ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Automatic Grade and Quad Crossing Safety and Delay Optimization in Addis Ababa LRT

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In Partial Fulfillment of the Requirement for the Degree of Master of

Science in Electrical Engineering for Railway Systems

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June 20, 2016

Addis Ababa, Ethiopia

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Declaration

I, Kibrom Kidanu, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Abstract

The implementation of Light Rail Transit System (LRTS) as an integrated form of public transportation, with the rail corridor running through city centers and connecting major commercial centers, presents interference with other modes of transportation especially road transport. So at the intersection of the two modes of transport safety becomes the critical issue. This thesis presents new ideas in developing a system which minimizes the risk at level/quad crossing. So a radar based automatic and coordinated system has developed in this thesis to solve the obstacle detection mechanism in Addis Ababa Light Rail Transit al Level/Quad Crossing (LQC) which is not yet adopted on the line.

After reviewing all the available technologies designed for minimizing risk at level/quad crossing here a radar based safety enhancing technology have been presented. Every specification of 122GHz radar system has been mathematically modeled and simulated.

A coordination algorithm for both modes of transport have been developed so unwanted interference will be mitigated. Here the radar signal is considered as an actuator to control the train and traffic signaling system. In addition to this, an optimization equation for minimizing the risk and time delay; and maximizing track and road utilization have been developed and simulated. It shows as the time delay is reduced to 8.6136sec from 10.6706sec.

A possible interfacing mechanism with the existed system of Addis Ababa Light Transit signaling system has been presented.

Keywords: Level crossing, Grade crossing, Bi-signaling, Time delay, Quad Crossing, Preemption, train signaling, optimization, traffic light, simplex algorithm

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List of Abbreviations and Symbols

AALRT	Addis Ababa Light Railway Transit
AASHTO	American Association of State Highway and Transportation Officials
AC	Alternating Current
ADC	Analog to Digital Convertor
ADM	Add Drop Multiplexer
A_e	Effective Area
AFCT	Audio Frequency Track Circuits
AGCS	Automatic Grade and quad Crossing System
AP	Advance Preemption
APT	Advance Preemption Time
A_r	Amplitude of the received waveform
A_t	Amplitude of the transmitted waveform
ATC	Automatic Train Control
ATP	Automatic Train Protection
B	Radar Bandwidth
BCLE	Boolean Crossing Logic Equation
BPF	Band Pass Filter
C	Speed of light
CBTCS	Communication Based Train Control System
CCB	Crossing Control Box
CCTV	Closed Circuit Television
CEPT	European Conference of Postal and Telecommunications Administrations
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
CSD	Clear Storage Distance
CT	Connecting Train
CW	Continuous Wave

DC	Direct Current
DDS	Direct Digital Synthesizer
DFT	Discrete Fourier Transform
DMI	Driver Machine Interface
DSP	Digital Signal Processing
DT	Train Detector
e.i.r.p	Equivalent Isotropically Radiated Power
ECC	Electronic Communications Committee
ECTRI	European Conference of Transport Research Institutes
EMC	Electro-Magnetic Compatibility
ERA	European Railway Agency
ERC	Ethiopia Railway Corporation
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
E-W	East- West Line
f	Frequency
F	Noise figure
FAR	False Alarm Rate
F_b	Beat Frequency
FFT	Fast Fourier Transform
FMCW	Frequency Modulated CW Signal
FoV	Field-of-View
f_r	pulse repetition frequency
FSK	Frequency Shift Key
G	Antenna gain
G_s	Gain of the system
GSM	Global System for Mobile telecommunications
GSM-R	Global System for Mobile telecommunications of Railway

HFTC	High Frequency Track Circuits
IF	Intermediate Frequency
IR	Infrared Range
ISM	Industrial, Scientific, and Medical
ITS	Intelligent Transport Systems
k	Boltzmann's constant
LAN	Local Area Network
L_{Atm}	Atmospheric loss
LC	Level Crossing
LNA	Low Noise Amplifier
LO	Local Oscillator
LoS	Line of Sight
LPF	Low Pass Filter
LQC	Level/Quad Crossing
L_s	System loss
L_t	Total attenuation loss
L_{win}	loss term associated with the type of window (weighting) used in computing FFT
MDS	Minimum Detectable Signal
MMW	Milli-Meter Wave
MPT	Maximum Preemption Time
MSTP	Multi-Service Transport Platform
MTBF	Mean Time Between Failures
MTCD	Minimum Track Clearance Distance
MTI	Moving Target Indication
MUTCD	Manual for Uniform Traffic Controlled Devices
N_0	Receiver noise power density
NBF	Narrow Band Filter
NLOS	NonLine of Sight

N-S	North-South Line
OCC	Operation Control Center
OOK	On-Off Key
P_{av}	average transmitted power from the radar
PCM	Programmable Control Module
P_{cw}	CW average transmitted power over the dwell interval
P_D	probability of detection
PFA	Probability of False Alarm
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
PRF	Pulse Repetition Frequency
PS	Pre-Signal
PSD	Power Spectral Density
P_t	Transmitted Power
Q	Stands for Marcumsq
QCT	Queue Clearance Time
R	Range to target
RCS	Radar Cross Section
RF	Radio Frequency
RF	Radar Frequency
RTD	Round Trip Delay
SA	Angular resolution as a distance between the two targets
SAR	Synthetic Aperture Radar
SDH	Synchronous Digital Hierarchy
SELCAT	Safer European Level Crossing Appraisal and Technology
SHR	Super Heterodyne Receiver
SIW	Substrate Integrated Waveguide
SNR	Signal to Noise Ratio

SP	Simultaneous Preemption
S_r	Received Signal
SRD	Short Range Devices
ST	Separation Time
STM-n	Synchronous Transfer Module level n
T	Temperature in Kelvin
TD	Dwelling Time
T_{Dwell}	Dwell time or look time or time on the target
T_i	period transmitted pulse equivalent to Dwell time of CW
ToF	Time-of-Flight
TRP	Total Radiated Power
Tx/Rx	Transmitter/ Receiver
UWB	Ultra Wide Band
V_C	Efficient airborne clutter volume
VCO	Voltage Controlled Oscillator
V_t	Target velocity
α	Grazing angle
α'	Depression angle
γ	Angle between the target heading
ΔR	Range resolution
η	Volume clutter reflectivity
λ	wavelength
σ_0	Normalized radar cross section of the target
σ_{S0}	Reflectivity of surface clutter
σ_t	Target cross-section
τ	Transmitted pulse length
μ	Attenuation coefficient

Chapter One

Introduction

1.1. Background

The Ethiopian Government has been undertaking mega railway transportation projects, which aims to enhance the railway transportation network within the country by connecting to adjacent countries, cities, and ports. Finalization of this project will provide efficient mobility; improve the export and import activities and boosting the economic development. Addis Ababa LRT and National Railway Networks are the major projects constituted in the plan. Hence, Ethiopian Railway Corporation (ERC) is the only government corporation responsible for managing all these projects. According to the ERC construction agreement, the major companies those under construct more than 60% of the systems are held by Chinese companies. Most of the equipment those need to operate, control and monitor of the overall railway systems are manufactured and imported from different countries (especially: from China) [1].

AA LRT grade (Level) crossing constitutes the intersection of two modes of transportation, which differ in the physical characteristics of their traveled ways and also in their form of operation. In recent years, light rail transit (LRT) has established a significant presence in many urban areas. The ability of LRTs to operate in a broad range of environments, its attractiveness to passengers, frequency of operation and its capacity have made the LRT an increasingly viable public transportation option for many urban areas. The LRT allows smooth, comfortable, environmentally friendly and quiet travel around town. It extends into the city downtown, enhances the character of downtown areas, is economical to use, can make sharp turns and is convenient to ride on. LRT grade crossings and quad gate crossings are more prevalent in urban settings and it is imperative that these locations be carefully analyzed and designed such that this mode of transportation operates in synchronization with on-street automobile and pedestrian traffic [1].

Under all circumstances, the signaling systems must be supported by advanced technology in such a way that risk will be minimized to the minimum level. Especially level or quad crossings have been identified as a particular target point in road and railway infrastructure, seriously affecting their safety. In road and railway infrastructure level crossing systems requires a high level of safety. Modern level or quad crossings (or railroad crossings in American terminology) have come a long way from the early days of human railway employees waving red flags and shining lanterns to clear railroad tracks or vehicles and pedestrian traffic for oncoming trains. Road users must follow road rules and signs and pay attention to the road environment when approaching rail crossings. International police statistics show that up to 95 percent of crashes at railway crossings are caused by driver error and out of this 44 percent happened at crossings without an electronic warning system such as flashing lights and/or boom gates. This is largely attributable to inattention, driver distraction, risk taking, and disobeying and lack of knowledge of the road rules and sometimes suicide. In almost every case that the motorist failed to stop and give way to the train at the level crossing and that there was little the train driver could do to prevent the collision or minimize its effects [2].

Nowadays level crossings are protected either passively or by active/automated systems. Passive protection systems provide only a stationary sign warning of the possibility of trains crossing. Their message remains constant with time. Active protection systems activate automatic warning devices (i.e., flashing lights, bells, barrier, etc.) as they detect an approaching train. Comparison among the railway level crossings in terms of 'driver compliance' clearly indicates that drivers react differently to different protection systems, particularly the passive protection systems which are commonly used in rural areas. Based on the field results it is concluded that on average there is less driver compliance to passive crossings than to active ones[3].

Due to this reasons, active system of protection supporting safe driving and an information collection infrastructure for sensing level crossing conditions and supplying key information to the railway operator and train driver is mandatory to prevent an accident. Active warning systems for level crossings have traditionally been train-oriented and geared more towards protecting railway assets than helping vehicles and pedestrians make better split-second decisions. Although protecting and monitoring the condition of railway assets remain crucial objectives in ensuring journey reliability and preventing derailments, smart level crossings go even further by providing more accurate, real-time information to pedestrians, vehicles, train drivers, and even a faraway OCC (operation control center). Development efforts are currently underway to come up with a practical infrastructure of this type. The information collection infrastructure is expected to detect instantaneously the positions and velocities of obstacles on roads, such as things that have been dropped, or that have fallen on the road, standing or running vehicles [2]. This technology is essential for constructing a smart way of accident prevention in our country Ethiopia. Since our country is constructing a new electrified railway infrastructure, accidents must be prevented or minimized especially in level or quad crossings, because the higher rate of accident is in these areas.

In the signaling preliminary design for the Addis Ababa LRT, there is no system for detecting an obstacle to prevent an accident, the responsibility is fallen to the train operator who is driving on sight. But what if an obstacle is there on the level crossing due to different circumstances, what if he couldn't see further because it is foggy, night….etc. So in all cases an automatic accident prevention system must be developed as a solutions.

1.2. Statement of the problem

Due to the following reasons level or quad crossings is more important area in railway transportation because it cause serious damage and cause more catastrophic accidents if a proper safety measure is not taken into consideration.

- With LRTs approaching grade crossing at speeds up to 70 km/hr, based on the alignment type, there is little opportunity for crossing users to error (make a mistake) and recover safely or for LRV (light rail vehicles) operators to avoid collisions. Therefore, the adequate perception of crossing control devices and warning systems by crossing users is critical to the overall safety of LRT operations.
- Drivers also engage in numerous behaviors at crossings that may increase the risk of an accident. For example, the driver disregarded a stop sign, failed to look for a train, distracted, and had a judgment error involved roadway conditions that limited the drivers' ability to see the crossing or train.
- When any vehicle get a problem unable to move on the junction (railroad crossing) while a train is heading towards the level/quad crossing. Appropriate and automated detection system is a must here to stop the train with a maximum breaking distance from the grade crossing.
- Another important issue in grade crossing is traffic queues which have potential impact for extending across nearby crossings. Alternatively, the traffic backed up from a nearby downstream railroad grade crossing could interfere with the signalized highway intersections. Safety concerns occur when traffic queued back on to intersection. Similarly, traffic flow issues arise when traffic queued for a train arrival spills back onto the intersection. A potential

conflicting movement occurs when motor vehicles queue back across the tracks at a highway-rail grade crossing due to red traffic signal indications at the adjacent intersection.

- Keeping the safety on top priority, there must be maximum utilization of track as well as the road with a minimized time delay on both modes of transportation.

Thus, safety assurance is one of the prominent challenges in the railway industry. In safety-critical Automatic Train Control system (ATC) it is often necessary to fully analyze all failure modes of a system to prove its safety. This is a challenging task where microprocessors are concerned. For microprocessor based ATC system, safety is embodied within proprietary software, in combination with sophisticated hardware and both have complicated and unpredictable failure modes. This makes it risky to use those devices for safety critical applications. A means to guarantee safety and a method to validate it is a must [15].

To overcome these limits, this thesis proposes an intelligent level/quad crossing system to balance the above disadvantages of the existing system and make train or vehicle drivers, pedestrians, etc.) more secure. The proposed level/quad crossing system informs vehicle drivers and pedestrian that train is approaching at the same time it informs the train driver about the status of level/ quad crossing. This is a two-way signaling system. Another important feature of this system is that it will coordinate and optimize the delay that will be introduced so that it will maximize track utilization and minimize risk to minimum possible level.

As it has been explained in the introduction part, to prevent the fatal accident occurrence a system which can detect an obstacle on level crossing and inform the railway operator and train driver whether there is an obstacle or not has got to be developed. Then on this paper, the proposed solution for this problem is the Radar system of obstacle detection. The system of accident prevention using radar technology is going to be designed and analyzed. This radar detection technology will, in turn, used to transform the normal train signaling system to a special **Bi-signaling system** which coordinates the signaling of both mode of transport i.e. the train signaling system and traffic signaling system. Along with this, the best optimization algorithm will be developed such that maximizing track utilization, maximizing safety and minimizing time delay.

1.3. Literature Review

Reference [6] deals investigation and design of an intelligent railway level crossing system to prevent accident for AALRT. It uses 77GHz MMW radar for detection of both the train and obstacles at the level crossing. It also provides the performance evaluation of the different obstacle detection technologies. But here using radar detection system for trains is a little bit impractical and it is better if we use the traditional train detection method.

Reference [15,19]

These books explain the basic Radar Systems Analysis and Design Using MATLAB® concentrates on radar fundamentals, principles, and rigorous mathematical derivations. It also provides the user with a comprehensive set of MATLAB 5.0 software that can be used for radar analysis and/or radar system design. All programs accept user inputs or execute using the default set of parameters. Each chapter provides all the necessary mathematical and analytical coverage required for a good understanding of radar theory. Additionally, dedicated MATLAB functions/programs have been developed.

Reference [16] presents new ideas at the circuit and system level for remote sensing, short range radar, active imaging, and multi-Gb/s radios, up to 145 GHz and in both state-of-the-art nanoscale CMOS and SiGe BiCMOS technologies. The system and circuit level implementation of a mm-wave precision distance and velocity sensor at 122 and 145 GHz is presented. Both systems feature a heterodyne architecture to mitigate the receiver 1/f noise, as well as self-test and calibration capabilities along with simple packaging techniques to reduce the overall system cost.

Reference[17] investigates the design and realization of integrated planar antennas for millimeter-wave applications. The state-of-the-art antenna integration and packaging technologies are extensively studied, and an antenna design flow is proposed. System demonstrators with integrated antennas are realized and measured. The 60 GHz demonstrator with on-PCB differential bunny-ear antenna and a novel bond-wire compensation scheme achieves a data rate of 3.6 Gbit/s over a 15-meter distance, which was the best-reported analog front-end without beam forming function in silicon technology regarding both the data rate and transmission distance at the time of its publication. A 245 GHz single-channel transmitter and a single-channel receiver with integrated on-chip antennas are also demonstrated. An effective isotropic radiated power (EIRP) of

7–8 dBm is achieved for the transmitter, which is the highest reported value at 245 GHz for a SiGe transmitter with a single antenna so far. Furthermore, the receiver has the highest reported integration level for any 245 GHz SiGe receiver. A 245 GHz 4-channel-transmitter array with an integrated on-chip antenna array is also realized to achieve spatial power combining, which offers 11 dB higher EIRP than a single-channel transmitter.

Reference [39] designed and characterized the pulse Doppler radar designed to detect targets at short range (R < 7 m). To minimize the shortest detectable range, a sub-nanosecond transmitted pulse-width is desired. UWB design techniques were combined with a pulse Doppler radar architecture to demonstrate a full radar, including the transmitter, receiver, simulated channel, and post processor. The transmitted pulse train has a 2.5 GHz carrier frequency, a 730ps pulse-width, and a 1 GHz 10 dB-bandwidth. The PRF of the radar is 20 MHz, which allows unambiguous range and Doppler detection with a single PRF. The peak transmitted power is 1.2 W. The characteristics of the transmitted waveform provide fine range accuracy (R = ±0:03 m), facilitate a short minimum range, and allow for an efficient transmitter design. The receiver was designed to complement the transmitter; it has a homodyne architecture and is pulsed to isolate a specific detectable range.

Reference [48] analyzes the feasibility of using a millimeter wave (MMW) radar system for detection of highway vehicles within grade crossings. The sensor system is designed to provide a warning signal whenever a vehicle appears within the danger area of the grade crossing using wave Band's spinning grating antenna. This has been supported by a demonstration of a field test results.

1.4. Objectives

1.4.1. General Objectives

The main objective of this work is to coordinate, optimize and automate a system developed at the grade and quad gate crossing for both modes of transport in such a way that time delay and risk are minimized.

1.4.2. Specific Objectives

Specifically, it is aimed to:-

- To reduce traffic delay on LQ crossing
- Optimize traffic flow at LQ crossing from both side of transport

- To reduce fatal and catastrophic accident on grade and quad crossings
- To improve conflict movement of Pedestrian on grade and quad crossings
- To minimize traffic queue of vehicles near quad crossing

1.5. Methodology

The methodology to be employed to achieve the objectives of the research is summarized in the flow chart below.

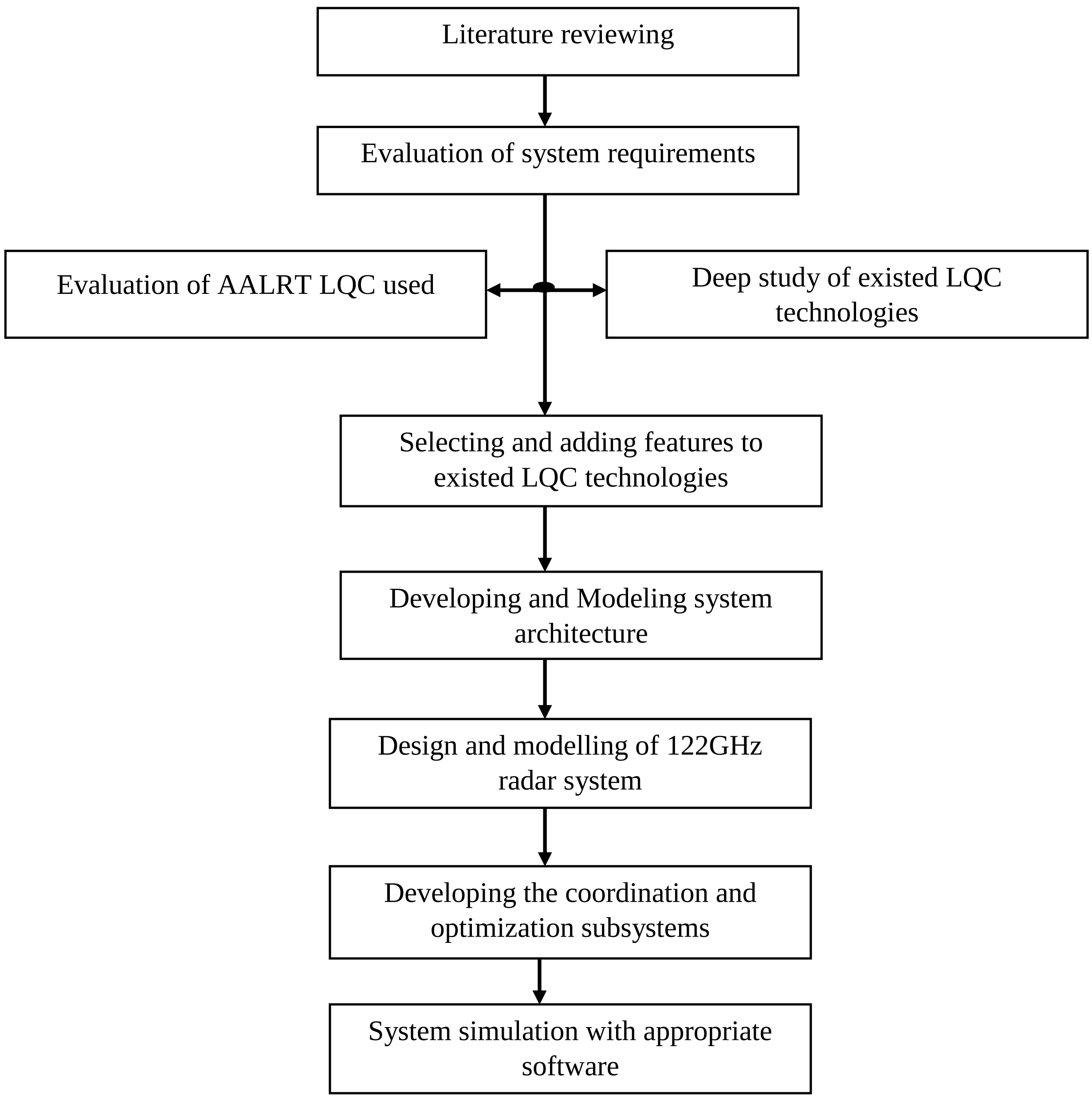


Figure 1 Methodology employed for this thesis

1.6. Scope and Limitations

1.6.1. Scope

The performance analyses will be based on simulation of the proposed techniques as prototype implementation is not feasible due to cost and time constraints. But as much as possible, an attempt has been made to drive analytical expression that will help to support the simulation.

1.6.2. Limitation

Here are challenges on the study:

- Shortage of time
- Shortage of reference materials especially journals published related to this thesis are hard to find.
- Internet access problem, very slow and tiresome.

1.7. Contributions

In all the literature and materials seen so far, safety at level crossing has been investigated at various levels. However, some of the differences in the previous work and the current work are underlined in the following points.

- In this thesis, radar based detection system and the existed train detection have been coordinated to automate and mitigate manual safety assurance at LQC.
- Best Coordination algorithm has been developed, giving radar signal indicator the priority between the train and traffic controllers.
- Another interesting feature of this thesis is an optimization algorithm have been developed for minimizing both time delay and risk and maximizing track and road utilization.

1.8. Thesis Organization

This thesis is organized in seven chapters. The first chapter includes an introduction which provides clear information about the background of the thesis work, statement of the problem, research method and limitation of the thesis. And literature of different scholars have been presented.

Chapter two is about the main components of level/quad crossing have been presented, which includes the highway (road) components and railroad components.

Chapter three explains the preliminary conditions for train and obstacle detections. Here the current technologies of obstacle detection and train detection technologies have been presented. A possible selection criteria's have made in this section.

Chapter four is about the design of the Level/quad crossing, the entire system architecture, system structure. The detection subsystem, radar design as its core have been dealt. The 122GHz radar components and mathematical modeling have been in detail covered to be designed. The 122GHz transceiver design, radars DSP design, choice of why 122GHz over the other frequencies and choice of FMCW over Pulsed radar and SFR have been covered in this chapter.

Chapter five covers the coordination (BCLE) and optimization subsystem design. Here starting from the normal traffic light controller algorithm to coordinated algorithm which includes the radar signal indicator, train signal indicator, traffic light indicator and pedestrian light indicators have been explained. An optimization equation for time delay mitigation has been covered too. The possible interfacing methods of the system AGCS with the CBTCS have been covered.

Chapter six is about MATLAB simulation results and discussion based on the result. MATLAB codes have been developed to get results of what It have been modeled in the previous two consecutive chapters. For example (Range versus SNR for different RCS and Range versus SNR for different transmitted power etc.). After having the simulation results, discussions have been made for every simulation.

The final chapter is conclusions and recommendations. On this chapter, the work has been concluded based on the result obtained and discussed in chapter six. Further recommendations were suggested for the development of new model or improvement of the results in this thesis.

Chapter Two

Components of a Level/quad Crossing

A highway-rail grade crossing can be viewed as simply a special type of highway intersection or two transport mode intersection, in that the three basic elements of any intersection are present: the driver, the vehicles, and the physical intersection. As with a highway intersection, drivers must appropriately yield the right of way to opposing traffic; unlike a highway-highway intersection, the opposing traffic—the train—must only rarely yield the right of way to the highway vehicle. Drivers of motor vehicles have the flexibility of altering their path of travel and can alter their speed within a short distance. Train operators, on the other hand, are restricted to moving their trains down a fixed path, and changes in speed can be accomplished much more slowly. Because of this, motorists bear most of the responsibility for avoiding collisions with trains.

The components of a railroad grade crossing are divided into two categories: the highway (road) and the railroad. The highway component can be further classified into several elements including the roadway, drivers, pedestrians and bicyclists, and vehicles. The railroad component is classified into train and track elements. The location where these two components meet must be designed to incorporate the basic needs of both highway vehicles and trains.

Traffic control devices are utilized to provide road users with information concerning the crossing. Typically, an advance warning sign and pavement markings inform the motorist that a crossing lies ahead in the travel path. The crossing itself is identified and located by the use of the cross-buck. These traffic control devices—the advance sign, pavement markings, and cross-buck—are termed "passive" because their message remains constant with time.

"Active," traffic control devices tell the motorist or vehicle whether or not a train is approaching or occupying a crossing and, thus, give a variable message. Typical active traffic control devices are flashers or flashers and automatic gates. A highway traffic signal may also be interconnected to the crossing signals and would form part of the traffic control system at the crossing which will be given a detail design issue for this thesis in the proceeding chapters.

2.1. Highway (Road) Components

A. Drivers

The driver is responsible for obeying traffic control devices, traffic laws, and the rules of the road. Highway and railroad engineers who plan and design initial installations or later improvements to traffic control systems at railroad grade crossings should be aware of the several capabilities, requirements, needs, and obligations of the driver. This information will help them, through the proper engineering design of improvements, assist drivers in meeting their responsibilities.

B. Vehicle

The design and operation of a railroad grade crossing must take into account the numbers and types of vehicles that can be expected to use it. In this regard, crossings are exposed to the full array of vehicle types found on highways, from motorcycles to truck tractor/triple-trailer combinations, although the use of crossings by the largest vehicle types is rare. Typically, the largest vehicles that will use at-grade crossing are full-size passenger buses like anbesa bus, public bus or design trucks such as WB-50 Truckers. The vehicles utilizing highway-rail grade crossings have widely different characteristics that will directly influence the design elements of the crossing. Equally important is the cargo these vehicles carry, especially children in school buses and hazardous materials in trucks.

Several physical and performance characteristics influence the safety of vehicles at crossings. These include vehicle dimensions, braking performance, and acceleration performance.

Vehicle dimensions: The length of a vehicle has a direct bearing on the inherent safety of the vehicle at a grade crossing and, consequently, is an explicit factor considered in the provision of sight distances. Long vehicles and vehicles carrying heavy loads have longer braking distances and slower acceleration capabilities; hence, long vehicles may be exposed to a crossing for an even greater length of time than would be expected in proportion to their length. Vehicle length is explicitly considered in determining the effect of sight distance and the corner sight triangle on the safe vehicle approach speed toward the crossing and in determining the sight distance along the track for vehicles stopped at the crossing. The design lengths of various vehicles are specified by the American Association of State Highway and Transportation Officials (AASHTO) [40].

Braking performance: One component of stopping sight distance is a function of a vehicle's braking performance. If a crossing experiences a significant percentage of heavy trucks, any given sight distance will dictate a slower speed of operation to allow for the braking performance of these vehicles.

Acceleration performance: Acceleration of vehicles is important to enable a stopped vehicle to accelerate and clear the crossing before a train that was just out of sight or just beyond the train detection circuitry reaches the crossing. Large trucks that have relatively poor acceleration capabilities coupled with long lengths are particularly critical in this type of situation. There are three phases of operation for a truck that has stopped at a crossing: start-up when the clutch is being engaged; acceleration from the point of full clutch engagement; and continued travel until the crossing is cleared.

Another aspect of the acceleration performance of vehicles at crossings is the design of the crossing approaches coupled with the condition of the crossing surface. Crossings and approaches on a steep grade are difficult and time-consuming to cross. Also, vehicles will move more slowly over crossings that have rough surfaces.

Special vehicles: Three vehicle types are of particular concern for crossing safety: trucks carrying hazardous materials; any commercial motor vehicle transporting passengers; and school buses. Collisions involving these vehicles can result in numerous injuries and/or fatalities, perhaps in catastrophic proportions if certain hazardous cargoes are involved. More or less whatever vehicle is on the LQC being pile some measures must be taken to stop the train from entering the junction.

C. Pedestrians

In 2004, collisions involving pedestrians at crossings accounted for only 3.6 percent, or 111, of all crossing collisions [40]. As can be expected, these collisions almost always result in an injury or fatality. In 2004, there were 73 pedestrian fatalities, comprising 6.8 percent of all crossing fatalities. These statistics was reported as they do not include pedestrian collisions occurring elsewhere along railroad tracks.

One difference between the driver and a pedestrian at a grade crossing is the relative ease with which a pedestrian can enter the track-way even if pedestrian gates are provided. It is important to understand four contributing factors that may motivate pedestrians to enter railroad right of way to establish effective preventive measures.

First, as a consequence of urban development, railroads often act as physical dividers between important, interrelated elements of communities. Second, railroads have always attracted juveniles as "play areas." Third, at or near commuter stations, passengers frequently use shortcuts before or after boarding a train. Fourth, some people are prone to the wreckage.

Several types of preventive measures might be employed, including:

- Fencing or other devices for enclosing rights of way.
- Grade separation.
- An additional signing like sound alarming as the train is approaching.
- Safety education.
- Surveillance and enforcement.

Among these here in AA-LRT they have used fencing of the entire route and alarm and gate preventative measures at the level/quad crossing. Now in this thesis again this preventative measures will be automated and optimized with the help of active radar system scanner that will be installed at the level/quad crossing so that the risk of life's and catastrophic damages will be reduced.

D. Roadway

A major component of the crossing consists of the physical aspects of the highway on the approach and at the crossing itself. The following roadway characteristics are relevant to the design and control of highway-rail grade crossings:

- Location—urban or rural.
- Type of road—arterial, collector, or local.
- Traffic volumes.
- Geometric features—number of lanes, horizontal and vertical alignment, sight distance, crossing angle, etc.

- Crossing surface, elevation, and illumination.
- Nearby intersecting highways.

Urban crossings often carry more vehicular traffic than rural crossings and have sight restrictions due to developed areas. Urban crossings also involve obstructions to continuous traffic flow, such as controlled intersections, driveways, business establishments and distracting signs, significant lane interaction, and on-street parking. All other factors being the same, especially train volumes, collision frequency increases with increasing traffic volume. However, traffic volume alone is not a sufficient forecaster of collisions at crossings rather it is the sum resulted due to the above-bulleted characteristics.

E. Traffic Control Devices

Traffic control systems for highway-rail grade crossings include all signs, signals, markings, and illumination devices and their supports along highways approaching and at railroad crossings at grade. The function of these devices is to permit safe and efficient operation of highway and rail traffic over crossings. The responsibility for the design, placement, operation, and maintenance of traffic control devices normally rests with the governmental body having jurisdiction over the road or street. For the purpose of installation, operation, and maintenance of devices constituting traffic control devices at highway-rail grade crossings, it is recognized that any crossing of a public road with a railroad is situated on the right of way that is available for the use of both highway traffic and railroad traffic on their respective roadway and tracks. This requires joint responsibility in the traffic control function between the public agency and the railroad. The determination of need and the selection of devices at a grade crossing are normally made by the public agency having jurisdiction. Subject to such determination, the design, installation, and operation of such devices shall be in accordance with the principles and requirements set forth in MUTCD [41].

Due to the character of operations and the potentially severe consequences of collisions, traffic control devices at highway-rail grade crossings and on the approaches thereto must be viewed as a system. The combination of approach signs and pavement markings on the roadway approach and the cross-bucks or signals at the crossing provide the road user with multiple notices of the presence of the crossing and the likelihood of encountering a train. For those sections where rail tracks run within a roadway, which is a common practice for light rail and streetcar operations, traffic control may be provided by a combination of signs, pavement markings, and typical "highway" type control devices such as STOP signs and traffic signals. Motorist comprehension and compliance with each of these devices is mainly a function of education and enforcement. The traffic engineer should make full use of the various traffic control devices as prescribed in MUTCD to convey a clear, concise, and easily understood message to the driver that should facilitate education and enforcement [40].

2.2. Railroad Components

For the purpose of simplicity, the railroad components of highway-rail grade crossings have been divided into three categories: train, track, and signaling.

A. Train

Variation in rail movements occurs on the micro or macro scale, such as at individual highway-rail grade crossings. Thus, the design of traffic control systems at crossings must allow for a wide variation in train length, train speed, and train occurrence. Long trains, such as unit trains, directly affect the operation of highway traffic over crossings and indirectly affect safety as well. Unit trains consist of as many as 100 freight cars with the same lading. Coal and grain are two major commodities transported in unit trains across a long haul transport and may cross intercity ways along the way. Because of their lengths, unit trains will take longer to pass over a crossing and, in effect, close the crossing to highway traffic for a longer period of time.

In addition, some communities have passed ordinances restricting train speed for the purpose of improving safety. However, this practice directly reduces the level of service and maximum resource utilization for highway traffic and may also affect safety. Because of the longer period of time during which the crossing is closed to highway traffic, a motorist may take risks by passing over the crossing just ahead of a train. In many cases, risks such as these are not successful, and collisions result.

Trains other than unit trains typically consist of a variety of cars and ladings. A few cars may be picked up along the way and may be dropped off from the same train or may be taken to a railroad yard where a new train is made up of cars with similar destinations.

It is obvious that trains must stop to pick up cars, but it is unfortunate that some of these pick-up points are located in the central portion of communities. This results in trains moving slowly over the crossing or even standing on the crossing as the pick-up is made. With the lengths of freight trains today, an entire community can be physically divided by a freight train stopped on all of its crossings. Railroads have operating procedures designed to prevent extensive blockage of crossings, and many states have passed regulations prohibiting the blockage of crossings for various lengths of time.

A freight train can be divided to allow highway traffic to pass through, but this practice requires the braking system to be filled with air, which can take considerable time [40].

Railroads carry passengers in addition to freight, although this mode of transportation has declined during recent decades due to the construction of the interstate highway system, the convenience of the automobile, and the speed of the airplane.

Some private railroad companies continue to operate passenger trains, particularly for commuter service in urban areas. Some municipal, regional, and state authorities have taken over railroad commuter services. For example, many light-rail transit companies are in operation and are being constructed in the United States with numerous crossings and longitudinal street use.

Locomotives and cars obviously form a train, but for crossing purposes, any rail operation over a highway is of concern, whether it is one or more engines or a group of cars pushed over a crossing. Most locomotives today are diesel-electric or straight electric, although some railroads operate steam locomotives as special passenger trains for historical purposes.

B. Track

In the United States, railroad trackage is classified into six categories based upon maximum permissible operating speed. FRA's track safety standards set maximum train speeds for each class of track [40], as shown in Table 1.

Table 1: Maximum Train Speeds by Class of Track

Class of track	Freight	Passenger
Class 1	10mph	15 mph
Class 2	25 mph	30 mph
Class 3	40 mph	60 mph
Class 4	60 mph	80 mph
Class 5	80 mph	90 mph
Class 6	110 mph	110 mph
Class 7	125 mph	125 mph
Class 8	160 mph	160 mph
Class 9	200 mph	200 mph

The rolling resistance that provides many of the technological advantages for railroads as a means of transportation is made possible by the steel wheel rolling on a steel rail. This steel-wheel-to-steel-rail contact involves pressures of more than 50,000 pounds per square inch, which are then reduced to pressures acceptable to the underlying soil by a series of steps, going from the rail to a steel plate under the rail (tie plate), which spreads the load over a wooden/concrete tie, which spreads the load over rock or slag ballast, which spreads the load to a sub-ballast (usually gravel, cinders, or sand), which spreads the load to the subgrade consisting of either the native soil below or some superior material obtained off-site.

Rail is rolled from high-quality steel. Rail being rolled today weighs from 115 to 140 pounds per yard and is 6 to 8 inches high. For the last 50 years, the standard rail length has been 39 feet for transportation in 40-foot cars [40]. In track, these rails are held together by bolted joint bars or are welded end to end in long strings. Bolted joints are, however, less rigid than the rest of the rail so that the rail ends wear more rapidly. Continuously welded rail is often used today, particularly on mainline tracks. Rail is welded into lengths of about 1,500 feet and taken to the point of installation. The remaining joints can be eliminated by field welding in place.

Spikes or other rail fasteners are used to connect the rail to the ties for the primary purpose of preventing the rail from shifting sideways. Because rail has a tendency to move lengthwise, rail anchors are used, particularly on heavy-duty track.

Ballast is used to hold the ties in place, to prevent lateral deflections, and to spread out the load that averages about 100 pound-force per square inch just underneath the tie. Ballast must be able to resist degradation from the effects of tie motion that generate "fines" that may "cement" into an impervious mass. Ballast must also provide good drainage, which is especially important for the strength of the subgrade and also prevents mud from working its way up to contaminate the ballast.

Railway track is normally maintained by sophisticated, high production, mechanized equipment. The track surface is maintained by tamping machines that raise the track and compact the ballast under the ties. In this process, it is often necessary to raise the track a few inches. The best track stability will occur if this raise can continue through the crossing area instead of leaving a dip in the track. The lowering track is a very costly operation and can lead to subgrade instability problems. Track components are generally replaced as needed.

Similar to highways, railroad track is classified into several categories dependent on its utilization in terms of traffic flow. Main tracks are used for through train movements between and through stations and terminals. Branch line trackage typically carries freight from its origin to the mainline on which it moves to its destination or to another branch line to its destination. Passing tracks sometimes called sidings, are used for meeting and passing trains. Sidetracks and industrial tracks are used to store cars and to load or unload them.

C. Signaling

During the early years of railroading, methods had to be devised to ensure that two trains did not meet at the same time on the same section of track. This was initially accomplished through the use of timetables and train orders. Block signal systems were developed, which indicated to the locomotive engineer whether or not a train was ahead in the next block of track. These signals were set manually until the track circuit was developed, which sensed the presence of a train in the block and set the signals automatically. The track circuit was designed to be fail-safe, so that if the battery or any wire connections were to fail or if a rail was broken, a clear signal would not be displayed. Insulated joints were used to define the limits of the block. Various types of track circuits are utilized in automatic traffic control device installations at highway-rail grade crossings. (Explicitly defined almost all of them in the next chapter)

Chapter Three

Preliminary Conditions for Train and Obstacle Detection

3.1. Level/ Quad Crossing

Level crossing (LC) can be defined as "an intersection of a road and a railway on the same level, where roads and rail include different operator and responsibilities" [5]. Quad crossing can be defined as again the intersection of these two modes of transport on the same level but both modes of transport have got a double entry and double exit. Intersections near highway-rail grade/level crossings typically occur where a roadway parallels a railroad or light rail transit track and another roadway crosses the tracks and intersects the parallel roadway. Other intersections near highway-rail grade crossings are formed where the tracks pass diagonally across two roadway approaches to the same nearby intersection. Based on the definition, level/quad crossing protection is the common task of all those involved in the operation and oversight of roads and railways. LQC come under the purview of laws, regulations, administrative provisions, and directives. Here is an example of double entry and exit level/quad crossing as in figure 1.

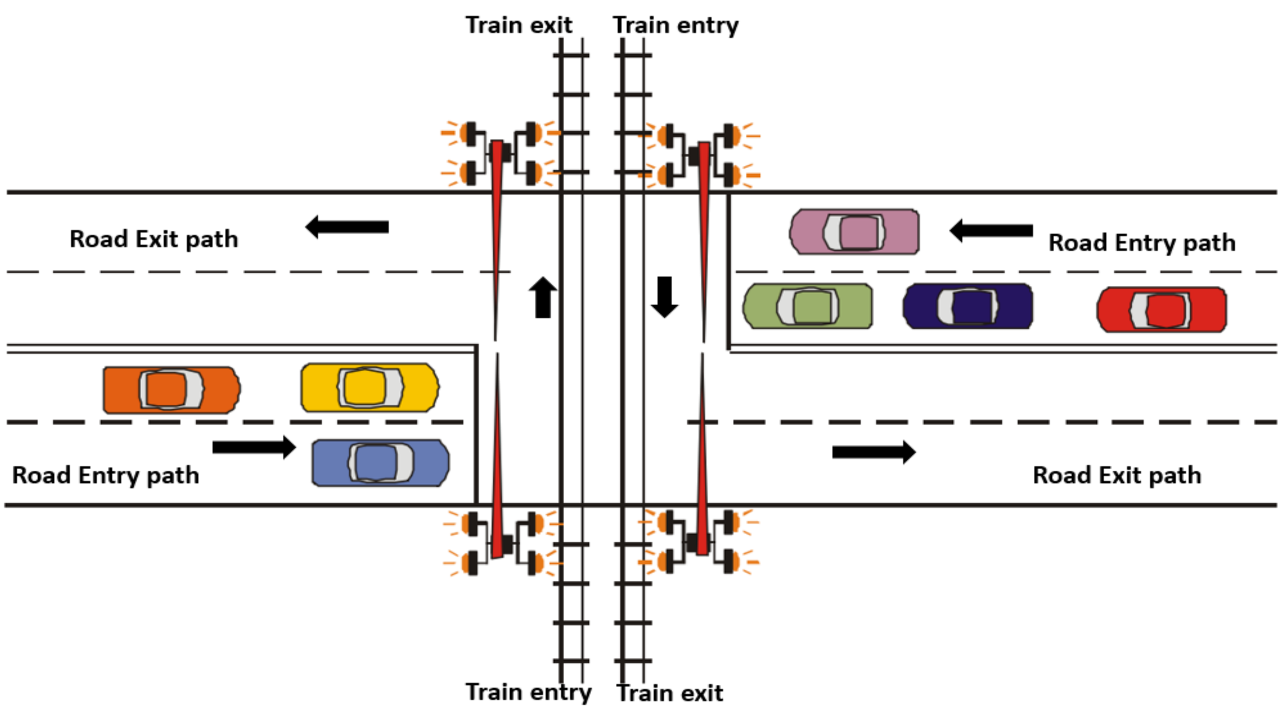


Figure 2: Structure and Components of Level/ quad crossing

ERA (European Railway Agency) classified LCs into two groups: active LCs (group A) and passive LCs (group B) (Figure 2) [5].

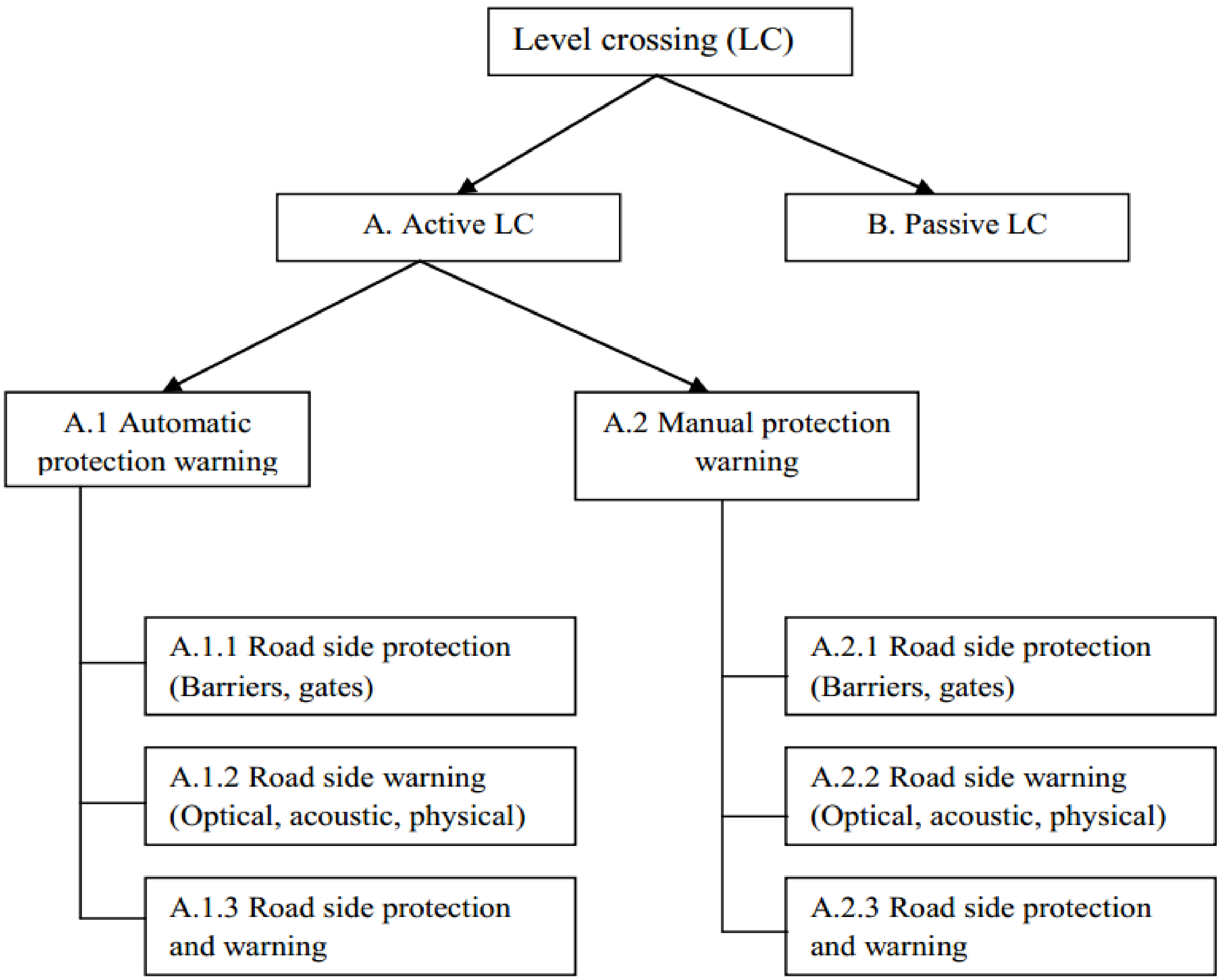


Figure 3: Level Crossing Classification According to ERA

The simplest description for passive type LCs may be all LCs equipped with any warning signs, plates, devices, or any other protection equipment, which is permanent and independent of any traffic situation. The first analysis of operational LC risk was carried out on the basis of the active and passive LC types as defined per the European Railway Agency for the purpose of defining Common Safety Indicators. It defines an active LC as an LC where the crossing users are protected from, or warned of, the approaching train by the activation of devices when it is unsafe for the user to cross the LC. In the case of an automatic active LC (A.1 in Figure 2), these devices are activated by the approaching train. Manual active LCs (A.2) are activated by humans when there is no railway signal interlocked with control train movements. In the case of passive LC (B in Figure 2), there is no warning system and/ or protection system showing when it is unsafe for the user to cross the LC. SELCAT project carried out an analysis of accident statistics by comparing operational risk according to the different LC types. As a basis for comparison, seven basic LC types as defined per ERA were taken into account. The individual risk for road LC user was compared as per the different LC types. As a basis for operational risk comparison, the seven level crossing types defined by ERA have been taken. However, only five of these types could be identified (the A1.1 and A2.2 were not clearly identified) when analyzing the 66 collected national level crossing types of countries involved in SELCAT project. Risk considering the accidents (Acc), fatalities (Fat) or injuries (In) at LC of a particular type are covered deeply [5].

For the European countries involved in Safer European Level Crossing Appraisal and Technology (SELCAT), the highest risk applies to LCs with warning lights (A 1.2), followed by the automatic LC with warning lights and barriers (A 1.3). Therefore, the main conclusions drawn from the statistics analysis by the European Conference of Transport Research Institutes (ECTRI) in 2008 are as follows:

- Safety at LCs is a definite problem for rail companies as they have no control over actions of road vehicle drivers and pedestrians at LCs and as it represents 29% of total accidents in a rail system compared to the road sector which represents 0.9% of total accidents. Clearly, while LCs represents a significant risk area for the safe operation of a rail network, this is in fact only a small element of the overall road safety issue.
- The highest operational risk in Europe is attributed to automatic LCs fitted with warning lights but without barriers. The second highest risk is attributed to automatic LCs with warning lights and with barriers.
- The results of investigations into causes of LC accidents have identified inappropriate or inadequate human behavior as the main source of the problem. Human factors play an important role for both the road and the rail. Violations of traffic regulations, disregard of warning signals, and trespassing by road vehicle drivers and pedestrians contribute to most of the fatalities. In terms of rail, staff with safety related responsibilities (i.e. manually operated LCs, warnings given by train drivers, supervision, and fallback operations)

are particularly vulnerable to human errors [5]. Therefore, the design of new technological solutions which will help increase people's awareness of risk at LCs, the operational speed of the train and it will minimize the impact of intentional and unintentional hazardous human behavior. The solution suggested for these problems on the LC is to use the active and automatic warning system in addition to the automatic train braking system which is called in this thesis the "Intelligent level crossing accident prevention with detection technology".

3.2. LQC Object Detection Technologies

Since LQC is a risky part of rail transportation system, it has got to be protected using reliable, fast and cost-effective means of technology to prevent an accident before happening or to minimize the risk [6]. At the LQC there are two cases to be considered. The first case is there must be a train detection system used to inform as if a train is approaching towards level/quad crossing. The second case is there must be again an obstacle detection i.e. motor vehicle or pedestrian detector which controls the wayside train signaling system used to inhabit train entrance to the intersection upon detection of anything on the LQC. So here we must select an appropriate coordinated technology or device for both cases in such a way that safety is insured. In this thesis , it is called Obstacle Detection System. Thus, obstacle detection systems appear as a breakthrough solution to improve LQC safety and lower the number of fatalities.

3.2.1. Train Detection Technologies

The track circuit is the fundamental method of train detection [7]. The first track circuit, based on a DC technology, has been invented at the end of the nineteenth. Over the years, the continuous technological development has enabled to realize track circuits in an increasingly performing way by using AC technology and modulations, but the basic principle for train detection is still the same.

An alternative approach is the Axle Counter system, which uses a "check-in/check-out" logic. By comparing the result for the axles counted in a block section with the result for those counted out, it is possible to know the status of the track section (free or occupied).

Track circuits contribute also for the vehicle's speed control since the electrical signals used for train detection can be exchanged between wayside and onboard for the transmission of speed commands. This can be realized through a modulation of the track signal and is known as “coded track circuits”. Perhaps, no single invention in the history of the development of railway transportation has contributed more towards safety and dispatch in that field than the track circuit.

Since the birth of railway signaling, train detection has been considered a primary need [7]. For this purpose, railway tracks are divided into blocks of varying length. Each block stands out from the adjacent ones by means of an insulated joint between rails and it permits the detection of the presence of a train. Track circuits operational principle is based on an electrical signal impressed between the two running rails. The presence of a train is detected by the electrical connection between the rails, provided by the wheels and the axles of the train (wheel-to-rail shunting). However, this is not the only function that track circuits perform in a railway signaling system because the detection information is used also to control train speed and ensure safe operation, by means of the transmission of speed commands to wayside signaling devices and to the trains [7]. A common operational scenario can summarize the track circuit operation: if a train attempts to approach too close to the LQC, the locations information provided by the track circuits is used to command a speed reduction or a trip of the train, avoiding a possible collision only if there is an obstacle detected on the LQC area. In all cases, the LQC is signaled so that a train entering the intersection gets the sufficient braking distance [3] to enter the block at a speed not greater than the commanded speed. In the case of a zero-speed command, the train must be able to stop before approaching the end of the LQC. Let see some of the technologies used for train detection and choose one of them up on some economic merit analysis.

A. THE DC TRACK CIRCUIT

The basic DC track circuit was invented by Dr. William Robinson and first used in a railway application in 1872 [8] [9]. The track circuit consists of a block section defined at each edge by insulated joints on the rails. The insulated joints provide electrical insulation between a track circuit and the adjacent tracks. The signal source (in this case a battery) is connected to the rails at one edge of the block section, while the receiver (a relay) is connected to the other edge. When no train is present, the track circuit is unoccupied, and the direct current supplied by the battery is transmitted by the running rails to the relay and energizes it or “picks it up”. When the relay is energized, the green signal light is turned on (Figure 3).

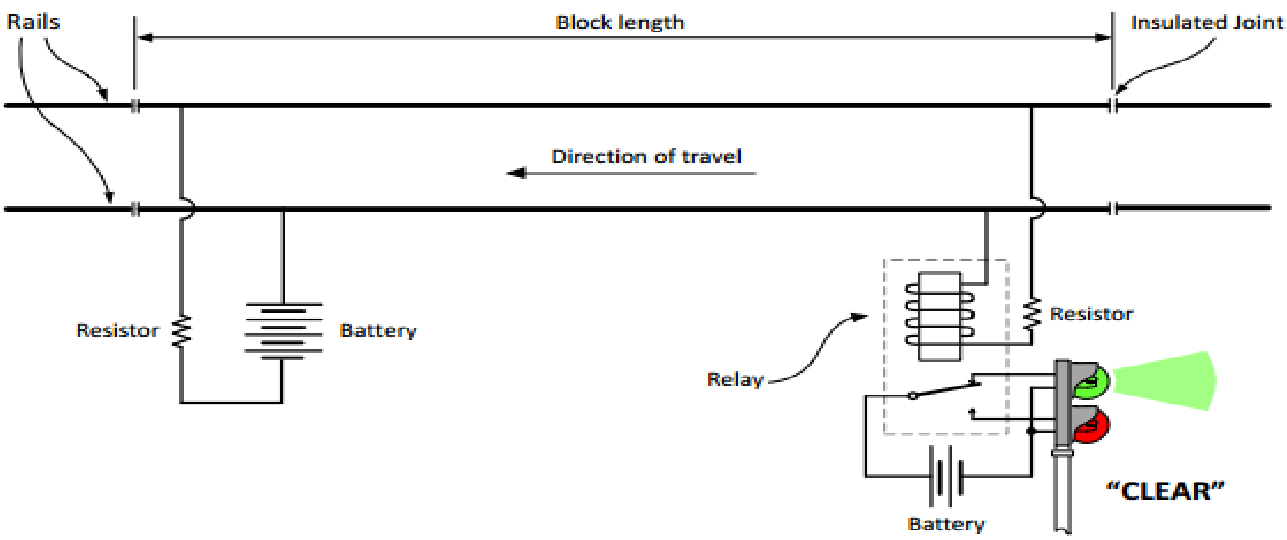


Figure 4: Unoccupied Block [8]

When a train approaches the block, its wheels and axles connect the two running rails together shorting the battery and thereby reducing to zero the current through the relay. This causes the relay to "drop" (Figure 4), turning off the green signal light and turning on the red light to indicate that the block is occupied by a train. A series resistor with the battery protects it by limiting the current that it must provide when a train is present.

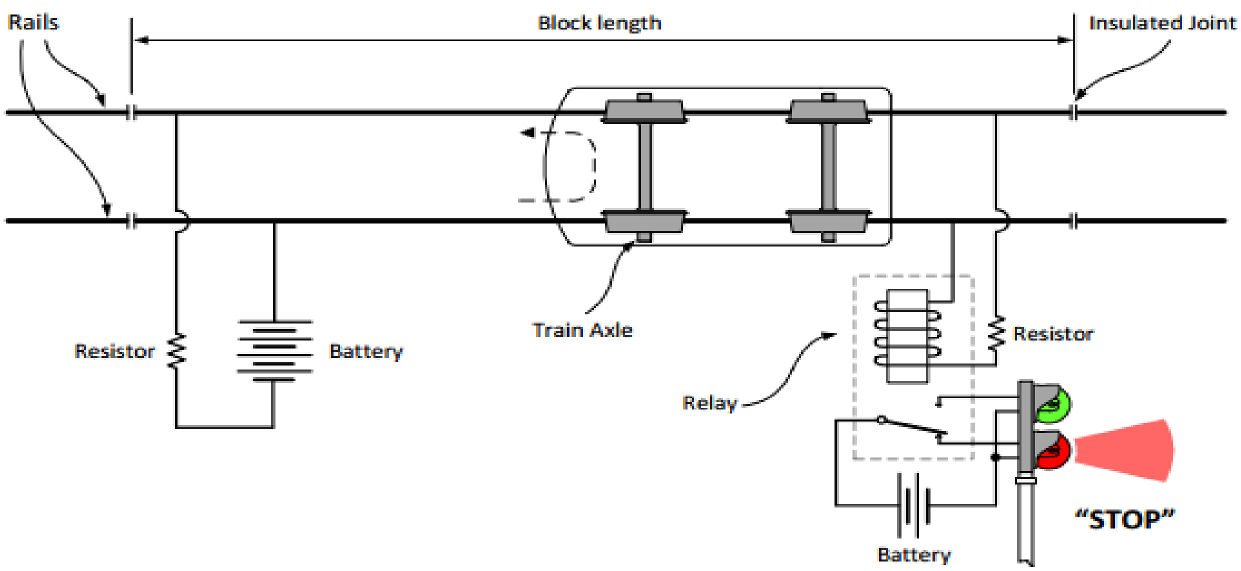


Figure 5: Occupied Block [8]

Even in the simple form shown in Figure 4, it can be noticed that the breaking of any conductor or the loss of power in the circuit will cause either a red signal or no signal at all to be displayed. A red or "dark" signal must be always interpreted as a stop command. To put it another way, all signaling systems are designed so that a green signal (meaning proceed) is presented only when the track circuits provide positive information that it is safe to do so.

The double-rail DC track circuit is susceptible to interference when the running rails are used as the return for DC electric propulsion current. Indeed, they are generally installed only in non-electrified sections, and only where there is no concern with stray currents circulating in the earth or in the rails. The main modern application of the double-rail DC track circuit is in railway with diesel-powered locomotives.

B. Low-Frequency AC Track Circuit

The AC track circuit is energized by an alternating electrical current with a frequency of 83.5Hz [7], to avoid interference from the 50Hz traction current. Except for the type of current and apparatus used, the AC track circuit is similar in operation to the DC track circuit described above. Its principal advantage is that it is immune to interference from stray currents so that it can be used on electrified tracks. Figure 5 shows a simple AC track circuit. Similarly to the DC track circuit, the AC track circuit consists of a block section. The AC signal source (Transmitter in Figure 5) is connected to the rails at one edge of the track circuit while the receiver is connected to the opposite edge. A band-pass filter and a rectifier are used to extract a DC signal from the AC track circuit current, for the operation of the track relay. Unless the use of AC signal, the general principle of operation is the same.

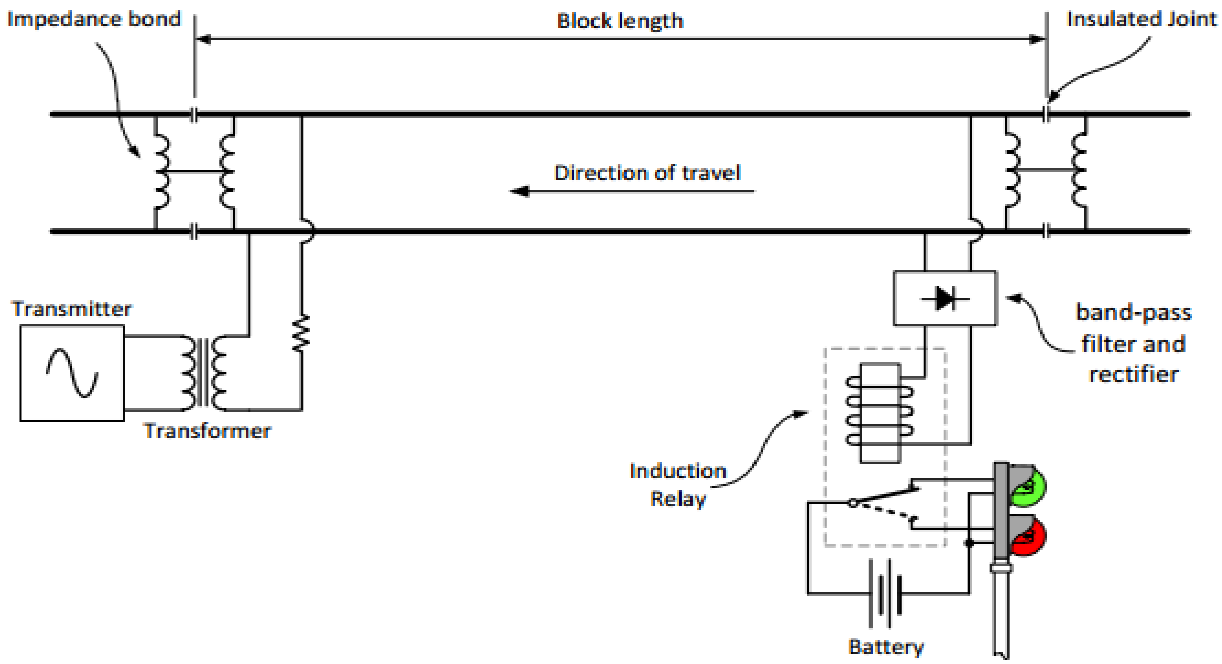


Figure 6: AC Track Circuit [8]

In addition to the signal source and the receiver, the AC track circuit contains a pair of impedance bonds for each pair of insulated joints. An impedance bond is a center-tapped inductance which is connected across the rails on both sides of the insulated joints. The center taps of the pair of impedance bonds are connected together as shown. The purpose of the impedance bonds is to provide continuity between the track circuits for the DC propulsion power and to distribute the propulsion current between the two running rails. The impedance bonds do this while still maintaining a relatively high impedance at the signaling frequencies between the two rails and between adjacent track circuits

When no train is present, the alternating current supplied by the transmitter at the left side of the diagram in Figure 5, is transmitted by the running rails to the relay and "picks it up" .

The energized relay turns on the green signal light, exactly as in a DC track circuit. The wheels and the axles of a train entering the track circuit connect the two running rails together and the current through the relay is reduced, causing the relay to "drop". This connects the bottom set or relay contacts, turning off the green light and turning on the red light to show that the block is occupied. The resistor in series with the transformer (at the left in the diagram) protects the transformer by limiting the current that it must provide when a train is present.

C. High-Frequency AC Track Circuit

Some AC track circuits use an alternating electrical current at a frequency in the range of hundreds or thousands of hertz. Because this frequency range corresponds roughly to the spectrum of audible sound, such circuits are sometimes called audio frequency track circuits (AFTC) [10]. High-frequency track circuits (HFCT) eliminate the need for insulated joints in the running rails [10]. Because insulated joints are expensive to install and to maintain, eliminating them leads to a significant cost reduction. Eliminating insulated joints also allows the track circuit to operate with the continuous welded rails being used in some newer installations. Figure 4 shows a simple high-frequency AC track circuit. Since no insulated joints are present in the running rails, the edges of the block are established by special transformers connected to the rails. The transformer winding attached to the rails is usually a single turn of heavy copper bar stock. The transformer core is often a toroid. The other transformer winding is tuned to resonate at the operating frequency by a capacitor. The transmitter is the AC signal source and provides electrical energy at the operating frequency in the audio frequency range.

The receiver, in this case, is not simply a relay, but an electronic circuit which responds to the electrical signal provided by the transmitter, and usually includes a tuned filter, rectifier, and amplifier for the signal frequency. Electrically, the track circuit zone inside the rail-to-rail shorts looks like two tuned LC circuits in parallel, with the inductance of the enclosed section of track in between them in series. The capacitors are adjusted so that the enclosed section of track is tuned to the track circuit frequency. When no train is on the track, the signal from the transmitter is received and detected at the receiver, and it is used to keep the track relay energized and the green signal light turned on. When a train approaches the track circuit it shunts the track circuit and, depending on the positions of the wheels, either de-tunes the circuit or shorts the transmitter or receiver (or both). Any of these cause the track relay to be de-energized and relay to drop, turning off the green light and turning on the red light. The circuit illustrated in Figure 6 is highly simplified, but in practice, it is necessary to accommodate the adjacent track circuits on either side. Rather than installing two separate transformers for each track circuit, a second resonant winding

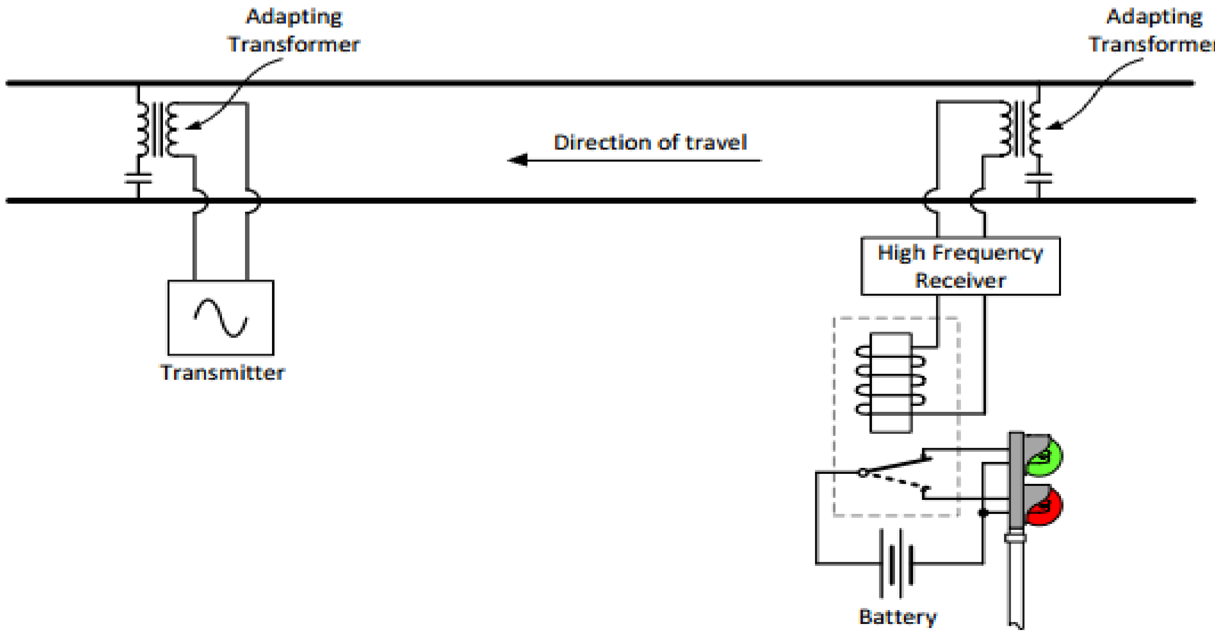


Figure 7: High-Frequency AC Track Circuit [8]

D. AXLE COUNTER SYSTEM

All of the track circuits described up to this point operate following the closed-circuit principle. Any disruption of the circuit by a train passing along the rails or by power or component failure, "opens" the circuit and causes a stop indication to be displayed by the signal system. An alternative approach to track circuit design uses a "check-in/check-out" logic. Simply stated, this circuit is based on the principle that once a train is detected or "checked in" to a block, it is assumed to be there until it is "checked out" by being detected in an adjacent block. The presence of a train may be detected only intermittently at the time when it enters a new block. Axle counters are installed at each edge of the section of track (Figure 7); when the number of axles counted at the entrance to the section is the same as the number of axles counted at its exit, that means the train has passed through the section.

A detection point comprises two independent couple of detectors, therefore, the device can detect the direction of a train by the order in which the detectors are passed. As the train passes a similar counting head at the end of the section, the counter decrements. If the net count is evaluated as zero, the section is presumed to be clear for a second train [10]. The detector senses the wheels by evaluating the changes in the magnetic coupling between the coils placed at each rail side (Figure 8). The system consists of:

- Sensor coils for train wheels detection;
- An electronic unit (electronic junction box) for signal conditioning and counting of the wheels;
- An evaluator unit which compares the number of the wheels entering the rail section and the wheels exiting the section.

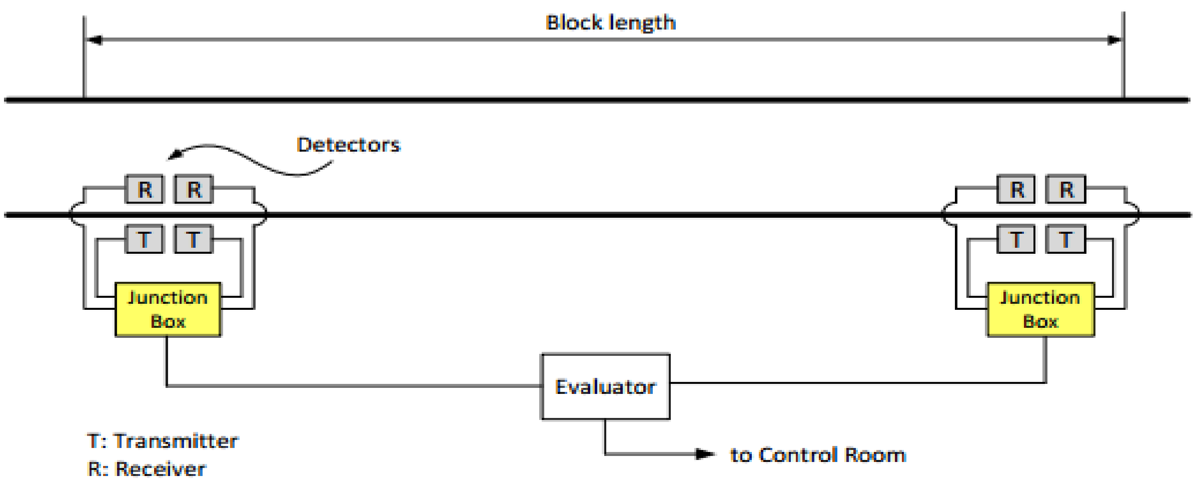


Figure 8: Schematics of Railway Axle Counter System [8]

The comparison result states the occupation status (section clear or occupied). Axle counter detector makes use of electromagnetic flux linkage between two coils mounted on either side of the rail, to detect the passage of the wheels. The magnetic flux generated by the transmitting coil flows through the path with lower reluctance. In the presence of the wheel, the magnetic path is shaped through the wheel and rail, causing less flux flow in the receiving coil and hence lower induced voltage in the receiver.

Figure 9: Distribution of Magnetic Flux [9]

In order to detect the passage of a wheel, the induced voltage in the receiving coil is continuously monitored and its changes beyond some predefined threshold is interpreted as existence or absence of a wheel. In other words, the wheel detector detects the wheel when the amplitude of induced voltage in the receiving coil is less than a threshold level. Axle Counter has some operational disadvantages, like the effects of a temporary loss of power to the signal system. With conventional track circuits, this eventuality causes all track circuits to indicate occupancy (fail-safe), but when the signal power is restored, the real occupancy situation is still indicated. With the Axle Counter system, the loss of signal power may destroy the “memory” circuits in charge of “remembering” that a train has entered a block. Thus, when the signal power is restored, the information on block sections which are occupied may have been lost. In this case, the identity and location of each train in the affected portion of the system must be established before the entire transit system can be operated again safely. In a small transit system, the identification and location of each train may not be difficult to establish. However, in a large complex system even a short-term interruption of a portion of the system can create a bottleneck which makes the full system restoring very difficult. Thus, axle counter systems do not find application as the primary train detection system in rail rapid transit systems. Axle counters are used in some cases where track circuits are hard or impossible to operate (e.g., where metal sleepers are provided, making track circuit operation impossible without re-installing the track, or where conditions are such that there are too much electrical noise and conductivity problems that make track circuits an unsuitable solution).

3.2.2. Obstacle/Target Detection Technologies

It is important to understand what is meant here by 'obstacle/target detection': in this context it is a means of identifying the presence of an object on LQC as the train approaches and/or the presence of train which is approaching to the LQC. So that by providing information to guide a suitable response collision can be avoided or the consequences minimized. Obstacle/target detection is not just about the type or technology of the detector; what is done with the output is also critical for an effective system [15]. At present, there are no obstacle detection systems in operation at LQC in Ethiopia. However, there is growing use of these systems in other countries.

Normally, an obstacle detection system would:

- Improve safety at LQC for all users (road and rail)
- Cause no or minimal delays for both train and road users
- Be affordable in terms of costs to install, operate and maintain
- Be practical to use and maintain

These requirements are often in conflict. For example, it might be possible for a particular system to offer good safety benefits, but only at the expense of causing significant operational disruption (which itself can introduce safety risks). Another issue is the requirement for any candidate obstacle detection system(s) to interface effectively with the existing railway infrastructure, rolling stock and operations standards.

Even though the obstacle detection on the level crossing is discussed and discovered widely, the detection of both the train and/or obstacle at LQC using the radar technology is included in this thesis. The train detection device and obstacle/target detection device must be in a perfect synchronization in such a way that only one condition is permitted on the LQC.

The detection of vehicles, pedestrians or other obstacles approaching an LQC requires setting up of detectors. Numerous object presence detection technologies have been developed and implemented, with varying degrees of success and satisfaction. These have included technologies that utilize infrared light, video analytics, microwave radars, and buried (embedded) technologies such as magnetometers and inductive loops.

The choice of the appropriate detector depends strongly on external factors, e.g. environmental conditions or the size of the object to detect. Obstacle detectors can be divided into two major categories: conventional and advanced.

Conventional obstacle detection has been used to prevent crashes between trains and vehicles (optical beam, sonic detection, inductive loop). Obstacle detection systems using advanced methods are constituted by Radar Method and video imaging [13].

Today, there are a number of trigger technologies installed at LQC, but they all serve the same purpose: they detect fixed or moving object when passing at particular points at the LQC. But they all have their own merits and demerits in terms of accuracy of detection, environmental conditions, and cost. Let's see some of the Detection technologies used at LQC.

I. Optical beam method

The principle is as follows: optical emitters are placed on one part of the crossing, each one emitting a directed optical beam with a defined field of emission. Then a photon detector intersects the field of emission of the emitter. If the beams are interrupted, it means that an object is located on the crossing. This technique has the advantage that is easy to replace, but it has many important drawbacks: very expensive cost for installation, need to have several detectors along the crossing, traffic needs to be stopped for installation, and it is unusable in a period of heavy snow. Electronic waves passing between transmitters and receivers can detect obstacles in a similar manner to the optical beam method. However, optical beam method cannot detect pedestrians [14].

Figure 10: Optical Beam Method [14]

II. Ultrasonic Detectors

Another technique consists in using ultrasonic detectors (Figure 10) which rely on differences in ultrasonic reflection times for detection. They transmit pulses of ultrasonic energy towards the roadway. The pulse is then reflected back more quickly when a vehicle passes through. As an advantage, sonic detectors can detect both stationary and moving vehicles. However, the disadvantages reside in their price and installation cost. Additionally, they are extremely sensitive to environmental conditions (inaccurate in congested conditions) [14].

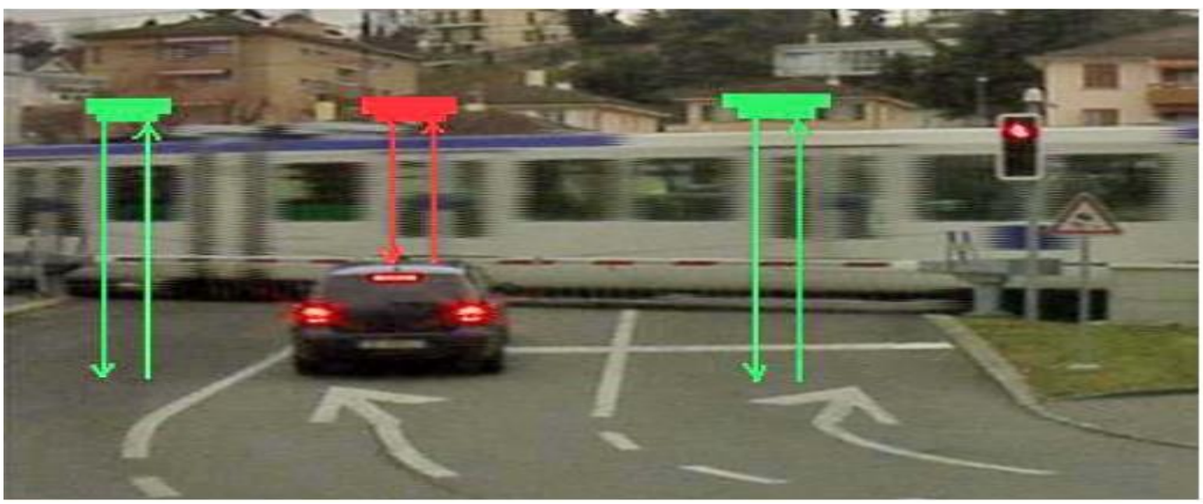


Figure 11: Ultrasonic Detection Method [14]

III. Infrared and Video Analytics

Visible and non-visible light emission and detection (e.g. infrared) operate at wavelengths that can be obscured easily by rain and snow, and occasionally overwhelmed by background sunlight. Despite the sophistication of video systems and the ability of analytic processing to recognize and classify vehicles, these systems are unreliable without sufficient light levels. As with infrared detection systems, the performance of video analytic systems may be impaired by the presence of rain, fog, snow, or the glare of bright background sunlight [3][24].

IV. 3D Lidar Laser Detection Method

Another object detection system has recently been designed by Hisamitsu [14] based on a 3D lidar (Light Detection and Ranging) technique in which the principle is the following: 3D lidar emits a laser pulse to an object and measures the time that it takes for the reflected laser to return to the receiver (time-of-flight method). It acquires the distance from that object. (Figure 11) shows the object detection method used by the 3D lidar, a laser pulse is emitted in a way that it scans the entire area of a level crossing in the horizontal and vertical directions. The 3-D coordinate's values of each point measured from the reflected laser are returned to the 3-D lidar.

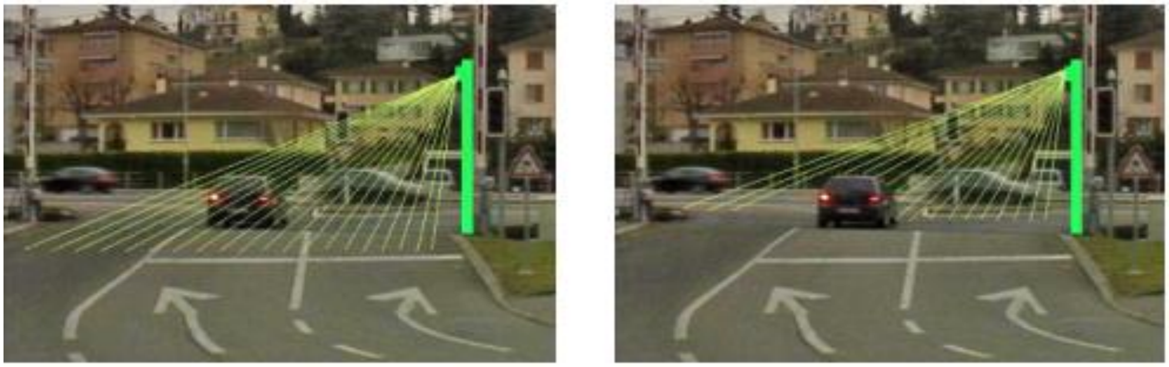


Figure 12: Laser Detection Method [14]

V. Buried Inductive Loops

The inductive loop is probably the most common form of vehicle detection. Buried inductive loop systems are most typically utilized in crossing applications in the transportation industry. A wire is embedded under the roadway. A magnetic flux is generated around it. When a vehicle is passing over the wire, the flux is cut causing an increase in inductance, and the detection of an obstacle. This is what happens when a car pulls up to the intersection. The huge mass of metal that makes up a car alters the magnetic field around the loop, changing its inductance. This system is easy to install and is not subjected to environmental conditions. The main drawbacks are that it cannot detect pedestrians or bicycles, and the high cost of installation and maintenance, because it needs a large number of loops to be efficient.

VI. Radar Detection Method

The principle of this technique is as follows: Microwaves are sent from a transmitter based on the side of the roadway. The microwaves are reflected back to a receiving antenna with a different frequency. This change is picked up and reflects the presence of a moving object due to the Doppler Effect. Radar presents a lot of advantages such as the fact that traffic does not need to be disrupted for installation and it is immune to electromagnetic interference. The disadvantage is that it is hard to maintain.

3.2.3. Selection Among the Technologies

Summarizing, optical beam and sonic detectors are definitely too expensive, not accurate enough and they need a high number of sensors. They are also too sensitive to environmental conditions. The most relevant technologies for object detection at level crossings are radar, inductive loops, and video imaging. The problem with inductive loops is that they detect only metal objects. Nowadays, many vehicles use carbon and aluminum fiber, which are not well detected by the system. Afterward, the maintenance of such a system is hard because it is located on the road. That is why focusing on radar and video based methods is important and now present some realizations and utilizations of these technologies.

A number of non-contact distance sensors have been reported in the past, primarily based on lasers, but also on other technologies like ultrasound and microwaves that are less widespread. Lasers offer unparalleled range and accuracy [26, 27] but are very sensitive to low visibility atmospheric conditions such as dust, sand, fog, and rain, rendering them unusable in a variety of applications, especially in automotive and industrial environments like video imaging. Furthermore, an opaque material like mud, smoke or oil that builds up on the opening of the sensor can severely impair its operation. This would be highly undesirable in automotive detection environments where mud and dust are always present in the car exterior. Likewise with ultrasound, apart from the fact that their operation can be affected by the same environmental conditions as the lasers [28], their non-directive nature can cause nearby objects to interfere with the measurement.

Microwave and mm-wave sensors have the potential to overcome these shortcomings. They are immune to most atmospheric variations and may even penetrate thin materials like paper, wood, and plastic. Several such implementations of microwave ranging systems have been proposed [29, 30–32]. However, they are all composed of discrete components and do not account for the difficulties that would arise in Nanoscale silicon technologies, especially 1/f noise. Furthermore, the frequency of operation of the reported microwave systems is relatively low, less than 77 GHz, leading to large antenna sizes and low directivity, making them impractical for many applications especially to what to be used in this thesis.

At a higher frequency of operation, the transmitter output power decreases due to the inherent lower transistor power gain, which, in combination with the higher free space loss, will inevitably lead to a smaller range. However, as will see in section 4.3, this problem can be partially alleviated by employing higher gain antennas and for most of the aforementioned applications, a range of approximately 23 m is adequate, and can be achieved with only moderate output power (<20dBm).

Chapter Four

System Design and Modeling

System Architecture

The complete architecture of the system extends from the detection of any movable or fixed object on the intersection to taking measures on both modes of transport's signaling so that there will be a full safety assurance and optimized delay i.e. maximum track and road utilization.

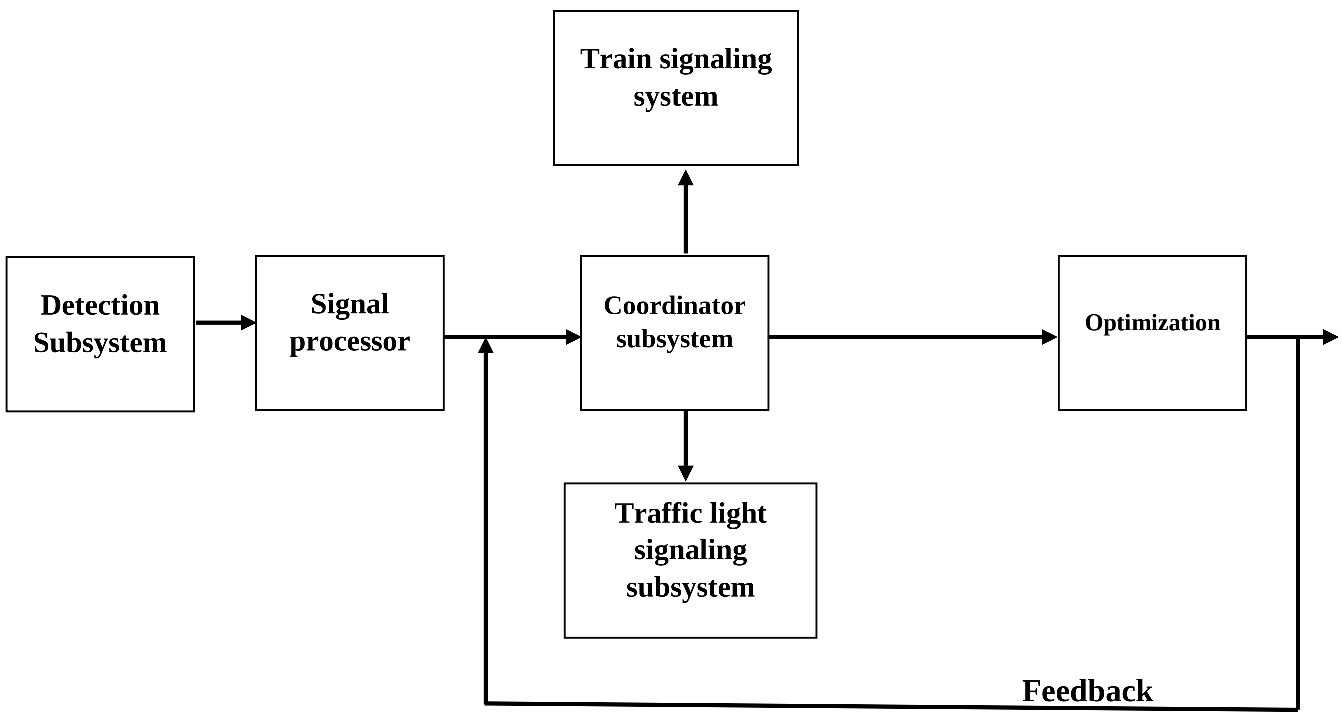


Figure 13: The Total Architecture of the System under Design

4. Detection Subsystem

The detection sub-system here am designing is responsible for detecting any kind of obstacle either fixed or moving on the LQC. It have been notified on section 3.2 above that it uses a millimeter wave radar detection method to detect any object/obstacle on the LQC up on making different merits of the radar system. The general block for the detection subsystem includes a set of components to apprehend the required tasks. These include Track circuit, Two/Four MMW radar detectors, and precision checker DSP and Programmable controllers.

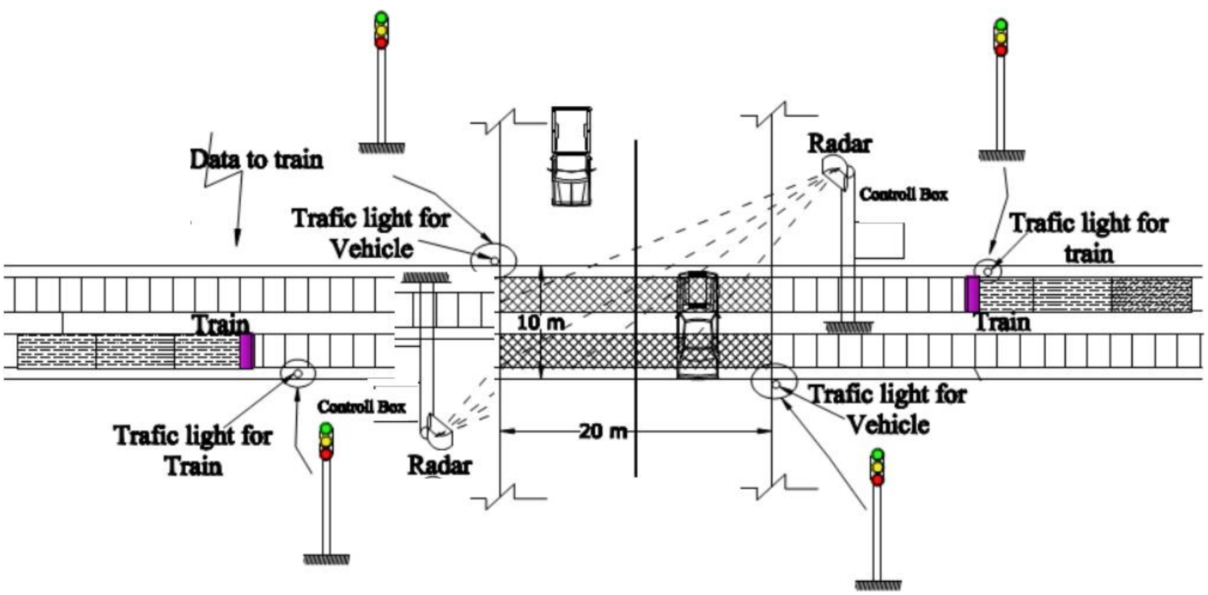


Figure 14: Detection Sub-Systems External Structural Configuration for Single Junction

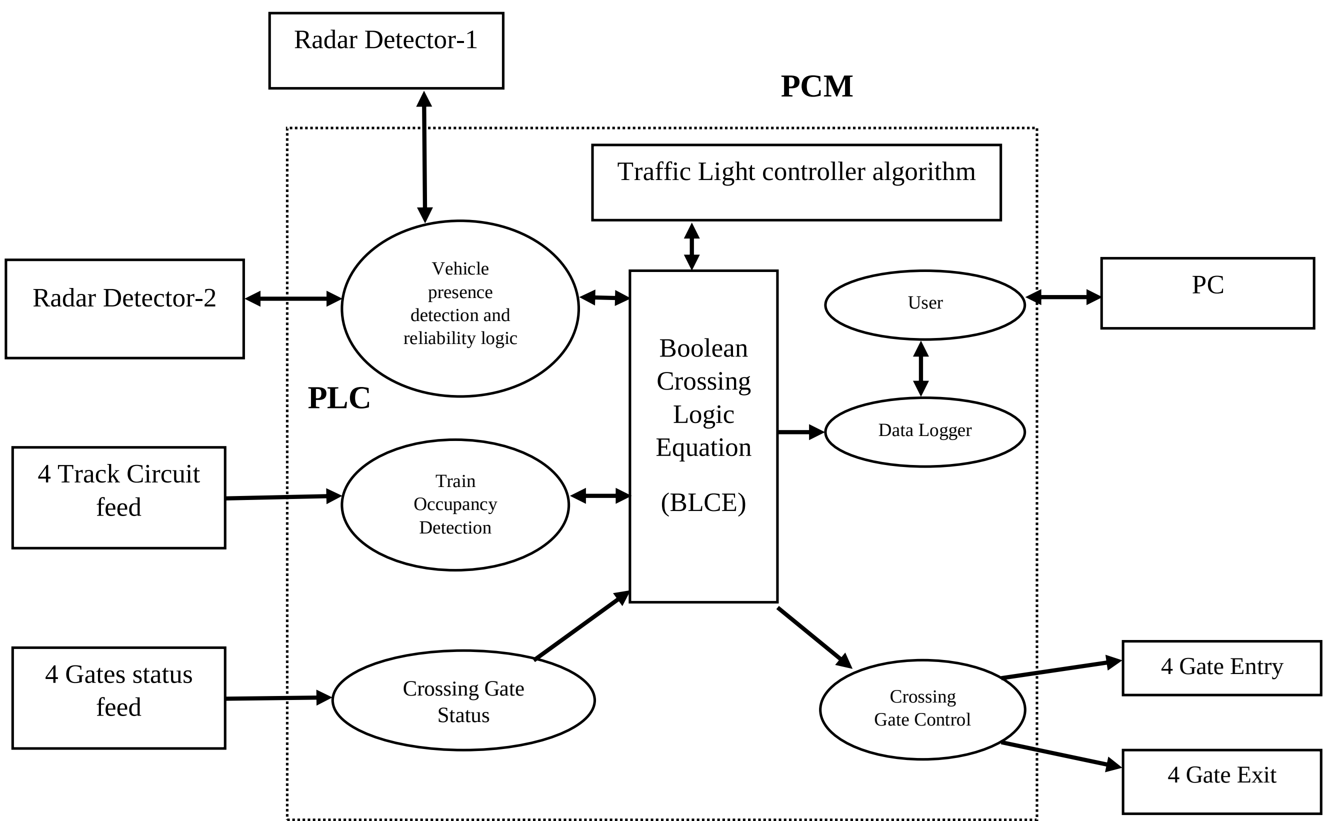


Figure 15: The Detection Subsystem for Single Junction Level/quad Crossing Architecture

The Detection Sub-System function assignment is shared between a dedicated Programmable Coprocessor Module (PCM) and the actual PLC (Programmable Logic Controller) module. The PLC performs most of the crossing logic and interfacing while the PCM is dedicated to serial communications.

The heart of the Detection Sub-System is the Boolean Crossing Logic Equations (BCLE) software component. It is responsible for performing all grade-level crossing control logic. The BCLE accepts

- ✓ Train occupancy data from the Train Occupancy Detection component,
- ✓ Gate status data from the Crossing Gate Status (CGS) component, and
- ✓ Vehicle stall data stall data from Radar Detectors and Determination components.

The BCLE processes this data to produce the correct control signals for each pair of crossing gates. Other outputs from the BCLE functional component include test-loop outputs for periodically testing the integrity of the radar detectors especially for double junction level crossings and messages sent to the PCM for data logging purposes.

The PCM's Data Logger software component accepts and parses data messages from the BCLE. The Data Logger formats that data for recording and sends it to the User Interface component. The User Interface component handles the serial communication to the user terminal. It displays selected crossing controls and indicator status to the user and accepts user commands to affect certain non-critical operations of the Detection Sub-System.

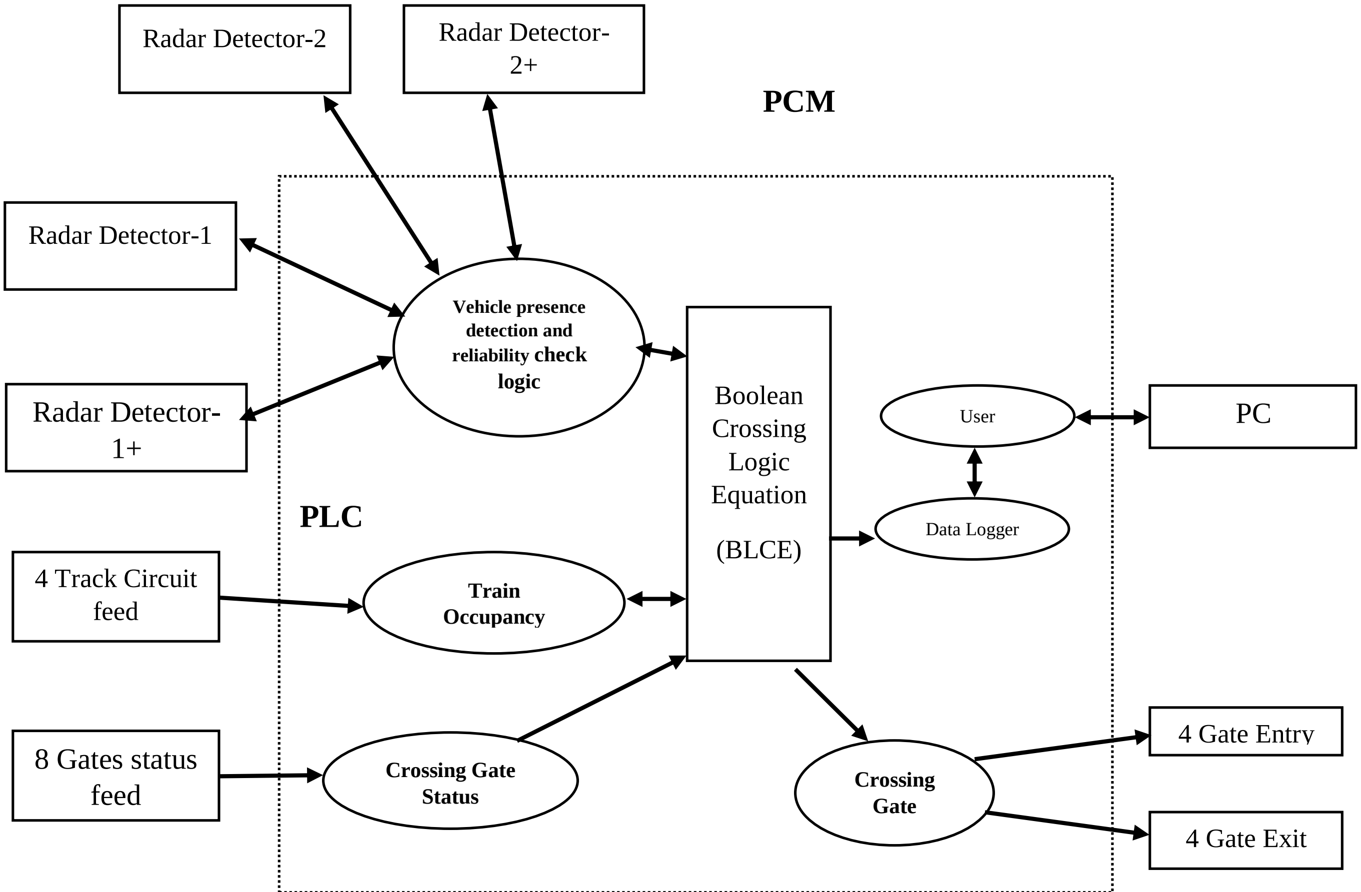


Figure 16: The Detection Subsystem for double Junction Level/quad Crossing Architecture

4.1. 122GHz MMW Radar System Design

Introduction

The word RADAR is an abbreviation for RAdio Detection And Ranging. In general, radar systems use modulated waveforms and directive antennas to transmit electromagnetic energy into a specific volume in space to search for targets. Objects (targets) within a search volume will reflect portions of this energy (radar returns or echoes) back to the radar. These echoes are then processed by the radar receiver to extract target information such as range, velocity, angular position, and other target identifying characteristics. Radars can be classified as ground-based, airborne, spaceborne, or ship-based radar systems. They can also be classified into numerous categories based on the specific radar characteristics, such as the frequency band, antenna type, and waveforms utilized. Another classification is concerned with the mission and/or the functionality of the radar. This includes weather, acquisition and search, tracking, track-while-scan, fire control, early warning, over the horizon, terrain following, and terrain avoidance radars. Phased array radars utilize phased array antennas, and are often called multifunction (multimode) radars [15][19].

A phased array is a composite antenna formed from two or more basic radiators. Array antennas synthesize narrow directive beams that may be steered, mechanically or electronically. Electronic steering is achieved by controlling the phase of the electric current feeding the array elements, and thus the name phased arrays is adopted [12].

Radars are most often classified by the types of waveforms they use, or by their operating frequency. Considering the waveforms first, radars can be Continuous Wave (CW) or Pulsed Radars (PR). CW radars are those that continuously emit electromagnetic energy, and use separate transmit and receive antennas. Unmodulated CW radars can accurately measure target radial velocity (Doppler shift) and angular position. Target range information cannot be extracted without utilizing some form of modulation. The primary use of unmodulated CW radars is in target velocity search and track, and in missile guidance. Pulsed radars use a train of pulsed waveforms (mainly with modulation). In this category, radar systems can be classified on the basis of the Pulse Repetition Frequency (PRF), as low PRF, medium PRF, and high PRF radars.

Low PRF radars are primarily used for ranging where target velocity (Doppler shift) is not of interest. High PRF radars are mainly used to measure target velocity. Continuous wave, as well as pulsed radars, can measure both target range and radial velocity by utilizing different modulation schemes.

Table 2: Radar Frequency ranges [15]

Letter of designation	Frequency (GHz)	New Band Designation
HF	0.003-0.03	A
VHF	0.03-0.3	A<0.25; B>0.25
UHF	0.3-1.0	B<0.5; C>0.5
L-band	1.0-2.0	D
S-band	2.0-4.0	E<3.0; F>3.0
C-band	4.0-8.0	G<6.0; H>6.0
X-band	8.0-12.5	I<10.0; J>10.0
Ku-band	12.5-18.0	J
K-band	18.0-26.5	J<10.0; K>20.0
Ka-band	26.5-40.0	K
MMW	Normally >34.0	L<60.0; M>60.0

From the table 2 it conclude that a radar system is designed for different purposes at different frequency ranges. High Frequency (HF) radars utilize the electromagnetic waves' reflection off the ionosphere to detect targets beyond the horizon. Very High Frequency (VHF) and Ultra High Frequency (UHF) bands are used for very long range Early Warning Radars (EWR). Because of the very large wavelength and the sensitivity requirements for very long range measurements, large apertures are needed in such radar systems. Radars in the L-band are primarily ground based and ship based systems that are used in long range military and air traffic control search operations. Most ground and ship based medium range radars operate in the S-band. However, most weather detection radar systems are C-band radars. Medium range search and fire control military radars and metric instrumentation radars are also C-band. The X-band is used for radar systems where the size of the antenna constitutes a physical limitation; this includes most military multimode airborne radars. Radar systems that require fine target detection capabilities and yet cannot tolerate the atmospheric attenuation of higher frequency bands may also be X-band. The higher frequency bands (Ku, K, and Ka) suffer severe weather and atmospheric attenuation. Therefore, radars utilizing these frequency bands are limited to short range applications, such as the police traffic radars, short range terrain avoidance, and terrain following radars. Milli-Meter Wave (MMW) radars are mainly limited to very short range Radio Frequency (RF) seekers and experimental radar systems [15].

So in this thesis , Milli-Meter Wave (MMW) radars will be designed at 122GHz frequency for a short range and fine target detection application to ensure safety at LQC.

Properties of MMW Spectrum

Here a question may be asked why using of the milli-meter wave range for this thesis. There are some important properties MMW spectrum:

- Ranges between: 30-300 GHz (λ ranges: 1-10mm)
- Millimeter wave signals can travel **only a few miles** or less that is why it is going to be used for this thesis for short range detection method
- Do not **penetrate solid** materials very well.
- Not affected by **natural environments** (rain, fog, air turbulence, or sunlight) or the color of the targets to be detected.
- Compared to the microwave band or lower frequencies, this wave has a significant **Doppler shift** and makes possible the high precision measurement of relative velocities and fine targets.

A MMW radar detection method is chosen due to the following reasons:

- High Resistance to the environmental impairments (foggy, Snow, day-night, atmospheric attenuations etc.)
- Cost –of- Installation and Maintenance is a little bit small in comparison to other Obstacle /target detection methods
- High MTBF (Mean Time Between Failure)
- Accuracy of Detection i.e
  - High Probability of Detection
  - Low Probability of False Alarm

4.1.1. Architectures of MMW Radar

From the detection sub-system architecture, a two and four radars for single and double junction LQC is used respectively. So in this section, it will describe and model what components exactly will the radar system have?

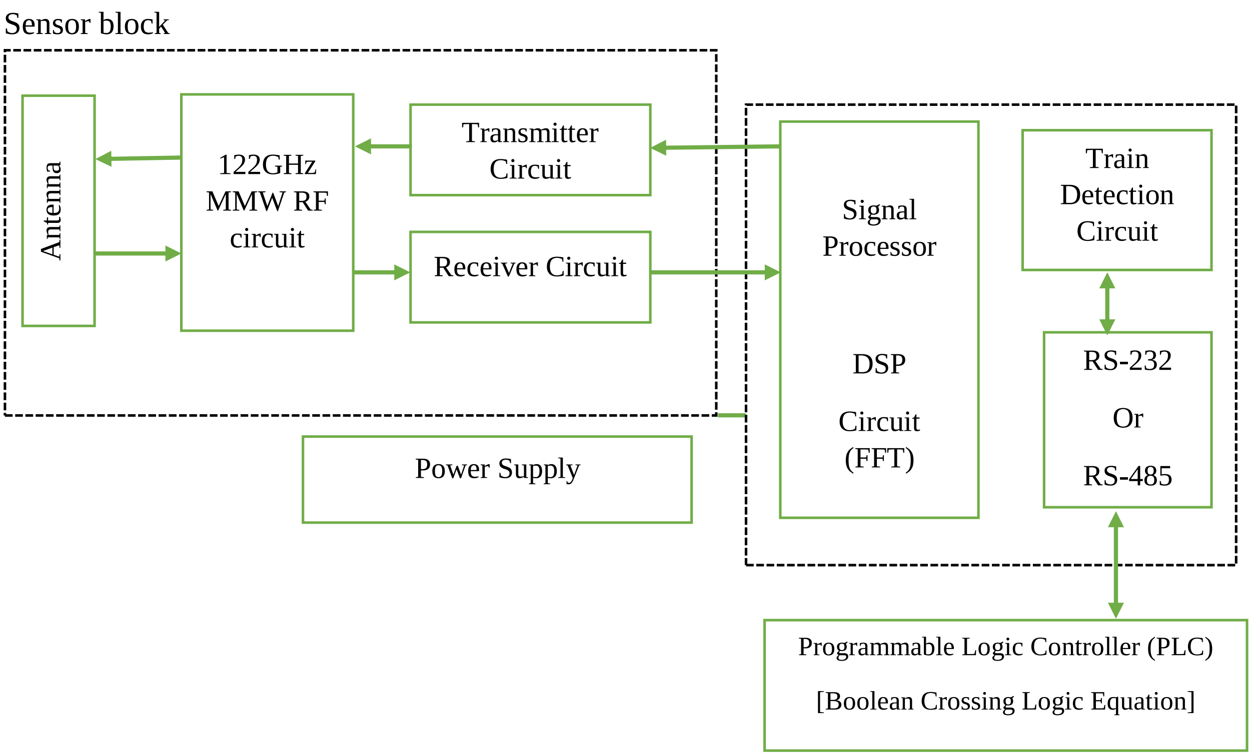


Figure 17: The general block diagram of the radar detection system interfacing with PLC

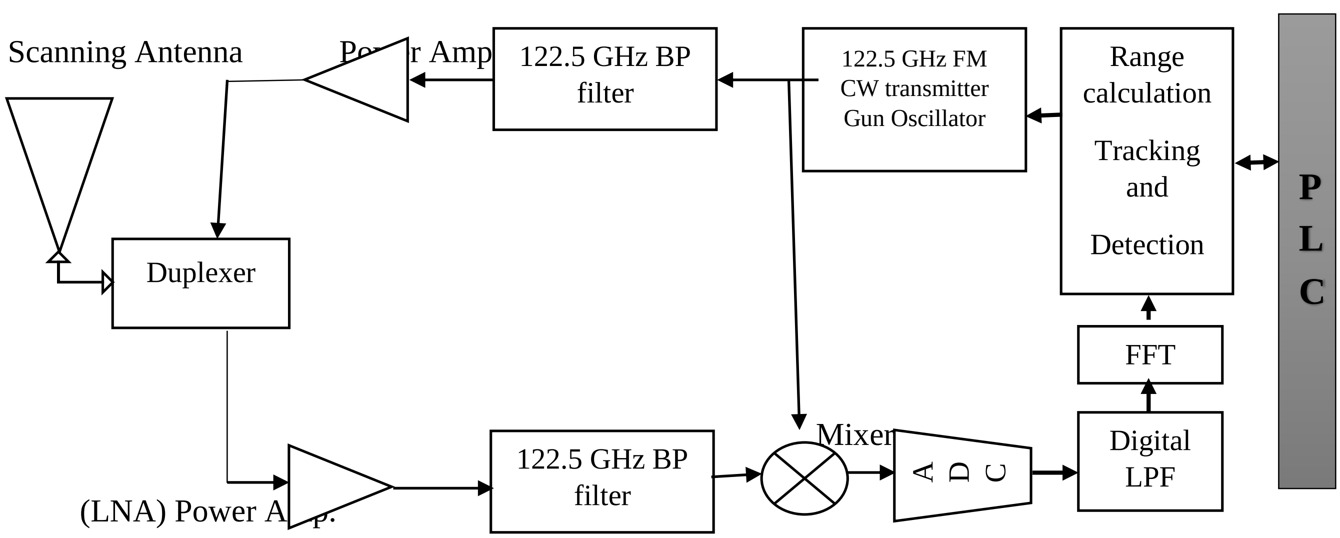


Figure 18: Internal components of radar system

As it can be seen from figure 17 wavefronts, transmitted by a wave generator (sound, microwaves, light etc.) hit a fixed or moving target. Depending on the direction of the motion of this object, the wave fronts are either “compressed“ or “diluted“, which finally means a shift in frequency. The signal, shifted in frequency and reflected, is subtracted from the unchanged transmit signal in a relatively simple mixer (for experts called “homodyne“ mixing) and results in a sinusoidal intermediate frequency (IF). It doesn’t matter whether the sensor moves relatively to the object or the object moves relatively to the sensor.

4.2. 122 GHz MMW Radar Components

In this section, a brief description of the major components of the 122 GHz MMW radar will be covered.

4.2.1. Antenna (Sensor)

The antenna consists of a rotating drum that contains a grating designed to create a beam of the desired shape and scanning angles. Millimeter wave energy from the transmitter is coupled to a dielectric waveguide placed in proximity to the drum. Energy is coupled from the waveguide and directed toward a parabolic reflector that shapes the resulting beam in the elevation plane. The drum is rotated by a dc motor at a constant rate, which in turn causes the generated beam to scan in the horizontal plane. The antenna system includes the antenna, transmission lines and waveguides from the transmitter to the antenna and the transmission line and waveguide from the antenna to the receiver as a single unit of monolithic IC. In some publications, the duplexer is included as a component of the antenna system [14][15].

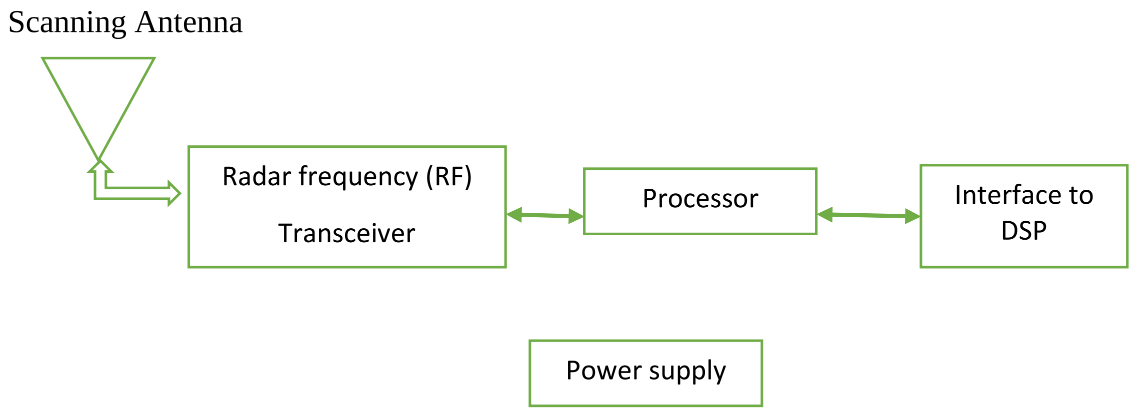


Figure 19: Sensor Block Diagram

Near/Far-Field Effect

Most radar applications sense targets in the antenna far-field region where the radiated power density varies inversely with the square of the distance and in which the antenna pattern remains constant for each angle. The beginning of the far-field region occurs at a distance R_{min} for which

$$R_{min} = \frac{D^2}{\lambda}$$ ---Equation 1

The above Equation results in R_{min}=0.463m for the radar of obstacle detection used in this study[15].

Methods of Radar Scanning

Scanning is the systematic movement of the Radar Antenna Beam in a finite pattern while searching, detecting or tracking a target. Scanning is dependent upon the purpose of the radar, antenna size, and design. For example, the search mode scan may be different than the track mode scan so do to detection scan. There are so many methods of scanning among which are:

Mechanical Scanning

- ✓ The entire antenna is moved to the desired pattern.
- ✓ The energy feed source is moved relative to a fixed reflector
- ✓ The reflector can be moved relative to a fixed feed source

Electronic Scanning

- ✓ Electronically switching between sets of feeder sources
- ✓ Varying the phase between elements in a multiple element arrays
- ✓ Comparing the amplitude and phase signals received by a multi-element array.

Frequency scanning

Fast scanning millimeter wave radar sensors offer a small and lightweight option as stand-alone devices and combine simultaneously area surveillance and projectile detection purposes. The gathered information about the observed scene and the capability to spot projectiles of near target object could give us a triggering signal for controlling of the traffic light signaling. Using the FMCW technique with triangular chirp in combination with a frequency scanning meander antenna

[18] offers a high average power, a good velocity (Doppler shift) and range resolution. In the case of a scanning radar approach, it is impossible to use a mechanically steered antenna because of the low rotational velocity with respect to the velocity of the vehicles and speed of arrival of the train towards the LQC. An alternative is given by using electrically steered radar beams, but in most cases conventional array-feed antennas are very complex, large and expensive due to the necessary phase shifter and power distribution networks and restrict a mobile usage. The usage of a substrate integrated waveguide (SIW) "leaky wave antenna" allows steering of the main lobe by a simple frequency shift and leads to a significant reduction of the array dimensions.

The demanded radar design requires good measurement accuracy, high update rates and also the detection of very low radar cross section (RCS) objects in tough radar environments. The hardware concept will be based on a broadband 122GHz -123 GHz FMCW frontend demodulated signal received to be processed and give the required information.

4.2.2. 122GHz Antenna Design

Using BCB (Benzocyclobutene) as an additional dielectric above SiGe BiCMOS wafer it can be easily integrated the antenna transceivers into a single wafer IC [19]. It enables the full integration of the mm-Wave transceiver and antenna on a single chip to achieve a system-on-chip. The critical parameters for on-chip antenna designs are the chip size and chip thickness. On reference [17] two 122 GHz antenna designs with different feeding methods i.e. microstrip transmission line direct feed and proximity coupled feed were implemented. They have made field measurements and almost they have got similar results of antenna gain with the simulations they have made. The single chip antenna design offers flexibility in routing the feed lines, which can be an advantage when more antenna elements are required within the very limited chip area.

The measured gain they got is 3.4 dBi at 122.5 GHz with the simulated efficiency of about 50%, which is considerably higher than that of antennas realized on ordinary low-resistivity silicon. The 3-dB gain bandwidth covers the 122–123 GHz ISM band. Only two layers of BCB and copper layers were deposited on the wafer for the trial of the technology and verification of antenna integration method in their design. No additional processes like making metalized and polymer-filled cavity under the radiator were applied to keep the fabrication procedure simple and low cost. They demonstrate it for a promising approach for short range applications for high volume products which is why it suits for this application. They have expected again that with one more deposition layer the efficiency, gain, and bandwidth of the antenna could be further increased. Moreover, the antenna and circuits can be integrated vertically on the same chip, thus saving the chip area and reducing the cost [17].

4.2.3. Duplexer/ Coupler

A duplexer is essentially an electronic switch that permits a radar system to use a single antenna to both transmit and receive in bistatic transceiver architecture. The coupler is sensitive to the direction of the signals, routing the Tx output to the antenna and the reflected signal to the Rx, thus isolating the two. The duplexer must connect the antenna to the transmitter and disconnect the antenna from the receiver for the duration of the transmitted pulse. The receiver must be completely isolated from the transmitted pulse to avoid damage to the extremely sensitive receiver input circuitry. After the transmitter pulse has ended, the duplexer must rapidly disconnect the transmitter and connect the receiver to the antenna. As previously mentioned, the switching time is called receiver recovery time, and must be very fast if close-in targets are to be detected. Additionally, the duplexer should absorb very little power during either phase of operation. Low –loss characteristics are particularly important during the receive period of duplexer operation. This is because the received signals are of extremely low amplitude [16].

There are certain design trade-offs in selecting either monostatic or bistatic transceiver architecture. It is in bistatic transceiver design where Tx and Rx are coupled together so that the need for duplexer or coupler is dealt.

In continuous wave radar, the transmitter and receiver operate simultaneously, resulting in Tx to Rx leakage problems. Therefore, the Rx must remain linear to avoid being blocked by the strong Tx signal. The increased linearity comes with a noise figure cost. For example, in [21] a 77GHz receiver with input 1-dB compression point of -22dBm and associated double-sideband noise figure of 4.8 dB is reported, whereas in [23, 22] a receiver at the same frequency and in a similar SiGe technology exhibits an input power 1dB of -0.3 dBm and DSB noise figure of 14 dB. For a transmit power of 7 dBm, typical of 77 GHz automotive radar, the former Rx would require a Tx-to-Rx isolation of at least 30 dB while in the latter, an isolation of approximately 10 dB would suffice. Designing an on-chip coupler with 30 dB of isolation over different process corners is extremely challenging, necessitating the use of a bistatic architecture. In the second case, an integrated directional coupler can easily be employed but with a **noise penalty** in the receiver, on top of which one must add the loss of the coupler itself.

At 122 GHz, the guided half-wavelength is approximately $\lambda g/2 = c/(\sqrt{\epsilon_r} f0) = 600\mu$m and if the antenna is integrated on-chip, it will still require a small, but still a considerable amount of silicon area, comparable to that of the transceiver itself. Furthermore, if two antennas are on the same die, their mutual coupling is going to increase due the small distance between them, diminishing the advantage of the bistatic architecture. Consequently, if an on-chip antenna is to be employed, the monostatic architecture is the preferred approach. The increased receiver noise figure will be circumvented by a moderate increase in the measurement time to overcome the accuracy degradation.

4.2.4. Radar Frequency Signal Generator

Depending on the application, the radar transmit signal can be pulse or CW. CW transmissions employ low continuous power compared to the high peak power of the pulsed radars. However, CW radars using unmodulated waveforms cannot measure the target's range. The issue is addressed by frequency or phase modulation of the signal. The frequency modulated CW signal (FMCW) has many advantages over pulse radars. They spread the transmitted energy over a large modulation bandwidth providing good range resolution and their circuitry is well-matched to solid-state transmitters leading to low cost and high-reliability systems. The purpose of the radar and the expected characteristics of the targets, in addition to the demands of moving target indication (MTI) and electromagnetic compatibility (EMC), are some of the factors that determine waveform design. For the W-band radar, a CMOS digital VCO is used to generate the basic or starting FMCW signal.

4.2.5. Transmitter

The transmitter generates powerful continuous pulses of electromagnetic energy at precise intervals. The required power is obtained by using a high-power microwave oscillator, such as a magnetron, or a microwave amplifier, such as a klystron, that is supplied by a low-power RF source. The main components in transmitters are the up-converting mixer or commonly called frequency multiplier, filters, and the power amplifier. The IF signal is converted into the RF frequency signal by mixers or frequency multipliers. The undesired harmonics and images are attenuated using band pass filters. Finally, the power amplifier provides amplification of the transmit signal before it excites the antenna. Couplers are commonly used to provide a sample of the transmit signal or the LO for the receiver down converter. Specifically, for this application, a transmitter have the following components: a frequency double, two directional adage coupler, and two detectors to detect the forward and backward signals [20]. The frequency doubler employs a push-push 2^{nd}-harmonic generator and a common base amplifier on the top. The measured conversion gain from 60 to 120GHz must be 2.5dB to have a peak output power 5dBm.

4.2.6. Receiver

The receiver accepts the weak echo signals from the antenna system, amplifies them, detects the pulse envelope, amplifies the pulses, and then routes them to the indicator. One of the primary functions of the radar receiver is to convert the frequency of the received echo signal to a lower frequency that is easier to amplify. This is because radar frequencies are very high and difficult to amplify. This lower frequency is called the intermediate frequency (IF). The type of receiver that uses this frequency conversion technique is the superheterodyne receiver (SHR). Superheterodyne receivers used in radar systems must have good stability and extreme sensitivity. Stability is ensured by careful design and the overall sensitivity is greatly increased by the use of many IF stages. The necessary considerations for the design of the transceivers i.e. TxRx are covered in the next section 4.3.

4.2.7. Synchronizer

The synchronizer ensures that all circuits connected with the radar system operate in a definite timed relationship. It also times the interval between transmitted signals to ensure that the interval is of the proper length. Timing signals are used to ensure synchronous circuit operation and are related to the pulse-repetition frequency (PRF). The PRF can be set by any stable oscillator, such as a sine-wave oscillator, multivibrator, or a blocking oscillator. That output is then applied to pulse-shaping circuits to produce timing pulses. Associated components can be timed by the output of the synchronizer or by a timing signal from the transmitter as it is turned on.

4.3. 122 GHz Transceiver Design

Reference [16] presents two distance sensors radars, at 122 and 144 GHz respectively. The 122 GHz sensor is designed based on the proposed IQ heterodyne architecture whereas the 144 GHz follows the heterodyne with built-in calibration. In both cases, the transceivers are based on fundamental frequency oscillators and he claimed as the first such transceivers reported in the literature operating above 100 GHz.

In both cases, the proposed circuits attempt to minimize the power consumption, in order to render the sensors feasible for use in portable systems. This is achieved by eliminating all the circuit topologies operating from 2.5 V or higher, commonly found in bipolar designs [16].

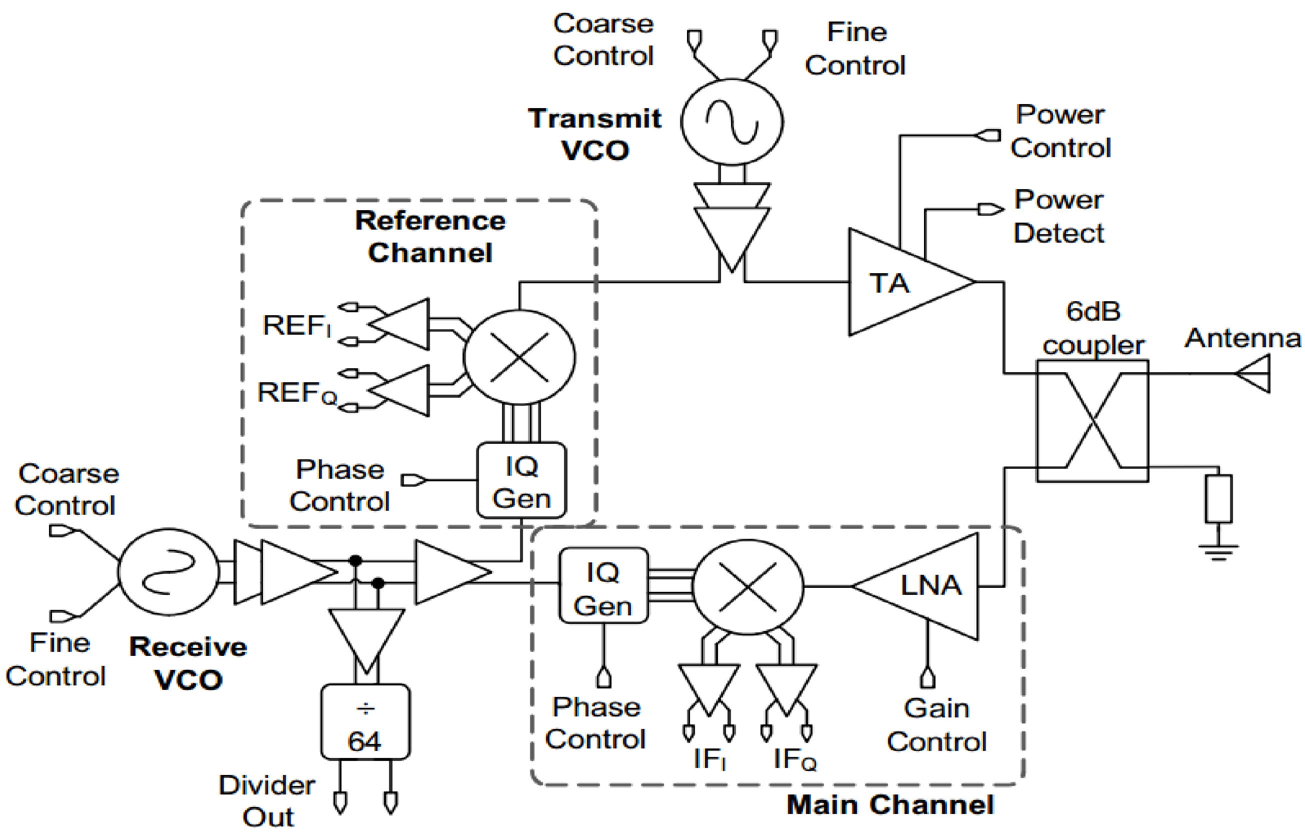


Figure 20: Block diagram of the 122GHz Transceiver [17]

The block diagram of the proposed monostatic 122-GHz transceiver is illustrated in Figure 19. Two fundamental frequency Voltage Controlled Oscillators (VCOs), operating at a frequency difference of up to 5 GHz, are employed to generate transmit and receive LO signals, allowing for an adjustable receiver output frequency. The signal from the receive VCO is distributed to the two IQ mixers and to a divide-by-64 chain whose output, at approximately 1.9 GHz, is provided to an off-chip (Phase Locked Loop) PLL that locks the VCO to a stable frequency reference.

The local transmit and receive VCO outputs are also down converted by a second quadrature receiver. The reference path IQ downconverter is identical to the main receiver, apart from the low noise amplifier, which has been omitted since the amplitude of the two multiplied signals are large enough for the mixer noise to be irrelevant. The reference receiver serves a dual purpose. First, it can be used to lock the transmit VCO in an external PLL. Second, it provides the phase reference for the main receiver.

The primary consideration for selecting the IQ heterodyne architecture over the simple heterodyne, despite its increased complexity, has been the minimum realizable IF frequency of the system. Specifically, when the two VCOs operate at a sufficiently small frequency offset, they will injection lock each other, due to the finite isolation between them, forcing themselves to oscillate at precisely the same frequency. In the system of Figure 19, this would result in the transceiver turning into a homodyne radar, with adverse impact on the SNR.

Consider the proposed heterodyne transceiver (Tx-Rx) of Figure 20. The Tx LO is tuned at frequency f_0 and the transmitter generates a CW signal:

$$T_x(t) = A_{Tx} cos(2\pi f_0 t)$$ --Equation 2

After being reflected by the target, it appears at the input of the receiver:

$$Rx(t) = A_{Rx} \cos(2\pi f_0 t - 2\pi f_0 \tau_D)$$ --Equation 3

Where τ_D is the round trip delay (also known as the time-of-flight, ToF) of the pulse given as: $\boldsymbol{\tau_D} = \frac{2R}{c}$ where R is the distance to the target or the range and c is the speed of light.

Unlike the homodyne transceiver [17], the receiver now has a separate VCO that is tuned to a slightly different frequency to that of the transmitter, $f_0 - f_{IF}$. As a result, the receiver output is at a finite frequency f_{IF}:

$$IF(t) = A_{Rx} \cos(2\pi f_{IF} t - 2\pi f_0 \tau_D)$$ ---Equation 4

The phase of the IF signal cannot be measured directly as it would depend on the start time of observation. To circumvent this problem, a separate reference receiver is introduced, which also generates a sinusoid at f_{IF} but whose phase is independent of the target distance:

$$REF(t) = A_{REF} \cos(2\pi f_{IF} t + \varphi_{ref})$$ ---Equation 5

The phases of the IF and REF output sinusoids are compared, yielding $\varphi 1 = 2\pi f_0 \tau_D - \varphi_{ref}$.

The process is repeated at the next frequency step $f_0 + \Delta f$ where the Rx LO is tuned at $f_0 + \Delta f - f_{IF}$, yielding $\varphi 2 = 2\pi(f_0 + \Delta f)\tau_D - \varphi_{ref}$. When $\varphi 1$ and $\varphi 2$ are subtracted, φ_{ref} vanishes and the distance can be calculated directly.

The advantage of the heterodyne transceiver becomes apparent when the IF frequency f_{IF} is set to a larger value than the 1/f noise corner frequency fc. In that case, the receiver filter that will act on the IF and REF outputs and will cut-off the 1/f noise, drastically improving the SNR compared to that of the homodyne transceiver. A simple way to implement the filter and simultaneously calculate the phase difference between the IF and REF outputs is to directly digitize them, calculate their DFTs and subtract the phases of the Fourier coefficients that correspond to frequency f_{IF} [24, 25]. The phase error due to noise then becomes [24]:

$\sigma_\varphi = \frac{1}{\sqrt{SNR0}}$ where *SNRo* is the SNR at the IF output of the receiver

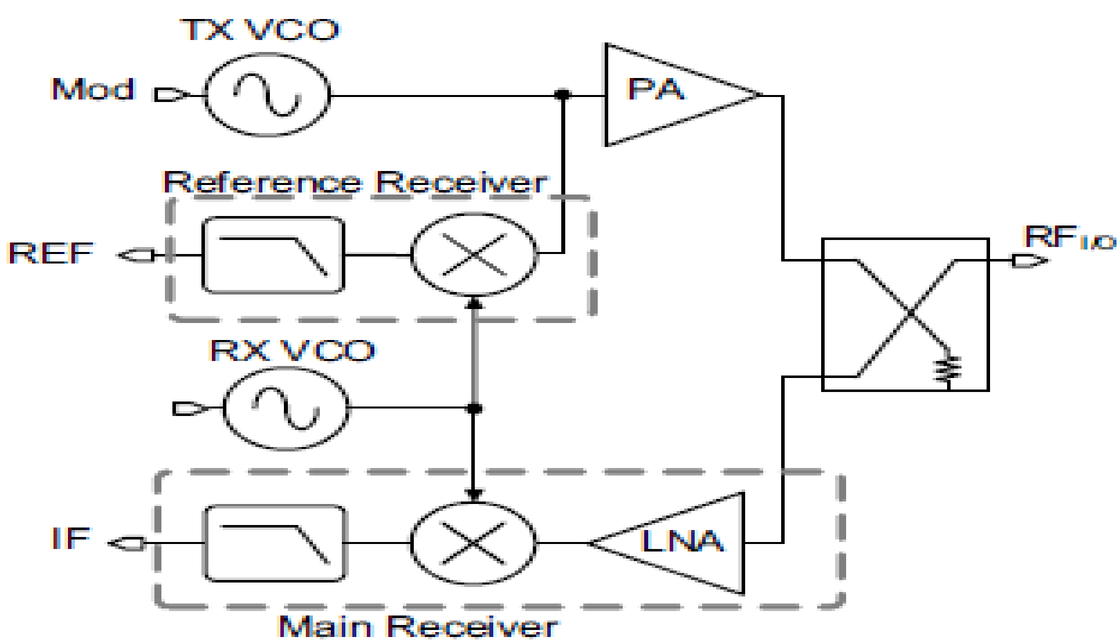


Figure 21: Heterodyne radar transceiver architecture [17].

Assuming that the frequency f_{IF} is larger than the 1/f noise corner, the *SNRo* at the IF output, after the calculation of the DFT, is calculated:

$SNRo = S_i^2\tau s/Ni$

Where *Si*, is the amplitude of the sinusoid and *Ni* is the white noise PSD. In this case,

$S_i^2 = P_{RX}G_{RX}$ and $Ni = k_BT_FG_{RX}$ resulting to: $SNRo = G_{RX}P_{RX}\tau s/ k_BT_FG_{RX} = P_{RX}\tau s/k_BT_F$

The $\sigma\varphi$ of the heterodyne TxRx can be improved by a factor of √2 with the IQ architecture of Figure 120. The operation of this system is identical to the one of Figure 20, apart from the fact that quadrature receivers are introduced at both the reference and receive channels. The output sinusoids are now complex and the estimation error becomes [24]:

$\sigma_\varphi = \frac{1}{\sqrt{(2SNRo)}}$ which is identical to that of the homodyne TxRx.

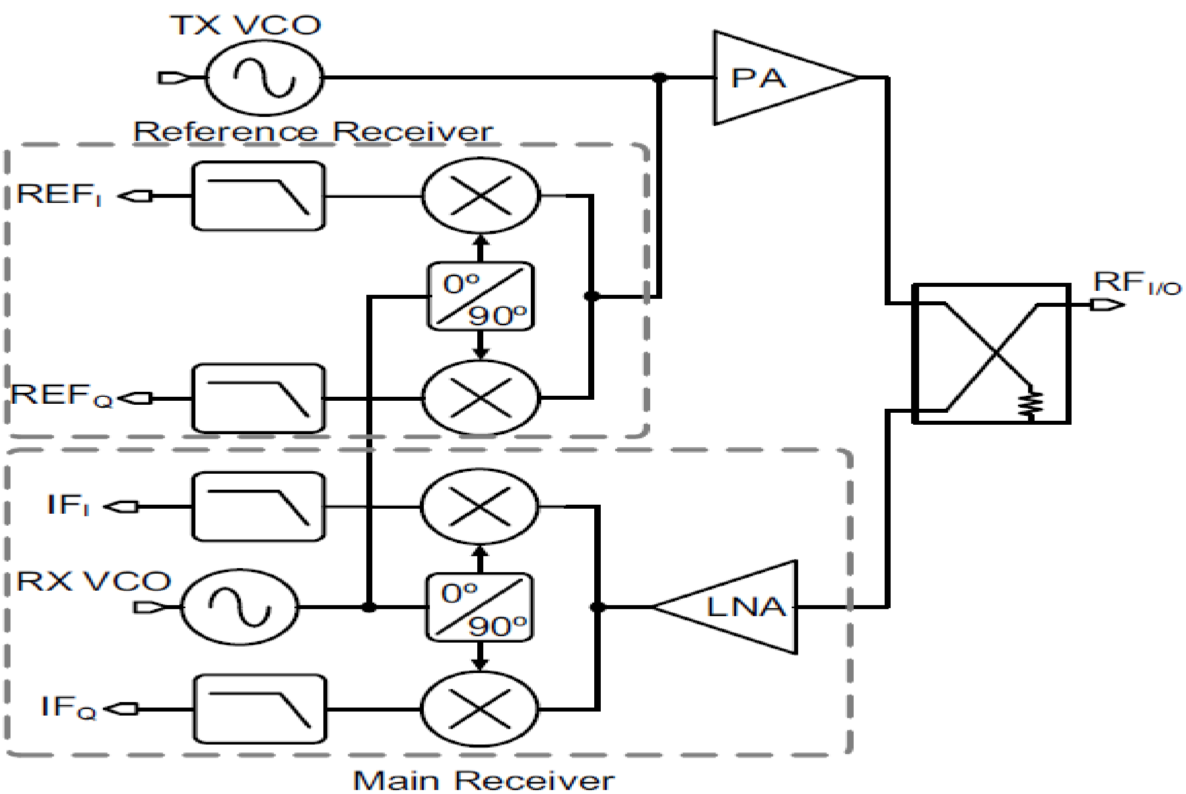


Figure 22: IQ heterodyne transceiver architecture

But it does mean that there are no disadvantages associated with the proposed heterodyne architectures it has got its own design considerations to achieve this. First, the system complexity is increased substantially compared to the homodyne case, as two oscillators and two mixers are required. The increased complexity inevitably leads to increased design effort, especially at 122 GHz, as well as to additional power dissipation. Furthermore, having two oscillators on the same die operating at a small frequency offset poses a new design challenge because of the finite isolation that can be achieved on the die. At small offsets, the two oscillators will tend to injection lock each other and force the system to operate at zero-IF, negating the heterodyne advantage. To avoid this adverse condition, f_{IF} needs to be sufficiently large to avoid injection locking. However, in that case, f_{IF} could be too high to be directly digitized by a simple ADC and further down conversion might be necessary.

4.4. 122 GHz MMW Radar Mathematical Modeling

There are several parameters that quantify the performance of a radar system. The degree to which each parameter needs to be satisfied depends largely on the application. For example, the case of a single large nearby target has vastly different requirements from that of an airborne radar that has to detect extremely fast moving objects at distances of several hundred kilometers. These differences will be explained in each metrics making recommended design issues for this thesis.

4.4.1. Range

The target's range, R, is the distance between the radar and the target computed by measuring the time delay, Δt; it takes a pulse to travel the two-way path between the radar and the target. Since electromagnetic waves travel at the speed of light, c= $3x10^8$ m/s, then:

$$R=\frac{c\Delta t}{2}$$

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

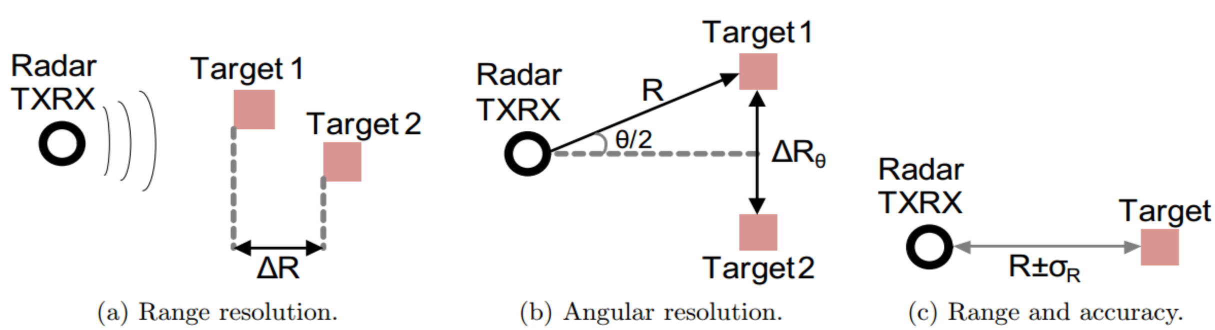


Figure 23: Important radar performance metrics

4.4.2. Range Resolution

Range resolution, denoted as ΔR, is a radar metric that describes its ability to detect targets in close proximity to each other as distinct objects. Radar systems are normally designed to operate between a minimum range R_{min}, and maximum range R_{max}. The distance between R_{min} and R_{max} is divided into

M range bins (gates), each of width ΔR,

$$M=\frac{R_{max}-R_{min}}{\Delta R}$$

Targets separated by at least ΔR will be completely resolved in range, as illustrated in Figure 22. Targets within the same range bin can be resolved in cross range (azimuth) utilizing signal processing techniques.

Consider two targets located at ranges R1 and R2, corresponding to time delays T1 and T2, respectively. Denote the difference between those two ranges as ΔR:

$$\Delta R= R2\text{-}R1=\frac{c(T_2-T_1)}{2}=\frac{c\delta t}{2}$$ ---Equation 6

Now, one must try to answer the following question: What is the minimum δt such that target 1 at R1 and target 2 at R2 will appear completely resolved in range (different range bins)? In other words, what is the minimum ΔR?

Just as it can be seen from equation 12 above ΔR must be given as:

$$\Delta R=\geq \frac{c\tau}{2}=\frac{c}{2B}$$ --Equation 7

Where $\tau = 1/B$, B-Bandwidth of the radar system and τ *is pulse width of the signal transmited*. Therefore for this thesis the bandwidth used is 300MHz which will result a range resolution of 0.5m as shown in the Figure 23. This result is considerably good for vehicle and pedestrian identification on the LQC. The range resolution for different bandwidth values which means for different transmitter power and pulse width of the signal transmitted is given the graph below.

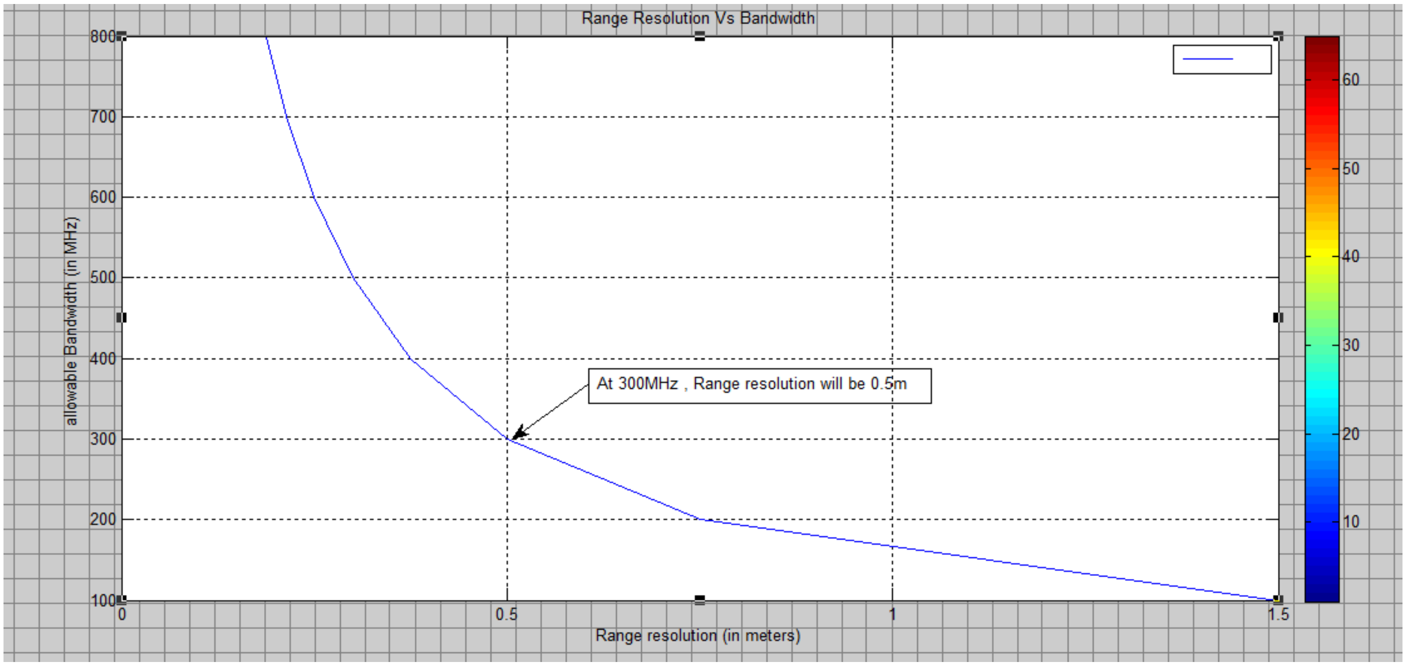


Figure 24: Range Resolution Vs Bandwidth

In general, radar users and designers alike seek to minimize ΔR in order to enhance the radar performance. As suggested by Eq. (13), in order to achieve a fine range resolution one must minimize the pulse width. However, this will reduce the average transmitted power and increase the operating bandwidth. Achieving fine range resolution while maintaining adequate average transmitted power can be accomplished by using pulse compression techniques.

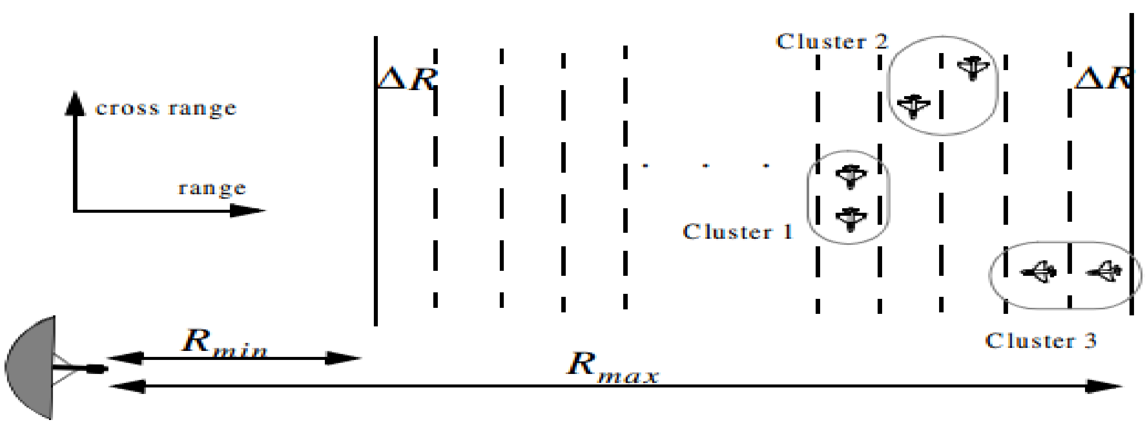


Figure 25: Resolving targets in range and cross-range.

Interestingly, it is independent of the center frequency of operation, although there is a clear advantage in operating at higher frequencies due to the higher fractional bandwidths available. The range resolution is the most important parameter considered in this thesis since it deals with automotive radars where closely spaced cars and motorcycles, bicycles or pedestrians need to be accurately resolved near the LQC.

4.4.3. Angular Resolution

The angular resolution, depicted in Figure 22 (b), represents the minimum lateral distance, ΔR_θ at which two targets at the same distance from the radar can be unambiguously separated. This parameter depends on the target distance R and the 3 dB beamwidth θ of the radar transceiver antenna as follows [34]:

$$\Delta R_\theta \geq 2R\sin\frac{\theta}{2} \quad \text{------- Equation 8}$$

Where the assumption is made that the power in the side lobes of the antenna is low enough to be ignored.

For every antenna, the beam-width depends on its physical diameter, d, and on the wavelength of operation, λ[35]:

$$\theta = k_\theta \frac{\lambda}{d} \quad \text{------- Equation 9}$$

Where k_θ is a proportionality factor dependent on the antenna type ranges mostly from 0.9 to 1.43. For example, when θ is measured in radians and the antenna is parabolic, k_θ =1.2. Substituting in (14),

$$\Delta R_\theta = 2R\sin\frac{K\theta\lambda}{2d} = 2R\sin\frac{K\theta C}{2fd} \quad \text{------- Equation 10}$$

As a result, at higher frequencies, better angular resolution can be obtained with constant antenna size.

The directivity, D of the antenna is also related to the beam-width. Assuming an elliptical beam spot, D is expressed as follows [35]:

$$D = \frac{16}{Sin\theta_{az}Sin\,\theta_{el}} \cong \frac{16}{\theta_{az}\theta_{el}} \quad \text{------- Equation 11}$$

Where θ_{az} and θ_{el} are the azimuth and elevation beamwidth angles in radians. The angles θ_{az} and θ_{el} define the field-of-view (FoV) of the radar, i.e. the maximum angles inside which a target is visible. Assuming a circular spot size, θ=θaz=θel:

$D = \frac{16}{\theta^2}$--*Equation 12*

Consequently, the antenna directivity is inversely proportional to the square of the beam-width, i.e, higher antenna gains will result in narrower beamwidth.

Typically, radar systems that aim for high angular resolution cannot simply use a high gain-low beam-width antenna to resolve multiple targets. This would severely restrict their field-of-view and limit what the radar can "see". As a result, beam steering with phased arrays or MIMO radar with multiple beams are commonly employed.

4.4.4. Doppler Frequency

Radars use Doppler frequency to extract target radial velocity (range rate), as well as to distinguish between moving and stationary targets or objects. The Doppler phenomenon describes the shift in the center frequency of an incident waveform due to the target motion with respect to the source of radiation. Depending on the direction of the target's motion this frequency shift may be positive or negative as illustrated in Figure 125. A waveform incident on a target has equi-phase wave-fronts separated by λ, the wavelength. A closing target will cause the reflected equi-phase wave-fronts to get closer to each other (smaller wavelength). Alternatively, an opening or receding target (moving away from the radar) will cause the reflected equi-phase wave-fronts to expand (larger wavelength)

As a matter of fact, only the component of the velocity vector pointing parallel to the direct connection sensor-object can be calculated. The mathematical formula to compute the Doppler frequency looks as follows:

$F_{Dopp}=2f_0 \frac{v}{c_0} \cos\alpha$ ---*Equation 13*

Where:

f_D - Doppler- or differential frequency

f_0 - transmit frequency of the radar

v - Magnitude of the velocity of the moving object

c_0 - velocity of light

α - angle between the actual direction of motion and the connecting line sensor-object

So for this thesis it uses 122.5 GHz transmit frequency for the radar System and thus Doppler formula will be reduced to:

$$F_{Dopp}=227 \frac{Hz}{Km/_h} v * cos\,\alpha \qquad \text{---Equation 14}$$

Thus with this formula the expected Doppler frequency can easily be calculated as well as the pass-band of the following IF-amplifier can be predicted. Mostly in this thesis , it doesn't give a detail issue of tracking the speed of the object around the LQC since am interested in detecting whether there is an obstacle or not on the intersection. For instance, it makes no sense to design the upper-frequency limit of the signal conditioning part of a unit detecting human beings as higher than 1.6 KHz since this corresponds to a speed of 6.8 km/h of a (pretty fast) pedestrian. On the other hand, when using radar sensors to check the speed of a car or motorbike the amplifier got to have an upper-frequency limit of at least 50 kHz corresponding to 220 km/h. This is shown in Figure 25.

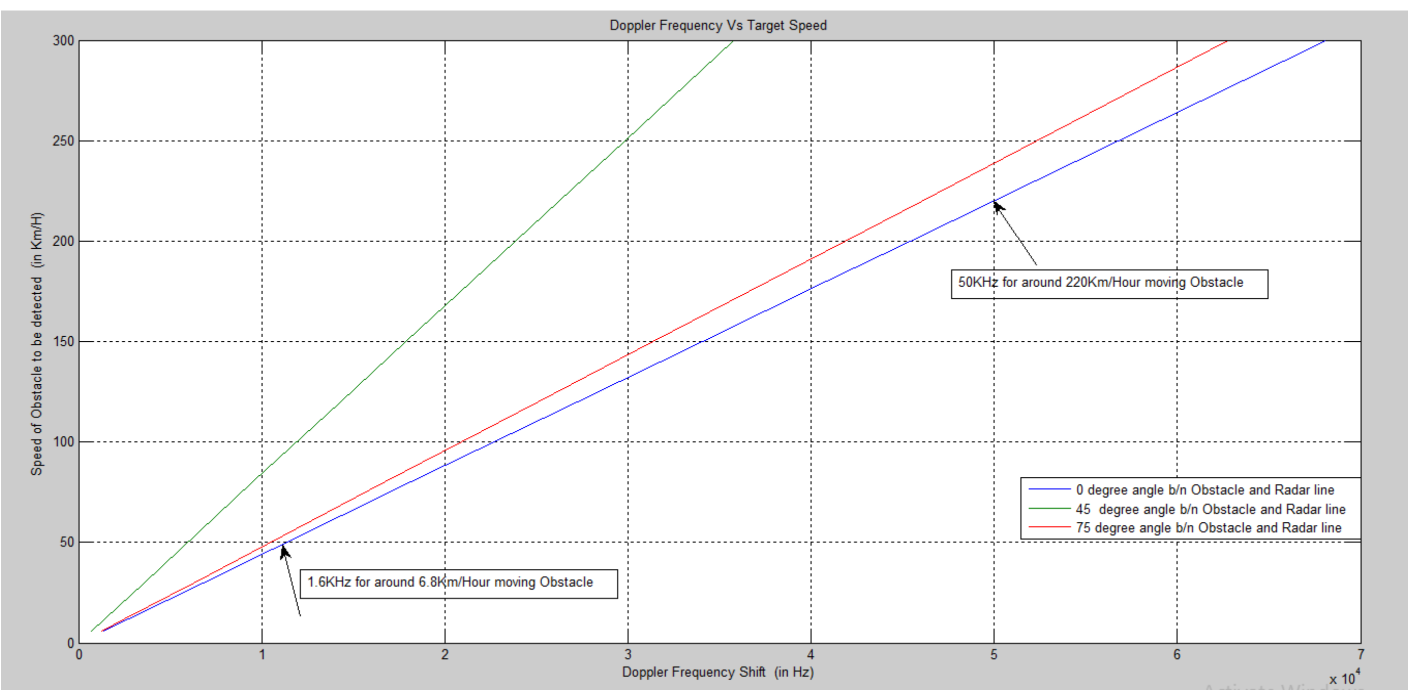


Figure 26: Doppler Frequency Versus Speed of Obstacle to be Detected on LQC

A velocity measurement is definitely possible with more or less technical effort. Since am dealing with single individual objects, "zero-crossing-counting "of the Doppler signal might be sufficient. The longer the integration time is, the more accurate the results will be. Multiple targets cannot be treated trivially anymore. In this case, digital signal processing with A/D conversion and following FFT is required, since "zero-crossing-counting" won't work or would definitely lead to significant errors.

Purely stationary objects can only be detected by CW radar modules when using the FMCW technique. For this approach, the microwave oscillator got to be a VCO, where its frequency can be swept periodically and monotonously. The simplest function over time is a linear chirp.

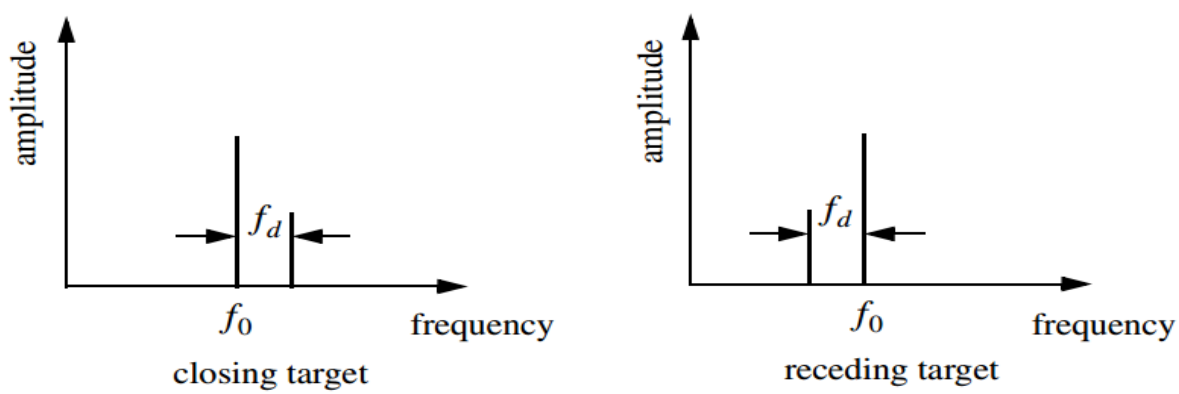


Figure 27: Spectra of radar received signal.

4.4.5. Range and Accuracy

The range of a radar, R_{max}, is the maximum distance where a target can be unambiguously detected. The range primarily depends on the link margin and the Signal-to-Noise Ratio (SNR) at the output of the receiver and consequently, on the available integration time between successive measurements.

The accuracy of the radar, graphically illustrated in Figure 22c, is the average absolute error in the detected distance R. It is represented by the standard deviation, σ_R, and depends on the SNR, as well as, on systematic errors such as the non-idealities of the radar waveform. Obviously, due to the increasing free space loss with distance, the accuracy of a radar degrades with increasing distance to the target.

4.4.6. Radar Equation

The radar equation varies according to the type of radar that we design whether it is continuous wave or pulsed radars. Here in this thesis, it illustrates what will be the parameters for CW radar equation design considerations.

Considering a radar with an Omni-directional antenna (one that radiates energy equally in all directions). Since these kinds of antennas have a spherical radiation pattern, we can define the peak power density (power per unit area) at any point in space as:

$$P_D = \frac{Peak\ transmitted\ power}{Area\ of\ the\ sphere} \quad \frac{watt}{m2}$$ ---Equation 15

The power density at range R away from the radar (assuming a lossless propagation medium) is

$$P_D = \frac{P_t}{4\pi R^2}$$ ---Equation 16

Where P_t is the peak transmitted power and $4\pi R^2$ is the surface area of a sphere of radius R . Radar systems utilize directional antennas in order to increase the power density in a certain direction.

Directional antennas are usually characterized by the antenna gain G and the antenna effective aperture A_e. They are related by:

$$A_e = \frac{G\lambda^2}{4\Pi}$$ ---Equation 17

Thus, the total power delivered to the radar signal processor by the radar antenna will be given generally for any radar as:

$$P_{Dr} = \frac{P_t * G_t * G_r * \lambda^2 * \sigma}{(4\pi)^3 * R^4}$$ ---Equation 18

Equation 18 above suggests that in order to double the radar maximum range, one must increase the peak transmitted power sixteen times; or equivalently, one must increase the effective aperture four times.

But In practical situations, the returned signals received by the radar will be corrupted with noise, which introduces unwanted voltages at all radar frequencies. Noise is random in nature and can be described by its Power Spectral Density (PSD) function. The noise power N is a function of the radar operating bandwidth, B. More precisely

$N = Noise\ PSD * B$--Equation 19

The input noise power to a lossless antenna is: $N_i = kT_eB$

Where k= 1.38x10^{-23} joule/degree kelvin is Boltzmann's constant, and T_e is the effective noise temperature in degree Kelvin.

In the presence of a real atmospheric modeling, attenuation due to different factors are taken into account. Therefore the minimum Detectible power at the receiver is given by:

$S_{min} = P_r = \frac{P_t * G_t * G_r * \lambda^2 * \sigma * G_p}{(4\pi)^3 * R^4 * L}$--Equation 20

Where:

P_r = received power

P_t = transmitted power

G_t, G_r= Transmitting, and Receiving antenna gain respectively

G_p = Gain of the system

λ = wavelength

σ = target cross-section

$L = L_s + L_{ATM}$ = total attenuation loss

L_s = system loss (> 1.0)

L_{ATM} = atmospheric loss (> 1.0)

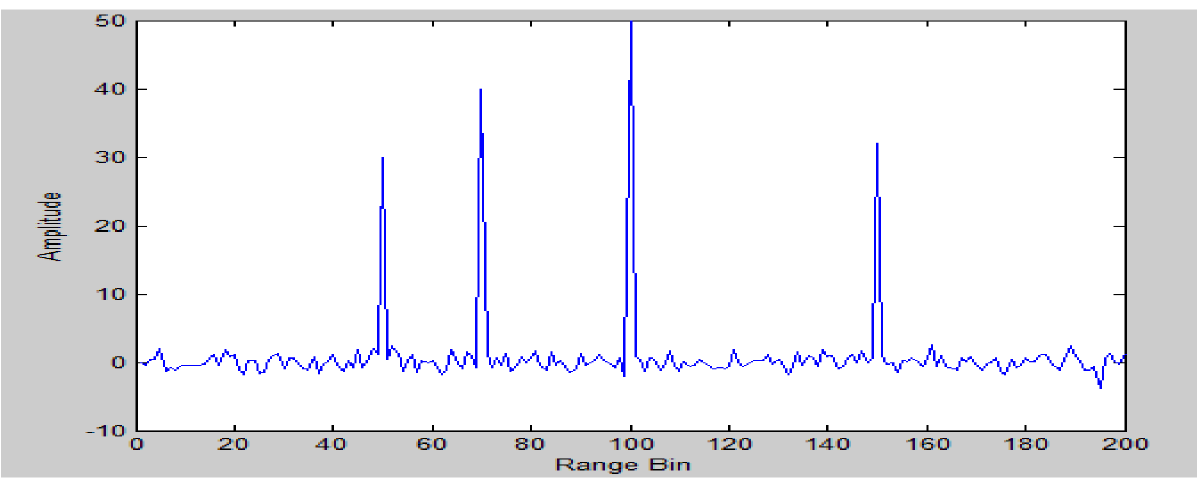
R = range to target

The minimum Detectible signal is defined as the useful echo power at the reception antenna, which gives on the screen a Detectible blip. The minimum Detectible signal at the receiver input-jack leads to the maximum range of the radar; all other nominal variables are considered as constant [2]. A reduction of the minimal received power of the receiver gets an increase of the maximum range. The maximum range R_{max} is the distance beyond which the target cannot be detected due to insufficient received power Pr. For every receiver, there is a certain receiving power as of which the receiver can work at all. This smallest workable received power is frequently often called MDS – Minimum Detectable Signal in radar technology [17].

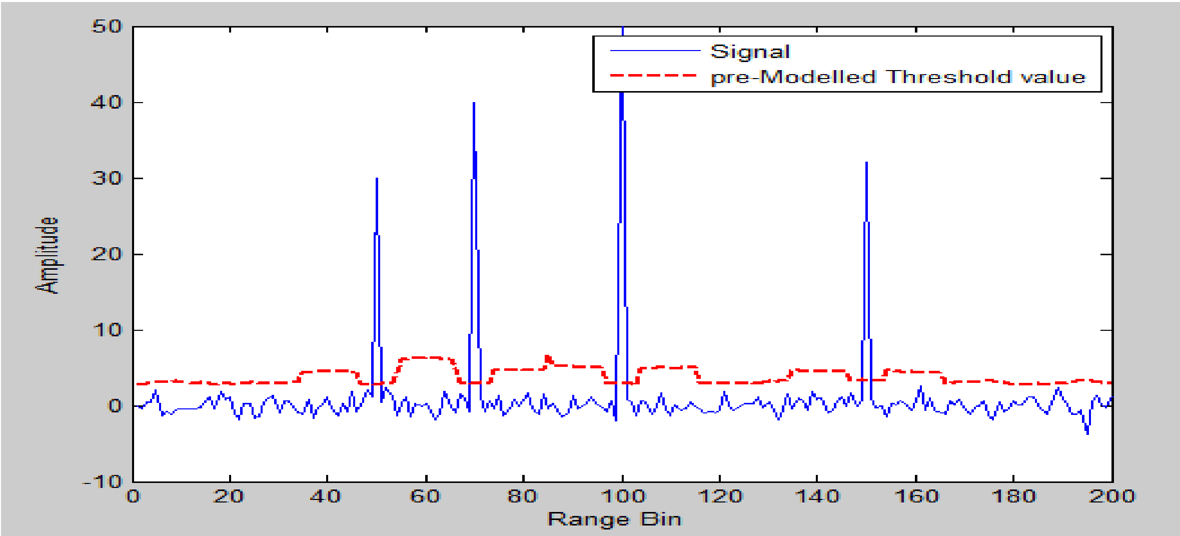
For example for a 15dB SNR receiver the MDS (receiver sensitivity) can be found as [47]:

$S_{min}= SNR_{min}*kT_0BNf= 9.128*10^{-14}$ watt= -130.3960dBm

In most cases the optimal performance of a radar system can be obtained using the technique of threshold detection. In this method, the magnitude of each complex sample of the radar echo signal, possibly after signal conditioning and interference suppression is compared to a pre-computed threshold. If the signal amplitude is below the threshold, it is assumed to be due to interference signals only. If it is above the threshold, it is assumed that the stronger signal is due to the presence of a target echo in addition to the interference, and a detection or “hit” is declared. In essence, the detector makes a decision as to whether the energy in each received signal sample is too large to likely have resulted from interference alone. If so, it is assumed a target echo contributed to that sample. In this case, the radar environment must be modeled effectively and efficiently so as to have the threshold value of the operating environment of the radar. Figure 27 (a) and (b) below demonstrates this.



(a)



(b)

Figure 28: Illustration of the Threshold Detection

It is always desirable that the minimum detectable signal (S_{min}) be greater than the noise power. The fidelity of a radar receiver is normally described by a figure of merit called the noise figure F. The noise figure is defined as:

$$F = \frac{(SNR)input}{SNR\ output} = \frac{S_i/N_i}{S_0/N_0}$$ --Equation 21

Thus, combining the above equations, the minimum detectable signal power considering L –the radar lose and F noise figure, can be written as [15]:

$$(SNR_0)_{min} = \frac{P_t * G_t * G_r * \lambda^2 * \sigma}{(4\pi)^3 * R^4 * k * T_e * B * F * L}$$ --Equation 22

Hence due to the different designs of the transceiver in CW and pulsed radars the radar equation in equation 21 can be written as [15]:

For CW radars:

$$(SNR_0)_{min} = \frac{P_{cw} * T_{dwell} * G_t * G_r * \lambda^2 * \sigma}{(4\pi)^3 * R^4 * k * T_e * F * L * L_{win}}$$ --Equation 23

For pulsed radars:

$$(SNR_0)_{min} = \frac{P_t * G_t * G_r * \lambda^2 * \sigma * T_i * f_r * \tau}{(4\pi)^3 * R^4 * k * T_e * F * L} = \frac{P_{av} * G_t * G_r * \lambda^2 * \sigma * T_i}{(4\pi)^3 * R^4 * k * T_e * F * L}$$ ------------------------------------Equation 24

Where:

$P_{av} = Pt * \tau * f_r$ - average transmitted power from the radar

$\tau = pulse\ width$

f_r = pulse repetition frequency

P_{cw} = CW average transmitted power over the dwell interval

T_{Dwell} = Dwell time or look time or time on the target

F = Noise figure

L_{win} = loss term associated with the type of window (weighting) used in computing the FFT

T_i = period transmitted pulse equivalent to Dwell time of CW

All the other terms in the equations are described earlier in the general radar equation.

The overall receiver sensitivity is directly related to the noise figure of the radar receiver. It becomes clear, that a low noise figure receiver is accomplished by a good design in the very front-end components. An aspect to a very low noise figure receiver is achieved through minimizing the noise factor of the very first block. This component usual is characterized by a low noise figure with high gain. This is the reason for the often used denomination, low noise preamplifier (LNA) which enables detection of a target in a noisy environment.

4.4.7. Grazing Angle and Beamwidth

For SAR detection, an accurate range map of the environment can be constructed through the scanning of a pencil beam. This is an antenna pattern with a single, narrow lobe. Millimeter-wave radar provides a pencil beam with a relatively small antenna aperture. The beam-width is proportional to the wavelength and is inversely proportional to the antenna aperture. A constant antenna aperture shapes narrower beams at shorter wavelengths:

$$\Theta = k\frac{\lambda}{D}$$ ------------------------------------Equation 25

Where k is a factor which varies 0.9 to 1.4 depending on the shape of the reflector and the feed illumination pattern. From [36] the value of k is estimated 1.2 for the design of 77GHz MMW radar design and this thesis will consider the value of k to be the same even for the 122GHz MMW radar. i.e. is $\Theta = 1.2 * \frac{\lambda}{D}$.

Most radar applications sense targets in the antenna far-field region where the radiated power density varies inversely with the square of the distance and in which the antenna pattern remains constant for each angle. The beginning of the far-field region occurs at a distance R_{min} for which

$$R_{min} = \frac{D^2}{\lambda} \quad \text{----------Equation 26}$$

Equation (33) results in 0.463m for the radar used in this study. Therefore, sensor targets often fall within the near-field region where the antenna pattern is range-dependent. Earlier work with millimeter-wave radar for robotic perception shows [37] deformation of the beam in near-field conditions which suggests complex beam geometries and more difficulty in data interpretation.

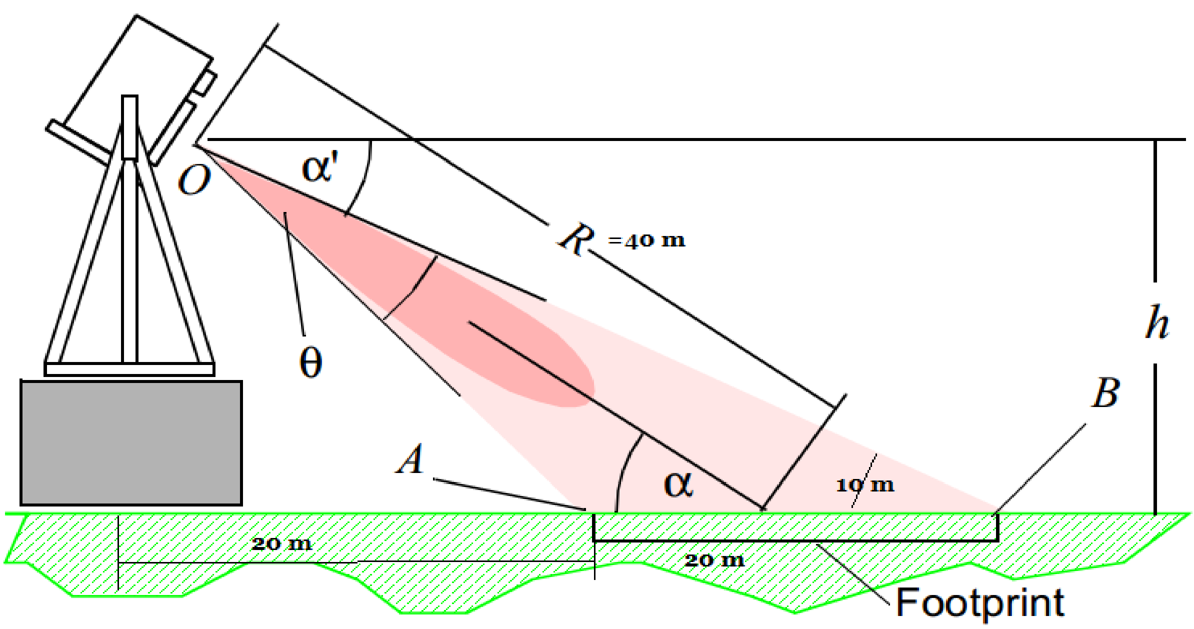


Figure 29: Scheme of a pencil beam (beam-width Θ) sensing terrain at grazing angle α. The footprint is defined by the proximal border (A) and the distal border (B) and the sensor-depression angle is α'

The radar-location height is limited by the maximum mast height. The scanning pencil beam intersects the ground at near-grazing angles with potential specular reflection. Specular reflection may impede range measurement for grazing angles. Figure 28 represents the pencil beam hitting the LQC area at a grazing angle. The origin of the beam at the center of the bistatic antenna pair is O. The proximal and distal borders of the footprint area illuminated by the divergence beam are A and B, respectively. The height of the beam origin with respect to the LQC level is h. The slant range or major axis of the ellipse from the beam origin to the intersection of the beam axis and the LQC center is R.

Grazing angles stretch the pencil-beam footprint. This results in the range-echo spread. Figure 28 illustrates the grazing angle and footprint. This scheme assumes that backscatter exists and that the footprint is within far-field conditions, which give the beam a conical shape. The footprint is the major axis of an ellipse with longitude |AB| determined by a slant range to the surface R with grazing angle $\boldsymbol{\alpha}$ and with beam-width $\boldsymbol{\Theta}$. For pencil beams the footprint length can be approximated as [36]:

$$|AB| = \frac{R*\theta}{sin\alpha} \quad \text{------------Equation 27}$$

The width of the echo spread in the radar signal S_{echo} is |OB|-|OA|, different from the footprint length on the surface. A theoretical value for S_{echo} results from:

$$S_{echo} = \frac{h}{sin(\alpha-\theta/2)} - \frac{h}{sin(\alpha-\theta/2)} \quad \text{------------Equation 28}$$

So to find all the parameters let us take h=7m and thus R= $\sqrt{h2 \ + (20 + AB)2} \approx 4o\ m$

$$sin\alpha = \frac{h}{R} = \frac{7m}{40m} = 0.175\ , \quad \alpha = 10°$$

$$|AB| = \frac{R*\theta}{sin\alpha}\ wich\ implies, \qquad \theta = \frac{|AB|*sin\alpha}{R} = \frac{20m*sin10}{40} = 0.0875rad \approx 3°$$

From equation (32) which relates the beam-width function of the wavelength and the hardware antenna aperture. At 122 GHz, a wavelength of 2.46mm and 3° beam results in a d=33.74-mm antenna aperture. A narrower beam produces more accurate terrain maps and obstacle detection at the cost of the size of the antenna. The lobe structure of the antenna radiation pattern outside the main-lobe consists of a number of side-lobes. Side-lobes result in a fraction of the radiated energy illuminating areas other than those in the desired main lobe directions and in receipt of reflected energy from undesired directions. When the attenuation of side-lobes is poor, targets in directions other than those of the main-lobe appear in the radar signal.

It will be assumed that the platform carrying the radar maintains both fixed altitude h and zero velocity V=0m/s (stationary radar). The antenna 3dB beam width is θ, and the elevation angle (measured from the z-axis to the antenna axis) is β. The intersection of the antenna beam with the ground defines a footprint |AB| as shown in the Figure 29.

The minimum slant range to the swath is R_{min}, and the maximum range is denoted R_{max}, and β= 90-α as illustrated in the Figure 29. It follows that

$$R_{max}=\frac{h}{\cos(\beta-\theta/2)} \cong 47m$$

$$R_{min}=\frac{h}{\cos(\beta+\theta/2)} \cong 35m$$

$R=\frac{h}{\cos\beta} \cong 40$ *the same as computed before* --*Equation 29*

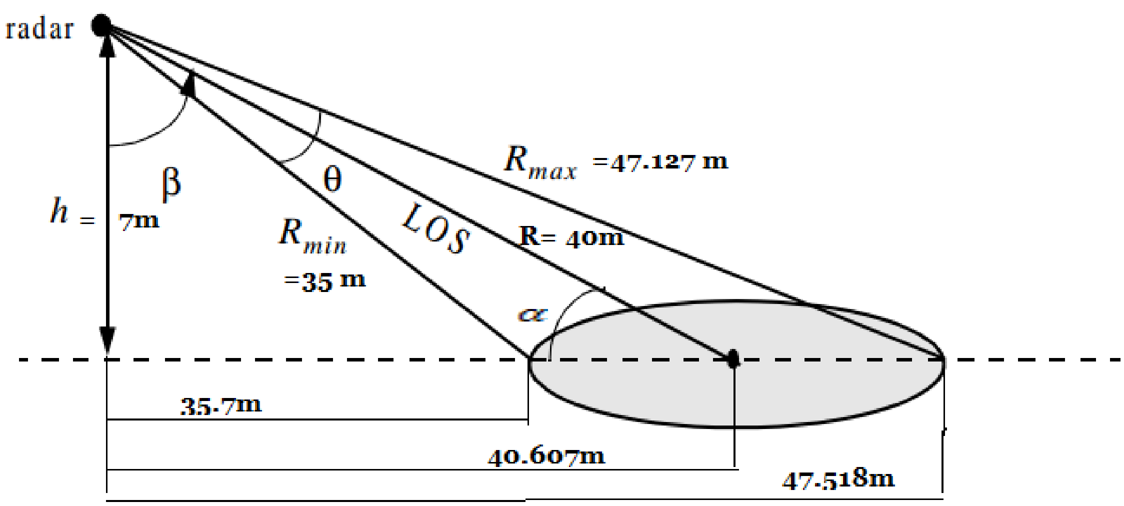


Figure 30: Minimum and maximum range computations.

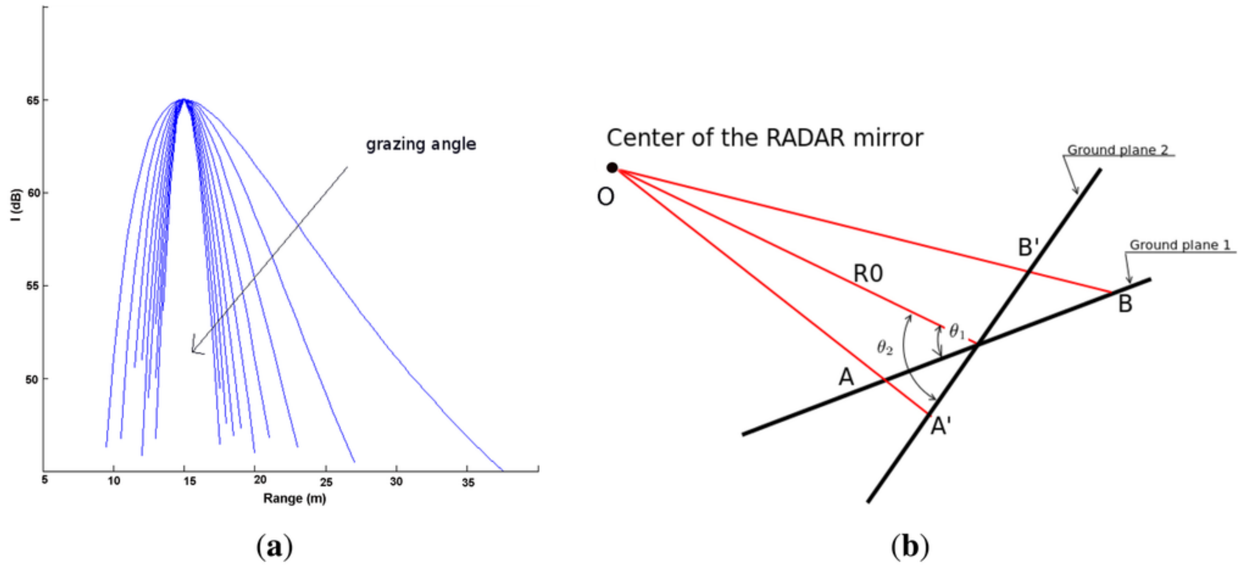


Figure 31: Change in the ground echo model for increasing grazing angles Ө1 and Ө2

4.4.8. Antenna Gain

Antenna gain is the measure of the antenna's ability to focus outgoing energy into the directed beam. Antenna gain describes the degree to which an antenna concentrates electromagnetic energy in a narrow angular beam. The two parameters associated with the gain of an antenna are the directive gain and directivity. The gain of an antenna serves as a figure of merit relative to an isotropic source with the directivity of an isotropic antenna being equal to 1. The power received from a given target is directly related to the square of the antenna gain, while the antenna is used both for transmitting and receiving.

$$G = \frac{Maximum\ radiation\ intensity}{Average\ radiation\ intensity}$$

Increasing the gain comes at a cost, although it is beneficial to design high gain antennas at higher frequencies, due to their smaller size, the resulting beamwidth is significantly smaller. This highlights the fact that the antenna "gain" is not a typical power gain, as for example defined in amplifiers. It is merely a focusing factor that compares the antenna to the isotropic radiator. Low antenna beam-width implies that only one, or a few closely spaced receivers, that have their antennas well aligned with the transmitter, will be able to receive the necessary power, i.e, the link will be directional.

In this case for the radar antenna that it have designed to transmit and receive the power it will have an antenna Gain:

$$G = \frac{4\pi\, A_e}{\lambda^2} = \left[\frac{\pi d}{\lambda}\right]^2 e_A \text{------} \quad \textit{Equation 30}$$

Where:

A - is the area of the antenna aperture, For a circular dish antenna, $A=\pi D^2/4$, giving the second formula above.

d - is the diameter of the parabolic reflector, if it is circular

λ - is the wavelength of the radio waves.

e_A - is a dimensionless parameter between 0 and 1 called the aperture efficiency. The aperture efficiency of typical parabolic antennas is 0.55 to 0.70.

So the gain of the antenna in this work will be evaluated as follow taking all the parameters that have considered earlier and take e_A=0.65:

A_e= e_A*A= $\frac{\pi d2}{4} = \frac{\pi*(33.74mm)2}{4} = 0.000894m^2$

$$G = \frac{4\pi * 0.000894}{(2.46mm)2} = 1856.61 \approx 32.69dB$$

Using equation 16 to calculate the directivity of the antenna under consideration here:

D=$\frac{16}{\theta 2} = \frac{16}{(3°)2} = \frac{16}{(0.0524)2} = 5827.2 \cong 37.65dB$

4.4.9. Radar Cross-Section

When the radar radiated energy impinges on a target, the induced surface currents on that target radiate electromagnetic energy in all directions. The amount of the radiated energy is proportional to the target size, orientation, physical shape, and material, which are all lumped together in one target-specific parameter called the Radar Cross Section (RCS) and is denoted by σ .

The radar cross section is defined as the ratio of the power reflected back to the radar to the power density incident on the target,

$\sigma = \frac{P_r}{P_d}$

Which is a measure of the effectiveness of the target as a radar reflector. The RCS of a target is formulated as the product of the normalized radar cross section of the target σ_0 (m^2/m^2), also called reflectivity of the target, and the projected effective area (A_e) of the target, and is expressed as [38]:

$\sigma = \sigma_0 A_e \ (m^2)$ --*Equation 31*

This automatic obstacle detection and LQC signaling condition controller detect different obstacle sizes which are given in tabular below from [6]:

Table 3: Radar cross section assumed values

Obstacle RCS in m^2	Obstacle RCS in dBsm
0.1	-10
1	0
10	10
50	16.989
100	20

The smallest target ($0.1m^2$) that the system must detect reliably is that of a human for obstacle detection. To detect a man at 47 meter range, a transmitter power of about 100 mW should be used, the aim being to obtain a detection probability of 99.99% [16].

4.4.10. Selection of the Transmitting Frequency

The most promising frequencies for MMW radar appear to lie in the 76-77GHz band and the 122-123 GHz band. The unlicensed ISM band at 122 GHz - 123 GHz is ideal for the application under consideration for several reasons. First, the 1 GHz of available bandwidth is sufficient for the detection of a single and multiple large targets. Second, the maximum allowed Effective Isotropically Radiated Power (EIRP), i.e. the product of the antenna gain times the output power $G_T x P_o$, is 20 dBm, which is adequate for detection operation up to 47 m. Third, the possibility of an integrated antenna becomes viable, thus avoiding the cumbersome and high-cost packaging solutions that would be required at a lower band like 60GHz or 77 GHz. Lastly, as illustrated in the figure 31 , the atmospheric attenuation at 122 GHz is insignificant, even in high humidity, indicating that the environmental conditions will not impede with the correct operation of the system.

Table 4: Industrial, Scientific, Medical (ISM) unlicensed Bands [39]

Frequency band	Bandwidth	Transmit Power	λ In the air
2.4 GHz	80MHz	100mW(20dBm) EIRP	12.5 cm
5.2 GHz	100MHz	200mW(23dBm) EIRP	5.8 cm
60 GHz	0.5GHz	10W (40dBm) EIRP	5 mm
122.5	1GHz	100mW(20dBm) EIRP	2.5 mm
245 GHz	2GHz	100 mW(20dBm) EIRP	1.25 mm

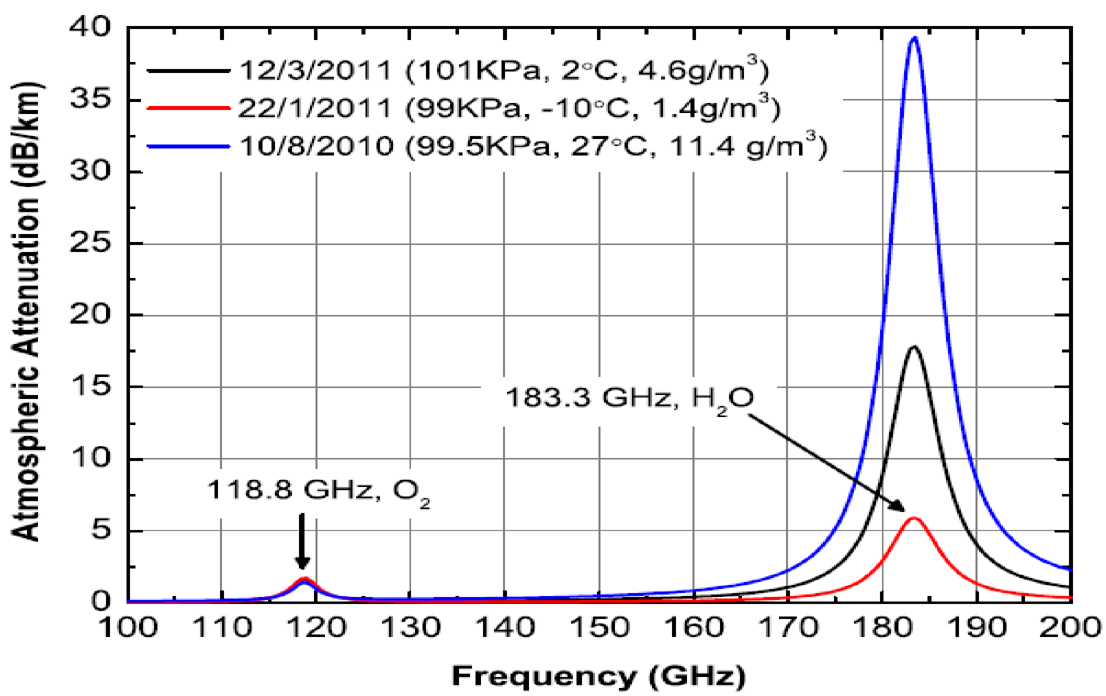


Figure 32: Atmospheric attenuation versus frequency in three days in Toronto, Canada based on the ITU-R P.676-8 model. The attenuation difference between the three days is due to the humidity [17].

4.4.11. External and Internal Losses

These are the sum of all loss factors which affect the normal operation of the radar systems receiver. This is a value that is calculated to compensate for attenuation by precipitation, atmospheric gasses, and receiver detection limitations. The attenuation by precipitation is a function of precipitation intensity and wavelength [6]. For atmospheric gasses, it is a function of elevation angle, range, and wavelength. Since all of this is taken into account for e.g. 3 Decibels loss, all signals are weakened by half the value. Some of these losses are unavoidable. Some of these can be influenced by radar technicians. In this design the losses due to internal factors, rain and atmosphere are going to be included for the design purpose. Because of the small size of the suspended particles that make up dust and smoke over the LQC area, have a negligible effect on MMW radar operation that is considered and 0.1dB approximation of fog attenuation have been taken into account.

As the radar signal is propagated through the atmosphere, its amplitude and intensity are reduced through the atmospheric attenuation process. For the MMW simulation, this attenuation is accounted for in the return power equation by the loss factor L_{Atm} given by [46]:

$$L_{Atm} = 2\mu R \qquad \text{Equation 32}$$

Where: μ is the attenuation coefficient for temperature, rain, fog…etc., and it is generally given in units of dB/km as shown in the Figure 31 [17] and R-Range in Km.

4.4.12. The Clutter RCS Losses

One another item to consider is the clutter. Clutters are divided into surface and volume clutters. Surface clutter, often called area clutter, includes ground terrains with different vegetation's, rocky surfaces, snow and water surfaces. Area clutter manifests itself a major hazard in helicopter landing in unknown areas under poor visibility conditions. It is a major concern for helicopter searching for targets at low grazing angles. The ground clutter RCS can be calculated from:

$$(\sigma)_{surface} = A_e * \sigma_{so} \qquad \text{Equation 33}$$

Where σ_{S0} is the reflectivity of surface clutter and A_e is the projected efficient area of the surface clutter. The surface clutter at low grazing angles is often referred to as diffuse clutter, A_e is given by:

$$A_e = \frac{R_c * \theta_{3db} * C * \tau * Sec\ \alpha}{2\beta} \qquad \text{Equation 34}$$

Where C is the speed of light, τ is the pulse length, β is the beam shape factor, θ_{3dB} is the beam-width and α is the grazing angle and R_c is the range of the clutter from the radar.
Thus, the power returned by the surface clutter is given by:

$$P_{sc}=\frac{P_t*G^2*\lambda^2*\sigma_{S0}*C*\tau*Sec\ \alpha}{(4\pi)^3*R_c^3*L_t*2\beta} \text{------- Equation 35}$$

Volume clutter normally includes rain, snow, dust and fog. Volume clutter manifests itself by degrading or scattering and absorbing the radar transmitting energy. But mostly it is a critical concern for helicopter and airplane detection and searching for vertical or air targets and landing in poor weather environments. For this case, it has a little effect on the performance of the radar system since considering for a limited range and small scanning area.

The volume clutter RCS is represented as:

$$(\sigma)_{Volume}= V_c*\eta \text{------- Equation 36}$$

Where η is the volume clutter reflectivity in m^2/m^3 and V_C is the efficient airborne clutter volume. Assuming that the azimuth and elevation beamwidth are identical, at a given volume clutter range R_C, the radar resolution cell (volume) is measured by:

$$V_C=\frac{\pi*R_c^2*\theta_{3db}^2*C*\tau}{8\beta^2} \text{------- Equation 37}$$

Therefore, the power returned by the volume clutter can be derived as:

$$P_{VC}=\frac{\pi*P_t*G^2*\lambda^2*\eta*\theta_{3db}^2*C*\tau}{8*(4\pi)^3*R_c^2*L_t*\beta^2} \text{------- Equation 38}$$

In short range applications, especially, all-environment helicopter operations; the receiver noise may not be the major factor in comparison with the ground clutter power, which may be much higher than the thermal noise power [6]. This simulation shall take account of various signal-to-clutter ratios (SCRs). The SCR is defined as the ratio of the received target power to the received clutter power and is given as follows [46]:
For the surface clutter:

$$SCR_s= \frac{\sigma_t}{\sigma_s} = \frac{\sigma_t}{A_e*\sigma_{S0}} \text{------- Equation 39}$$

For the volume clutter:

$$SCR_v = \frac{\sigma_t}{\sigma_v} = \frac{\sigma_t}{V_S * \eta}$$ --Equation 40

According to the modelling of the surface and volume clutters in [6], he used 0.01m2 and 0.01m3 respectively for the surface and volume clutters and it is used this modelling in this thesis too for modelling and simulating of the surface and volume clutters since that thesis is done for the same line but different frequency of 77GHz.

4.5. 122GHz CW Radar DSP

Continuous Wave (CW) radars utilize CW waveforms, which may be considered to be a pure sine wave of the form $\cos 2\pi f_0 t$. Spectra of the radar echo from stationary targets and clutter will be concentrated at f_0. The center frequency for the echoes from moving targets will be shifted by f_d, the Doppler frequency as it is discussed in section 4.4. Thus, by measuring this frequency difference CW radars can very accurately extract target radial velocity. Because of the continuous nature of CW emission, range measurement is not possible without some modifications to the radar operations and waveforms.

Figure 32 shows a simplified CW radar block diagram. The appropriate values of the signal frequency at different locations are noted on the diagram. The individual Narrow Band Filters (NBF) must be as narrow as possible in bandwidth in order to allow accurate Doppler measurements and minimize the amount of noise power.

In theory, the operating bandwidth of a CW radar is infinitesimal (since it corresponds to an infinite duration continuous sine wave). However, systems with infinitesimal bandwidths cannot physically exist, and thus, the bandwidth of CW radars is assumed to correspond to that of a gated CW waveform.

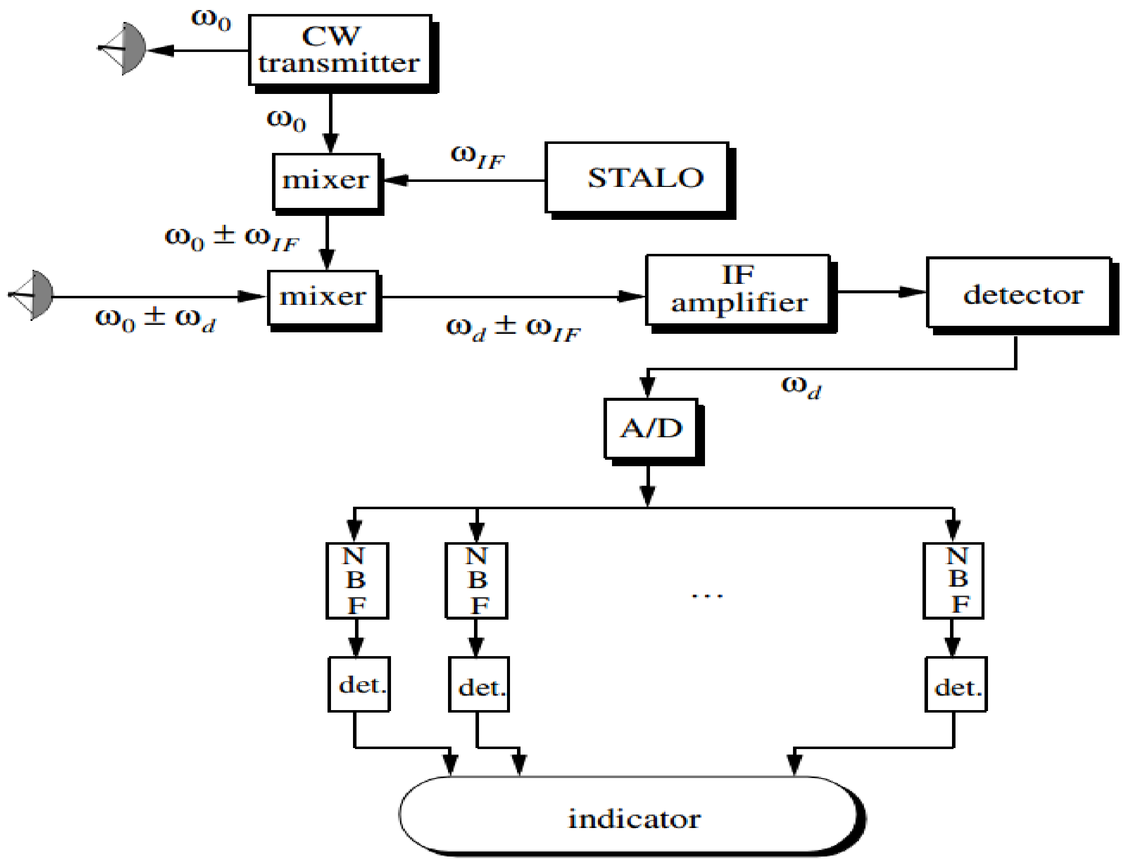


Figure 33: Simplified Radar DSP Block Diagram [15]

The NBF bank (Doppler filter bank) can be implemented using a Fast Fourier Transform (FFT). If the Doppler filter bank is implemented using an FFT of size N_{FFT} , and if the individual NBF bandwidth (FFT bin) is Δf, then the effective radar Doppler bandwidth B is $(N_{FFT} * \Delta f)/2$. The reason for the one-half factor is to account for both negative and positive Doppler shifts. Since the range is computed from the radar echoes by measuring a two-way time delay, then single frequency CW radars cannot measure target range. In order for CW radars to be able to measure target range, transmit and receive waveforms must have some sort of timing marks. By comparing the timing marks at transmit and receive, CW radars can extract target range.

The CW radar receiver declares detection at the output of a particular Doppler bin if that output value passes the detection threshold within the detector box. Since the NBF bank is implemented by an FFT, only finite length data sets can be processed at a time. The length of such blocks is normally referred to as the dwell time or dwell interval. The dwell interval determines the frequency resolution or the bandwidth of the individual NBFs. More precisely,

$\Delta f = 1/T_{Dwell}$---Equation 41

T_{Dwell} is the dwell interval or look time or time on the target. Therefore, once the maximum resolvable frequency by the NBF bank is chosen the size of the NBF bank is computed as:

$N_{FFT} = 2B/\Delta f$ --Equation 42

B is the maximum resolvable frequency by the FFT. Factor 2 is needed to account for both positive and negative Doppler shifts. It follows that the look time is then computed as:

$T_{Dwell} = N_{FFT}/2B$ ---Equation 43

As it can be concluded from Eq. 43 that the look time or integration time can be controlled either by a number of NBF banks or bandwidth.

Here is the flow chart algorithm in the DSP of the processor:

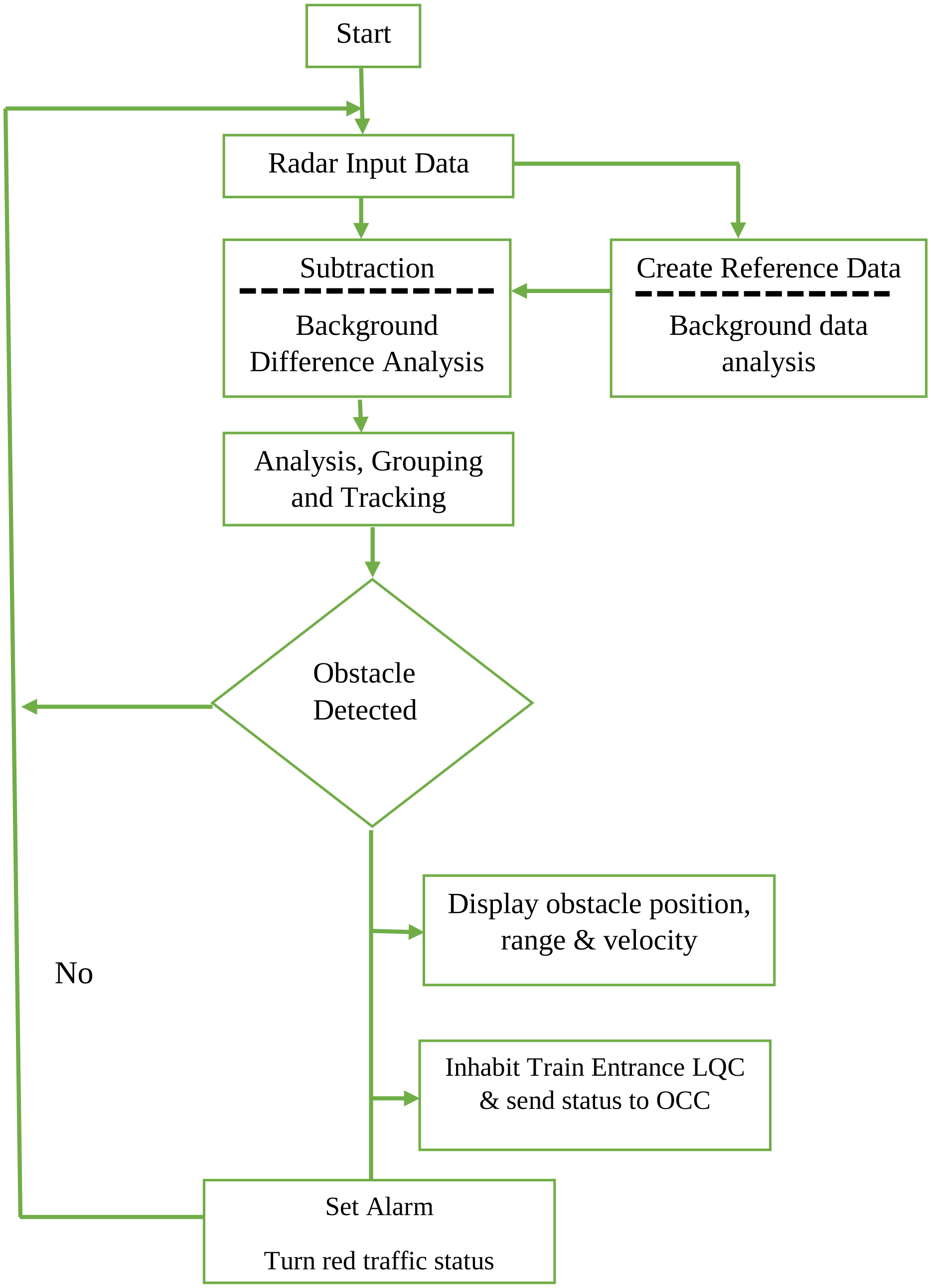


Figure 34: Radar's Obstacle Detection Algorithm

4.5.1. The Frequency Modulation Continuous Wave (FMCW) Method

This section presents the most common signal waveforms employed for detecting distance obstacle FMCW from the three commonly known radar waveforms which are: pulsed radar, Step Frequency Radar (SFR) and Frequency Modulated - Continuous Wave (FMCW). Each type of radar essentially requires a different modulation in the transmitter and slightly different receiver architectures. Each of them has their own advantages and disadvantages with regard to the range accuracy and system complexity.

The Frequency Modulated - Continuous Wave radar (FMCW) is the most common type of continuous wave radar and has been widely adopted in 77 GHz automotive radar systems [6,16,28]. The main drive behind developing continuous wave (CW) systems is that, in contrast to the pulsed radar which transmits short bursts of energy, the CW radar generates constant output power over time. As a result, the peak power required by the transmitter circuits for the same amount of transmitted energy is significantly lower in the CW case, rendering its implementation much friendlier to silicon integrated circuits.

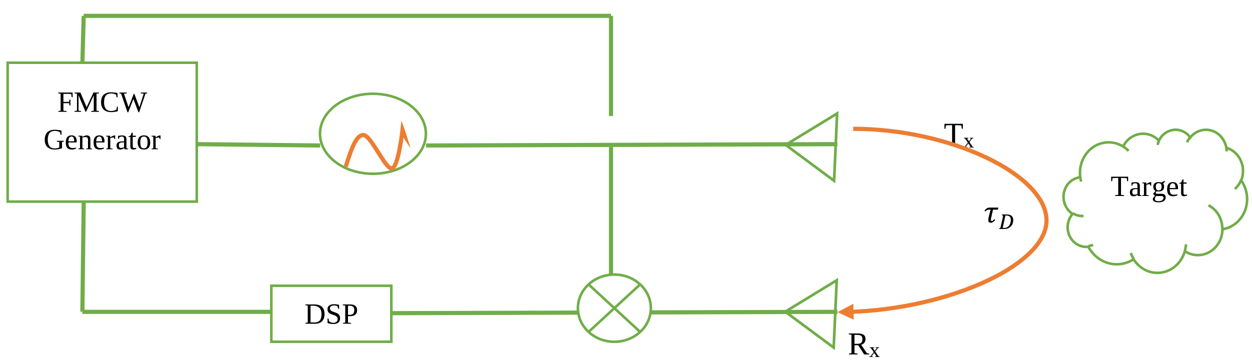


Figure 35: Generic FMCW Block Diagram

The block diagram of a generic FMCW system is illustrated in Figure 34. The transmitter generates a continuous wave signal whose frequency is modulated by alternating upwards-downwards ramps, also known as chirps, shown in Figure 35 (i-ii).

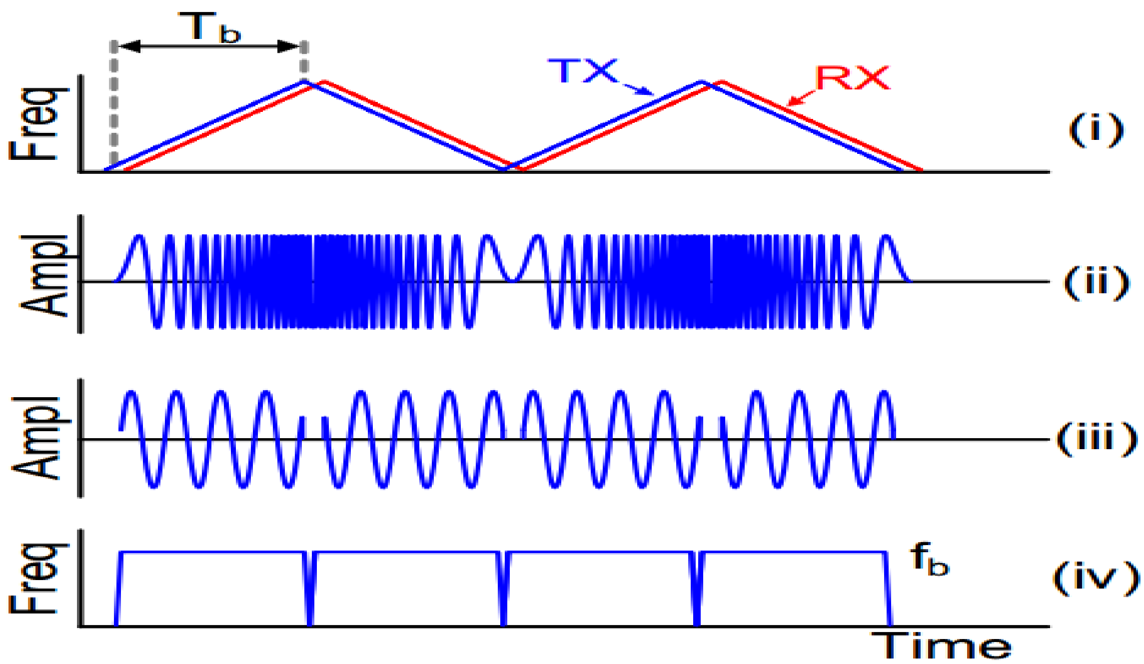


Figure 36: The FMCW Waveforms

Assuming that each ramp linearly sweeps the transmit frequency from f_0 to $f_0+\Delta f$ over time T_b, the transmitted signal can be expressed as:

$$Tx(t)= A_t\, Cos(2\pi f0t + \frac{2\pi\Delta f}{T_b}\int_0^t \tau d\tau) \text{ --- Equation 44}$$

$$= A_t\, Cos(2\pi f0t + \frac{\pi\Delta f}{T_b} t^2)$$

The transmitted signal is reflected by the target, arrives at the input of the receiver with round-trip delay τ_D and gets multiplied by the transmitted signal:

$$Rx(t)= A_r\ \ Cos(2\pi f_0(t- \tau_D) + (\pi\frac{\Delta f}{T_b}(t-\tau_D)^2) * Cos(2\pi f_0 t + \frac{\pi\Delta f}{T_b} t^2) \text{ --------------------------- Equation 45}$$

After low pass filtering:

$$Rx(t)=Ar\ Cos(2\pi\frac{\tau_{D*}\Delta f}{T_b} t + 2\pi f_0\, \tau_D - \frac{\tau_D^2\Delta f}{T_b}) \text{ --- Equation 46}$$

$$= Ar\ Cos(2\pi\frac{\tau_{D*}\Delta f}{T_b} t + \phi)$$

Therefore, the receiver output contains a low frequency beat tone, depicted in Figure 35 (iii-iv), at

$f_b = \frac{\tau_D * \Delta f}{T_b} = \frac{2\Delta f R}{cT_b}$ --Equation 47

The beat tone encodes the distance information in frequency. If many targets are present, equation (46) will result in the linear superposition of several sinusoids, each at a frequency related to the distance of a specific target. Therefore, the distances can be calculated from the IF signal using a simple Fast Fourier Transform (FFT) as in Figure 32 or other, more advanced, spectral estimation techniques such as the Root-MUSIC algorithm [16]. If the target is moving, its speed can be easily calculated from the beat frequency difference between the upwards and downwards ramps.

Similarly with the pulsed radar, the range resolution of the FMCW radar is:

$$\Delta R \geq \frac{c}{2\Delta f} = \frac{c}{2B} = 0.5m \; as \; being \; found \; previously.$$

And the maximum range is related to the chirp period:

$$R_{max} \leq \frac{cT_b}{2}$$

$$which \; results \; T_b \geq 0.333\mu \sec \; and \; T_b \geq 3.08nsec \;\; for \;\; R_{max} = 50m \;\; and \;\; R_{min} = 0.463m \; used \; in \; this \; paper \; respectively.$$

Where the assumption that $T_b \geq \tau_D$ was made. Since $\tau_D = 1/B = 3.33$nanosec.

There are two important aspects that usually plague the performance of FMCW systems. First, the transmitter and receiver operate simultaneously leading to significant TX-to-RX leakage problems. Because of this, most FMCW radars have to employ separate antennas for the transmitter and receiver (bistatic radar). In case a single antenna is used in a monostatic FMCW radar, highly linear receiver circuits are required, resulting in higher receiver noise and higher power consumption [16].

The second consideration has to do with the ramp generation process. A common method of generating a frequency ramp is to drive an adequately wideband Phase Locked Loop (PLL) with a Direct Digital Synthesizer (DDS), which in turn, is based on a multi-bit Digital-to-Analog Converter (DAC) as shown in Figure 32. However, due to the finite frequency resolution of the DDS, as well as its limited precision, the generated ramp will have a staircase-like shape. Therefore, the generated ramp will be nonlinear, which will have a deleterious impact on the beat frequency, rendering equation (47) incorrect and resulting in systematic errors in the detected range.

4.5.2. Probability of False Alarm and Detection

The probability of false alarm is defined as the probability that a sample of the signal will exceed the threshold voltage when the noise alone is present in the radar's receiver without any tangible obstacle on the LQC. The False Alarm Rate (FAR) is calculated using:

$$FAR = \frac{false\ targets\ per\ PRT}{the\ number\ of\ range\ cells} \text{------------------Equation 48}$$

False alarms are generated when thermal noise or sudden environmental impairments exceeds a pre-set threshold level, by the presence of spurious signals. These spurious signals may be either internal to the radar receiver or from sources external to the radar, or by an equipment malfunction. If the detection threshold is set too high, there will be very few false alarms, but the signal-to-noise ratio required will inhibit detection of valid targets. If the threshold is set too low, the large number of false alarms will mask detection of valid targets. So here an optimized and longtime learned radars to the internal or external parameters over the footprint of the LQC area are needed in order to minimize the FAR. As a result, the P_D versus SNR for different PFA has been simulated.

The probability of detection (P_D) is the probability that a sample of the signal under consideration will exceed the threshold voltage in the case of noise plus signal. So designing of the radar's probability of detection to be nearest to 1 is very important for complete detection of obstacles near or on LQC. The received and demodulated echo signal is processed by threshold logic. This threshold shall be balanced so that as of certain amplitude wanted signals being able to pass and noise will be removed. Since high noise exists in the mixed signal tops which lie in the range of small wanted signals the optimized threshold level shall be a compromise. Wanted signals shall on the other hand, reach the indication as of minimal amplitude, while the false alarm rate may not increase. A lot of field work must be incorporated in the LQC to set the radar threshold value considering all impairments into account.

$$P_D = \frac{Detected\ Targets}{All\ possible\ Detections} x100\% \text{------------------Equation 49}$$

The system must detect, with greater than or equal to 99.9% probability at the defined range and footprint area, for a 0.1 square meter radar cross section.

Assuming that the radar signal is a sine waveform with amplitude A, the P_D will become a complex formula to compute and different scientist have developed an approximation for this formula which we consider here the Parl's approximation. Parl developed an excellent algorithm to numerically compute the complex P_D integral. It is summarized as follows:

$$Q[a,b] = \begin{cases} \frac{\alpha_n}{2\beta_n} exp\left(\frac{(a-b)^2}{2}\right) & a < b \\ 1 - \frac{\alpha_n}{2\beta_n} exp\left(\frac{(a-b)^2}{2}\right) & a \geq b \end{cases}$$ --Equation 50

Parl's approximation is numerically computed to find the probability of detection of radar using the Matlab function "marcumsq.m" found its code at the end appendix of this thesis [15].

It is also possible to get the probability of detection (safety) of the radar system for the PFA of 10e-8 for one-year duration of time using the equation below [15].

$P_D = e^{-\lambda_D t}$--Equation 51

Where λ_D is dangerous failer rate and it is given by:

$$\lambda_D = \frac{PFA}{t} = \frac{10^{-8}}{1year} = \frac{10^{-8}}{8760hrs} = 1.14155 * 10^{-12}$$

Then the probability of detection will be then: $P_D = e^{-1.14155*10^{-12}*8760} = 0.99999999$

Which shows that the probability of detection of this radar will be 99.999% almost efficient enough with higher MTBF.

4.5.3. Radar Parameters

Here in table 5, every parameter of the radar system which have been mathematically modeled in this chapter have been summarized.

Table 5: The Complete radar Specifications Used for This system

Radar parameters	Specification	Units of measurement
Radar type	Continuous wave (CW)	-
Modulation used	FM, FMCW	-
Center frequency	122.5	GHz
MDP at 15dB	-130.3960	dBm
Noise figure	6.5	dB
Target σ's	0.1, 1.0, 10.0, 50.0, and 100.0	M^2
Antenna gain	32.69	dB
40mm/hour Rain Attenuation	15	dB/Km
Transmit loss	1	dB
Random (fogy season) loss	0.1	dB
Receive loss	1	dB
Bandwidth	300	MHz
Signal processing gain	13.599	dB
Minimum range	0.463	Meters
Maximum range	50	Meters
Temperature	290	$°k$
Operating wavelength	2.46	mm (millimeter)
Range resolution	0.5	Meters
PFA	10^{-8}	
Antenna elevation beamwidth (α')	80	Degrees
Azimuth beam-width (Θ)	3	Degrees
Scan rate	30	Scans/sec
Antenna aperture (d)	33.74	mm (millimeters)
Angle of depression (α)	10	Degrees
Directivity (D)	37.65	dBi
Azimuth field of view	45	Degrees

Chapter Five

Modeling the Coordination and Optimization Subsystem

5.1. Traffic and Train Signaling System

The increase in urban traffic has resulted in traffic congestions, long travel times and increase hazards to pedestrians. Due to this problem the government of Ethiopia introduces the Light Rail Transit in Addis Ababa to permit people to have a lot of alternative mode of transport. These scenarios necessitate the use of new methods in the design of traffic light control and train signaling control for vehicles, pedestrian and train crossings.

In this section traffic light algorithm and train signaling methods will be presented and based on this the preempted coordinated algorithm will be developed which is called Boolean Crossing Logic Equation or Coordination Equation in this thesis.

5.1.1. Traffic Light Signaling System

There are a lot of algorithms developed for traffic light control system through time with different caring capabilities. Here, in this case, it will not be redesigned but we will take one method to explore the techniques for traffic light control system for a four-way, two-lane junction as shown in Figure 36 below:

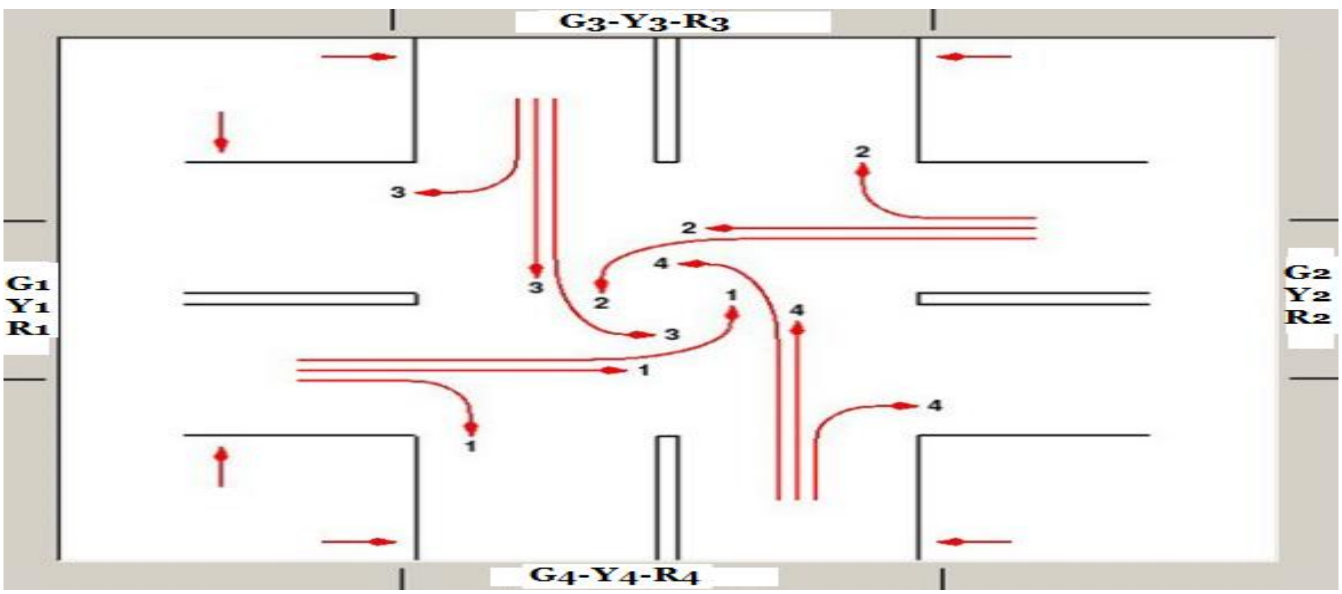


Figure 37: Traffic flow illustration for a four-way, two-lane junction

There are two ways generally to the design of a traffic light controller which are conventional and intelligent traffic controllers. In a conventional traffic light controller, the traffic lights change at constant cycle times which is clearly shows that it doesn't really care on which lane is more congested than the other. Just every lane have got a pre-specified time allocated for each lane and then every vehicle through that lane is allowed to pass to the other three lanes as shown in Figure 36. There will be a transition time from one lane to another lane.

The intelligent traffic light control system calculates the cycle time based on average traffic load and the dynamic nature of the traffic load, which reduces the problem of congestion. This method is interesting because it eliminates the heavy traffic on either of the lanes due wasting of the time on a free lane. There are so many techniques of making for the traffic light control to be intelligent. For example [42] applied the genetic algorithm technology in the traffic control system and pedestrian crossing to provide intelligent green interval responses based on dynamic traffic load inputs, thereby overcoming the inefficiencies of the conventional traffic controllers. They apply such technology to a four-way, two-lane junction based on two sets of parameters: vehicles and pedestrians queues behind a red light and number of vehicles and pedestrians that passes through a green light. The algorithms dynamically optimize the red and green times to control the flow of both the vehicles and the pedestrians.

But here whatever technology can be used for the traffic light control, it needs to coordinate this with the train signaling system so that risk of collision at the LQC will be reduced to a certain amount. To do so here in this thesis a conventional traffic controller is used and the algorithm for coordination with the train signaling system is developed since Addis Ababa LRT uses it.

From Figure 36 above in each of the double lanes there are certain symbols (G_i Y_i R_i) which represent Green, Yellow and Red of each of the lanes, and the subscript i represents each of the four ways adopted by the vehicles.

5.1.2. Traffic Light Controller Algorithm

To do so here true represented by 1 and False represented by 0. On/Off of the lights is here represented by 1/0 that means. Based on this there are 12 lines of inputs three from each path/lane. It will be presented here in tabular form for each of the 12 combinations. It have 4 change of phases up on 45-

second interval with 3 second transition period between ongoing phase and the next phase. Data of the times are taken from Ethiopian Transport minister of the Ethiopian street traffic light design.

Table 6: Traffic Light Controller phase Patterns

Symbols from the path	Phase-One	Transition time	Phase-Two	Transition time	Phase-Three	Transition time	Phase-Four	Transition time
G1-Y1-R1	1-0-0	Y2 yellow for 3 seconds	0-0-1	Y3 yellow for 3 seconds	0-0-1	Y4 yellow for 3 seconds	0-0-1	Y1 yellow for 3 seconds
G2-Y2-R2	0-0-1		1-0-0		0-0-1		0-0-1	
G3-Y3-R3	0-0-1		0-0-1		1-0-0		0-0-1	
G4-Y4-R4	0-0-1		0-0-1		0-0-1		1-0-0	

In state diagram form:

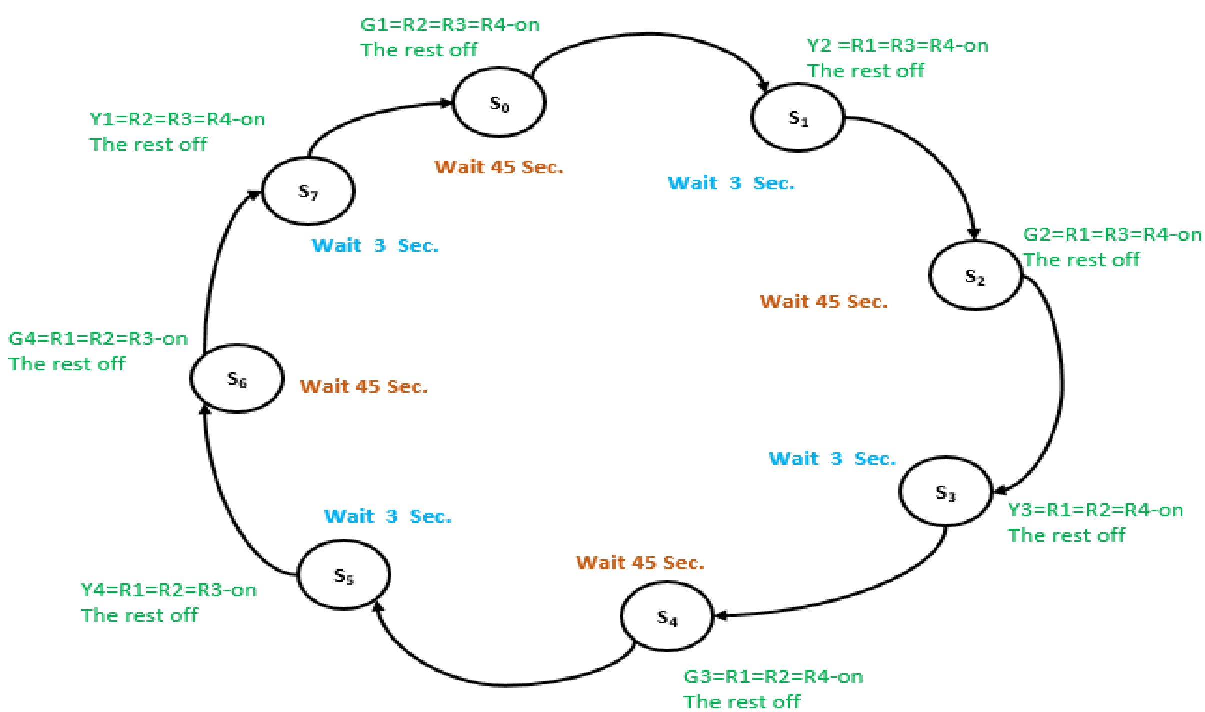


Figure 38: State Diagram of Traffic Light Controller

Where in Figure 37. S_i (i=0 to 7) represents the eight states of transition for one complete cycle for a 180seconds of time.

The manual for the use of this traffic light controller is presented in the form of a flow chart below so that every driver must be obeyed by it for ensuring safety.

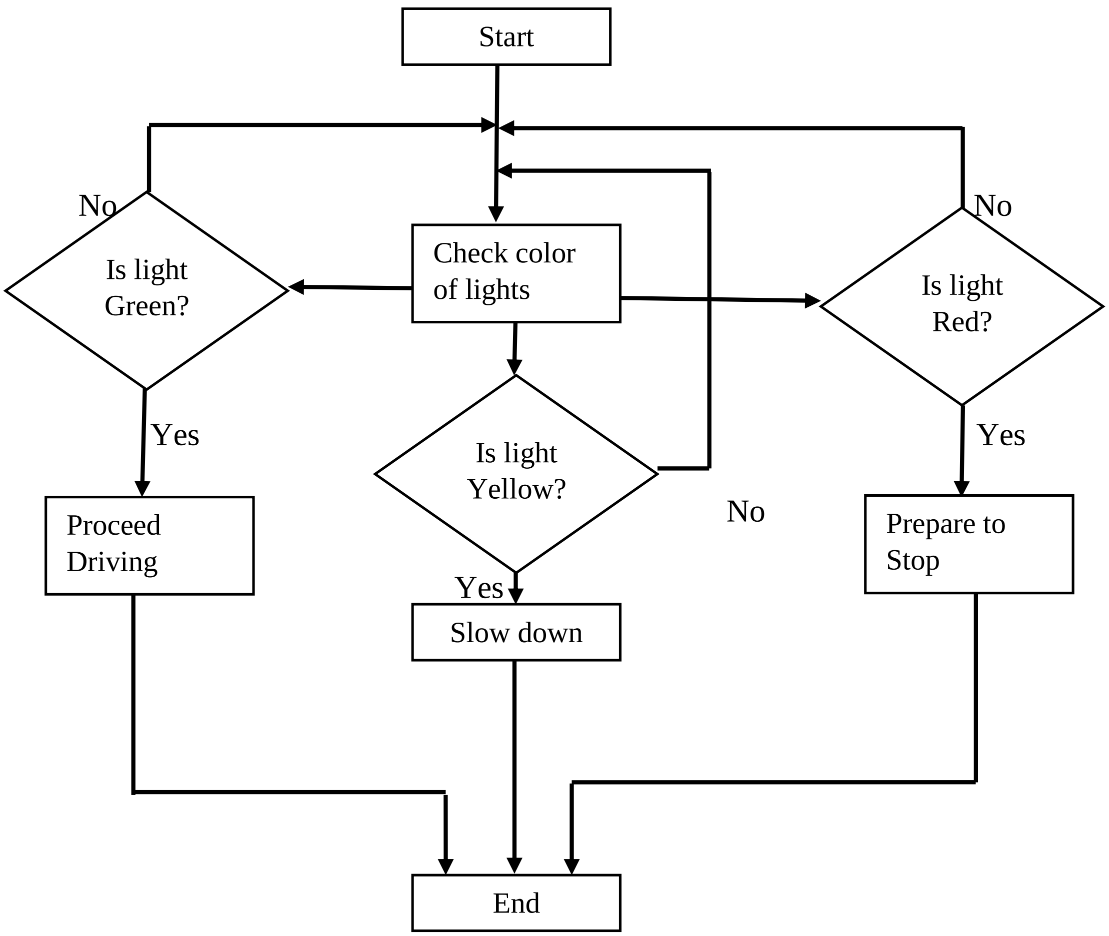


Figure 39: Manual for the Traffic Light Controller Designed

As it can be seen from the table 6 and state diagram of Figure 37 just a fixed time will be given to each of the lanes with a fixed transition time. But later on it will be adjusted to coordinate with the train signaling system to change the controller to its special preemption system. So before the discussion of the coordination algorithm it will be better to see the train signaling system.

5.1.3. Train Signaling System

According to the design principle of the AA-LRT signaling system, the signaling system of the Project is composed of operation assistant dispatching system in control center, control system in the switch area of the main line, route request system, signaling system at crossings, computer based interlocking system in the depot, and Carbone signaling system. The composition of the system overall composition is shown in Figure 39.

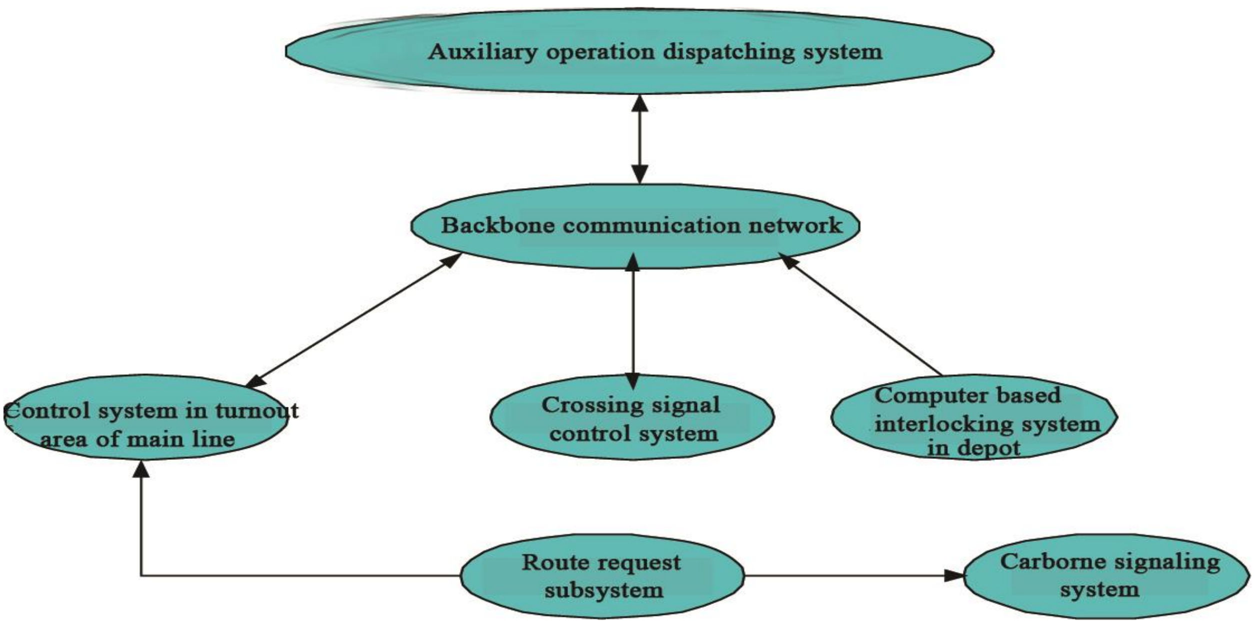


Figure 40: Modular Construction of total train signaling System for AA-LRT [43]

Now in this thesis , it is interested to provide additional i.e. Automating and delay minimizations with ensuring safety at the LQC with the help of the radar system detector.

The AA-LRT line of the Project has level crossings with the urban public transport roads at 5 places. To ensure the operation service level of the urban mass transit, the public transportation operation shall be organized in such manner that LRT is given the priority to pass through the level crossings, But in case the bulleted conditions in section 1.2 of this thesis are happening the train must stop before it gets into the LQC. With respect to the operation requirements and safety at level crossings, the crossing signaling control system of AA-LRT currently must provide the following functions:

- Allow the train at the level crossing to be given the priority to pass through the level crossing as much as an obstacle is not detected on the LQC;

- In case the radar system detects fixed or moving obstacle across the junction the train must stop before it gets into the LQC.
- Detect trains approaching and leaving the level crossings.
- Control the signal at crossings;
- Monitor the crossing signal state and transmit relevant information to the operation assistant dispatching system.

This whole process function by the LQC signaling system is charted in a flow chart of Figure 40:

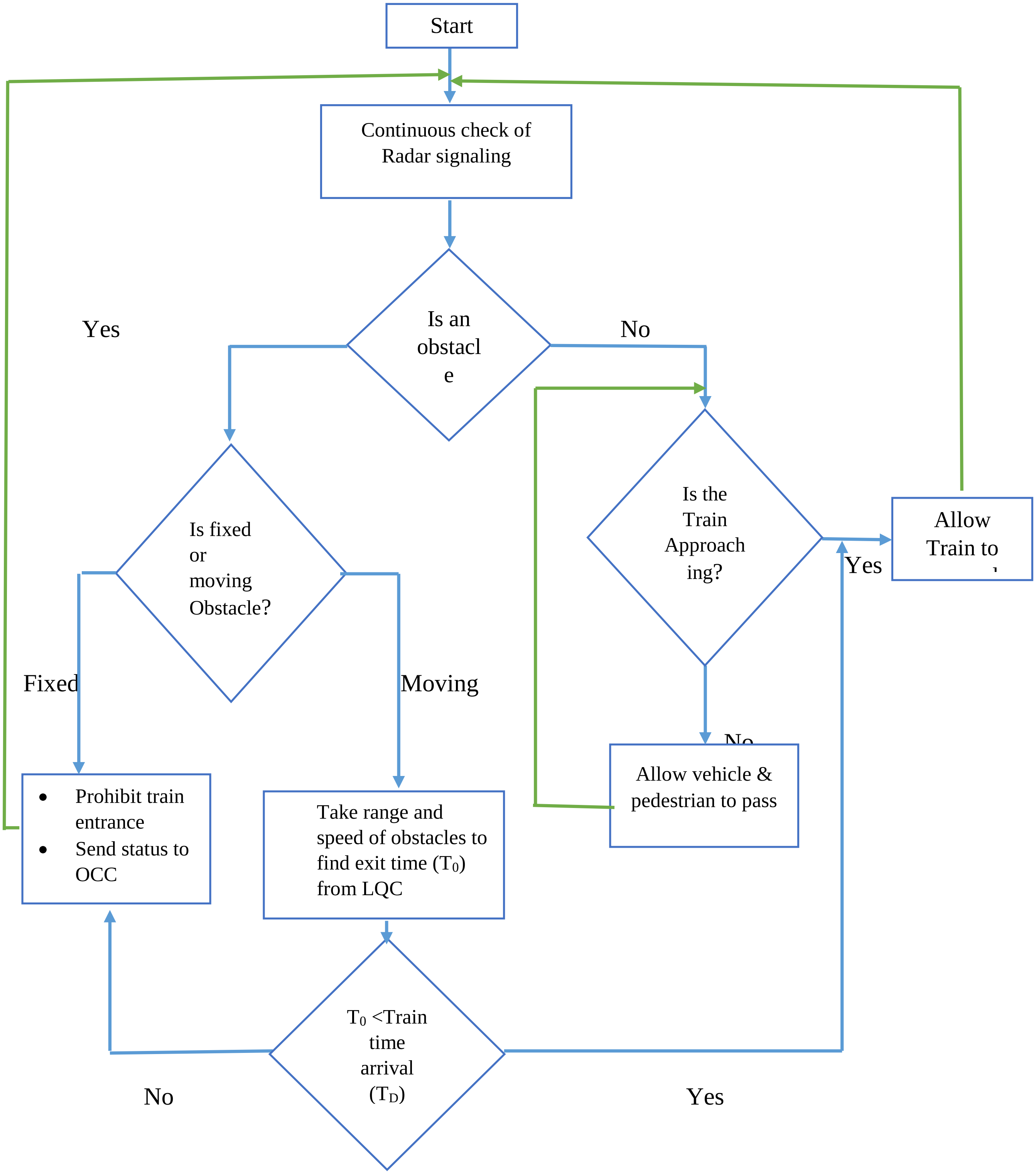


Figure 41: Modular coordinated LQC signaling flow diagram

5.2. Coordination (BCLE) Algorithm

The passing priority of LRT at level crossings is mostly realized through the interface between the Radar signaling result, the LRT signaling system and the traffic light control system of the roads. The radar signal controls the status of both the traffic as well as the train signaling system i.e. it transmits the status of the LQC whether an obstacle is there or not to both signaling controls. If an obstacle is not detected on the junction then the train signaling system transmits the information of the train's approaching the level crossing to the traffic light control system of the roads. After receiving such information, the traffic light control system of the roads will control the traffic signal light so as to allow the train can have the priority to pass through the level crossing.

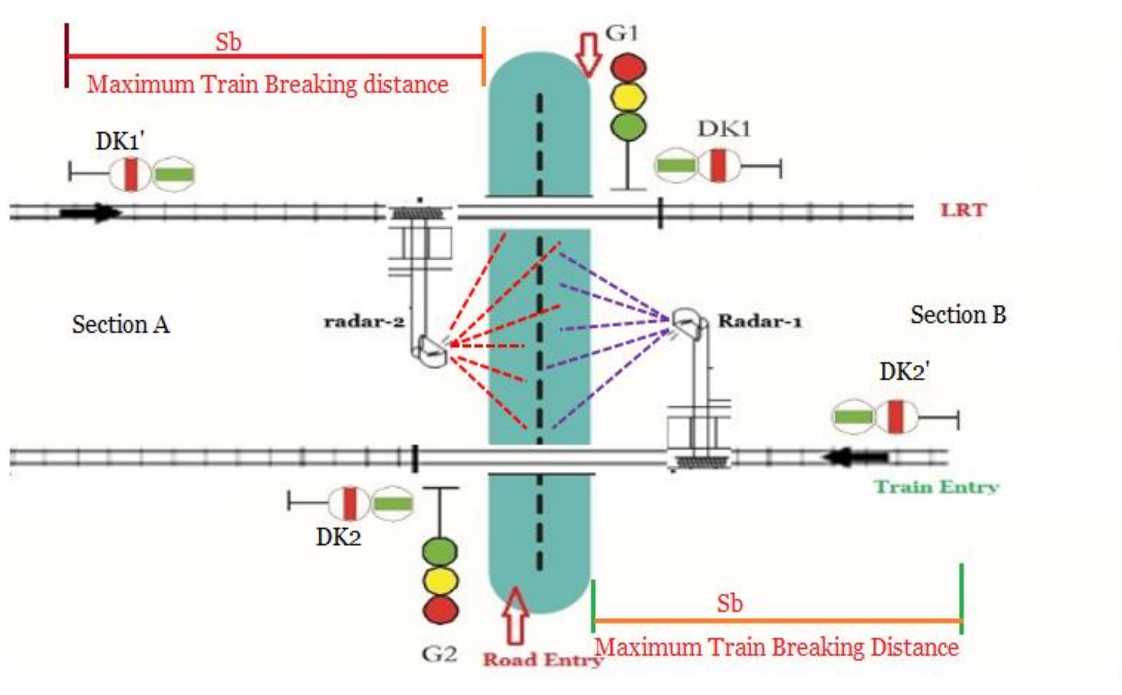


Figure 42: Equipment Diagram of the Crossings Signaling Control System

As it is explicitly stated in AA-LRT signaling it was designed as if the train signaling system controls to the traffic light controller ideally but since there are no traffic lights and manual driving mode by viewing is adopted for the Project, the running speed of the train is controlled manually by the driver.

But this is not safer due to a lot of circumstances as they are bulleted in section 1.2 of this thesis . So to accommodate these situations a radar system for obstacle detection introduced as it is depicted in

Figure 41 assuming the train is running from Station B to Station A for example. The control principle of Figure 41 is generally described as follows:

- When the two radars (Radar-1 and Radar-2) detects an obstacle on the LQC, the road signal G1 and G2 in the signaling system at the crossing may take two conditions: 1) If train is heading towards LQC there must show a stable red light which prohibits motors and pedestrians to pass through the level crossing) If not G1 and G2 may take green or yellow depending on the obstacle type on the LQC. At the same time, the signals DK1' and DK2' found at maximum train breaking distance must warn the train with red light from entering the LQC and the signals DK1 and DK2 must indicate a red light, which prohibits the train from passing through the level crossing.
- If the train is not behaving to the signals DK1' and DK2', these signaling must trigger through the OCC an emergency break so that the train will not enter by any means to the LQC with an obstacle.
- When the train does not occupy the track section A or B, the road signal G1 and G2 in the signaling system at the crossing indicates a stable green light, which allows the motors and pedestrians to pass through the level crossing. Meanwhile, the signal DK1 and DK2 indicates a red light, which prohibits the train from passing through the level crossing.
- When the train is detected to occupy the track section A or B, the road signal indicates a yellow light and initiates an acoustic alarm to remind the motors and pedestrians already in the crossing area to pass through the level crossing at a faster speed and to stop the motors and pedestrians that intend to enter the crossing area.
- After the train passes through the track section A or B, the road signal resumes the stable green light, which allows the motors and pedestrians to pass through the level crossing. Meanwhile, the signal DK1 and DK2 indicates a red light, which prohibits the train from passing through the level crossing.

To develop the complete Boolean Crossing Logic Equation (BCLE) at LQC , the traffic light phase pattern in Table 6 and the state diagram in Figure 37 will be changed in somehow they will accommodate the train signaling system and radar signaling into account.

The BCLE in flow chart is first developed in Figure 42:

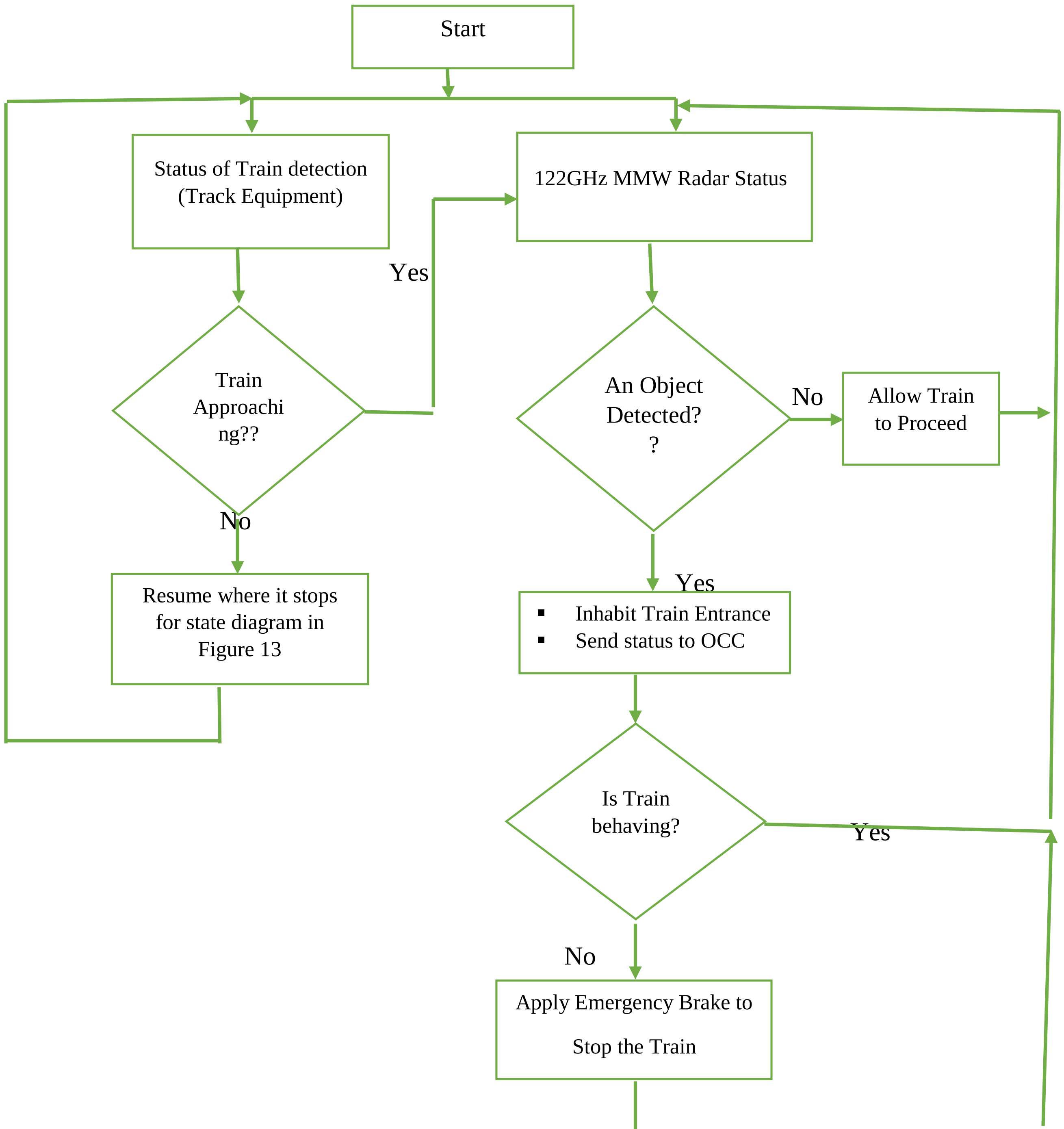


Figure 43: BCLE Algorithmic development

Figure 37 will be modified into the following state diagram of Figure 43, when all parameters from radar signaling controller, train signaling controller and traffic signaling controller are taken into consideration.

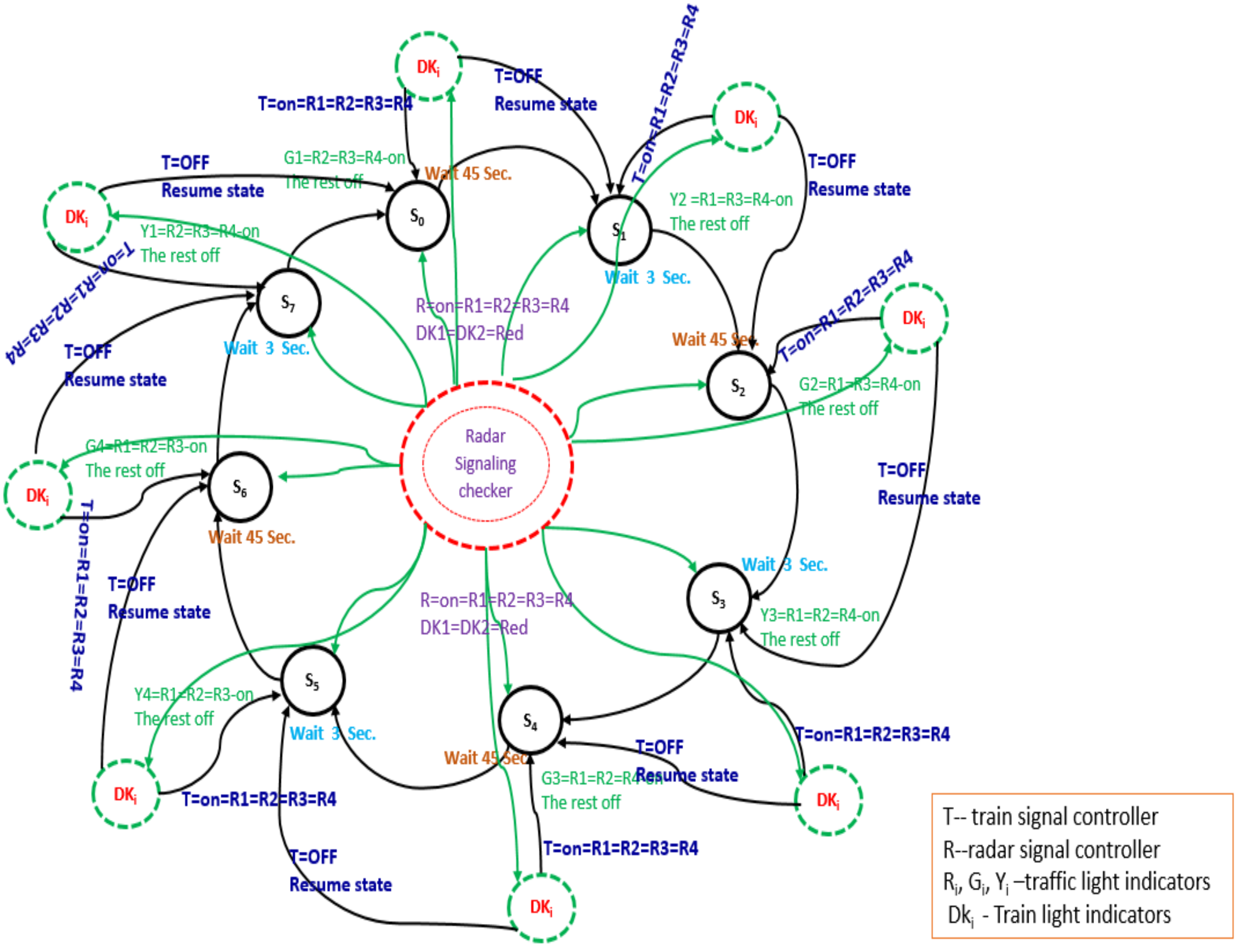


Figure 44: BCLE State Diagram

Table 6 will be modified into the following form taking all signaling considerations into account at the LQC.[1]

[1] DK_i- Train signal status indicator, S_i- Vehicle (Traffic Light indicators) states
R- radar signal indicator, R_i- Red light state, G_i- Green light state, Y_i- Yellow light state

Table 7: Coordinated Signaling System pattern at LQC[2]

Radar Status	Train Signal status	Light symbols	Train Signal indicators				Q-I	Transition time	Q-II	Transition time	Q-III	Transition time	Q-IV	Transition time
			DK1	DK2	DK1’	DK2’								
R=0	T=0	G1-Y1-R1	0-0-1	0-0-1	0-1-0	0-1-0	1-0-0	Y2=on 3”	0-0-1	Y3= On 3”	0-0-1	Y4 =on 3”	0-0-1	Y1 = on 3”
		G2-Y2-R2	0-0-1	0-0-1	0-1-0	0-1-0	0-0-1		1-0-0		0-0-1		0-0-1	
		G3-Y3-R3	0-0-1	0-0-1	0-1-0	0-1-0	0-0-1		0-0-1		1-0-0		0-0-1	
		G4-Y4-R4	0-0-1	0-0-1	0-1-0	0-1-0	0-0-1		0-0-1		0-0-1		1-0-0	
	T=1	G1-Y1-R1	1-0-0	1-0-0	1-0-0	1-0-0	0-0-1		0-0-1		0-0-1		0-0-1	
		G2-Y2-R2	1-0-0	1-0-0	1-0-0	1-0-0	0-0-1		0-0-1		0-0-1		0-0-1	
		G3-Y3-R3	1-0-0	1-0-0	1-0-0	1-0-0	0-0-1		0-0-1		0-0-1		0-0-1	
		G4-Y4-R4	1-0-0	1-0-0	1-0-0	1-0-0	0-0-1		0-0-1		0-0-1		0-0-1	
R=1	Don’t care	G1-Y1-R1	0-0-1	0-0-1	0-0-1	0-0-1	x-x-x		x-x-x		x-x-x		x-x-x	
		G2-Y2-R2	0-0-1	0-0-1	0-0-1	0-0-1	x-x-x		x-x-x		x-x-x		x-x-x	
		G3-Y3-R3	0-0-1	0-0-1	0-0-1	0-0-1	x-x-x		x-x-x		x-x-x		x-x-x	
		G4-Y4-R4	0-0-1	0-0-1	0-0-1	0-0-1	x-x-x		x-x-x		x-x-x		x-x-x	

Note from the table that the colors of 0s and 1s show the current indication for the light symbols. X symbol indicates the don’t care conditions, i.e. if there is an obstacle on the LQC the vehicles may allow to pass based the algorithm of normal traffic light controller which depends on the type of obstacle. And strictly it is shown that if the radars status shows as if there is an obstacle all the train light indicators must show red.

5.3. Interfacing AGCS with CBTCS

As per the signaling preliminary design of AA-LRT a transmission bearing platform of the Project, function of the transmission system is to transmit quickly, accurately and reliably the information such as voice, data and image that is needed for operation and management of all stations, depots, substations, level crossings and the control center of the Project. The information includes:

- Telephone information
- Radio communication information
- Monitoring information of the substation

[2] Q-I,II,III and IV- Quadrant I,II,III and IV of the traffic light junction
0-False state, 1- True state, x- don’t care state , T- Train approaching state

- Video monitoring image information
- Monitoring information of each communication subsystem
- Other information on operation and management

According to the network formation of AA-LRT for data transmission network for East-West line,1st Phase is to provide with IP data. At present the following three types of IP data transmission technologies are contained: MSTP based on SDH, RPR technology , and Gigabit Ethernet technology.

MSTP (Multi-Service Transport Platform) is the most matured transmission net technology , it maintains SDH network and protection technology , and provide with IP interface by inserting of the second layer switching processing module. However, MSTP focus on providing of intrinsic powerful TDM intersection capability and conventional SDH/PDH interface, it cannot get advantages of technology and construction cost in the field of IP data transmission.

RPR (Resilient Packet Ring) is a new IP ring net transmission technology, which is made up of optical fiber , it may provide switching protection while node and optical cable are on fault, RPR has strict QoS definition and service grade classification, and can give full support to business which is requested a high real-time. However , RPR is practically seldom used, and the cost of equipment is around 2-3 times of Ethernet that has the same capability [1].

Gigabit Ethernet technology is the most applicable for data transmission, it obtain advantages of high standardization, high bandwidth utilization, easy to connect with other networks, simplified agreement, easy to expand the port speed, simplified network structure, and low cost, so it is widely used in international internet, municipal broad bond and internet services between enterprises.

As for Addis Ababa light rail project （East-West line, 1st phase）, it is recommended that Gigabit Ethernet to be used for data transmission and upon the assumption of fully meeting the requirement of the project. According to the electricity power supervision, IP telephone, closed-circuit television monitoring, which undertaken by the1st phase transmission network, considering of extra business may be added in the future, it is recommended that the transmission speed of the network shall not be less than 1Gb/s [1]. In accordance with the characteristic of the equipment of Gigabit Ethernet, Hierarchical Star Network Architecture shall be used for data transmission network, the core/convergence layer of the system shall be control center, and the substations along the line shall be work as access layers.

Two set of Ethernet exchanger with routing capacity of 1000M was set up at the control center, as the core/convergence exchange equipment for the whole transmission network. One set of Ethernet exchanger with capacity of 100M/1000M shall be set up at each substation, as access layer exchanging equipment for the transmission network.

In accordance with the type of services and the bandwidth estimate, transmission system of the AA-LRT Project is constructed using MSTP equipment based on SDH whose transmission capacity is designed based on STM-16 [44]. ADM equipment is set for transmission system at all mixed traction and step-down substations (including mixed traction and step-down substation at sections), depots and the control center. The two-core optical fiber in the optical cable laid on both sides of the lines is used to form an E-W transmission loop and an N-S transmission loop, which are tangent to each other at the control center to form the transmission system. The transmission system is protected by the protection ring at the two-fiber bidirectional multiplexing section. Schematic diagram of system composition is as follows in figure 44:

Type of Services and Bandwidth Requirements for the AA-LRT project is tabulated below to use the advantage of the reserved bandwidth available for future developments.

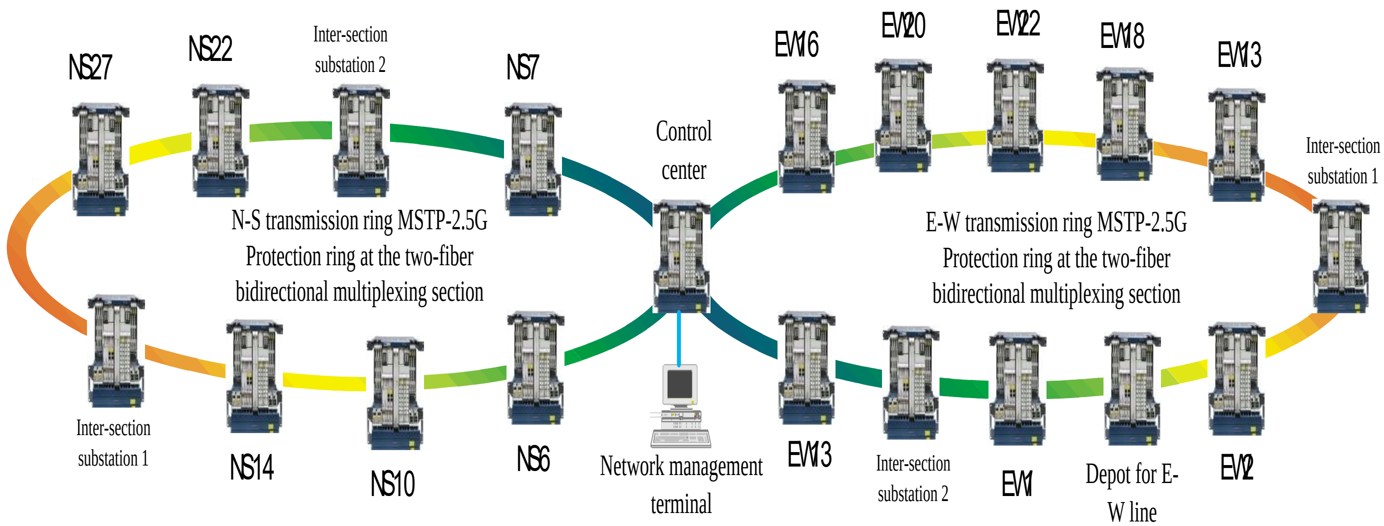


Figure 45: Schematic Diagram of Transmission System for AA-LRT Project [44]

Table 8: Type of Services and Bandwidth Requirements for AA-LRT [44]

S/N	Name of Service	Species	Interface Type	Bandwidth Allocation	Remarks
I. Internal Subsystems of Communications Systems					
1	Tel.	Voice	FE	100Mb/s	Bus shared
2	Radio Communication	Voice	FE	10Mb/s	Bus shared
3	Video monitoring information	Data	FE	2*100Mb/s	Bus shared
4	Communications power network management	Data	FE	10Mb/s	Bus shared
II. Other Systems					
5	Monitoring information of the substation	Data	FE	10Mb/s	Bus shared
III. Reservation					
6	Reserved	Data	FE	4×10Mb/s	Bus shared

As it is shown in Table 8 above there is 40Mbps free bus shared bandwidth which is going to be used here for LQC data transmission to OCC.

The complete interfacing of all the components used for automating and detecting an obstacle around LQC is given in Figure 46 below. The radars are used for continuously monitoring the LQC area which is 10mx20m designed on the previous chapter as the footprint of the radar system, whether any kind obstacle is found or not. This status of the radar system will be given for the DSP of the radar and for both radars accuracy checker then after the result will be fed as a binary input to the BCLE. The BCLE (Boolean Crossing Logic Equation) is responsible for enabling and disabling to all, the train light indicators, Pedestrian light indicators, traffic light indicators based on the data that comes from radars and the DT (Train Detectors) as per the state diagram of Figure 43 or Table 7.

If the status of the radar detector is positive means if there is an obstacle on the LQC, the BCLE PLC will control the traffic light controller and at the same time the status will be sent to the wayside network switch (ADM) over LAN twisted pair cable. ADM (Add Drop Multiplexer) will be responsible for adding data to and from wayside network to the fiber optic network which routes the data to OCC.

So here for this typical thesis there are five LQC points in AA-LRT line and thus, there will be five ADM or wayside switch used for routing the current status of the LQC to OCC to control the train dispatching system. There will not be any disturbance to the train signaling systems of the other blocks other than these with LQC. So trains will behave on what was before in the train signaling system but in addition on the LQC, they must include the radar systems results too so that there will be the safest method ever employed.

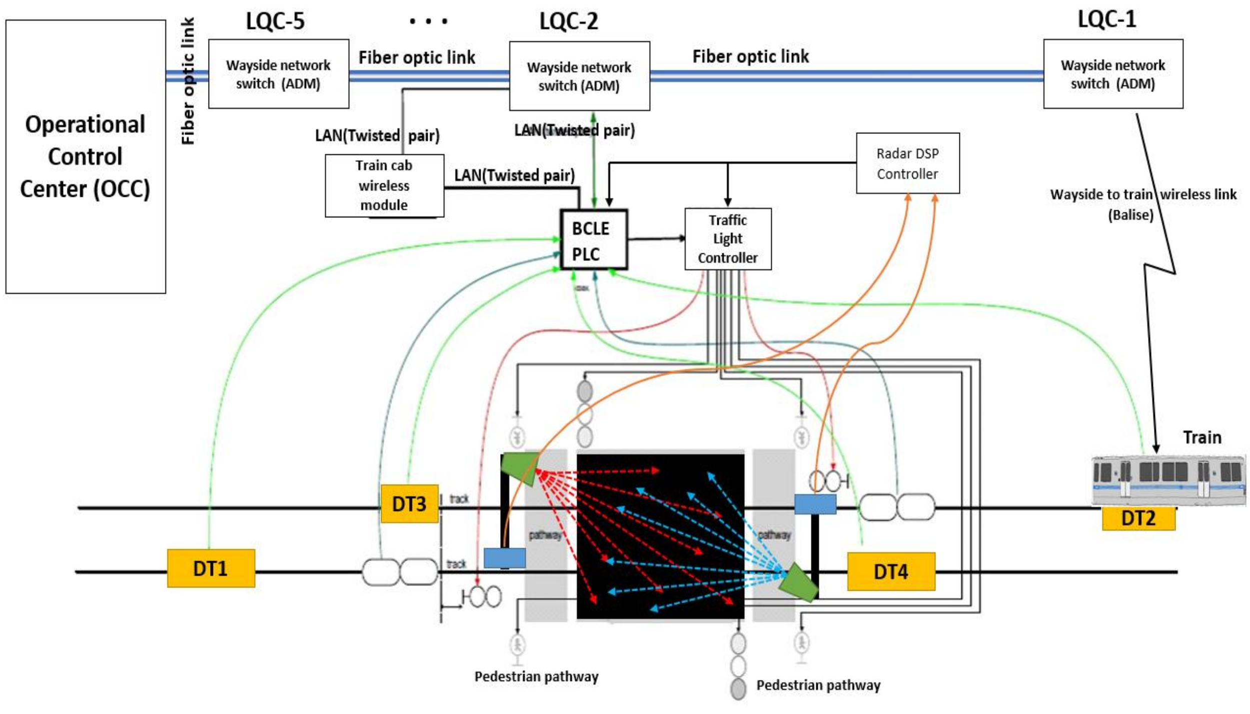


Figure 46: 122GHz MMW Radar Configuration with entire network elements of system

The detailed wiring of the LQC component is given in Figure 45, there are four pedestrian light indicators which are installed at the two entry and two exit lines for pedestrian used for as a notification as if a train is heading towards the LQC or not. There are again four train light indicators which are installed between start and end of the maximum breaking distance (S_b) as shown in Figure 41 for the double railway lines. These are used for the train for not entering the LQC if an obstacle is detected by indicating consecutive yellow and red lights as per the MUTCD standards. If the train is not behaving as per the signaling displayed, the OCC is responsible for applying an emergency brake before it enters the LQC. The Vehicle (Traffic) light indicators are used again for controlling of motor vehicles for not entering of the LQC based on the status of the Radars and DT's. Their number depends on the type of crossing. If it is a normal level crossing i.e. single road with double rail crossing two light indicators may be enough and for double level/quad junction crossing it is mandatory to have four light indicators. This will only change the input and output module of the PLC, not the entire algorithm of controlling the signaling system at the LQC.

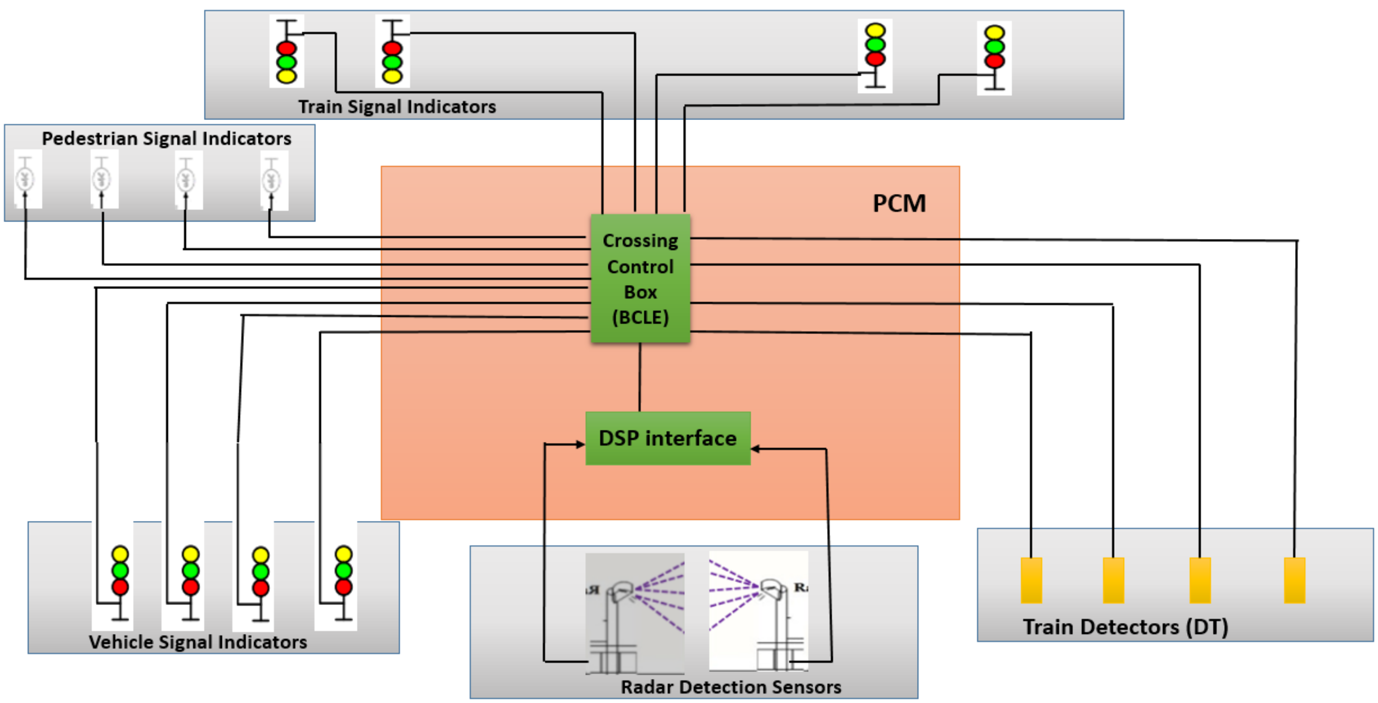


Figure 47: Detailed wiring of LQC components

The train detectors DT_{1-4} are advanced, integrated circuit design, a detection unit for grade or LQ crossings. As it is shown in Figure 47 there is a Carbone antenna used for transmitting a signal indicating as if a train is heading towards LQC and then the DT is responsible for receiving this signal and transferring to the BCLE PLC so that every LQC component will be abided by the BCLE algorithm to control all the conditions at the junction.

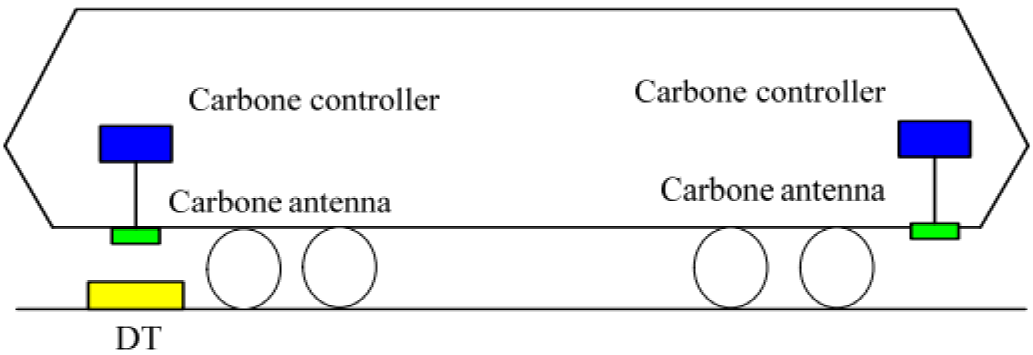


Figure 48: On-Board equipment diagram

5.4. Formulating and Modeling the Optimization Subsystem

5.4.1. Level/Quad Crossing Parameters

Minimum Track Clearance Distance (MTCD): For standard two quadrant railroad warning devices, the minimum track clearance distance is the length along a highway at one or more railroad tracks, measured either from the railroad stop line, warning device, or 4 m (12 feet) perpendicular to the track centerline, to 2 m (6 feet) beyond the track(s), measured perpendicular to the far rail, along the centerline or right edge line of the highway, as appropriate, to obtain the longest distance.

Clear Storage Distance (CSD): The distance available for vehicle storage or queue measured 2 m (6 feet) from the rail nearest the intersection to the intersection STOP BAR or the normal stopping point on the road or highway. At skewed crossings and intersections, the 2-m (6-feet) distance shall be measured perpendicular to the nearest rail either along the centerline, or right edge line of the highway, as appropriate, to obtain the shorter clear distance.

Queue Clearance Time (QCT): The time required for the design vehicle stopped within the minimum track clearance distance to start up and move through the minimum track clearance distance. If pre-signals are present, this time, should be long enough to allow the vehicle to move through the intersection, or clear the tracks if there is sufficient clear storage distance.

Train Clearance Time (TCT): The time needed for the train to leave the LQC. This depends on the speed of the train and the type of the LQC where the train is passing.

Pedestrian Clearance Time (PCT): is the time needed by a normal walking person to pass the 10m distance along the LQC.

Separation Time (ST): The component of maximum preemption time during which the minimum track clearance distance is clear of vehicular traffic prior to the arrival of the train. This is the breaking time required because if minimum track clearance distance is not met hopefully the train must apply breaking.

Maximum Preemption Time (MPT): The maximum amount of time needed following initiation of the preemption sequence for the road or highway traffic signals to complete the timing of the right-of-way transfer time, queue clearance time, and separation time.

Advance Preemption (AP) and Advance Preemption Time (APT): Notification of an approaching train is forwarded to the road or highway traffic signal controller unit or assembly by railroad DT equipment for a period of time prior to activating the railroad active warning devices. This period of time is the difference in the maximum preemption time required for highway signal operation and the minimum warning time needed for railroad operations and is called the advanced preemption time. APT is called sometimes Radar Processing Time (RPT).

Simultaneous Preemption (SP): Notification of an approaching train is forwarded to the road or highway traffic signal controller unit or assembly and railroad active warning devices at the same time. SP is achieved when the radar processing capability is very high and is ignored to be considered

Pre-Signal (PS): Supplemental road or highway traffic signal faces operated as part of the highway intersection traffic signals, located in a position that controls traffic approaching the railroad crossing and intersection.

Dwelling Time (TD): is used to specify the time that a train stays at a station. A minimum dwell time specifies the minimum time needed for passengers to alight and board.

Connecting Train (CT): is planned relation of the trains between their arrival and departure times at a certain node in this case at LQC. Such combining of trains obviously requires both trains to be concurrently present at the LQC.

Running time (RT): is the single trip time the train takes to finish a given track from starting to end with-out stopping /waiting to alight and aboard passengers. It is the time needed for a train to travel from one station to next nearest LQC.

5.4.2. Mathematical Modelling of Time Delay

Here every parameter of time is taken with regard to the AA-LRT Meshalekiya's LQC specification and some of the data are taken arbitrarily since real data are hard to find about it. That is because what it matters here is the optimization equation rather than the numerical data latter may be substituted the real data.

The main objective is to reduce the time delay for both the vehicle and the train around LQC and to do so it needs to be analyzed and calculated for how long did each of these constraints hold the LQC. Taking the minimum and maximum running speed of the trains to be 12Km/hr and 70Km/hr with 20m of the LQC length it will be found as:

TCT_{min} = 0.02Km/(12Km/hr)=0.001667hours=6sec

TCT_{max}=0.02Km/(70Km/hr)=0.000286hours=1.029sec

Average TCT for mechalequiya is found to be for average running speed limit given to be 35Km/hour and is:

TCT_{ave}=0.02Km/(35Km/hr)=0.000573hours=2.057sec

This TCT_{ave} is the time needed for a single train to leave the LQC so for both trains TCT_{ave}=4.114sec.

Let $TCT_{Stadium\_LQC}$ and $TCT_{Meshalekya\_LQC}$ are the times required for the train to come to LQC from stadium and meshalekya respectively. Thus, the train will contribute twice time to the time delay at the LQC which will be used later for driving minimization equation.

For the vehicle QCT again the average running speed of 30Km/hr have been taken for the vehicles passing along the 10m LQC.

Vehicle QCT_{ave} = 0.01Km/(30Km/hr)=0.0003333hours=1.2sec

For the pedestrian PCT will be calculated considering for a normal person walking speed of 6.8Km/hr for 10m LQC

PCT_{ave}=0.01Km/(6.8Km/hr)= 0.00147hour=5.29sec

The total distance between stadium and meshalekya is 908m and the distance between the stadium and the LQC is 750m and the distance between the LQC and the Meshalekya station is 108m and length of the double circular junction is around 50m (by inspection).

The radar system scans the LQC with 30scans/sec. Thus, the time needed for once scan of the LQC area is called the Radar Scanning Time (RST) which is found to be 0.0333sec/scan. This is an important parameter used for determining on-time optimizing of vehicular passage through the LQC by comparing the time of exit of the vehicle and time of arrival of the train towards the LQC.

So it can be calculated the RT of the train towards LQC with 35Km/hr running speed as follows

$RT_{Stadium\_LQC}$= 0.75Km/(35Km/hr)=0.02143hour=77.143sec

$RT_{Meshalekya\_LQC}$= 0.108Km/(35Km/hr)=0.0031hour=11.109sec

For a running speed of 35Km/hour, the maximum breaking distance is given to be 40.8m which results in Breaking Time (BT) of 0.0011657 hours or 4.197sec. This is, in other words, the separation time needed. So here it can conclude that the following safety constraint must be considered critically:

$$QCT + PCT - BTA \gg RST \quad \text{------------} \quad \textit{Equation 52}$$

$$\textit{which results in a safety constraint of } \; QCT + PCT \geq 4.23$$

5.4.3. Optimization Equation for Time Delay

Now let us drive the minimization equation for minimizing the time delay based on the specifications given in section 5.4.2.

So the time delay at LQC is the sum of vehicle QCT, twice TCT, PCT, and RST.

Let x_1 is QCT, x_2 is TCT, x_3 is PCT and x_4 is RST. Note that all constraint time windows are in seconds.

Thus, the minimization linear programming equation will be formulated as

$Min\ f(x) = x_1 + 2x_2 + x_3 + 2x_4 \leftrightarrow Objective\ function$ -----------------------------------Equation 53

Subjected to:

$x_1 + 2x_2 + x_3 \geq 8.547$ $Minimum\ requirment\ constraint$ ----Equation 54a

$x_1 + x_4 \leq 1.2333$ $Radar\ specification\ constraint$ ----Equation 54b

$x_1 + x_3 + x_4 \leq 6.5233$ $Maximum\ preemption\ time\ constraint$ ----Equation 54c

$x_1 + \quad + x_3 \geq 4.23$ $Safety\ requirment\ constraint$ ----Equation 54d

Variable bounds

$x_1 \leq 1.2$ --Equation 55a

$x_2 \leq 2.057$ --Equation 55b

$x_3 \leq 5.29$ --Equation 55c

$x_4 \leq 0.0333$ --Equation 55d

$for\ all\ x_1, x_2,\ x_3\ and\ x_4\ > 0$ --Equation 55e

Now we are left with setting up the standard linear programming for minimization using the simplex method, but first let write the linear programming in standard form as follow:

$$f(x) = C^T x\ \ and\ identify\ the\ vectors\ x\ and\ f$$

$Represented\ as\ \boldsymbol{X} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}\ \ and\ \ f = \begin{bmatrix} 1 \\ 2 \\ 1 \\ 2 \end{bmatrix}$ ---Equation 56

Express the constraints in the form $A_x \leq b$ and identify the matrix A and the vector b. To do this multiply the whole row of the constraint with $\geq (greater\ than\ )\ by$ -1 and change the sign to $\leq$. This gives the following arrangement.

$-x_1 - 2x_2 - x_3 \leq -8.547$ ---Equation 57a

$x_1 + x_4 \leq 1.2333$ ---Equation 57b

$x_1 \quad + \quad x_3 + x_4 \leq 6.5233$ ---Equation 57c

$-x_1 + \quad - \quad x_3 \quad \leq -4.23$ ---Equation 57d

Variable bounds

$x_1 \leq 1.2$ --Equation 58a

$x_2 \leq 2.057$ ---Equation 58b

$x_3 \leq 5.29$ --Equation 58c

$x_4 \leq 0.0333$ --Equation 58d

$for\ all\ x_1, x_2,\ x_3\ and\ x_4\ > 0$ --Equation 58e

So, the matrix A and vector b are rewritten as shown below:

$$A = [-1\ -2\ -1\ 0; 1\ 0\ \ 0\ 1; 1\ \ 0\ \ 1\ 1;\ -1\ \ \ 0\ \ -1\ \ 0]\ \ and$$

$$b = [-8.547; 1.2333; 6.5233; -4.233]$$

Solving using the built in MATLAB linprog () function we will get the following MATLAB results with the following formula the MATLAB code is found at the appendix of this thesis .

```
[x,fval,exitflag,output] =
linprog(f,A,b,Aeq,beq,ub,[],[],optimset('Display','iter'))-------------Equation 59
```

5.4.4. Analyzing the Optimization Result

Form the MATLAB result generated below shows that x = [1.2000 2.0570 5.2900 0.0333] and x_2= 2.0570sec which is the TCT (Train Clearance Time) reduced by half. To do so the train from the extremes of the LQC must meet at the LQC so that the time of waiting for the vehicles is reduced by half too. So the total minimum time delay must be 8.6136 sec which is the best optimized delay considering all constraints. It can be seen that if the trains come to LQC at different times then they will take double time which results in maximum time delay of 10.6706sec.

```
  Residuals:   Primal     Dual     Duality    Total
               Infeas    Infeas      Gap       Rel
               A*x-b    A'*y+z-f    x'*z      Error
  ---------------------------------------------------
  Iter    0:  5.93e+02 7.07e+00 2.50e+03 5.00e+02
  Iter    1:  6.26e+01 1.09e-15 2.74e+02 2.05e+01
  Iter    2:  3.06e-01 1.04e-15 4.61e+00 1.17e+00
  Iter    3:  1.24e-02 2.00e-15 5.95e-02 2.69e-02
  Iter    4:  1.11e-06 2.36e-15 5.32e-06 2.38e-06
  Iter    5:  1.11e-11 2.01e-15 5.32e-11 2.38e-11
Optimization terminated.

x =

    1.2000
    2.0570
    5.2900
    0.0333


fval =

    8.6136


exitflag =

     1


output =

         iterations: 5
          algorithm: 'interior-point'
       cgiterations: 0
            message: 'Optimization terminated.'
    constrviolation: 4.1345e-12
      firstorderopt: 1.0156e-11

fx >>
```

Chapter Six

Simulation Results and Discussion

On the previous two consecutive chapters modeling of the entire system have been made. The detection subsystem with the core of the radar system has been mathematically modeled. On chapter five the coordination and optimization algorithms have been developed and modeled.

6.1. Simulation Model

The challenges of modeling the radar systems is modeled as in Figure 48 as a reference:

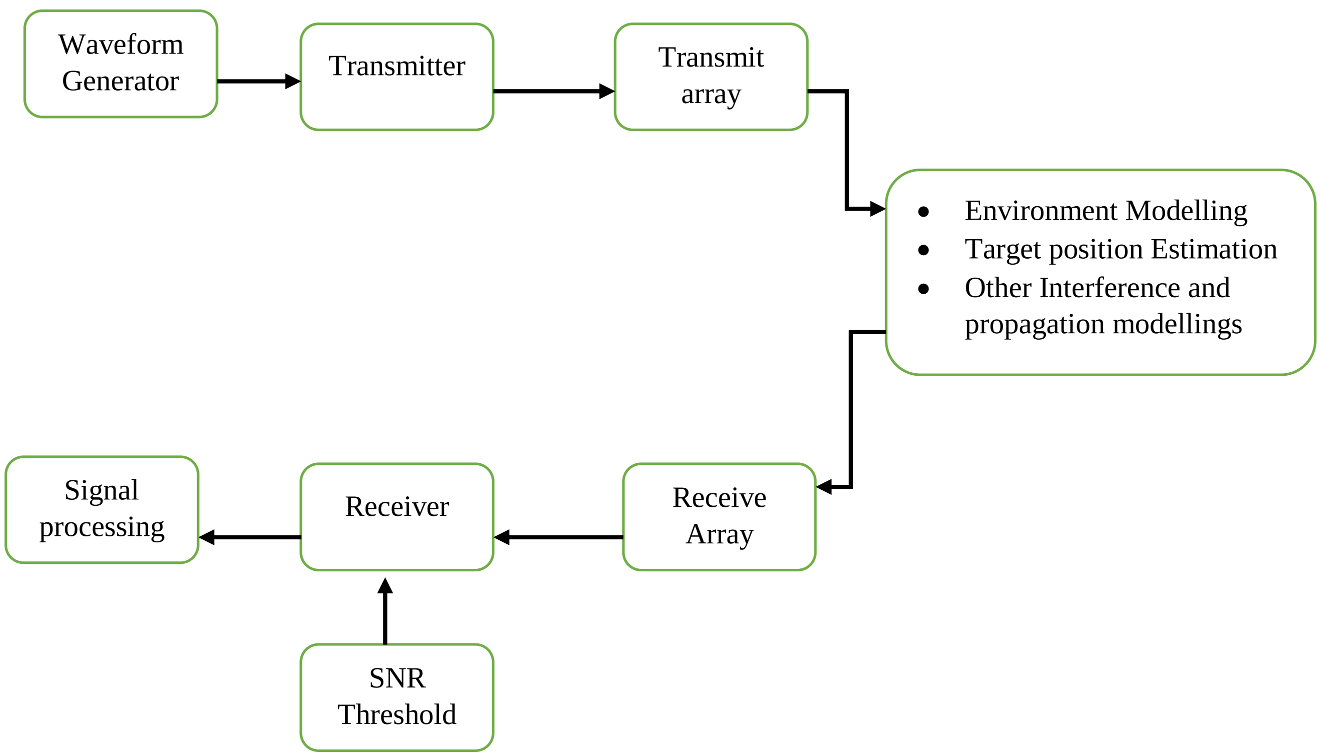


Figure 49: Simulation Model of the Radar system

6.2. Result and Discussion

Here the different simulation results of[3] the radar system will be evaluated in detail. The simulation is based on the MDS- Minimum Detectible Signal by the sensitive radar receiver's performance. As per the design and mathematical modeling given in chapter four the bandwidth of the radar system affects how close obstacles can be isolated and be detected as different obstacles. This helps to clearly identify any obstacle which is very close to the background objects like fences and polls around the LQC. As it can be seen from the Figure 49 at B=300MHz it can detect up to 0.5m close objects. As the bandwidth is doubled from 300MHz to 600MHz hopefully the radar's range resolution reduces to 0.25m which means even very close obstacles can be detected as two different obstacles. But it can't keep increasing the bandwidth because it need to design a transmitter pulse with pulse width of in the order of nanoseconds. For example from the Figure 49. The pulse width decreases from 3.49ns to 1.75ns which at the demand of complex transmitter pulse generator.

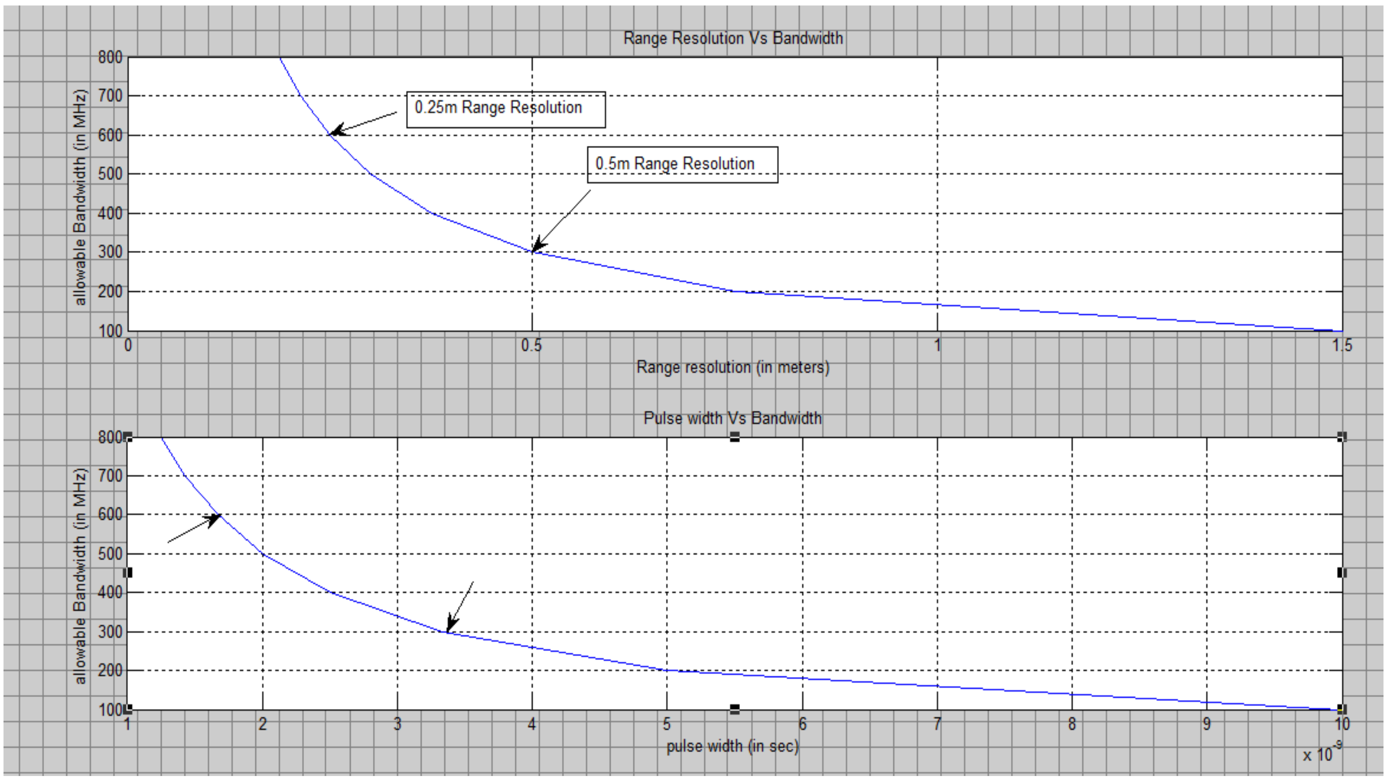


Figure 50: Bandwidth effect on the Radar Parameters

When it comes to the Doppler's frequency shift which is important radar parameter for moving obstacle detection. Here it have chosen 6.8Km/Hr (1.8889m/sec) which is a normal man's speed while crossing the LQC to 220Km/Hr (61.11m/sec) of the fastest car crossing through the LQC. This speed represents 1.6 kHz to 50 kHz Doppler frequency shift as shown in Figure 50. Once more again the angle between the radar's sights with respect to the obstacles motion is important. So here radar's position of installation with respect to the motion of the pedestrian and vehicle must be almost zero to entertain a good velocity tracking. Since accurate speed tracking is very important for optimization of the time delay and efficient utilization of the track and the roads and minimize risk which modeled in section 5.4.

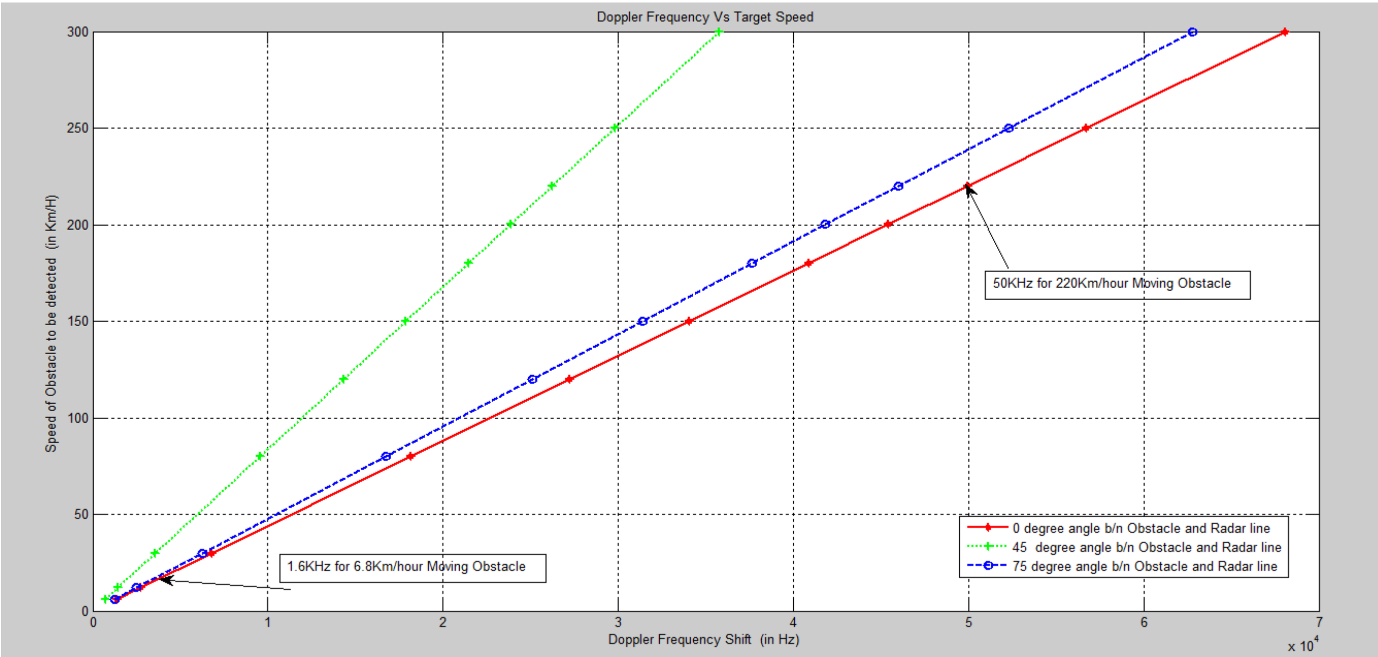


Figure 51: Doppler frequency shift for a different angle of radars sight to obstacles motion.

From figures 51 and 52, the obstacles ranging from a single object of 0.1m^2 to large trucks of 100m^2 have been detected with a maximum range of 50m. Clearly it can be seen from both figures that every point on the threshold SNR line is below every point for other RCS values even for the smallest target considering of 0.1m^2. The threshold SNR value for p_t=100mW, 0.01m^2 surface clutter at the 50m range, for example, is around 185dB but at the same transmitted power and range for RCS of 0.1m^2 is 208dB which is much higher than the threshold.

Another point that can be deduced from figures 51 and 52 is that MDS or SNR increases as the radar cross section increases. There is a great difference between Figure 51 and Figure 52. Figure 51 shows simply the SNR versus detection range for different radar cross section without considering the effects of rainfall attenuation, temperature variation, and fog. But Figure 52 shows all the effects taken into considerations: a 40mm/hour rainfall modelled in [6] taken to be 1.5 dB, the extreme temperature variation of Addis Ababa taken from [45] of to be between 278.5 $°k\,(48.89dB)$ to 304.15$°k$ $(49.6618dB)$ which accounts about 0.7653 dB and 0.1 dB fog attenuations are simulated in the Figure 52. From this what we can deduce is that the variation of the temperature have a little effect on the performance of the radar system.

From section 4.4 again it have designed the antennas near field region to be $R_{min} = d^2/\lambda$ which results in 0.463m for the radar used in this study. Therefore, sensor targets often fall within the near-field region where the antenna pattern is range-dependent which is clearly shown in the figures 6.4 and 6.5 below. There will be a maximum point of SNR received beyond 0.463m.

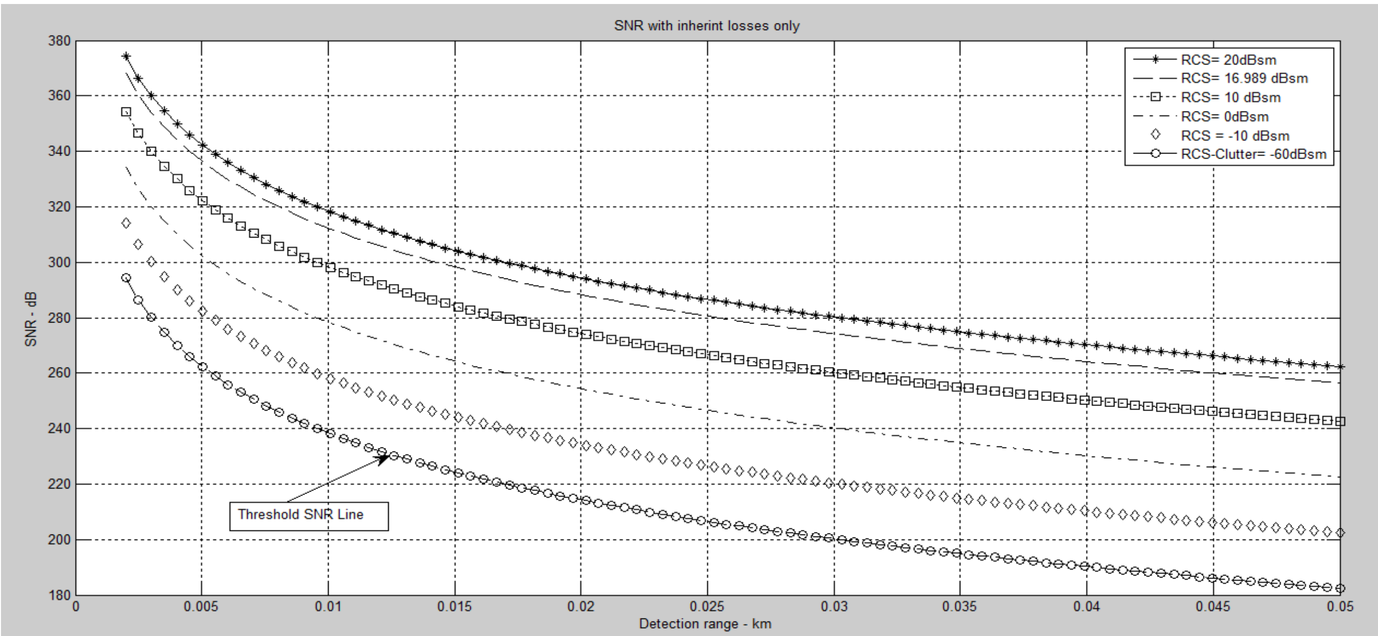


Figure 52: SNR Versus Detection Range for without any losses taken into consideration

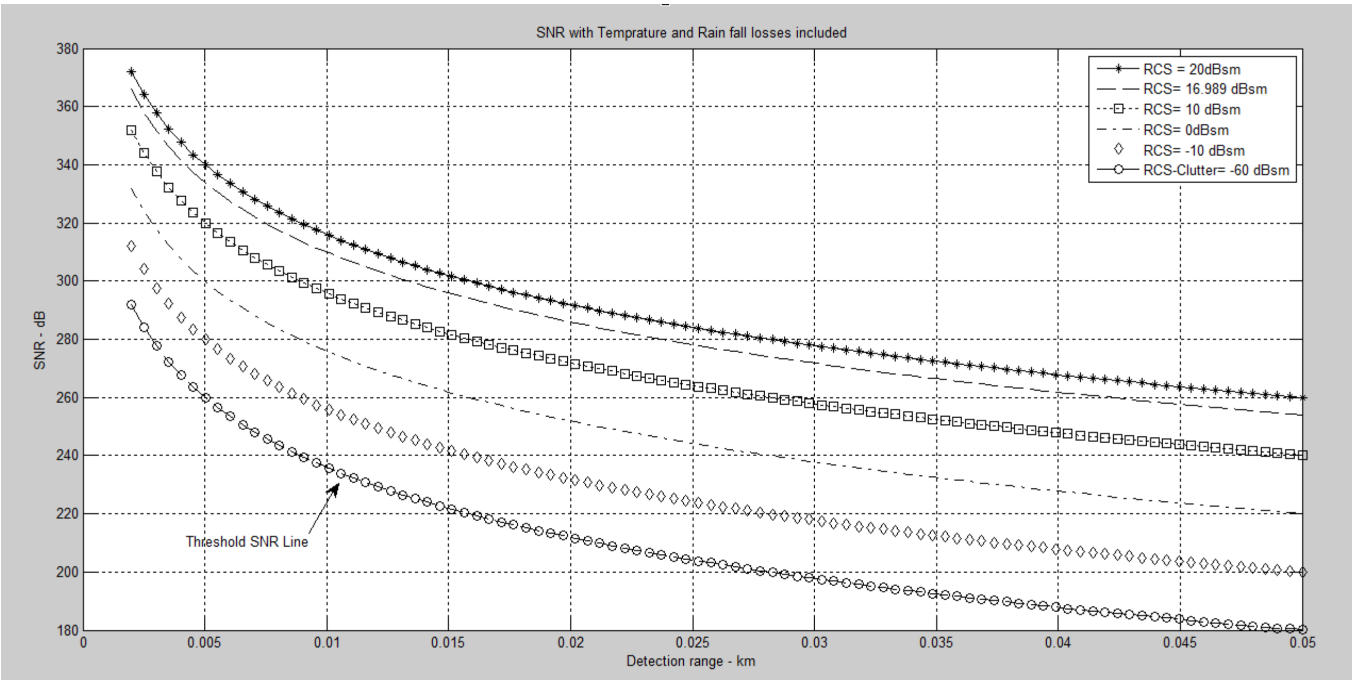


Figure 53: SNR Versus Detection Range without any losses taken into consideration

From Figure 53 doubling the peak power (3 dB) has little effect on improving the SNR. One should consider varying other radar parameters such as antenna gain to improve SNR or detection range. i.e. for example if the transmitted power is doubled from 50mW to 100mW at 25m range detection the SNR increases slightly from 209dB to 221dB. But if the gain of the antenna is doubled hopefully the SNR will increase four times or if decrease the range of detection by half the SNR will increase sixteen times. So for this thesis the MDS at maximum range detection of 50m and peak transmitted power of 100mW and default RCS of $0.1m^2$ have been designed to be 205dB as shown in Figure 53.

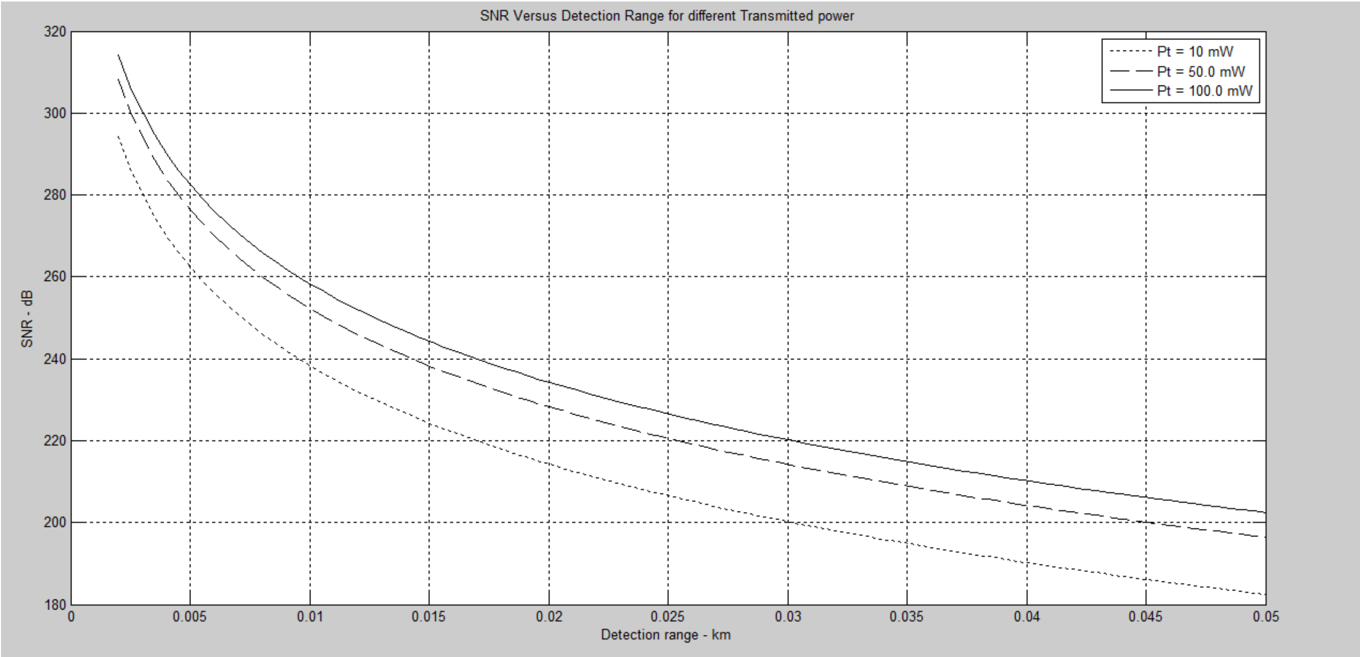


Figure 54: SNR versus Detection Range for Different Transmitted power

In Figure 54 and 55 the Minimum Detectible Signal- MDS is defined as the useful echo power at the reception antenna, which gives on the screen a Detectible blip. Taking all the parameters of the LQC the threshold value can developed below which it is considered not an obstacle. But this is achieved by continuously learning the radar receiver to the footprint of the LQC under consideration. After the threshold values are decided then the radar DSP will help to process the received signal whether an obstacle is there or not. The threshold value decision may be made adaptive to the different factors. So Figure 55 shows peak shoots above the broken line indicated as a threshold will be considered as an obstacle.

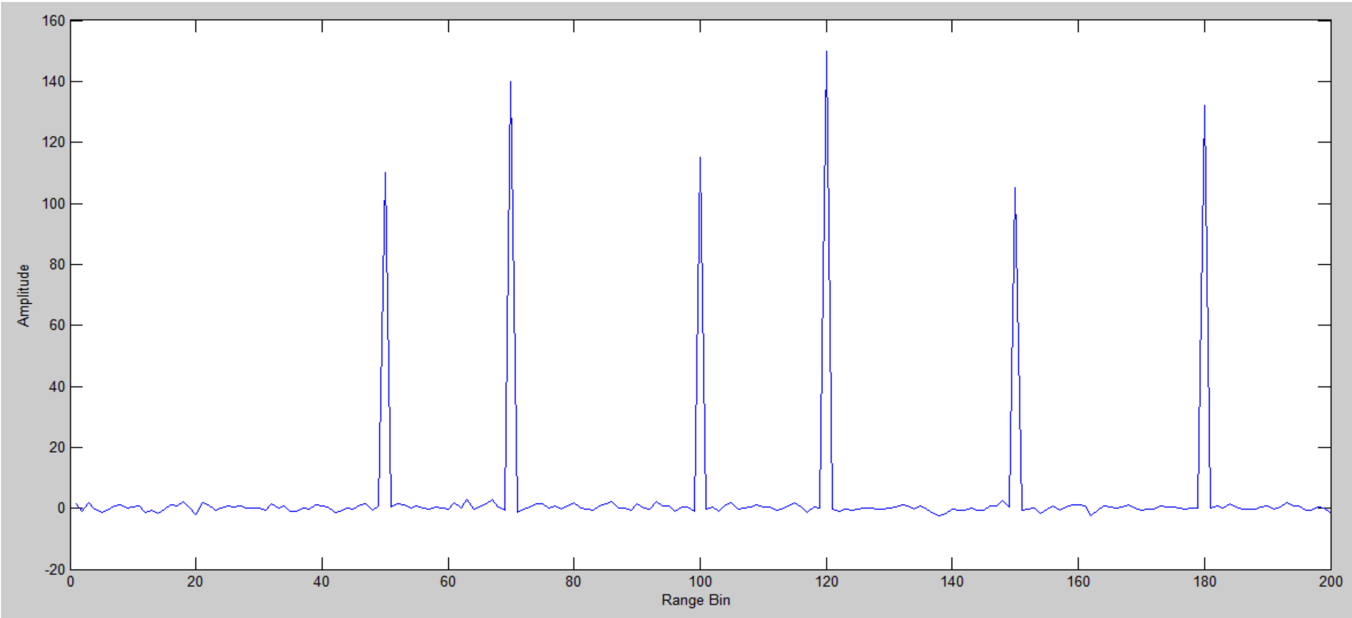


Figure 55: Received Signal Analysis With-out Threshold Detection

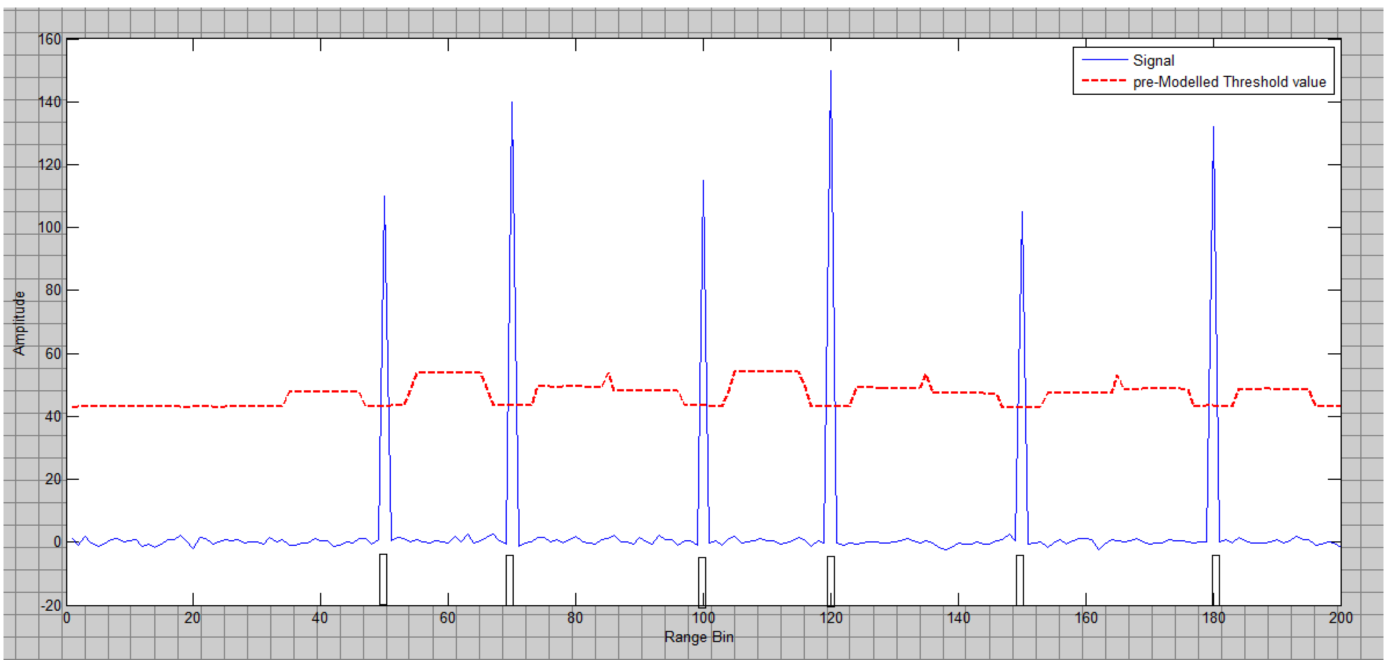


Figure 56: Obstacle Detection with Pre-Defined Threshold Value

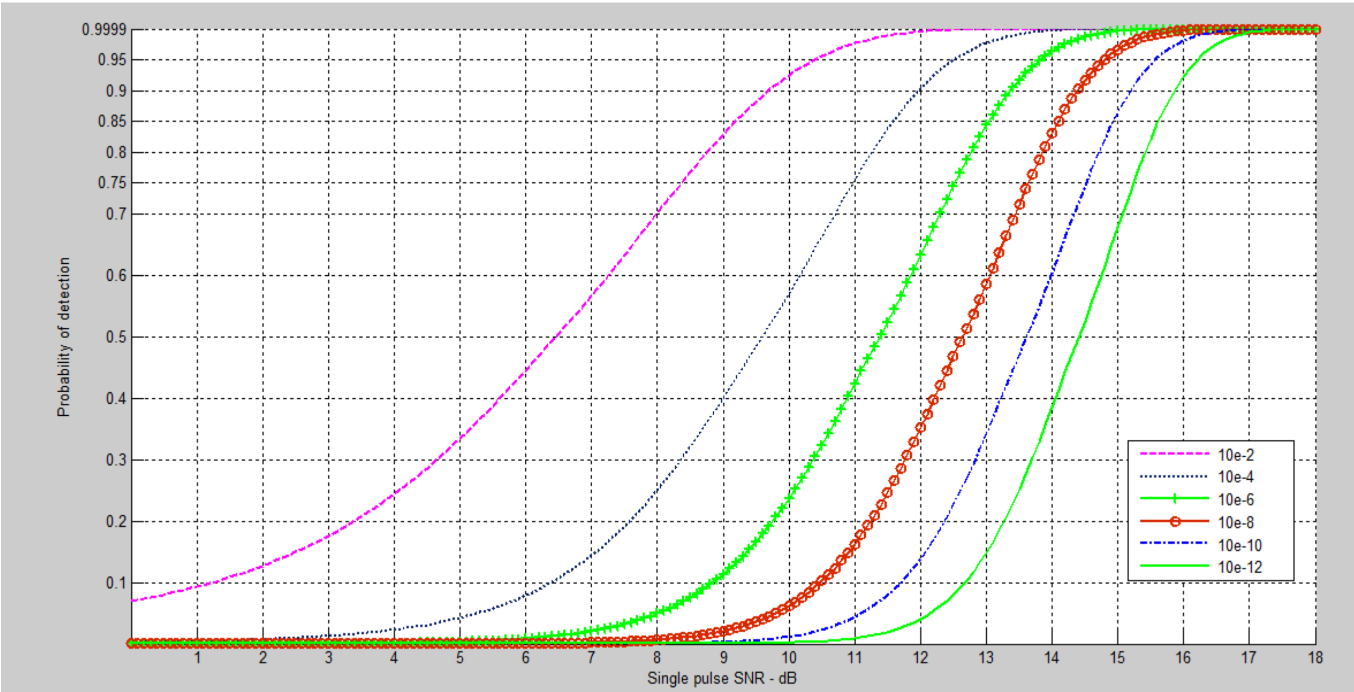


Figure 57: P_D versus SNR for different FAR and 6 nfa

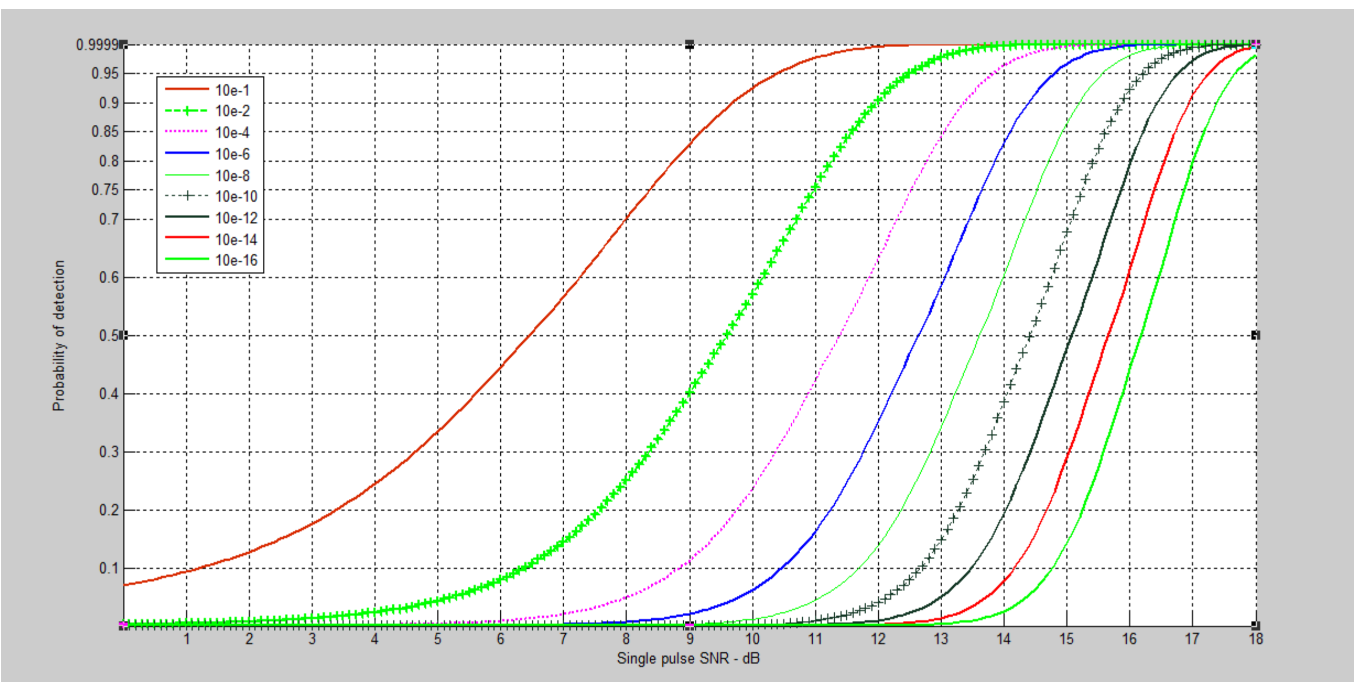


Figure 58: PD versus SNR for different FAR and 9 nfa

As shown in the figure 58 and 59 they show the effect of temperature variation on the received SNR and it is very small even on the extreme temperature variations.

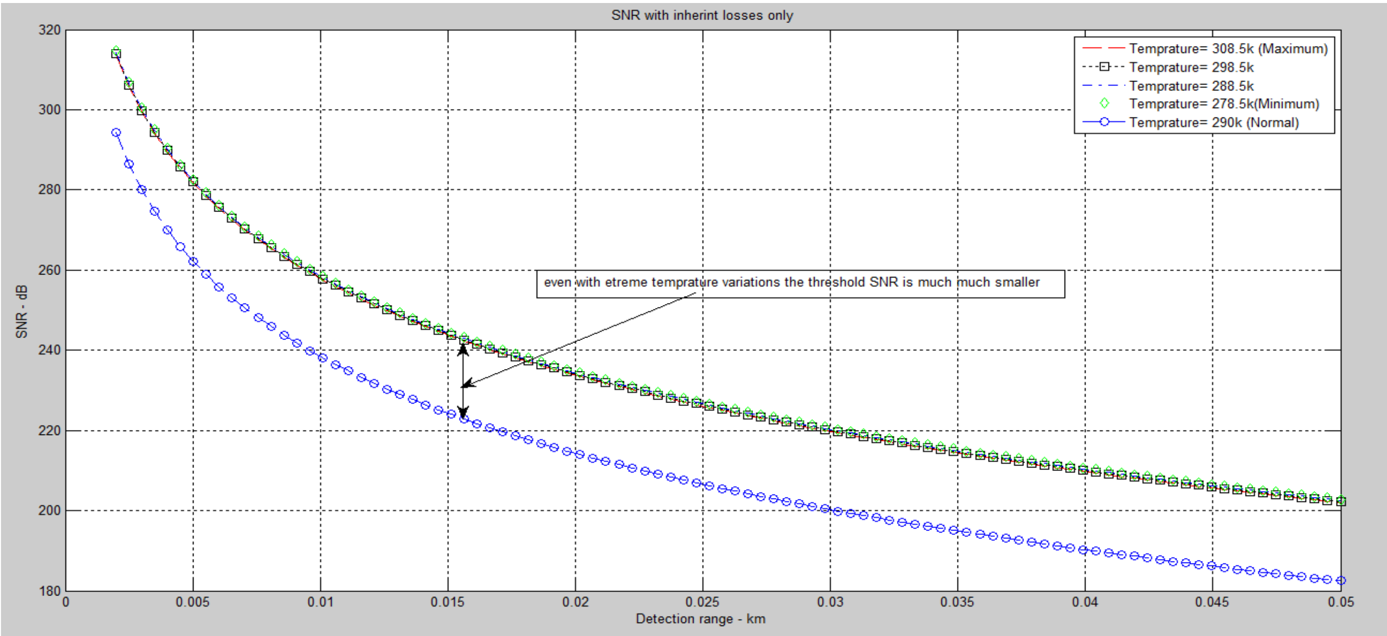


Figure 59: Effect of temperature variation on the SNR versus detection range without considering other losses.

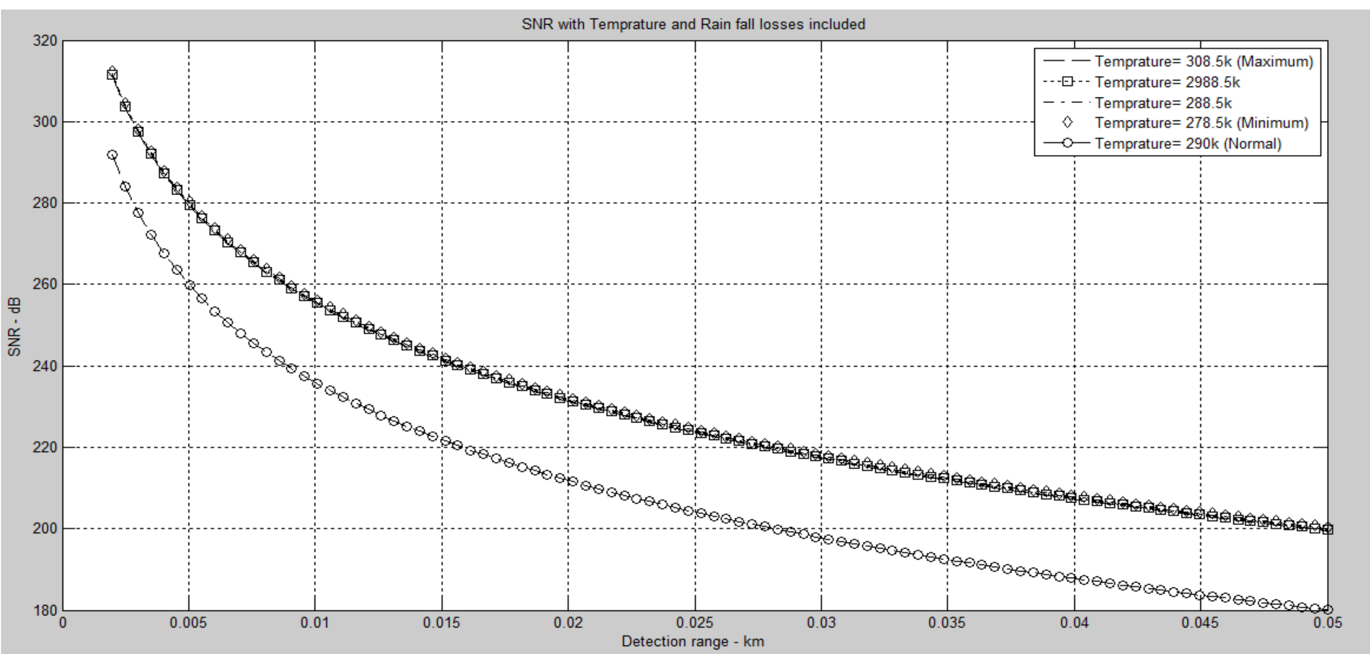


Figure 60: Effect of temperature variation on the SNR versus detection range considering other losses too.

When the temperature varies from 278.5 k (minimum) to 308.5k (maximum) the graphs look exactly overlapped but they have little different values though they are above the threshold value by far larger value. It is shown their effect in figure 60 which is the zoomed version of figure 58.

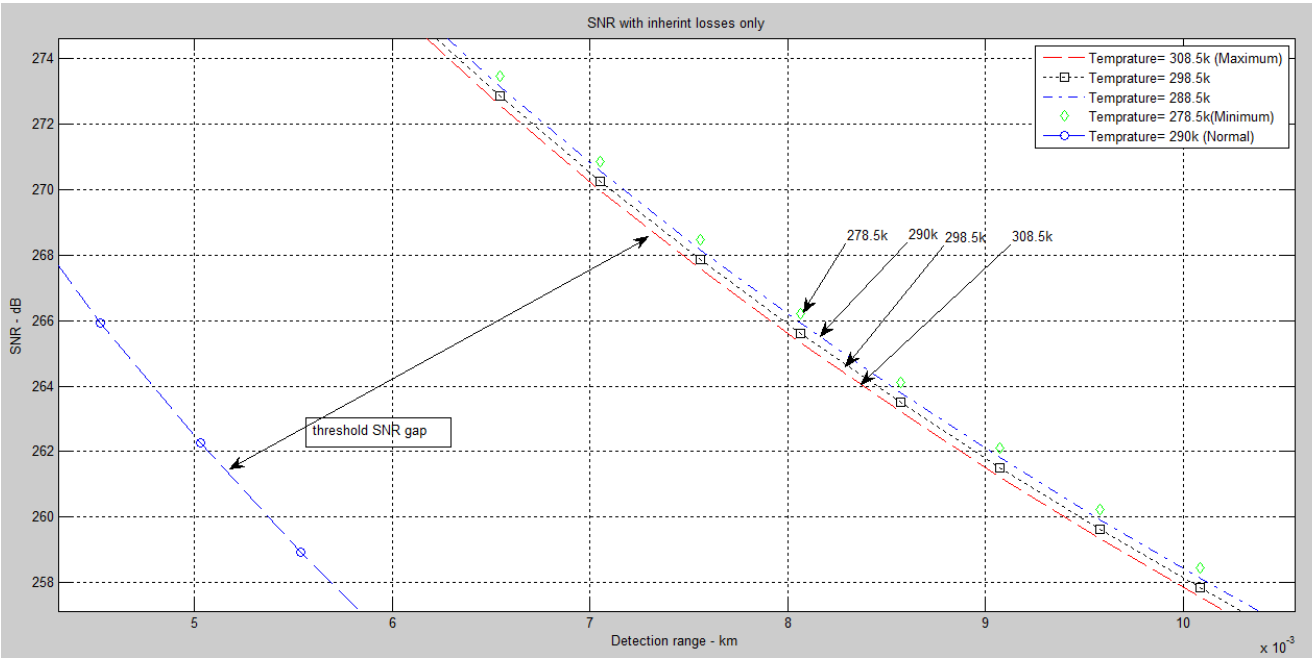


Figure 61: Repetition of figure 58 zoomed to show the effect as if they are not exactly overlapped

Chapter Seven

Conclusion and Recommendation

7.1. Conclusion

This thesis has been aimed at developing an automatic control device for detection, coordination and optimization of safety at level/quad crossing where both road and rail vehicles intersect. A 122GHz FMCW MMW radar has been designed for this automation purpose, detection of an obstacle at LQC and reporting the status to wayside active devices and the OCC. The complete transceiver design and mathematical modeling of the radar system considering the different weather conditions (in the presence of rainfall, foggy season and temperature variation), the size of target and distance of target have been also conducted. The footprint coverage and beam-width projection with the height installation of the radar system over the LQC are presented.

The best coordination algorithm with optimized time delay for both trains and road vehicles has been in detail explored. The complete set of algorithms for which how the radar signal indicator controls both the train signaling system and traffic light signaling system which is called the Boolean Crossing Logic Equation have been developed.

Finally, the interface of the system developed here with the existed AA-LRT was presented at system theoretic level. Here the existed DT system and radar signal are used as actuators to control the traffic light controller and pedestrian light indicators.

The mathematical models developed for the radar system haven simulated using MATLAB 2013 and the possible discussions on the results of the simulation have been made.

So generally the radar system is shown to be the promising technology with good performance, reliability, permanency with a reasonable cost which fulfill the enduring dream of making practicable for railway industry's safety automation at LQC. And hopefully, it provides with a minimum risk of accidents and maximum utilization of the tracks and roads which means it promises to reduce the time delay introduced to both modes of transport.

7.2. Recommendation

First and for most it is strongly recommended for ERC (Ethiopian Railway Corporation) to give me a chance to implement a prototype for this work and be used as a promising technology for ensuring safety at LQC (Level/quad crossing), and ;

Based on the work of this thesis, I recommend for further researchers the following important issues:

- Developing of a data logger system at the OCC from the radar system's DSP and developing of LQC numbering system for each LQC of the line under consideration.
- Studying of the EMC issues for the radar system.
- Developing load based traffic adjustments for the traffic light controller and self-adjustments based on the real value of the radar signal interpretation using the Genetic algorithm.

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Appendix

Matlab code for optimization simulation

```
close all;
clear all;
f=[1;2;1;2];
A=[-1 -2 -1 0; 1 0 0 1; 1 0 1 1; -1 0 -1 0];
b=[-8.547;1.2333; 6.5233;-4.233];
lb=zeros(4,1);
ub=[1.2; 2.057; 5.29; 0.0333];
Aeq=[];
beq=[];
options = optimset('LargeScale', 'off', 'Simplex', 'on');
[x,fval,exitflag,output] = linprog(f,A,b,Aeq,beq,ub,[],[],optimset('Display','iter'))
```

Matlab code to generate for Figure 49 (Range Resolution Simulation)

```
close all;
clear all;
c=3*10e8;
B=[100,200,300,400,500,600,700,800];
k=size(B)
taw=1./(B*1e6);
Delta_R=zeros(1,8);
for i=1:8

Delta_R=300./(2*B);

end
subplot(2,1,1);
plot(Delta_R,B);
xlabel ('Range resolution (in meters)');
ylabel ('allowable Bandwidth (in MHz) ');
title('Range Resolution Vs Bandwidth');
grid on;
subplot(2,1,2);
plot(taw,B);
xlabel ('pulse width (in sec)');
ylabel ('allowable Bandwidth (in MHz) ');
title('Pulse width Vs Bandwidth');
grid on;
```

Matlab code used to generate Figure 50. (Doppler frequency shift)

```
close all;
clear all;
```

```
c=3*10e8;
V=[6, 12, 30, 80, 120, 150, 180, 200, 220, 250, 300];
Alpha1=0;
Alpha2=45;
Alpha3=75;
k=size(V)
F_Doppler1=zeros(1,11);
F_Doppler2=zeros(1,11);
F_Doppler3=zeros(1,11);

for i=1:11

F_Doppler1=227.*V*cos(Alpha1);
F_Doppler2=227.*V*cos(Alpha2);
F_Doppler3=227.*V*cos(Alpha3);

end
plot(F_Doppler1,V,'-*r',F_Doppler2,V, ':g',F_Doppler3,V,'--b');
legend ('0 degree angle b/n Obstacle and Radar line','45  degree angle b/n Obstacle and Radar
line','75 degree angle b/n Obstacle and Radar line');
xlabel ('Doppler Frequency Shift  (in Hz)');
ylabel ('Speed of Obstacle to be detected  (in Km/H) ');
title('Doppler Frequency Vs Target Speed');
grid on;
```

Matlab function used to generate for **radar_com.m [15]**

```
function [snr] = radar_com(pt, freq, g,gs, sigma, te, b, nf, loss, range)
% This program implements the radar equation
c = 3.0e+8; % speed of light
lambda = c / freq; % wavelength
p_peak = mag2db(pt); % convert peak power to dB
lambda_sqdb = mag2db(lambda^2); % compute wavelength square in dB
sigmadb = mag2db(sigma); % convert sigma to dB
four_pi_cub = mag2db((4.0 * pi)^3); % (4pi)^3 in dB
k_db = mag2db(1.38e-23); % Boltzman's constant in dB
te_db = mag2db(te); % noise temp. in dB
b_db = mag2db(b); % bandwidth in dB
range_pwr4_db = mag2db(range.^4); % vector of target range^4 in dB
num = p_peak + g + g + lambda_sqdb + sigmadb+gs;
den = four_pi_cub + k_db + te_db + b_db + nf + loss + range_pwr4_db;
snr = num - den
return
```

Matlab code used to generate for Figure 51 and 52

```
% Use this program to reproduce Figure 51 and 52
close all
clear all
pt = 100e-3;  % peak power in Watts
freq = 122.5e+9; % radar operating frequency in Hz
g = 32.69;  % antenna gain in dB
gs = 13.599;  % System gain in dB
sigma_Threshold=0.01; %Threshold clutter RCS in meter square
sigma = 0.1; % radar cross section in m squared
te = 290.0;  % effective noise temperature in Kelvins
b = 300e+6;  % radar operating bandwidth in Hz
nf = 6.5;    %noise figure in dB
loss = 2.11; % radar losses in dB, when the 40mm/hr rain and Temprature variations are excluded it
becomes 2.11dB
loss1=2.11+1.57+0.7653+0.1; % 1.57dB the rain fall effect incoporated and 0.1dB foggy season
effect
                    % 0.7653dB is difference Temprature of Addis Ababa
                    % with Max= 304.15k and  Min=278.5k
R = linspace(2.0e-3,0.05,96); % target range 2.0e-3 - 0.25 km, 496 points
snr1 = radar_com(pt, freq, g,gs, sigma, te, b, nf, loss, R);
snr2 = radar_com(pt, freq, g,gs, sigma*10, te, b, nf, loss, R);
snr3 = radar_com(pt, freq, g,gs, sigma*100, te, b, nf, loss, R);
snr4 = radar_com(pt, freq, g,gs, sigma*500, te, b, nf, loss, R);
snr5 = radar_com(pt, freq, g,gs, sigma*1000, te, b, nf, loss, R);
snr0 = radar_com(pt, freq, g,gs, sigma_Threshold, te, b, nf, loss, R);
% Computation of SNR considering 40mm/hr and temprature variation and fog
snr11 = radar_com(pt, freq, g,gs, sigma, te, b, nf, loss1, R)
snr22 = radar_com(pt, freq, g,gs, sigma*10, te, b, nf, loss1, R)
snr33 = radar_com(pt, freq, g,gs, sigma*100, te, b, nf, loss1, R)
snr44 = radar_com(pt, freq, g,gs, sigma*500, te, b, nf, loss1, R)
snr55 = radar_com(pt, freq, g,gs, sigma*1000, te, b, nf, loss1, R)
snr00 = radar_com(pt, freq, g,gs, sigma_Threshold, te, b, nf, loss1, R);
% plot SNR versus range
figure(1)
rangekm = R ./ 1.0;

plot(rangekm,snr5,'-*k',rangekm,snr4 ,'--k',rangekm,snr3,':sk',rangekm,snr2,'-
.k',rangekm,snr1,'dk',rangekm,snr0,'--ok')
grid
legend('RCS= 20dBsm','RCS= 16.989 dBsm','RCS= 10 dBsm','RCS= 0dBsm','RCS = -10 dBsm',
'RCS-Clutter= -60dBsm')
xlabel ('Detection range - km');
ylabel ('SNR - dB');
title('SNR with inherint losses only');
figure(2)
```

```
plot(rangekm,snr55,'-*k',rangekm,snr44,'--k',rangekm,snr33,':sk',rangekm,snr22,'-
.k',rangekm,snr11,'dk',rangekm,snr00,'--ok')
grid
legend('RCS = 20dBsm','RCS= 16.989 dBsm','RCS= 10 dBsm','RCS= 0dBsm','RCS= -10 dBsm',
'RCS-Clutter= -60 dBsm')
xlabel ('Detection range - km');
ylabel ('SNR - dB');
title('SNR with Temprature and Rain fall losses included');

snr1 = radar_com(pt, freq, g,gs, sigma, te, b, nf, loss, R);
snr2 = radar_com(pt*.5, freq, g,gs, sigma, te, b, nf, loss,R);
snr3 = radar_com(pt*0.1, freq, g,gs, sigma, te, b, nf, loss,R);
figure (3)
plot(rangekm,snr3,':k',rangekm,snr2,'--k',rangekm,snr1,'k')
grid
legend('Pt = 10 mW','Pt = 50.0 mW','Pt = 100.0 mW')
xlabel ('Detection range - km');
ylabel ('SNR - dB');
title('SNR Versus Detection Range for different Transmitted power');
```

Matlab code used to generate for Figure 53

```
close all;
clear all;

% Pt- Transmitted power;
% freq- Operating frequency of the radar system
% g-Gain of the transmitter and Receiver antenna, both considered the same
% sigma-Radar Cross section
% te- operating temperature
% b- Bandwidth of radar signal processing
% nf- Noise figure
% Loss- the Radar loss
% parameter assigning
% ==============================================================
c = 3.0e+8;
k=1.38e-23;
pt1=10e-3;
pt2=50e-3;
pt3 = 100e-3 % peak power in Watts
freq = 122e+9  % radar operating frequency in Hz
g = 32.69 % antenna gain in dB
sigma = 0.1  % radar cross section in m square
te = 290.0  % effective noise temperature in Kelvins
b = 6.0e+6  % radar operating bandwidth in Hz
```

```
nf = 10.0  % noise figure in dB
loss = 2.11  % radar losses in dB with out tepmrature variation and rainfall loss
R=[0,20,30,40,50];    % % maximum range in meters
lambda = c / freq;
gs=10  %the radar System Gain in dB
%==============================================================
p_peak1 = mag2db(pt1);
p_peak2 = mag2db(pt2);
p_peak3 = mag2db(pt3);

lambda_sq = lambda^2;

lambda_sqdb = mag2db(lambda_sq);
sigmadb = mag2db(sigma);
four_pi_cub = mag2db((4.0 * pi)^3);
k_db = mag2db(k);
te_db = mag2db(te)
b_db =mag2db(b);
R_db=mag2db(R.^4)

SNR1=zeros(1,5);
SNR2=zeros(1,5);
SNR3=zeros(1,5);
for i=1:5

   SNR1=(p_peak1 + g + g + lambda_sqdb + sigmadb+gs)-(four_pi_cub + k_db + te_db + b_db + nf + loss + R_db);
   SNR2=(p_peak2 + g + g + lambda_sqdb + sigmadb+gs)-(four_pi_cub + k_db + te_db + b_db + nf + loss + R_db);
   SNR3=(p_peak3 + g + g + lambda_sqdb + sigmadb+gs)-(four_pi_cub + k_db + te_db + b_db + nf + loss + R_db);

end
% SNR1= mag2db((pt1*g^2*lambda^2.*sigma)./((4*pi)^3*k*te*b*f.*(R.^4)));
% SNR2= mag2db((pt2*g^2*lambda^2.*sigma)./((4*pi)^3*k*te*b*f.*(R.^4)));
% SNR3= mag2db((pt3*g^2*lambda^2.*sigma)./((4*pi)^3*k*te*b*f.*(R.^4)));

plot(SNR1,R,SNR2,R,SNR3,R);
legend ('Pt====10mW','Pt====50mW','Pt====100mW');
xlabel ('Range  (in meters) ');
ylabel ('SNR of the Radar System (in dB)');
title('SNR Versus Range for different Transmitted power with Zero loss');
grid on;

% db2mag((pt+lambda_sqdb+g_sqdb+sigmadb)-(for_pi_cub+))
```

Matlab Code for Generating Figure 54 and 55

```
close all;
clear all;
s=randn(200,1);
s([50, 70, 100,120, 150,180])=[110 140 115 150 105 132];
figure,plot(s);
xlabel ('Range Bin ');
ylabel ('Amplitude');
refLength=12;
guardLength=3;
offset=43;
cfarWin=ones((refLength+guardLength)*2+1,1);
cfarWin(refLength+1:refLength+1+2*guardLength)=0;
cfarWin=cfarWin/sum(cfarWin);
noiseLevel=conv(s,cfarWin,'same');
cfarThreshold=noiseLevel+offset;

figure,plot(s);

hold on,plot(cfarThreshold,'r--','LineWidth',2)
legend('Signal','pre-Modelled Threshold value')
xlabel ('Range Bin ');
ylabel ('Amplitude');
```

MATLAB function caller code for marcumsq.m [15]

```
close all;
clear all
for nfa = 2:2:12
b = sqrt(-2.0 * log(10^(-nfa)));
index = 0;
hold on
for snr = 0:.1:18
index = index +1;
a = sqrt(2.0 * 10^(.1*snr));
pro(index) = marcumsq(a,b)
end
x = 0:.1:18;
set(gca,'ytick',[.1 .2 .3 .4 .5 .6 .7 .75 .8 .85 .9 .95 .9999])
set(gca,'xtick',[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18])
loglog(x, pro, 'g');
end
hold on
xlabel ('Single pulse SNR - dB')
ylabel ('Probability of detection')
```

grid

MATLAB code for marcumsq.m parls Approximation

```
function PD = marcumsq (a,b) % This function uses Parl's method to compute PD
max_test_value = 10000.; % increase to more than 1000 for better results
if (a < b)
alphan0 = 1.0;
dn = a / b;
else
alphan0 = 0.;
dn = b / a;
end
alphan_1 = 0.;
betan0 = 0.5;
betan_1 = 0.;
d1 = dn;
n = 0;
ratio = 2.0 / (a * b);
r1 = 0.0;
betan = 0.0;
alphan = 0.0;
while betan < max_test_value,
n = n + 1;
alphan = dn + ratio * n * alphan0 + alphan;
betan = 1.0 + ratio * n * betan0 + betan;
alphan_1 = alphan0;
alphan0 = alphan;
betan_1 = betan0;
betan0 = betan;
dn = dn * d1;
end
PD = (alphan0 / (2.0 * betan0)) * exp( -(a-b)^2 / 2.0);
if ( a >= b)
PD = 1.0 - PD;
end
return
```

Emulated Matlab code to generate Figure 56 from marcumsq.m

```
function createfigure(X1, YMatrix1)
%CREATEFIGURE(X1, YMATRIX1)
%  X1:  vector of x data
%  YMATRIX1:  matrix of y data

%  Auto-generated by MATLAB on 16-Jun-2016 19:59:32
```

```
% Create figure
figure1 = figure;

% Create axes
axes1 = axes('Parent',figure1,...
    'YTick',[0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.75 0.8 0.85 0.9 0.95 0.9999],...
    'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18]);
grid(axes1,'on');
hold(axes1,'all');

% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'Parent',axes1,'LineWidth',2);
set(plot1(1),'LineStyle','--','Color',[1 0 1],'DisplayName','10e-2');
set(plot1(2),'LineStyle',':',...
    'Color',[0.0392156862745098 0.141176470588235 0.415686274509804],...
    'DisplayName','10e-4');
set(plot1(3),'Marker','+','Color',[0 1 0],'DisplayName','10e-6');
set(plot1(4),'Marker','o','Color',[0.847058823529412 0.16078431372549 0],...
    'DisplayName','10e-8');
set(plot1(5),'MarkerSize',8,'LineStyle','-.','Color',[0 0 1],...
    'DisplayName','10e-10');
set(plot1(6),'Color',[0 1 0],'DisplayName','10e-12');

% Create xlabel
xlabel('Single pulse SNR - dB');

% Create ylabel
ylabel('Probability of detection');

% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.78196086287079 0.19447342532338 0.108722976370035 0.186368477103301]);
```

Emulation MATLAB code for Figure 57.

```
function createfigure1(X1, YMatrix1)
%CREATEFIGURE1(X1, YMATRIX1)
%  X1:  vector of x data
%  YMATRIX1:  matrix of y data

%  Auto-generated by MATLAB on 16-Jun-2016 20:26:22
```

```
% Create figure
figure1 = figure;

% Create axes
axes1 = axes('Parent',figure1,...
    'YTick',[0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.75 0.8 0.85 0.9 0.95 0.9999],...
    'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18]);
grid(axes1,'on');
hold(axes1,'all');

% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'Parent',axes1,'LineWidth',2);
set(plot1(1),'MarkerSize',4,'Color',[0.847058823529412 0.16078431372549 0],...
    'DisplayName','10e-1');
set(plot1(2),'Marker','+','LineStyle','--','Color',[0 1 0],...
    'DisplayName','10e-2');
set(plot1(3),'LineStyle',':','Color',[1 0 1],'DisplayName','10e-4');
set(plot1(4),'Color',[0 0 1],'DisplayName','10e-6');
set(plot1(5),'MarkerSize',4,'Marker','.','Color',[0 1 0],...
    'DisplayName','10e-8',...
    'LineWidth',0.5);
set(plot1(6),'Marker','+','LineStyle',':',...
    'Color',[0.0705882352941176 0.211764705882353 0.141176470588235],...
    'DisplayName','10e-10',...
    'LineWidth',0.5);
set(plot1(7),...
    'Color',[0.0705882352941176 0.211764705882353 0.141176470588235],...
    'DisplayName','10e-12');
set(plot1(8),'Color',[1 0 0],'DisplayName','10e-14');
set(plot1(9),'Color',[0 1 0],'DisplayName','10e-16');

% Create xlabel
xlabel('Single pulse SNR - dB');

% Create ylabel
ylabel('Probability of detection');

% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.152524038461539 0.605069330832633 0.0731523378582202
0.275825346112886]);
```