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Modelling and Performance Analysis of Millimetre Wave Radar for Connected Vehicles

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Abstract
Radar is an essential aspect of Advanced Driver Assistance Systems (ADAS), which acts as an intermediate stage in the development of self-driving vehicles. Fast signal processing with the accurate result is critical for radar, which is used in the connected vehicles to compute distances of objects near it. Various Environmental and physical parameter analysis is necessary for an efficient implementation of the radar signal processing algorithm, which is the main objective of this paper. This paper model millimeter radar and analysis performance of signal processing algorithm with the Environmental and physical parameter.
Keywords. *Radar, FMCW, MUSIC algorithm.*

1.INTRODUCTION

Automotive radars are used in vehicles to estimate the range and speed of the nearby vehicles, which provides a base for ADAS (Advanced Driver Assistance Systems). Most of the automotive radars currently in use are in the range of 77-81 GHz frequency bandwidth. This bandwidth is following the regulations set by the government; however, this bandwidth also provides better range resolution and velocity resolution, which makes it advantageous in detecting closely spaced bodies. Continuous-wave radar (CW radar) is used for the connected vehicle application, where a stable frequency of a continuous wave is transmitted and then received from any reflecting objects using which objects are detected using the Doppler effect. Unmodulated and modulated CW radars are used. Among that, the modulated one like Frequency-Modulated Continuous-Wave radar (FMCW) provides better performance.

FMCW sweeps the frequency band continuously, so at any time, the beat frequency between the transmitted and received signals will be the same. This beat frequency is related to time delay, which can be used to calculate the range as follows.

$$f_b = \frac{2v_r f_o}{c} \pm \frac{f_m 4R}{T_r C} \quad (1)$$

$$V_r = c(f_{b+} + f_{b-})/4f_o \quad (2)$$

$$R = -T_r c(f_{b+} + f_{b-})/8f_m \quad (3)$$

Where fb+ is the beat frequency up the ramp and fb- is down the ramp, Vr is the relative speed of the target. R is the range. Tr denotes the total duration of the up and down ramps. Carrier frequency, speed of light, and modulation frequency are denoted by fo, c, fm, respectively.

A two-step FFT is carried out over many Pulse-Repetition Intervals(PRIs) using a four-step detection process, consisting of range processing, digital beamforming doppler processing, and detection[1] can be used. Doppler radar measurement carried out on the speed of the moving vehicles is another standard method; it can be used to measure the speed of the moving target accurately. Data processing of radar analog IF signal is done through a Fourier transform of the baseband signal. Doppler frequency

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is extracted through frequency spectrum analysis to achieve this. To improve the real-time performance of the system, the FIFO module of ping-pong to store the sampling data interleaving[2]. These can be implemented on an FPGA using fully parallel and pipelined architecture to support high-speed algorithm processing[1]. FMCW radar is prone to ambiguities related to the distinction of range and velocity. An alternative method to resolve these ambiguities is by use of chirp-sequence-based FMCW radar[3]. The computational complexity is higher; hence, the processing time is more top too as a consequence of the requirement to generate a large number of chirps. Another alternative is to use an FDA-based radar system that can resolve targets closely spaced by using range-depended beampatterns [4]. The performance of a radar system can be done by studying how different factors affect the mean-square error(MSE) of the system. The MSE analysis for FFT units provided in[5] considers all the quantization errors providing a robust answer for MSE.
The range resolution also plays an essential role in the processing of the radar signals. The range resolution can be made adaptive as proposed in [6] by using a rough resolution for long-range(>200m) an excellent resolution for a medium-range target (~100m) and high resolution for very close targets, where there is a high collision probability. The MUSIC algorithm is found the most effective for short-range and high-resolution range estimation.

2.LITERATURE SUYVAY

Few works are processed for the millimeter radar signal processing, which is discussed in this section.
Blind-spot detection and warning system are proposed [7] for daytime and nighttime. It involves millimeter-wave radar, signal processing for radar target detection, blind spot area calibration methods. Line frequency modulated continuous wave millimeter-wave radar was used to detect moving targets with Around 98% accuracy of detection.Enhancing vehicle-to-vehicle communications by millimeter radars is analyzed [8]. The characteristics of the communicating-radar propagation channel are theoretically and experimentally investigated.

An IEEE 802.11ad-based radar for long-range radar (LRR) applications at the 60 GHz band is proposed [9]. It exploits the preamble of a single-carrier physical layer frame with Golay complementary sequences. Joint waveform design for automotive radar target detection and mmWave vehicular communication system is presented. Receiver algorithms for target detection, range, and velocity estimation, even for multi-target, are analyzed. In a single-target case, a gigabits-per-second data rate is achieved with cm-level range accuracy and cm/s-level velocity accuracy. The target vehicle is detected with a high probability (above 99.99%) at a low false alarm rate of 10^{-6} for an equivalent isotropically radiated power of 40 dBm up to a vehicle separation distance of about 200 m.
An overview of the millimeter-wave technology for automotive radar applications is presented with measurement results of the fully integrated radar front ends [10].
An investigation of the influence of target geometry and position on the accuracy of its range estimation using a W-band FMCW radar is done [11]. The impact of different bandwidths on accuracy is also analyzed. Besides that, a method to optimize the size of a target for the target accuracy, antenna field regions-based target placements also carried out.
A walking person target detection, which is not possible under conventional FMCW radar is addressed [12]. The Hough transform is employed for capturing the energies of most Doppler bins to enhance the detection performance. The method is based on the ordered statistical-constant false alarm rate but tailored to Doppler-spread targets.
The Multifrequency Bifocusing (MFBF) imaging algorithm is proposed with the W-band using FMCW radar to enhancing detection to avoid collisions and pedestrian detection in vehicles[13]. The work explored the feasibility of using the Intermediate Frequency (IF) signal provided by homodyne FMCW radar with 77 GHz as input to the algorithm.
The cumulative distributive error function value proves that it is possible to use intermediate frequency for signal processing algorithm to detect the object .in the same direction our work also utilizes the IF frequency for detection target, but we have analyzed the impact of the physical and environmental factor on the performance of the algorithm which is not addressed in the above work.

The photonic radar is proposed under adverse weather perceptions [14]. It is intended as an alternative for the microwave radar. It is reported that the microwave radar's performance is reduced d by atmospheric fluctuations that minimize the range detection distance. They have simulated the linear frequency-modulated photonic radar using Matlab and Optisys. As our work, they also analyzed the performance of the optical radar in the presence of weak-to-strong atmospheric fluctuations. But their work of optical radar system is costlier and has many practical issues for the deployment.

3. METHODOLOGY

The radar is designed with a carrier frequency of 77GHz, which is mostly used by the automotive radar. The generating of the up-sweep linear FMCW waveform generation uses the MATLAB phased array toolbox.

One of the radars' requirements is that the Sweep time of the signal must be around 5 to 6 times of the round trip time. In this simulation, We take the maximum range as 200m and the maximum speed of the car as 230 km/h. Another critical issue in the radar simulation is the modeling of the target. For this, we used mathematical modeling, which response by taking the car distance and velocity information. The transmitted signal hitting on the target and receiving the reflected wave on the receiver is made using this mathematical model. A free space channel model is employed in this work.

Antenna, transmitter, and receiver are created with a specific antenna aperture and gain value. An isotropic antenna model is applied for this simulation. When the receiver obtains the signal, it is dechirped by mixing the transmitted and received signal, and the beat frequency examined. The dechirped signal will consist of the frequency of the signal that is linked to the range of the target. Doppler frequency can't be easily differentiated from the beat frequency, to overcome this issue instead of single sweep in a pulse, we use multiple sweeps. The received signals stored in the buffer till to reach the specified number of sweeps, which is set 64 sweeps in this simulation. after getting 64 sweeps data, the processing of FFT takes place, and Doppler shift and beat frequency are calculated. From this result, the range and velocity of the target vehicle can be estimated.

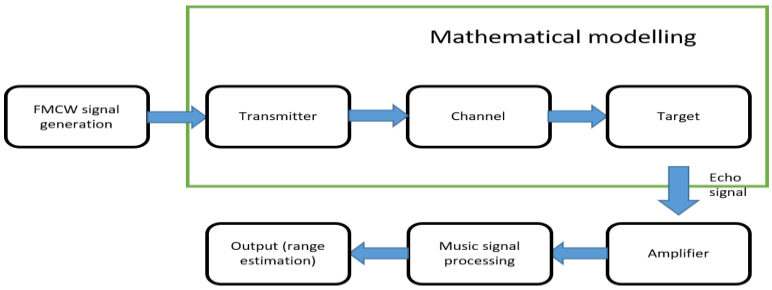

Figure 1. Block Diagram of radar system

Figure 1 shows the entire process of the radar system. The FMCW wave is first generated, transmitted, and received through a free space channel. The receiver first amplifies the signal, and then signal processing is carried out on the wave, which includes the Music algorithm and FFT, to estimate the range.

2.1 FMCW Generation and Tone Extraction

FMCW radar signal can be used for the estimation of both range and velocity. The range is the distance between the target vehicle and the vehicle which has the radar. The signal is generated from the MATLAB environment. The transmission of the signal, target refection, and reception of the reflected signal is carried out with the mathematical model, which is simulated in the MATLAB. After receiving the reflected wave from the target, the first task is to find the tones from the beat of the signal, which is carried out FFT algorithms.

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2.2 ROOT MUSIC ALGORITHM

Music (Multiple Signal Characterization) is a promising algorithm for the range and velocity estimation for automotive radars. It is a super-resolution algorithm compared to basic FFT and is less sensitive to white noise. The ensemble-averaged correlation matrix is the basis for this algorithm. The eigen analysis on the correlation matrix is carried out to obtain the MUSIC spectrum. The MUSIC algorithm will make use of this spectrum to search for beat frequency.
From [2], we can see that the MUSIC algorithm can be used in multiple objects, DOA tracking scenarios. The computational time is based upon the eigenvalue decomposition complexity, which is generally O(N^3) [3].

3. EXPERIMENTAL RESULTS

The mathematical model for target refection and signal propagation is simulated in MATLAB with the FMCW radar signal generation. The parameters with initial values given in table 1 have been set for the simulation of the system in MATLAB. The Mean Square Error (MSE) value computed between the actual range and estimated range is used a performance measure in this work.

Table 1 Simulation Parameters

Parameter	Value
Carrier frequency	77GHz
Maximum range of target	200m
Range resolution	1m
Maximum speed of target	230km/h
Sweep time	7.33µs
Sweep bandwidth	150 MHz
Maximum beat frequency	27.30MHz
Sample rate	150MHz

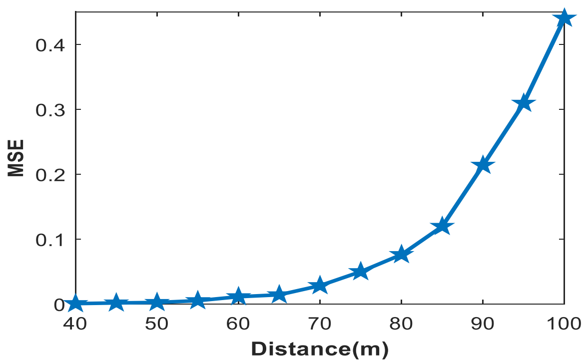


Figure 2 Distance vs MSE

The mean square error performance is analyzed with the increased distance between the radar and the target. This analysis is carried out to show the robustness of the system with respect to the weak signal, which is happening when the distance between the target and radar increases.Figure 2 shows the variation of Mean Square Error (MSE) with increasing distance, which shows that the error in the short and medium-range is lower than in the more extended range.

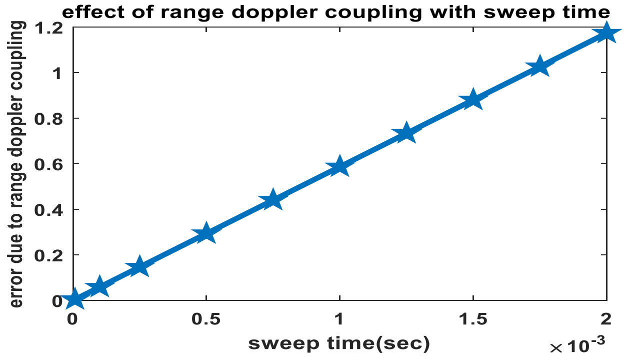


Figure 3Error due to range doppler coupling vs Sweep Time

The impact of the sweep time on the performance of the system also analyzed. Figure 3 shows error in range computation concerning the variation of sweep time. The error due to the range-Doppler coupling is seen to be varying linearly with a sweep time.

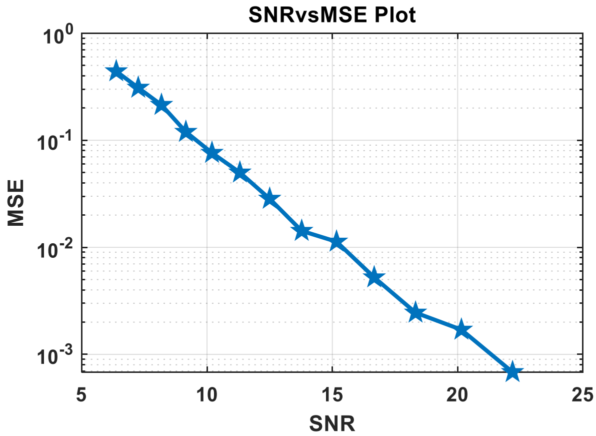
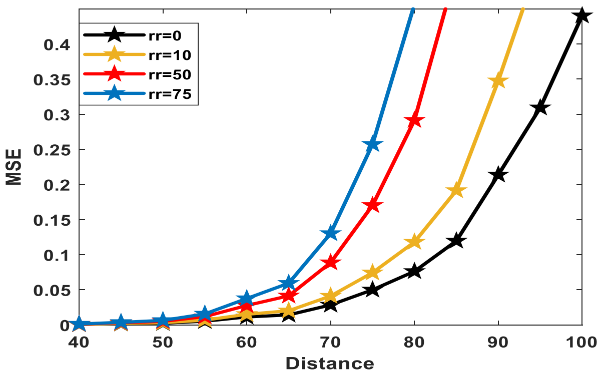


Figure 4 SNR vs MSE

The signal to noise ration plays a vital role in the performance of the radar, which is also explored in this study. Figure 4 shows the relationship between the SNR and MSE of the Radar Wave signal range



estimation. the figure shows that the error value getting decreases with the increased SNR .

Figure 5Effect of Rain Rate

The effect of the physical parameter like temperature and rainfall on the performance is analyzed.

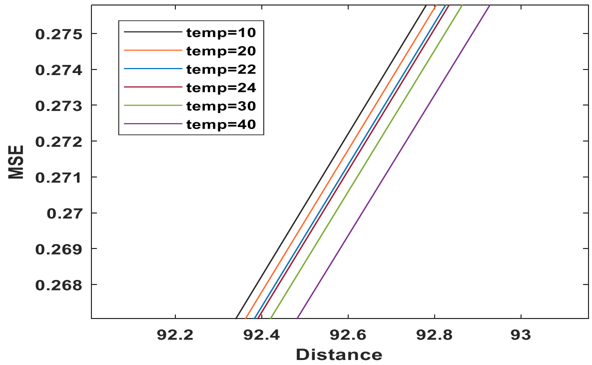


Figure 6 Effect of Temperature

Figure 5 and figure 6show the impact of rain and temperature on the channel on the performance of radar in terms of the MSE value . It is observed that the rainfall rate has a quite significant impact on the MSE, which increases with increased rain rate. On the other, the temperature variation in the range of 10-45 Celsius does not have a considerable effect on performance in terms of the MSE.

Table 2 gives the comparison of the maximum range that can be detectable for the given SNR in comparison with the literature [14] .from the table 2 we can observe that for the heavy rain case fro the SNR =20dB the proposed mechanism can detect up to 1690meter where the literature method able to do 1600meter.

Table 2 Performance comparison

Parameter	Proposed	Literature [14]
Detection range in heavy rain at SNR =20	1690meters	600meters (non coherent) 1600meters(coherent)

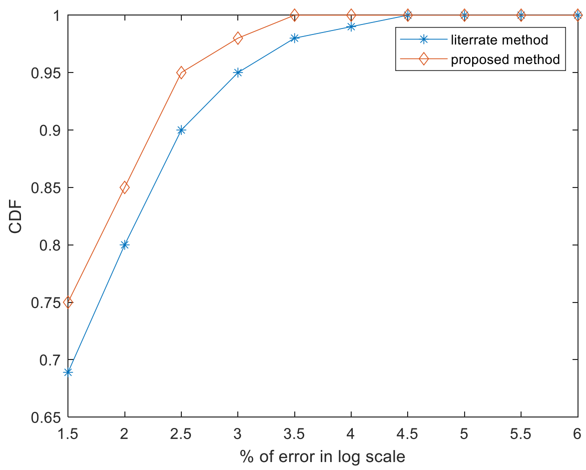


Figure 7.CDF of error comparison

Figure 7 compares the cumulative distributive function of the error value between the proposed mechanism and the literature method [13]. This figure proves that for 95% of the time, the error in detection will be 2.5% only, whereas, for the literature method, it will be 3%.

4. CONCLUSIONS

In this paper, an FMCW radar system is simulated, and signal processing is done using the MUSIC algorithm in MATLAB. Various parameters were chosen to be studied, and the system's performance is studied by varying these parameters. It is observed that MSE increases with an increase in the distance between the target and the radar. The system's performance is studied when the channel is affected by natural factors such as rainfall and different temperature conditions. The performance of the system, in terms of MSE, is not seen to have a notable change in temperature but does have a significant change with a varying rainfall rate. The sweep time also plays a vital role as the range-Doppler coupling effect is observed to be varying linearly. The future work involves the optimization of the signal processing algorithm and further implements the signal processing algorithm on an FPGA board.

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