Sitting Duck
Final Report

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Abstract – The evolving capability and portability of smart phones has facilitated reliable access to the resources of the internet from nearly anywhere in our society. While incorporation of these devices in our day to day tasks can provide great efficiency and utility, there are specific settings where the use of these devices is unwelcome. For example, the integrity and fairness of today's popular academic and professional assessment metrics (SAT, GRE, MCAT, GMAT, college exams) is greatly compromised by test-takers exploiting unauthorized use of smart phones during testing. The current established solutions are not as effective as they could be. The Sitting Duck project delivers a working system that demonstrates an automated tool for detecting, locating, and providing objective evidence of unauthorized cell phone usage within a standard testing environment. This design utilizes a phased antenna array and methods of radio frequency interferometry, real-time signal processing, and video processing.

Keywords – testing integrity, radio frequency, cell phone, antennas, interferometry, signal processing, remote sensing

I. INTRODUCTION

As consumer mobile device technologies continues to progress, we are seeing an increase of their utilization in our day to day tasks. The widespread use and accessibility of smart phones makes their presence nearly ubiquitous in our society. However, there are specific settings, including standardized testing at academic institutions or exam centers, which explicitly prohibit use of these devices.

The rationale behind these "no cell phone" policies is tied to the capability of consumer smart phones' ability to access the vast resources of the internet without connecting to local area networks. The integrity and fairness of many of today's academic and professional assessment metrics (SAT, GRE, MCAT, GMAT, college exams) is greatly compromised by test-takers exploitation this unauthorized advantage.

As a result of the miniaturization of smart phones, standard proctoring and video monitoring practices have become much less effective in enforcing "no cell phone" zones at standardized testing facilities. In fact, they may be prone to false positive identification of unauthorized phone usage. Since many standardized testing facility authorities are not capable and/or permitted to monitor the usage history of individuals' personal devices, it is difficult for them to collect reliable, objective evidence of unauthorized cell phone use.

A. *Established Solution*

There are multiple solutions available to address the challenge of unauthorized cell phone use in standardized test-taking situations. However, each has its limitations and is better fit for different settings/environments.

The establishment of "no cell phone" policies is the most basic non-engineering solution. However, adherence to these policies relies on individual honesty, which is in no way implicit.

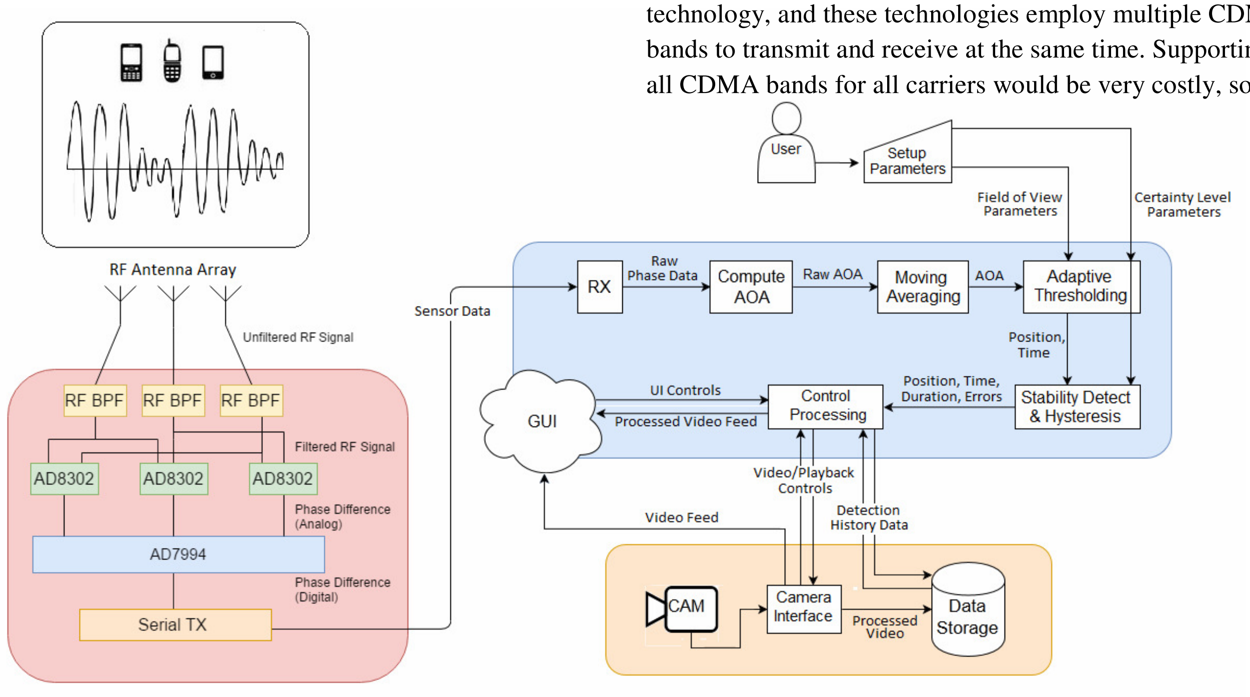
The use of live proctors is standard practice in academic settings and standardized test facilities with "no cell phone" policies. While this solution provides an actual vehicle for enforcing the policies, it does not scale effectively with test-taker volume. Furthermore, a live proctor's hearsay identification of unauthorized behavior lacks objective evidence and can be prone to false positive findings.

Handheld radio frequency (RF) detectors, usually in single antenna configuration, can be used to alert a live proctor of nearby RF activity. While it provides an objective measurement supplemental to eyewitness account, this engineering solution does not scale effectively with test-taker volume and requires as much if not more manual effort than the live proctor solution.

RF shielding and active jamming is an engineering solution that provides comprehensive protection against unauthorized cell phone usage. This active mitigation solution, which interferes with RF signal propagation, blocks potentially authorized transmissions. Active jamming is a federal violation in the United States. [1]

B. *Usage*

The Sitting Duck project aims to provide a more effective tool for facilitating "no cell phone" policies inside a standard testing environment. The ideal system will identify when and where cell phone activity occurs while recording relevant detection data. A video monitoring system also records HD video that can be used in combination with the detection data as objective evidence of unauthorized cell phone use. This design utilizes a phased antenna array and methods of radio frequency interferometry, real-time signal processing, and video processing.



A user with no prior knowledge of the principles of RF technology or electromagnetic propagation will be able to watch a live stream of activity in a room. A cell phone transmitting data will be displayed as an overlay on the stream and will allow the user to react accordingly.

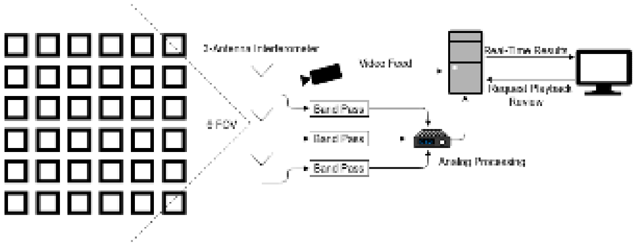


Fig (1): Visual Representation of Specifications

C. *Specifications*

The model environment selected for developing the proof of concept system is an average standardized test-taking facility. We specify this environment to be a square room of floor dimension 40 feet by 40 feet. The device should be able to accurately detect a cell phone transmitting anywhere in the room, so the specification for detection area is bounded at a range of 40 feet. We have assumed that standardized test-taking settings place test-takers approximately six feet apart from one another in a grid-like fashion. We have translated this separation into our error tolerance for localization.

Modern cell phones operate using 3G/4G/LTE technology, and these technologies employ multiple CDMA bands to transmit and receive at the same time. Supporting all CDMA bands for all carriers would be very costly, so CDMA Band 0, centered at 850 MHz, was chosen for proof of concept.

This device will allow the user to respond in quickly to the threat cell phone use will cause in the area. This will require the device to be easy to use, and also have a reasonably short latency. We define the latency requirement as a delay from transmission detection to UI presentation of 30 seconds or less. To facilitate the ease of use, cell phone detection information will need to be presented in an interpretable manner. A live stream of the area of interest will be provided via USB camera, and an overlay will be made on the live stream to pinpoint usage in the area. The user will also be able to replay recordings of past events.

<u>REQUIREMENTS</u>

- Localize detection at 40’ range to within ±5°
- Receives frequencies at 850MHz
- <30 seconds of device latency
- Easy to use video overlay of events
- Ability to play back past recordings

II. DESIGN

Though modern cell phones have a very small physical form factor, they are not easily concealed in the electromagnetic spectrum. To detect cell phone use in an area, three antennas will receive RF signals within the 800MHz - 900MHz band. Our three antenna setup is a triple single-pair interferometer design, which provides three phase difference measurements. These three phase differences can be used to triangulate the position of a device emitting in such a band. Using two interferometer pairs at different locations in the room for detecting the transmission source was considered, but having a system that was reasonable to set up was considered a priority. Thus a single package system was chosen.

Cell phone signals propagated through the room are received by the antennas, which form three single-pair interferometers. The unfiltered RF signals are bandpass filtered and the phase differences are measured and quantized.

The digital phase difference values from the sensing subsystem are processed in the computation subsystem to produce an accurate localization of the detected transmission. User-defined parameters that will define the detection field of view as well as the certainty level desired are utilized in this block. The probability of multiple signals being received by the antenna array simultaneously is slim, but overlaps are detected and sent to control processing to be handled.

The position calculated must be displayed in an easily interpretable way to the user. A camera is used to record activities within the area of interest, and is recorded for later processing. The position information is used to create an overlay of past and present signal events in the room, which is then used to modify the live feed. The live feed with overlay is saved to be used for evidence and can be played back at any time.

A. *Sensing Block*

The sensing portion of the project receives, filters, and distinguishes phase differences of RF inputs in hardware. The equations and methods used to determine the transmission source location were based on work done in [6]. The front end of the sensing block consists of a three antenna phased array. This array receives transmitted cell phone signals, the sources of which the system locates. Pictured in Figure 3, the antennas labeled 1-3 illustrate the reception of a cell phone transmission from a source, and the triangulation of the source position via azimuths.

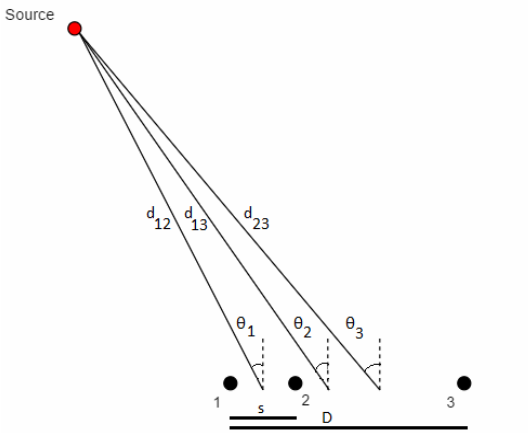


Figure (3): Antenna Array with Azimuths to source shown

The phased array of three antennas receives the transmitted cell phone signal for the system to analyze. This array is spaced as in Figure (3).

When a transmission signal propagates to the antenna array it will be received by each antenna at distinctly different times proportional to the unequal distances traveled. The greater distance of one path introduces a phase difference between the signals received at each of the antennas.

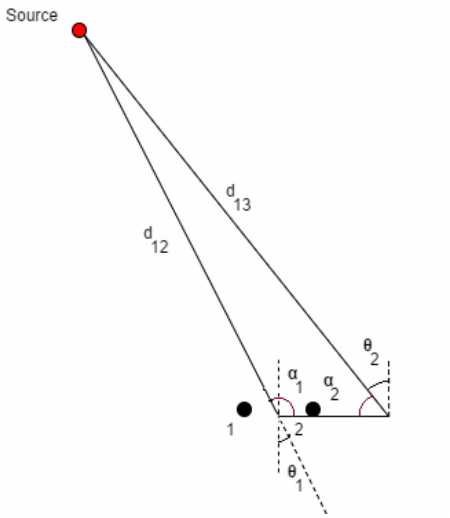


Figure (4): Interferometer with angle of arrival shown

This phase difference can be used to calculate an angle of arrival from the midpoint between two antennas seen in Eq. (1).

$$\theta_{AOA} = \arcsin\left[\frac{\left(\lambda_{min} * \left(\left(\frac{\Delta\Phi}{2\pi}\right) + I\right)\right)}{s}\right] \quad \text{Eq. (1)}$$

The minimum wavelength, λ_{min}, is known because the chosen frequency range is known. s is the chosen distance between the antennas and can be seen in Figure (3). ΔΦ is the phase difference between received signals from the antennas. I denotes the potential phase ambiguity from the received signals. This ambiguity is resolved by setting the distance between antennas 1 and 2 to less than or equal to half a wavelength.

$$I = i * 2\pi \qquad where(-n < i < n)$$

Eq. (2)

$$n = s/\lambda_{min} * \sin(\theta_{max})$$

Eq. (3)

The maximum angle of arrival specified for the system is 45° and if s is less than half a wavelength then n will be less than 1. 'i' is integer value in the range (-n,n). This makes ambiguity I term zero for calculating the angle of arrival.

The direction finding method that uses the phase difference of a signal arriving at separate antennas is known as phase interferometry. Each antenna pair is considered an interferometer and an array of three antennas forms three interferometers consisting of antennas 1 and 2, 2 and 3, and 1 and 3. Thus, when a signal is received at the interferometers, three angles of arrival can be measured which can be used to approximate the position of the signal source relative to the interferometers as seen in Figure (3). Each angle of arrival yields an azimuth to the source. Thus the location of the source can be triangulated by finding the intersection of the three azimuths.

The antenna array changed during experimenting and was reduced from three antennas to two antennas. This was due to antenna to antenna coupling. The antennas were spaced too close in the array which causes coupling effects that made the phase differences between antennas unusable. The spacing between the antennas was adjusted for larger spacing but this did not mitigate the coupling. The array when reduced to two antennas was able to accurately give an accurate angle of arrival for the source. This angle of arrival from the two element array had a sign ambiguity so whether the source was to the left or right of the array was not possible to determine.

a) RF Bandpass Filter: For this project the 800-900MHz operating frequency band is specified for proof of concept. A bandpass filter will allow signals of only the desired frequency band to pass through the sensor subsystem. The circuit design for the implemented filter, seen in Figure (5), is a third-order maximally-flat bandpass filter. The method used for determining the filter elements was from. [3]

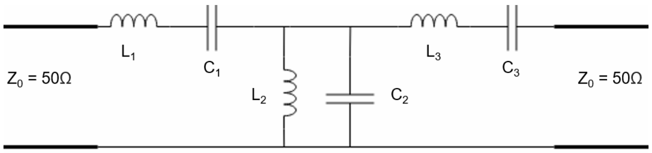


Figure (5): Lumped Element Schematic of Bandspass Filter

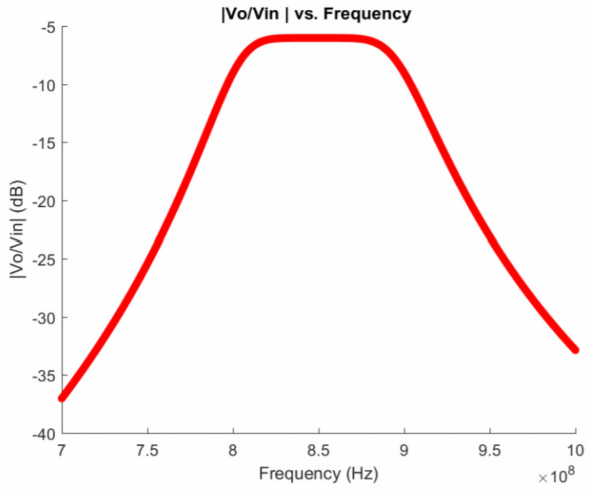


Figure (6): Transfer function of Bandpass Filter

The plotted transfer function of the filter can be seen in Figure (6). The filtered signal is then passed to a phase detection unit. This circuit will be fabricated using lumped elements and will fulfill the printed circuit board requirement for the project.

The transfer function in Figure (4) shows that the filter will pass the desired frequency band and filter out the other bands.

The printed circuit board layout for the filters was designed in Eagle and sent out for fabrication. The characteristic impedance of the transmission lines in the filter were not correct so the filter was fabricated with the correct transmission line characteristic impedance of 50 ohms.

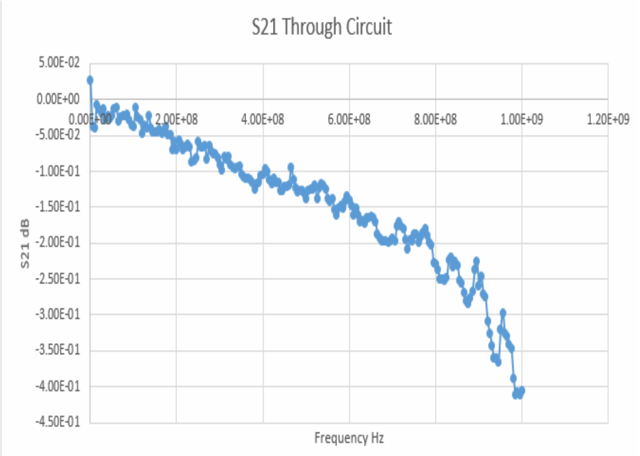


Figure (7): Insertion Loss of Throughput for Filter PCB

The final filter PCB throughput achieved under 0.5dB of loss in the designed frequency band. This is seen in Figure (7). The filters with the surface mount parts did not have the passband they were designed for due to an issue with the size of the components chosen and the quality factor of the surface mount inductors chosen was too low. Premade bandpass filters with a passband of 720-900MHz were chosen in place of these.

b) Phase Detection: This component consists of three AD8302ARU RF logarithmic-amplifier phase detectors that receive in two input RF signals each and compute the phase difference between them in real-time. The unit outputs a DC voltage ranging from 30mV to 1.8V that corresponds to a value of phase difference between 0° and 180°. [4]

c) Analog to Digital Converter: The ADS1256 analog to digital converter (ADC) is samples the AD8302ARU DC voltage level outputs and converts them into analog phase measurement representations in digital format. The ADS1256 ADC provides 8 channels of 30k SPS throughput at 24 bit resolution and communicates with the computer via the SPI interface. [5]

d) Video Camera: The Raspberry Pi Camera Module v2 receives high-definition video through its integrated Sony IMX219 8-megapixel sensor and communicates with the computer through the CSI port and built-in C libraries. The camera module supports 1080p30 and 720p60 video modes with satisfactory colour fidelity and low-light performance. Video post-processing for localization overlay presentation is achieved using OpenCV C libraries compatible with the computer and H264 and MP4 formats.

e) System Housing: The housing was designed with an integrated aluminum ground plane to improve the consistency of our signal detection. All the core components, with exception the camera and antenna array, were housed underneath the ground plane. The antennas were fastened directly to the ground plane, and the camera was positioned above. The filters, power splitters, AD8302 phase detectors, power board, and computational components were then mounted to a single board, referred to as the control board. The control board was then mounted within the internal compartment of the project housing to create sufficient organization for all components.

The camera was mounted to an extending camera poll to make the project compactable while still allowing the camera to rise high enough for a view of the detection area. The project had user interface ports and carrying handles mounted to the outside to increase portability.

We experimented with the inclusion of antenna shielding in order to mitigate the effects of signal multi-pathing, but we ultimately chose not to shield the array in the final design. This is because, after prolonged testing, we determined that the shielding did not significantly improve our ability to accurately process transmitted signals.

B. *Computation Block*

The function of this block is to identify signals of interest and to subsequently determine the position, duration, time, and other relevant descriptors of those signals. That data, in conjunction with user input, is used to control video recording processes, data storage and retrieval events, and GUI presentation.

1) RX: During operation, the ‘RX’ component continually receives samples of three inputs, each representative of a phase difference measured in the sensing block, which are measured by an AD8302ARU RF detector and quantized by the ADS1256 ADC. The phase difference values are calculated from the sample inputs based on a simple linear relationship between voltage and phase difference specified by the AD8302ARU RF detector manufacturer. [4] This phase difference data is passed to the next component in batches.

The functionality described was been modeled successfully in MATLAB and implemented in C. C implementation performance was evaluated and met specification requirements.

2) Identify Signals: The real-time phase difference samples are processed by the 'Identify Signals' component algorithm to identify actionable data, which is defined as signals of interest to the user dependent on user configurable setup parameters. Stable signals are identified by lightweight real-time signal processing methods that look for a threshold duration of stable inputs from the AD8302ARU RF detector. This is achieved using a variety of smoothing and moving exponential average heuristics which reliably distinguish "flat" signals associated with stable transmissions from a stationary location. Hysteresis methods are used to distinguish redundant and multiple-sourced signals.

The functionality described was modeled successfully in MATLAB and implemented in C. C implementation performance was evaluated and met specification requirements.

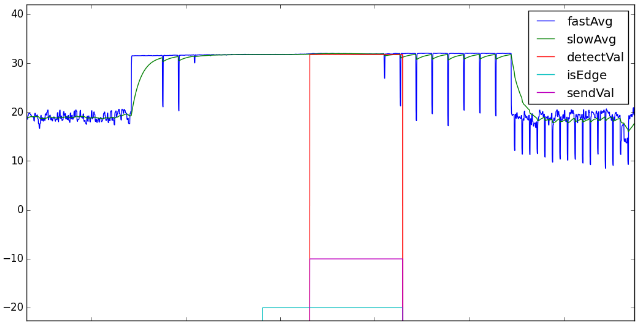
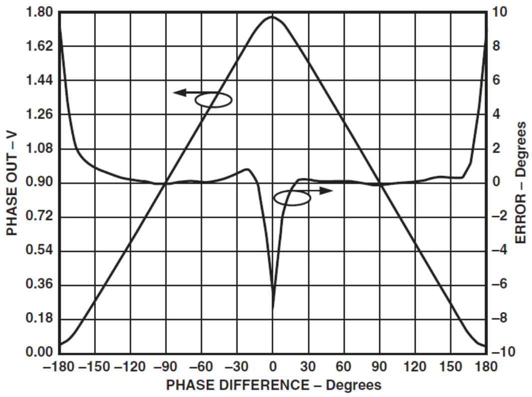


Figure (8): Stable signal detection using moving exponential average heuristics, stability thresholds, and hysteresis

3) Compute AOA: Given known values for signal frequency and antenna separation, the properties of RF electromagnetic waveforms and the method of phase-interferometry (as described in section II-A) provide the expressions necessary to derive angle of arrival values. The 'Compute AOA' component algorithm calculates, for each individual sample in the batch, the possible angles of arrival from each interferometer. However, the AD8302ARU RF detector's VPHS output, which represents the phase difference measure, produces a sign ambiguity, as seen in Figure (9). [4]



TPC 27. VPHS Output and Nonlinearity vs. Input Phase Difference, Input Levels –30 dBm, Frequency 900 MHz

Figure (9): Visualization of AD8302ARU RF detector VPHS output response illustrates resulting sign ambiguity of phase data. [4]

To account for this sign ambiguity, each phase difference value is resolved to both possible angle of arrival values. (Conveniently, these angle of arrival values are opposite.) Thus, each sample of 3 phase differences yields 6 angles of arrival that are passed to the next component.

The functionality described has been modeled successfully in MATLAB and was implemented in C. C implementation performance was evaluated and met specification requirements.

4) Control Processing: The 'Control Processing' component interfaces the user interface, camera block, and storage.

Although data from the camera block is always presented by live feed to the GUI through a separate interface, the camera block must be quickly passed an input when a transmission of interest is detected for recording events to be realizable. This trigger, which occurs when the 'Identify Signals' block detects a persisting and stable signal, prompts the camera block to write a recording to a storage component. This recording is present in a cyclic buffer that contains the most recent video data.

This stored video data is associated with descriptive data, provided from the 'Multiple/Overlap Handling' component, consisting of position, duration, and time of detection.

The user input from GUI controls video playback and detection history presentation through this block, which queries the data storage structure for stored video and descriptive data by event and presents it to the GUI display.

The structure and functionality described was implemented in C and performance met specification requirements.

C. Camera

The function of this block is to produce video that will allow the user to correlate the position of cell phone use relative to the antenna array and the cell phone's position in the room. The Raspberry Pi Camera Module v2 receives high-definition video through its integrated Sony IMX219 8-megapixel sensor and communicates with the computer through the CSI port and built-in C libraries. The camera module supports 1080p30 and 720p60 video modes with satisfactory colour fidelity and low-light performance. Video post-processing for localization overlay presentation is achieved using OpenCV C libraries compatible with the computer and H264 and MP4 formats.

D. User Interface

The purpose of this block is to allow the user to communicate to the device easily. User input is only necessary during the setup process of system operation, and requires input parameters that define the operating environment. This process involves visually selecting the area of interest on a live camera image during the setup process. The user will be displayed the live video stream during detection events described in II-C. The UI allows easy to access log and playback options while not recording.

a) Video Post-Processing: A visual representation of event locations will be interpreted more easily than in a log file of distance, direction, and time. An image is automatically created using a homography of the setup parameters and AoA of event detections. These event overlay images will be unique to each triggered video event, and are alpha-blended to the video during video post-processing which occurs after every recording session.

The overlay is created using a blank matrix with an aspect ratio related to the number of rows and columns in the region of interest, which is marked in red on the edges of the matrix. Ambiguous angles are drawn on the template from the bottom midpoint edge of the matrix using trigonometric functions. A homography is found during the setup phase, which relates the four corners of the region of interest to the four corners of the template. The transform matrix is used to warp the altered template which results in a final mask to be added to each frame of the triggered video.

The alpha-blending process composites a translucent foreground color with a background color, resulting in a newly blended color. This is done pixelwise, the product being a translucent overlay over the base image. The translucent foreground describe above is the event position mask, which contains the positions of all events within a specified period.

Video processing uses OpenCV and Pi Camera Module 2 C libraries.

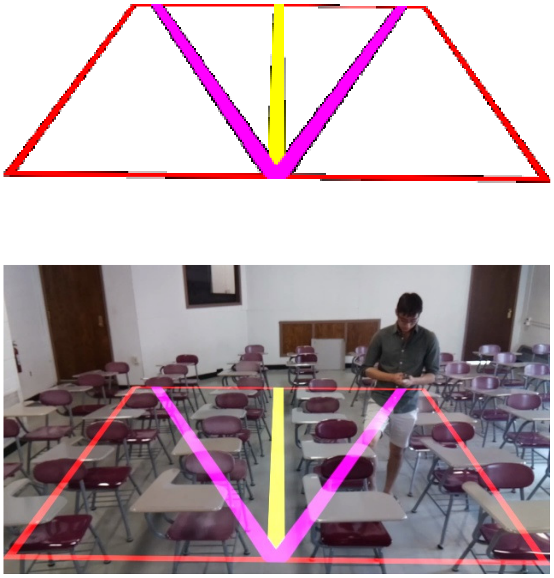


Figure (11): Result of alpha blending a single frame with an ambiguous angle azimuths (pink), zero angle azimuth (yellow), and region of interest (red).

b) Video Compression: Evidence produced by Sitting Duck needs to be portable and have a reasonable file size. The storage of raw video is unreasonable, and compression is required. A design change was implemented that stored video in terms of events rather than a recording session, which significantly saved on storage space. This compression is done in real time, and then again in processing, and will encode the alpha blended frames that contain event information. Encoding will be implemented using the Raspberry Pi's GPU, where unaltered video is stored in .h264 format, and then once again using the VideoWriter function in OpenCV once frames have been altered with the even position overlay in .avi format, which results in minimal degradation in quality of frames.

c) Video Playback: The user will need some way to observe recording sessions at a later date. Video playback will be supported, and the user can choose view recordings that exist on the file system. This system will have the ability to start, stop, pause, as well as the ability to seek throughout the length of the video.

d) Computer: The desired system was specified to be portable, with only a monitor, keyboard, mouse, and power cord necessary for operation. The computer chosen was a Raspberry Pi 2 Model B (RPi2). The use of the RPi2 over a laptop computer granted many design benefits.

The RPi2 900MHz quad-core ARM Cortex-A7 CPU with 1GB RAM granted enough processing power for real-time signal processing, real-time video processing, and video post-processing. The GPU supported Pi Camera Module v2, which with built-in C libraries handled recording and saving of files, took a significant amount of load off of the processor. The RPi2 also natively supports the SPI interface for easy communication with the ADS1256 ADC.

III. PROJECT MANAGEMENT

Preliminary conversation regarding the viability of this as a design project was productive. Preliminary research was distributed evenly, and individual goals have been clearly outlined since the end of PDR. Our MDR goals were designed to demonstrate the viability of each subsystem, and all of these goals were accomplished. Jonathan Yam was responsible for designing the signal processing and interferometry algorithms in addition to the system interface design (to include control processing). Sensor system design, including antenna system integration and RF bandpass filter design, was delegated to Sean, who is continuing as a graduate student at the University of Massachusetts Amherst with an interest in RF. Jonathan Jamroga handled video capture and processing, as he had experience with image and video processing libraries. Michael Sheehan is the project manager and has the responsibility of power systems and subsystem integration. System testing was a collaborative effort. Collaboration and fluid management responsibilities evolved throughout the project duration.

IV. CONCLUSION

Specification requirements were met by the Final Project Review deadline. The system in its entirety is easily operable by a layperson. The functionality is efficient to specification on an RPi 2 (900MHz quad-core ARM Cortex-A7 CPU with 1GB RAM) for durations dependent only on evidence logging capacity (which is dependent on disk space).

Production cost is estimated to be between $225.00 and $260.00.

ACKNOWLEDGEMENTS

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