Human Activity Detection Using Radio Waves
Final Report

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1 Abstract

The ability to detect human presence wirelessly from outside the room is essential for security and emergency situations. For example, a hostage situation where the number of people is to be detected or during a disaster such as a fire.

The project aim is to create a short range wireless target (human) detector using radio signals in the form of a radar.

The device should be able to detect movement of the human located on the other side of the wall. There is a wide spectrum of signals which can be used for human detection. The amateur radio band can be used in this implementation making experimentation with the concept convenient.

Simulation of the environment and radar is done on MatLab and SimuLink. The following simulation creates an environment in which the motion of a target is mathematically detected in the form of channel estimates and static targets are eliminated (walls, ground, objects in room).

2 Concept

As this implementation is 'through the wall', signal reflected by the wall (AKA flash) is stronger than signal reflected from objects on the other side of the wall due to the attenuation of signal when it passes through a dense object. The attenuation further doubles due to the location of the receiver being on the same side as the transmitter. The reflected signal at the receiver is small in magnitude due to the small RCS (radar cross section) of the human (approx. $1m^2$) when compared to the wall.

To eliminate flash effect i.e. to isolate reflected signal from the human, we perform iterative nulling. When all objects are static, we receive a zero value for the channel. When the human is in motion, we receive a non-zero value for the same.

We have simulated a system consisting of 2 transmitters and 1 receiver. A MIMO (multiple input multiple output) channel is implemented to simulate a multipath propagating environment. The signals sent over the channel will reflect off objects in the vicinity (e.g. walls, ground etc.). A Rayleigh fading distribution is considered in this case as we assume that there are multiple objects which are in the path of the signal transmission. The fading of the channel is determined by the Doppler shift.

A target has been simulated with RCS value of 1 (denoting $1m^2$) and varying velocities to accurately depict a human. A display block displays the channel estimate (zero or non-zero).

The elimination of flash effect has been implemented in 3 steps [1].

1. **Initial Nulling:** During the initial phase, no target is in motion and the entire channel is static. Each transmitter transmits the same signal one by one from their respective positions. The received signal from both the transmitters is recorded and channels are estimated for each. The ratio of the 2 channel estimates is calculated, negated and stored as a factor (p).

2. **Power Boosting:** The transmitted signal from one of the transmitters is multiplied by the p factor to create a strong signal which will result in distinguished reflection from the objects behind the wall, improving SNR.

3. **Iterative Nulling:** The original and the boosted signals are concurrently transmitted over the same channel and reflected off the targets. The receiver receives a linearly aggregated channel. Nulling is done to remove the residual reflections i.e. clutter from the static object. The channel cannot be estimated for each transmitter separately as the a combined channel is obtained at the receiver. The channel estimates are refined based on the fact that the channel estimates have a higher value than the errors in the channel. This is implemented mathematically as follows:

   The channel received at the receiver after the concurrent transmission from the two antennas is given by the equation:

   $$h_{res} = h_1 + h_2\left(-\frac{\hat{h}_1}{\hat{h}_2}\right) \approx 0 \tag{1}$$

   We assume that the new channel estimate for the second transmitter is equal to the initial estimate for the same i.e.

   $$\hat{h}_2 = h_2 \tag{2}$$

   The new estimate of h_1 is given by

   $$\hat{h}_1' = h_1 = h_{res} + \hat{h}_1 \tag{3}$$

   Similarly assume that there is accuracy in the new channel estimate and the previous estimate for the first transmitter i.e.

$$\hat{h}_1 = h_1 \tag{4}$$

The new estimate of h_2 is given by

$$\hat{h}_2' = h_2 = (1 - \frac{h_{res}}{\hat{h}_1})\hat{h}_2 \tag{5}$$

These iterations are done to obtain better values for h_1 and h_2 until the estimates found in the initial nulling converge. This is easily achieved as the same implemented algorithm converges exponentially fast.

The channel has been estimated using the least-square estimate method [3]. This method helps when the channel and noise estimates are unknown and the channel is treated like a black box.

Matrix X denotes the transmitted signal with dimensions of (t*N) where t is the number of transmitters and N is the number of samples.

Matrix Y denotes the received signal with dimensions of (r*N) where r is the number of receivers and N is the number of samples.

Matrix H denotes the channel with dimensions of (r*t) where r is the number of receivers and t is the number of transmitters.

Matrix V denotes the noise with dimensions of (r*N) where r is the number of receivers and N is the number of samples.

We know that,

$$Y = HX + V \tag{6}$$

Taking the transpose,

$$Y^T = X^T H^T + V^T \tag{7}$$

The least squares problem for channel estimation is denoted using the Frobenius norm (as all computations are on matrices).

$$||Y^T - X^T H^T||^2 \tag{8}$$

To solve this, we take the pseudo inverse of the channel transpose.

$$\hat{H^T} = ((X^T)^T X^T)^{-1} (X^T)^T Y^T \tag{9}$$

$$\hat{H^T} = (XX^T)^{-1} X Y^T \tag{10}$$

Taking transpose again,

$$\hat{H} = Y X^T (XX^T)^{-1} \tag{11}$$

Equation (11) is the final least squares channel estimation used in our implementation.

3 Initial Approach

To understand the working of target detection using a radar, we used an existing SimuLink model [2] and modified it according to requirements of our application. This gave us knowledge about working of the channel and methods to create a realistic environment with moving targets.

In the initial model, linear FM pulses were transmitted through a wide-band 2-ray channel multi-path channel simulating 2 propagation paths - the line of sight and a boundary reflection path.

A wide-band backscatter target was simulated and its position and velocity were determined. We considered the estimate position to be $7m$ from the radar and its velocity as $0m/s$. The cross section of the target is fixed as $1m^2$.

The reflected signal passed through the same wide-band 2-ray channel and received at a receiver preamplifier which amplified the signal using the gain.

Signal processing consisted of the following components. The main component of processing was the stretch processor (also known as dechirping). The target range ($6.5m$ - $7.5m$) was fed into this block and performed pulse compression.

The output was fed into a range-Doppler response block displaying a range-Doppler matrix.

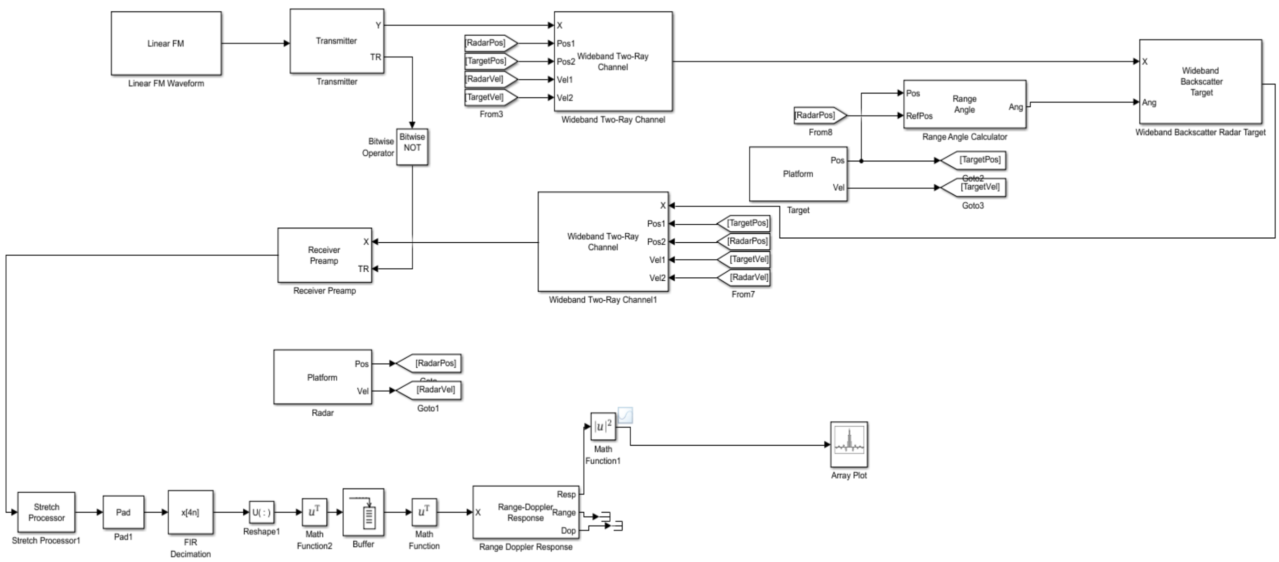

Figure 1: Initial implementation Simulink [2]

4 Implementation

The flash effect concept is used to simulate the detection of humans. Figure 2 shows the SimuLink model for initial nulling. A MatLab function block is used to generate a transmitter signal. Parameters such as operating frequency, sample rate and amplitude are defined for this signal.

The transmitter block amplifies the signal before transmission. This block is defined using parameters such as gain, power and loss factor. Next, a channel is simulated using multiple channel blocks. A free space channel block is used where the initial position and velocity of the transmitter and target are defined. A MIMO channel block is used to simulate a multi path Rayleigh fading channel.

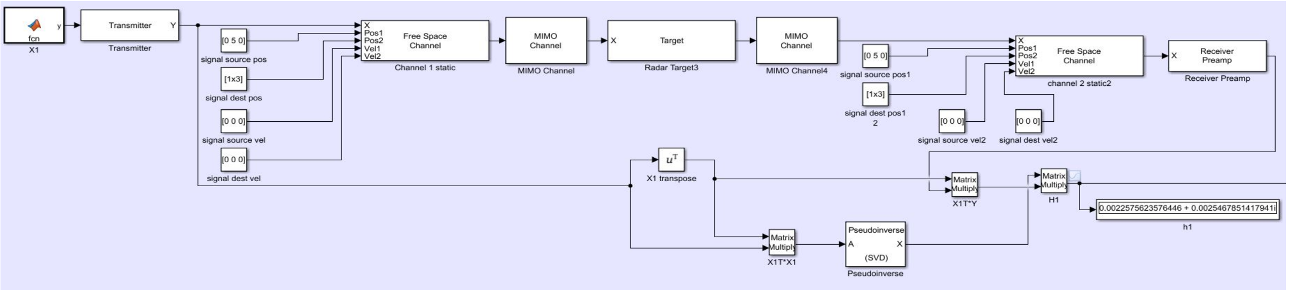

Figure 2: Initial Nulling

The RCS value is defined in the target block for a static object. The signal transmitting through the channel is reflected by the target and received at the receiver where the signal is amplified and thermal noise is added.

The calculation of channel estimates is done using signal matrices. Equation 11 is implemented in SimuLink to determine the channel estimate of one transmitter h_1. Similarly, the process is repeated for the second transmitter which transmits the same signal from a different location to determine the channel estimate h_2. The initial nulling gives the preamble value p = $-(h_1/h_2)$.

Power boosting is implemented as shown in Figure 3. The preamble (p) obtained during the initial nulling stage is multiplied with the transmitted signal from one of the transmitters. This boosts the transmitted power so that weaker reflections from the moving object are more detectable i.e. it improves the signal to noise ratio of the moving objects.

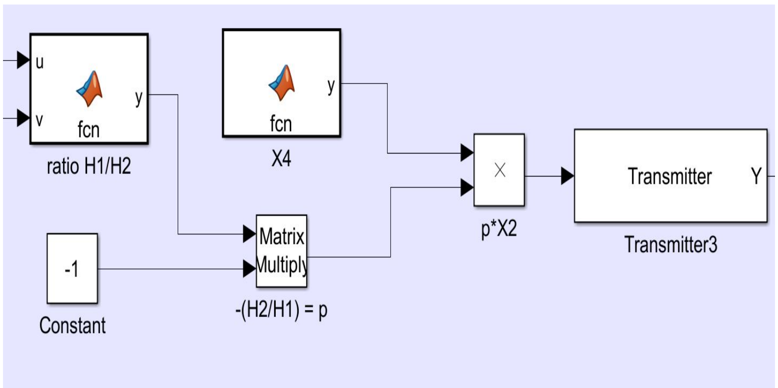

Figure 3: Power Boosting

Figure 4 and Figure 5 perform iterative nulling. Here, signals from both the transmitters are sent over the same channel. They are linearly added in the channel before being received at the receiver. The channel estimate is determined using Equation 11. The resultant channel estimate is the combination of the two transmitted channel estimates is

$$h_{res} = h_1 + h_2\left(-\frac{\hat{h}_1}{\hat{h}_2}\right) \quad (12)$$

When the target is stationary, the value of h_{res} is zero i.e. ideal condition for the implementation of this algorithm. When an object is in motion, the h_{res} value is a non-zero number. This indicates the presence of a moving target in the room.

The simulation is done for multiple test cases and the values of the channel estimates are noted to indicate if a moving target (i.e. human) is detected or not.

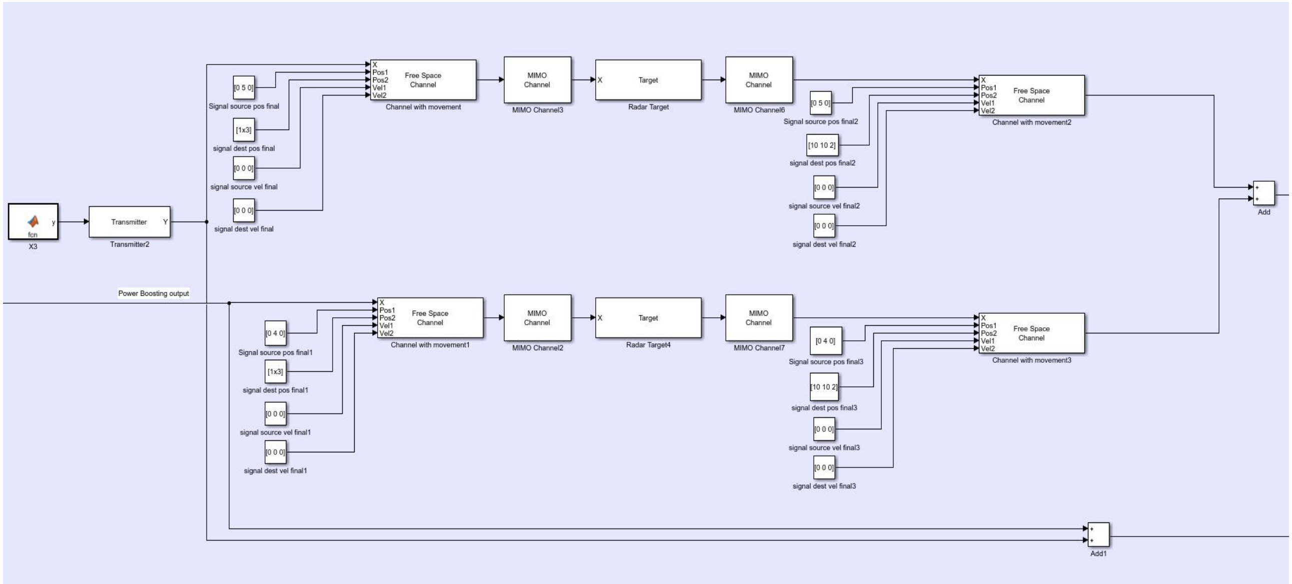

Figure 4: Iterative nulling part 1

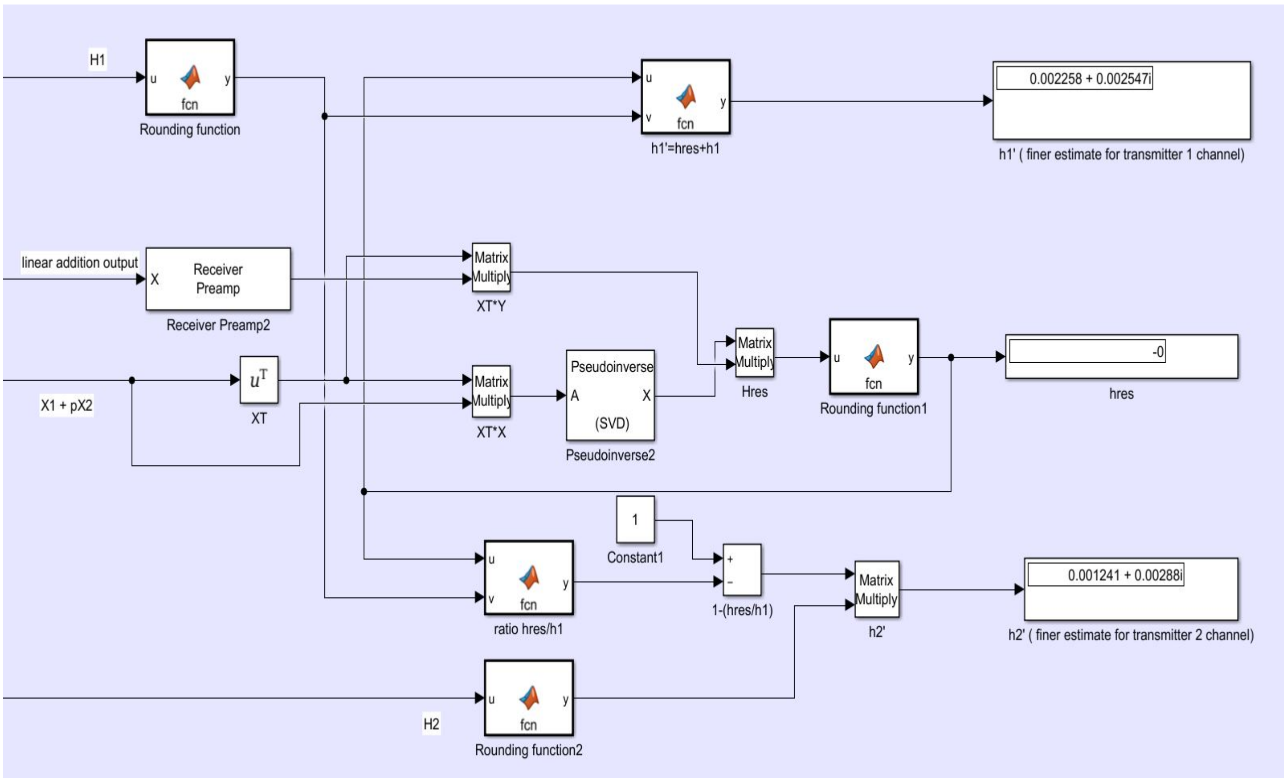

Figure 5: Iterative nulling part 2

5 Results

The blocks which are used to simulate the model are parameterized to define functionality of each block. A signal of $800Mhz$ frequency is generated at the transmitter with a Nyquist sampling rate of $100Hz$. The transmitter is assigned a peak power value of $5000W$ and a $20dB$ gain. The signal is propagated over the channel with the speed of light. the Doppler shift in the MIMO channel is set to $0.001Hz$. The receiver gain is assigned a $20dB$ value. For this case, the maximum one way propagation distance of the signal is set to $20m$.

A set of mathematical computations are performed on Simulink for test cases of varying target locations and velocities. The magnitude of channel estimate helps to determine the probability of detection of a moving object.

Table 1 displays the test cases where target velocity and positions are varied and channel estimates calculated. Since the velocity of a human varies between $1m/s$ and $12m/s$, we have considered 2 velocities for every position - $1.4m/s$ and $7m/s$. The source and targets are considered on a common plane i.e. only x and y axis values are varied. The transmitters are placed at a distance of $0.5m$ from each other on the y-axis i.e. transmitter 1 is at (0,5,0) and transmitter 2 is at (0,5.5,0).

Target position	Target velocity	h_{res}	Distance between target and source
(5,5,0)	(0,0,0)	0	5.006246
(5,5,0)	(1,1,0)	0.01464	5.006246
(5,5,0)	(5,5,0)	0.005759	5.006246
(10,5,0)	(1,1,0)	0.002865	10.003125
(10,5,0)	(5,5,0)	0.01018	10.003125
(12,5,0)	(1,1,0)	0.002037	12.002604
(12,5,0)	(5,5,0)	0.007076	12.002604
(15,5,0)	(1,1,0)	0.001328	15.002083
(15,5,0)	(5,5,0)	0.003931	15.002083
(5,10,0)	(1,1,0)	0.00001871	6.896557
(5,10,0)	(5,5,0)	0.00004638	6.896557
(10,10,0)	(1,1,0)	0.00006712	11.070795
(10,10,0)	(5,5,0)	0.0002469	11.070795
(12,10,0)	(1,1,0)	0.00008287	12.905909
(12,10,0)	(5,5,0)	0.0001854	12.905909
(15,10,0)	(1,1,0)	0.00005728	15.734119
(15,10,0)	(5,5,0)	0.0001155	15.734119
(5,15,0)	(1,1,0)	0.0001486	10.957304
(5,15,0)	(5,5,0)	0.0003743	10.957304
(10,15,0)	(1,1,0)	0.00000215	13.966478
(10,15,0)	(5,5,0)	0.000003901	13.966478
(12,15,0)	(1,1,0)	0.00001213	15.461646
(12,15,0)	(5,5,0)	0.00002347	15.461646
(15,15,0)	(1,1,0)	0.00001534	17.890291
(15,15,0)	(5,5,0)	0.00003468	17.890291

Table 1: Example test cases for varying target positions and velocities

The first entry in the table displays a channel estimate of zero value for zero velocity, showing that no target is detected due to its static nature.

We observe that channel estimate for a target located at points such as (12,15,0) or (10,15,0) are very low and the ability to detect theses is hampered. At these locations the target is approaching the maximum propagation distance and is harder to detect.

We have taken 2 constant velocities and varied the positions (varying x-axis position for a constant y-axis position and vice-versa) to view the effect on channel estimate.

From Figure 6, we observe that the channel estimate value peaks when the object is in line-of-sight (approx. where $Y = 5m$) of the transmitter.

It is also observed that in majority of the cases (figures 6 and 7) , the value for velocity (1,1,0) is lower than for velocity (5,5,0). This leads us to conclude that slower objects are more difficult to detect.

From graphs 4 and 8 (figures 6 and 7), where the constant $X = 15m$ and constant $Y = 12m$ respectively, the slope is closer to 0. This displays the property of lower probability of detection for targets further away from the transmitter.

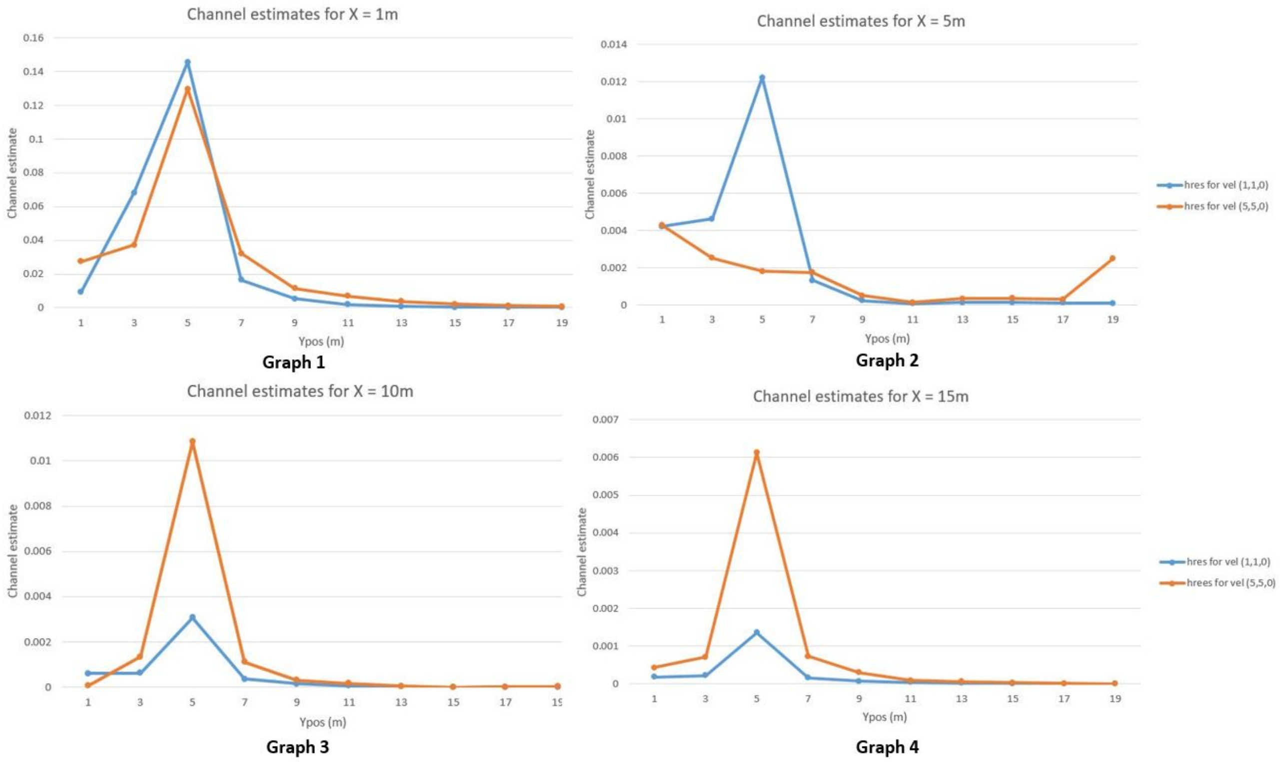

Figure 6: Graphs of channel estimates v/s y position when x position is constant

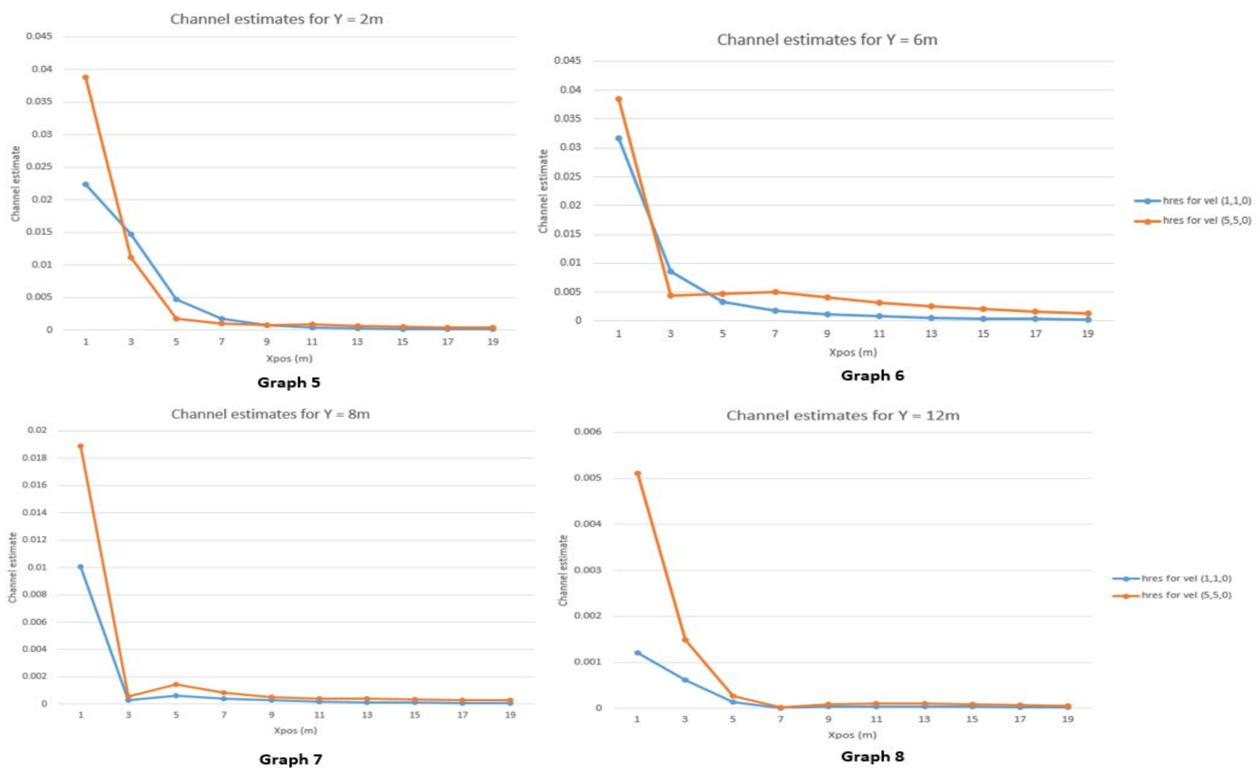

Figure 7: Graphs of channel estimates v/s x position when y position is constant

6 Conclusion

This model provides convenient human detection capabilities using radio waves i.e. the ability to detect objects wirelessly across the room. A mathematical model has been designed to eliminate the flash effect by using the LSE channel estimation technique. The signal propagation environment has been simulated using the Simulink tool. Various test cases are executed to simulate a moving object at varying distances from the transmitter and varying velocities and channel estimates are determined for each.

The paper [1] considers flash effect to be a major obstacle in target detection due to the low signal strength of the moving object in comparison to the static object. This problem has been tackled in this project. In order to simulate this in a real environment, we need to set up two transmitters and one receiver, record the signals to be fed to the model implementing the nulling operation for elimination of flash.

References

[1] Fadel Adib and Dina Katabi, *See Through Walls with Wi-Fi!*, ACM SIGCOMM'13, Hong Kong, Aug. 2013.

[2] https://nl.mathworks.com/help/phased/examples/modeling-a-wideband-monostatic-radar-in-a-multipath-environment.html

[3] https://en.wikipedia.org/wiki/Channel_state_information