

VERIFICATION COVERAGE ANALYSIS AND IMPROVEMENT OF ASIC PIPELINE BLOCKS FOR AUTOMOTIVE SAFETY APPLICATIONS

Submitted in Partial fulfillment of the Requirements for the Award of
Bachelor of Engineering Degree in Electronics and Communication

by

KATUKOORI LAHARI (38130106)



DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with Grade "A" by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600 119

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of **Katukoori Lahari** (38130106) who carried out the project entitled "Verification Coverage Analysis and Improvement of ASIC pipeline blocks for automotive safety applications" under our supervision from December 2021 to April 2022.

Mrs. L. MAGTHELIN THERASE., M.E, Assistant Professor

Internal Guide

Dr. T. RAVI M.E., Ph.D.

Head of Department

Submitted for Viva Voce Examination held on_____

Internal Examiner

External Examiner

10 Feb 2022

To whomsoever it may concern

This is to certify Katukoori Lahari (38130106) doing B.E - Electronics and Communication Engineering at Sathyabama Institute of Science and Technology, Chennai has completed her internship for a period of three months effective from Dec 06, 2021 to Feb 10, 2022. She was reporting to Pushpanjali Gupta on a project titled "Verification Coverage Analysis and improvement of ASIC pipeline blocks for automotive safety applications" at MulticoreWare India (P) Ltd.,

We wish her all success in her future endeavors.

Yours sincerely



Shashikanth Jayaraman
Vice President - Human Resources

Registered Office: 9, 3rd Street, Elango Nagar, Virugambakkam, Chennai - 600 092

DECLARATION

I Katukoori Lahari (38130106) hereby declare that the Project Report entitled Verification Coverage Analysis and Improvement of ASIC pipeline blocks for automotive safety applications done by me under the guidance of Mrs. L. Magthelin Therase., ME, Assistant Professor, and Mrs. Pushpanjali Gupta at Uhnder (MulticoreWare pvt ltd) is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Electronics and Communication Engineering.

DATE:

PLACE:

SIGNATURE OF THE CANDIDATE

KATUKOORI LAHARI

(38130106)

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ABSTRACT

Radar can perceive beyond human visual capabilities. It can sense range and velocity, and it can do so through rain, snow and fog, conditions under which human eyes, cameras and lidar are far more limited. However, traditional radar is based on analog technology and has systemic weaknesses regarding image resolution and signal interference.

Hence, in Uhnder Digital Radar has been designed and implemented with digital modulation techniques that increase image resolution along with which the accuracy of Radar data has also been improved in this project.

In this project, Digital Radar has been analyzed with respect to verification and coverage using Universal Verification Methodology. The Digital Radar has been verified in such a manner that it enhances the features in perspective of safety to be used in automotive applications.

UHNDER INDIA



Overview:

Uhnder is revolutionizing automotive and automated mobility with the world's first digital imaging radar-on-chip. Uhnder is an automotive radar-on-chip company founded in 2015 by Manju Hegde. Uhnder's fully software-defined digital radar chip and sensor modules perceive objects that cameras, lidar, traditional analog radar, and the human eye can easily miss when safety matters most.

Uhnder's technology delivers the industry's first digital radar solution with better accuracy and the power to sense moving or standing objects, large or small, at both short and long distances in all-weather and lighting conditions, all while mitigating mutual interference between other radars.

Uhnder's digital radar can clearly identify a pedestrian crossing the road, a child entering the street from beside a parked car, or a bicyclist next to a guard rail, at levels of accuracy that legacy analog radar systems cannot achieve.

Digital radar provides 16 times better resolution, 24 times more power on target, and 30 times better contrast than today's analog offerings, improving detection capabilities for better road safety for all users – drivers, passengers, cyclists, and pedestrians. As more radars are fitted onto vehicles and other mobility solutions, interference among adjacent radar becomes problematic. Uhnder radar, based on Digital Code Modulation, mitigates this problem.

Uhnder Collaboration with MulticoreWare:

MulticoreWare has announced its partnership with Uhnder for the development of the later automotive radar technology. This collaboration is going to include Uhnder utilizing MulticoreWare operating offshore development centers (ODC). In addition to this, MulticoreWare will be working coordinated with Uhnder as well as its customers for radar related development and support. Uhnder is currently working on its first digital automotive Radar-on-Chip (RoC). It operates at 76-81 GHz, using Digital Code Modulation (DCM). It offers 4D High Contrast Resolution (HCR), with the help of which, this system can deliver a range and accuracy which other systems in the market currently do not offer.

MulticoreWare offers development, porting and optimization of computation intensive algorithms running on Multicore CPUs (Central Processing Unit), DSPs (Digital Signal Processing) and GPUs (Graphical Processing Unit).

The ecosystem at MulticoreWare offers support to all the Uhnder's activities. Apart from the ODC, Multicore Ware has also collaborated in several other important product developments.

Uhnder Collaboration with Spartan Radar:

Spartan, a leading sensor software company, and Uhnder, Inc., the leader in 4D digital imaging radar technologies for automotive and logistics mobility applications, are partnering to transform safety systems for ADAS (advanced driver assistance systems) and the AV (autonomous vehicle) industry. The partnership combines Uhnder's digital radar technology based on digital code modulation (DCM) and Spartan's exclusive sensor software to create next-generation perception solutions with new safety capabilities such as sharp contrast resolution (HCR) that helps differentiate closely spaced objects, critical for the safe commercialization of automated mobility.

Increasing safety is essential for passenger vehicles and commercial vehicles. According to government statistics, traffic fatalities between January and September

2021 increased 12% as compared to the same period in 2020. This represents the highest percentage increase over a nine-month period since the Department of Transportation began recording fatal crash data in 1975.

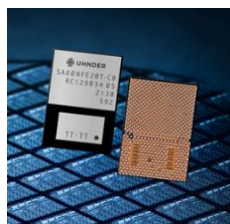
The combined Uhnder/Spartan solution can detect dangerous objects in the road, such as an abandoned tire or construction debris, more than 200 meters away and trigger the AEB (automatic emergency braking) in less than the blink of an eye. This advanced visibility and fast response is necessary for heavy trucks moving at highway speeds that need, at a minimum, the length of a football field to come to a full stop.

Uhnder future launches:

In April 2022, Uhnder will release its S80 radar-on-chip to mass production. The device will be the first 4D digital imaging radar solution and will have completed stringent automotive requirements.

Automotive Electronics Council (AEC) Q104 qualification, ISO 26262 Automotive Safety Integrity Level (ASIL-B) rating, Production Part Approval Process (PPAP) with its first Tier 1 automotive customer, Magna- With these milestones completed, the automotive industry will be another step closer to improving road safety for all.

Advanced driver-assistance systems (ADAS) and autonomous technologies are providing cars with sensing capabilities that exceed human abilities, such as identifying unseen objects and triggering automatic emergency braking (AEB) potentially faster than a human driver can. These capabilities depend on perception systems made up of cameras, radar and lidar that capture and track important environmental data around the vehicle.



Radar can perceive beyond human visual capabilities. It can sense range and velocity, and it can do so through rain, snow and fog, conditions under which human eyes, cameras and lidar are far more limited. However, traditional radar is based on analog technology and has systemic weaknesses regarding image resolution and signal interference. Uhnder believes its digital radar, which resolves these shortcomings, is the answer for next-generation ADAS and an autonomous future. Together with a leading tier 1 automotive technology company, Uhnder has developed the world's first commercially available automotive digital radar scheduled to debut on roadways in 2022. Uhnder's digital radar can clearly identify a motorcycle between two trucks, a pedestrian crossing the road, a child entering the street from beside a parked car, or a bicyclist next to a guard rail as shown in the below figure, at levels of accuracy that legacy analog radar systems cannot achieve.

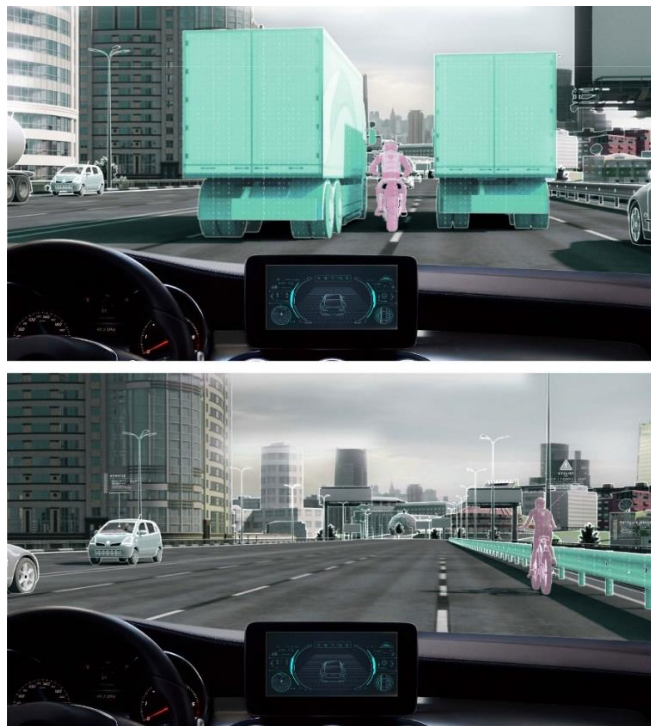


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List of Abbreviations

1. RADAR – Radio Detection and Ranging
2. RoC – Radar on Chip
3. SoC – System on Chip
4. RF – Radio Frequency
5. IF – Intermediate Frequency
6. CMOS – Complementary Metal Oxide Semiconductor
7. PCB – Printed Circuit Board
8. ADAS – Advanced Driver Assistance Systems
9. OEM – Original Equipment Manufacturer
10. MIMO – Multiple Input– Multiple Output
11. SIMO – Single Input- Multiple Output
12. ADC – Analog to Digital Convertor
13. DAC – Digital to Analog Convertor
14. FMCW – Frequency Modulated Continuous Wave
15. DCM – Digital Code Modulation
16. PRN – Pseudo Random Noise
17. TXU – Transmit PRN Translation Unit
18. IMC - Integrated Metrics Center
19. RTL – Register – Transfer Level
20. HDL – Hardware Description Language
21. DUT – Design Under Test
22. UVM – Universal Verification Methodology

CHAPTER 1

1.1. INTRODUCTION

1.1.1. Concept of RADAR

RADAR stands for Radio Detection and ranging machine. It is an electromagnetic device used to stumble on the place and distance of an item from the factor in which the RADAR is placed. It really works with the aid of radiating strength into the area and tracking the echo or meditated sign from the items. It operates in the Ultra High Frequency and microwave variety.

A radar is an electromagnetic sensor, used to be aware, track, locate, and pick out unique items which are at sure distances. The operating of radar is, it transmits electromagnetic strength within the course of goals to look at the echoes and returns from them. right here the goals are nothing however ships, plane, astronomical bodies, automotive automobiles, spacecraft, rain, birds, bugs, and many others. Instead of noticing the target's area and speed, it additionally obtains their form and size every so often.

The main goal of radar as compared with infrared and optical sensing gadgets is to find out far flung goals below tough weather conditions & determines their distance, range, through precision. Radar has its personal transmitter that is known as a supply of illumination for putting objectives. normally, it really works in the microwave place of the electromagnetic spectrum that is calculated in hertz whilst frequencies increase from four hundred MHz to forty GHz. The essential additives which are used within the radar

Radar undergoes quick development during the years 1930-the 40's to reach the requirements of the navy. Its miles are nonetheless universally used through the armed forces, wherever several technological advances have created. Simultaneously, radar is likewise applied in civilian packages specially in controlling air visitors, remark of climate, navigation of deliver, surroundings, sensing from far

off regions, statement of planetary, measurement of pace in commercial packages, space surveillance, law enforcement, and so forth.

1.1.2. Working Principle

Most radar sets employ pulse radar wherein the transmitter sends out short intense bursts or pulses of energy of about one microsecond duration with a long interval of several hundred micro-seconds between the successive pulses. When sufficient time has elapsed to permit the reception of the echoes from the most distant desired objects, the transmitter sends another short pulse and the cycle repeats.

The transmitting antenna also functions as the receiving antenna. The reflected signal after amplification of several million times is used to deflect the electron beam in a cathode ray tube. The echo picked up by the receiver strengthens or deflects the flow of electrons in the tube, causing a point of light to appear on the screen which remains visible by phosphorescent after-glow until fresh echoes are noticed the next revolution of the scanning antenna.

The angular bearing to the target is determined by measuring the direction from which the reflected energy is received. It is expressed in two components; azimuth angle measured in the horizontal plane and elevation angle measured in a vertical plane. The indicator tube is arranged to directly display the target co-ordinates and distance.

The electromagnetic signal is produced by the transmitter unit and is radiated in space by the radar antenna. While the receiver performs extraction of information from the signal received by the radar antenna.

Whenever an electromagnetic wave is transmitted by the system then it reflects or re-radiates some of its parts on experiencing a variation in the conductivity of the medium. This variation in conductivity arises due to the presence of an object either stationary or moving. Thereby producing an echo.

The radar system receives the echo with the help of an antenna to analyze it and have the location of the object.

The range to an object is determined by the measurement of the time taken by the radiated signal to reach the object and come back to the radar. And the location of the stationary object in the space is determined from the angle pointed by the antenna when the echo received is of maximum amplitude.

For a moving object because of the Doppler effect, there exists a shift in the frequency of the re-radiated signal. And the frequency shift shows proportionality with the radial velocity of the object.

1.1.3. Factors affecting Radar Performance

1. Transmitter power and antenna size

The maximum range of a radar system depends in large part on the average power of its transmitter and the physical size of its antenna. (Power-aperture) There are practical limits to each. Some radar systems have an average power of one megawatt. Phased-array radars about 30 meters in diameter are common, some are much larger. There are specialized radars with fixed antennas, such as some HF over-the-horizon radars and the U.S. Space Surveillance System (SPASUR), that extend more than one mile.

2. Receiver noise

The sensitivity of a radar receiver is determined by the unavoidable noise that appears at its input. At microwave radar frequencies, the noise that limits detectability is usually generated by the receiver itself i.e., by the random motion of electrons at the input of the receiver rather than by external noise that enters the receiver via the antenna. A radar engineer often employs a transistor

amplifier as the first stage of the receiver even though lower noise can be obtained with more sophisticated devices.

The receiver is designed to enhance the desired signals and to reduce the noise and other undesired signals that interfere with detection. A designer attempts to maximize the detectability of weak signals by using “matched filter,” which is a filter that maximizes the signal-to-noise ratio at the receiver output. The matched filter has a precise mathematical formulation that depends on the shape of the input signal and the character of the receiver noise. A suitable approximation to the matched filter for the ordinary pulse radar, however, is one whose bandwidth in hertz is the reciprocal of the pulse width in seconds.

2. Target size

The size of a target as seen by radar is not always related to the physical size of the object. The measure of the target size as observed by radar is called the radar cross section and is given in units of area (square meters). It is possible for two targets with the same physical cross-sectional area to differ in radar size, or radar cross section. For example, a flat plate 1 square meter in area will produce a radar cross section of about 1,000 square meters at a frequency of 3 GHz when viewed perpendicular to the surface. A cone-sphere (an object resembling an ice-cream cone) when viewed in the direction of the cone rather than the sphere could have a radar cross section of about 0.001 square meter even though its projected area is also 1 square meter. In theory, the radar cross section has little to do with the size of the cone or the cone angle. Thus, the flat plate and the cone-sphere can have radar cross sections that differ by a million to one even though their physical projected areas are the same.

The sphere is an unusual target in that its radar cross section is the same as its physical cross-sectional area (when its circumference is large compared with the radar wavelength). A sphere with a projected area of 1 square meter has a radar cross section of 1 square meter.

Commercial aircraft might have radar cross sections from about 10 to 100 square meters, except when viewed broadside, where the cross sections are much larger. Most air-traffic-control radars are required to detect aircraft with a radar cross section as low as 2 square meters, since some small general-aviation aircraft can be of this value. For comparison, the radar cross section of a man has been measured at microwave frequencies to be about 1 square meter. A bird can have a cross section of 0.01 to 0.001 square meters. Although this is a small value, a bird can be readily detected at ranges of several tens of kilometers by long-range radar. In general, many birds can be detected by radar, so specific measures must usually be taken to ensure that their echoes do not interfere with the detection of desired targets.

The radar cross section of an aircraft and that of most other targets of practical interest fluctuate rapidly as the aspect of the target changes with respect to the radar unit. It would not be unusual for a slight change in aspect to cause the radar cross section to change by a factor of 10 to 1,000.

3.Clutter

Echoes from land, sea, rain, snow, hail, birds, insects, auroras, and meteors are of interest to those who observe and study the environment, but they are a nuisance to those who want to detect aircraft, ships, missiles, or other similar targets. Clutter echoes can seriously limit the capability of a radar system; thus, a significant part of radar design is devoted to minimizing the effects of clutter without reducing the echoes from desired targets. The Doppler frequency shift is the usual means by which moving targets are distinguished from the clutter of stationary objects. Detection of targets in rain is less of a problem at the lower frequencies since the radar echo from rain decreases rapidly with decreasing frequency and the average cross section of aircraft is independent of frequency in the microwave region. Because raindrops are spherical (symmetrical) and aircraft are asymmetrical, the use of circular polarization can enhance the detection of aircraft in rain. With circular polarization, the electric field rotates at

the radar frequency. Because of this, the electromagnetic energy reflected by the rain and the aircraft will be affected differently, which thereby makes it easier to distinguish between the two.

4. Atmospheric Effects

Rain and other forms of precipitation can cause echo signals that mask the desired target echoes. There are other atmospheric phenomena that can affect radar performance as well. The decrease in density of the Earth's atmosphere with increasing altitude causes radar waves to bend as they propagate through the atmosphere. This usually increases the detection range at low angles to a slight extent. The atmosphere can form "ducts" that trap and guide radar energy around the curvature of the Earth and allow detection at ranges beyond the normal horizon. Ducting over water is more likely to occur in tropical climates than in colder regions. Ducts can sometimes extend the range of an airborne radar, but on other occasions they may cause the radar energy to be diverted and not illuminate regions below the ducts. This results in the formation of what are called radar holes in the coverage. Since it is not predictable or reliable, ducting can in some instances be more of a nuisance than a help.

Loss of radar energy due to atmospheric absorption, when propagation is through the clear atmosphere or rain, is small for most systems operating at microwave frequencies.

5. Interference

Signals from nearby radars and other transmitters can be strong enough to enter a radar receiver and produce spurious responses. Well-trained operators are not often deceived by interference, though they may find it a nuisance. Interference is not as easily ignored by automatic detection and tracking systems, however, and so some methods are usually needed to recognize and remove interference pulses before they enter the automatic detector and tracker of a radar.

6. Electronic countermeasures

The purpose of hostile electronic countermeasures (ECM) is to degrade the effectiveness of military radar deliberately. ECM can consist of:

- (1) noise jamming that enters the receiver via the antenna and increases the noise level at the input of the receiver
- (2) false target generation, or repeater jamming, by which hostile jammers introduce additional signals into the radar receiver to confuse the receiver into thinking that they are real target echoes
- (3) chaff, which is an artificial cloud consisting of many tiny metallic reflecting strips that create strong echoes over a large area to mask the presence of real target echoes or to create confusion, and
- (4) decoys, which are small, inexpensive air vehicles or other objects designed to appear to the radar as if they are real targets. Military radars are also subject to direct attack by conventional weapons or by antiradiation missiles (ARMs) that use radar transmissions to find the target and home in on it. A measure of the effectiveness of military radar is the large sums of money spent on electronic warfare measures, ARMs, and low-cross-section (stealth) aircraft.

Military radar engineers have developed several ways of countering hostile ECM and maintaining the ability of a radar system to perform its mission. It might be noted that a military radar system can often accomplish its mission satisfactorily even though its performance of ECM is not what it would be if such measures were absent.

1.1.4. Types of Radar System

There exist different radar systems.

1. Monostatic Radar System

A monostatic radar system uses a single antenna for transmission as well as reception purposes.

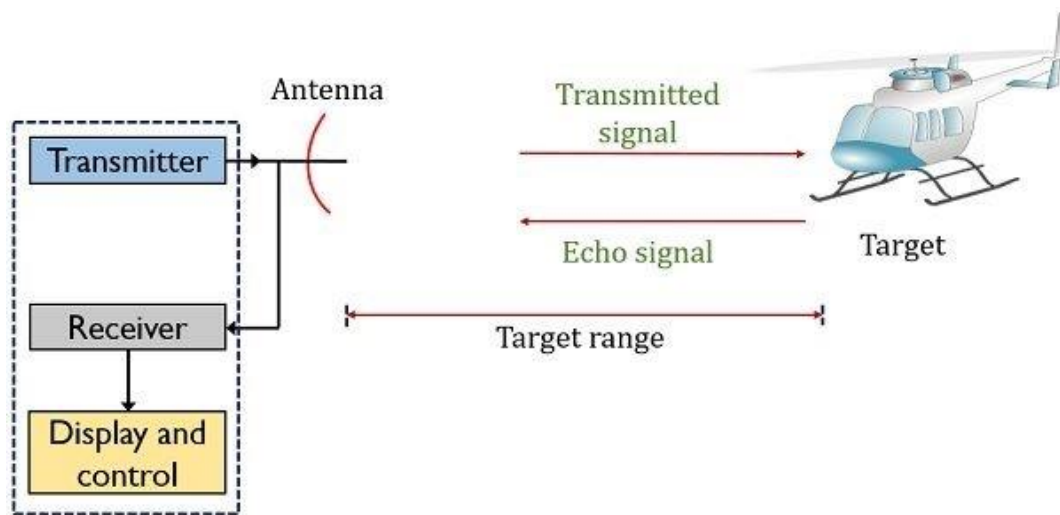


Fig 1.1. Monostatic Radar System

2. Bi- static Radar System

A bi-static radar system utilizes independent antenna for transmission and reception of the signal

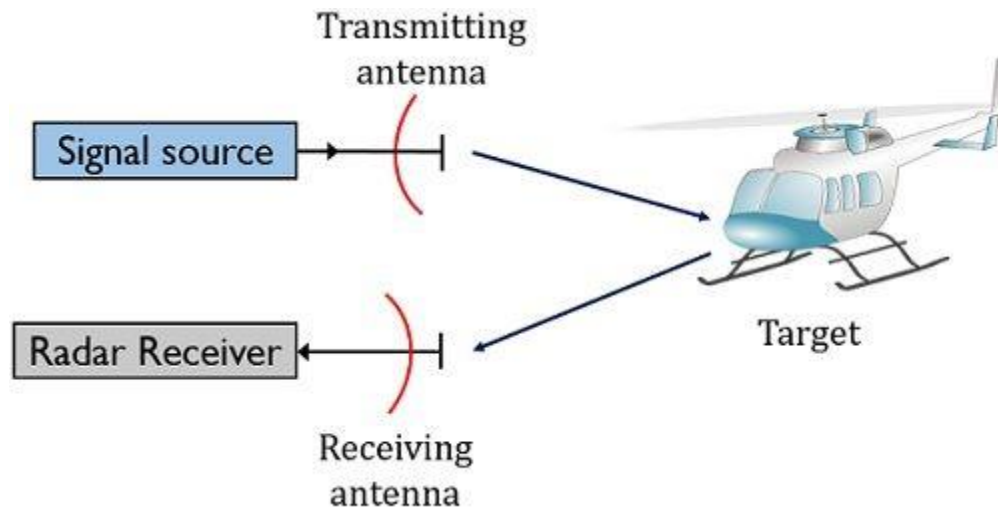


Fig 1.2. Bistatic Radar System

3. Doppler Radar

It is a special type of radar that uses the Doppler Effect to generate data velocity regarding a target at a particular distance. This can be obtained by transmitting electromagnetic signals in the direction of an object so that it analyzes how the action of the object has affected the returned signal's frequency.

This change will give very precise measurements for the radial component of an object's velocity within relation toward the radar. The applications of these radars involve different industries like meteorology, aviation, healthcare, etc.

4. Monopulse Radar

This kind of radar system compares the obtained signal using a particular radar pulse next to it by contrasting the signal as observed in numerous directions otherwise polarizations. The most frequent type of monopulse radar is the conical scanning radar. This kind of radar evaluates the return from two ways to measure the position of the object directly.

5. Passive Radar

This kind of radar is designed to notice as well as follow the targets through processing indications from illumination within the surroundings. These sources comprise communication signals as well as commercial broadcasts. The categorization of this radar can be done in the same category as bistatic radar.

6. Instrumentation Radar

These radars are designed for testing aircraft, missiles, rockets, etc. They give different information including space, position, and time both in the analysis of post-processing & real-time.

7. Weather Radars

These are used to detect the direction and weather by using radio signals through circular or horizontal polarization. The frequency choice of weather radar depends on a compromise of performance among attenuation as well as precipitation reflection as an outcome of atmospheric water steam. Some types of radars are designed to employ Doppler shifts to calculate the wind speed as well as dual polarization to recognize the types of rainfall.

8. Mapping Radar

These radars are used to examine a large geographical area for the applications of remote sensing & geography. As a result of synthetic aperture radar, these are restricted to quite stationary targets. There are some radar systems used to detect humans after walls that are more different as compared with the ones found within construction materials.

9. Navigational Radars

These are the same to search radars but, they available with small wavelengths that are capable of replicating from the ground & from stones. These are commonly used on commercial ships as well as long-distance airplanes. There

are different navigational radars like marine radars which are placed commonly on ships to avoid a collision as well as navigational purposes.

10. Pulsed Radar

Pulsed Radar sends high power and high-frequency pulses towards the target object. It then waits for the echo signal from the object before another pulse is sent. The range and resolution of the Radar depend on the pulse repetition frequency. It uses the Doppler shift method.

The principle of RADAR detecting moving objects using the Doppler shift works on the fact that echo signals from stationary objects are in the same phase and hence get canceled while echo signals from moving objects will have some changes in phase. These radars are classified into two types

Pulse-Doppler

It transmits high pulse repetition frequency to avoid Doppler ambiguities. The transmitted signal and the received echo signal are mixed in a detector to get the Doppler shift and the difference signal is filtered using a Doppler filter where the unwanted noise signals are rejected.

Moving Target Indicator

It transmits low pulse repetition frequency to avoid range ambiguities. In an MTI RADAR system, the received echo signals from the object are directed towards the mixer, where they are mixed with the signal from a stable local oscillator (STALO) to produce the IF signal.

This IF signal is amplified and then given to the phase detector where its phase is compared with the phase of the signal from the Coherent Oscillator (COHO) and the difference signal is produced. The Coherent signal has the same phase as the transmitter signal. The coherent signal and the STALO signal are mixed and given to the power amplifier which is switched on and off using the pulse modulator.

11. Continuous Wave

The continuous wave RADAR does not measure the range of the target but the rate of change of range by measuring the Doppler shift of the return signal. In a CW RADAR electromagnetic radiation is emitted instead of pulses. It is used for speed measurement.

The RF signal and the IF signal are mixed in the mixer stage to generate the local oscillator frequency. The RF signal is then transmitted signal and the received signal by the RADAR antenna consists of the RF frequency plus the Doppler shift frequency. The received signal is mixed with the local oscillator frequency in the second mixture stage to generate the IF frequency signal.

This signal is amplified and given to the third mixture stage where it is mixed with the IF signal to get the signal with Doppler frequency. This Doppler frequency or Doppler shift gives the rate of change of range of the target and thus the velocity of the target is measured.

1.1.5. Structure of Radar System

The whole radar system is composed of the following devices.

- Antenna Unit (Antenna+ Motor): Antenna that radiates waves, Motor that rotates the Antenna
- Transceiver Unit: Unit generating waves and processing the signal
- Processing Unit: Unit processing signals from radar components and external devices
- Display Unit: Display of Radar screen and connected sensor data
- Control Unit: Radar controls

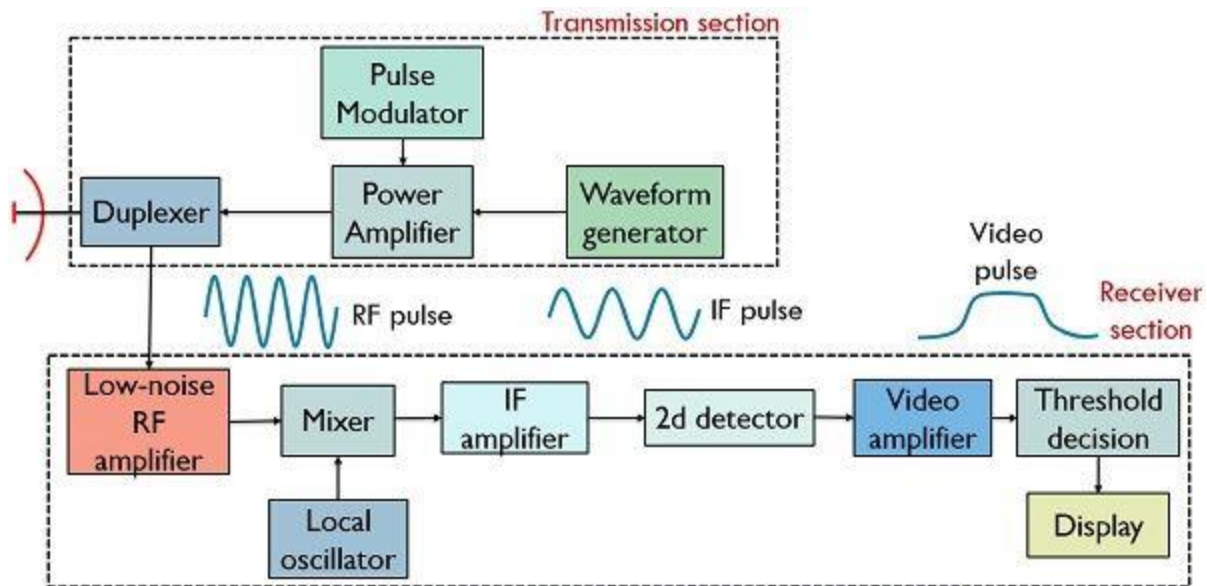


Fig 1.3. Basic block diagram of Radar system

1.1.6. Components of Radar

The transmitter section is composed of the following units:

1. *Waveform Generator:* The waveform generator (usually a magnetron) generates a radar signal at low power which is to be transmitted into space.

2. *Transmitter:* The signal generated by the waveform generator is fed to the transmitter. The transmitter section can be a magnetron, travelling wave tube or a transistor amplifier.

In the case of pulse radar, magnetrons are widely used as transmitters but whenever there exists a need for high average power then amplifiers are used.

3. *Pulse modulator:* A pulse modulator is used to build synchronization between the waveform generator and transmitter. The pulse modulator causes the turning on and off the power amplifier according to the input pulses generated by the waveform generator.

4. *Duplexer*: A duplexer is used to form isolation between transmitter and receiver section. A duplexer allows the use of a single antenna for both transmission and reception purposes. However, both the sections operate at different power levels, therefore, a duplexer is used to isolate the two sections. Thus, the signal from the transmitter is provided to the antenna through the duplexer. As the duplexer short circuit, the input of the receiver section.

Also, the re-radiated signal received by the common antenna is fed to the receiver section using duplexer.

The following components are present inside the receiver section:

5. *Low noise RF amplifier*: The receiver must be superheterodyne. The unit acts as the input stage for the receiver section. The RF amplifier generates an RF pulse which is proportional to the echo of the transmitted signal.

6. *Mixer and Local Oscillator*: The RF pulse received from the low noise RF amplifier is converted into an IF pulse. Usually, the RF amplifier acts at the input stage of the receiver section but sometimes the mixer acts at the input stage by eliminating the RF amplifier. However, this leads to a less sensitive receiving section due to the high noise figure of the mixer.

7. *IF amplifier*: The IF pulse generated by the mixer circuit is amplified by the IF amplifier. It acts as a matched filter and increases the SNR of the received signal. Also, it enhances the echo detecting ability of the receiver section by reducing the effects of unwanted signals.

The receiver's bandwidth is associated with the bandwidth of the IF stage.

8. *Demodulator*: This unit is nothing but a crystal diode that performs demodulation of the signal by separating the transmitted signal from the carrier.

9. *Video Amplifier*: This unit amplifies the received signal to a level that can be displayed on the screen.

10. *Threshold decision*: This unit makes the decision about the existence of the target in space. It has a threshold limit set which is compared with the magnitude of the received signal.

If the threshold value is surpassed by the output signal, then this shows that presence of the target. Otherwise, it is assumed that only the noise component is present in space.

11. *Display*: The display unit shows the final output of the receiver section. Plan position indication (PPI) is typically used as the radar display unit. It presents the range and location of the object by mapping it in polar coordinates. PPI is implemented with CRT.

The output signal modulates the electron beam of the cathode ray tube to permit the electron beam to sweep from the center in the outward direction of the tube. And this sweep shows rotation in synchronization with the pointing of the antenna.

1.1.7. Performance measures of Radar

Radar systems provide direct measurements of the range, the radial velocity, and the direction of the object being measured. The direction can be in terms of the azimuth angle, elevation angle, or both. Radars can be designed to achieve different performance objectives among any of these measurement dimensions. The parameters to optimize, as shown in Table 1.1, include coverage, accuracy, resolution, and scan time.

Table 1.1. Common Performance Parameters of Radar

Parameters	Description
Coverage	Minimum and maximum value of the specified dimension within which an object can be detected
Accuracy	Error in estimating the specific measurement of the object
Resolution	Smallest offset of two objects that can be separately detected (resolved) in the specified dimension
Scan Time	The time needed to generate an image (location, velocity) of the objects in the environment

1.1.8. Applications of Radar

Military Applications

- In air defense, it is used for target detection, target recognition, and weapon control (directing the weapon to the tracked targets).
- In a missile system to guide the weapon.
- Identifying enemy locations on the map.

Air Traffic Control

- To control air traffic near airports. The Air Surveillance RADAR is used to detect and display the aircraft's position in the airport terminals.
- To guide the aircraft to land in harsh weather using Precision Approach RADAR.
- To scan the airport surface for aircraft and ground vehicle positions

Remote Sensing

- It can be used for observing whether or observing planetary positions
- Used for Monitoring Sea ice to ensure a smooth route for ships.

Ground Traffic Control

- It can also be used by traffic police to determine the speed of the vehicle
- Controlling the movement of vehicles by giving warnings about the presence of other vehicles or any other obstacles behind them.

Space

- To guide the space vehicle for a safe landing on the moon
- To observe the planetary systems
- To detect and track satellites
- To monitor the meteors

1.2. RADAR ON CHIP

1.2.1. *Concept of Radar on Chip*

Traditionally, the use of radars was limited to military purposes. However, with advances in the fabrication of semiconductor technologies (CMOS, BiCMOS), it has become possible to manufacture radar-on-chip.

Nowadays, radar-on-chip is abundantly present in the consumer market. The radar signals can both “see” objects behind walls kilometers away and create images of the inside of the human body.

The first generation of radar-on-chip included a low-noise amplifier (LNA), a double-balanced resistive mixer, a voltage-controlled oscillator (VCO), and an active balun buffer amplifier. In the figure below, the chipset uses a quadrature receiver architecture.

A radar system typically consists of a radar transceiver, antenna, and circuitry to process/extract information from radar signals. The radar transceiver includes the signal synthesizer, power amplifier (PA), low-noise amplifier (LNA), mixer, and baseband circuitry.

A modern radar has all the key circuitry integrated onto a single chip or PCB. Due to the small feature size, various consumer applications can be deployed on a single chip using sophisticated embedded signal processing and control circuits.

Compared to camera-based technologies, radar systems can easily obtain a target's range, speed, and angle without being affected by weather extremes. This has altogether enabled the mass use of radars in autonomous cars, healthcare monitoring devices, and IoT applications.

Radar chips have found solid ground in the automotive industry and are available in a host of consumer devices at low costs. Various auto-manufacturers are

employing radars in their own ADAS technology. The ultimate benefit here is public safety on roads.

The boom of radar chips in biomedical devices, by contrast, remains distant. Certain organizations have found beneficial use of radar sensors to monitor building occupancy during COVID-19. The radar systems in these smart buildings can measure room occupancy for social distancing and even monitor the heartbeats and temperature of individuals for infection.

Considering the outbreak of COVID-19 where the world did not have the infrastructure to effectively control the spread of disease, technologies such as radar systems may yield immense benefits in biomedical devices in the future.

1.2.2. Radar Chips in Automotive Applications

The capabilities of the radar system are continuously expanded by phased array, digital beamforming, and multiple-input multiple-output (MIMO) techniques.

a. Radar and Beamforming

For example, the Tesla Model 3 uses one radar (Continental ARS4-A) and has digital beamforming capability, scanning for short- and far-range distances. This is used for forwarding collision warning, emergency brake assist, collision mitigation, or adaptive cruise control (ACC).

Two companies, RFISee and Vayyar, offer promising products that use phased array and MIMO techniques, respectively, in tandem with radar systems.

b. Radar and Phased-Array Technology

RFISee has released the industry's first phased-array 4D imaging radar-on-a-chip. The high-resolution, low-cost radar sensor can generate a real-time 3D location and velocity map of a car's surrounding objects.

Because phased array is a costly technology, its adoption in the automotive industry has been a concern, which is why radar use was initially limited to advanced military systems such as F-35 fighter jets. With RFISee's radar-on-chip solution, the receivers ensure a much-improved radar image, a better signal-to-noise ratio, and a detection range of obstacles such as cars and pedestrians that Vayyar says is six times broader compared to existing radars.

Prototypes of RFISee's radar are under evaluation by top automotive OEMs (Original Equipment Manufacturers) and Tier-1s, the company says.

c. Radar and MIMO Technology

Another startup from Israel, Vayyar, has recently developed automotive-grade radar chips based on MIMO technology. The chip covers imaging and radar bands from 3 GHz-81 GHz with 72 transmitters and 72 receivers. Enhanced by an integrated, high-performance DSP (Digital Signal Processors) with large internal memory, Vayyar's sensor executes complex imaging algorithms without any need for an external CPU.

Vayyar also produces radar-based imaging solutions for applications such as smart homes and robotics. In comparison, the phased array-based radar system from RFISee is targeted specifically at automotive applications.

1.2.3. Challenges in Radar Signal Processing

Signal processing for radar systems is a vast and fascinating discipline that covers numerous techniques and touches on many application areas. Military and security applications have always been the main drivers of radar development. However, more recently, radar has become a key technology for civilian applications including air, maritime, and ground traffic control, in addition to urban sensing and indoor monitoring. Radar not only affects our present time worldwide, but also shapes our future.

With the advent of coherent pulse radar, velocity measurements have become possible by exploiting the Doppler effect. In contrast to camera images and many other sensors, radar can provide quantitative data on range and speed. Today specialized radars measure range as well as azimuth and elevation angles, enabling target detection and localization. Through Synthetic Aperture Radar (SAR), Inverse SAR (ISAR), or Interferometric SAR (InSAR), a 3D image of an object can be obtained. In recent years, passive radar systems have been gaining considerable and increasing attention for both target detection and ground imaging. Applications of radar techniques span from ocean current monitoring to Earth digital elevation mapping, from automotive to biomedicine, from industrial monitoring in IoT scenarios to through the wall imaging, from the detection of vital signs and discerning the activities of daily living to UAV monitoring. There are also many key radar applications in agriculture, forestry, soil moisture monitoring, geology, geomorphology and hydrology, oceanography, land use, land cover mapping, and archeology.

Radar has a long history, and judging from the growing applications of active sensing, it has an illustrious and bright future. Future radar systems should effectively support a massive variety of applications with novel hardware solutions and innovative signal processing techniques. Several grand challenges inherent to future radar systems are outlined in the following.

1. Sparse Sensing and Sparse Array Design in Radar

Sparse sensing, or compressed sensing, has been successful in solving the problems of target detection, estimation, and classification in radar applications. It combines nonlinear reconstruction algorithms and pseudorandom linear measurements to solve underdetermined linear equations that define many inverse problems. In their study, Ender describes the application of CS techniques for pulse compression, radar imaging, and air space surveillance with array antennas. Over the last decade, CS and sparse signal reconstruction methods have been widely applied to tackle traditional radar problems, e.g., high-

resolution target Direction of Arrival (DOA) estimation, as well as emerging problems, e.g., spectrum sensing in cognitive radar. More recently, sparse sensing was combined with machine learning to solve the problem of missing or limited data. Optimization methods with sparse regularizations and constraints have been applied in both phased arrays and multiple-input multiple-output (MIMO) radar platforms for efficient radar aperture design under a given number of frontend receivers. Sparse array design with different objective and cost functions have benefited from recent advances in convex optimizations and semidefinite quadratic programming. Global optimization methods, like particle swarms or simulated annealing, have been applied for array design with flexible antenna placements. Another successful design approach is the cyclic algorithm (CA) that optimally matches the designed and desired beam patterns via iteration. A sparse antenna array has several advantages in the high-resolution thinned configurations for phased array and multi-input multi-output (MIMO) radar. Whereas structured sparse arrays, such as Nested and Co-prime arrays, seek to increase the virtual aperture and available degrees of freedom to handle more sources than physical antennas, unstructured sparse array design can be time-varying and is guided by the knowledge learned from the sensed environment. Research into the design of sparse arrays is an area that is indeed catalyzing a growing interest in the scientific community.

2. Radar Waveform Optimization

Waveform optimization for system parameter estimation is an emerging topic in signal processing with applications in radar and remote sensing. In radar, waveform adaptation in different domains, such as spatial, temporal, spectral, and polarization, is aimed at dynamically improving system performance. Such capability is enabled by new computing architectures, high-speed and off-the-shelf processors, arbitrary digital waveform generators, solid-state transmitters, and modern phased arrays with multiple transmit and receive channels, etc. Waveform optimization improves radar detection, classification,

identification, localization, and tracking. New optimization methods and techniques are currently under investigation to deal with challenging radar waveform designs involving practical constraints, such as constant modulus, spectral constraints, waveform similarity, and finite or discrete-phase alphabet.

3.Cognitive Radar

Cognitive radar is a recent and growing research area that offers substantial benefits for defense and civilian radar systems. Although many research efforts have focused on perception-action cycles, few of them have demonstrated the learning component and many aspects of the field contain open problems. A radar that can perform online learning to execute better actions and adapt its operational parameters based on its situational awareness can have potential benefits. Additionally, cognition is typically investigated for a single radar system. However, the distribution of perception-action cycles over multiple radar nodes, at different operating levels, starting from signals and multiple radar functions to the mission level, have a huge research potential. Cognitive radars should take advantage of all the available degrees of freedom and sources of diversity including location, frequency, code, beam patterns, revisit time, PRF, and polarization when choosing future actions. These actions should be cognizant of low-observable targets, drones or swarms of UAVs, dense and contested spectrum use, and adversarial activities. The most relevant enabling technologies for the future development of cognitive radar are adaptive waveform design, numerical optimization, RF System-on-Chip (RFSoc), all-digital radar arrays, machine learning, and deep learning.

4.Machine Learning for Radar

Machine learning (ML) has achieved momentous results which are attributed to major investments of many countries as well as massive cooperation among members of the international scientific community. In particular, the

use of ML techniques has made it possible to improve the performance of some signal processing techniques based on traditional approaches and to overcome their intrinsic limitations. Following the success of using ML techniques in many engineering fields, the radar community has also begun to apply ML techniques to solve classic radar problems and to address traditional challenges from a new perspective. As already mentioned, ML is one of the enabling technologies for new cognitive radar systems, more over there has already been an extensive development of signal processing algorithms based on ML that have found application in various fields related to radar systems. Some traditional applications have benefited most from the use of ML. Specifically, radar imaging and classification is an area where ML has contributed significantly. In particular, in the scientific literature, we can find many applications of ML to solve problems related to the processing of radar signals, e.g., for the recognition and classification of radar emitters, processing and classification of radar images, noise suppression in the radar image, automatic target recognition (ATR), target detection, anti-jamming techniques, adaptive waveform design, dynamic antenna array selection, cognitive electronic warfare (CEW), reconstruction from measurements with missing data, high-resolution Direction of Arrival (DOA) estimation, and many others for an exhaustive and comprehensive analysis of the state of the art of ML and especially deep learning (DL) applications in the radar and remote sensing fields). The proposed algorithms include conventional machine learning based on feature engineering combined with appropriate classifiers, such as support vector machines (SVM), decision trees (DT), random forest (RF), and empowerment methods. They also include automatic feature learning such as deep learning. It is now recognized that a higher degree of automation improves radar environmental awareness, irrespective of the type of application considered. The adaptivity of the radar, both on transmit and receive, should be intelligently regulated through accurate environmental awareness made possible by ML.

5.Coexistence of Radar and Communication Systems

In recent years, there has been an explosive growth in wireless communications, especially for applications in the Industrial Internet of Things (IIoT). On the other hand, radar technology has evolved in the direction of ever-increasing functionality. A modern radar system must be able to dynamically change the transmission waveform and operating frequency band, depending on the specific information collected in real time from the surrounding environment. Due to the rapidly growing demand for finite spectral resources, the desire for better and more flexible use of the spectrum is also increasing. On the other hand, commercial wireless industry strives for greater access to the spectrum and has eyed and sought use of the frequency bands traditionally assigned to radar systems, which has led to the so-called problem of spectrum erosion. As part of the search for efficient resource sharing and new technological solutions, it has recently been recognized that the competition for bandwidth between radar and communication systems can be alleviated by jointly and optimally designing the two systems, realizing them on a single platform. In this respect, the platform is not just a radar or communication system, but a multifunctional system whose waveforms and operations support multiple activities and tasks simultaneously. The topic of dual-function radar communication systems has attracted the interest of theoretical researchers and practitioners from both the radar and communication scientific communities. The design of joint dual-function radar communication systems is a timely and relevant research topic and requires innovative ideas and technological solutions. Research underway focuses on established and emerging areas such as cognitive spectrum sensing for resource allocation in communication systems, adaptive waveform design for modern radar systems, and MIMO radar and communication system designs, to name a few. Examples of open problems and methods can be found in two recent special issues, one of the IEEE Trans. on AES devoted to Spectrum Sharing and the other of the Elsevier

Digital Signal Processing journal devoted to the Co-operation and Joint Design of Communications and Radar Systems in a Crowded Spectrum.

6. Radar for Advanced Driver Assistance Systems

Radar technology is one of the enabling technologies for advanced driver assistance systems (ADASs) and highly automated driving (HAD). In recent years, we have witnessed a leap in new systems and new signal processing techniques tailored to the field of automotive radar. Although current automotive radar technology is still based exclusively on the principle of frequency modulated continuous wave (FMCW) radar, modern automotive radars are expected to be more flexible and to allow for adaptive selection of waveform parameters as well as dynamic use of transmit and receive channels. This flexibility calls for multipurpose radar sensors, which can perform functions ranging from adaptive cruise control to automated parking. Additionally, the implementation of advanced autonomous driving functions requires radar sensors to work in symbiosis with lidar and cameras. All this justifies the growing research and development in the field of automotive radar systems in both industry and academia. For example, the use of SIMO (single-input multiple-output) and MIMO (multiple-input multiple-output) radar systems has provided automotive systems with the capacity for spatial filtering to achieve the necessary spatial resolution for obstacle Direction of Arrival (DOA) estimates. Problems related to target blindness, snow, rain, and near-field detection are also still relevant and require further investigation. One of the great challenges in automotive radar concerns adaptive filtering for the mitigation of interference at various radar sensors. This problem will be increasingly important soon, given the increasing number of vehicles equipped with radar sensors in heavy traffic situations. In addition to the coexistence of multiple radars in a crowded traffic environment, spectrum sharing with communication systems is also a major concern.

Other challenges and opportunities evolve around the phenomenology of the sensed signals, system architecture, circuit technology, automotive SAR imaging, object identification, and advanced signal processing techniques. An increasing role of machine learning is also expected in signal processing algorithms for detection and classification in automotive radar. The automotive radar community is at the forefront of technologies that promise to provide fully autonomous driving cars, and several automotive radar industry groups are investing heavily in solving these problems.

7. Radar for Biomedicine and e-Healthcare

The civilian or dual-use applications of radar sensors are experiencing enormous growth, thanks to the maturation of millimeter wave technology which allows for reliable low-cost radar sensors. Among the areas that have benefited most from these developments are undoubtedly those of health monitoring and biomedicine. Indeed, intelligent healthcare systems are undergoing a rapid transformation from the conventional specialist and a hospital-focused style to a distributed patient-centered system. Some technological developments have encouraged this rapid evolution of intelligent healthcare systems, including those related to radar technology and machine learning techniques. These technologies, together with 5G and Internet of Things (IoT), are crucial for the evolution of future smart health services. There is a plethora of applications of radar sensing in biomedicine. For example, radar imaging techniques are becoming a promising alternative, or at least complementary techniques, to existing imaging modalities for detecting breast cancer and monitoring response to treatment. Although many excellent results have already been achieved, there are still several outstanding challenges, such as the low signal-to-noise ratio, tissue heterogeneity, and low resolution. Radar-based remote monitoring of human vital signs and activities is also an application area that has sparked great research interest due to its potential applications in patient health monitoring in hospitals, elderly homes, rehabilitation centers, and care facilities.

However, there are still many open problems related to the low signal-to-noise ratio, high aspect angles, obstacles, dynamic environments, discrimination of similar activities, non-focal motion, and the large and time-varying nature of human activities. Overcoming the challenges in healthcare and biomedical applications requires further advancement of the state of the art in statistical signal processing and machine learning techniques.

8. Micro-Doppler Radar

A moving point-like target introduces a frequency shift in the narrowband radar return due to the Doppler effect. However, in the real world, any target has a complex structure, the body is not fully rigid, and any structural component of the target may not follow an ideally straight-line motion. As a result, motion contains a component called micro-motion, which includes the effect of vibration, rotation, and acceleration. Micro-motion and its induced micro-Doppler effect were introduced to characterize the movement of a target. Thus, extraction and analysis of radar micro-Doppler characteristics have become an active research area. Micro-motion can be observed in many applications, such as rotating propellers of a fixed-wing aircraft, rotating rotor blades of a helicopter, engine-generated vibration in a vehicle, rotating antenna on a ship, swinging arms and legs of a walking person, flapping wings of a bird, and the heartbeat and respiration of a person. Over the past few years, it has been proven that micro-Doppler characteristics can be exploited to extract a signature of a target and because of this, it found applications in many areas such as enhanced target detection, characterization, and tracking. Modern high-resolution radars, equipped with advanced signal processing algorithms, have a better capability to extract micro-Doppler features, which allow classical problems such as non-cooperative target detection and classification to be solved in a more efficient way. This also paves the way for new applications, such as human activity

monitoring, urban and indoor surveillance, healthcare, automotive applications, and manufacturing.

1.2.4. Digital Radar

Digital radar works by transmitting long radiated signals using solid state equipment. This requires less power and can be processed digitally. With returning echoes varying in strength dependent on what they are bouncing off, being able to process the echoes helps improve the quality of the signal and its usability.

The digitized echoes can be represented on color high-definition screens. In these cases, the reliability of the echo signal can be color coded to help guide the user. Given the lack of moving parts, digital radar should become cheaper to buy, run and maintain over time.

CHAPTER 2

2.1. DIGITAL RADAR vs CONVENTIONAL RADAR

2.1.1. Introduction and advantages of Digital RADAR

In conventional radar systems, pulse waveforms are generated at frequencies well below the final RF and then up-converted using analogue mixers, oscillators, and filters to RF. In the receive chain, analogue RF components mirroring those in the transmission chain down-convert incoming radar signals to an intermediate frequency (IF) prior to digitization by an analogue to digital converter (ADC).

Conventional radars emit microwave pulses with analog amplifiers, filters, and limiters. A measurement is calculated to determine how long it takes for the wave to bounce back and the difference in time is then translated into an on-screen image. Due to component tolerances, it becomes difficult to modify the signal or upgrade performance with analog radar systems. Digital radars do not utilize microwave pulses, but a continuous signal. This allows for low distortion of original information. Digital signal processing is mathematically driven and not component driven. It leaves a very predictable performance with no tolerance issues and allows for future features and performance upgrades via software instead of replacing costly hardware. Digital radar offers boaters greater target definition and clarity, and even uneducated radar users can utilize overlay features to get a better idea of their situational awareness.

The demand for mobile communications and broadband data conversion devices has driven the development of low-cost, high-resolution ADCs and digital to analogue converters (DACs) capable of operating at over 2 giga samples per second (Gsps). Some of these devices have sufficient analogue bandwidth to under-sample signals in their 2nd and 3rd Nyquist zones, enabling them to be used to process E/F band RF signals without the need for analogue up or down conversion.

There are many advantages to the digital radar approach:

- They use a processor that is 25 times more powerful, which gives users more information and processes up to 256 colors and graded target returns.
- Enhanced signal to noise ratios, which improve small target detection especially in rough seas or heavy rain.
- It allows the user to have true dual range radar with the ability to see targets on long and short ranges at the same time with no loss of detection capabilities.
- Presets that enable users to have “one touch” settings for locating birds, harsh weather conditions, offshore cruising, and harbor settings.
- Instantaneous pulse bandwidths ranging up to 1 GHz using currently available components
- Native high range resolution (HRR) pulse waveforms
- Variable range gate sizes down to approximately 0.2 m
- Reduced component count and complexity
- Low probability of intercept (LPI)
- Software-based capability upgrades
- Applicability to multi-function radars (MFRs)
- Reduced receive/transmit module size
- Potential for coherent operation in combination with pulse-to-pulse agility through digital processing
- Potential for significant technology-led performance improvements

2.1.2. Concept of Digital Radar

A concept study was conducted to assess the capabilities of the hypothetical E/F band digital radar. The proposed architecture is illustrated in Figure 2.1. For comparison, a typical conventional radar architecture is illustrated in Figure 2.2.

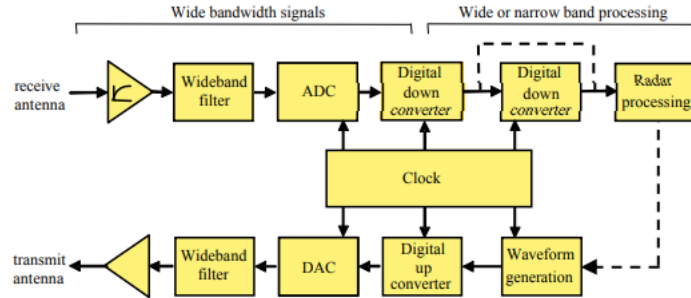


Fig 2.1. Digital Radar architecture

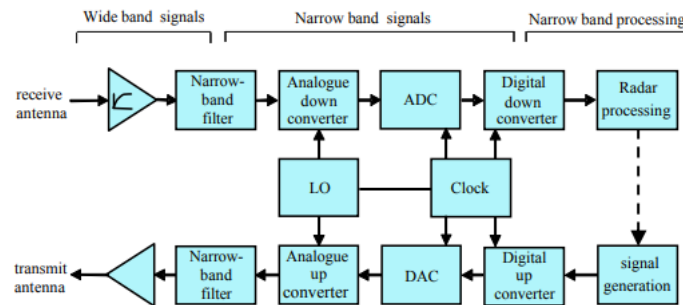


Fig 2.2. Conventional Radar architecture

Digital Radar Receiver

In the concept receiver, a wideband analogue low noise amplifier (LNA), sensitivity time control (STC) and bandwidth control filter would precede high speed ADC clocked at between 2 gsps and 2.4 gsps. The ADC would be used to directly under-sample RFs in its 3rd Nyquist region (i.e., between 2.4 GHz and 3.6 GHz for a 2.4 Gsps clock). The digitized signals would be digitally down-converted to a processing frequency appropriate to the required range resolution.

Digital Radar Transmitter

In the concept transmitter, a return-to-zero DAC clocked at between 2 Gsps and 2.4 Gsps and driven from a digital synthesizer would generate signals in its 1st Nyquist zone and digital images in its 2nd and 3rd Nyquist zones. An analogue bandwidth control filter would pass only the 3rd Nyquist signals, which would be amplified and transmitted into free space. A wideband digital synthesizer would permit the generation of almost arbitrary pulse waveforms, and hence would be amenable to adaptive radar control where the transmission waveforms and bandwidth are optimized according to the target and environment. It would also be amenable to software-based capability upgrades. Based on the performance of currently available components, the maximum instantaneous bandwidth would approach 1 GHz, which is easily sufficient for HRR operation.

2.1.3. Modelling Study Discussion

According to the modelling study, For the narrowband thermal noise limited case, the performance of the digital radar system was shown to be comparable to a conventional system implemented using modern COTS components. For the HRR wideband case, the modelled SNRs were like ideal theoretical predictions. It is envisaged that the digital radar would operate in narrowband mode for basic surveillance and an adaptive bandwidth mode for target identification, burn through and LPI. The results show the fundamental viability of the digital radar concept.

The proposed architecture is potentially applicable to a range of radar types, including high performance MFRs, surveillance radars and low- cost marine, vehicle-mounted and man-portable radar systems.

However, since the performance of digital technology is expected to continue to progress strongly and further outstrip that of analogue technology for the near future, it is considered likely that a variation of the digital radar architecture will prevail in the future.

2.2. MODULATION TECHNIQUES FOR DIGITAL RADAR

Modulation techniques play a key role in radar technology. The mode of transmission makes an enormous difference in the performance of radar and hence the technique will change as per the application.

The two most used techniques are Frequency Continuous Modulated wave (FMCW) and the Pulsed Doppler technique. FMCW is commonly used in industrial as well as automotive applications, while in military applications, the Pulsed Doppler is widely accepted.

2.2.1. Frequency Modulated Continuous wave (FMCW)

In the FMCW technique for automotive industry, the starting frequency is usually around 76-77 GHz, and it is linearly modulated to reach a maximum of 81GHz over a given time period. This waveform is called a chirp. A frame consists of 'N' such chirps, each lasting for a given chirp time ' T_c .' The bandwidth of each chirp and the slope are also crucial to the performance of the FMCW radar. These parameters have a direct influence on the maximum range, maximum velocity, and their corresponding resolutions. A general FMCW can be seen in figure 2.3.

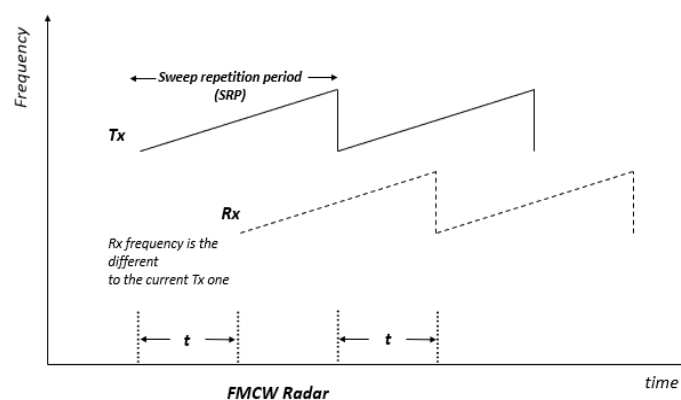


Fig 2.3. FMCW Radar

In the FMCW technique, the distance of the object is calculated by the difference in frequency observed between the received signal and the transmitted signal at the same time instant. This is achieved by mixing the transmitted and received signals and an intermediate frequency signal is generated. A Fourier transform on this intermediate frequency signal (also called beat frequency) yields information on the distance of the object with a good degree of accuracy.

2.2.2. Pulsed Doppler

Now the pulsed doppler on the other hand sends a signal for a short duration and waits for the return signal. The duration of the signal and the 'wait time' are parameters that must be taken into consideration while designing such a system. A general pulsed doppler signal looks like figure 2.4.

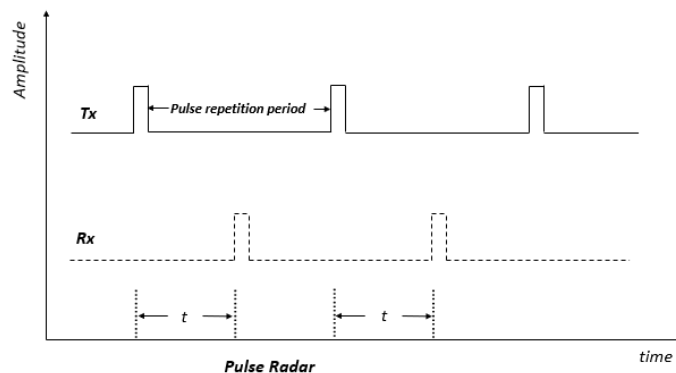


Fig 2.4. Pulse Radar

However, in the pulsed doppler, the time difference between the received signal and transmitted signal is used to measure the distance of the object. Now measuring frequency changes is much easier than measuring time difference in electronic systems. Thus, this leads to a better resolution in FMCW and hence is preferable in automotive applications.

Moreover, the Pulsed doppler technique requires that the minimum time difference must be above a certain limit. This leads to a blind spot and hence minimum observable distance in pulsed doppler is larger than in the case of FMCW making it disadvantageous in automotive applications.

Pulsed doppler however sends its pulse over a shorter period and hence the power of the signal sent can be larger. Thus, the power of the received signal from an object farther away is likely to have more power than in the case of FMCW. Thus, maximum range with a given power constraint is going to be higher in the case of Pulsed doppler.

2.2.3. Culmination

Faster real-time processing is mandatory for automotive application, new processors can solve complex math required by FMCW. These processors are also inexpensive and as a result FMCW is best suited for automotive application. Furthermore, the doppler velocity can be calculated with better accuracy in the Pulsed doppler technique. As a result, the pulsed doppler method seems to be a clear winner when it comes to military-based applications.

CHAPTER 3

3.1. PROPOSED WORK

The most common radar technology for automotive use to date has been Frequency Modulated Continuous Wave (FMCW) radar. Another type of radar, which has been used for military application is Digital Code Modulation (DCM). Due to the advancements of CMOS technology and advanced signal processing, it is feasible to provide a cost-effective DCM radar that meets demands of the automotive industry.

Table 3.1. Comparison of traditional FMCW and DCM radar

	FMCW/FCM	DCM
Analog Processing	Complex – larger analog for increased number of Virtual Receivers (VRx's).	Simpler – smaller analog for increased number of VRx's.
Signal Processing	Partially done in analog circuitry.	Mostly done in digital which allows the use of advanced signal processing algorithms.
Range Response	Broad range response that may hide small objects in proximity of a large object. Low High Contrast Resolution (HCR).	Sharp thumbtack-like range response due to near ideal auto-correlation function of long spreading codes providing much greater HCR.
MIMO Support/Angular Resolution	Multiple VRx has been challenging for FMCW. Low HCR.	Native support for a large number VRx. High HCR.
Interference	Interference is highly dependent on the chirp parameters used by the interfering and victim radars and may result in a high Interference Susceptibility Factor (ISF).	Robust against interference from other DCM radars. Always low ISF.

3.1.1. Introduction to Vehicles Automation

There has been an increased demand for improved automotive radar systems to further the automation features in Advanced Driver Assistance Systems (ADAS) and to enable the path to higher levels of autonomous driving. The Society of Automotive Engineers (SAE) has defined six levels of driving automation, as shown in Figure 3.1, from no automation (Level 0 or L0) to full automation (Level 5 or L5). ADAS and autonomous driving could reduce accidents by 90% and significantly reduce the number of people killed in automotive accidents, which is significant considering that globally, 1.25M people die yearly from these accidents. Since radars can operate at night and in major vision impairing weather conditions such as fog, snow, and heavy rain, they are an essential sensor to enable vehicle automation. Compared to vision-based systems, radars also have the advantage of being able to inherently detect dopplers, which allows for perfectly accurate speed estimation of moving objects.

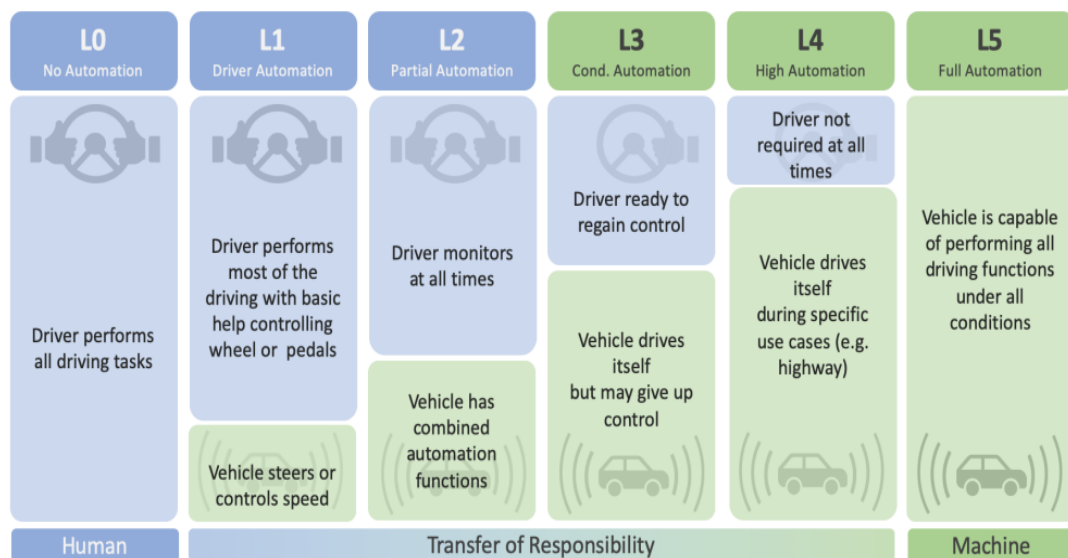


Fig 3.1. Vehicle Automation Levels

Today, an increasing number of automobiles contain various radar systems, such as long-range radar (LRR), mid-range radar (MRR), or short-range radar (SRR). The LRR is typically used for detection of objects at large distances (e.g., up to

300 m) over a narrow angular region to help in emergency braking, collision warning, and adaptive cruise control. The MRR has a wider field of view and can typically detect objects up to 150 m and can detect objects approaching at crossroads (laterally); it may be used for cross traffic alert functions. In contrast, the SRR can detect objects over a wide angular region at a short distance and is usually used for park assistance, cross-traffic alert, pedestrian/cyclist detection, rear-collision warning, and lane change assistance. To ensure safer driving as well as autonomous driving, a car may contain multiple LRRs, MRRs, and SRRs as shown in Figure 3.2. In general, the higher the level of driving automation, the greater the number of sensors that are required.

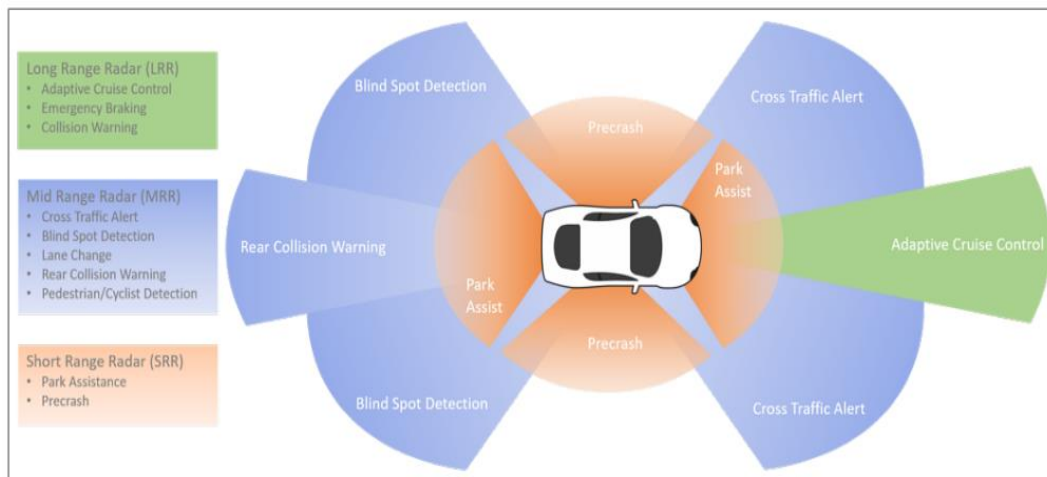


Fig 3.2. Automobiles can have Multiple Long-Range, Mid-Range, and Short-Range Radars

To improve the capability and reliability of ADAS in current cars, as well as overcome the challenges to advance to fully automated driving (L5), automotive radar systems need to provide a much higher resolution in azimuth and elevation, as well as provide better accuracy and discrimination. These advanced radar capabilities are required to address use cases such as those shown in Figure 3.3, which are challenging for traditional radars. Without higher resolution, better accuracy, and improved discrimination, a radar system can have difficulty

identifying an open lane in traffic on a highway, a stalled car at the entrance of a tunnel or under a bridge, small debris on the road, or a bicyclist beside a car.

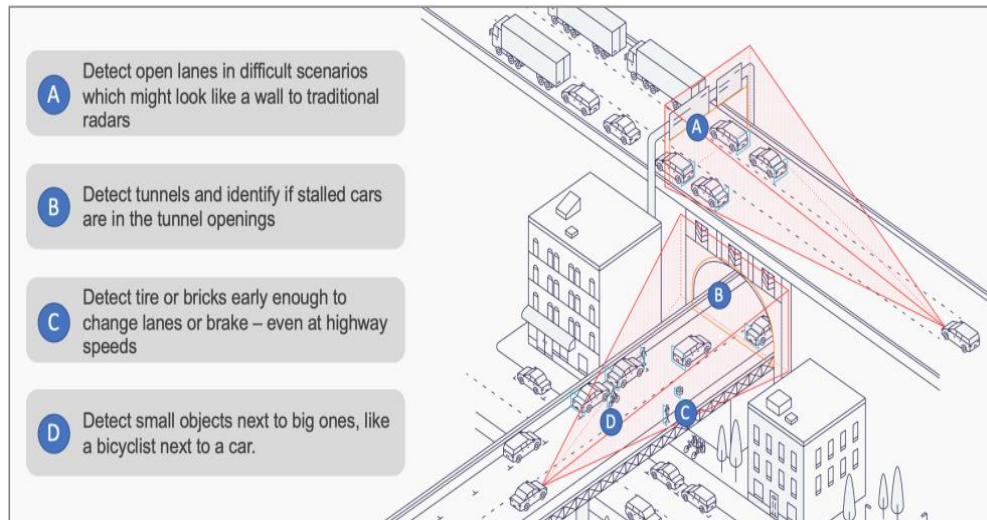


Fig 3.3. Important Radar Use Cases

In addition, radars must provide more robust interference mechanisms towards other radars on the road, especially with increasing deployment of higher levels of automation, i.e., cars with multiple radars. Radar is a technology which is particularly susceptible to self-interference (interference from other radars on the same car) or cross interference (interference from radars in other cars). This interference susceptibility is a significant limitation to the wide deployment of radars.

The most common radar technology for automotive use to date has been Frequency Modulated Continuous Wave (FMCW) radar, the most recent version of which is called fast chirp modulation (FCM). Another type of radar, which has been used for military applications, but until recently was too expensive for high volume use cases like automotive, is Digital Code Modulation (DCM), an instance of a Digitally Modulated Radar (DMR). However, advances driven by the

communication and computing industry, such as advanced signal processing, state of the art CMOS technology, and low-power high speed analog-to-digital converters, are now making it possible to design cost effective DCM radar systems that meet the increasing demands of the automotive industry.

3.1.2. Range Processing of FMCW Signals

The transmitted FMCW signal is reflected off a target and received. The received signal, in the case of a stationary target, is an attenuated and time-shifted version of the transmitted signal. The frequency-time relation for the transmitted signal is shown as the blue line in Figure 3.4, while the frequency of the received signal is shown as the red dashed line.

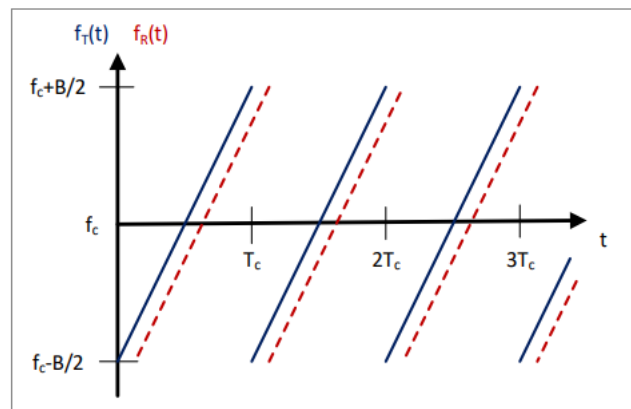


Fig 3.4. FMCW Frequency of Signals

Based on propagation of signals at the speed of light, the delay τ is related to the range by

$$R = \tau c / 2 \text{ or } \tau = 2R / c$$

where c is the speed of light, and the factor of 2 is due to the round-trip time from the transmitter to the receiver. This is true for any type of radar signal, not just FMCW/FCM signals.

The beat frequency of the signal after mixing and filtering is proportional to the delay between the transmitter and receiver and thus proportional to the range of

the target. Suppose R_m is the maximum range of a target to be detected. The maximum delay is $\tau_m = 2 R_m/c$. The maximum frequency shift is then $f_m = 2B R_m / (c T_c)$. The minimum frequency shift is 0 corresponding to a target at distance 0. The filter must have a bandwidth at least as large as this maximum beat frequency. Equivalently, with receive low pass filter bandwidth of B_r , the largest range that can be detected is

$$R_m = c T_c B_r / (2B)$$

This equation provides a fundamental trade-off in FMCW radars among chirp duration, transmit signal bandwidth, receive filter bandwidth, and maximum range. For example, if the chirp duration is 30 μ s, the sweep bandwidth is 300 MHz, and the filter bandwidth is $B_r = 15$ MHz, then the maximum range is 225 m. For automotive applications, this might be considered an LRR. If the sweep bandwidth is 750 MHz, the sweep time is 50 μ s, and the filter bandwidth is $B_r = 4.5$ MHz, then the maximum range is 45 m and would be considered an SRR.

The signal after mixing and filtering is then digitized using a sampling rate f_s and then processed using fast Fourier transform (FFT) to analyze the frequency contents of the received signal. The frequencies present in the signal correspond to the ranges of the targets. Due to the digitization of the signal, any frequency above the Nyquist rate of the sampling frequency will alias into lower frequencies, and thus, the corresponding range will fold over to lower ranges. There is then a limit based on the sampling rate, f_s , where the ranges can be estimated unambiguously. This limit is given by

$$R_u = c T_c f_s / (2B)$$

By carefully choosing the receive filter bandwidth, the sampling frequency, and the filter order, the signal energy of objects beyond the unambiguous range in the receive signal can be reduced. When two objects are separated by a distance Δd , the difference in the corresponding frequencies in the receive signal is

$$\Delta f = 2B \Delta d / c T_c$$

The minimum frequency delta that can be detected using Fourier processing is equal to the inverse of the chirp (observation) time, i.e.,

$$\Delta f > 1/T_c$$

This leads to the range resolution of

$$R_r = c/2B$$

3.1.3. Range Processing of DCM Signals

In DCM radars, range processing is performed using a matched filter to determine the correlations of the received signal with various delays of the transmitted signal. There are two types of such correlation functions that can be used based on how the transmitted signal is generated.

- Non-repeating code transmission: In this case, different codes are transmitted from one transmission time (pulse) to the next. The matched filter output is represented by the aperiodic autocorrelation function of the code.
- Periodic code transmission: Here, the same spreading code is transmitted periodically. The matched filter output is represented by the periodic autocorrelation function of the code.

We illustrate these concepts through an example where there are three targets at various distances with different reflectivity (e.g., distinct size (RCS) objects). The matched filter output of the non-repeating code transmission is shown in Figure 3.5. The example shown in this figure belongs to a class of codes known as maximum-length sequences (m-sequences).

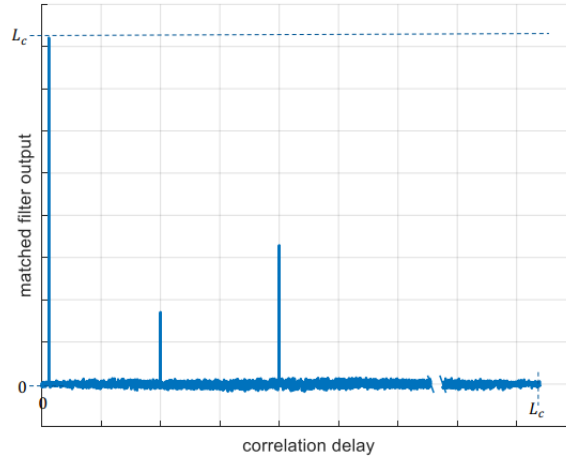


Fig 3.5. Matched Filter Output for a Three Target Scenario

Using the same target scenario with three targets as in Figure 3.5, Figure 3.6 shows an example where multiple periods of the same spreading code are transmitted.

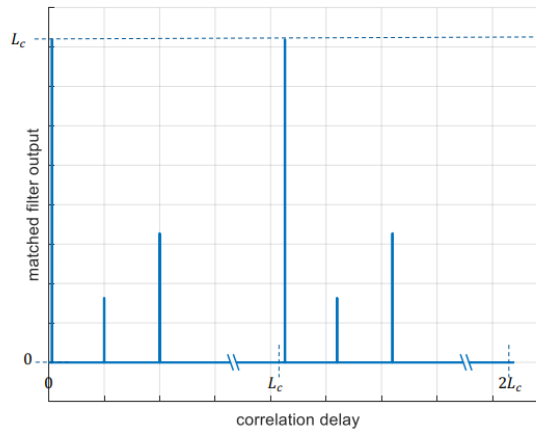


Fig 3.6. Matched Filter Output with Periodic Signal

In the latter case, the output repeats itself with a repetition period equal to the duration of the matched filter's impulse response corresponding to the length of the spreading code used. The fact that the output is a constant value in between target locations is a property of the m-sequence used as the spreading code.

There are many codes that can be used depending on the objective of the radar system and the desired performance. Some codes, like Barker codes, have good

aperiodic autocorrelation functions, while others have excellent periodic autocorrelation functions. Codes with good aperiodic autocorrelation are desirable if the transmitted spreading code does not repeat. As shown in Figure 3.5 and Figure 3.6, when a single period of the code is transmitted, the output of the matched filter (Figure 3.5) for a maximum length sequence (known for good periodic autocorrelation) results in off-peak values higher than those when sent periodically (Figure 3.6). Increasing the length of the code improves the ratio of the off-peak autocorrelation function to the peak of the autocorrelation function.

The width of the spike in the matched filter output is proportional to the chip duration. That is, the width of the spike is inversely proportional to the chip rate or the signal bandwidth. Thus, larger bandwidths yield smaller width spikes and better range chip scale, and thus, the width of the spike in terms of range will change proportionately to chip duration.

The range resolution R_r for a DCM system is the width of the spike in the matched filter output. Two targets that are closer than the corresponding time interval of the width of the spike will be indistinguishable. Thus, the range resolution is

$$R_r = (T_c/2) c$$

where T_c is the chip duration and c are the speed of light. Since chip duration is inversely proportional to the bandwidth of the signal B , i.e., $T_c = 1/B$, the above range resolution is equivalent to that in FMCW radars.

$$R_r = c/2B$$

For the case of periodic code as seen in Figure 15, if a target is at a distance larger than $c (L_c T_c)/2$, where L_c is the number of chips in the spreading code before repeating, the target will produce an output that will appear like a target at a distance between 0 and $c (L_c T_c)/2$. For objects at a distance smaller than $c (L_c T_c)/2$, the range will be correctly determined. This is the maximum unambiguous range R_u .

$$R_u = c T_c L_c / 2$$

Two targets separated by the maximum unambiguous range will appear to the radar system as being at the same range. This is called range aliasing. If the chip duration, T_c , is decreased, then the range resolution would improve proportionally. As an example, if T_c is 1.33 nanoseconds corresponding to a chip rate of 750 Mchips/second, then the range resolution would be limited to 20 cm. For a periodic spreading code of length 1023, the maximum ambiguous range would be 204.6 m. For a periodic spreading code of length 4095, the maximum ambiguous range would be about 818 m. The unambiguous range for DCM can be increased by increasing the period of the code for a given chip duration. In the case of an aperiodic code, there is no range aliasing and thus ambiguity in range is nonexistent. One appealing feature of DCM radars is the sharpness of the peak. This is due to the use of the auto-correlation function as range response compared to using the FFT in FMCW radars. The FFT results in a much slower drop in range response around a target. This feature allows much better HCR performance in range for DCM radars.

3.1.4. Velocity Processing

Another goal of an automotive radar system is to estimate the differential velocity between the radar system and a target. Because the targets in the environment, or the radar itself, are moving, the signal reflected from an object will not have the same frequency as the transmitted signal. This effect is known as the Doppler effect and can be used to estimate the relative velocity of targets in the environment. If the differential radial velocity (towards or away from the radar) of a target relative to a radar is Δv , and the carrier frequency is f_c , then the Doppler frequency shift of the signal reflected from the target is

$$f_d = 2\Delta v f_c / c$$

where the factor of 2 comes from the fact that there is a Doppler shift going both ways: radar to target and target to radar. A radar scan for DMR/DCM consists of N repetitions of the spreading code (same code for periodic code but different

codes for aperiodic code) or $N \times L_c$ chips in a much longer spreading code. The received signal is filtered N times. The N samples of the matched filter output, when using both an in-phase and quadrature-phase down-conversion, produce complex numbers that will rotate around the circle at a rate proportional to the relative radial velocity. The technique is similar for FMCW/FCM radars. In these radars, the chirps (the frequency sweeps) are repeated N times. A plot of the Q-component vs. the I-component for the first few samples of the matched filter output is shown in Figure 3.7. The rate that the samples rotate around the circle is related to the Doppler shift of the received signal, and thus the radial velocity of the target relative to the radar system. The direction of rotation around the circle is an indication of whether the target is moving toward the radar system or away from it.

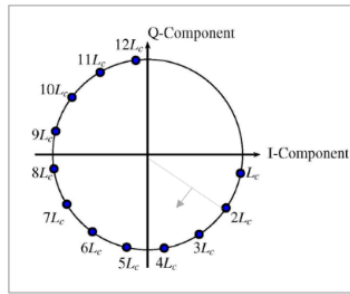


Fig 3.7. Samples of Matched Filter for Doppler

One approach to estimate the Doppler frequency, and thus the velocity, is to perform a fast Fourier transform (FFT) on the N complex samples. There is a maximum relative velocity that can be estimated without ambiguity. If the points in Figure 3.7 rotate completely around the circle in time, $L_c T_c$, then it would appear the object is not actually moving. A complete rotation represents a change of 2π in phase corresponding to a relative movement of the objects by one wavelength within a time period of $L_c T_c$. As such, in a radar, the velocity can be estimated unambiguously only over a certain range. That is, two different objects separated sufficiently may appear to have the same velocity. The possible range of unambiguous velocities, v , that can thus be estimated, is given by

$$-c / 4f_c T_c L_c \leq v \leq c / 4f_c T_c L_c$$

If there are N complex samples of the matched filter output, the velocity resolution possible, V_γ , is then the unambiguous range of velocities above divided by the number of samples, i.e.,

$$V_\gamma = c / 2f_c N T_c L_c$$

3.1.5. Angle Processing

In modern automotive radar, the angles of arrivals from targets are estimated using multiple transmit antennas or multiple receive antennas or both. There are several ways that multiple transmit antennas can be employed. One approach is to use various phase shifts of a single signal for each transmit antenna. This is called a transmit-side phased-array or beam steering approach. The radar focuses on the transmitted signal energy in a certain direction. Another approach, when multiple antennas are used in both transmit and receive, includes the use of the MIMO technique described earlier, increasing the virtual aperture, and hence, providing better angular resolution. Although the basic MIMO processing is similar for both FMCW and DCM radars, they differ on how signals are transmitted on the multiple transmit antennas.

In one approach, the radar can time multiplex the transmission on different antennas (TDM MIMO). In this approach, the radar transmits using a single antenna for some given time and then switches to another antenna. The interference between antennas is thus mitigated or eliminated. This is the most common implementation used in FMCW/FCM radars where the transmission is switched from antenna to antenna on a chirp-by-chirp basis. This approach has two major drawbacks. First, the maximum unambiguous velocity is reduced by a factor equal to the number of transmit antennas. Second, the scan time increases by the number of transmit antennas since each Tx must have enough time to transmit within its own window.

Table 3.2. Multiplexing Options for MIMO Systems

Type	Scan Time
TDM MIMO	Time Division Multiplexed MIMO: Only one Tx is active at a time; multiple Rx are active
CDM MIMO	Code Division Multiplexed MIMO: Multiple Tx are active at the same time within the same frequency band; multiple Rx are active
FDM MIMO	Frequency Division Multiplexed MIMO: Multiple Tx are active at the same time occupying different frequency bands; multiple Rx are active

The most advanced approach is for multiple transmitters to transmit simultaneously, which can be achieved by using code division multiplexing (CDM MIMO); a special code for each Tx, which is then separated within the Rx path to achieve a true MIMO radar system. This approach requires additional digital processing but allows an improved unambiguous velocity window as well as shorter scan time, which means higher update rates are possible.

It is also feasible to use FDM or frequency division multiplexing. This method is typically not used since it increases the signal bandwidth at the transmitter and the receiver proportional to the number of transmitters.

A radar system with N_T transmitters and N_R receivers has $N_T \times N_R$ transmitter-receiver pairs or virtual receivers. Using these $N_T \times N_R$ virtual receivers and the estimated range to the targets from multiple transmitters/receivers, a radar system can use the receive side beamforming approach to determine the azimuth or elevation angle or both, depending on the geometry of the antennas.

DCM naturally uses CDM MIMO where unique spreading codes are employed for different transmitters. At each receiver antenna, a filter matched to each of the N_T transmitter signals can be used. Spreading codes that are orthogonal to each

other can be used when transmitting to reduce self-interference (interference from other transmitters in the same radar), but at the expense of larger auto correlation sidelobes. There is a tradeoff between the autocorrelation properties of spreading codes and the cross correlation of spreading codes. The cross-correlation indicates the amount of interference from different antennas using different spreading codes, while the autocorrelation indicates the self-interference from one spreading code. The better the cross-correlation properties, the worse the autocorrelation properties. Figure 3.6 shows the case where eight transmitters are active at the same time but use different code sequences. We again use m-sequences with a three-target scenario for this illustration.

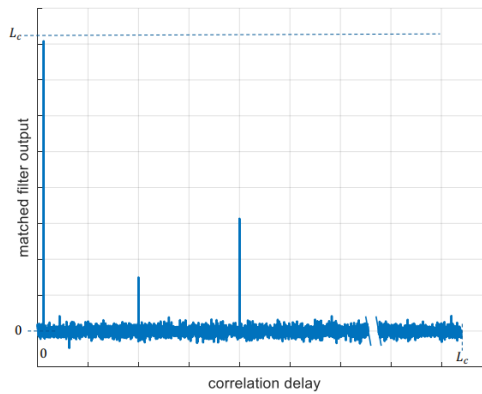


Fig 3.8. Averaged Matched Filter Output with Eight Transmitters Active

The filter output for a given receiver matched to a given transmitter spreading code now has contributions (due to cross-correlations between the codes) from the other transmitters. In this illustration, for a given receiver, we have a total of eight matched filter outputs corresponding to the eight transmitter codes. The MIMO processing for angle estimation performs a coherent summation in multiple directions (angles), and thus, effectively averages the multiple matched filter outputs. Figure 3.6 shows the average output of all the matched filters on one of the receivers.

If we compare Figure 3.8 with Figure 3.5, we see an increase in the off-peak signal energy in the MIMO case. This signal energy from the other transmitters spilling into the matched filter output for a given transmitter's code, known as the

channel isolation, is a major metric for MIMO operations. This channel separation can only be improved by using longer spreading codes (larger L_c).

Some modern FMCW/FCM radars also use this idea to encode the transmitted chirps (sweeps) using spreading codes across multiple transmitters by adding a chirp-to-chirp pseudorandom binary sequence (PRBS) phase code for each TX antenna. Channel isolation, as determined by the code length, is, however, much shorter than DCM (chirp rate being slower than the chip rate). For example, a scan time of 5 milliseconds with a chirp duration of 10 microseconds would provide use of 500 chirps. On the other hand, a DCM system with a scan time of 5 milliseconds and a chip duration of 1 nanosecond (for 1 GHz bandwidth) would have 5,000,000 chips in a scan, allowing many more transmit antennas to operate at the same time compared to phase coded FMCW/FCM. The ability to use many more antennas, along with extremely high channel separation, allows DCM radars to have extremely high HCR performance in angle.

3.1.6. Interference Considerations

The growing deployment of radars in vehicles brings the focus to one of the main challenges for all radars in the future – interference, specifically, interference from other radars. Automotive radar is inherently susceptible to interference from nearby interferers since the interferer's transmission has an R^2 advantage at the victim over received signals from targets. In case of direct line of sight interference, the interference power in the victim radar has one-way propagation loss. On the other hand, the desired signal, which are reflections from targets being measured, goes through two-way propagation loss. With the potential proliferation of multiple radars operating simultaneously in “close proximity” and direct line-of-sight, as illustrated in Figure 18 below, mutual interference will increase as more radars are deployed. As seen in Figure 3.9 a “victim” radar is attempting to determine targets in the FOV, but an interfering radar is jamming the victim radar.

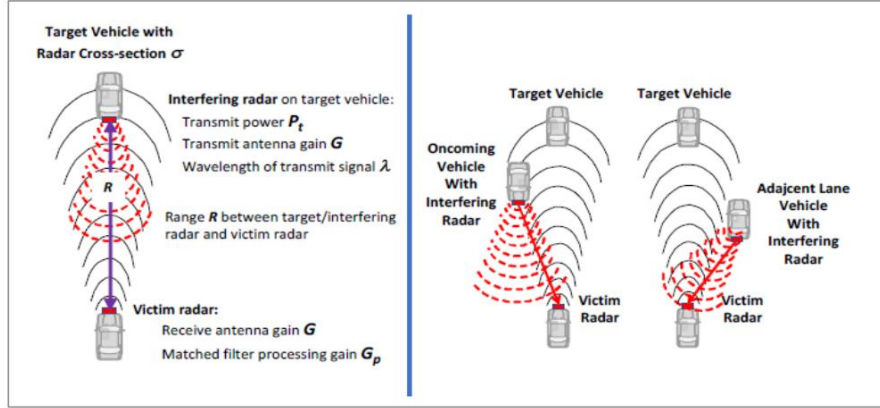


Fig 3.9. Interference Scenarios

The automotive radar waveforms and processing described here typically result in a broadband noise like spectrum for interfering signals, which may potentially increase the overall noise floor. The impact of interference can be measured using interference-to-noise ratio (INR). The INR is defined as the ratio of the power spectral density of interference, PSD_{int} , as seen by the victim radar, to the power spectral density of noise, PSD_{noise} , in the victim radar, in the absence of any external interfering radars.

$$INR = PSD_{int} / PSD_{noise}$$

The power spectral density of interference seen by the victim radar depends on the transmitted power from the interferer, and the distance of the interferer from the victim. It also depends on the processing done in analog and digital. In the analog domain, the bandwidth of the interference at baseband following down-conversion and demodulation determines its characteristics. In the digital domain, the processing tends to spread interference while concentrating the signals from targets in range and Doppler. If the interfering radar has bandwidth B , then the power spectral density PSD_{int} of the interference at the victim radar is given by

$$PSD_{int} = [P G_T \lambda L_{TX} N_{TX} / B (4\pi R^2)] [G_R \lambda L_{RX} L_f N_{RX} / 4\pi] (D_F) (K)$$

where $G_T(G_R)$ is the antenna gain for the interfering (victim) radar, λ is the wavelength of the radar signal, P is the transmitted power of the interfering radar, N_{TX} , (N_{RX}) is the number of transmitting (receiving) antennas for the interfering (victim) radar, L_{TX} (L_{RX}) is the transmit (receive) loss for the interfering (victim) radar, and L_F is the loss due to the fascia (e.g., auto bumper) of both radars. The duty factor parameter D_F accounts for the fraction of time the interfering radar operates within the dwell time and band of the victim radar; hence, the value of D_F varies from 0 to 1. Because the Interference Susceptibility Factor (ISF) (denoted in this paper as the constant K) depends on which kind of modulation the interferer and victim both have, we will describe the various interference characteristics for the several types of interfering and victim radars.

FMCW- FMCW Interference

Consider a victim radar and interfering radar both using FMCW/FCM modulation. Figure 3.8 illustrates the mechanism of interference and the resulting time domain and frequency domain responses. For down-conversion in the receiver, FMCW/FCM radar uses a replica (coupled version) of the transmitted FMCW/FCM signal. For the situation where the interfering FMCW/FCM signal crosses the victim FMCW/FCM signal, the interference appears as a linear chirp signal after down-conversion in the victim radar receiver, which, assuming “dissimilar fast crossing” slopes, covers a wide bandwidth as it sweeps through the victim radar passband. After bandpass filtering in the victim radar, the interference signal resembles an impulse-like signal in the time domain. The resulting frequency spectrum is broadband, and often well above the background noise floor, as illustrated in the simulated example using a representative automotive radar.

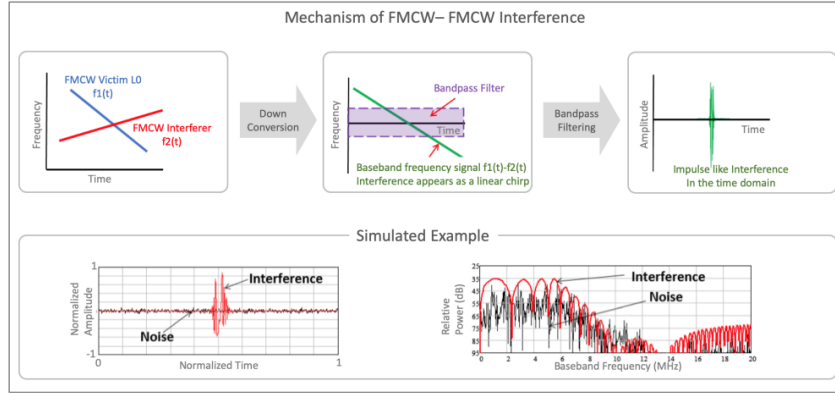


Fig 3.10. Time-Frequency Domain Characteristics of FMCW-to-FMCW Interference Mechanism

The factor K applies to the case of FMCW modulation for both the victim and interfering radars and is given by the ratio of the interference power spectral density at baseband (after down-conversion) in the victim radar, to the interference power spectral density in the victim radar receiver at RF (prior to down-conversion). That is,

$$K = \text{PSD}_1^{\text{BB}} / \text{PSD}_1^{\text{RF}}$$

In the equation for interference-to-noise ratio (INR), K for FMCW/FCM-to-FMCW/FCM interference is fundamentally the ratio of the chirp bandwidth transmitted by the interfering radar to the bandwidth of the interference chirp after down-conversion in the victim radar. For FMCW/FCM, the bandwidth after down-conversion in the victim radar depends on the difference in FM sweep (modulation) rate between the interfering and victim radars. Assuming the FM modulation rates of the interfering and victim radars produce "broadband" interference following down-conversion in the victim radar, that is, interference spread over no less than the baseband bandwidth of the victim radar, K ranges from a minimum value of 0.5 to a maximum value equal to the sweep bandwidth of the interfering radar divided by the baseband bandwidth of the victim radar. The factor K for FMCW/FCM interference depends on the FMCW/FCM sweep

rates of the interfering and victim radars, as well as their time and frequency alignment.

DCM- DCM Interference

For situations where DCM is used by either the victim or interfering radar, K is equal to unity. Consider a victim radar and interfering radar both utilizing DCM modulation. Figure 3.11 illustrates the resulting time domain and frequency domain responses. DCM interference with random, noise-like bi-phase coding using chip rate $\Delta f_i = 1/T_c$ is assumed and appears as a spread spectrum, noise-like signal with bandwidth $\Delta f_i = 1/T_c$ centered at carrier frequency f_c .

In this example, the DCM victim radar is assumed to transmit a DCM bi-phase coded, noise-like signal with the same chip rate, bandwidth, and carrier (center) frequency as the interfering DCM radar, but with an independent, uncorrelated spreading code. The victim DCM radar down converts the received signal with a constant local oscillator frequency at the common carrier frequency and demodulates the received signal with a delayed copy of the DCM bi-phase code. Following down-conversion, demodulation, and bandpass filtering in the victim radar, the interference appears as a noise-like signal in both time and frequency domains. The resulting frequency spectrum is broadband and often well above the background noise floor as illustrated in the example using representative parameters for an automotive radar.

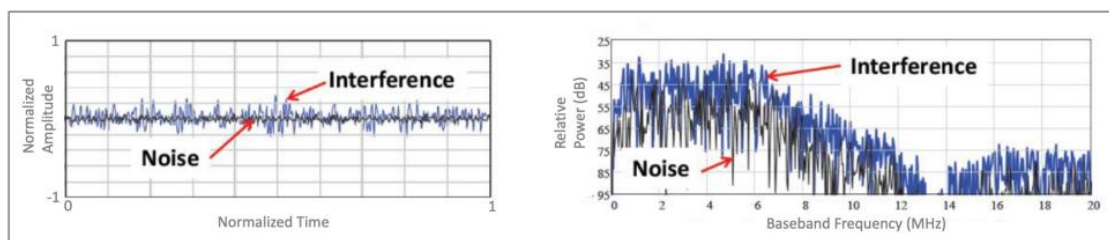


Fig 3.11. Time-Frequency Domain Characteristics of DCM-to-DCM Interference

DCM- FMCW Interference

Consider a victim radar with bi-phase DCM modulation, and an interfering radar with FMCW/FCM modulation, or vice versa. Figure 3.12 illustrates the interference mechanism and the resulting time domain and frequency domain responses. In both situations (DCM victim-FMCW/FCM interferer or FMCW/FCM victim-DCM interferer) the interference is noise-like in the time and frequency domains and the interference-to-noise ratio (INR) is the same.

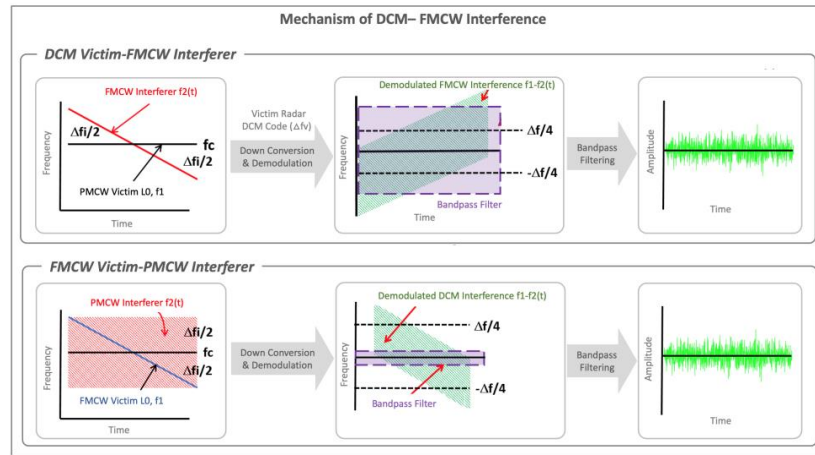


Fig 3.12. Mechanism of Bi- Phase Noise DCM-to-FMCW Interference

Down-conversion/demodulation and subsequent signal processing in the victim radar results in spreading of the interference in a noise-like fashion over the passband and/or detection band. The resulting interference-to-noise ratio is then given by the power spectral density of interference divided by the power spectral density of noise in the victim radar.

If the FMCW/FCM victim and interfering radar slopes are similar, the interference power is down converted into a narrow frequency band, increasing the power spectral density compared to that of dissimilar slopes ($K > 1$). Hence situations with phase modulation (DCM) for either the victim or interfering radar, results in lower interference-to-noise levels.

3.2. SOFTWARE DESCRIPTION

The entire project was implemented and verified on Linux Environment. Linux is the best-known and most-used open-source operating system. As an operating system, Linux is software that sits underneath all the other software on a computer, receiving requests from those programs and relaying these requests to the computer's hardware.

Linux OS has a set of utility tools, which are usually simple commands. It is a software which GNU project has written and published under their open-source license so that software is freely available to everyone. With the help of commands, you can access your files, edit, and manipulate data in your directories or files, change the location of files, or anything.

3.2.1. Cadence

Cadence Design Systems is the world's leading EDA technologies and engineering services company. Cadence helps its customers break through their challenges by providing leading edge electronic design solutions that speed advanced IC and system designs to volume production.

Cadence is a leading provider of EDA and semiconductor IP. Our custom/analog tools help engineers design the transistors, standard cells, and IP blocks that make up SoCs. Our digital tools automate the design and verification of giga-scale, giga-hertz SoCs at the latest semiconductor processing nodes. Our IC packaging and PCB tools permit the design of complete boards and subsystems. Cadence also offers a growing portfolio of design IP and verification IP for memories, interface protocols, analog/mixed-signal components, and specialized processors. And reaching up to the systems level, Cadence offers an integrated suite of hardware/software co-development platforms.

Cadence verification is comprised of core engines and applications that increase design quality and throughput, fulfilling verification requirements for a wide variety of applications and vertical segments.

3.2.2. Xcelium Logic Simulation

Cadence® Xcelium™ Logic Simulation provides best-in-class core engine performance for System Verilog, VHDL, SystemC®, e, UVM, mixed signal, low power, and X-propagation. It leverages single-core and multi-core simulation technology for best individual test performance and machine learning-optimized regression technology for best regression throughput.

Xcelium single-core simulation delivers best-in-class compile, performance, and throughput with compute platform flexibility, providing:

- Continuous performance optimizations for modern design styles and latest coding practices
- Up to 10X compile speedup with Xcelium incremental and parallel builds
- Throughput efficiency using save/restore with dynamic test reload
- Platform support for x86, Arm, and cloud compute platforms

The Xcelium simulator with mixed-signal option covers advanced digital features such as UVM, System Verilog Testbench, UPF/CPF, and SystemC. It also supports the simulation of languages such as Verilog-A, Verilog-AMS, VHDL-AMS, SystemVerilog Real Number Modeling (SVRNM), System Verilog, and mixed-signal features along with SPICE, and other digital-centric mixed-signal technologies, such as low power and mixed signal, code coverage and mixed signal, functional safety and mixed signal, and incremental elaboration and mixed signal.

3.2.3. *SimVision*

A unified graphical debugging environment within Cadence®Xcelium™ Parallel Logic Simulation, Cadence SimVision™ Debug supports signal-level and transaction-based flows across all IEEE-standard design, testbench, and assertion languages. It also supports concurrent visualization of hardware, software, and analog domains.

SimVision Debug can be used to debug digital, analog, or mixed-signal designs written in Verilog, System Verilog, e, VHDL, and SystemC languages or a combination thereof.

SimVision integrated debug supports signal-level and transaction-based flows across all IEEE-standard design, testbench, and assertion languages, in addition to concurrent visualization of hardware, software, and analog domains.

SimVision Debug provides a unified simulation and debug environment that allows Xcelium Simulation to manage multiple simulation runs easily and to analyze both design and testbench behavior at any point in the verification process—regardless of the composition.

Throughout the design and verification flows, SimVision Debug provides source browsing, transaction and mixed-signal waveform analysis, complete code/transaction/ assertion coverage analysis, integrated display and debug of power behaviors, hardware analysis checks, and seamless connections to downstream implementation flows. APIs (Application Program Interfaces) based on industry standards are available at all levels to enable user-defined checks and analysis. Design and testbench models can be interleaved in any language and any level of abstraction without the performance and integration overhead caused by co-simulation.

SimVision Debug comprises several analysis windows to address debug complexity. Some of these windows (available as toolbar buttons and menu choices) include:

- The Properties window, which lets you manage the cursors, markers, expressions, and other debugging objects that you have created during your SimVision Debug session
- The Design Browser window, which lets you monitor the signals and variables in the design
- The Waveform window, which plots simulation data along an X and a Y axis. Data is usually shown as signal values versus time, but it can be any recorded data
- The Source Browser, which gives you access to the design source code
- The Schematic Tracer, which displays a design as a schematic diagram and lets you trace a signal through the design
- The Memory Viewer, which lets you observe changes in the internal state of memory locations. During simulation, it also lets you set breakpoints, and force and deposit values to memory locations
- The Watch window, which lets you monitor selected signals and variables in the design in a more concise form than the Design Browser
- The Register window, which lets you use a free-form graphics editor to define any number of register pages, each containing a custom view of the simulation data
- The Expression Calculator, which lets you define expressions, which combine signals to form buses, conditions, and virtual signals

SimVision Debug offers interactive and/or post-process debug that supports OOP/AOP class-based debug environments. It supports full Logical Path Name as well as unique class object handles (direct handle to object in memory). SimVision Debug also provides many innovative visualization capabilities to debug dynamic data in post-processing mode.

Since the Universal Verification Methodology (UVM) defines class-based, transaction-driven testbenches, you need a debug environment centered on these elements. SimVision Debug enables you to access the environment through both the class inheritance and the instance trees. You can follow the simulation flow single-stepping through/over lines, method calls, and even into macros.

If the testbench uses transaction recording, debug becomes even easier. UVM provides automatic transaction recording so that you can view your test sequences. SimVision Debug adds a novel stripe chart view that allows you to visualize the sequential order of transactions across multiple streams.

3.2.4. IMC Coverage

The IMC is a register-transfer level (RTL) coverage analysis tool designed to load and analyze RTL coverage across the Cadence Xcelium™ Parallel Simulator, JasperGold® Apps, Palladium® XP Verification Computing Platform, Specman® Elite, and Perspec™ System Verifier technologies. The IMC provides a rich user interface for the vast array of RTL code coverage and functional coverage types. With the IMC, Cadence provides a unified and simplified visualization and analysis environment, which, combined with an equally powerful unified coverage database— UNICOV—ensures coverage interoperability and merging across Cadence functional verification tools.

The IMC allows you to converge on your coverage goals and achieve coverage closure more quickly than with traditional HTML or text-only reports. The IMC enables real-time analysis with an intuitive GUI (Graphical User Interface) and specially engineered views for each coverage type supported. The IMC supports all RTL metric types from all major EDA languages, ensuring that verification teams—from simulation users and formal experts to acceleration users and software teams—can utilize a single integrated coverage tool to maximize productivity and minimize confusion.

The IMC is a single-user tool that loads and views coverage from a single run or a single merged-coverage run. A familiar user interface and compatible workflow lets you easily shift from individual run analysis to largescale regressions with the Cadence Metric Driven Signoff Platform.

This tool has many benefits which include the following:

- Quickly generate unified coverage metrics with an intuitively organized environment, improves time to results with rapid sort, filter, and search processes
- Optimize your productivity with pre-defined GUI-based analysis windows
- Get up and run quickly with the metric-driven verification (MDV) methodology and integration with the vManager platform
- Improve your productivity with high-performance merger, rank, and reporting, scalable to exceptionally large designs

The TXU Block functions are:

- *PRN Mapping to Transmitters*

There are 8 PRN values delivered from the TXU-B, which then must be mapped to the 12 transmitters. The mapping occurs after the up-sample is performed, as each user of a particular PRN value must have the same up-sample operation applied. The ICU receives two copies of the PRN data, one that is at the chip rate, and corresponds to the assignments to live transmitters, this mapping is supplied by the ICU, and is used to provide downstream processing blocks with the transmitted chip rate PRNs. The second is the actual transmitter symbol rate data necessary for the ICU operation, which is composed of 12 transmitters of symbol rate data, as well as the squelch. As the RX modulators must stay coordinated with the transmitter modulators, each TX symbol rate value is delivered to both the TXU-T and the ICU.

- *Symbol/Sub-Symbol Programmable Delay*

For alignment purposes, it is necessary to delay the outputs to the DAC at an 8GHz resolution. For the fine grain delay, it is possible to alter the first sub-symbol sample to appear in any of the four lanes to the DAC. This effectively appears as an 8GHz delay at the output of the DAC and is the finest granularity possible on the transmitter. To save delay area, any delay over one symbol is managed at the symbol rate. The symbol level delay is variable from 1-16 clocks.

- *Chip Shaping Up-sample*

To move from chip rate to symbol rate, a programmable function is available to apply a random distribution against a set of selection values that maps between the available PRNs. As interference must be removed from the received data, the random mapped PRNs must be delivered to the ICU. The eight PRNs that have been generated in the PGU are mapped to the 12 transmitters, and the same mapped data is sent to the

ICU. Additionally, the eight active PRNs are delivered as both symbol rate and chip rate to the ICU.

- *UMSK FSM Input Mapper*

Prior to the modulator, a mapper is used on the inbound PRN data. One option with the mapper is to alter the rotation pattern of the data stream. As initially defined, the mapper converts a constant input based on a $1\ j\ 1\ j$ pattern. Using the mapping signal, the pattern is modified to utilize a $1\ j\ -1\ -j$ pattern for a constant input.

- *UMSK Modulator*

The modulator takes the mapped bits and generates an address to read from the IQ value RAM (Random Access Memory). The address is based on a two bits state value representing the prior 2 bits, the current bit being modulated, and the next two bits. This generates five bits address to the RAM, although this is the location where the sub-symbol delay is applied, so it is an indirect connection through the delay element.

- *UMSK IQ Value RAM*

The IQ values are stored in a RAM for delivery to the DAC, with four values stored per address, representing the 4x symbol to DAC rate. If a sub-symbol delay is required, it is necessary for the RAM to deliver the data in a manner that the first column of data appears first for the address, which due to the sub-symbol delays, means that the value may appear on any of the four lanes.

- *BPSK Modulator*

The BPSK modulator maps the +1 and -1 values to a programmed eight bits value, and the complement value. Out of reset this value is set to +127 and -127.

- *IQ Squelch*

To provide a means to stop transmitting, a squelch input from the TXU-B indicates that the output from the RAM should be zeroed, regardless of any input address delivered to the RAM.

- *PRBS per DAC Lane with BPSK*

To provide the ability to inject a modulation value on the DAC, a PRBS generator is available to drive data onto each lane through a BPSK modulator. Rather than a mux, this point is implemented as an added to the stream. Each lane I and Q has independent capability to insert data, while BPSK ordinarily needs to only operate on the I values, to permit testing of the Q paths, both the I and Q have independent controls, that if the Q control is enabled, the BPSK values will be inserted on the Q paths. The PRBS is available even if the data is squelched.

- *DC Offset Compensation*

To remove I and Q offsets, a 2's complement value can be added independently to the I and Q data paths. This value is available even if the data is squelched.

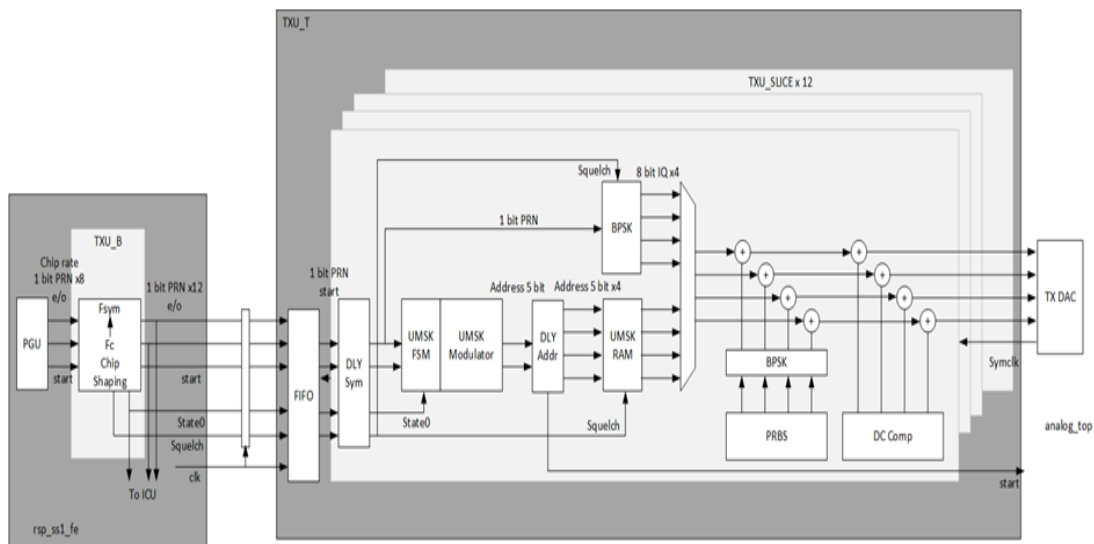


Fig 3.14. High level diagram of TXU Block

3.3.3. Transmit PRN Translation Unit-B (TXUB)

The overall Transmit PRN Translation Unit is split into two related but independent components, a TXUB located on the D-Die which upconverts PRN chip rate data to symbol rate data, and a TXUT located on the A-Die which modulates the symbol rate PRNs for transmission. This document covers the

TXUB operation. The name TXUB is a legacy of the first implementation of the system where the TXU was split between a block placed at the bottom of the analog subsystem and a separate block placed at the top of the analog subsystem. This is the module that has legacy to the bottom of analog subsystem block.

The key features of TXUB are:

- Implement an up-sample from Chip to Symbol rate
 - Programmable rate from 1 to 8
- Implement a chip shaping function
 - Based on randomized function to select current or next PRN to use
- Observes modulator state and provides an indication when the machines end in state 0
 - Maintains alignment between ICUD and TXUT modulators
- Maps PRN generators to TX Channels
 - Any to any
 - Broadcast single PRN to 2 to 12 Channels
 - Send nothing to a Channel
 - Enforces the number TX Channels implemented from the provisioning fuses

Interface Description

There are four main interfaces on the TXUB. The first is the APB programming interface, which operates from the APB clock. This is the standard implementation of the APB interface, used throughout the chip.

The first data path interface is from the PGU, which delivers data and control to the TXUB. This control is operating at chip rate, with an enable indicating which of the data values is valid. Control is always valid from the PGU.

The second data path interface stays on the D-Die and is the up-sampled data sent to the ICUD for cancelation. This data includes the control signals that identify the expected state of the modulator, and an enable is used to identify the valid data passed. The enable permits the clock to run independent of the data rate, with the data rate being formed based on the actual clock rate, and the number of enables generated.

The final data path interface is the link to the A-Die and contains the PRN data and all necessary control to drive the behavior of the TXUT. Enables are used to decouple the interface link clock from the data rates passed between the two die. So long as the link clock is fast enough, data will be transferred between the two die, with an enable to bring the actual data rate down to the necessary rate.

Functional Safety

The APB interface is protected from bit flips through a parity mechanism. Should any configuration bits flip, an interruption will be generated to indicate that the APB detected an error in programming. To validate that update are correct before being applied with an update, a CRC is checked on the programmed, but not yet applied values. Should there be any additional writes to these registers, or the CRC not match the expected value for the programming, an interruption will be generated.

To validate independence of signal data paths, the selectors in the TXUB permit any PGU generator to be directed to any TX DAC. In addition to moving any PGU generator to any TX DAC, the same PGU generator can be mapped to multiple TX DAC outputs, to be able to validate that the same value to multiple outputs results in the same output at all mirrored data paths.

As this is the last block on the D-Die, the number of enables observed, not the number of valid data values, as there are two per enable, are counted, and a

mismatch between the expected count and the actual count per start will be indicated with an interrupt generation.

3.3.4. Scan Configurations

➤ Chip Rates

- Support for chip rates up to 2GHz

Table 3.3. Chip rates

Chip Rate	Duty Cycle	LC	Comments
1-2 Gchips/s	100%-50%	11K	The HW can only support up to 1Gchips/s, everything above will result in a reduced duty cycle.
62.5Mchips/s - 1Gchips/s	100%		

- Note: This is assuming the correlator can be run at 1 GHz, it might only be running at 800MHz, in which case there will be a reduced duty cycle.

➤ Range Bins

- The HW supports 128 Range bins - additional range bins are supported in "Replay Mode" - which means we will replay the same PRI multiple times towards the correlator. This only works if the chip rate is low enough so that we can process it e.g., 2x faster
- Note: This is assuming the correlator can be run at 1 GHz, it might only be running at 800MHz, in which case there will be a reduced duty cycle.

Table 3.4. Range bin classification

Chip Rate	Range Bins	Max LC	Comments
1 Gchips/s - 2 Gchips/s	128	11K	In Quiet mode the max number of LC's could be increased to 22K, but the duty cycle would also be significantly larger.
62.5Mchips/s - 1Gchips/s	128	16M	
62.5Mchips/s - 400Mchips/s	256	11K	Assuming the Correlator is running at 800MHz.
62.5Mchips/s - 266Mchips/s	384	11K	Assuming the Correlator is running at 800MHz.
62.5Mchips/s - 200Mchips/s	512	11K	Assuming the Correlator is running at 800MHz.

➤ **LC**

- The max. number of supported LC's depends on the mode we are operating in.

Table 3.5. Description of LC and QDU mode

Max LC	QDU Mode	Comment
16M	Bypass	This is only possible if the QDU memory is not used for throttling, quiet, replay or loopback mode.
11K	Replay, Throttle	In case of replay (more than 128 range bins are required), throttling (chip rate is above 1Gchips/s) the max. number of LC on a per PRI basis is limited to 11K. One QDU memory is used to store the incoming PRI while the other QDU memory is used to replay/throttle.
22K	Quiet, Loopback	In case of quiet/loopback mode the full QDU memory can be used to store a PRI (up to 22K) - but that also means the duty cycle will be larger.

➤ *FFT Engine*

- Throughput: one complex number every clock cycle - FEU can operate at up to 700MHz (800MHz)
- Support Zero Padding and Windowing up to 5040 points FFT
- FFT support
- Full throughput: 105, 112, 120, 126, 140, 144, 168, 180, 210, 240, 252, 280, 315, 336, 360, 420, 504, 560, 630, 720, 840, 1008, 1260
- Reduced throughput: 1680, 2520, 5040
- Channelizer support for even numbers of FFT points

➤ *Beam Forming*

- The beam forming matches the FFT throughput and can process 1 complex point every clock cycle for up to 64VRx's.s

PRBS-31 (each PRI is LC long)

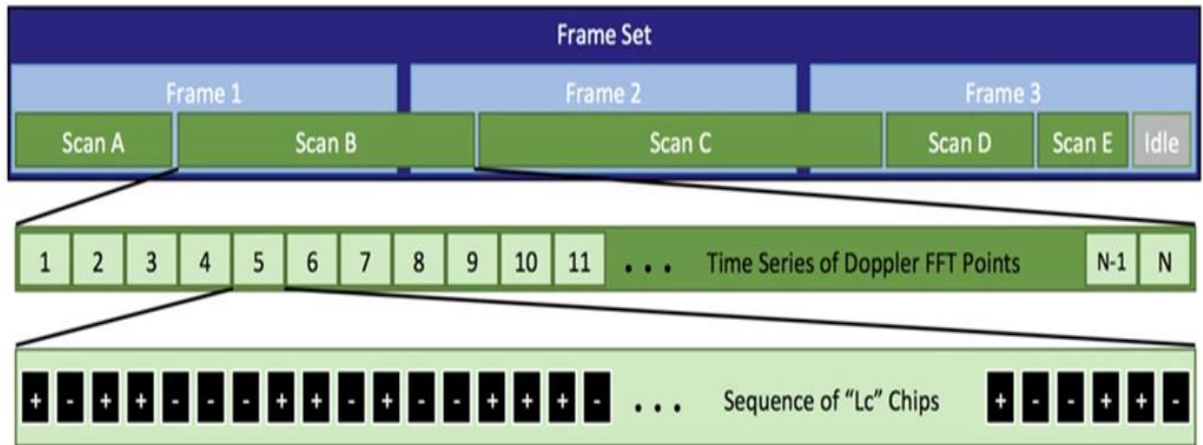


Fig 3.15. Scans Frameset

Normal Periodic Scan (e.g., APAS or M-Sequence - with k=4 Hadamard outer code for 4 Tx system)

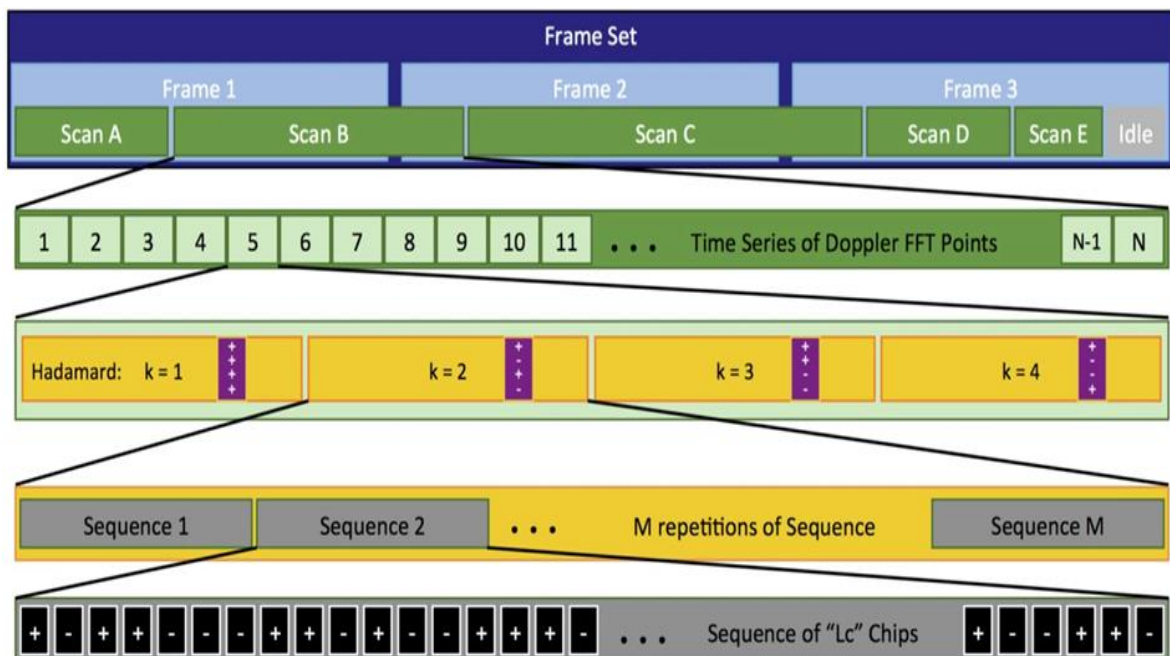


Fig 3.16. Normal Periodic Scan

Normal Periodic Scan (showing discarded sequences Q,1)

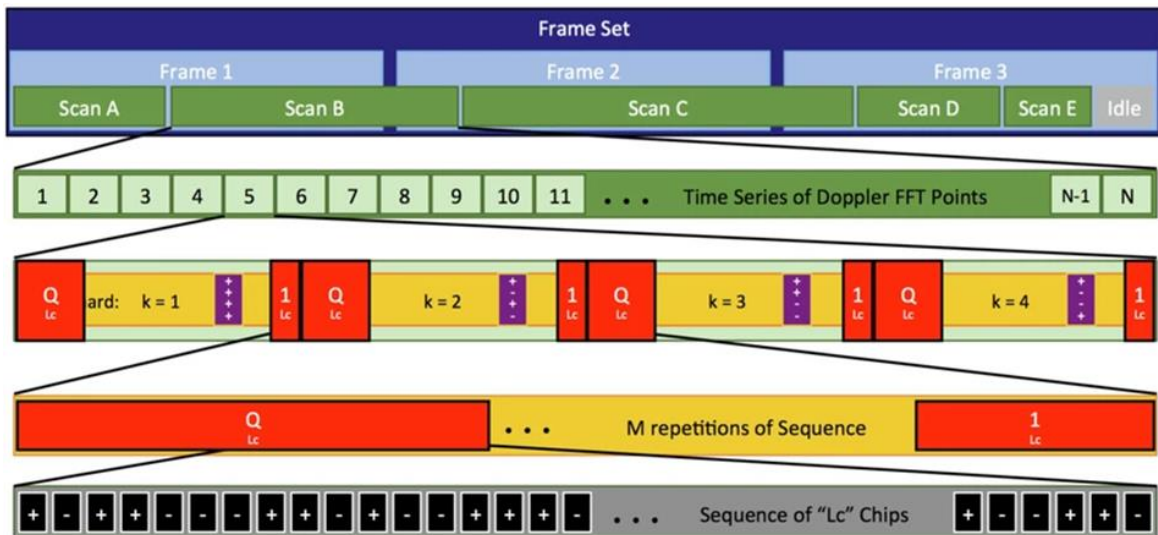


Fig 3.17 Normal Periodic Scan (showing discarded sequences Q,1)

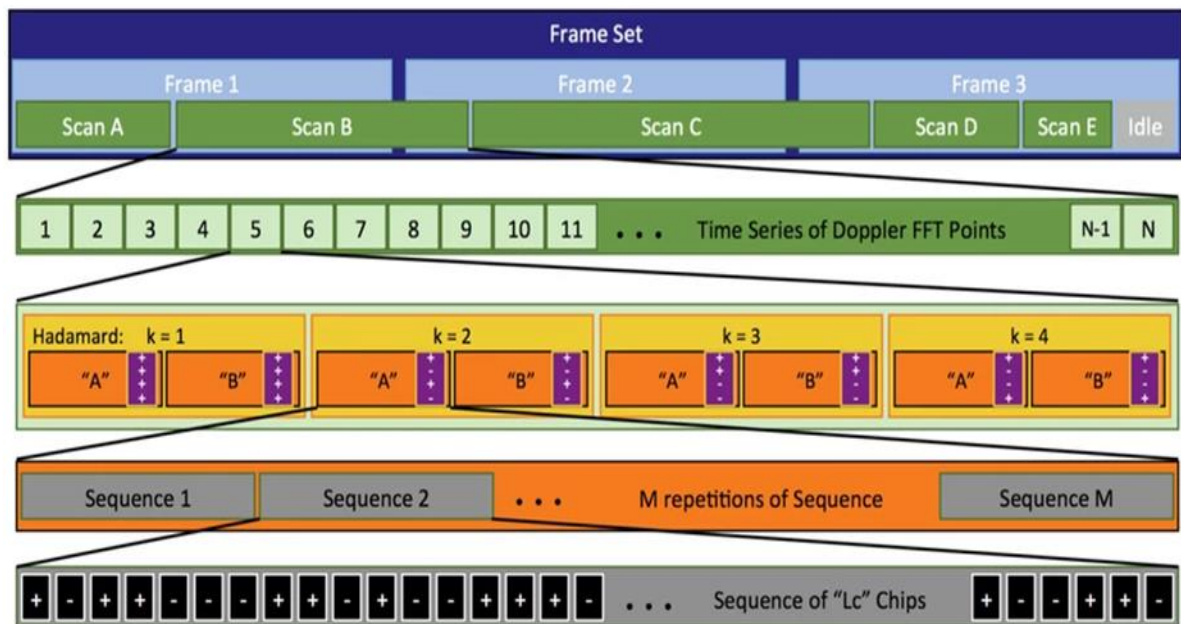


Fig 3.18. Detailed block of M sequences and Lc sequences

3.3.5. Addition of Test cases

Automotive radar sensors are used on the body segment. They can be used for position sensing, motor control, comfort features and HMI (Human Machine Interface) applications. There are distinct categories of automotive radar sensors that designed to meet specific needs: Short-Range Radar (SRR), Mid-Range Radar (MRR), and Long-Range Radar (LRR).

Short-range radar systems are used for automotive applications in which the car is moving slow, or an obstacle is located near the vehicle such as in blind spot detection sensors or lane change assist radar sensors. Using milli meter-wave radar sensors in vehicles allows the radar system to transmit electromagnetic wave signals that can then be recaptured and used to determine the range, velocity, and angle of an object when the wave signal is reflected by an object in its path.

Both SRR and MRR radar sensors can also be placed on all four corners of the vehicle. This is called a corner radar and can detect obstacles or pedestrians before they are visible to the driver and deploy automatic emergency braking (AEB). Long range radar sensors are most used in the front section of vehicles as they can better detect traffic changes from farther distances ahead. As sensor content is expected to grow further as interior and comfort is becoming a key differentiation factor for OEM's, automotive radar sensor manufacturers require high quality and reliable radar sensor technology to meet their specific needs.

Additionally, 4D automotive imaging radar sensors are increasingly being used in autonomous vehicle designs as they offer excellent detection of both moving and stationary objects from greater distances and with better accuracy than traditional radar sensors. This is due to utilizing a multi-input, multi-output (MIMO) 48-antenna array which, when compared to less than 5 transmitting and receiving

antennas in regular radar sensing solutions, allows a dataset to be created of the car's surroundings.

Using radar sensors for automotive collision warning and avoidance is especially important for automated driving where vehicles need to be able to react and reliably avoid hitting objects and people.

This Radar chip resolution enables the system to distinguish between adults, children, and infants, to distinguish the rough shape of the body, and to sense your body position, all in a non-photographic method that does not invade anyone's privacy. The fourth dimension, of course, is time; it will scan the car several times a second and track changes and movements over time. Few testcases are added to improve the functioning of Radar safety for automotive applications. The test cases are:

- TXUB antenna configuration test for counting PRN
- TXUB antenna configuration test for interrupt check
- TXUB antenna configuration reset test
- TXUB antenna configuration custom parity test

All these test cases are planned, implemented, and executed for improving functional safety.

3.3.6. Coverage Analysis

Coverage dominates every aspect of verification for today's complex IP and chip designs. Coverage metrics provide critical feedback on what has been verified and what has not, especially when automated stimulus generation techniques are used. All modern hardware design and verification languages include constructs for functional coverage specification and support a range of structural coverage measures (line, block, expression, etc.) as well. Coverage closure and bug rates play key roles in project management deciding when to tape out a

design. It is unacceptably risky to commit to silicon before achieved coverage reaches 100% of the target goals, or at least asymptotically converges toward those goals.

Coverage specification is now built into verification plans as well as languages. Engineers no longer define, and hand-code long lists of tests for specific features. Instead, they specify the coverage properties that show when these features have been exercised. Planning is the first phase of the typical SoC verification process. The second is execution, in which simulation using constrained random verification (CRV) is the primary method of generating stimulus and checking results, and the reported coverage documents exactly which parts of the design have and have not been verified.

Code coverage is a completion metric that indicates how much of the code of the Design Under Test (DUT) has been exercised. It does not indicate that the code is correct or even that all necessary code is present.

Code coverage can never be used to indicate the quality of the product but can be useful to identify holes in the verification that has been performed. As such, it is often used to gate completion of verification process but never as way to indicate sufficiency of verification.

There are several types of code coverage:

1. *Statement/Line Coverage*

This gives an indication of how many statements (lines) are covered in the simulation, by excluding lines like module, end module, comments, timescale etc. This is important in all kinds of design, and it is to be 100% for verification closure. Statement coverage includes procedural statements, continuous assignment statements, conditional statement, and Branches for conditional statements etc.

2. *Block Coverage*

A group of statements which are in the begin-end or if-else is called a block. Block coverage gives the indication that whether these blocks are covered in simulation or not. The nature of the block coverage & line coverage looks similar. Block coverage looks for a group of statements called block and line coverage/statement coverage checks whether each statement is covered.

3. *Conditional/Expression Coverage*

This gives an indication how well variables and expressions in conditional statements are evaluated. Conditional coverage is the ratio of number of cases evaluated to the total number of cases present. If an expression has Boolean operations, the entries which is given to that expression to the total possibilities are indicated by expression coverage.

4. *Branch/Decision Coverage*

In Branch coverage or Decision coverage reports, conditions like if-else, case and the ternary operator statements are evaluated in both true and false cases.

5. *Toggle Coverage*

Toggle coverage gives a report that how many times signals and ports are toggled during a simulation run. It also measures activity in the design, such as unused signals or signals that remain constant or less value changes.

6. *State/FSM Coverage*

FSM coverage reports, whether the simulation run could reach all the states and cover all transitions or arcs in each state machine. This is a complex coverage type as it works on behaviour of the design, that means it interprets the synthesis semantics of the HDL (Hardware Description Language) design and monitors the coverage of the FSM representation of control logic blocks.

3.4. LANGUAGES AND METHODOLOGIES

3.4.1. *System Verilog*

Hardware Description Languages like Verilog and VHDL are used to describe hardware behavior so that it can be converted to digital blocks made up of combinational gates and sequential elements. To verify that the hardware description in HDL is correct, there is a need for a language with more features in OOP (Object Orient Programming) that will support complicated testing procedures and is often called a Hardware Verification Language.

SystemVerilog is an extension of Verilog with many such verification features that allow engineers to verify the design using complex testbench structures and random stimuli in simulation.

Verilog was the primary language to verify functionality of designs that were small, not complex and had less features. As design complexity increases, so does the requirement of better tools to design and verify it. SystemVerilog is far superior to Verilog because of its ability to perform constrained random stimuli, use OOP features in testbench construction, functional coverage, assertions among many others.

A hardware design mostly consists of several Verilog (.v) files with one top module, in which all other sub-modules are instantiated to achieve the desired behavior and functionality. An environment called testbench is required for the verification of a given Verilog design and is usually written in SystemVerilog these days. The idea is to drive the design with different stimuli to observe its outputs and compare it with expected values to see if the design is behaving the way it should.

To do this, the top design module is instantiated within the testbench environment, and design input/output ports relate to the appropriate testbench component signals. The inputs to the design are driven with certain values for

which we know how the design should operate. The outputs are analyzed and compared with the expected values to see if the design behavior is correct.

The SystemVerilog verification methodology relies on 3 building blocks, which can be used separately, or all together:

- *Stimuli* the design using automatically generated random scenarios - constrained-random (CR) test generation.
- *Check* the behavior of the design (assertions) and the output data (scoreboard) to verify correctness of operation.
- *Measure* the functional coverage metrics to provide feedback to the generation and analyze progress of verification

Applying the above methods that include iterative process of simulation, debug and coverage measurement is known as Coverage Driven Verification. The goal of a Coverage Driven Verification methodology is to maximize verification effectiveness and at the same time, minimize redundancy and ineffective verification work.

The SystemVerilog language contains commands and constructs to support CDV including commands for constraint-random generation, assertions, and functional coverage measurement.

Measuring coverage is a critical component of the CDV methodology. The SystemVerilog coverage measurement commands (like cover group and cover point) provide feedback regarding the completeness of the verification process and guide the next steps of verification so that effort and resources are applied to improve overall verification.

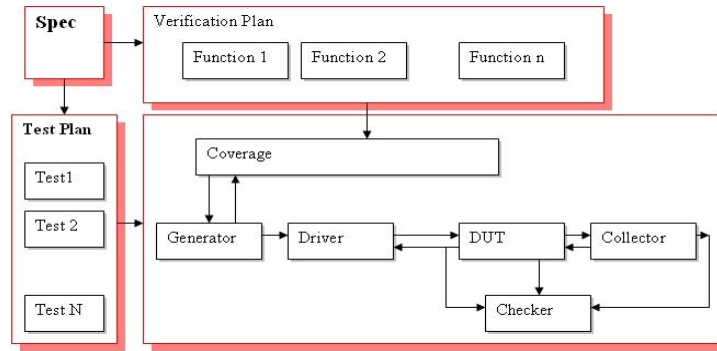


Fig 3.19. SystemVerilog Verification

3.4.2. Universal Verification Methodology

Universal Verification Methodology (UVM) is a methodology for the functional verification of digital hardware, primarily using simulation. The hardware or system to be verified would typically be described using Verilog, SystemVerilog, VHDL or SystemC at any appropriate abstraction level. This could be behavioral, register transfer level, or gate level. UVM is explicitly simulation-oriented, but UVM can also be used alongside assertion-based verification, hardware acceleration or emulation.

If you currently run RTL simulations in Verilog or VHDL, you can think of UVM as replacing whatever framework and coding style you use for your testbenches. But UVM testbenches are more than traditional HDL testbenches, which might wiggle a few pins on the design-under-test (DUT) and rely on the designer to inspect a waveform diagram to verify correct operation. UVM testbenches are complete verification environments composed of reusable verification components and used as part of an overarching methodology of constrained random, coverage-driven, verification.

UVM consists of class libraries needed for the development of a well-constructed, reusable SystemVerilog based Verification environment. In simple words, UVM consists of a set of base classes with methods defined in it, the

SystemVerilog verification environment can be developed by extending these base classes.

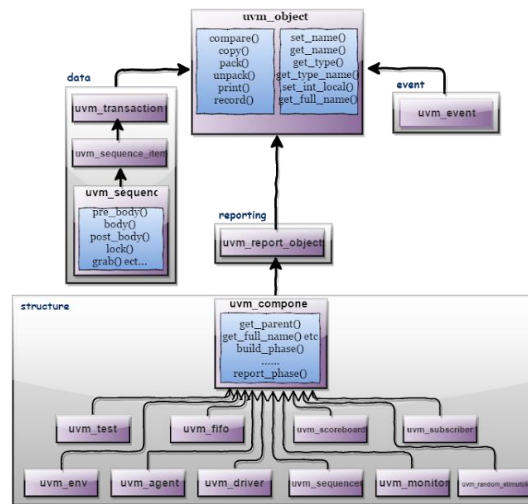


Fig 3.20. UVM Class Hierarchy

3.4.3. SystemVerilog Verification Using Universal Verification Methodology (UVM)

Verification of complex systems should not be reliant on manual inspection of detailed waveforms and vector sets. Functional checking must be automated if the process is to scale well, as must the collection of verification metrics such as the coverage of features in the verification plan and the number of bugs found by each test. Along with the verification plan, automated checking and functional coverage collection and analysis are cornerstones of any good verification methodology and are explicitly addressed by SystemVerilog and UVM. Checkers and a functional coverage model, linked back to the verification plan, take engineering time to create but result in much improved quality of verification.

All simulation-based verification suffers from the issue that you can never run enough test vectors to exhaustively test the whole design, or even any significant part of a complex design. One way to address this issue is using constrained random stimulus. The use of random stimulus brings two significant benefits.

Firstly, random stimulus is great for uncovering unexpected bugs, because given enough time and resources it can allow the entire state space of the design to be explored free from the selective biases of a human test writer. Secondly, random stimulus allows compute resources to be maximally utilized by running parallel compute farms and overnight runs. Of course, pure random stimulus would be nonsensical, so adding constraints to make random stimulus legal is an important part of the verification process and is explicitly supported by SystemVerilog and UVM.

The best way to approach the verification process is to start with simple directed (non-random) tests to bring up the design, then move to fully random tests to explore the state space in a broad fashion and flush out as many bugs as possible with minimum human effort devoted to test writing. This will typically achieve much less than 100% functional coverage, and the remainder of the verification process is spent defining a series of tests, each of which constrains and shapes the random stimulus in a unique way to push the design into interesting corner cases. The state space of a typical design is so vast that random stimulus alone is not enough to explore all the key use cases yet directed or highly constrained tests can be too narrow to give good overall coverage. Constrained random stimulus is a compromise between the two extremes, but effective usage comes down to making a series of good engineering judgements. The solution is to use the priorities set in the verification plan to direct verification resources to the key areas.

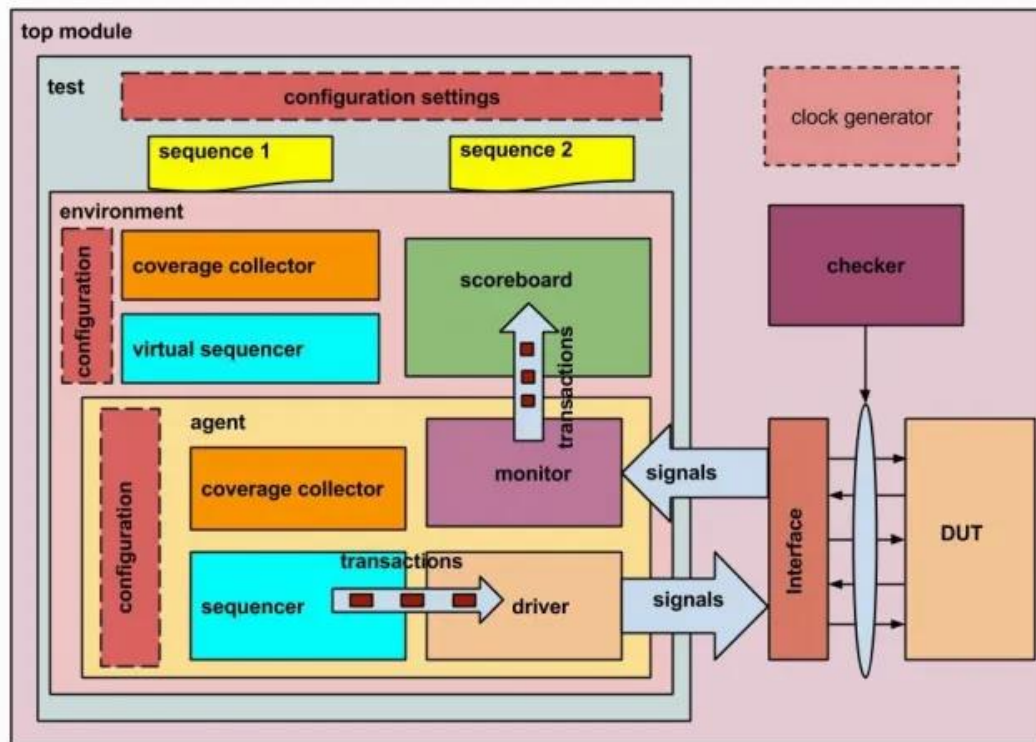


Fig 3.21. UVM Environment with Components

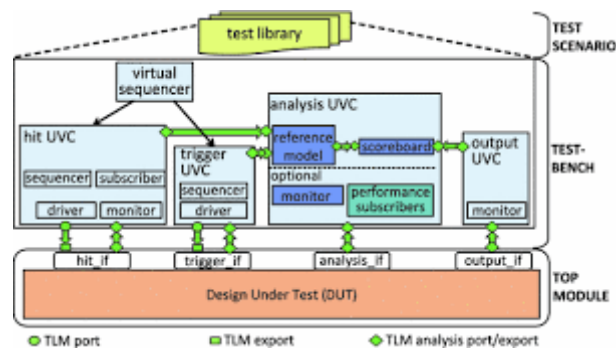


Fig 3.22. SystemVerilog-UVM Testbench

CHAPTER 4

4.1. RESULTS

4.1.1. TXUB antenna configuration test for counting PRN

This testcase was implemented to count the PRN which are at chip rate coming from PGU and are given to TXUB. The result of this testcase has been written using systemverilog using UVM. It is tested using plusargs in Linux. The test has passes which resulted in the next test case i.e., TXUB antenna configuration test for interrupt check.

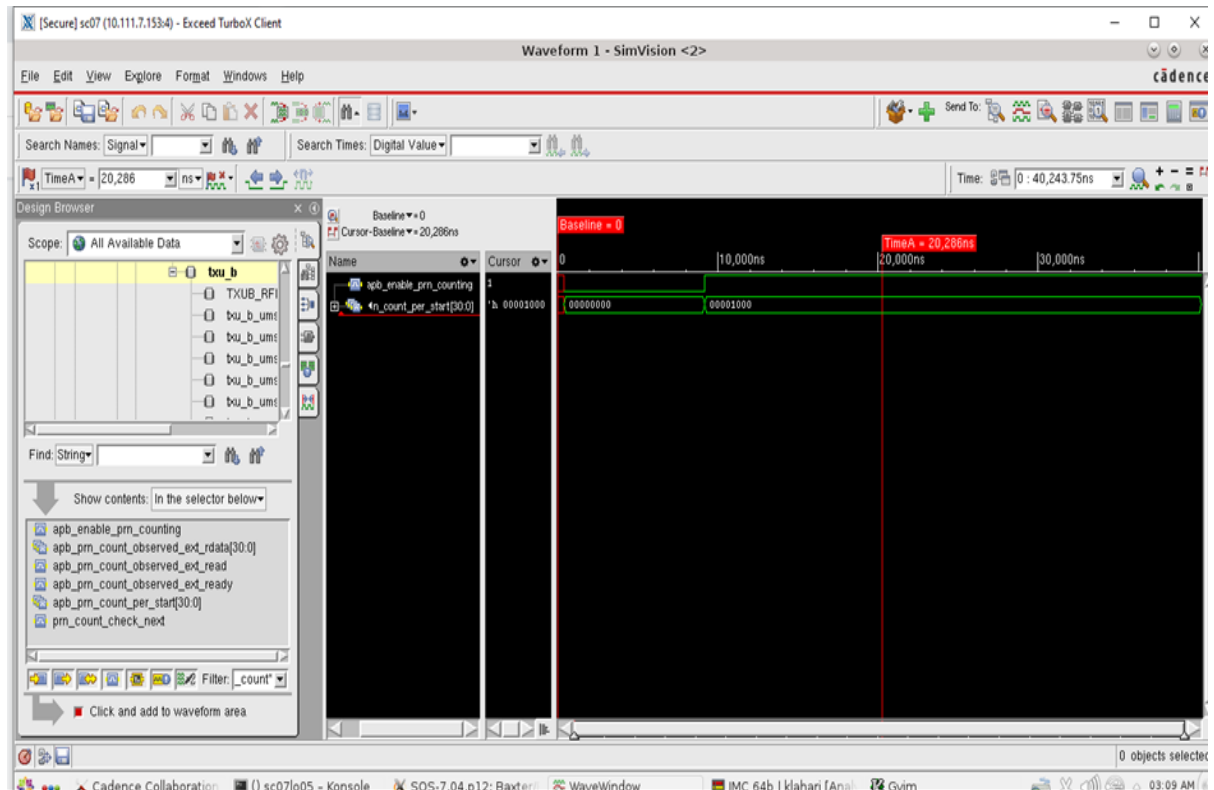


Fig 4.1. Waveform for PRN count

4.1.2. TXUB antenna configuration test for Interrupt check

Antenna configuration test for Interrupt check testcase is implemented to check for the interrupt when PRN count is not in the range i.e., when it is not in the range of product of pri_config and lc_config. The result of this testcase is shown below.

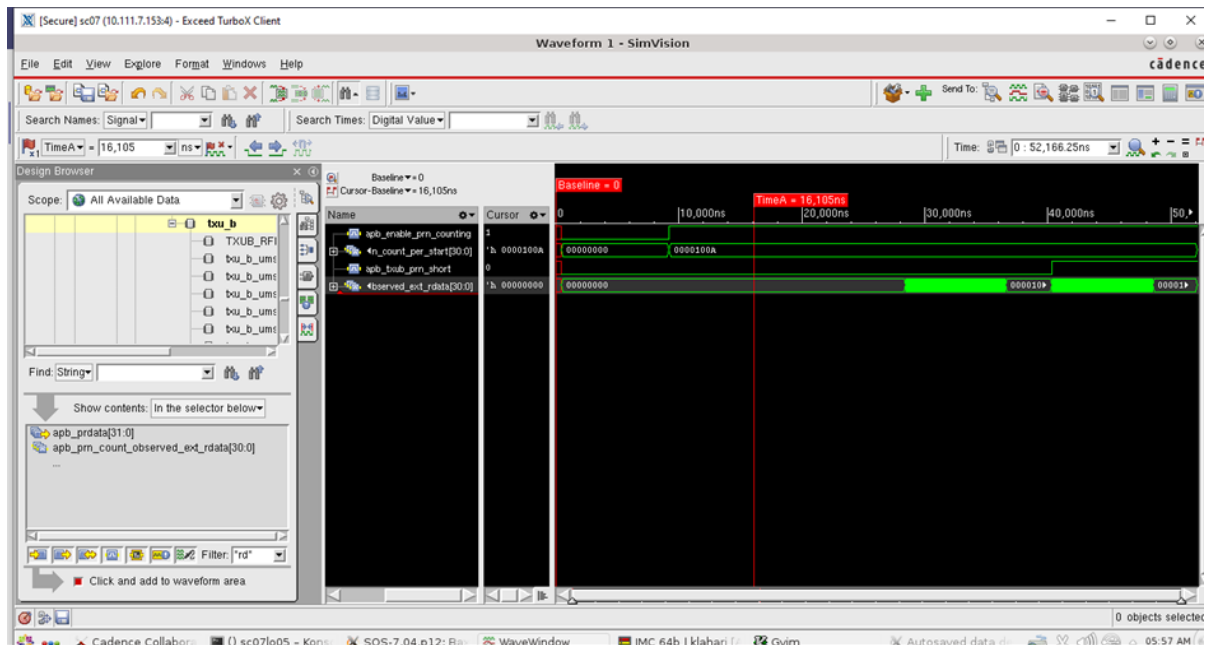


Fig 4.2. Waveform for Interrupt Check

4.1.3. TXUB Antenna configuration test for reset and custom parity

These two tests are implemented to avoid collision and the overheating of chips which is mandatory for the function of the Radar. Post this test a regression was ran with enabling coverage to test for all the testcases. The below result has been shown.

```

[Secure] sc07 (10.111.7.153:4) - Exceed TurboX Client
() sc07lo05 - Konsole

File Edit View Bookmarks Settings Help

[clk_agent] 16
[get_name()] 1
[ssl_env] 780
[txuB_scoreboard_i] 745510
[uvm_test_top] 4
xm_specman is doing end-of-test operations
Checking the test ...
Checking is complete - 0 DUT errors, 0 DUT warnings.
Wrote 1 cover_struct to ./cov_work/scope/cdn_apb_psif_api_top_sni_sv1/sn.ucd
End-of-test operations are completed
*Denali* [48571250 ps] uvm_test_top.ssi_env.apb_master_reg : End of Test Summary: Write transfers sent: 674 Read transfers sent: 106
*Denali* [48571250 ps] uvm_test_top.ssi_env.apb_master_ram : End of Test Summary: Write transfers sent: 0 Read transfers sent: 0
xmsim: *N,COVCGN: Coverage configuration file command "set_covergroup -new_instance_reporting" can be specified to improve the scoping and naming of covergroup instances. It may be noted that subsequent merging of a coverage database saved with this command and a coverage database saved without this command is not allowed.
xmsim: *N,COVSRP: mce_cmn_intr (File: /projects/sabine/asimov/work/klahari/sos_repo/asimov/rtl/rsp_ss/mce/mce_config_top.sv, Line: 95): Un-expanded nets of structs, MDAs of structs and Enum MDAs cannot be smart-refined. There might be other such nets in the design.

coverage setup:
workdir : ./cov_work
dutinst : ssi_top_tb(ssi_top_tb)
scope : scope
testname : cdn_apb_psif_api_top_sni_sv1

coverage files:
model(design data) : ./cov_work/scope/icc_4dc82a70_591ad468.ucm
data : ./cov_work/scope/cdn_apb_psif_api_top_sni_sv1/icc_4dc82a70_591ad468.ucd
TOOL: xrun(64) 21.03-s003: Exiting on Dec 28, 2021 at 22:04:13 PST (total: 00:15:31)
'-- Test Passed --' not found in $RF_SIM_USER_SCRATCH_AREA/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/xrun.log Time for debug !!.
[67] sc07lo05::/projects/sabine/asimov/work/klahari/sos_repo/asimov/verif/projects_links/sim/asimov/ssl/metadata > $RF_SIM_USER_SCRATCH_AREA/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/xrun.log
/rscatch/sabine/asimov/klahari/simulation/sos_repo/user/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/xrun.log: Permission denied.
[68] sc07lo05::/projects/sabine/asimov/work/klahari/sos_repo/asimov/verif/projects_links/sim/asimov/ssl/metadata > cd $RF_SIM_USER_SCRATCH_AREA/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/xrun.log
/rscatch/sabine/asimov/klahari/simulation/sos_repo/user/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/xrun.log: Not a directory.
[69] sc07lo05::/projects/sabine/asimov/work/klahari/sos_repo/asimov/verif/projects_links/sim/asimov/ssl/metadata > $RF_SIM_USER_SCRATCH_AREA/blocks/ssl/tests/ssl_txub_antenna_cfg_test_1/

```

Fig 4.3. Result for reset and custom parity test

Regression Summary @ Jan-18 : 02:15:03 (Click on the completed compile/lab for accessing the log)

Block	Compile	Elab	#Tests	#Pass	#Fail	#InConc	#InProg	#Pend
ssl	Pass	Pass	10	10	0	0	0	0
Total	---	---	10	10	0	0	0	0

Buddy Session: /rscatch/sabine/asimov/klahari/simulation/sos_repo/user/buddy/jan_18_01_43_37

Coverage Snapshot @ Jan-18 : 02:16:21

Instance	Overall	Block	Expr	Toggle	FSM-State	FSM-Xtion	Assertion	Covergroup
ssl (#merged tests: 10) (#excluded tests: 0)								
adl	25.94%	63.50%	40.41%	10.71%	23.64%	1.89%	n/a	n/a
ctu_be	3.92%	43.14%	47.46%	0.09%	9.45%	0.00%	n/a	n/a
ctu_fe	3.59%	44.33%	0.00%	0.01%	25.00%	0.00%	n/a	n/a
icu	12.41%	56.19%	33.79%	2.18%	20.00%	0.00%	n/a	n/a
ptu	12.57%	71.53%	32.68%	1.48%	20.00%	0.00%	n/a	n/a
qgu	12.83%	65.41%	10.04%	1.01%	16.28%	1.16%	n/a	n/a
rsu	11.34%	48.28%	30.19%	1.06%	20.00%	0.00%	n/a	n/a
scu	12.58%	61.75%	26.80%	2.36%	10.81%	0.00%	50.00%	n/a
ssl_be	6.92%	53.44%	31.09%	0.74%	11.50%	0.00%	50.00%	n/a
ssl_fe	15.56%	58.95%	24.72%	4.63%	25.16%	6.89%	87.50%	n/a
ssl_top	9.30%	55.52%	25.20%	1.72%	17.06%	2.32%	50.38%	n/a
txu_t	22.29%	70.46%	48.63%	7.98%	11.11%	0.00%	n/a	n/a
ctu_be_fcov	23.08%	n/a	n/a	n/a	n/a	n/a	n/a	23.08%
ctu_fe_fcov	28.13%	n/a	n/a	n/a	n/a	n/a	n/a	28.13%
ptu_fcov	55.05%	n/a	n/a	n/a	n/a	n/a	n/a	55.05%
qgu_fcov	28.33%	n/a	n/a	n/a	n/a	n/a	n/a	28.33%
rsu2_fcov	43.72%	n/a	n/a	n/a	n/a	n/a	n/a	43.72%
scu_fcov	30.38%	n/a	n/a	n/a	n/a	n/a	n/a	30.38%

Fig 4.4. Verification and Coverage Result of regression

4.1.4. Coverage Result

Several types of coverage analysis have been performed to ensure that the entire code is covered and thus ensuring more safety of radar chips. Before the coverage analysis, it was observed that all the signals were not being included and the result is shown below.

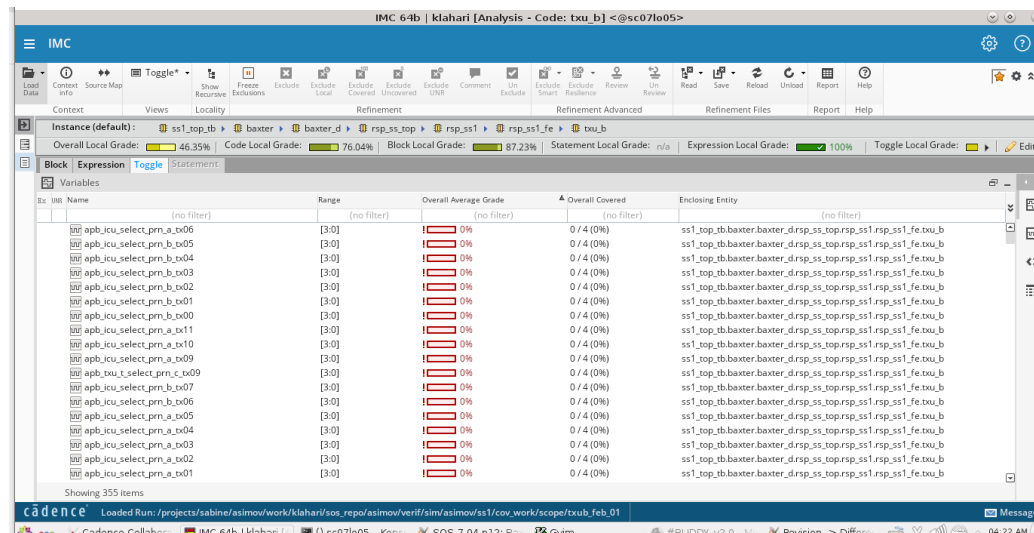


Fig 4.5. Result before Coverage Analysis

Post implementing code and after the coverage analysis, the refinement is applied and all the signals are included, and the result is shown in figure 4.6.

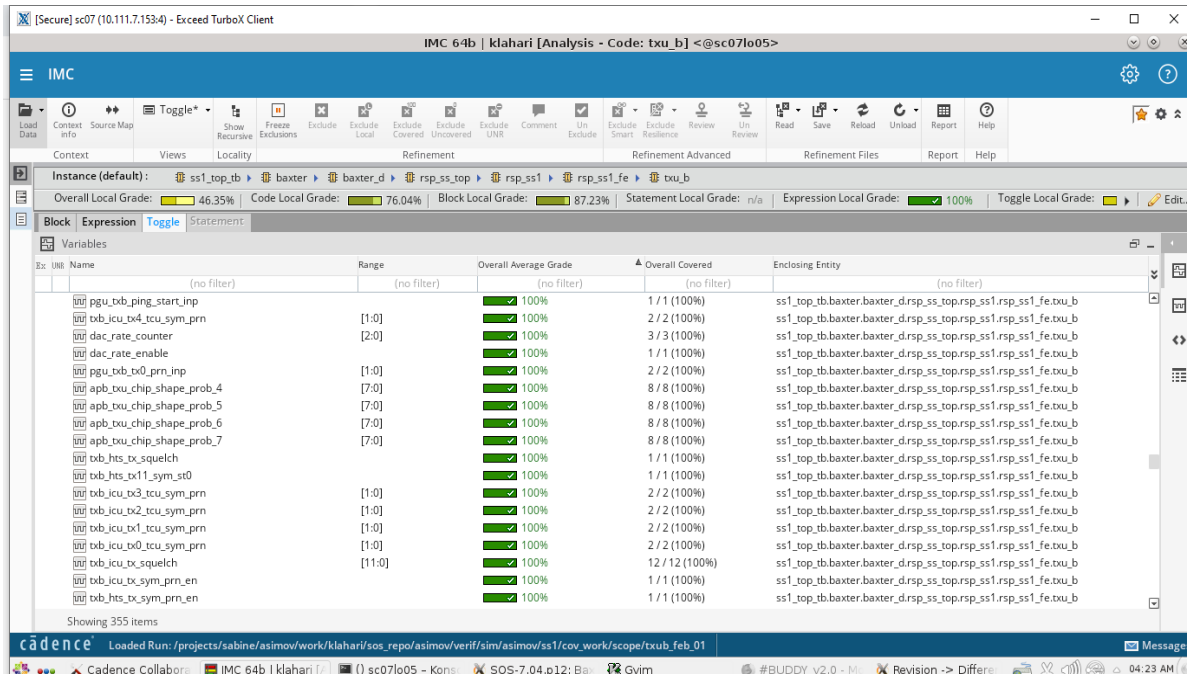


Fig 4.6. Result after coverage analysis

After merging all the codes, the repository was upgraded and the coverage has increased to 95.55% as shown in the below figure.

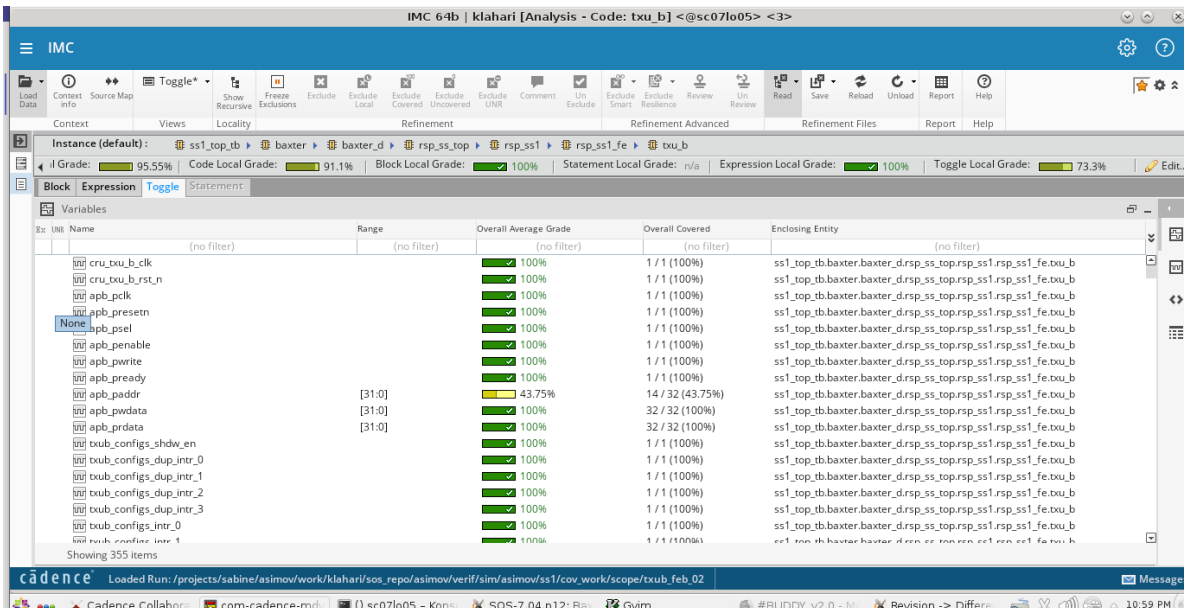


Fig 4.7. Result after merging all the coverage analysis

4.2. CONCLUSION

A Digital RADAR chip which is designed for Automotive applications has been verified and improved the overall coverage of chips. From the results it is observed that the coverage has been increased from 23.56% to 95.55%. The proposed coverage analysis has enhanced the overall performance of the RADAR chip and required safety can be achieved by introducing it to the automotive industry.

