise this capability, may, in some cases, not support it properly yet, be subject to large offsets and measurement errors, frequent outliers, or crashes when asked to respond "too often."

Many Wi-Fi adapters cannot be used as access points because of regulatory restrictions on their channels. Channels may be marked "passive scan only" or "no IR" (i.e. cannot "initiate radiation"). Generic Intel 8260, Intel 8265, Intel 9260 Wi-Fi cards do "support" FTM RTT, but are not allowed to act as access points (due to "no IR" restriction on channels in the 5GHz band) and so are not useful as FTM RTT responders.

Wi-Fi access points tend to be replaced less often than say smartphones and laptops. APs tend to be replaced only when some major new feature is touted (such as higher data rates and more channels in 802.11AC). Unfortunately FTM RTT was introduced at a time when no such major advantage was simultaneoulsy being proferred. As a result relatively few installed APs support FTM RTT at this point. This will change as soon as powerful new features are introduced, as in 802.11AD for example.

Appendix B
Android API and Java Reflection

Access points that support the IEEE 802.11mc FTM RTT protocol, but do not advertise this capability, are awkward to use because Android API **WiFiManager.getScanResults**() marks them as not supporting 802.11mc in the **ScanResult**, and so the **WifiRttManager.startRanging()** call on the corresponding **RangingRequest** fails — without even trying.

One work-around is to use Java reflection [32], to set the **FLAG_80211mc_RESPONDER** bit in the **flag** field in the **ScanResult** (the "setter" methods **setFlag()** and **clearFlag()** are blacklisted and so can't be used by third-party applications).

A more flexible approach is to use the hidden **addResponder** method in the **Builder** inner class of the **RangingRequest** class. For this one needs to build an instance of the **ResponderConfig** class "by hand." A **ResponderConfig** instance contains the MAC address (BSSID), responder type (AP), 80211mc support flag, channel width, frequency, center frequency, and preamble type. One advantage of this approach is that one can build a **RangingRequest** *without* needing the results of a Wi-Fi scan (which takes time, and is heavily throttled in Android 9) — The information about the APs may come "out of channel" — from a file say (which may also contain information about the physical location of the APs — see also Appendix C). Needless to say, this requires more Java reflection magic.

In this regard, it may be helpful to know that the specified center frequency field in the **ResponderConfig** is *ignored* and replaced by a stored value from the most recent Wi-Fi scan. There are a number of implications, aside from the obvious one that one cannot control the center frequency of the AP in this fashion. One is that an AP can't be used for ranging if it hasn't been "seen" recently in a Wi-Fi scan. Another is that an AP can't be used right after it switches channels — at least not until the next Wi-Fi scan picks up the new channel information. By the way, it is important to know which channels APs use, since the offset in the FTM RTT reported distance is typically different in different channels.

As an aside, Windows 10 does not currently support 802.11 FTM RTT (while it does support Wi-Fi scans using **WlanScan**()).

Appendix C
How to get the locations of the responders

In recovering the location of the initiator (smartphone), one needs to know the locations of the responders (APs). This information can be provided "out of channel" in a file that lists all of the APs in a building — along with their properties.

It may be more convenient (and the method scales better) if the APs themselves broadcast this information. The IEEE 802.11-2016 standard provides for that. Location Configuration Information (LCI) can provide latitude, longitude, altitude and their uncertainties. Location Civic Report (LCR or CIVIC) can provide a "civic" address in a standardized key-value format. Corresponding "getter" methods **getLci()** and **getLcr()** of **RangeResult** are blacklisted in Android and so not available to third-party applications. However, the **getUnverifiedResponderLocation()** method is available to obtain a **ResponderLocation** from a **RangeResult** and this has the available location information.

Presently, only Compulab's "Wi-Fi Indoor Location Device" (WILD) provides for specification of LCR and CIVIC information about the access point (using entries **-lci=...** and **-civic=...** in the **hostapd.config** file). Sadly, at this point, no other Wi-Fi access point allows specification of the location of the access point.

Appendix D
Placement of responders

In the 2-D examples in Fig. 14 the green dots are the locations of responders (APs), while the red dots are potential positions for the initiator (smartphone, STA). The constant error curves show how position may be poorly localized in some direction yet well constrained in a direction at right angles. In placing the responders, the aim is to make the constant error curves small and round in most of the work space. Symmetrical layouts for the responders seem to work well, as shown on the left in Fig. 14, while somewhat suprising results may be achieved with asymmetrical layouts, as shown on the right in Fig. 14. Note also that location can be recovered reasonably well even outside the convex hull of the responders — up to a point.

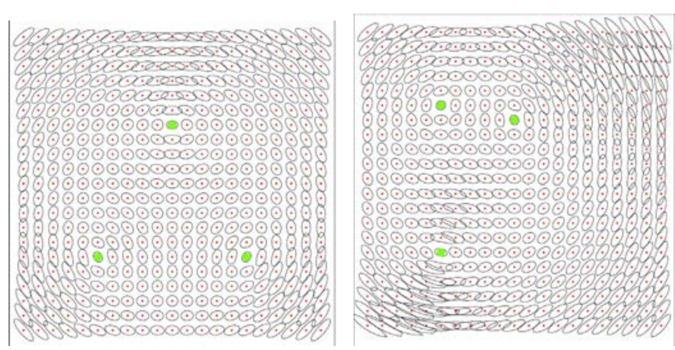

Fig. 14. Quality of location determination near three responders (2-D case). Left: Symmetric arrangement. Right: Asymmetric arrangement.

For 3-D, cubic volume of interest (or a rectangular brick shaped volume with not-too-different side lengths), placing four responders at the vertices of a tetrahedron embedded in the cube has appealing properties (these points are at the four "even" vertices of the cube (left side of Fig. 15). With six responders, the vertices of an octahedron have good properties (these six points are at the face centers of the cube (see right side of Fig. 15). Both of these configurations avoid placing any subset of (more than three) responders in a plane.

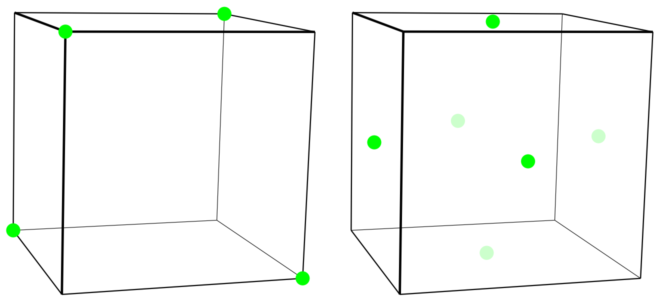

Fig. 15. Left: Placement of 4 responders (3-D case) Right: Placement of 6 responders (3-D case)

Adding a responder somewhere in the middle of the volume also improves overall location accuracy determination quality (See e.g. right side of Fig. 11).

Placing responders at regular intervals along a line (a corridor say), while providing simplicity of installation, may not be a good idea if location accuracy is of importance.

Appendix B

WMU WS Final Report

Prototype Wayfinding System

Participant Assessment Final Report

Robert Wall Emerson, PhD

Dae Shik Kim, PhD

Executive Summary

The prototype Indoor Wayfinding System was assessed with 14 participants who were blind. The primary goal of achieving an acceptable level of positional accuracy was achieved. Comments from participants were generally very positive and centered around how system functionality be improved in terms of how to best communicate information, improving consistency, and adding desirable features. Many participant issues regarding system performance and consistency would be addressed by installing more nodes to improve positional accuracy in all areas. Primary suggestions for possible added features include adding obstacle detection, adding voice input for control, creating options for controlling the amount and kind of navigation feedback given, optimizing the amount of directions before turns must be made, and adding tactile feedback through vibration.

Participant Demographics

Fourteen participants (10 men, 4 women) with visual impairments took part in tests to assess and offer feedback on the prototype Indoor Wayfinding System. The average age was 37.4 and ranged from 21 to 58. Six participants had been born blind or lost their vision before the age of 5. All had been legally blind for at least 8 years (average = 25.9). The participants were all independent travelers with the long cane but had a range of training and experience with using the cane. The least amount of time that a participant had been a cane traveler was 2 years (although this participant had used a dog guide for 7 years). One participant had used the long cane for only 3 years.

Participant Mobility Skills

Participants demonstrated a range of orientation and mobility skills as well as a range of levels of sophistication with technology. Orientation and mobility skills were categorized as

Poor, Fair, Good or Excellent. Only one participant was categorized in the "Excellent" category as he had received training as an O&M instructor and typically traveled at a level above that of the other participants. Of the other participants, 4 were classified as "Poor" (mainly due to issues with orientation), 4 were classified as "Fair", and 5 were classified as "Good".

The classification of the categorization was as follows:

Poor: makes incorrect turns (wrong direction), not aware when environment does not match with intended location, confuses directions, relies more on tactual information from walls

Fair: able to navigate routes but shows some hesitation in maintaining orientation and making route decisions like turns, turns often not smooth but require more exploration of walls before and after a turn, not as likely to create an effective mental map of a route

Good: smooth and efficient movement through an environment, minimal contact with walls for extra guidance, able to problem solve orientation issues, creates usable mental map, demonstrates knowledge of what will be needed to complete a route

Excellent: all the same characteristics as the previous category but with a noticeable increase in smoothness of overall movement, effective use of reflected sound

Participant Technology Skills

Participants demonstrated a range of comfort and proficiency levels in terms of technology use. Interestingly, when asked, 10 of the 14 participants rated themselves a 7 or 8 out of 10 on use of technology, specifically wayfinding apps. However, based on observation of participant use of the phone and app and also based on other comments made by participants on how much they use technology and what they use it for, a wider range of categorization was shown. Sophistication with technology was categorized as Poor, Fair, Good and High as follows:

Poor: little experience with smartphone apps or wayfinding apps

Fair: some use of smartphone apps, perhaps some exposure to wayfinding apps, unable to problem solve digital interface if issues arise

Good: uses smartphone apps, some use of wayfinding apps, able to navigate within a digital environment relatively well

High: extensive experience with smartphones and wayfinding apps, aware of different platforms and their features, knowledgeable about access issues and how to deal with them

Four participants were classified as "Poor" (3 of whom classified themselves correctly), 3 were classified as "Fair", 2 were classified as "Good" and 5 were classified as "High".

Test Protocol

All participants traveled 4 routes within the first floor of the College of Health and Human Services building. On two routes a participant used the wayfinding system and on two a set of route directions were verbally given to the participant. Participants were allowed to use whatever techniques or strategies they wished to complete a route, barring asking for more direction to their destination. Note that on occasion a participant was given a redirection from the experimenter when it became clear that they would not find the destination due to improper functioning of the system or due to the participant travelling too far off route without realizing it.

Navigation Test Results

Eliminating routes where the system malfunctioned to an extent that rendered the trial unusable, the participant did not reach their destination, or additional directions were too extensive, the average time to reach a destination when using the system was 2:27 (SD = 1:11) and the average time to reach a destination without the system was 2:17 (SD = 1:51). This difference was not statistically significant ($t(40)=.30$, $p=.77$). For all participants that had valid trials with and without use of the navigation system, 8 participants were faster without the system and 4 were faster with the system. When route completion speed was compared for these 12 participants using a paired samples t-test, the difference remained non-significant ($t(11)=.59$, $p=.57$).

Of the four participants who were faster when using the system, all had at least fair technology skills (they had a range of orientation and mobility skills). This suggests that many of the participants who were slower when using the system were slowed due to the need to interact with the system. Those with very good travel skills did not need the system and were able to travel better without it and those with poor travel skills tended to get too caught up in trying to follow the system directions without adding enough of their own problem solving skills. This highlights, when using any wayfinding system, to make sure that a person has a good basic level of travel skills so that they do not rely overly on the information from the system but rather use it to augment their travel. The most efficient participants were those who used their own skills for the majority of the travel but used information from the system to check on when to turn and when they had gotten close to a destination. However, a series of ANOVA analyses indicated that there were no significant effects of orientation and mobility skill category or technical sophistication category on route completion time, either with or without use of the navigation system.

Of the 28 routes traveled using the navigation system, there were 11 failed trials. Only four of these were failed due to navigational errors made by the participants. The remaining 7 failed trials were due to the wayfinding system losing connection with the participant's movements, indicating that the participant was off route when they were not, not announcing arrival at the destination, or failing to reorient the participant when they passed a turn or destination. When not using the system, there were only 2 out of 28 failed trials: one where the participant started out in the wrong direction, and one where the participant reversed direction orientations halfway through a route.

All of the participants appeared to be able to interact with the app with minimal instruction. However, only two participants made use of the function of repeating a system command. This might have been due to the shortness of the routes and the fact that often enough the system would lock up in a loop of asking for the participant to rotate repeatedly or give an off route message that the participants generally were not traveling a route long enough to want to hear the last direction again. Several participants were also fast enough travelers that they completed a route leg quickly and so had no need of repeating a direction. In general, the user interface appeared to operate in a manner that participants experienced as logical and appropriate.

Summary of Participant Comments

Individual participant comments can be found at the end of this document. However, participant suggestions fell into several categories:

(1) Navigational performance

- improve accuracy of turning directions
- improve consistency
- add obstacle detection (e.g., LIDAR)
- eliminate feedback loops

(2) App interface or GUI

- add voice input for control
- add option for output via Bluetooth earphones
- allow for entry of personal POIs

- create preferences
    - for amount of navigation feedback (e.g., getting more as destination approaches)
    - speed and type of voice
    - level of description of environmental features
    - control categories of destinations

(3) Improved feedback

- optimize amount of directions before turns must be made
- improve (or replace) use of step counts
- add tactile feedback through vibration
- match destination language in app to actual signage at destination

There was generally a positive impression of the system. Even when the system did not work well or was not accurate, these events were discounted. It is almost as though any assistance in wayfinding is seen as positive, no matter how good or consistent it is. There was some tendency to ignore minor inaccuracies since participants knew the system was still under development. Since people who are blind are so often faced with technology that is not accessible for them at all, a system that is designed to be accessible, no matter how effective, is seen as a positive.

Some participants were concerned that they needed to hold the phone in some orientation while travelling. There was some discussion of being able to put the phone in a pocket and just listen to directions with a Bluetooth headpiece or to use voice activation to interact with the system. There were also several comments about the inconvenience of having to hold a phone in your free hand while using a cane.

Some participants liked the level of verbosity while others wanted much more. Having a toggle or choice of three levels of verbosity would address the needs of a wide range of participant needs. The kind of information offered might also be a choice in settings. For example, some participants want only basic turn information, as is currently being given. Others might want to know the next turn after their current turn so they can mentally plan for it. Others might want to know important environmental features they are passing like doorways, water fountains, stairs, and benches. Others might also want to be told about locations they are passing like bathrooms, classrooms, offices, etc. So there might be two information settings: more or less route information and more or less environmental information.

Recommendations for Further Development

- Keep essential nature of the design and user interface.
- Keep the "prepare to turn" and "prepare to arrive" feature.
- Do not rely so much on step counting for distance traveled. When user position is determined by step count based on a set stride length, people with longer or shorter strides will get increasingly incorrect positions as routes get longer. Instead of relying on step count, explore other options for tracking a user's position as they travel a route.
- Make sure that destinations referred to in the system agree with the print and braille signage for those destinations. This will most likely have to be completed by having people physically note, for every destination in the system, what the physical sign on the destination door says.
- System needs to be able to adjust to user orientation as the user is traveling. If the user makes a wrong turn or begins walking the wrong direction, the system needs to be able to recognize this and prompt the user to stop and restart a route from their current position.

It would also be useful to have a button the user could press to indicate that they feel lost and want to restart a route from their current location.

- System should provide an overview of the route before the travel begins, then provide route information along the way.
- System should give users the option of getting more specific information that links destination and turns to environmental features. Some users benefit from linking turns and destination arrival to salient environmental features they will be passing. For example, “destination is on the right” is not as helpful as “destination is on the right in 30 feet” but more helpful is “destination is on the right in 30 feet, after the water fountain”. Guidance from an O&M Specialist might be helpful in determining what a useful salient feature is for a given destination or turn.
- System needs to be able to adjust to people not walking in a straight line, turning the wrong way, etc. With increased precision of the system, elimination of “dead zones”, and improved tracking of a user’s position on a route, the system will be better able to identify when a user goes in an incorrect direction. Note, however, that weaving form side to side in a wide hallway might appear to be going off route to an overly sensitive system. This should also be taken into consideration.
- System needs to be able to adapt to changes in orientation as a person is traveling without the person stopping.
- Explore adding settings for level of verbosity for directions given and possibly also for the kind of environmental features announcement.
- Explore the possibility of users not having to hold the phone after setting a route and beginning navigation.

- The sensitivity of the user turning in place for initial heading should be reduced. As long as the user is within about 20 degrees of the correct heading, information gathered as they travel (e.g., cane contacting a wall to the right or left) should allow the user to correct their travel heading.

Individual Participant Comments

P1

- needs to improve accuracy, especially of turns

- need to fix orientation issue where app gets caught in loop asking user to turn

- needs to be voice activated

- want to be able to listen to it through a bluetooth earphone

- would be useful to be able to input your own destinations or POIs

- could be extrapolated to add an obstacle detection component with LIDAR or FLIR

P2

- liked the anticipated direction before turns

- giving distances in feet was a good frame of reference, as was degrees when turning

- interface was intuitive and straight forward

- verbal directions were adequate but more detail would have been helpful (an open area is past the corner, café is on left just before a hallway opening on the left, etc.)

- destinations need to have more information than that you have simply arrived

P3

- found my places quicker with the app

- reduce double tap sensitivity

- perhaps add voice activation instead of double tapping

P4

- liked how it gives distances and tells you to get ready to turn
- a completed version of the system would be particularly useful in airports and hospitals
- consistency of system performance needs to be improved (too many off route indications in a clear hallway or times it could not decide on a clear direction)
- would be good to have an option to have indication of distance to turn or destination spoken more often, perhaps to have the distance spoken more the closer a person gets to a decision point
- should provide a preview of the route before the person starts walking and getting turn information
- might be useful to be able to choose different voices as well as changing the speed of the voice
- would be nice if the system could catch up to a person who is already walking (be started as a person is traveling)
- would be nice if the system announced important environmental features that you are passing as you travel
- would be good to have an adjustable setting for how much information the system gives

P5

- loved it all
- pretty accurate (even though the app was not very accurate for her)
- helpful in airports
- liked how it categorized the choices of destinations
- would be useful if it gave more information about environment, especially upcoming items of interest

P6

- gives good preparation before turning (prepare to turn)
- reliance on step counts leads to inaccuracies
- level of accuracy for destinations needs to be improved, especially once it is dealing with destinations that are all very close to each other
- use of tactile indicator like vibration would help people with hearing loss (indication that a turn or destination is coming up soon)
- use of vibration to indicate when a person is facing the correct direction would help
- make sure that the verbal directions are the same as the signage for a destination

P7

- option selection was clear and easy
- made things easier for me than walking on my own due to my orientation issues
- getting caught in repeated requests to turn was frustrating and confusing
- sensitivity to turning needs to be reduced
- would be good if information was provided more frequently
- would be good to have different levels of the amount of information offered

P8

- would be very useful in airports
- app interface is simple to use
- level of information offered is appropriate
- calculation of turning orientation is not accurate
- needs a lot of improvements in the accuracy and consistency
- relying on counting steps leads to inaccuracies that the system cannot adjust to

- would be useful if user could add their own POIs, perhaps have POIs crowdsourced or added by non-users to grow the network (beyond most common POIs)

- would be useful to have the option of having the system indicate POIs the user is passing that they might not otherwise be aware of

- would be good to have different levels of verbosity available for the user to choose from

- would be good if this indoor system could be merged with an outdoor wayfinding system for places like a college campus

P9

- layout of the app was clear and concise

- it was inconvenient to have to handle the phone and tap while also traveling. It would be good to at least be able to put the phone away while walking. Might be able to mount the phone on the cane for walking.

- the directions in feet was confusing since it is hard to know how far 61 feet is, especially when you don't know how long your stride is (might be possible to have an option where distances are left out)

- should give an overview of the route before the traveler starts, then give turn by turn directions (allows a person to mentally prepare for what comes next on a route)

- maybe allow voice activation instead of tapping

P10

- app kept up with my stride, was accurate with turns

- level of input was good

- useful in airports

P11

- giving the number of feet is helpful
- layout of the options and menus is clear
- system does not indicate whether you are lost or the system is lost (relates to need for increased consistency)
- system did not indicate I was at my destination on one route
- needs to tune down the sensitivity on degrees of rotation, requires a great deal of patience
- accuracy needs to be improved
- would be good to have it give more information as a person gets closer to the destination
- menu item in the phone needs to match what is on the braille placard on the wall by the destination door
- would be useful to have an overview of the entire route spoken out before travel is started, followed by turn by turn information
- would be nice to not have to always hold the phone while traveling but to be able to put it away and still hear the directions

P12

- easy to use
- voice was talking too fast
- needs to be more accurate
- needs to be more consistent
- use of voice command would be good (inconvenient to hold a phone in the free hand)

P13

- definitely see the value for a complicated environment, if I can learn to trust it
- very sensitive in the alignment part, which can lead to problems
- if the system can get back on path, it can be useful, but the system does not help a user get back on a path if they get off
- syncing of system and user positioning is important so that placement of turns is accurate
- it would be helpful if the system would tell the user that they do not have to hold it in a particular way when walking
- it would be useful for the app to link directions to environmental features (e.g., turn left after the second hallway)
- it would be ideal to get an overview of the route before starting to walk

P14

- good to let the user know the distance to a turn or destination
- system needs to recalculate when a user makes a wrong turn or goes the wrong way
- system should give more specific information that links destination and turns to environmental features (turn right in 30 feet, after water fountains)
- could give specific information about a destination like whether the door is inset or flush with the wall