CHALMERS
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Radar Communication for Interference Reduction in Automotive Applications

Master's thesis in Communication Engineering

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

MASTER'S THESIS 2018:NN

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Master's Thesis 2018:NN
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Typeset in LaTeX
Printed by [Name of printing company]
Gothenburg, Sweden 2018

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Abstract

The increment in demand of transportation system leads to increase number of vehicles and hence traffic congestion and accidents also increase. Information sharing among vehicles is crucial in decreasing the accidents and it makes the transportation system safe and fast. Automotive radars are introduced to the driving system and uses for detection of other targets around. By considering the ability to extract both position and velocity of targets from reflected signals, we use FMCW radar. However, if more than one FMCW radars transmit at a time or within the vulnerable period, mutual interference of signals happen. Mutual interference causes to increase noise floor of the received signals and affects the detection system outcome. Hence mutual interference leads to increase both probability of mis-detection and the probability of ghost target detection. To mitigate the effect of signal interference, we use RadCom system that combines both features of radar and communication systems. Radar and communication signals are multiplexed in frequency and a separate frequency band is allocated for each system. The communication system uses to control the MAC by scheduling the time slots for radar signal transmissions. In addition, we CSMA for MAC control of the communication channel among different vehicles. Under CSMA, one-persistent with backoff and p-persistent without backoff are simulated and compared concerning the time required for communication contention. We use the probability of target mis-detection and probability of ghost target detection as performance measurement parameters.

Keywords: backoff, vulnerable period, RadCom, CSMA, chirp, FMCW, mutual interference.

Acknowledgements

I would like to thank my supervisor Dr.Canan Aydogdu at Chalmers University of Technology. It would be difficult to finish my thesis this time without her help and continuous follow up. I would like to thank my examiner Pr.Henk Wymeersch; he helps me throughout the thesis starting from finding the thesis, guidance and valuable comments. I also thank Swedish Institute (SI) for giving me a scholarship to study my master thesis at Chalmers. I also would like to say thank you to my family and friends for all round help and motivations.

Abebe Haftu Fitur, Gothenburg, October 2018

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1
Introduction

Human beings need a safe, comfortable, and fast transportation system. In order to satisfy these needs, there is progressive development in solving the emerging challenges. The main difficulties in transportation industry are accidents and traffic congestion [1, 2]. In order to make the transportation system fast enough, safe and environment-friendly extensive research and development are required [3, 4]. The mobility of people and goods increases, this leads to an increment in number of vehicles and hence causes traffic congestion, which in turn increases the occurrence of accidents [1]. To mitigate potential accidents, sharing traffic information among vehicles is essential and requires introduction of wireless communication systems for vehicular environments [5, 6]. Incorporating radar technology and wireless communication to transportation systems plays a crucial role in developing and satisfying the demand of modern transportation systems. In recent years radar technology is becoming a key feature of automotive industry in modern vehicular transportation systems [2, 7, 8]. Automotive radars are crucial in accident avoidance by giving alert and other relevant information to drivers. Previously, radar technology used for military, civil aircraft and marine navigation, now it standardized to be used in automotive industry [8].

1.1 Problem Description

Two or more radars transmitting at the same time and frequency results in signal interference among radar signals, which is called mutual interference. The increase in demand to use millimeter wave (mmWave) radars increase the probability of more than one radar being in transmission and hence the occurrence of mutual interference [9, 10]. Mutual interference of signals increases noise floor level and thus it leads to ghost target detection and decreases the probability of detection. Avoidance of mutual interference among radar signals is crucial for having a better object detection and estimation of both position and velocity of targets [10, 11, 12, 13].

Figure 1.1 depicts mutual interference of signals from four cars. The four vehicles transmit their signals and as is shown in the figure the signals interfere with each other. Hence a combination of reflected signal and interfering signals is received. Processing the combined signal gives a wrong detection outcome like ghost target detection and mis-detected targets. Having wrong detection outcomes means the vehicle exposed to a potential accident. Effect of ghost target and mis-detection of

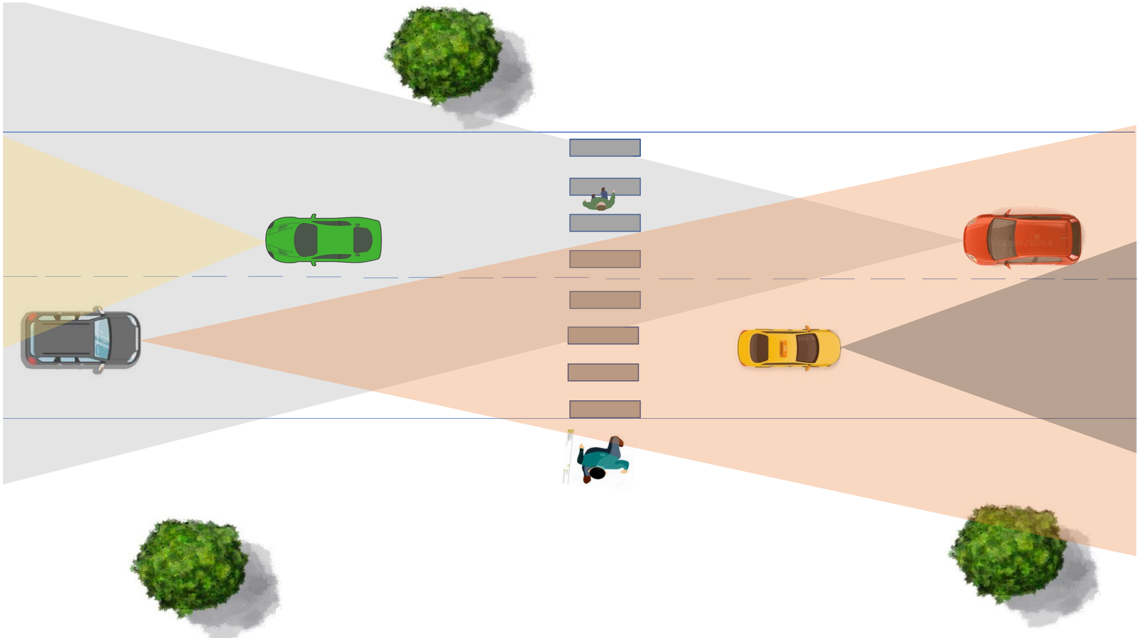

Figure 1.1: Mutual interference of signals from four cars with front side radars and including pedestrian line for passengers.

a target is even worse in autonomous driving.

Current automotive radars couldn't avoid mutual interference between signals. Combining communications systems and radar systems using the same hardware, radar communications (RadCom) can aid for avoidance of mutual interference. RadCom allows sharing of information among vehicles and can be used to create schedules for radar transmission time. Transmitting at different times avoid mutual interference and hence increases the probability of detection and decreases false alarm rate [2, 11, 14]. In reality, in a vehicular network, the number of vehicles and topology type varies very fast. Therefore, using time division multiple access (TDMA) and frequency division multiple access (FDMA) in communication systems is difficult. Both TDMA and FDMA depend on number of vehicles to share the available resource in between. The functionality of carrier sense multiple access (CSMA) is less dependent on the number of vehicles. It instead works by channel sensing. However, for p-persistent CSMA number of vehicles is still required to determine the cut off probability value.

1.2 Related Works

Frequency modulated continuous wave (FMCW) radar is one type of radar technology applied in modern vehicles. FMCW radar became popular in contemporary transportation because of its ability to extract both position and velocity of a target[9]. Radar altimeter means radar used to measure the exact height of airplanes, especially during landing [15]. Starting from mid-1930 FMCW radar was used for radar altimeter functionality. FMCW radar has many design advantages, capability for short ranges estimation and low average power ratio requirement than other radar systems. The main drawback of FMCW radar is antenna coupling. Transmit and receive antenna coupling limit the dynamic range of radar systems [16].

Interference primarily affects receiver noise floor, and as a result, it masks the reflected signal if it is combined with low receiver power [17]. While one FMCW radar transmitting and other FMCW radars also transmit at overlapping time and frequency or within vulnerable period mutual interference happens [11]. Besides mutual interference, interference can happen also from other incumbent frequency users like surveillance radars. By considering the interference impact, different countermeasures are proposed to mitigate it. The countermeasures are categorized as polarization, time, frequency, coding, space and strategic [17]. One method of detecting the presence of interference is comparing signal slope with the determined threshold value. If the signal slope is less than the threshold, there is no interference detected and normal signal processing followed. However, if the signal slope is above the given threshold interference is discovered. The region identified with interference is marked and padded by zero or substituted by mean slope value to mitigate the interference effect. Weighting function could also be used to suppress the interference instead of zero padding [17, 18]. Another interference detection technique proposed is comparing the threshold with voltage variation in two samples in a row instead of taking signal slope. Once the interference detected the mitigation technique is using zero padding [17, 19]. However, both techniques are effective for strong short duration interference, they are not applicable for long duration interference like interference stayed for the whole chirp time.

Dedicated Short Range Communication (DSRC) defined for short to medium range communication systems that can support public safety using vehicle to vehicle (V2V) communication [20]. The problem is spectrum scarcity in 5.9 GHz band of DSRC [21]. The commonly used multiplexing technique for resource sharing among radar system and communication system is orthogonal frequency division multiplexing (OFDM). The available spectrum is divided to both radar and communication, separately allocated both bandwidth and carrier frequency for radar and communication purpose [11, 22, 2, 23].

1.3 Contributions

The task is to combine the future of radar technology and communications systems and to mitigate interference from multiple vehicles. Both systems, radar and communication systems, work collaboratively for a better detection system with better safety systems. FMCW radar is set to use for radar side for object detection. One persistent CSMA with backoff and P-persistent CSMA without backoff are deployed for a communications system and we compare their respective performance. By identifying the vulnerable period that leads to having mutual interference, the thesis uses

RadCom system to avoid from transmitting more than one FMCW radar at a time or within the vulnerable period. The communication system schedules radar signals, and it is vital in mitigating mutual interference among radar signals. Hence the thesis contributes by analyzing and mitigating interference of signals that is a useful input for autonomous driving with a better safety. The thesis also applied radar time division multiple access (rTDMA) approaches to share the available resources in between the FMCW radars. Besides that radar and communication systems multiplexed using frequency division multiplexing (FDM).

We show that how RadCom mitigates effect of mutual interference from multiple vehicles environment. Results from RadCom compared to radar only systems, they have higher probability of detection and lower false alarm rate. We also show that how the selection of reasonable threshold value is important is maximizing object detection probability while keeping false alarm rate low.

1.4 Thesis Outline

Chapter two gives an overview of necessary background including FMCW radar systems (transmitter and receiver), estimation process for range and velocity of target objects, vehicle to vehicle communication systems and the joint RadCom system of radar and communications. Chapter three dictates implementation of RadCom system model, analysis of mutual interference, vulnerable period, parameters that affect vulnerable period, probability of interference, RadCom, multiplexing of radar and communication systems, CSMA with backoff and without backoff are discussed in this chapter. Chapter four includes simulations results and discussion on the simulations results. A probability of detection, probability of mis-detection and false alarm rate, including a comparison between 1-persistent CSMA with back off and p-persistent CSMA without back off concerning time needed for communication contentions.

2

Background Theory

2.1 Radar Basics

In a Radio Detecting and Ranging (Radar) system, a transmitted electromagnetic energy pulse is reflected from object and a small portion of the transmitted pulse is received. Once part of the transmitted signal is received, it follows some necessary signal processing to determine the required radar parameters. Mostly the required parameters are distance and relative velocity of objects. Radar can be categorized into two types, primary and secondary radars. For primary radars, the transmitted signal reflecting off the target and received back a small portion of it with the same frequency as it is transmitted. In primary radars, it is possible to know the distance of the target but can't get additional information about the object. Primary radars are also called non co-operative radars. For secondary radar, the targets must have a transponder (transmitter and receiver) that co-operate to make the transmitted signal coded with information of the target before it reflects. From secondary radar, it is possible to know additional information such as distance and identification code of the target [15, 24].

Depending on the technology used, radars are classified as pulse radar, surveillance, continuous wave (CW) radar and FMCW radar [15, 24]. CW radar transmits continuous wave with constant frequency and it uses the Doppler effect to measure relative speed of the target. In CW radars since the transmitted signal is with constant frequency, they can't measure distance of the target [24]. Pulse radar transmits repetitive short and powerful pulses for object detection. It measures object distance measured by runtime difference or comparison of characteristics change of Doppler spectrum. The leading edge of the transmitted pulse is the reference for runtime measurement. In most cases, pulse radar is used for long distance located object detection and requires high transmitter power. Usually, when radar is used with no description, it refers to pulse radar [15, 24]. For general radar systems like pulse radar, distance is calculated by considering the time taken for a round-trip of the transmitted signal. The formula used for distance calculation in pulse radars is given

$$R = \frac{c\Delta t}{2} \tag{2.1}$$

where Δt is the time taken for a round trip of the transmitted signal and c is the speed of light.

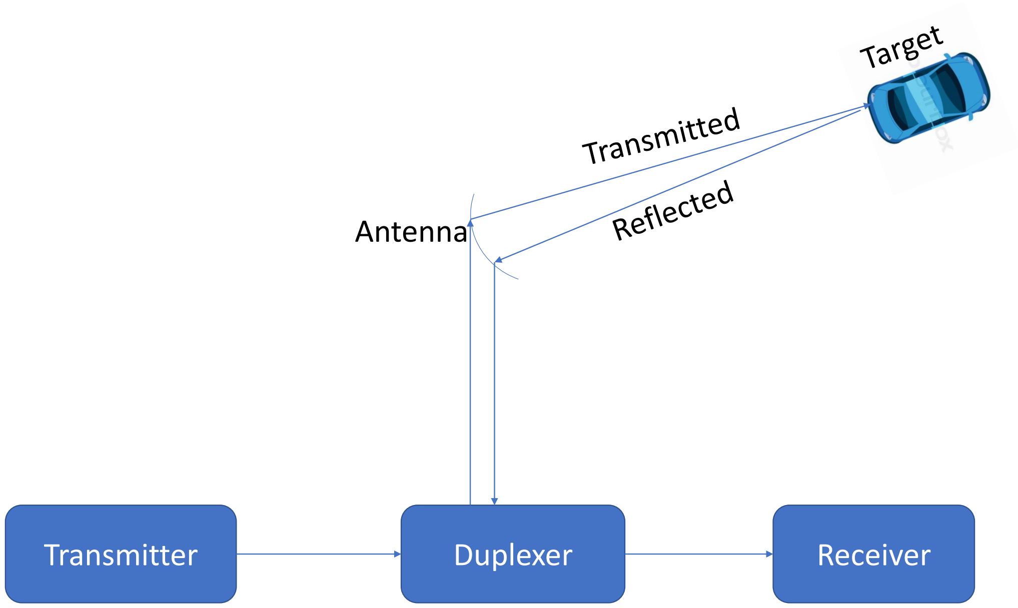

Figure 2.1: General simplified block diagram of radar systems.

The general simplified block diagram of radar system is given in figure 2.1. The transmitter produces pulses or chirps depending on the radar technology that is going to transmit. Duplexer uses to switch antenna alternatively between transmitter and receiver. The switching is necessary to protect the receiver from being affected by the high power transmitted signal [24]. The receiver demodulates, amplifies and processes the received signal to extract the desired information. The antenna is responsible for both transmitting and receiving signals.

FMCW radar transmits frequency modulated continuous ramp signals. The ramp signal frequency varies with time and is useful to estimate the range and relative velocity of the target [25]. FMCW radar is similar to CW radars. However, FMCW radar changes the operating frequency with time unlike CW radar. FMCW radar can determine short distance, extracting of both range and relative velocity of objects with high accuracy [24].

2.1.1 FMCW Transmitter

In FMCW radar, we have different frequency modulation techniques or waveform. The commonly known modulations schemes are [24]:

- Sawtooth waveform: This modulation scheme is used for longer range detection and it has negligible influence of Doppler frequency in distance estimation.
- Triangular waveform: The average frequency difference in both rising and falling edge of signal Δf is used to determine distance of objects. Its drawback is for the case of having many reflections the measured Doppler frequencies can't uniquely associate with targets and hence this wrong assignment can lead to ghost target detections.
- Square-wave waveform: This modulation type uses for a short range and pre-

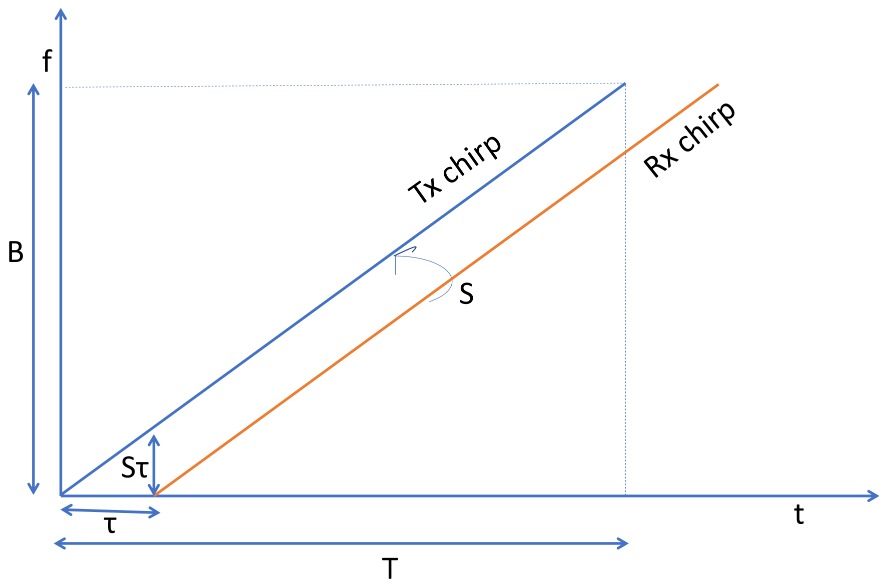

Figure 2.2: Sawtooth modulated chirp with frequency versus time plot.

cise range estimations by comparing the phase difference of two reflections. The problem with this modulation scheme is reflections from different objects cannot separate from each other and this creates confusion on the estimated range.

- Stepped waveform (Staircase voltage): It has the same positive and negative sides with square-wave modulation scheme. This scheme used to expand the unambiguous of the measured range.

In this thesis, FMCW radar with a sawtooth modulation scheme types are used due to their ability to estimate long-range distance. A sawtooth modulated chirp is given in figure 2.2. In object detection systems, we have parameters that indicate if the system is good enough for the designed purpose. For autonomous driving, some of the parameters are like range resolution, velocity resolution, maximum detectable range, and maximum detectable velocity. The parameters mainly depend on how we choose values of chirp bandwidth B, chirp time T, chirp slope, sampling frequency and carrier frequency [26].For FMCW radar system, the maximum detectable distance depends on sampling frequency and slope of the transmitted frequency modulated chirp. We can understand the longer chirp time leads to have maximum detectable distance. The maximum detectable distance for FMCW radar is given

$$d_{max} = \frac{cf_s}{2S} \tag{2.2}$$

where c is speed of light and S is slope of the designed chirp and it is the ratio of chirp bandwidth and chirp time $S = B/T$. Besides this the round trip time for the chirp is shown in figure 2.2. The round trip time is given by

$$R_{trip} = \frac{2d}{c} \tag{2.3}$$

where d is distance of the object.

Another required parameter for autonomous driving is range resolution. Range resolution in a sense it is the minimum distance between two objects that can precisely be detected and estimated. Range resolution depends on chirp bandwidth. FMCW transmitter with larger chirp bandwidth has a better range resolution [27, 26]. The range resolution for FMCW radars is given

$$\Delta R = \frac{c}{2B} \tag{2.4}$$

Other parameters to consider in autonomous driving are the maximum detectable relative velocity and velocity resolution. A system to be regarded as a good enough detection system, it should have a reasonable velocity resolution and high maximum detectable relative velocity. So, the designed FMCW radar should be able to detect higher relative velocity among objects. Especially during objects moving in the opposite direction with the radar, the relative velocity could be high. The used carrier frequency and chirp time are the control values for maximum detectable relative velocity. The maximum detectable velocity is given by

$$v_{max} = \frac{\lambda}{4T} \tag{2.5}$$

where λ is a wavelength. What we can see from this equation is a shorter chirp time lead to a lower maximum detectable velocity of the FMCW radar system [27, 26].

Velocity resolution measures how the detection system detects more than one closer velocities. The designed FMCW radar should precisely detect velocities of objects moving in close speed. For FMCW radars, the velocity resolution is given in equation 2.6. If the FMCW radar transmitter is with a longer frame time T_f, then we have a better velocity resolution [26].

$$\Delta v = \frac{\lambda}{2T_f} \tag{2.6}$$

Where T_f is frame time, that includes chirps time and times uses for signal processing.

What we can observe from equation (2.2) – (2.6) is that there is a tradeoff in selection of chirp bandwidth and chirp time. Chirp bandwidth has a different effect on maximum detectable velocity and range resolution. Large chirp bandwidth leads to a better range resolution and low maximum detectable distance. Similarly chirp time has a different effect in maximum detectable relative velocity, maximum detectable distance, and velocity resolution. Having a longer chirp time means having a

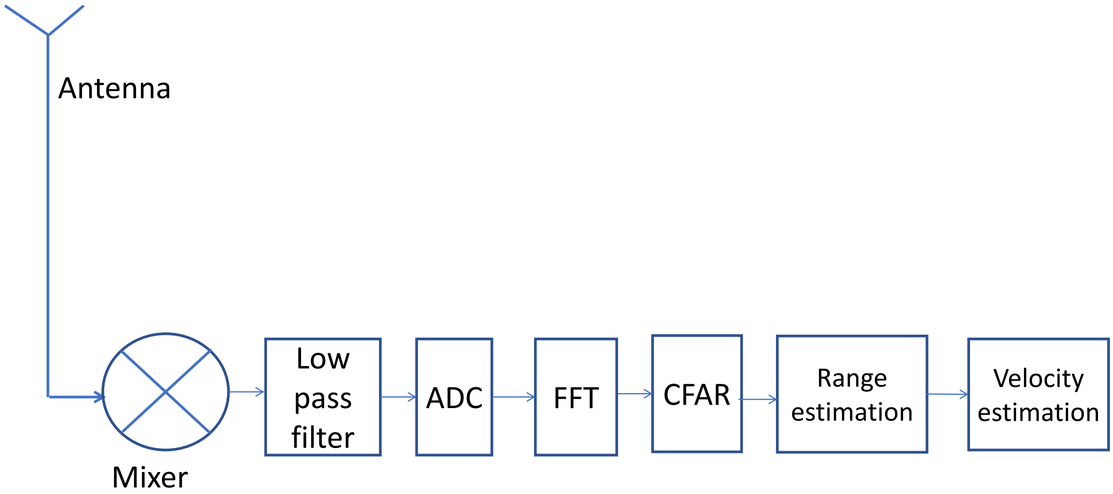

Figure 2.3: General receiver block diagram fro FMCW radars.

good velocity resolution, more extended maximum detectable range, and lower maximum detectable relative velocity in our detection system. So, there is a tradeoff in choosing chirp time depending on which one is most important: velocity resolution or maximum detectable velocity. One way for keeping both velocity resolution and maximum detectable relative velocity optimum is using shorter chirp time but many of chirps resulting longer frame times [26, 27].

2.1.2 FMCW Receiver

The FMCW radar receiver process the received signal to extract the desired pieces of information about objects. Figure 2.3 depicts basic blocks of FMCW radars receiver activities.

2.1.2.1 Mixer

In FMCW radar, the received reflected frequency modulated signal is fed to a mixer with a copy of the transmitted signal as shown in figure 2.4. The mixer output signal contains multiple harmonics. The signal harmonics correspond to the time difference between the transmitted signal and received signal. The frequency of the mixer output signal is the instantaneous frequency difference between the copy of frequency modulated transmitted chirps and received reflected signals. This frequency difference or intermediate frequency (IF) is called beat frequency. The beat frequency is useful for range estimation of the object that reflected the signal [28, 29, 30, 26, 31].

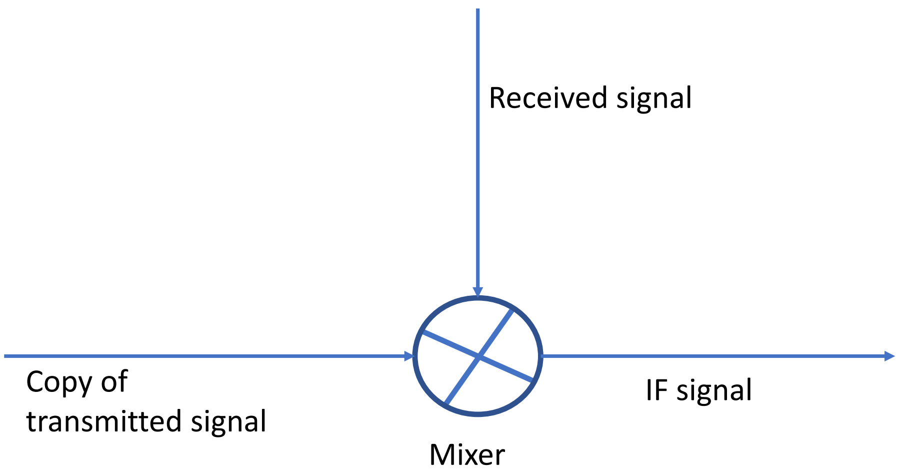

Figure 2.4: Copy of transmitted and signal and received signal feeding to mixer.

2.1.2.2 Low pass filter

The signal from the mixer passes through a low pass filter and make it ready for the decimation process and analog to digital converter (ADC). As the object distance increases, the correspondent IF frequency also increases. An object located at a maximum detectable distance creates a maximum IF frequency. So, a cut-off value for the low pass filter should be the IF frequency that can be produced by maximum detectable distance. After low pass filtering the signal frequency is less than the IF frequency generated by the maximum detectable distance [26].

2.1.2.3 Decimation

Once the IF signal passes through low pass filter, decimation and ADC converter follow before further digital signal processing. The signal after a process of low pass filter and decimation becomes a digital signal. As we can understand from equation 2.2, the sampling frequency is depending on the slope of the frequency modulated chirp and maximum detectable distance. Generally this sampling frequency is hardware limited in automotive radars, which limits in turn the maximum detectable range.

2.1.2.4 Fast Fourier Transform

Once the signal is digitized, fast Fourier transform (FFT) is applied to estimate the range and velocity of the targets. Two dimensional FFT (2D-FFT) is used to estimate both distance and relative velocity of the objects. 2D-FFT signal processing also called range FFT and Doppler FFT [31, 29, 25, 32]. Range FFT and Doppler FFT are used for range estimation and velocity estimation respectively. Range FFT performed first and Doppler FFT followed on the output of the range FFT

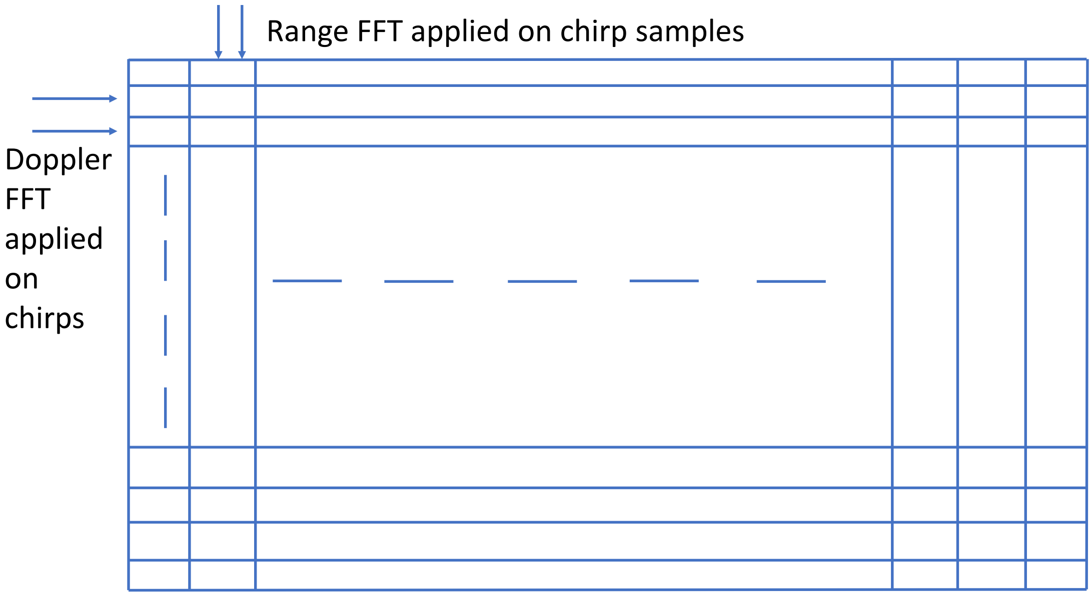

Figure 2.5: Structure of the digitized signal and how two dimensional FFT performs. Range FFT held on column wise for the chirp samples and Doppler FFT held row-wise for the reflected chirps.

[26, 29, 25, 32]. The digitized signal is set in a matrix form as is shown in figure 2.5 [25]. The column of the matrix represents the index of the frequency modulated chirps and the row is for the samples of each chirp.

2.1.2.5 CFAR

The signal out from range FFT is with different amplitude and peaks. The spikes are corresponding to the distance of objects. Constant false alarm rate (CFAR) detection is used to determine index of the peak locations [33, 34, 29, 32, 35]. CFAR estimates the noise power of a signal from the specified training cells using one of the CFAR detector algorithms. The common CFAR detection algorithms are cell average CFAR (CA-CFAR), greatest of cell averaging CFAR, smallest of cell averaging and order statistics CFAR (OS-CFAR). Greatest cell averaging CFAR works by selecting the larger average out of the training cells average and rear it in the training cells. Hence the bigger cell average used to compare with threshold and this algorithm is implemented in the thesis. Figure 2.6, depict how greatest CFAR work based on the signal strength of the selected training cells. To avoid ghost target detection, we use the intersection from CFAR detection and peaks these can be found using MATLAB command *findpeak* and that given by the star in the figure. CA-CFAR still, further divided to And-CFAR and Or-CFAR detectors. In AND-FAR, if the amplitude of the signal is above than both CA-CFAR threshold and OS-CFAR threshold, then there is a target detected at that index otherwise not. Similarly for Or-CFAR, if the amplitude of the signals is above than either of the CA-FAR threshold or OS-CFAR threshold, then that target is detected otherwise no target detected [35, 36, 37].

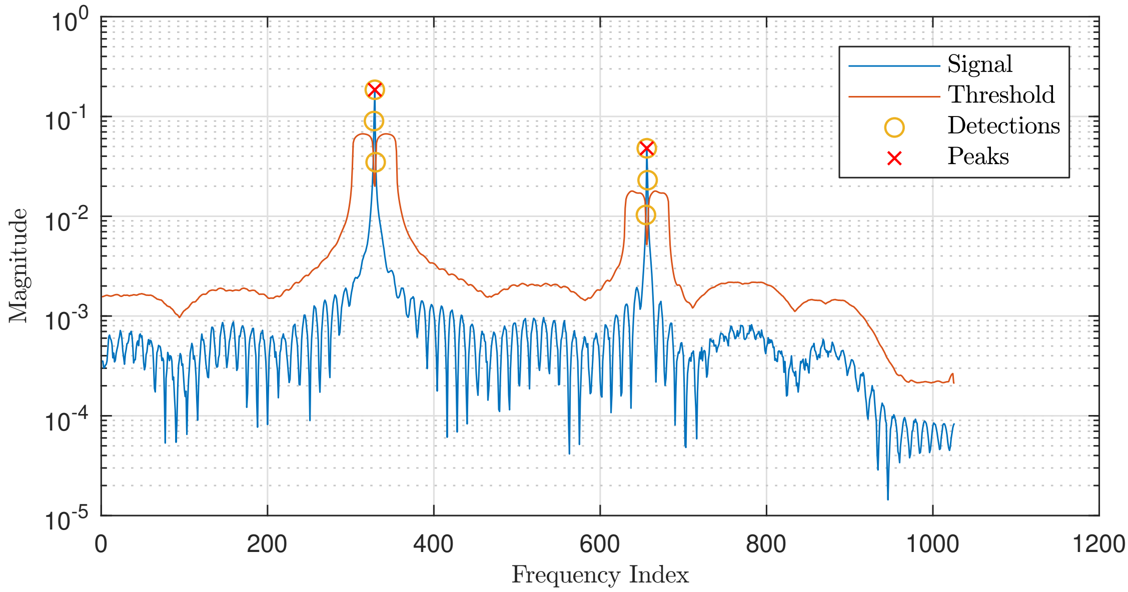

Figure 2.6: CFAR detection using 10dB threshold on out of the range FFT. We have two targets at 50m and 100m from the FMCW radar.

2.1.2.6 Range Estimation

In object detection, the first thing to be considered is distance of the object. In autonomous driving, vehicles should learn how many other vehicles are around, how far they are and their perspective direction. Mixing up a reflected signal with the copy of the transmitted signal gives IF signal. A single object that reflects the transmitted signal produces single tone in IF signal as shown in figure 2.7b. The IF signal also contains phase changes among the consecutive chirps. Applying Fourier transform on this IF signal produces a single peak in IF spectrum as shown in figure 2.8.

For having more than one close objects, there will be multiple reflections as shown in figure 2.7c. As a result, different tones appear in IF signal. Figure 2.7d depicts the generation of various tones in IF signal from different reflections. Besides that multiple peaks also appear in the IF spectrum as shown in figure 2.9. The frequency of these peaks is directly proportional to an object distance. The lower frequency in IF signal corresponds to a shorter distance and longer distance corresponds to larger IF frequency [26, 31, 29, 25, 32].

If more than one object located at the same distance from the FMCW radar, the reflections from all of them arrive at the same time. Range FFT gives only a single peak on the IF spectrum [26, 29]. At this time, the FMCW radars assume only one object is available at that distance, which is not true. To solve this gap, an FFT across the phase difference of the reflected chirps is necessary. This FFT across the second dimension is called Doppler FFT and it is required to find different velocity objects at the same distance.

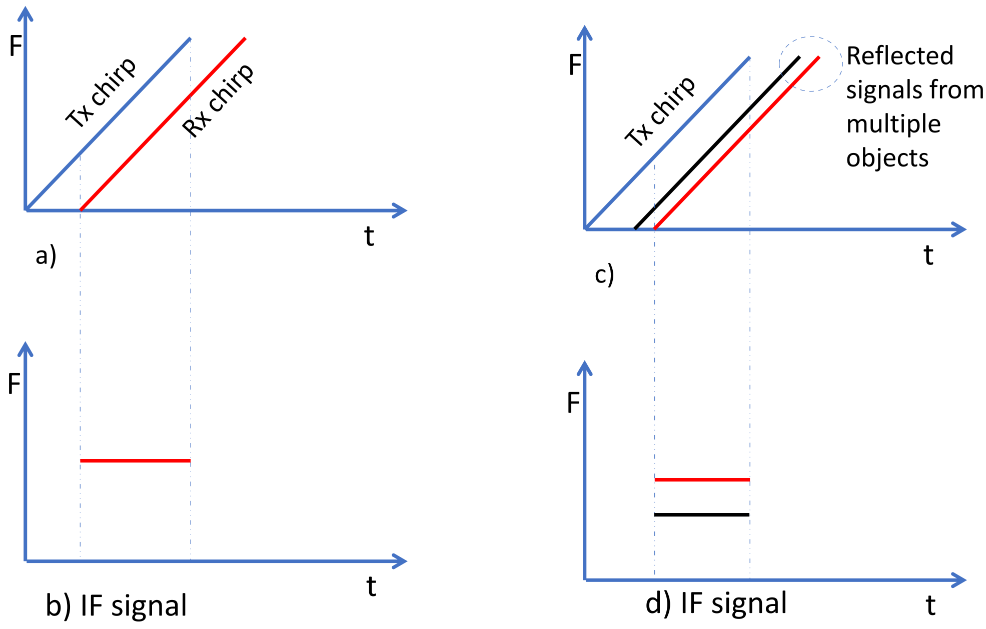

Figure 2.7: IF signal and IF frequency spectrum of received signal in dB from one and two reflections.

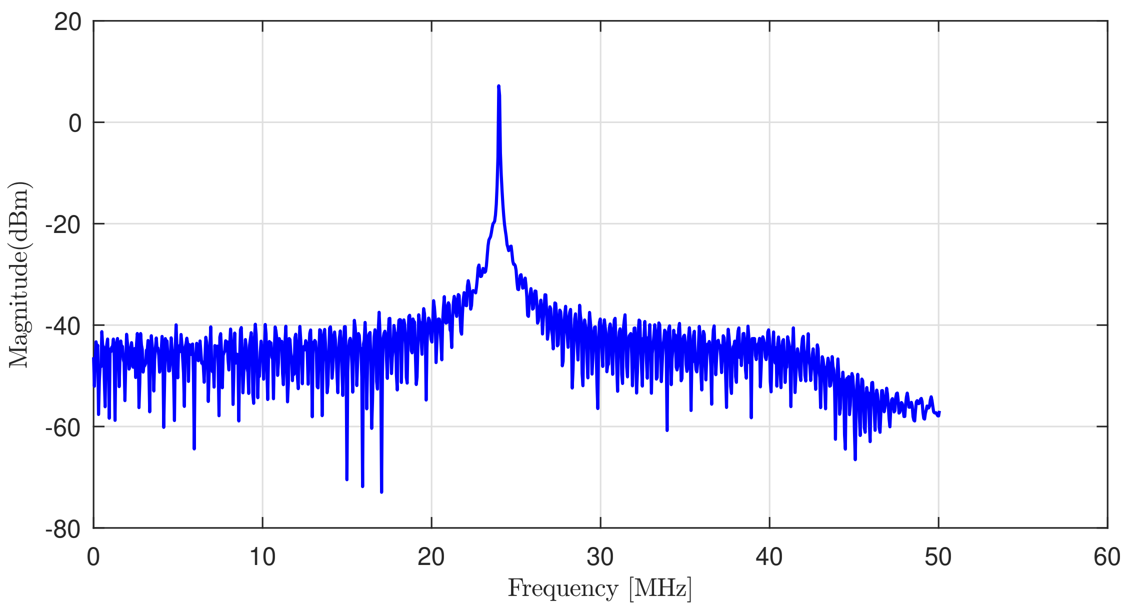

Figure 2.8: If spectrum of received signal in dB from one reflection.

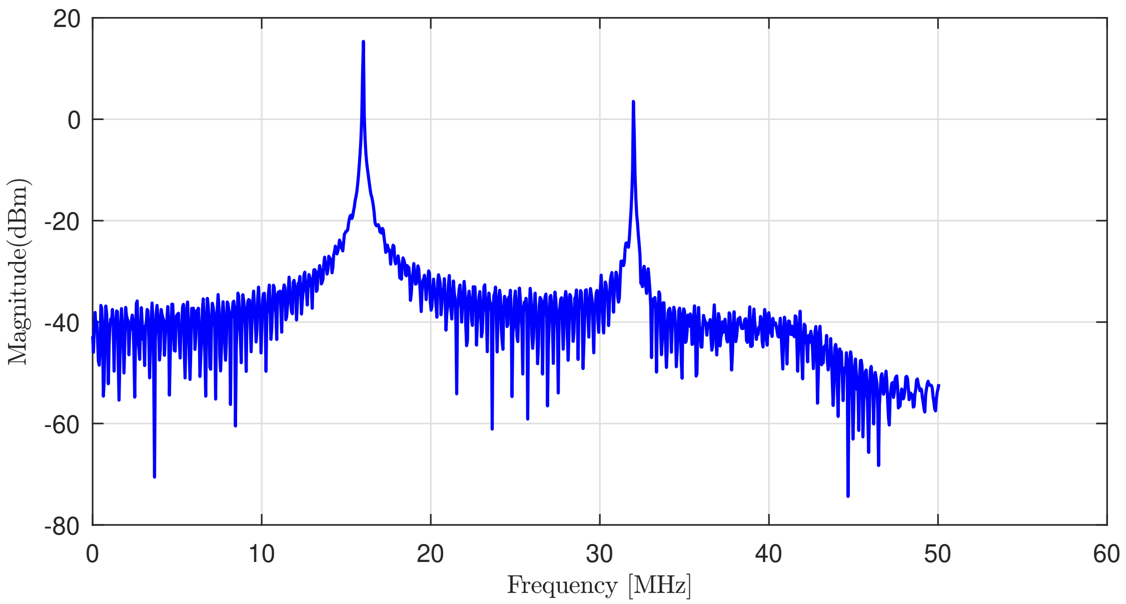

Figure 2.9: If spectrum of received signal in dB from two reflections.

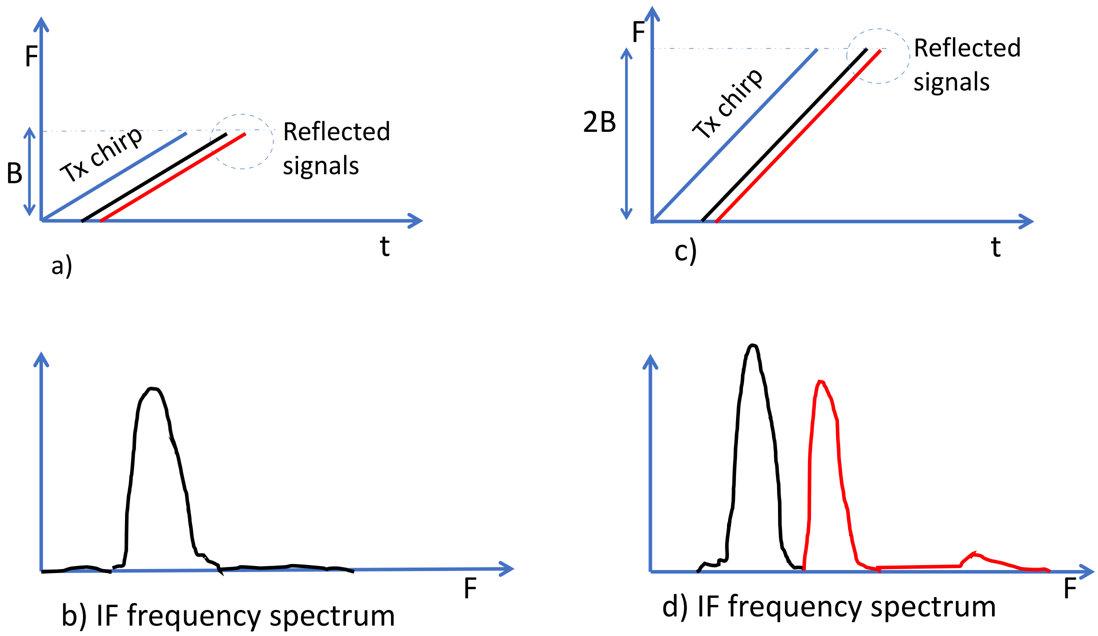

Figure 2.10: Importance of bandwidth in determining range resolution.

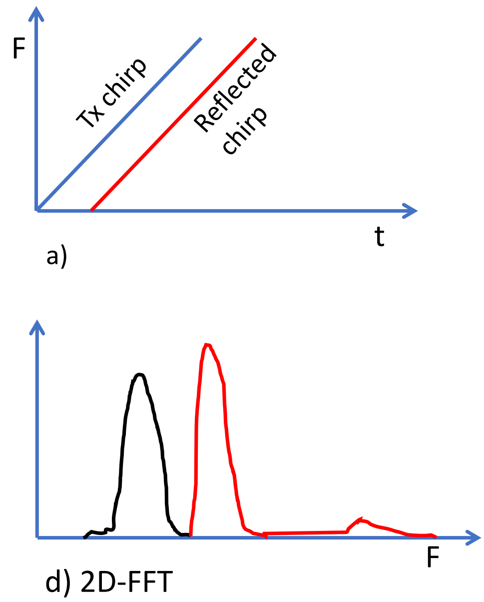

Figure 2.11: Resolving two objects located at the same distance but have different velocity using 2D-FFT.

Figure 2.10 depicts effect of bandwidth in range resolution like it introduced in equation 2.4. Figures 2.10a and 2.10b dictates two closely spaced objects cannot resolve using bandwidth B and they appear as one object in the IF spectrum. If we make the bandwidth double, the objects resolved and appear as two objects as is given in figures 2.10c and 2.10d.

2.1.2.7 Velocity Estimation

After the FMCW radar determines the number of objects around with their respective distance, the next parameter to find is the relative velocity of objects. For FMCW radar, one way of determining targets relative velocity is 2D-FFT. From the range estimation, we need to bear as range FFT held across the column of the IF signal. Doppler FFT performed across a row of the IF signal, like it shown in figure 2.5. Doppler FFT dedicated to relative velocity estimation of objects. The measured phase difference across the frequency modulated chirps corresponds to the motion of the objects. Doppler FFT uses these changes to estimate relative velocity of objects. A small motion of objects can produce a change in phase of IF signal but not in IF signal frequency. The phase of the object is very sensitive to small change in position of the objects. Doppler FFT produces peaks that correspond to angular frequency and the angular frequency corresponds to the relative velocity of objects. So, Doppler FFT provides peaks for each relative velocities [26, 31, 29, 25].

In the case of having two or more objects located at the same distance away from the FMCW radar but with different relative velocities, the range FFT gives only a single peak that correspondent distance. However, by applying Doppler FFT, we can determine the number of objects exists in that distance as shown in figure 2.11.

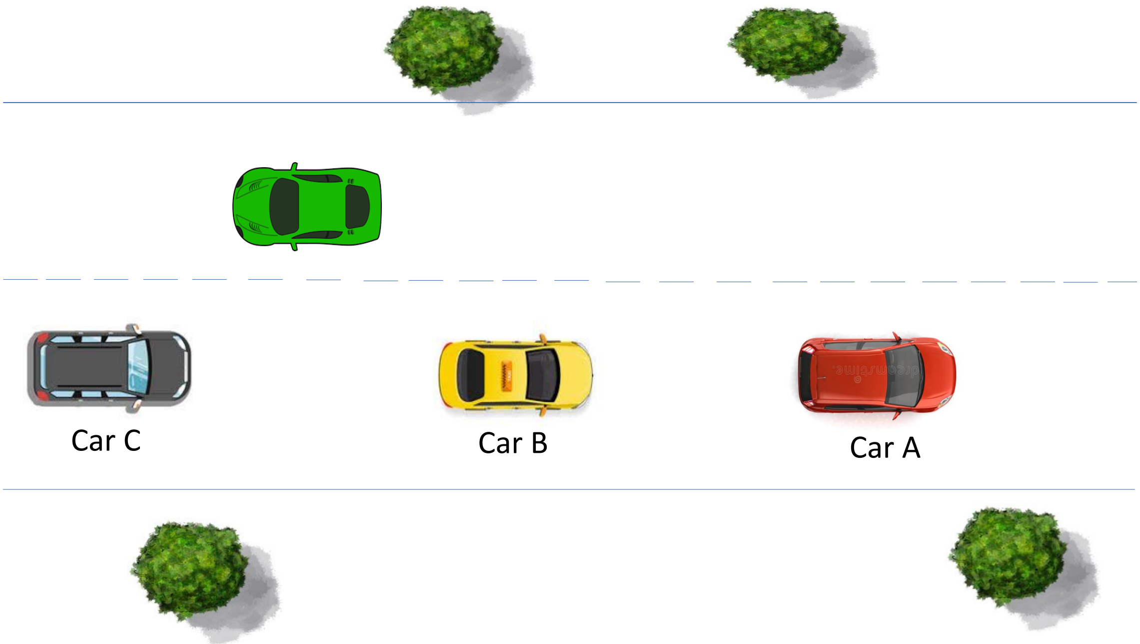

Figure 2.12: Network of four cars and three of them are in the same lane.

The Doppler FFT produces two peaks from single reflection.

What about two more objects located at the same distance and relative velocity but different locations? Both range FFT and Doppler FFT produce only a single peak. The angle of arrival for reflections is required. Multiple antennas are necessary to consider the perspective of entry for reflections. By examining the angle of arrival of the reflections, the number of objects can be determined. Many antennas provide a better angle resolution [26].

2.2 V2V Communication Basics

DSRC defines from short to medium range communication systems that can support public safety using V2V communication [20]. Let us consider we have three cars A, B and C and all moving on the same lane to the same direction as shown in figure 2.12. If car A suddenly brakes, since there is no line of sight between car A and car C, car C cannot be aware of it until car B brakes. Using V2V communication, Car A sends a wireless message about the thing that happened hence both car B and car C can take appropriate action to avoid the potential accident that would happen. However, wireless communication is unreliable due to packet collisions, channel fading and obstacles, etc [20].

In order to avoid packet collision during wireless communication, a rule on how to divide the shared channel in a fair and predictable way in between the participating vehicles is required. Media medium access control (MAC) works on how to share the shared channel. Most of the applications in ITS require real-time communications. The standard that can support this real-time delivery is IEEE 802p.11p. IEEE

802p.11p is a standard for wireless access for the vehicular environment (WAVE) in DSRC based communications [5, 38, 39].

In a vehicular environment, the vehicular ad hoc network (VANET) is unstructured and fast changing in topology because of the high mobility of the vehicles. In VANET there is no central system for node coordination. Hence it is difficult to deploy a centralized MAC protocol like TDMA, FDMA and code division multiple access (CDMA). In VANET introducing a centralized system is not applicable because of the fast varying topology [5, 23].

The IEEE 80p.11p MAC protocol applies CSMA with backoff principle. In CSMA, the MAC protocol does not need a central system; simply vehicles sense the wireless channel before packet transmission. If the channel is idle, send the packet otherwise differ the communication and keep sensing the channel. The property of working without having central system helps to deploy CSMA in distributed networks [5].

2.3 Radar Communications (RadCom)

In 5.9 GHz band, spectrum scarcity is becoming an issue due to the rapidly increasing in development and demand in vehicular communication [40, 41, 42]. However, there is enough bandwidth allocated for automotive radars in 79 GHz frequency band. Therefore use the bandwidth in 79 GHz for RadCom and hence the bandwidth scarcity in 5.9 GHz gets relief and that bandwidth uses for other DSRC features [40].

Radcom uses the same hardware for both radar and communication systems [11, 43, 44]. Hardware reusing saves in cost and space needed for the coexistence of the two systems. The idea of hardware reusing is not a new concept, in the 1970's NASA used the same radio frequency (RF) hardware for both radar and communication systems [45]. A full duplex radar operation is required for the radar system to formulate the integration framework with the communication system. This new integration of radar and communications motivated by the recent developments of systems in mutual interference cancellation [43]. Both radar and communication can't solve the vehicular traffic congestion independently. So, their integration plays a great role in minimization of signal interference.

Recent developments on RadCom are focused on finding techniques to make the joint system functional, efficient and also how the two systems share the physical and network layer. Different methods have proposed for integrating the systems. One proposed technique for combining the two systems is using CDMA [45]. Another technique suggested by [46] is direct sequence spread spectrum (DSSS). The widely used multiplexing method for the joint system is applying OFDM waveforms [40, 47, 48, 49]. Radar and communication signals are multiplexed in frequency.

3

Interference Analysis

3.1 System Model

Figure 3.1 depicts a sequence of transmitted chirps, multiple reflections and processing time for received signals. Transmitted chirps are with blue color and reflected chirps are with black color. Besides this, frame time and processing time are given in the figure. Processing time is used to process the reflected signals to extract the required information. Frame time (T_f) includes the time needed for all transmitted chirps and signal processing time. Mathematical representation for frequency modulated chirp as a function of time is given by

$$c(t) = \exp(j2\pi(f_c + \frac{B}{T}t)t) \tag{3.1}$$

where t is time, f_c is carrier frequency, B is bandwidth and T is chirp time .

The transmitted signal is a sequence of chirps and hence the equivalent mathematical model for the combined transmitted signal is given by

$$s(t) = \sqrt{P_{\text{tx}}} \sum_{n=1}^{N} c(t - nT) \tag{3.2}$$

where P_{tx} is the transmitted power and N is the number of transmitted chirps.

Received power from free space propagation model is given by

$$P_{rx} = \frac{P_{tx} G_{\text{tx}} G_{\text{rx}} \lambda^2 d^{-2}}{(4\pi)^2} \tag{3.3}$$

where d is separation distance, G_{tx} and G_{rx} are transmitter and receiver gains respectively [24]. We consider disc model for this thesis. We assume vehicles reflect strong signal.

However, the reflected signal covers the distance twice for going and reflecting. Hence the received signal is further reduced by a factor of d^{-2} and the reduced received power is given by [11]

$$P_{rx} = \frac{P_{tx} G_{\text{tx}} G_{\text{rx}} \sigma \lambda^2 d^{-4}}{(4\pi)^2} \tag{3.4}$$

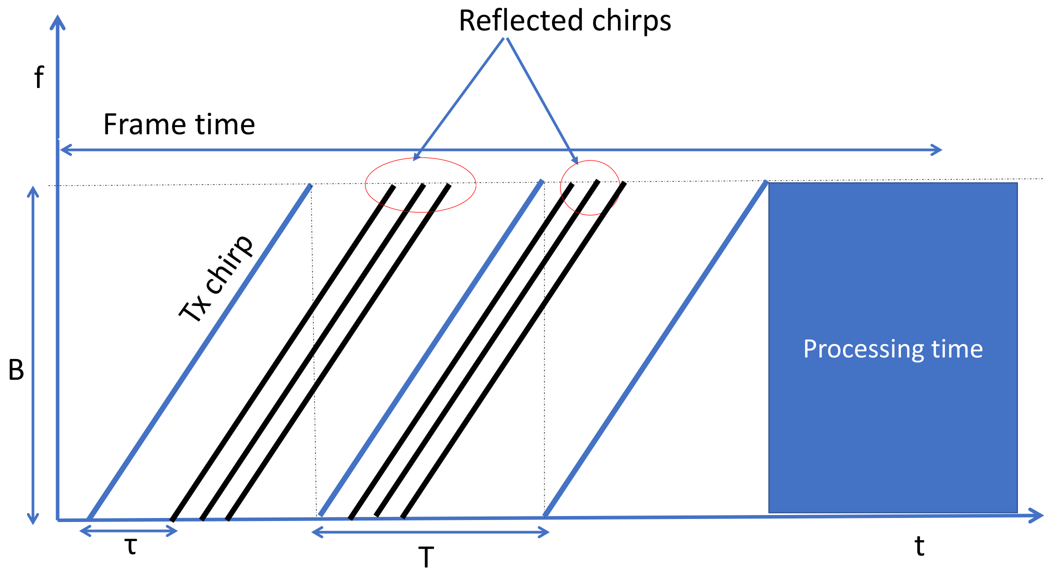

Figure 3.1: Frequency versus time FMCW chirp with reflected chirps from multiple targets.

where σ is a radar cross section area. A sample n of a received signal that reflected from a single target at the output of ADC converter given by

$$r_n = \sqrt{\gamma P_{\text{tx}} d^{-4}} \exp\left(j2\pi \frac{B(2d/c - 2\tau_D)}{T} nT_s\right) + w_n \tag{3.5}$$

where τ_D is a Doppler time shift, $\tau_D = Tvf_c/Bc$ and v is relative velocity, $\gamma = G_{\text{tx}}G_{\text{rx}}\lambda^2/(4\pi)^2$ and w_n is additive white Gaussian noise [11].
For the case of M targets located at a distance d_i, the received signal is a sum of M reflected signals. The n^{th} ADC sample of the M reflections is given by

$$r_n = \sum_{i=1}^{M} \sqrt{\gamma P_{\text{tx}} d_i^{-4}} \exp\left(j2\pi \frac{B(2d_i/c - 2\tau_{\text{Di}})}{T} nT_s\right) + w_n \tag{3.6}$$

Here, received signals which reflected more than once are ignored and also assume that line of sight (LOS) exists between ego vehicle and each target.

3.2 Mutual Interference Analysis

The mutual interference model from multiple targets is described. Besides this, vulnerable period is determined by considering different parameters and also probability of interference occurrence on chirp and frame level is described.

3.2.1 Mutual Interference Model

Let's consider; we have one interfering vehicle which has identical FMCW radar with ego vehicle. Both vehicles are approaching to each other and have a distance

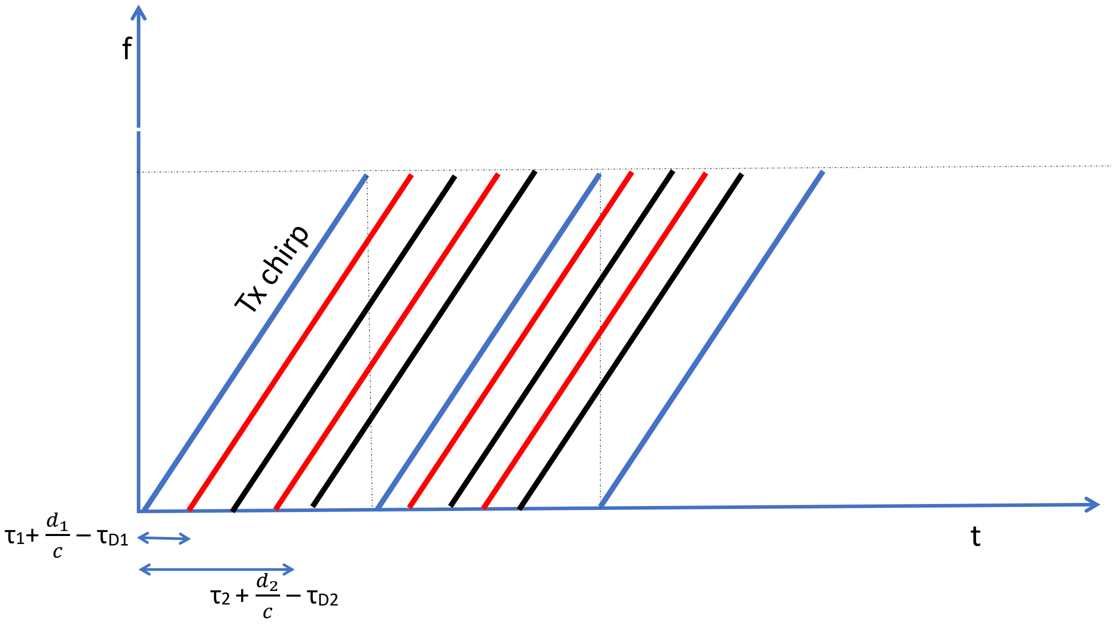

Figure 3.2: Reflected signals and mutual interference of signals from others around.

d in between and τ is the time delay for interfering FMCW radar before it start sending after the ego radar start transmission. Hence the interfering signal arrives a $\tau + d/c - \tau_D$ as shown in figure 3.2. A sample n of the received signals at the output of the ADC is given by

$$\tilde{r}_n = \begin{cases} r_n & \tau \notin V_p \\ r_n + \sqrt{\gamma P_{\text{tx}} d^{-2}} \exp\left(j2\pi \frac{B(\tau + d/c - \tau_D)}{T} nT_s\right) & \tau \in V_p \end{cases} \tag{3.7}$$

If τ is out of V_p the received signal remains unaffected by the interfering signal and hence (3.7) is reduced to (3.5). However, if τ is inside V_p, the received signal is sum of the reflected and interfering signals.

For the case of M interfering targets as shown in figure 3.2. Blue colored chirps are transmitted, black colored chirps are reflected and red colored chirps are interfering signals. The n^{th} sample of the received signal is given by

$$\tilde{r}_n = r_n + \sum_{\tau_i \in V_p} \sqrt{\gamma P_{\text{tx}} {d_i}^{-2}} \exp\left(j2\pi \frac{B(\tau_i + d_i/c - \tau_{\text{Di}})}{T} nT_s\right) \tag{3.8}$$

If none of the interfering radars transmits within the vulnerable period, the received signal remains unaffected and equation 3.8 gets reduced to equation 3.6. Otherwise, the received signal is the sum of reflections and interfering signals.

From equations (3.6) – (3.8), the reflected signal has a multiplier of d^{-4} and the interference signal has a multiplier factor of d^{-2}. Hence the interference signal is

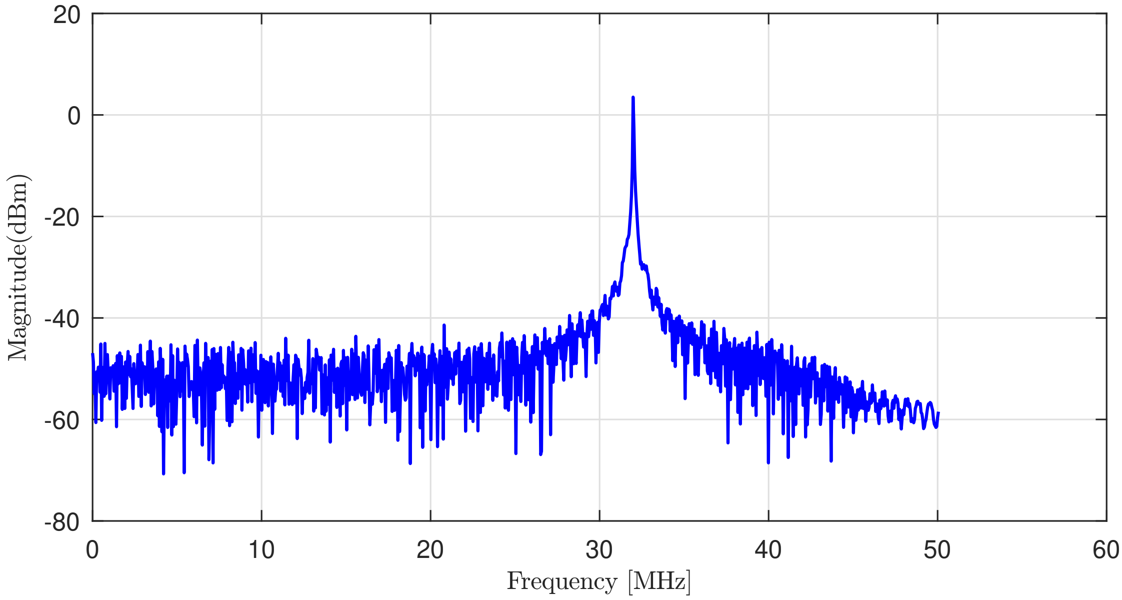

Figure 3.3: FFT of interference free received signal from a target located at a distance of $d = 100m$, $B = 1GHz$ and $T = 20\mu$s.

stronger than the reflected signal. The interference signal is dominant over the reflected signal. Hence this interference dominance affects the detection system and leads to ghost target detection and mis-detection of targets.

The time all interfering radars transmit out of vulnerable period, the reflected signal remains unaffected and hence the detection process is smooth. Figure 3.3 depicts FFT output of interference-free received signal reflected from a target located at 100m away. Since there is no interfering signal, the peak corresponds to the target is higher than the noise floor of the received signal and hence not challenging to select a threshold value for targets detection.

Figure 3.4 shows FFT of received signal containing interfering signal from a target located at $d = 100m$ and $\tau = 0s$. Both ego and interfering radar start transmitting at the same time. From the figure, reflected signal available at 33.3s MHz and the interfering signal at 16.67 MHz. Since the τ is zero, the interfering signal arrives within the vulnerable period. The transmitted signal covers a round trip and hence it covers 200m in total while the interfering signal covers half of it, which is only 100m. Hence the reflected signal is weaker than the interfering signal and as a result of that, the *ghost target* gets detected and depending on the selected threshold target mis-detection could also happen. Comparing both figure 3.3 and figure 3.4, the interfering signal boosts the noise floor of the received signal.

3.2.2 Vulnerable Period

From the previous discussions, avoiding transmission during the vulnerable period is essential for smooth target detection. It is vital to determine the vulnerable

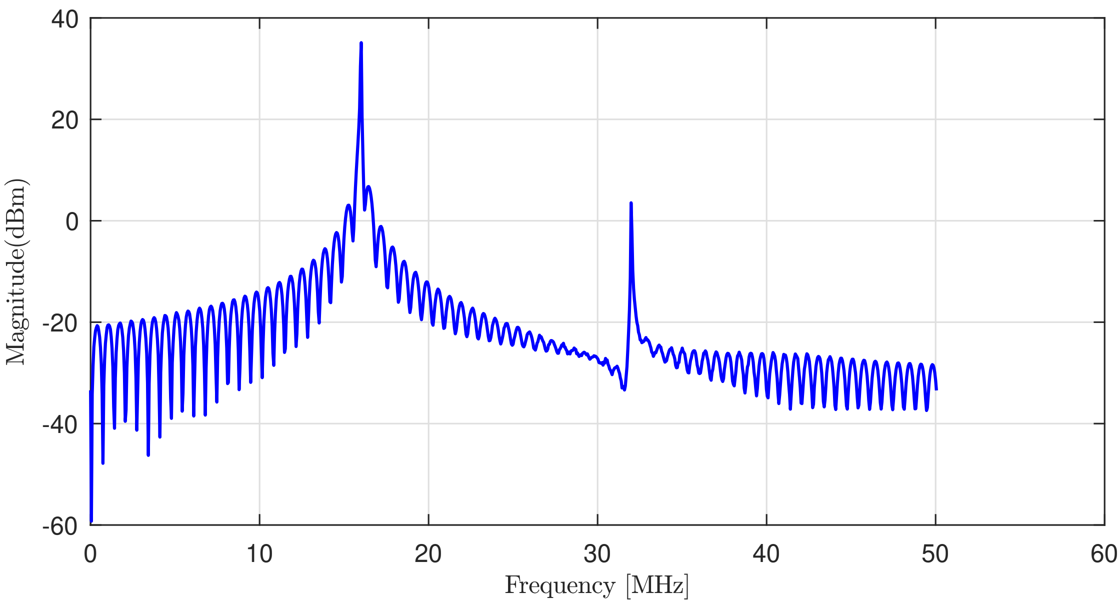

Figure 3.4: FFT of received signal containing interfering signal from a target located at a distance of $d = 100m$, $B = 1GHz$, $T = 20\mu s$ and $\tau = 0s$.

period by considering all the possible parameters cause to extend its interval. The vulnerable period parameters are propagation delay, Doppler effect, imperfections of low pass filter and multipath reflections. Hence by incorporating effect of the parameters, V_p given by [11]

$$V_p = \left[-\frac{2d_{max}}{c} - \frac{T}{BT_s} - \frac{T\, v_{\max}\, f_c}{B\, c}, \frac{2d_{max}}{c} + \frac{T\, v_{\max}\, f_c}{B\, T}\right]. \tag{3.9}$$

where $d_{\max} = cT/(4BT_s)$ and $v_{\max} = c/(4Tf_c)$.

3.2.3 Probability of Interference

Considering the effect of signal interference on detection system, further analysis is essential. From the specified vulnerable period, the interference occurrence probability at chirp and frame level for both single and multiple interfering targets can be formulated.

3.2.3.1 Interference probability from a single target

Let consider we have only a single interfering target beside ego vehicle. The probability of interference at chirp and frame level is [11]:

- *Interference probability of single chirp*: Probability of interference for a single chirp is the ratio of vulnerable period and chirp duration $P_{\text{in}}^{(c)} = V_p/T$. The formulated probability of interference for a single chirp is given by

$$P_{\text{in}}^{(c)} \approx \frac{2}{BT_s} + \frac{1}{2BT} \tag{3.10}$$

- *Interference probability of frame:* Here we need to consider the time interval for the whole frame. Probability of frame interference is a ratio of vulnerable period times number chirps over the frame time $P_{\text{in}}^{(f)} = NV_p/T_f$. From the previous discussion, frame time includes time duration for all transmitted chirps and also time used for signal processing. Hence probability of frame interference is given by

$$P_{\text{in}}^{(f)} = \frac{P_{\text{in}}^{(c)} NT}{T_f} \tag{3.11}$$

The probability of interference could be higher if we consider all conditions expand the vulnerable period.

3.2.3.2 Interference probability from multiple targets

In this case, the probability of interference is determined in the same way as for a single interfering target but having many interference sources. Let's consider we have a network of M vehicles and the ego vehicle can receive an interference signal from any of them.

Let us recall a probability logic that probability summation of all possible cases is *one*. Keeping this probability logic in mind, the summation probability of with interference and interference free is *one*. The probability of interference free frame considering interfering target is $P_{\text{fr}}^{(f)} = 1 - P_{\text{in}}^{(f)}$. Hence for M interfering targets interference free frame is $P_{\text{fr}}^{(M)} = (1 - P_{\text{in}}^{(f)})^M$. Therefore, the probability of interference for M interfering targets is $P_{\text{in}}^{(M)} = 1 - P_{\text{fr}}^{(M)}$. Finally, by assuming all the interfering targets have the same probability, the Probability of interference frame level from M interfering targets is given by

$$P_{\text{in}}^{(M)} = 1 - (1 - P_{\text{in}}^{(f)})^M \tag{3.12}$$

In general, the probability of interference with multiple interfering targets, the average probability of interference shall be determined. For more general directed graph topology with $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is a vertex in the graph and $\mathcal{E}$ is an edge between the ego target and a vertex. The average probability of interference for multiple interfering targets is given by [11]

$$\bar{P_{\text{av}}} = \frac{1}{|\mathcal{V}|} \sum_{i \in \mathcal{V}} P_{\text{in}}^{(M_i)} \tag{3.13}$$

where M_i represents the number of edges between ego vehicle.

4

RadCom for Interference Reduction

We have seen the interference signal is stronger than the reflected signal due to the different distance coverage. Hence, it detects ghost target but it mis-detects the actual target. So, interference mitigation techniques are required. RadCom enhances the detection system by reducing mutual interference using radar and communication system features. RadCom introduces MAC control that let targets use the channel with a different time or frequency depending on the channel accessing technique in use. In RadCom systems, the important concepts are how to share the available resource among radar and communication systems. Besides this how radar signals multiplexed and how vehicles share the wireless channel during communication mode.

4.1 Multiplexing

Using a joint waveform for both radar and communication system multiplexing, multiplexing can be avoided. However, using the joint waveform instead of multiplexing is not suitable for automotive applications due to the limited capability of the available ADC converters. This limitation in capability of ADC converter does not support modulated FMCW signals with full communication systems since it leads to low data rates [11]. Hence multiplexing is required and we multiplexed the two systems in frequency.

Considering the drawback of using joint waveform in automotive applications, we use FDM. Multiplexing in frequency adds spectral flexibility and efficiency to the system. FDM divides the given bandwidth to both communication bandwidth (B_c) and radar bandwidth (B_r). In order to reuse the radar ADC converter for communication system, $B_c < 1/2T_s$. Hence we can use the same ADC for both signals.

4.2 Radar Medium Access Control

The goal is to reduce signal interference if possible to avoid it entirely. Considering all the FMCW radars use the same carrier frequency and other chirp design parameters and hence if more than one vehicles transmit at the same time or within the vulnerable period mutual interference is inevitable. Hence a rule should determine how the FMCW radars share the shared channel. The proposed solution is radar time division multiple access (rTDMA). The vehicles transmit their signal at different time slot and hence mutual interference can be avoided. Since the carrier frequency and bandwidth are constant and this helps in receiver design simplicity. In radar frequency division multiplexing (rFDMA), the carrier frequency and bandwidth in use could vary with time hence the receiver design and signal processing could be challenging comparing to rTDMA due to a narrow band in a congested vehicular network.

FMCW radars transmit at different time slots and the time slot width should at least size of the vulnerable period. This time division is crucial in mitigating the effect of mutual interference. The implemented communication system deals with time slots selection. After N consecutive chirps, there is one idle chirp at the end to avoid overlapping chirps that help in mitigating mutual interference. Besides that, the idle chirp helps in maximizing the number of possible targets without mutual interference [11]. The maximum possible number of targets ($M_{\max}$) share the channel without having mutual interference using rTDMA is at most $T/|V_p|$. Since the frame time includes signal processing time besides, the possible value of $M_{\max}$ can further increase. By considering a perfect RadCom system, the upper limit for $M_{\max}$ is given by

$$M_{\max} \leq \frac{T_f}{(N+1)|V_p|} \tag{4.1}$$

4.3 Communication Medium Access Control (cCSMA)

We understand communication is vital for mutual interference mitigation. Having a common understanding and information sharing is achieved using a dedicated communication system. The communication system uses a separate frequency band. A separate bandwidth is allocated for communication purpose. CSMA is proposed for accessing the shared communication channel. Since the number of vehicles varies fast in the vehicular network, CSMA is advantageous to use over TDMA and FDMA. Both TDMA and FDMA needs a central system for controlling but there is no central system in VANET.

Communication contention performs first before radar signal transmission. In the communication contention, vehicles broadcast communication packet that contains starting time for radar signal transmission. Once vehicles around receive the communication packet, they are aware of the occupied slots and they select other idle slots. Once, the communication contention successfully did radar signal transmission follows it. The rTDMA uses time slots determined during the communication contention. All vehicles are assumed to have the same clock and is crucial to make all vehicles clock synchronized. Clock synchronization can be achieved with the help

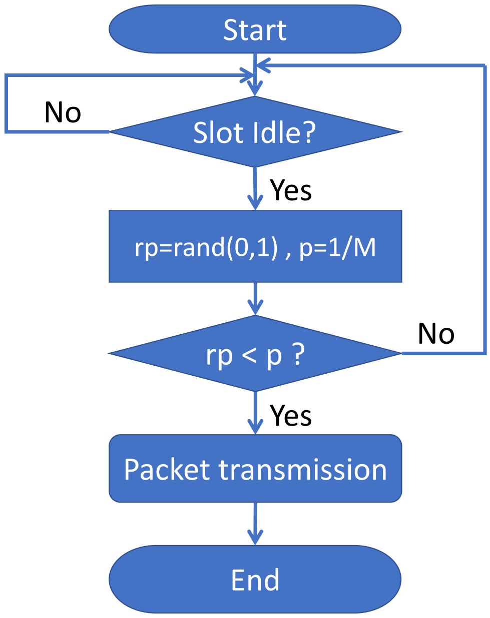

Figure 4.1: P-persistent CSMA without backoff flowchart.

of GPS systems.

Under a further division of cCSMA, there are two approaches, P-persistent CSMA without Backoff and one-persistent CSMA With Backoff. Both are discussed and compared. The backoff value is randomly generated and it indicates for how long the transmitter should wait before sending the communication packet. Backoff values varies from zero to contention window $(W_c - 1)$ size. Contention window is the maximum possible backoff value. In reality, due to the fast-changing number of vehicles, it is difficult to wait for an acknowledgment (ACK) of packet delivery. We didn't simulate ACK that determines successful packet delivery. To substitute ACK and avoid packet collision, we simulated backoff and p-persistent approaches instead.

4.3.1 P-Persistent CSMA Without Backoff

This approach works by determining the number of targets around and uses that to determine the cutoff probability value. The cutoff probability determines by $1/M$, where M is the number of interfering targets. In reality it is difficult to get the exact number of targets because of fast-changing topology and number of vehicles. It can use the recent number of detected targets or use the average number of recent detections. Another possible option is using machine learning that learns on how the number of targets vary.

Figure 4.1 depicts flowchart for P-persistent CSMA without backoff. The vehicle starts by sensing the channel if it is available for transmission or not. If the channel is busy, delay the transmission and keeps sensing until it gets it idle. If it gets the channel available for transmission, it generates a random number between zero and one $[0, 1]$. Compare the random number with $1/M$, if the random number

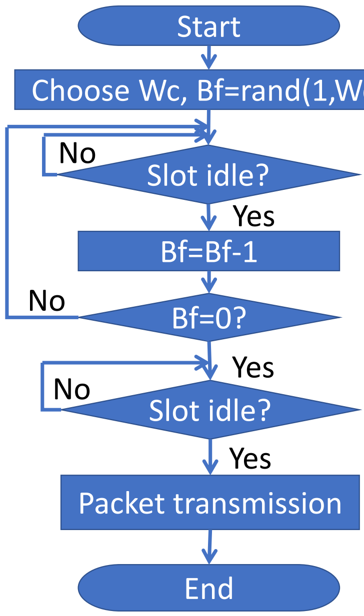

Figure 4.2: One-Persistent CSMA with backoff flowchart. Where $B-f$ is backoff and W_c is the contention window.

is less than $1/M$, the target broadcast the communication packet. However, if the randomly generated number is greater than $1/M$, the target back to channel sensing state and do the same steps again.

4.3.2 One-Persistent With Backoff

This approach uses a backoff algorithm instead of the probability requirement. For this algorithm the cutoff probability is always *one* that is why it is named one-persistent. In one-persistent CSMA, the contention window and backoff values determine the waiting time of communication packet transmission. For unsuccessful packet transmission, exponential backoff rule is applied. Exponential backoff rule is for each unsuccessful packet transmission contention window multiplied by 2^u until contention window reaches the maximum contention window size. Where u is the number of unsuccessful transmissions for that packet [5].

Figure 4.2 depicts flowchart of one-persistent CSMA with backoff. It starts by choosing contention window size and generation of backoff value. The target checks channel if it is available for transmission or not. If the channel is busy, the target keeps sensing until it gets idle. Once the channel is sensed idle, it decreases the backoff counter by one and back to the channel sensing state again. This process repeats until the backoff value becomes zero. When the backoff value becomes zero, the target checks the channel once more if the channel is still idle, transmit the communication packet. However, if it gets it busy, it keeps sensing until it becomes idle. Once the channel becomes idle, the target sends the communication packet automatically.

5

Results

This chapter discusses simulation results of the proposed approaches. The next two sections are about simulation parameters used and discussion on simulation results. In addition, it shows the comparison of results obtained from different methods with a help of simulation figures.

5.1 Simulation Parameters

Table 5.1: Radar simulation parameters

Parameter	Value
Chirp time (T)	20 μs
Frame duration (T_f)	20 ms
Time slots per frame	10
Radar bandwidth	0.96 GHz – 1 GHz
Maximum detectable distance (d_{max})	150 m
Maximum detectable velocity (v_{max})	140 km/h
Transmitter power (P_{tx})	1 Watt
Number of chirps (N)	99
Carrier frequency (f_c)	77 GHz
Sampling time (T_s)	0.01 μs
Chebyshev low-pass filter order	13
Thermal noise temperature	290 K
Receiver's noise figure	4.5 dB

Table 5.2: Communication simulation parameters.

Parameter	Value
Communication bandwidth B_c	40 MHz
Packet size	600 Bytes
Modulation scheme	16-QAM
MAC	p-persistent CSMA with $p = 1/M$
	1-persistent with backoff
Maximum contention window	6,12,24,48

The used simulation parameters for both radar and communication systems are summarized in tables 5.1 and 5.2 respectively. All FMCW radars use the same simulation parameters. The FMCW radar is designed to achieve $1m/s$ velocity resolution, $150m$ maximum detectable distance and $140km/h$ of maximum detectable relative velocity. Among the different chirp waveform, the FMCW radar uses frequency modulated chirps with a sawtooth waveform. The average FMCW radar cross section for a car is approximated to $20dBsm$ [50, 51]. Using (3.9) the vulnerable period is approximated to $V_p = 4\mu$s. The maximum possible number of FMCW radars that can be in transmission during a single chirp time without creating mutual signal interference is $T/V_p = 5$. Using equation 4.1 up to 50 Vehicles can transmit without creating mutual interference.

5.2 Simulation Results and Discussions

Performance of the simulated system is discussed with a simulation plot. The performance comparison parameters are probability of detection, probability of misdetection and a probability of ghost target detection. The plots are from radar only and RadCom systems using different simulation parameters. For CSMA, the time required for communication contention is the measure for performance comparison between one-persistent CSMA with backoff and p-persistent CSMA with backoff. It is also described regarding how the selection of threshold is essential for a detection system. Hence, figures are available to show how the choice of a threshold value affects the performance compassion parameters. The threshold in a sense that use to determine a cutoff value for the FFT output signal during CFAR detection, either it is an object or not and hence the term threshold is used in this sense throughout the report.

One of the performance measurement parameter is probability of mis-detection of targets that describes targets left undetected and it is given by

$$P_{md} = \frac{N_{nd}}{N_a} \tag{5.1}$$

where N_{nd} is number of not detected targets and N_a is the number of actual targets. The other performance measurement parameter that dictates about false alarm rate is probability of ghost target detection is given by

$$P_{gd} = \frac{N_{gd}}{N_t} \tag{5.2}$$

where N_{gd} is number of tests which ghost target detected and N_t is number of total tests.

Figure 5.1 depicts the probability of mis-detection for having ego target and four more interfering target using $10dB$ threshold. The interfering targets located at a distance of $37.5m, 75m, 112.5m$ and $150m$ from the reference ego target. In RadCom the probability of mis-detection is zero. All of the four targets are detected and the effect of mutual interference is successfully mitigated. The probability of mis-detection for RadCom system is obtained out of 200 tests. For radar only system, the time delay τ for the interfering target transmission vary from zero to chirp

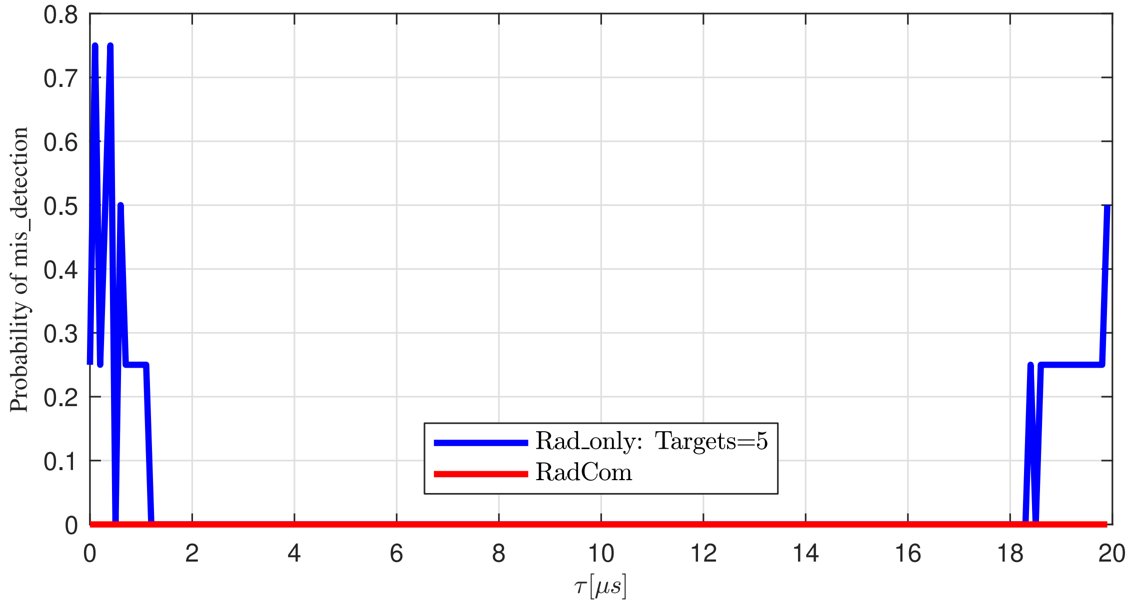

Figure 5.1: Probability mis-detection of target with and without RadCom systems. The simulation contains four other interfering targets besides the ego target and the threshold value is $10dB$.

time duration, which is $20\mu s$ $(0 \leq \tau < 20\mu s)$ and the ego target is transmit at $t = 0$. For radar only, the simulation runs 40 times for each delay and the average probability of mis-detection is zero out of the vulnerable period. However, at both sides of the vulnerable period $(0 \leq \tau < 2\mu s)$ and $(18 \leq \tau < 20\mu s)$, the probability of mis-detection varies from 0 up to 0.75. Since the noise floor level increases due the interfering signals, some of the actual targets remain undetected.

The RadCom system handles five targets without being affected by mutual interference and that satisfies the value analytically calculated. The ego vehicle starts transmission at $t = 0s$ and the interfering targets transmit at $4\mu s$, $8\mu s$, $12\mu s$ and $16\mu s$. The time difference between consecutive transmission is exactly the vulnerable period, which is $4\mu s$. Comparing the results from radar only system and RadCom system, signal interference affects mis-detection probability for radar only system while it is mitigated in RadCom system.

The probability of ghost detection provided information about wrongly detected targets, which they do not exist. Figure 5.2 depicts the probability of ghost target detection using $10dB$ threshold. The simulations contain four interfering targets besides the ego vehicle. The interfering targets are located at a distance of $37.5m, 75m, 112.5m$ and $150m$ from the ego vehicle. In RadCom simulation, the probability of ghost target is zero throughout the 200 simulation tests. In radar only simulation, the time delay for the interfering targets transmission time vary throughout the chirp time $(0 \leq \tau < 20\mu s)$. In radar only case there is ghost target detection in both ends of the vulnerable period, while no ghost target detected out of the vulnerable period. Comparing the two systems, RadCom system avoids ghost

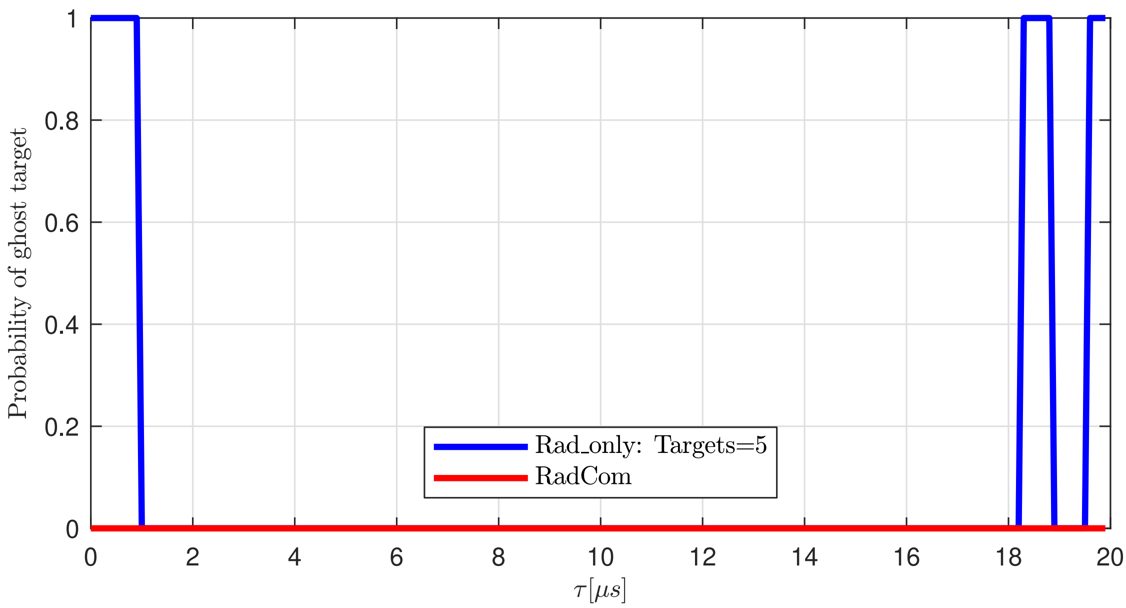

Figure 5.2: Probability of ghost target detection with and without RadCom systems. The simulation contains four other interfering targets besides the ego target and the threshold value is $10dB$.

target detection while radar alone is not.

One factor that affects the performance measurement parameters is the threshold selection. All the so far plots are obtained using a threshold of $10dB$. Decreasing the threshold value and how it changes the probability of mis-detection and probability of ghost target detection for radar only system is also discussed.
Figure 5.3 depicts the probability of mis-detection of targets using radar only system that having four interfering targets using $7dB$ threshold. The simulation parameters and the targets location are the same as with use in figure 5.1, the only difference is the threshold lowered from $10dB$ to $7dB$. Comparing the two figures, they have a close probability of mis-detection values, except on the right side of the vulnerable period. The threshold value of $7dB$ gives a relatively better average probability of mis-detection of targets.

Figure 5.4 depicts the probability of ghost target detection using $7dB$ threshold. The simulation parameters and the location of the target are the same as with we use in figure 5.2 except for the threshold value. It is sensible how the average probability of ghost target detection changed between the figures. Since the interfering signals increase noise floor of the received signal and the threshold value is decreased from $10dB$ to $7dB$ and hence it leads to an increase in ghost target detection. The ghost target detection in $7dB$ threshold is not only limited on vulnerable period but also it occurred even out of vulnerable period.

Figure 5.5 and 5.6 both they depict target detection using a threshold of $10dB$ and $7dB$ respectively. In both cases, we have four interfering targets and the ego target

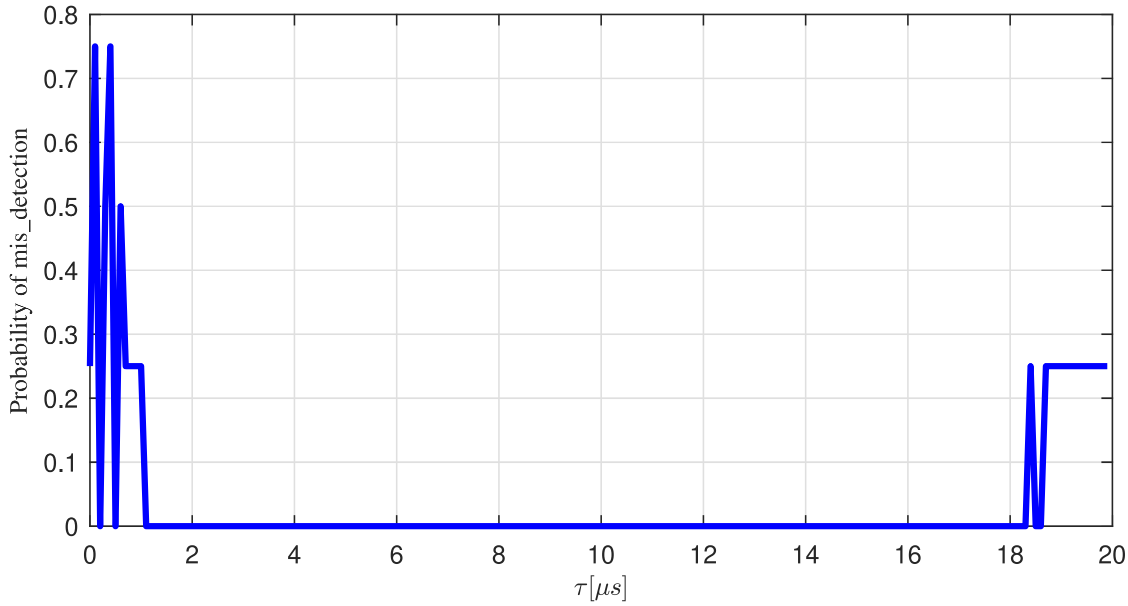

Figure 5.3: Probability mis-detection targets using radar only systems. The simulation contains four other interfering targets besides the ego target and the threshold value is $7dB$.

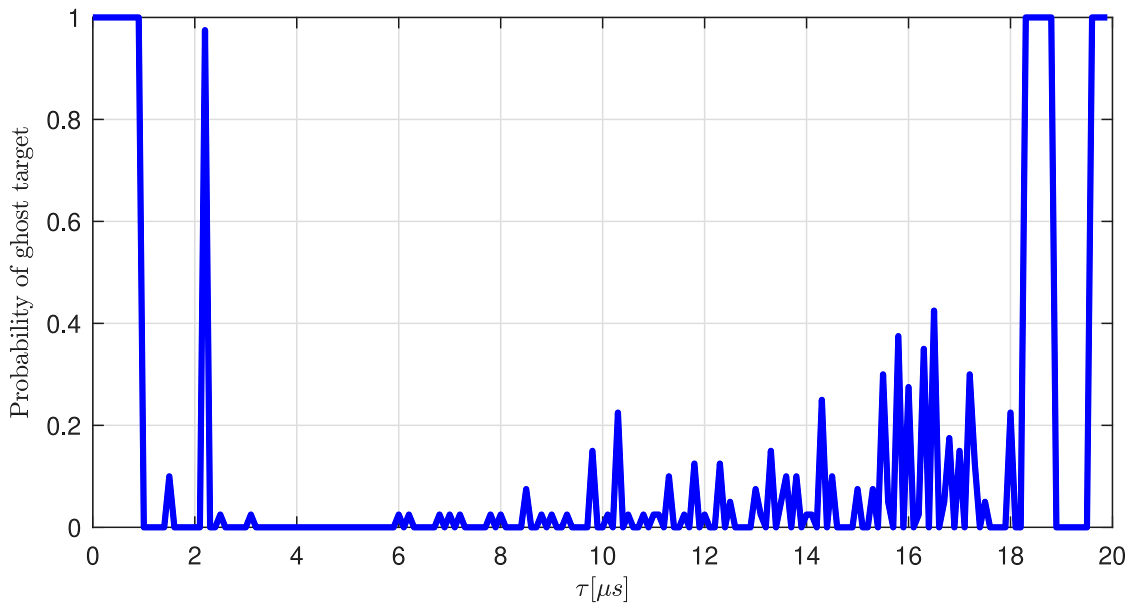

Figure 5.4: Probability of ghost target detection using radar only systems. The simulation contains four other interfering targets besides the ego target and the threshold value is $7dB$.

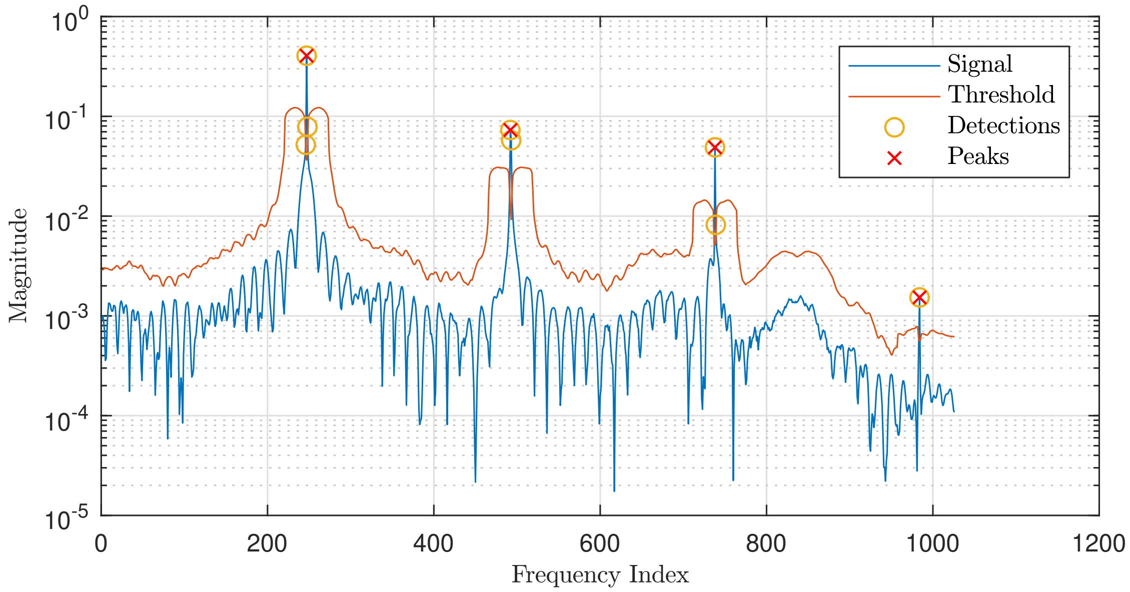

Figure 5.5: Target detection from output of the FFT signal using the implemented CFAR and the threshold value is $10dB$. We have more four interfering targets beside the ego vehicle.

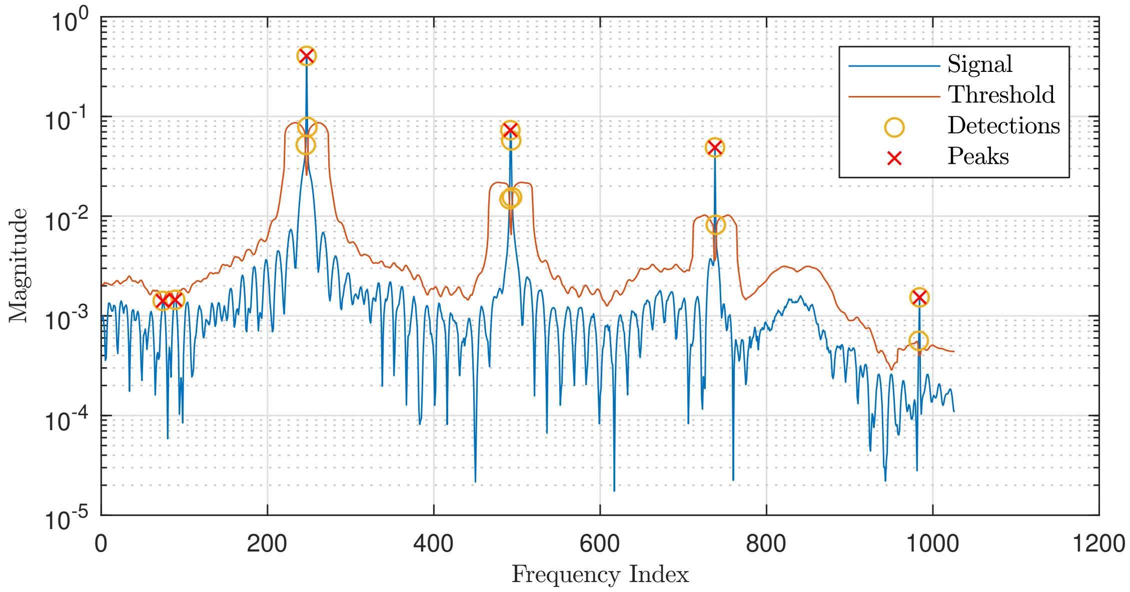

Figure 5.6: Target detection from output of the FFT signal using the implemented CFAR and the threshold value is $7dB$. We have more four interfering targets beside the ego vehicle.

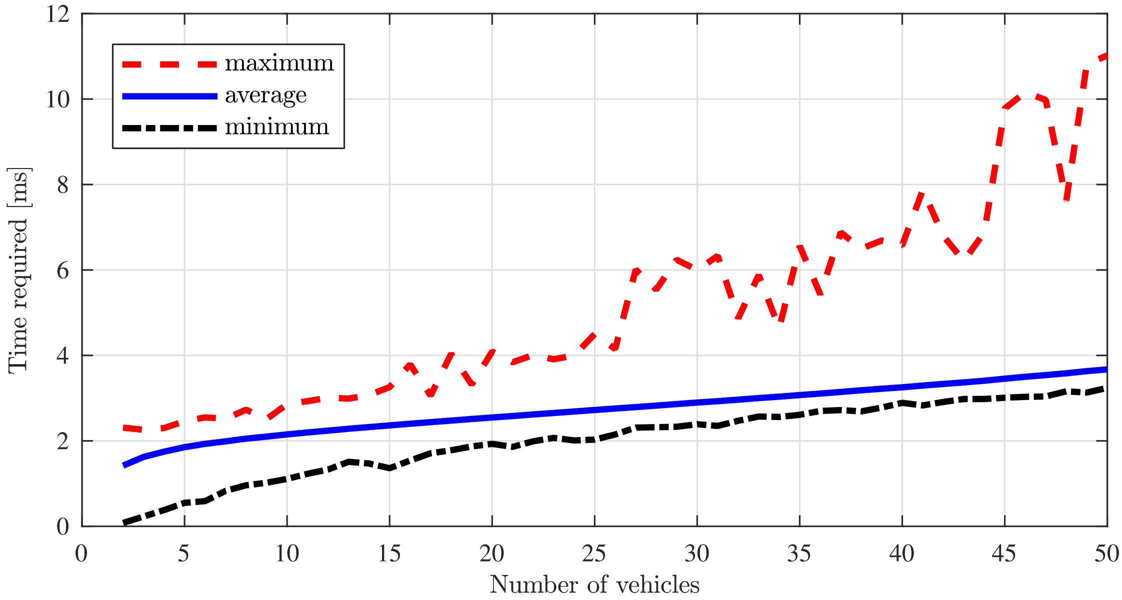

Figure 5.7: The required time for resolving the communication contention among the vehicles in RadCom using $B_c = 40$ MHz, one-persistent CSMA with backoff value of 6.

start transmission at $t = 0$ and the time delay for the interfering targets is $\tau = 2.2\mu s$. In figure 5.5, there is no ghost target detected and the four targets are precisely detected. However using $7dB$ threshold as given in figure 5.6, there is ghost target detection at the frequency index of 867.

By comparing results from $10dB$ and $7dB$ threshold values, there is a tradeoff between the probability of mis-detection and probability of ghost target detection in a selection of threshold value. Increasing the threshold value is advantageous in minimizing the probability of ghost target detection; however, it decreases the detection probability of targets. For the other way around, decreasing the threshold value is useful in maximizing detection probability of targets, but it increases ghost target detection.

From the previous discussions the approach for the communication system is CSMA and the communication contention held before radar signal transmission. Hence the performance measure for different CSMA approaches is the time it takes to finish the communication contention. Less time required for communication contention is crucial to avoid mutual interference in RadCom systems. In one-persistent CSMA with backoff since the backoff value is randomly generated, the required time is also not constant. Hence the average time required for communication should be determined. To get the average required time we performed $10,000$ tests. The time required for successful communication contention among p-persistent CSMA without backoff and one-persistent CSMA with backoff presented with simulation plots.

Figure 5.7 and 5.8, depict how the required time for communication contention vary

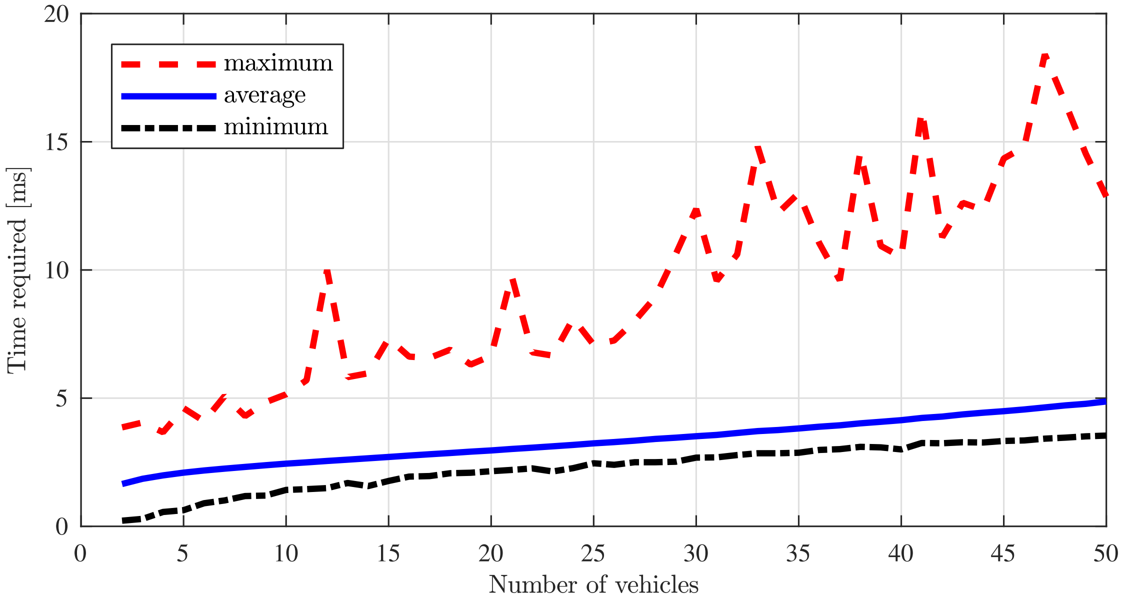

Figure 5.8: The required time for resolving the communication contention among the vehicles in RadCom using B_c = 40 MHz, one-persistent CSMA with backoff value of 48.

with selection of backoff in one-persistent CSMA with backoff. The two figures show the time required for communication contention versus the number of targets during one frame time with backoff values of 6 and 48 respectively. Both the figures show maximum, minimum and average time required from $10,000$ simulation tests. In both figures, the average and maximum time required for communication are less than the frame time, which is $20ms$. From the four plots, we can see the required time increases as backoff increases.

Figure 5.9 depicts time required for successful communication contention using p-persistent CSMA without backoff. Like one-persistent CSMA, the average and maximum required time is less than the frame time. Comparing with one-persistent, p-persistent needed less maximum possible time but it required higher average time for communication contention.
Figure 5.10 combines the average result from one-persistent CSMA with different backoff values and p-persistent CSMA. From the figure as backoff value increases, the required time also increases. Moreover, from the four backoff values the average required time in one-persistent CSMA is lower than the p-persistent CSMA required.However, p-persistent is better for low number of vehicles.

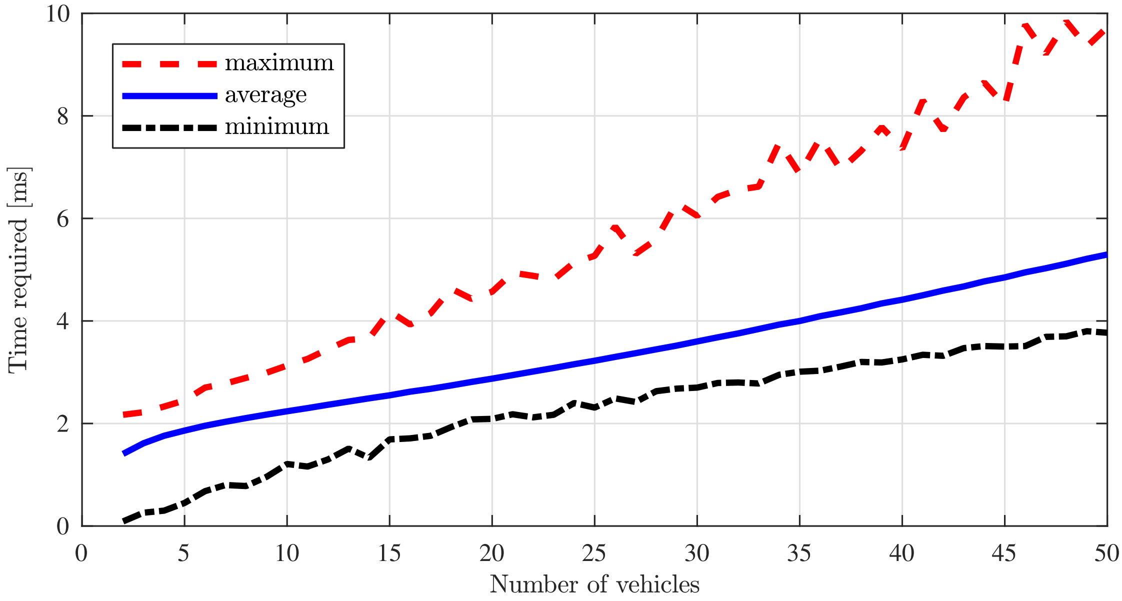

Figure 5.9: The required time for resolving the communication contention among the vehicles in RadCom using $B_c = 40$ MHz, P-persistent CSMA without back off.

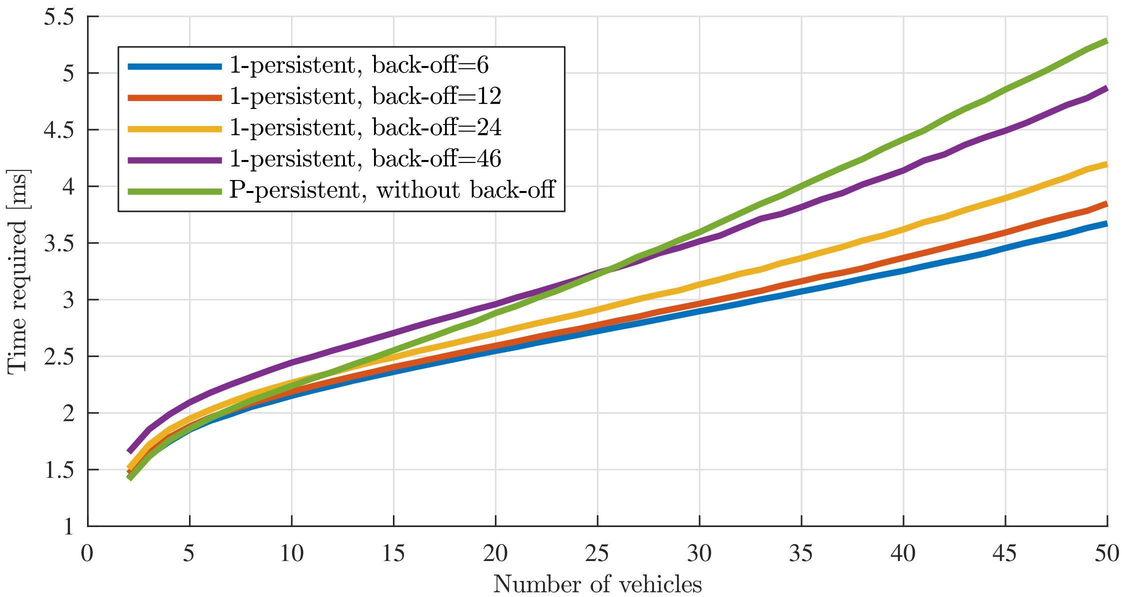

Figure 5.10: Compassion of time required for resolving the communication contention among the vehicles in RadCom using $B_c = 40$ MHz between P-persistent CSMA without back-off and one-persistent CSMA with backoff.

6
Conclusion

Unscheduled and random radar signal transmission leads to signal interference among FMCW radars. The interfering signal covers less distance than the reflected signal and hence it is stronger than the reflected signal. The interfering signal increases the noise floor of the received signal and consequently, the interfered signal appear as ghost target and the actual target remain undetected. The stand-alone radar system can not mitigate the effect of mutual signals interference and hence the detection outcome is not reliable. The communication system feature is Incorporating to the radar system to reduce the impact of mutual interference. RadCom combines both features of FMCW radar and communication systems and it uses the same hardware for both systems. The communication system is supplementary for FMCW radar by scheduling the transmission time for the different FMCW radars. This scheduling crucial in mitigating mutual interference by avoiding more than one FMCW radar from transmitting at a time or within the vulnerable period. Hence RadCom performed better than standalone radar regarding minimizing ghost target detection and the probability of target mis-detection. The two systems are multiplexed in frequency and a separate frequency band allocated for each of them. One-persistent CSMA with backoff and p-persistent CSMA without backoff are simulated for communication medium access control. The probability of target detection, probability of target mis-detection and probability of ghost target detection are used as a performance measurement of the proposed approach. For CSMA, the time required for communication contention is used as performance measurement between p-persistent CSMA and one persistent CSMA.

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Appendix 1