Advances in Intelligent Transportation Systems (AITS)
Vol. 1, No. 2, 2012, ISSN 2167-6399

www.worldsciencepublisher.org

Bandwidth Exploration in Radar System for Target Resolution

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Abstract: RADAR (Radio Detection and Ranging) system is used to detect the target with high resolution which requires a higher bandwidth, but due to the fact that bandwidth is a limited resource so it would be difficult to achieve high resolution. A technique i.e. Frequency hopping (FH) which can be used to solve the above problem. In this paper we have implemented a FH technique which can produce a bandwidth of 1GHz in simulation and in hardware. Also distinction of target has been done by using instantaneous bandwidth. We have use MATLAB simulator for the simulation.

Keywords: Frequency Hopping; Bandwidth; Target Resolution; RADAR.

1. Introduction

Radar [1][2] is a sensor system that is widely used to detect, locate and identify targets at great distances in all kinds of weather. The fundamental reason for radar's usefulness is its ability to interpret and extract information from the echo signals, and the fact that wavelengths of radar signals makes them relatively unaffected by atmospheric and weather-induced attenuation. Radar systems generally use longer wavelengths and hence suffer reduced image resolution compared with other systems. [3] Radar is still sensitive to objects whose length scales range from centimeters to meters. This is because radar waves scatter from objects whose size is on the same order as the transmitted signal wavelength or larger, and many objects of interest are in this range. High resolution radar resolves individual target scatterers by employing high bandwidth waveforms. Radars are now equipped with modes which produce high resolution radar imagery for target resolution.

All real systems are bandwidth limited [4].In addition, radar data is often corrupted by noise. Due to the limitation of the bandwidth another method can be employed i.e. Frequency Hopping.

In a single frequency transceiver system, it is often desirable to concentrate the frequency spectrum in as narrow a region of the frequency as possible in order to conserve available bandwidth and to reduce power. On the other hand the basic spread spectrum technique [5] is designed to encode the transmitted signal by spreading its power across as much of the frequency spectrum as possible. The same code is used in the receiver (operating in synchronism with the transmitter) to de-spread the received signal so that the original transmitted signal may be recovered. [6][7] In a FH system the available channel bandwidth is subdivided into a large number of continuous frequency slots. In any transmitting interval, the signal occupies one or more of the available frequency slots.[8]

2. System Model

In our model [9][10] we use a Linear FM signal as base band signal which is given by

$$s(t) = \cos[2\pi(f_c + \frac{Kt^2}{2})] \qquad (1)$$

Where f_c is the carrier frequency and K is the chirp rate. The received pulse is delayed by time $\tau_d = \frac{2R}{c}$ where R is the slant range to a point target and c is the speed of light. The result is

$$r(t) = \cos[2\pi(f_c(t-\tau_d) + \frac{K(t-\tau_d)^2}{2})] \qquad (2)$$

And since the wavelength $\lambda = \frac{c}{f_c}$, then

$$f_c(t-\tau_d) = f_c t - \frac{2R}{\lambda} \qquad (3)$$

We can write

$$r(t) = \cos[2\pi(f_c t - \frac{2R}{\lambda} + \frac{K}{2}(t - \frac{2R}{\lambda})^2)] \qquad (4)$$

To extract the chirp, this signal is base banded by multiplying by the carrier f_c term

$$r_b(t) = \cos(2\pi[f_c t + \phi(t)])\cos(2\pi f_c t) \qquad (5)$$

Where r_b is the base banded return signal and for generality, the chirp signal has been Symbolized by ϕ (t). The base banded result can easily be computed by using the complex exponential equivalent

$$r_b(t) = \frac{1}{2}[e^{-j(w_c t+\phi(t))} + e^{j(w_c t-\phi(t))}].\frac{1}{2}[e^{-jw_c t} + e^{-jw_c t}] \quad (6)$$

$$r_b(t) = \frac{1}{4}[e^{-j(2w_c t+j\phi(t))} + e^{-j\phi(t)} + e^{j\phi(t)} + e^{j(2w_c t+j\phi(t))}] \quad (7)$$

The terms containing $2w_c$ can be removed by low pass filtering so that the result of base banding becomes

$$r_b(t) = \frac{1}{2}[\frac{e^{-j\phi(t)}+e^{j\phi(t)}}{2}] \quad (8)$$

Substituting the results from base banding of Eqn. 9 we can write in terms of the Positive frequencies

$$r(t) = Ae^{-j\frac{4\pi R}{\lambda}} e^{j\pi K(t-\frac{2R}{\lambda})^2}] \quad (9)$$

To compress, we want to convolve the received signal with the conjugated form of the transmitted signal

$$h(t) = e^{j\pi K t^2} \quad (10)$$

To obtain

$$g(t) = e^{-j\frac{4\pi R}{\lambda}} \sin c(\pi K\tau_p(t-\frac{2R}{c})) \quad (11)$$

This can be approximated

$$g(t) = e^{-j\frac{4\pi R}{\lambda}} \delta(t-\frac{2R}{c}) \quad (12)$$

This gives us the phase and range bin of the reflector.

3. Linear Frequency Modulation

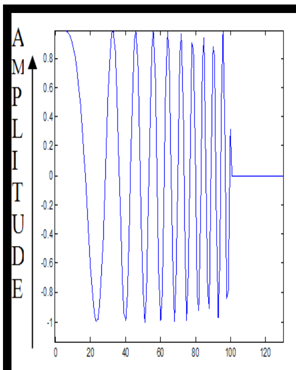
With the exception of using shorter transform limited pulses, which lower the signal to noise ratio for constant peak power waveforms, a common way to add bandwidth is by modulating the frequency of the signal. Of the various forms of modulation techniques, the most common and first to be conceived, is linear frequency modulation (LFM) [11][12]. The main idea behind LFM [13] is to sweep the frequency of the pulse linearly over its duration. The complex envelope of an LFM radar pulse is given by,

$$u(t) = \frac{1}{\sqrt{T}} rect(\frac{t}{T}) e^{i(2\pi f t+\frac{1}{2}\beta t^2)} \quad (13)$$

where T is the pulse duration, f is the carrier frequency, and β is the chirp coefficient defined by,

$$\beta = \frac{2\pi B}{T} \quad (14)$$

where B is the bandwidth and T is the pulse duration.



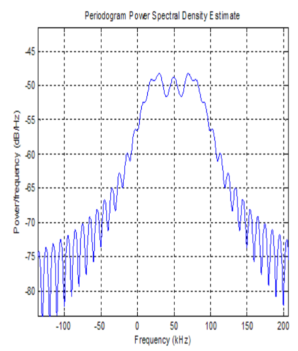


Figure 1. LFM Signal **Figure 2.** LFM spectrum

4. Frequency Hopping

The popular spread spectrum signal is obtained by randomly hopping [14][15] a data modulated carrier from one frequency to the next. In effect, the spectrum of the transmitted signal is spread sequentially rather than instantaneously. This leads to a ordered sequence of frequency hop. Analytically, the transmitted signal is given by

$$a(t) = \sum_{m=1}^{M} \Pi[\frac{t-(m+\frac{1}{2}t_o)}{t_o}]e^{j2\pi f_m t} \quad (15)$$

$$\Pi(\frac{t-a}{b}) = \begin{cases} 1\_for\_a-b/2 \le t \le a+b/2 \\ 0\_otherwise \end{cases} \quad (16)$$

Which describes a sequence of M frequencies $\{f_m\}=f_1.......f_m$. f_M each of chirp duration to corresponding to mt_o < t< $(m+1)t_o$ centered at $t=(m+\frac{1}{2})t_o$. This summation describes a sequence of frequencies used in different to time slots.

A computer interface to a frequency synthesizer can be used to randomly generate frequencies within a predefined bandwidth of B resolved into M frequency bins.

5. Radar Range

The range of the target can be computed by measuring the time Δt traveled by pulse to cover the two-way path between the radar and the target.[16]. As we know that electromagnetic waves travel at the speed of light, then

$$R = \frac{c\Delta t}{2} \quad (17)$$

Where R is in meters and Δt is in seconds. For the two-way time delay the factor of 1/2 is needed.

Range resolution, denoted as ΔR, which gives a close proximity of distinct targets as distinct objects. [17] There are mainly two range at which radar operate i.e. between a minimum range R_{min}, and maximum range R_{max}. [18] The distance between R_{max} and R_{min} is divided into M range bins, each of width ΔR,

$$M = \frac{(R_{MAX} - R_{MIN})}{\Delta R} \quad (18)$$

Targets which are separated by at least can be resolved in range and when the targets which are within the same range cell can be resolved in cross range (i.e. azimuth). Let us consider that two targets that are localized at ranges R_1 and R_2 with time delays t_1 and t_2, respectively. [19] The difference between those two ranges is given by:

$$\Delta R = R_2 - R_1 = \frac{c(t_2 - t_1)}{2} = \frac{c\Delta t}{2} \qquad (19)$$

To find the minimum ΔR, let us consider that two targets are separated by distance ct/4, where t is the pulse width. In this case, when the pulse trailing edge strikes target 2 the leading edge would have traveled backwards a distance ct, and the returned pulse would be composed of returns from both targets (i.e., unresolved return). However, if the two targets are at least ct/2 apart, then as the pulse trailing edge strikes the first target the leading edge will start to return from target 2, and two distinct returned pulses will be produced. [20] Thus, ΔR should be greater or equal to ct/2. And since the radar bandwidth B is equal to 1/t, then

$$\Delta R = \frac{c\tau}{2} = \frac{c}{2B} \qquad (20)$$

Maximum radar range R_{max} is given by

$$R_{MAX} = (P_t G^2 \lambda^2 \sigma / (4\pi)^3 S_{MIN})^{\frac{1}{4}} \qquad (21)$$

5. Matched Filtering

Matched filtering [21][22]is the correlation of a reference signal with an unknown signal, and is equivalent to the convolution of the unknown signal with the conjugated time-reversed reference signal. The matched filtering process requires a reference signal that is ideal, noiseless and centered in the middle of the footprint.

Figure 3 below shows a matched filter example where the transmitted radar signal is s(t), the received radar signal is modeled as a time delayed version of s(t) and the time reversed version of s(t) is the matched filter template, h(t). The convolution of the received signal and the matched filter produces a compressed pulse of energy centered around the time delay of radar reflection. [23]

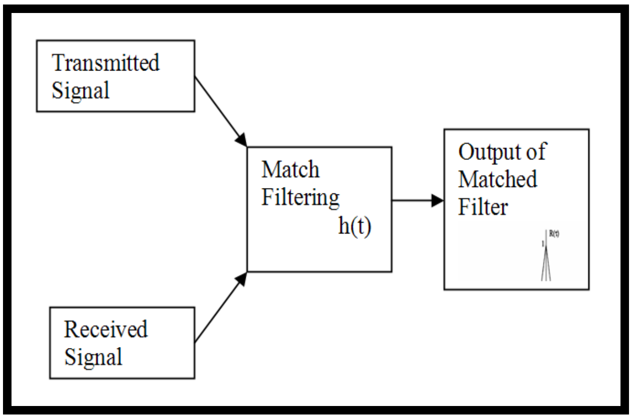


Figure 3. Match Filtering

In order to maximize the signal-to-noise ratio (SNR), the impulse response of the system should be given by [24, 25]

$$h(t) = Ks^*(t_o - t) \qquad (22)$$

Where h(t) is the impulse response, K is a scaling constant s(t) is the signal, and to is a time delay/reference point. To determine the output of a linear system, the input signal is convolved with the impulse response [26] [27] [28]

$$s_o(t) = (s * h)(t) = \int_{-\infty}^{\infty} s(\tau) h^*(\tau - t) d\tau \qquad (23)$$

Above Equation shows the signal output as a function of the input signal and the impulse response. If the assumption is made that there is no time delay for the input signal (i.e. to=0) the output signal can be reduced to the autocorrelation of the signal,

$$s_o(t) = K \int_{-\infty}^{\infty} s(\tau) s^*(\tau - t) d\tau \qquad (24)$$

τ is a dummy variable of integration, and s^* is the conjugate of s

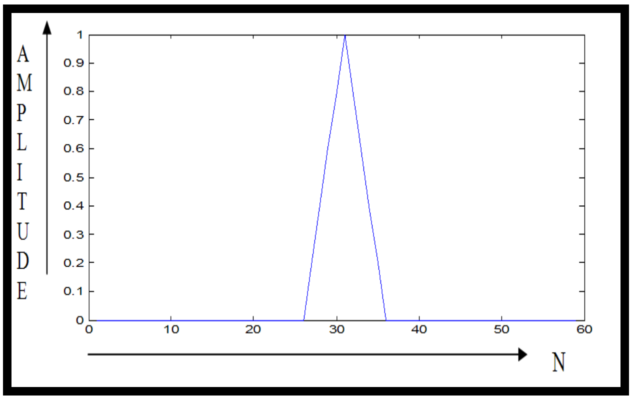


Figure 4. Match Filtered Signal

6. Stepped Frequency Hopped

For achieving of higher bandwidth we use method of FH. Instead of collecting a target scattering information in time domain, a stepped frequency waveform collects the information in the frequency domain. Once the information has been collected in the frequency domain it is transferred into an equivalent representation in the time domain. This transformation is normally achieved using the inverse Fast Fourier transform. Figure 5. illustrates a stepped frequency waveform. A sweep of n pulses is transmitted and received signals are stored for each pulse. The frequency of each pulse differs from the previous pulse by Δf. The effective bandwidth of the sweep is $n\Delta f$. [29] [30]

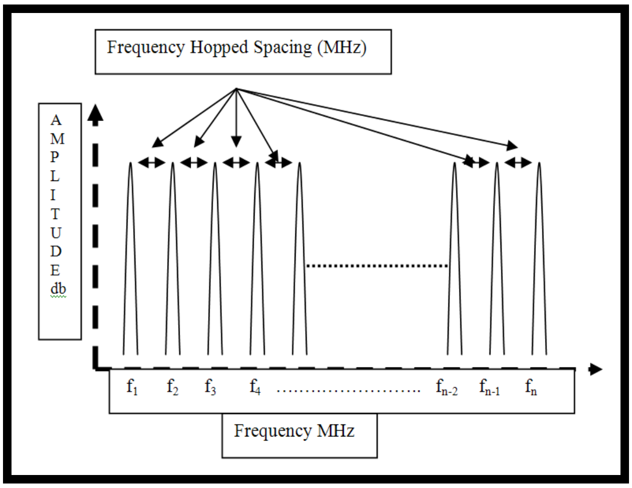


Figure 5. Frequency Hopped Model

7. Simulating Model

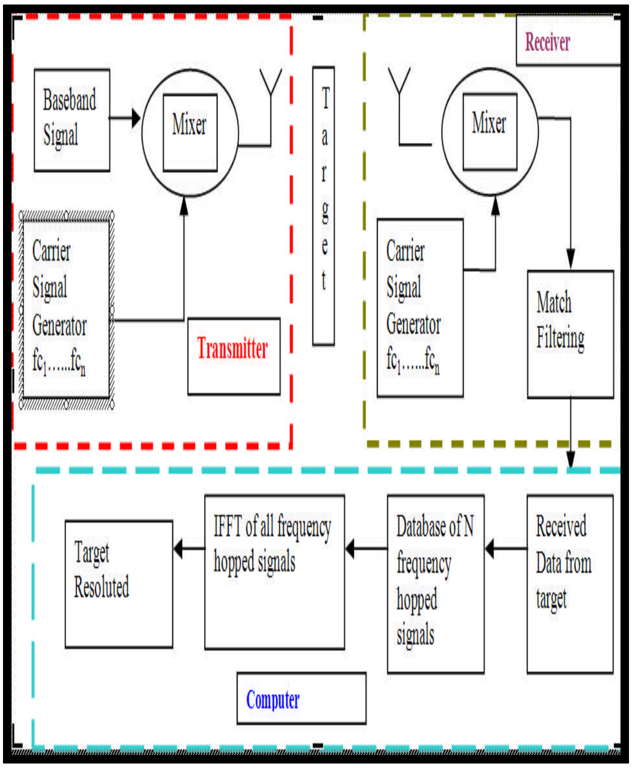


Figure 6. Simulating Model of Frequency Hopping

In the simulating model, the signal received from the target for different frequency hopped signal is stored in a database and the processing of the received signal is done. After processing of the received signal IFFT is done throughout. The signal is plotted and the required target peak is obtained.

7.1 Simulating Results

7.1.1 Instantaneous Bandwidth

Below fig shows the simulation of Variation of Instantaneous bandwidth with the target distance. In this 3 targets are used and with the higher bandwidth it is observed those targets are distinctly observed than that using lower bandwidth.

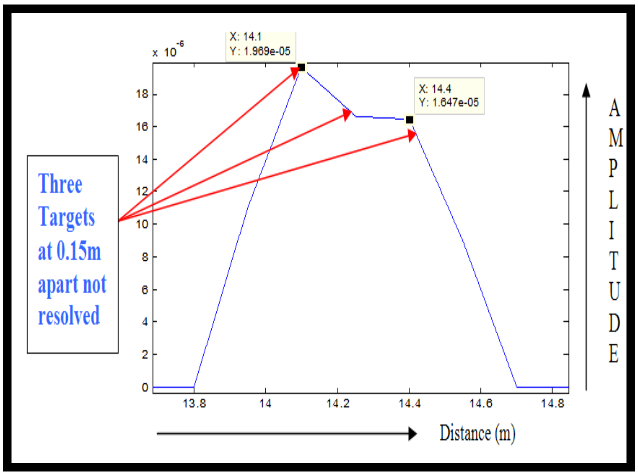


Figure 7. Three Targets not resolved when kept at distance of 0.15m apart with instantaneous Bandwidth of 600 MHz

Fig 7. shows when the separation distances between three target is less than 0.15m with bandwidth of 600 MHz targets are not resolved. Since the entire target lie in the same range cell of 0.25m.

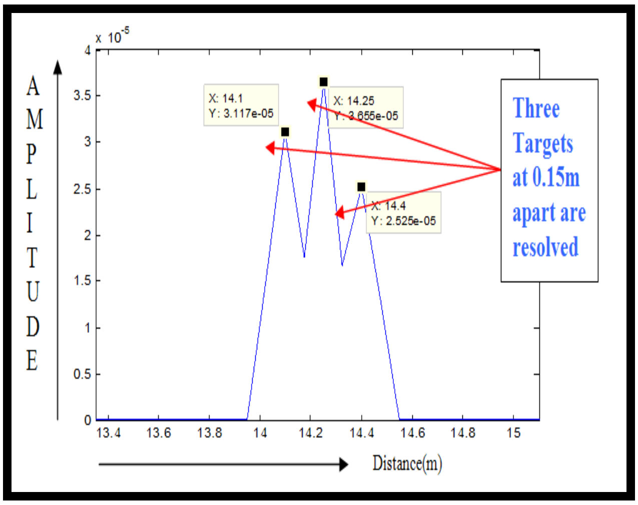


Figure 8. Three Targets resolved when kept at distance of 0.15m apart with instantaneous Bandwidth of 1 GHz 1000MHZ

Fig 8. shows the three targets which is kept at a separation distance of 0.15m is separable using a Bandwidth of 1GHz , resolution for 1GHz Bandwidth is 0.15m.In this we can see that three target are separated by 0.15m respectively.

7.2.2 Frequency Hopping Result Simulation

Below fig shows the simulation of Variation of bandwidth (using FH) with the target distance. In this 3 targets are used and with the higher bandwidth it is observed those targets are distinctly observed than that using lower bandwidth.

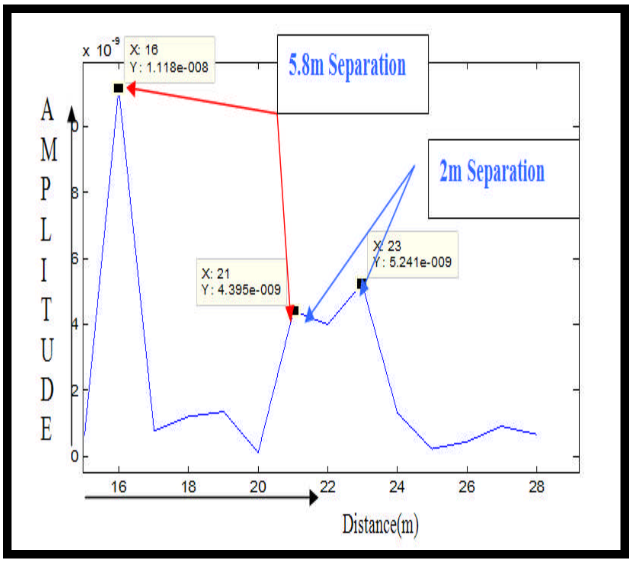


Figure 9. Three Targets bit resolved when kept at distance of 2m & 5.8m apart with system Bandwidth of 150 MHz

The Fig 9. shows three target where 1st & 2nd and 2nd & 3rd targets separation is 5.8m & 2m respectively. Here we find that target 2nd & 3rd is bit resolute with 150MHz bandwidth (30 frequency hopped data) as distance between 2nd & 3rd target is greater than 1m but target 1st & 2nd get distinctly resolute with 150MHz (25 frequency hopped data) as separation distance between 1st & 2nd is much greater than 1m.

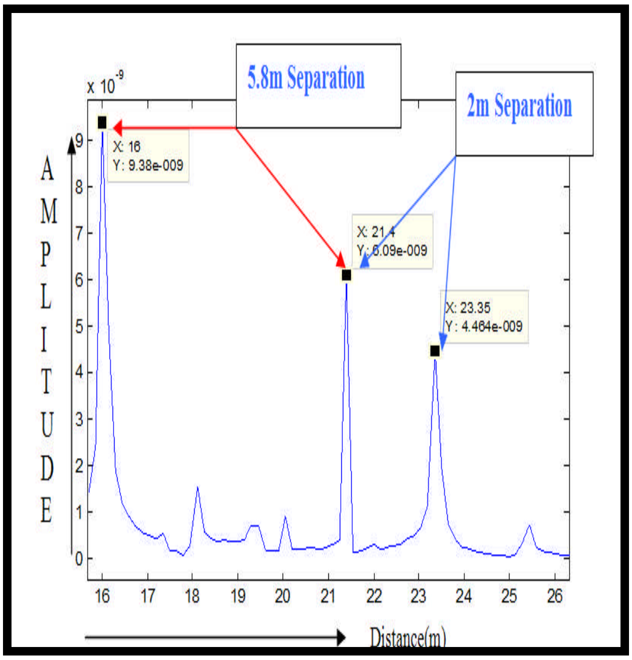


Figure 10. Three Targets distinctly resolved when kept at distance of 2m & 5.8m apart with system Bandwidth of 1GHz

The Fig 10. shows three target where 1st & 2nd and 2nd & 3rd targets separation is 5.8m & 2m respectively. Here we find that target 2nd & 3rd is distinctly resolute with 1GHz bandwidth (200 frequency hopped data) as distance between 1st, 2nd & 3rd target is greater than 0.15m.

8. Hardware Setup

In the transmitting side the base-band signal is generated using an Arbitrary waveform generator, from the VSG is used as an local oscillator signal generator and using a mixer the signal is converted from IF To RF signal and thus transmitted using horn antenna.

In the receiving section a low noise amplifier with high gain figure is placed at the front of the detector to improve the overall system noise figure. The first band-pass filter serves as the RF channel selector. The incoming RF signal is converted into an IF signal through heterodyning. The conversion of RF to IF is essential to reduce the amount of digital data needed to capture the input signal. The noise allowed into the system is limited by a IF band-pass filter. The noise level is reduces to a minimum by selecting the BPF bandwidth equal to that of the chirp bandwidth.

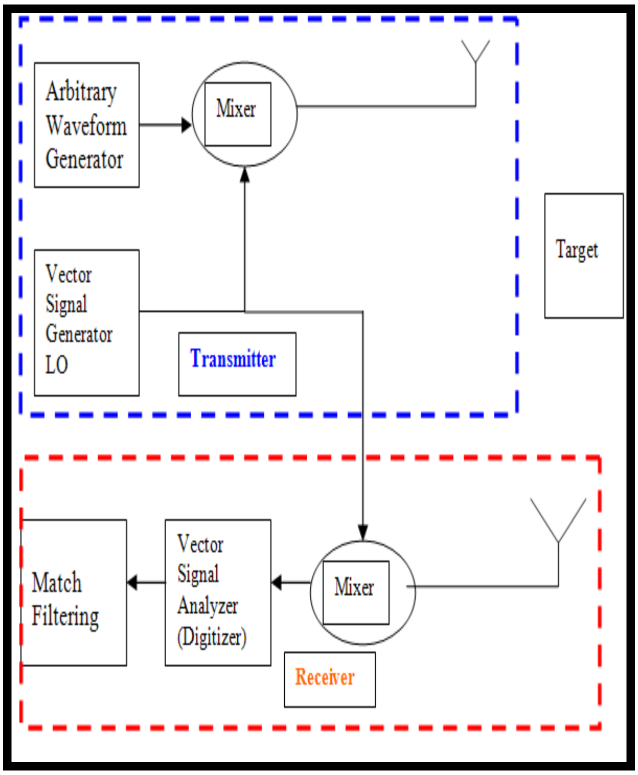


Figure 11. Hardware Model of Frequency Hopping

8.1. Practical Results

8.1.1 Instantaneous Bandwidth Variation

When the separation gap between two targets is less than 1.5m with bandwidth of 100 MHz targets are not resolved. When the bandwidth is further increased to 1GHz the targets get resolved.

But due to the limitation of the available limited bandwidth it becomes difficult to resolute targets which are closely spaced. Limitation of above leads to a new method called FH.

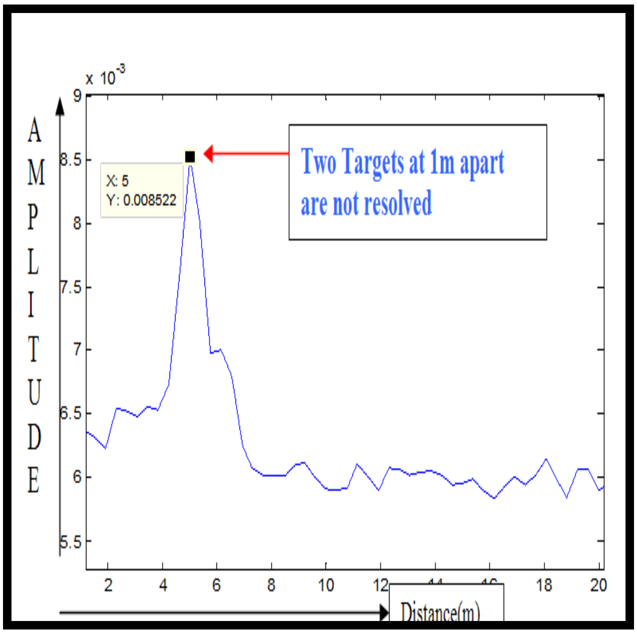


Figure 12. Two Targets not resolved when kept at distance 1m apart with instantaneous Bandwidth of 100 MHz

Fig 12. shows when the separation gap between two target is less than 1.5m with bandwidth of 100 MHz targets are not resolved. Since both the target lie in the same range cell of 1.5m.

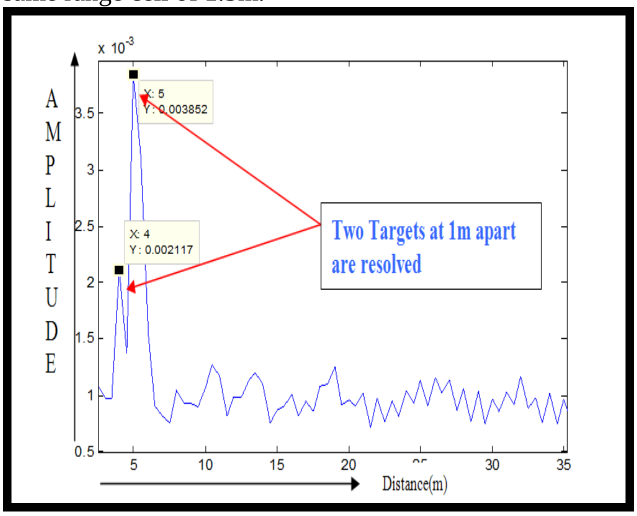


Figure 13. Three Targets resolved when kept at distance greater than 1m apart with instantaneous Bandwidth of 300 MHz

Fig 13. shows the two targets which is kept at a distance of less than 0.75m is separable using a Bandwidth of 300MHz ,Since resolution for 200MHz Bandwidth is 0.75m.In this we can see that two target are separated by 0.75m.

8.1.2 Frequency Hopping Practical Result

Below graphs shows the practical implementation of FH. As due to the limitation of available limited bandwidth FH method can be used to overcome the above. In the below figure shows two target with separation of 0.6m is resolved using FH of 5MHz and 200 data files for 1GHz bandwidth.

In below fig shows three target where 1st & 2nd & 3rd targets separation is 0.6m & 2m. Here we find that target is not resolute with 500MHz (100 data) but when 1GHz bandwidth is used target are distinctly resolute. There is disadvantage of using FH because it takes longer time to gain higher Bandwidth since many N data to be collected and process the data.

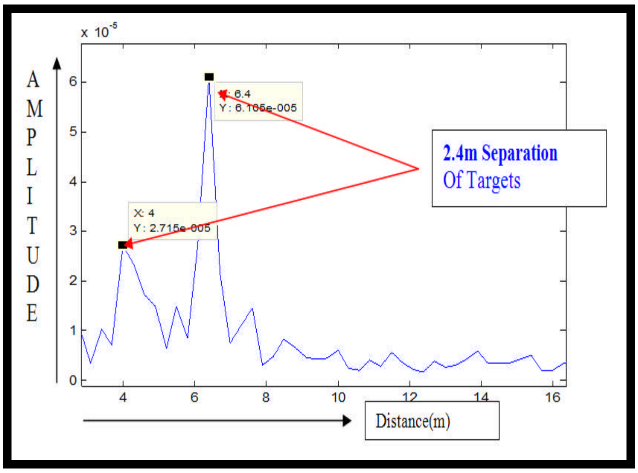


Figure 14. Three Targets not resolved when kept at distance of 0.6m & 2m respectively apart with system Bandwidth of 500 MHz

The Fig 14. shows three target where 1st & 2nd and 2nd & 3rd targets separation is 0.6m & 2m respectively. Here we find that target 1st & 2nd is not resolute with 500MHz bandwidth (100 frequency hopped data) as distance between 1st & 2nd target is less than 0.6m but target 2nd & 3rd get resolute with 500MHz (100 frequency hopped data) as separation distance between 2nd & 3rd is greater than 0.6m.

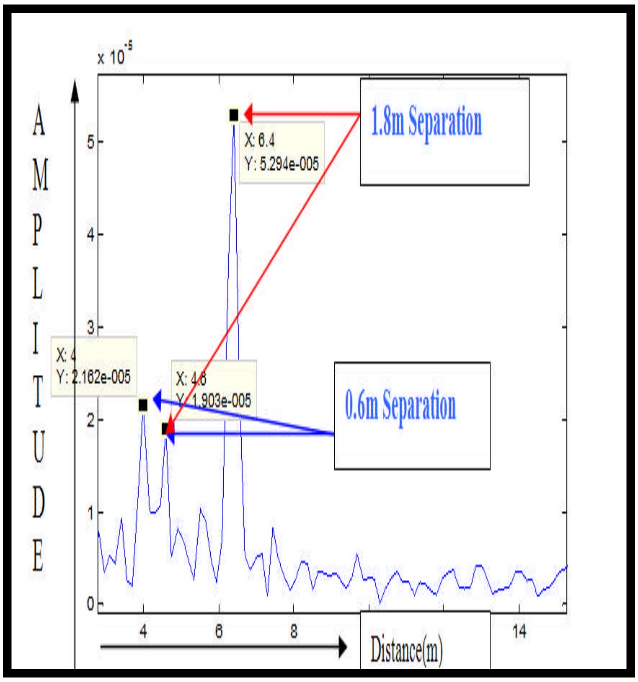


Figure 15. Three Targets resolved when kept at distance of 0.6m & 2m respectively apart with system Bandwidth of 1 GHz

The Fig 15. shows three target where 1st & 2nd and 2nd & 3rd targets separation is 0.6m & 2m respectively. Here we find that target 1st & 2nd is distinctly resolute with 1GHz bandwidth (200 frequency hopped data) as distance between 1st, 2nd & 3rd target is greater than 0.15m.

9. Conclusion

In this paper we have shown that due to limited availability of instantaneous bandwidth it is not possible to achieve the resolution to detect closely spaced target. Therefore it is necessary to adopt FH technique to achieve a bandwidth greater than 1GHz and therefore multiple targets could be resolute distinctly. This paper deals with the exploitation of bandwidth to design a high resolution radar system. From the simulated and experimented results, one can conclude that FH is an efficient and effective tool to overcome the limitation of the availability of instantaneous bandwidth by achieving high range resolution.

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