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Experimental approach for seeing through walls using Wi-Fi enabled software defined radio technology

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ABSTRACT

Modern handheld target detection methods are typically restricted to line of sight (LOS) techniques. The design of a new method to detect moving targets through non-transparent surfaces could greatly aid the safety of hazardous military and government operations. In this paper, we develop through-wall virtual imaging using Wi-Fi enabled software defined radio to see moving objects and their relative locations. We use LabVIEW and NI Universal Software Radio Peripheral (NI USRP2921 radios with Ettus Research LP0965 directive antennas) devices to detect moving objects behind walls by sending and receiving a signal with respect to the USRP's location. Based on the signal-to-interference ratio of our signal (rather than the traditional signal-to-noise method), we could determine the target object behind the wall. The two major applications for this project are: detecting an active shooter that is standing on the other side of the wall and detecting abnormalities in the human body such as breast cancer with more sensitive antennas. Likewise, firefighters, law enforcement officers, and military men would find more practical purposes for the use of this system in their fields. We evaluate the proposed model using experimental results.

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1. Introduction

The design of an easily moveable radar detection system would allow military and government operations to decrease the amount of money allocated to large equipment and also allow on-the-go operations in highly dangerous areas. Through wall imaging is a relatively new topic in engineering that uses wireless technology for imaging. In this paper, we develop a prototype system that uses a Wi-Fi enabled National Instrument USRP device with a directional antenna and LabVIEW in order to track or see moving objects/people through walls. First, we design a Virtual Instrument (VI) which can transmit a signal. Second, we create a VI that can receive a signal. Next, we use signal processing tools to compare the received reflected signal against the transmitted one in order to determine frequency shifts in the signals. The last thing to do is outputting the change in signals using peak values in the magnitude of the received signal, and displaying it when movement is detected by the system. Programmable USRP radios weigh less and cost less compared to current technologies that utilize radar to detect movement, and can be programmed to send a signal through the wall and receive the reflection as it bounces off an object on the other side. Furthermore, the advantage of using USRP devices is that they are programmable and operative in license free Industry, Scientific and Medical (ISM) bands – 2.4–2.5 GHz and 4.9–5.85 GHz.

The main idea of through wall imaging is to capture the reflection response of a signal as it travels through a medium. If the signal is traveling through the medium and suddenly reflects back toward the source, it can be determined that something was there and disrupted its path. Skin depth of a signal is a good method for measuring how far into a medium a signal should penetrate; because of the nature of signals and systems, the depth and material type of the wall we plan to send the signal through is very important [2,3]. If we use too much power then the object could essentially be missed by the transmitted signal; at the same time this concept of skin depth also helps us by cancelling out the probability that the object is not a person.

The first major concept that allows the radios to track movement is to compare the delay of the received signal compared to the signal that was sent; in this manner it is possible to determine whether the signal was sent out and came back to the receiver at a different frequency shift. Then the two signals are correlated using signal processing techniques and the output peaks that rise from

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the differences in the signal are displayed. Another important concept is the ability to determine the difference between a person and an inanimate object; this is done by monitoring the amount of power absorption. When the signal is sent through the medium, it hits the target and comes back to the USRP device, there will be significant power absorption and loss from the beginning to the end. We will be able to tell based on the estimated amount of lost power if the object absorbed more or less than a typical human body [2]. Another challenge to focus on is the flash effect from signal readings, directing the signal using Multiple Input Multiple Output (MIMO) methods, and differentiating between wall interference readings and target objective measurements (‘surveillance device uses Wi-Fi to see through walls - [6,8]). This is expanded more on this same solution while programming the USRP in LabVIEW using built in functions to render the target's location. Another concept is angular positioning to determine the target's location and depth inside the room; we use the projected radio signal and we generate a “bird's eye view” of the room based on the angle of the reflected signal [2,15].

In this paper, we develop through-wall virtual imaging using Wi-Fi enabled software defined radio to see moving objects and their relative locations. We use LabVIEW and NI Universal Software Radio Peripheral (NI USRP2921 radios [9,10,13,14] with Ettus Research brand LP0965 directive antennas) devices to virtually detect moving objects behind the wall by sending and receiving a signal with respect to USRP's location. We evaluate the performance of the proposed approach using experimental results by considering different scenarios.

The remainder of this report is as follows: Section 2 presents the preliminary design, Section 3 presents solution description, Section 4 deals with performance optimization, Section 5 presents project implementation and evaluation, and Section 6 concludes the paper.

2. Preliminary design concepts

In order to detect human/object movement, the system requires a transmitter and receiver to be working simultaneously together and based on the captured reflections in the received signal, we can determine if there was movement in the region of interest. We use the NI USRP devices that operate in ISM bands [9,10,11]. These devices comply with FCC regulations such as the maximum transmission power for wireless communication to be 30 dBm or 1 W, and the maximum gain of the antenna and transmission power in dBm should not exceed 36 dBm or 4 W.

2.1. Reflection of signals

The next important concept used in this paper is reflection of wireless signals. When the transmitter and receiver are both in free space and have a clear line-of-sight, LOS, it is possible to measure direct interference between the transmitted/reflected signals. However, it is very difficult when the LOS is no longer available. It can observe the difference in the behavior of the signals when the transmitter and receiver are both at fixed locations, in two different scenarios: free space LOS and reflected wall [8]. In this scenario, the transmitter is placed behind the receiver at a known distance r and both have a known distance to the wall, for the transmitter this distance is d. The following figure demonstrates how the signal travels to the wall from the transmitter and reflects the signal.

Fig. 1 shows the transmitted signal approaching the wall in a cone shape, meaning that the signal gradually opens up as the signal travels farther and at the point where it hits the wall, has two points where the signal reflects back. The captured reflection

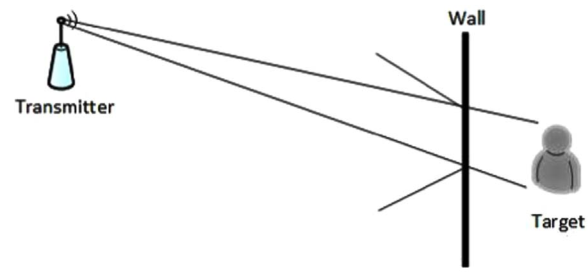

Fig. 1. Reflections of the transmitted signal on the wall.

at the receiver end will generally consist of the same phase, and add constructively to the signal power or be at a different phase and be deconstructive to the signal. When there is no other source of reflection other than the wall, the system will generate the peaks of the received signal which show that frequency shift, however, if another object was to cause a reflection, there would be more peaks in the system; this is the general theory behind radar target detection [5,8]. An important side note to make at this time, real-world systems may not reflect in one or two directions but rather disperse in many different directions in an equal amount of power, this is known as scattering. The system is now able to determine the delay time that it would take the receiver to catch the reflection of the wall and because of that, it is possible to know if there is movement on the other side of the wall.

2.2. Frequency shift

Through the use of radio frequencies inside the Wi-Fi spectrum, a virtual map of the location of objects indoors using the transceiver can be created. By directing our propagated signal toward the target, it is possible to provide measurements and trend data in relation to the original signal location. With the reflected interference received back from our targeted signal, the device should be able to detect high-accuracy movements of static and dynamic objects down to the smallest quantifiable value. This is the concept of Doppler resolution which focuses on the shifts in analog signals to capture complex movements within the scope of signal processing methods. Doppler frequency shift of a moving target is given as

$$F_D = \frac{2*V}{\lambda} \tag{1}$$

where F_D is the Doppler frequency shift, v is the speed of the wave source in meters per second and λ is the wavelength of the signal. Sending two angular signals and combining both transmissions into one formula with the intent to nullify stationary objects and converge on the position of our target. The Doppler shift presents the advantage to intricately detect human body shift movements by simply taking longer samples to determine real-time interference. Unfortunately, analog principles have their own limitations in terms of the timing in data processing. Extracting information from various samples, we improve upon Doppler output timing by integrating pipeline processing into the flow of sequences. Thus, Batch processing in [1,12] is proposed to build and verify fast cross-correlation results proving the effectiveness of human tracking through signal interaction under the Doppler system. Proven through various results and applied theory, we demonstrate the high accuracy potential of Doppler tracking and machine interactions by comparing the transceiver properties before the target and after the reception of the signal.

2.3. Matched filtering

A matched filtering in signal processing is obtained by correlating a known signal with the target signal. The match filter is the

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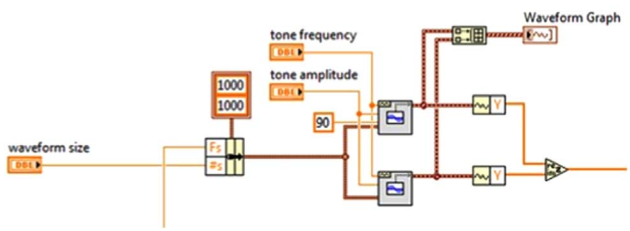

Fig. 2. Block diagram for the transmitted signal.

optimal linear filter for maximizing the signal to noise ratio with the presence of additive noise. In this case, the matched filter is the same original signal that was transmitted before any noise had been added into the signal.

Fig. 2 shows the block diagram in LabVIEW VI module of the transmitted signal and received signal. The transmitted signal is taken as an input x in the cross correlation VI and the input y is the signal received with added noise. By doing this, the cross correlation will match these two signals together to see the differences in the signals which is discussed further in the following section.

2.4. Cross ambiguity function

The CAF (cross ambiguity function), a 2-D time frequency analysis tool, is used to obtain the range and Doppler information of a target. The recorded reference r[n] and surveillance s[n] channels data undergo discrete cross ambiguity processing in LabVIEW. This process has a significant computational overhead which impedes real-time operation, where r[n] and s[n] are discrete time reference and surveillance signals in complex form. The operator '*' is a complex conjugate of signal, τ is the time delay, f_d is the Doppler shift, n is the total number of samples. The cross ambiguity function can be written as [1]

$$X(\tau, f_d)= \sum_{n=0}^{N} r[n]s^*[n+\tau]e^{-2\pi i f_d \frac{n}{N}} \tag{2}$$

Depending on the resolution of the Doppler shift, the sample rate, N, should closely match the Doppler by N-1 for integration time of this discrete system. Since the target can move their hand or body without changing positions, that can cause multiple Doppler shifts during that same integration time. Thus, a windowing method is used to obtain the specified Doppler sample according to the polarity and integration timing. The sequence impacts the range of bins on the CAF surface in order to exclude excess Doppler phenomenon. The processing time in the window should not exceed the shift time, allowing for each window to obtain the specified information coinciding where the previous window left off. With a minor overlap and new information per window this approach assists in the capturing of clearer Doppler trend data, narrower Doppler limitations and pipeline processing without losing much needed data; for this reason, only a portion of the data will be sampled in order to retain the accuracy of the system.

Fig. 3 is an example showing how a cross correlation works with two contentious signals. The transmitted signal is a sine wave with no noise and the received signal is the same signal with noise added the cross correlation VI takes the transmitted signal as x input and the received signal as y input. The cross correlation takes a complex conjugate of the imaginary part of the two signals and multiplies them together giving us the cross correlated signal. By doing this we can see the shifts in the received and the transmitted signal. In the cross correlation VI sample lengths of the x and y signals can be specified. To get accurate results the x and the y signals must have the same lengths.

Fig. 4 shows the cross correlated results between the two signals. Since these signals were manually generated by the simulation of a signal VI in LabVIEW, it only shows us one peak where the signal is different from the transmitted signal (Fig. 5).

2.5. Autocorrelation

Autocorrelation is one of the important concepts that helps in the design of our system; this function takes a signal and compares the original signal with its time delay [4]; this is mathematically modeled as

$$R(\tau) = \frac{1}{t_{max} - t_{min}} \int_{t_{min}}^{t_{max}} s(t)s(t-\tau)dt \tag{3}$$

Sending a reference signal and the delayed signal, this function relates them one to another, showing the results according to the similarities and differences they share over time. The length of the signals is convoluted part-by-part into matrices corresponding to the particular frequency bins that were transformed from the time-signal properties. This method allows a comparison of the original signal to the signal received then characterizes the results providing calculations and feedback from the target to a measurable value.

2.6. Time-varying filter

The time-varying filter is used for transient signals whose frequency evolves over time. We created a VI with time-varying filter that converts the time-domain signal to the joint time-frequency domain with the Gabor transform, this removes noise in the joint time frequency domain, and then reconstructs the time-domain

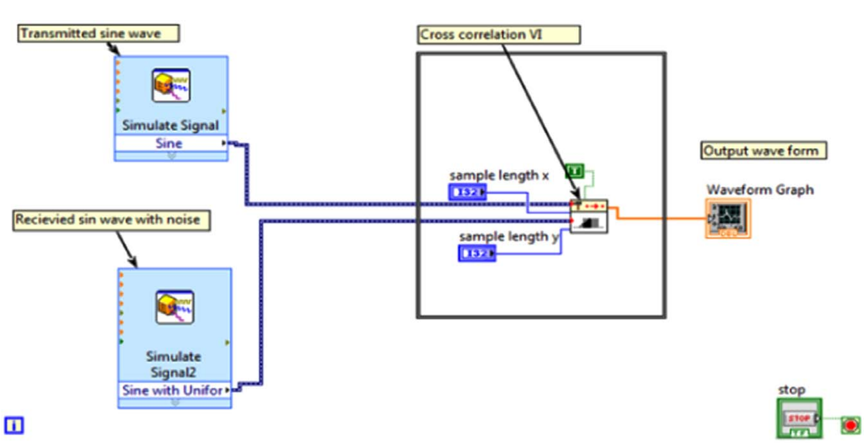

Fig. 3. Example of Cross Correlation between a transmitted sine wave and a received sine wave with Gaussian noise added to the reflected signal.

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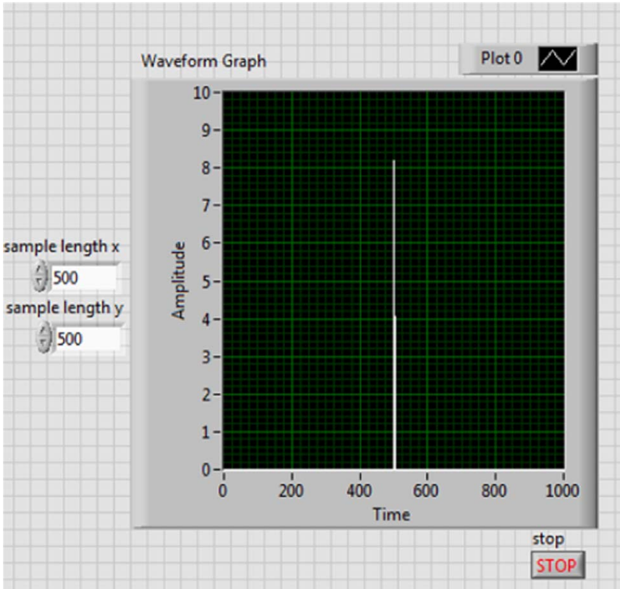

Fig. 4. Front Panel of the Cross Correlation of the transmitted sine wave and the received sine wave with Gaussian noise.

Fig. 5. System Experimental Setup with USRP, antenna and laptop.

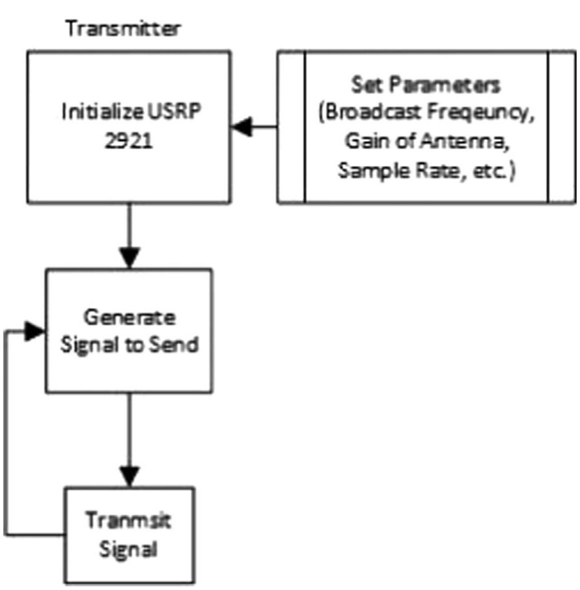

Fig. 6. Flow Chart for the Transmitting VI Module.

with the Gabor expansion by using the Gabor coefficients after applying a threshold. A certain threshold for a given frequency band can be specified to this filter. For instance, if a transmitted

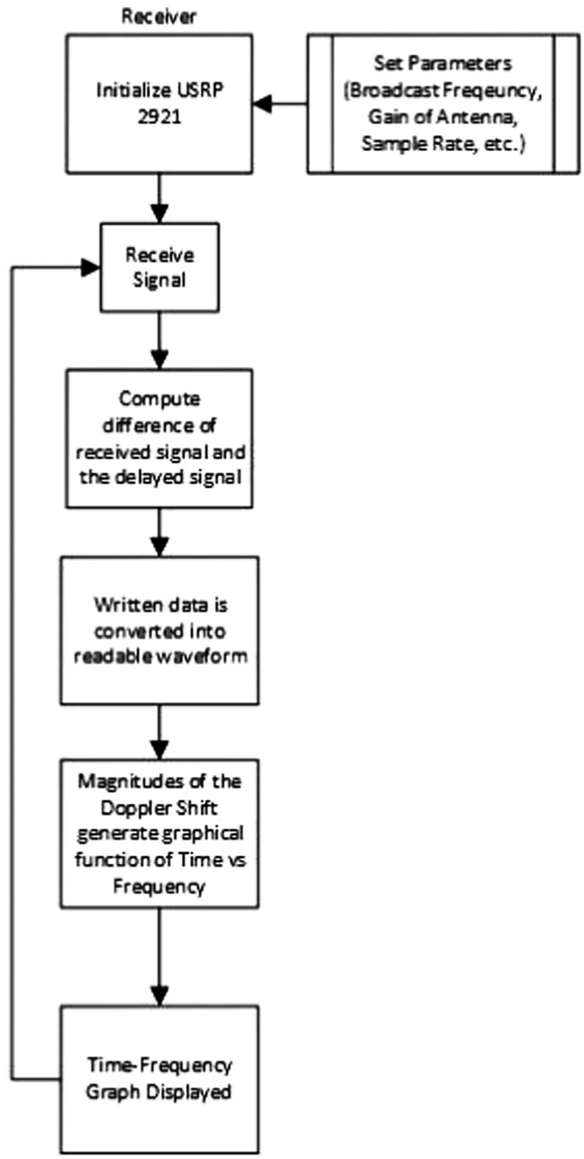

Fig. 7. Flow Chart for the Receiver VI module.

signal has a certain frequency the threshold in the filter has to be specified at the same frequency. By doing this the filter identifies white Gaussian noise and external noises added into the received signal. Once this process is completed the signal that we acquire would have minimal noise due to error in the program, which would not be a problem in detection. The peaks in the signal after the filter process are the detected objects with a varying velocity.

2.7. Short-Time Fourier Transform

The Short-Time Fourier Transform, STFT, determines the sinusoidal frequency and phase content of local sections of a signal as it changes over time. It divides a longer time signal in to shorter segments with the same length and then computes the Fourier transform on each shorter segment separately. Since this project consists of a continuous transmission of a sine wave we use the continuous-time STFT formula as

$$\{(t)\}(\tau,\omega) \equiv X(\tau,\omega) = \int_{-\tau}^{\tau} x(t)\omega(t-\tau)e^{-j\omega t}dt \qquad (4)$$

In the continuous-time case, the function to be transformed is multiplied by a window function, which is nonzero for only a

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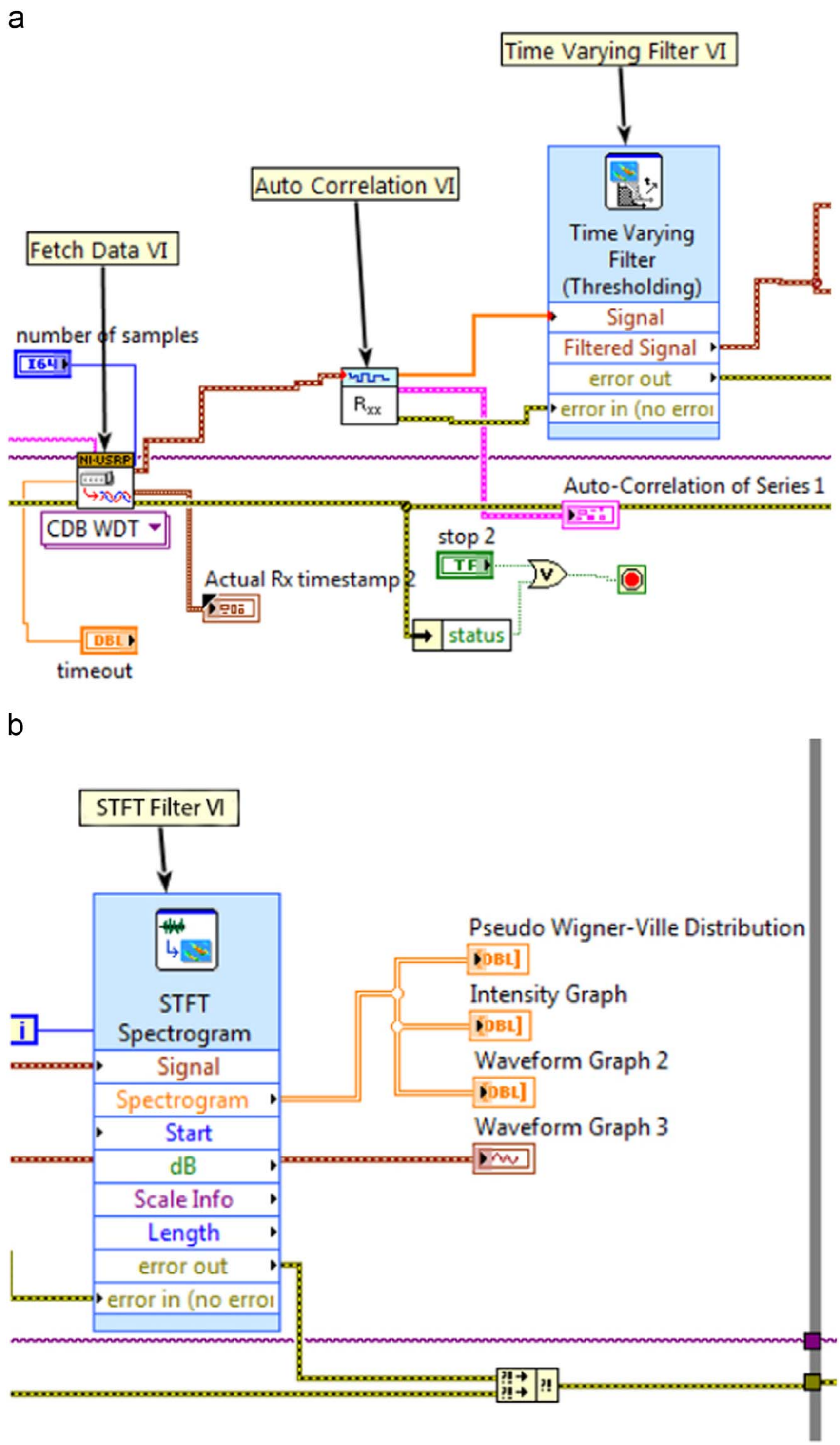

Fig. 8. (a) Block Diagram of Through Wall Imaging Receiver. (b) Block Diagram of Through Wall Imaging Receiver.

short period of time. The Fourier transform is a one dimensional function of the resulting signal that is taken as the window sliding along the time axis, resulting in a two dimensional representation of the signal. We implement the STFT function in LabVIEW VI that uses a Hanning window function centered at zero. In the STFT formula the $x(t)$ is the signal to be transformed. $X(\tau, w)$ is essentially the Fourier transform of $x(t)\ w(t-\tau)$, a complex function representing the phase and magnitude of the signal over time and frequency. This process is done by using the unwrap phase VI in LabVIEW. The phase unwrap VI is used both on the time τ and the frequency ω axis, by doing this it suppresses any jump discontinuity of the phase result of the STFT.

3. USRP and its configuration for through wall vision

The operation of the USRP is the primary device used in implementing the through wall imaging system. Programmed under the instruction of LabVIEW syntax and software defined radio, we configure our NI USRP 2921 devices to transceive signals across

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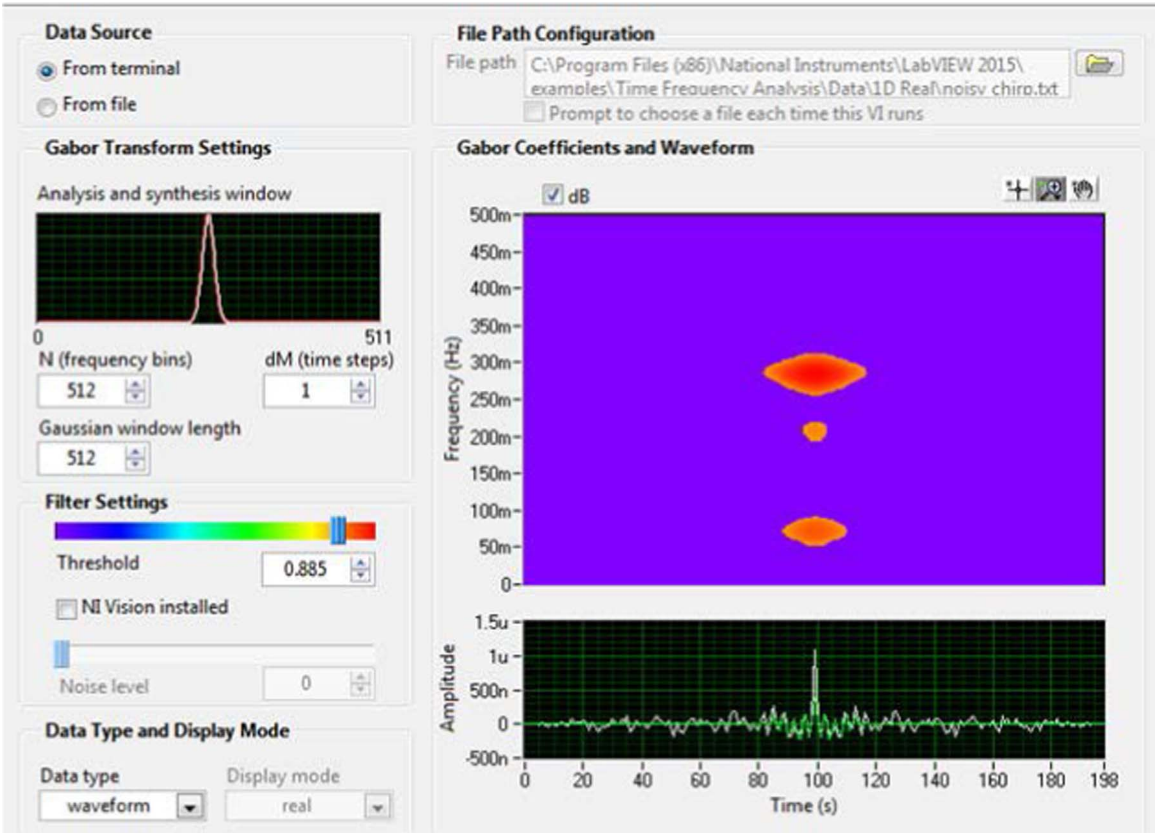

Fig. 9. Configuration of the Time-Varying Filter VI Block.

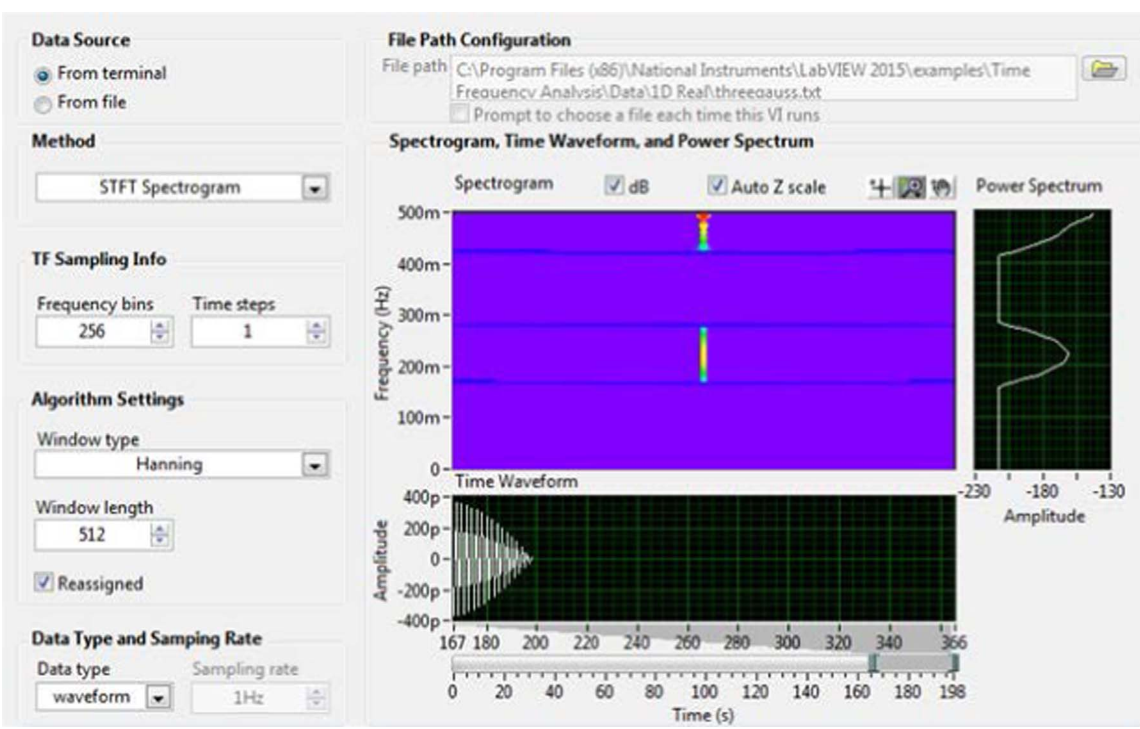

Fig. 10. Configuration of the STFT Filter VI Block.

objects we would like to track. Constructing a block diagram, we open the transmission session to configure the enabled channels to match our desired parameters at both transmission and receiving terminals (mismatch representation of signal parameters may cause discrepancies in the results). Defining the Wi-Fi radio frequency, gain, sample rate and timed delay, we set up our USRPs for transceiving. Writing the received data into an array by indices, we capture the complex form of the signal properties as a function of time. Computing the difference of the initial iterations versus delayed iterations, we store this information into matrix cells by

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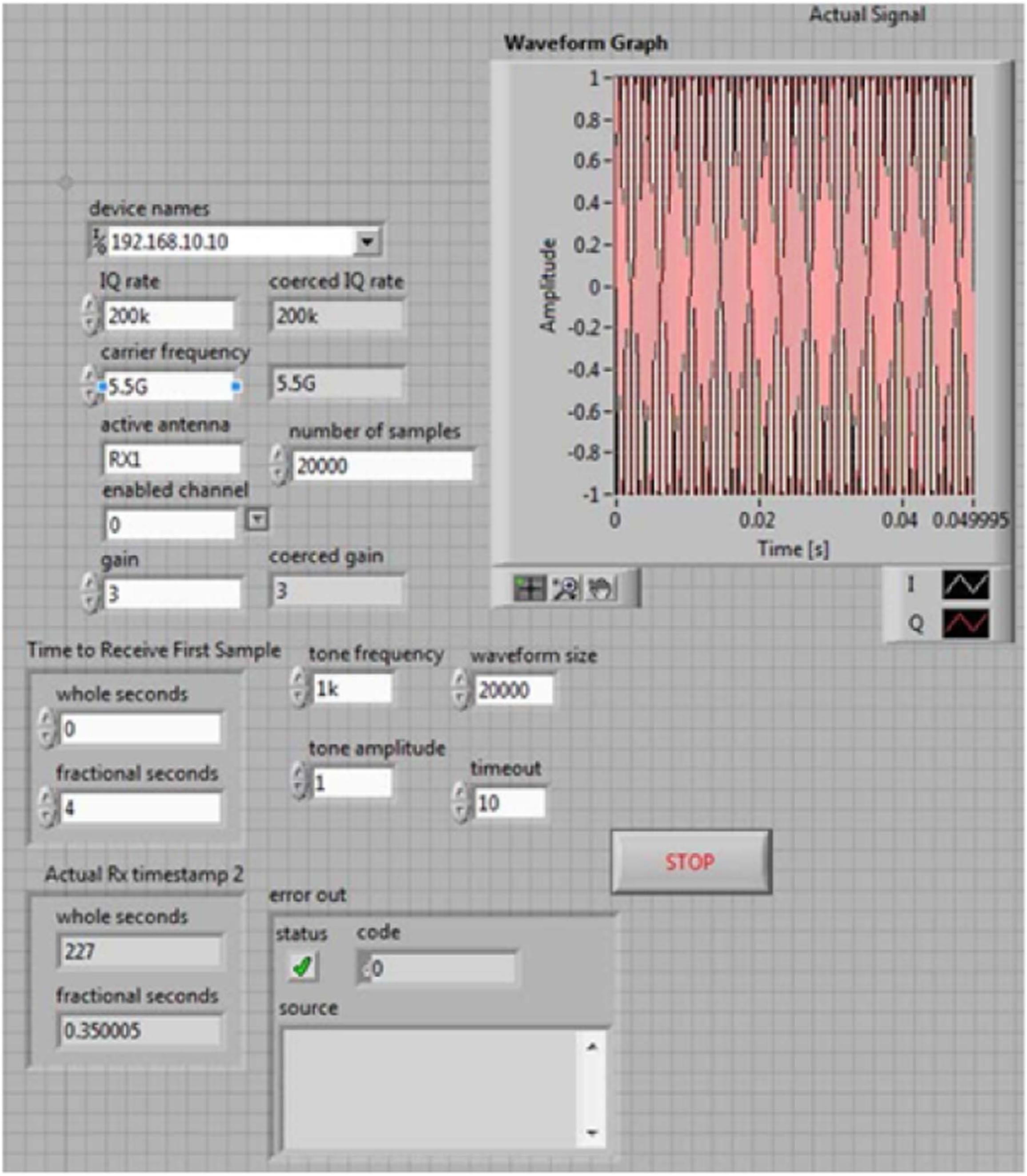

Fig. 11. Front Panel for the Transmitter VI Module.

which we pass using correlation techniques to manipulate it into a readable waveform.

The time stamped waveform is routed toward the ambiguity procedure for the intents and purposes of resolving the Doppler shifts and correlated values into a graphically based function of time and frequency. Manipulating the data type to be handled by our short-time Fourier transform, we perform spectral analysis and quadratic calculations on the windowed Doppler resolution and coefficients of the correlated instances to return the magnitudes of our time frequency represented signal acquisition. This method uses highly fast paced, programmable radio frequency devices in order to transmit a signal through the variable depth wall and reflect off of surfaces on the other side. This can be done with a single array antenna, however, by using more antennas to reflect off the surface, the return signal will begin to take the shape of the actual object it reflected off of. Fig. 6 shows the typical experimental set up with USRP, antenna and laptop.

4. Logical flow with methodology

Fig. 6 displays the logical flow of the transmitting VI module. The transmitting VI is only responsible for setting up the correct parameters, initializing the USRP and generating the signal to be broadcasted by the USRP; this process runs until the user stops it. This concept has been built on top of a method presented in “Tracking Wi-Fi Signals to Passively Using NI USRP and LabVIEW - Solutions - National Instruments” by National Instruments.

The receiver VI (Fig. 7) is responsible for picking up the signal and comparing it to what was known to be sent by the transmitter. Before running the system, the frequency, sample size, projected gain, and intended channels need to be configured to the

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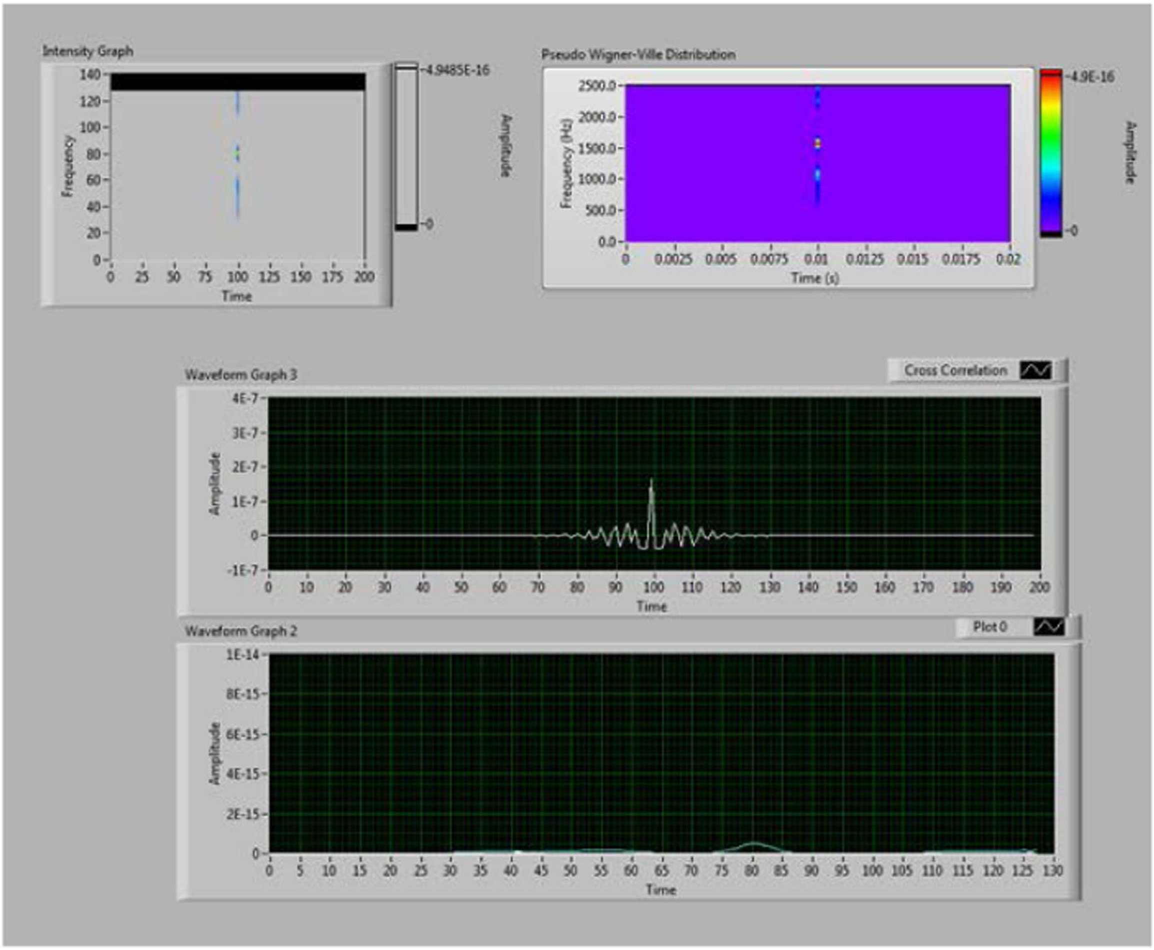

Fig. 12. Front panel for the receiving VI module.

Table 1
Legend for the Results Taken from Experimental Test.

Legend in Figs. 13 through 16	
1	This waveform shows the received signal from the USRP 2921.
2	The Intensity graph displays the reflected signal at the time and frequency that it is received.
3	This waveform graph displays the Autocorrelation of the received signal by comparing the signal with delayed signal from the reflection and generates peaks in the signal when there is a reflection.
4	This waveform shows the same information as the intensity graph, 2, however it shows each scan that allows us to see when the target is moving and briefly after they have come to a stop.

necessary conditions. Using the LabVIEW functions, we collate the data that is sent by the transmitter and compile them against previous samples to find the differences between the iterations. Recording the minor dissimilarities between signals, we insert those details into an array for further interrogation by our signal processing blocks. Filtering unwanted noise and harmonics, we choose boundary values to be accepted by our system. The shifts of Doppler magnitude are captured to identify frequency bins that are critical to the analysis of our target activity. Those magnitudes are associated with the frequencies and plotted according to the amplitude that is associated with the triggered time intervals and graphed on a time-frequency waveform.

The first process in this block is to initialize the USRP devices to propagate through walls using idle RF bands. We transmit a continuous signal on a millisecond delay, such that it negates premature wall reflections that we do not want to include in our system. The receiver fetches the sent data and assigns timestamp values to the sample receptions to be stored into the matrices. The cells in the matrix are translated from complex numbers to polar values, and compared to prior samples to be integrated back into the system for coherence interpretations. The delayed transmissions are entered into the cross ambiguity equation with the de-noised version of the signal. The corresponding results are characterized with respect to their transmission and matched with their initial band pass propagation. Transforming the signal using STFT, we take the resultant magnitudes from the index of our selected frequency. The shifted interference of the signals at different moments in time are output by time-frequency representations that are then graphed according to the target displacement relative to the peaks.

Fig. 8(a) and (b) show the overall components used to get the proper output waveform. The VI's in the block diagram are located in a while loop to make it a continuous signal processing for the Fetch data VI to get continuous data to make it a real time processing system. After the data has been captured it is broken down into a build array. After it has been broken down into a build array then it is processed into the autocorrelation VI to get the peaks of the received signal. After the auto-correlation, the signal still has external noise added into the signal. In order to eliminate the noise in the signal we use a time varying filter VI to put a threshold on the input signal to eliminate the noise in the signal. After the time varying filtering, the signal has minimal noise and is sent into a STFT Spectrogram to get a 2-Dimensional graph of the discovered target. This process has some errors because of the false detection peaks in the received signal.

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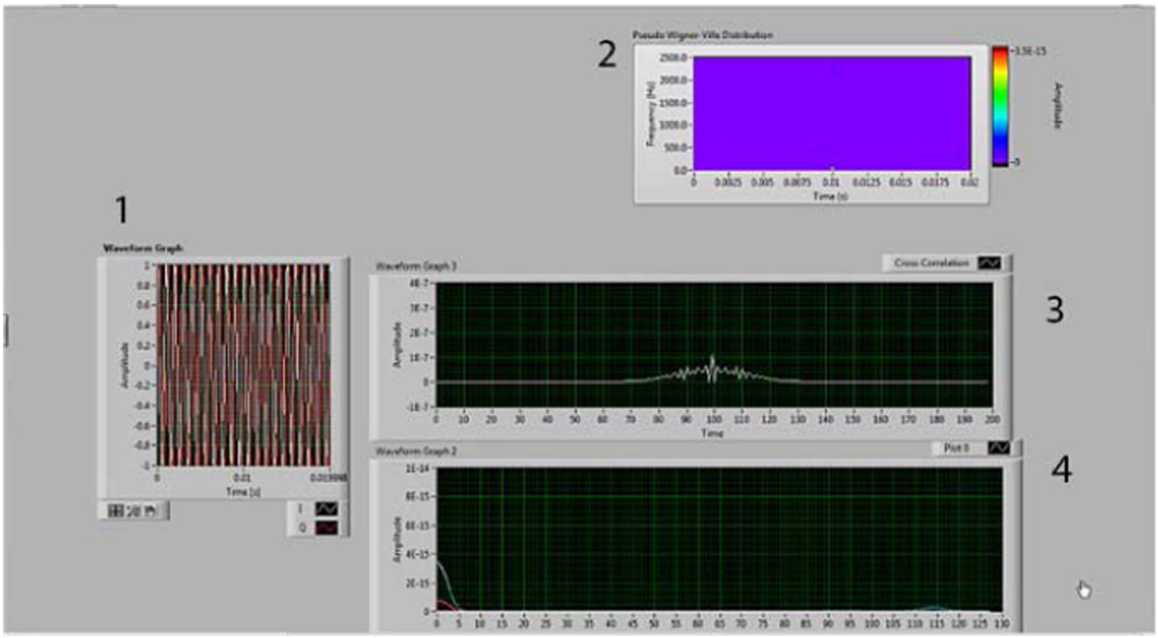

Fig. 13. Experimental Results without any movement.

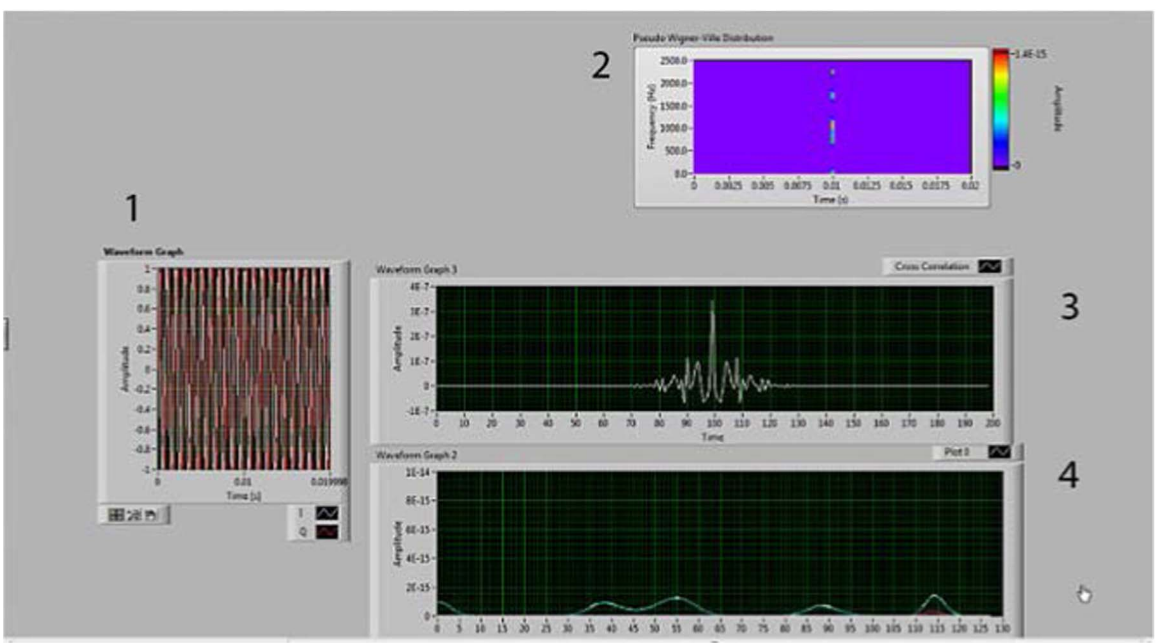

Fig. 14. Experimental results with first instance of object being detected.

Figs. 9 and 10 are the configurations for both the time-varying filter and the short-time Fourier transform filter, respectively. The time-varying filter has several input parameters and settings that allow for specific threshold of noise levels to filter out unnecessary components. It uses a Gabor transform that takes the frequency and the sampling rate and the number of time steps to output a series of Gabor coefficients; the resulting waveform is displayed as shown in Fig. 9. The STFT-filter computes the time-frequency representation of the signal as mentioned in earlier sections.

This filter setting helps us create a threshold for the received signal after it goes through autocorrelation. The VI lets pick an amount of frequency bins in the received signal to avoid break points in the signal. The threshold is set from the given information from the transmitted signal. Doing this helps the filter identify the external noise added into the received signal and eliminate the external noise with the threshold method. Some noises were not able to be eliminated, but that did not change much of our results due to the fact that the targets reflection was much higher than the noise added to the signal.

The Short Time Fourier Transform computes the quadratic joint time frequency representation for the input signal. The VI has a set amount of frequency bins that can be selected from the received signal to be displayed in the density graph. The display density graph is dependent on processing speed. Even though we only have 10% of the signal displayed, most of the data and information needed to detect the target was allotted in that 10% of the signal. The Hanning method was used in this filter due to the raised cosine window function in the Hanning filter. In the filter the two ends of the cosine just touch zero, so the side lobes roll off at about 18 dB per octave. This filter also has many other advantages such

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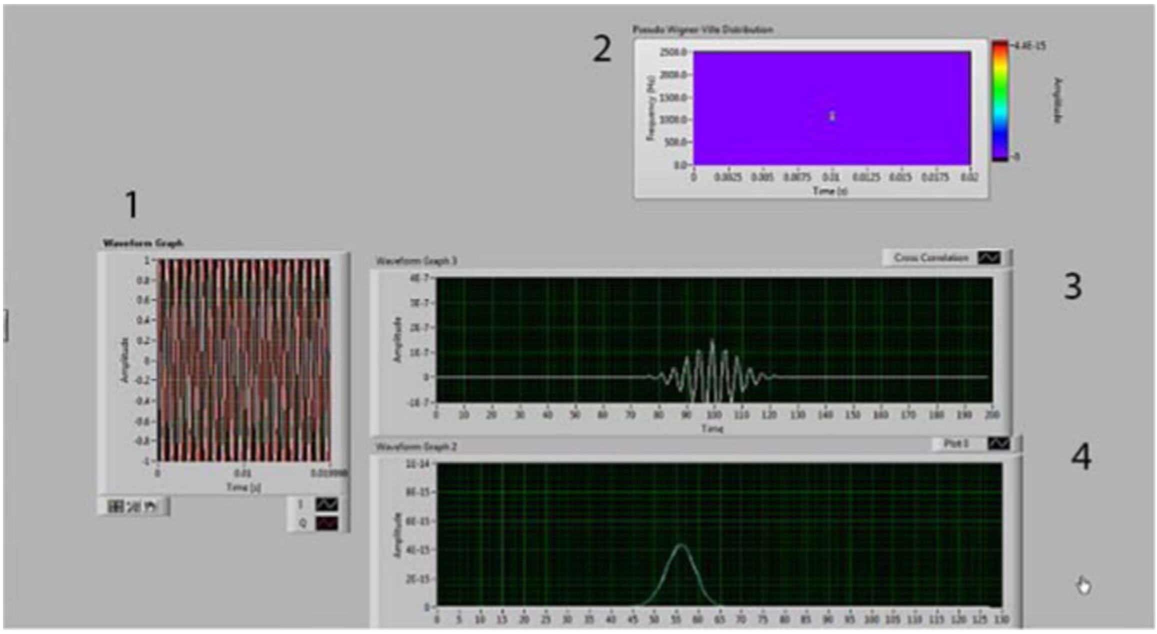

Fig. 15. Experimental results after couple of seconds of the object being detected.

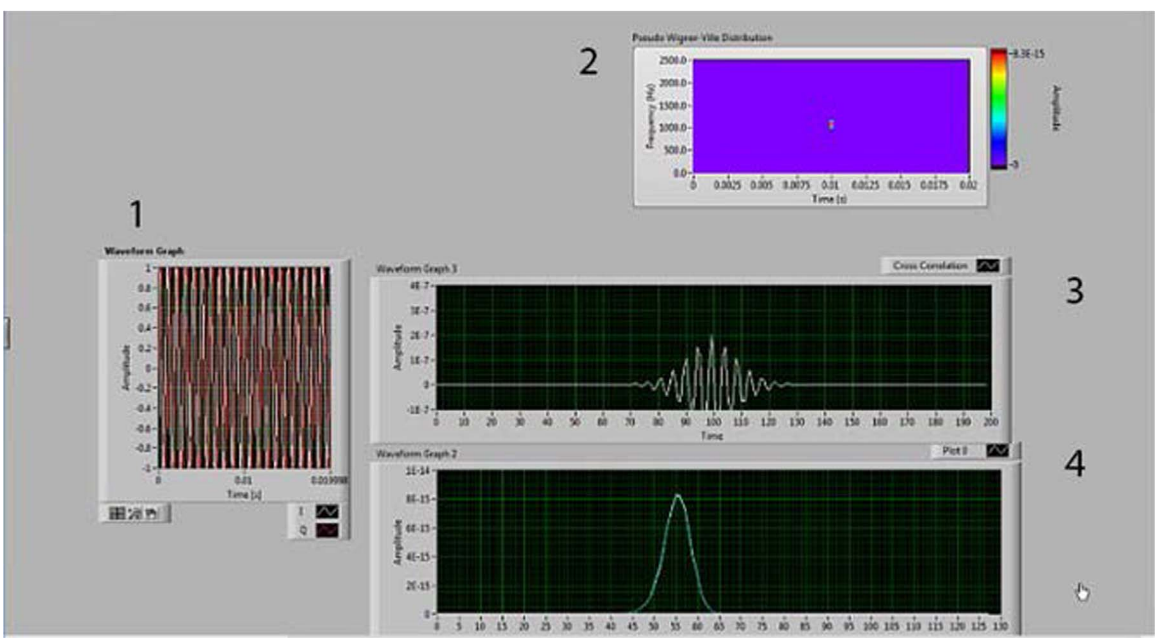

Fig. 16. Experimental results with movement detection after the target has remained in front of the transmitter.

as the time can be changed according to the signals amplitude. This filter has a specification where it can be changed to many other spectrograms, like the Gabor spectrogram, the adaptive spectrogram, the Wigner-Ville distribution, the Choi-Williams distribution, and the cone-shaped distribution.

Fig. 11 represents a typical front panel for the transmitting VI. Listed below are all the specific characteristics that the transmitter was set to.

- I/Q Rate: 200 K
- Sample per second Carrier Frequency: 5.5 G Hz
- Number of samples: 20000
- Gain: 3 dBm
- Tone Frequency: 1000 Hz

Fig. 12 displays two graphs on the front panel that are the intensity graphs for detecting the target in the spectrogram. Graph 3 in the front panel is the Autocorrelation of the received signal. The graph 2 represents the peak detection in the received signal after the filtering. The peak in graph 2 shows a peak where it has detected a target.

5. Experimental setup and results

The experimental test parameters are set for testing in corresponding VI modules. We used 5.5 GHz frequency with I/Q rate of 200 K, the signal being sent was at a tone frequency of 1 kHz and tone amplitude of 10 with a waveform size of 10 k. Note that the gain of the antenna affects the ability to broadcast further,

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however too high a gain begins to change the reflections of the signals and too many peaks will be observed; the experimental setup considers that both the antennas and the target are within less than 10 m from the wall. The system is run for a couple seconds to avoid any errors and to adjust to any possible static objects that are reflecting the signal. After a brief moment, the peaks settle down until a moving target enters the path. The Table 1 and Figs. 13–16 are taken from the experiment where the target walked into the room after the experiment started.

Figs. 13–16 listed in order of the target being detected show the moment before the target entered the room, as they began to walk in there are several smaller peaks. As the target gets to the center of the room, the side lobe peaks begin to fade away and a single magnitude is measured; this tells us that just one source of reflection is causing differences between the transmitted signal and the received version. These results do not tell the targets relative location or distance from the wall, just that there is movement being measured.

6. Conclusion

In this paper, we have presented the design and experimental results for seeing through-(non-transparent) walls using Wi-Fi enabled software defined radios to detect human/object movement. Performance of the proposed approach is evaluated using experimental results and the developed module has been able to detect object movement through a wall successfully. This method of detecting moving targets through a non-transparent surface could greatly help detect active shooters in the room or trapped people in disaster scenes where emergency-response people could not directly see them.

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