Automotive Radar Systems: Status and Future Developments

Jerry
Martinez

Advised by Janice Hudgings

Thesis submitted to
Pomona College
in partial fulfillment for the award of the degree of
Bachelor of Arts
in Physics

2015-2016

Acknowledgements

I’d like to thank my thesis advisor Janice Hudgings for her all her patience and guidance on this project. I would also like to thank my advisor David Tanenbaum for aiding me in my undergraduate career, and I’d like to thank Phil Choi and Dwight Whitaker for helping me when I needed them most. I would also like to say a huge thank you to Vicente Robles for all the support and guidance throughout the years and for giving me the strength to finish this thesis.

Table of Contents

1 Introduction

1.1 Introduction to Radar Systems

Road traffic crashes have become a major global challenge. Every year 1.2 million people are known to die in road accidents worldwide and as many as 50 million are injured.[1] Because of this, systems for the improvement of road safety have become a critical area of study. “Automotive radar systems […] have been identified as a significant technology for the improvement of road safety by the EC.”[1] Automotive radar devices are now appearing in passenger vehicles all over the world. These devices are used in advanced cruise control systems, collision warning systems, blind-spot monitoring, lane-change assistance, rear cross-traffic alerts, and back-up parking assistance. More recently, advancements in radar technology have allowed these systems to have the functionality of more preventative safety features such as collision mitigation.

Automotive radar systems are very complex and have varying designs and functions. But at the core; all automotive radar systems serve the same function. These systems contain radar sensors that note vital information, such as range, angle and Doppler velocity. With this information these systems can determine a particular driving situation and warn the driver in potentially dangerous events. If the driver does not take appropriate action in time and a crash is about to happen, advanced radar systems can take control of the vehicle to avoid the crash or lessen the accident’s severity. This high level of safety functionality is maintained in bad weather and no light, when driving conditions are at their worst.

Despite the large leaps in improving safety with automotive radar, there still many ways that these systems can be improved. Improving the range of object detection, accuracy of information, and issues with interference effects are just some of these ways. This paper will progress the steps made in this field, and relate the issues that still need to be addressed.

1.2 Motivation

1.2.1 Clinic Project

To better understand the goals of this paper, we must first address the relation between the Harvey Mudd Clinic project that this paper stems off of. To begin, the Harvey Mudd Clinic Team was assigned a specific project tied to improving automotive radar. As experts in the field of automotive radar, the sponsor of the project presented the clinic team with a specific list of issues to be addressed. This list is set by the Euro NCAP 2025 requirements for future automotive radar systems. They include:

- Detection and action at a quarter mile distance
- Sweep 150° field of regard in 50 ms
- Discern closely spaced objects to within a few degrees
- Sweep in elevation, not just azimuth

Another important task assigned to the team, was to conduct further research on how interference affects a radar system. These interference factors range from radar signals bouncing off of multiple objects to other vehicles on the road sending their own radar signals. These are all affects that will be researched and based on that information; the clinic team will create a simulation test bed where these factors can be studied more in depth. The team has chosen to focus efforts into this simulation and because of time constraints, cannot focus on the Euro NCAP requirements.

1.2.2 Thesis

My thesis aims to take charge of one of these requirements, lending the team a broader knowledge of radar while still satisfying a need of our sponsor. In particular, this research will focus on the needs of understanding and improving radar resolution.

The automotive radar industry is clearly moving towards improving active safety systems. These systems may take control of the vehicle from the driver by intervening with the braking or steering system. But in order for these systems to function, the quality of information required from the sensors to enable this active intervention needs to be sufficiently high, demanding both high spatial and angular separation.[2] Improved range resolution, a subset of spatial resolution, is also another requirement for improving these systems. Higher range resolutions allow systems to separate and discriminate between several small closely spaced objects in the radar field of view. [1]

Currently, many automotive radars work within narrow bandwidths and as a result have low spatial resolutions. With low spatial resolution, multiple objects on the road cannot be distinguished if they appear in the same range gate and objects are fused into one virtual object (see Figure 1). [3]

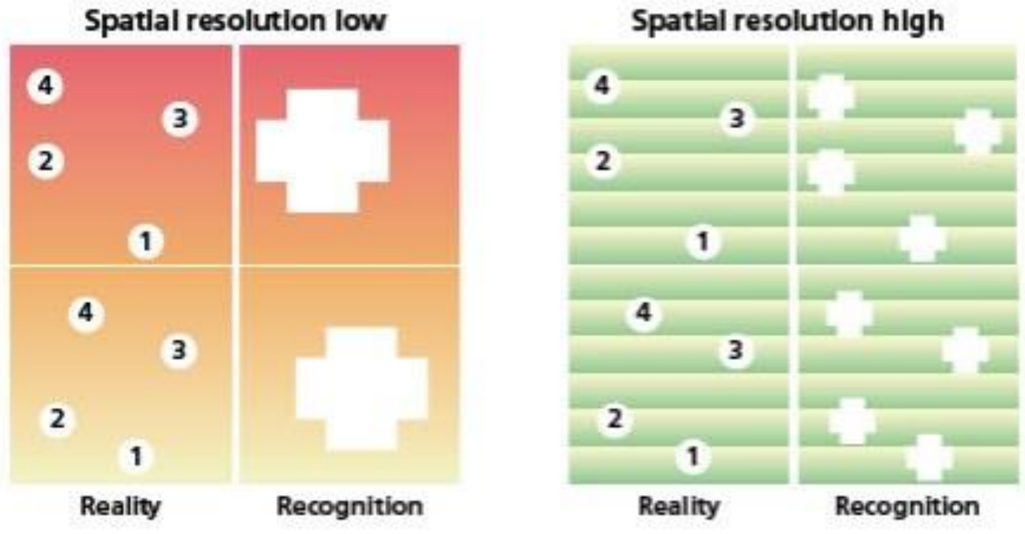

Figure 1 : Low Spatial Resolution vs High Spatial Resolution

A high-resolution system has the ability to determine whether a vehicle will crash into an object or narrowly miss. A low-resolution system will have a higher rate of false alarms and will have greater chances of creating safety hazards and vehicle accidents. The purpose of my research is to investigate the components which affect how well a radar system discriminates different objects, and more specifically investigate past/present methods used for improving spatial resolution.

1.3 Current Systems

Ever since the early 1990s when radar was first implemented onto commercial vehicles, automotive radar technology has continued to evolve and improve. As a result, today's markets of automotive radar systems have a variety of functionalities. Because of these variances, automotive radar systems have different forms of classification. These systems can be grouped by their bandwidth (narrow-band or wide-band), by their operation principle (pulsed or continuous wave) or by the covered area (shortrange, mid-range and long-range radar). In this paper, these systems will be classified with respect to their operating range and typical applications.

Current short-range radar (SRR) systems operate at the 24GHz range and usually require a large bandwidth ranging from 3-5GHz. They are typically operated in a pulsed mode, have a maximum range of detection up to 30 m and a wide horizontal angular coverage of about ±65◦ to ±80◦. Multiple SRR sensors are usually equipped to fully cover the nearest surroundings of a vehicle. Because of the large bandwidth , and large angular coverage, these systems have large angular and range resolution which allows these systems to accurately attain large amounts of information regarding the environment surrounding a vehicle and can be used for advanced safety measures such as such as collision mitigation, or blindspot monitoring to name a few. [4]

Mid-range radar (MRR) systems also use the 24 GHz frequency range but use a narrower bandwidth of around 200MHz. These systems operate in continuous wave mode using linear frequency modulation (LFM) or advanced modulation techniques such as frequency shift keying (FSK) or frequency-stepped continuous wave (FSCW). They have a maximum range of 70 m and an angular coverage of $\pm 40^\circ$ to $\pm 50^\circ$. Due to the low available bandwidth, these systems have low range resolution. Therefore, the primary targeted application for these sensors is the lane-change assistant. [4]

Long-range radar (LRR) systems mostly use the allocated 76-77GHz frequency range and operate in the continuous wave mode using FMCW. Some however, reach similar functionality using a narrow-band 24GHz frequency. The long-range sensors are implemented typically for Automatic Cruise Control. [4]

Typically, LRR sensor performance degrades for targets very close to the vehicle (< 20m), resulting in a drop of range measurement stability and angular measurement accuracy. The range resolution of most long range radar systems on the market today comes close to the physical limits imposed by the sensor's transmit frequency bandwidth. Because of this limitation, many vehicles on the road today use a combination of SRR and LRR to achieve multiple necessary functionalities. [4]

1.4 Improvements for the Future

As of today most automotive radar systems types (LRR,etc.) operate at separate frequency ranges. As described previously, SRR currently operate at the 24GHz range, and LRR operate at the 76GHz range. Originally it was expected that, by 2013, new systems for the 79 GHz band would be available and that the use of the 24 GHz band could therefore be phased out. However, the automotive industry has experienced significant delay in developing SRR systems to operate in the 79 GHz band, and it has become clear that new systems with 79 GHz technology would not be mature enough for commercial deployment in cars by 2013.

The phasing of the 24 GHz operation range stems from the fact that many other radio systems such as radio astronomy stations, earth exploration satellites and other satellite services also use this range for operation. As the requirement for all cars made to have a radar system by 2025 (according to the EURO NCAP requirements) was set, it becomes quite clear that operating in this range can lead to much interference. [5,6]

Though progress is being made towards resolving issues with operation in the new allotted frequency range, there are still major issues that need to be addressed. One of these issues has to deal with the accuracy of detecting and analyzing information from systems operating in this range. SRR in the past have operated with large bandwidths, and as a result issues with accuracy were practically nonexistent. These accuracy issues stem from the range and angular resolution of these systems and are issues that must be resolved in order for these systems to successfully operate.

2. Radar Resolution

The target resolution of radar is its ability to distinguish between targets that are very close in either range or bearing. This is an important characteristic for many radar systems such as weapons-control radar, which requires great precision and should be able to distinguish between targets that are only yards apart. In the same light, resolution is also important for automotive radar because an improved resolution can allow a vehicle to avoid potential devastating collision with other targets/vehicles on the road. Radar resolution is usually divided into two categories; range resolution and angular (bearing) resolution. [7]

2.1 Angular Resolution

Angular resolution is the minimum angular separation at which two equal targets at the same range can be separated. The angular resolution characteristics of a radar are determined by the antenna beam width represented by the -3 dB angle Θ which is defined by the half-power (-3 dB) points. The half-power points of the antenna radiation pattern (i.e. the -3 dB beam width) are normally specified as the limits of the antenna beam width for the purpose of defining angular resolution; two identical targets at the same distance are, therefore, resolved in angle if they are separated by more than the antenna beam width. So the smaller the beam width Θ, the higher the directivity of the radar antenna, and the better the bearing resolution. The angular resolution as a distance between two targets depends on the slant-range and can be calculated with help of the following formula:

$$S_A \leq 2R \sin\frac{\theta}{2} \qquad 2.1)$$

Where θ is equal to antenna beam width, S_A is equal to angular resolution as a distance between two targets, and R is equal to an antenna variable. [7]

2.2 Range Resolution

Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges. The degree of range resolution depends on the width of the transmitted pulse, the types and sizes of targets, and the efficiency of the receiver and indicator. Pulse width is the primary factor in range resolution. A well-designed radar system, with all other factors at maximum efficiency, should be able to distinguish targets separated by one-half the pulse width time. Therefore, the theoretical range resolution of a radar system can be calculated from the following formula:

$$S_r \leq \frac{c_o \tau}{2} \qquad 2.2)$$

Where $c_o$is the speed of light, τ is the transmitters pulse width, and S_r is the range resolution as a distance between the two targets. [7]

2.3 Range Equation

The radar equation provides the received power level as function of the characteristics of the system, the target and the environment. A well-known radar equation [8] for the system is given by

$$P_r = \frac{P_t A_{\mathrm{er}} A_{\mathrm{et}} \sigma}{4\pi R^4 \lambda^2 L_{\mathrm{sys}}}, \qquad (2.3)$$

where *Pr* is the received power, *Pt* is the transmitted power, *A*er and *A*et are the effective area of the receive and transmit antennas, respectively, *R* is the distance to the target, σ is the radar cross-section (RCS), defined as the ratio of the scattered power in a given direction to the incident power density and *L*sys is the system loss due to misalignment, antenna pattern loss, polarization mismatch, atmospheric loss [3], but also due to analog to digital conversion and fast Fourier transform (FFT) windowing. Taking into consideration that the effective area of the receive and transmit antenna is related to the wavelength λ and to the antenna gain *Gr* and *Gt*, as *A*er = *Gr*λ 2/4π and *A*et = *Gt*λ 2/4π, respectively, the radar equation can be rewritten as [4]

$$P_r = \frac{P_t G_r G_t \lambda^2 \sigma}{(4\pi)^3 R^4 L_{\text{sys}}}. \tag{2.4}$$

3. Types of Radar Systems

A lot of progress has been made for automotive radar during the last years. There are two main types of automotive radar; “long-range radar at 77GHz with a range capability up to 200m“ for automatic cruise control (ACC) and “short-range radar at 24/26 and 79GHz up to 30m“ for anti-collision. Long radar with narrow radiation beam enables an automobile to maintain a cruising distance, while short-range radar has attracted attention because of many applications such as pre-crush warning, stop-and-go operation and lane change assist. The short-range radar with a very broad lateral coverage has a few significant problems to be overcome such as target detection and clutter suppression. This is because the widely radiated radar echo contains not only automobile echo, but also unwanted echoes called clutter. It is actually not easy to detect a target echo in increased clutter. Ultra-wideband impulse-radio (UWB-IR) radar with high range-resolution has recently attracted much attention for automotive use, because it offers many applications such as pre-crush warning and lane change assist. [9]

3.1 Basic Radar Function

Radar systems are composed of a transmitter that radiates electromagnetic waves of a particular waveform and a receiver that detects the echo returned from the target. Only a small portion of the transmitted energy is re-radiated back to the radar, which is then amplified, down-converted and processed. The range to the target is evaluated from the travelling time of the wave. The direction of the target is determined by the arrival angle of the echoed wave. The relative velocity of the target is determined from the doppler shift of the returned signal. [4]

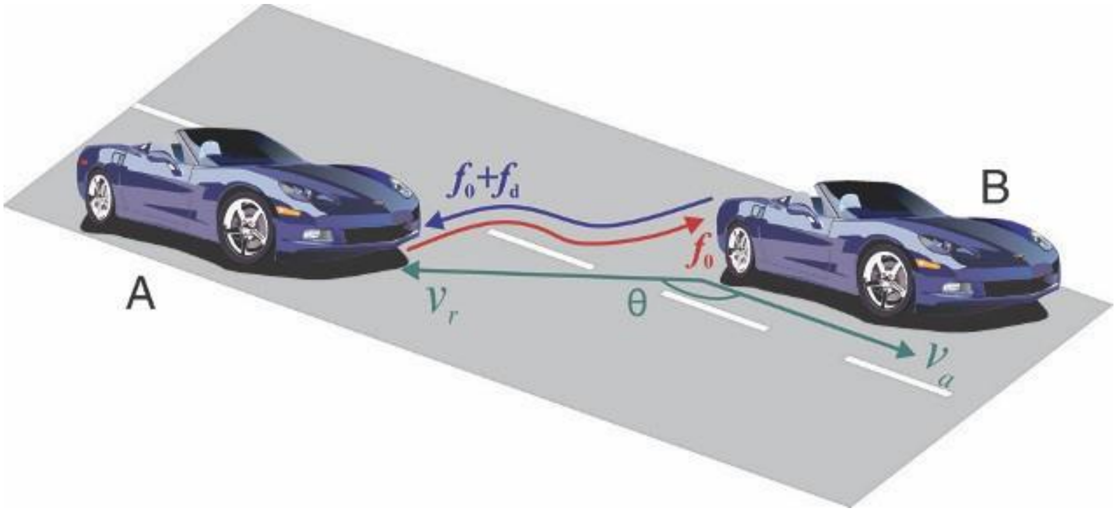

Figure 2: Signal being transmitted by vehicle A, and being reflected off of vehicle B with a Doppler shifted frequency [4]

3.1 Short Range Radar

Automotive short range radar is an important technology for present and future automotive active safety and comfort functions. The UWB approach provides a real-time high range resolution, which is of particular importance for the time critical safety functions, e.g. pre-crash. The European frequency regulation for UWB automotive SRR requires the shift from 24 GHz to the 79 GHz band in 2013. Beneath this, offers the application of the same the 79 GHz frequency range offers application of the same technology platform for LRR and UWB SRR. Furthermore, frequency dependent parameters as angular and velocity resolution, are improved significantly. [10]

As shown in Fig. 2 short range radar sensors can enable a variety of applications:

- ACC support with Stop&Go functionality
- Collision warning
- Collision mitigation
- Blind spot monitoring

- Parking aid (forward and reverse)
- Lane change assistant
- Rear crash collision warning

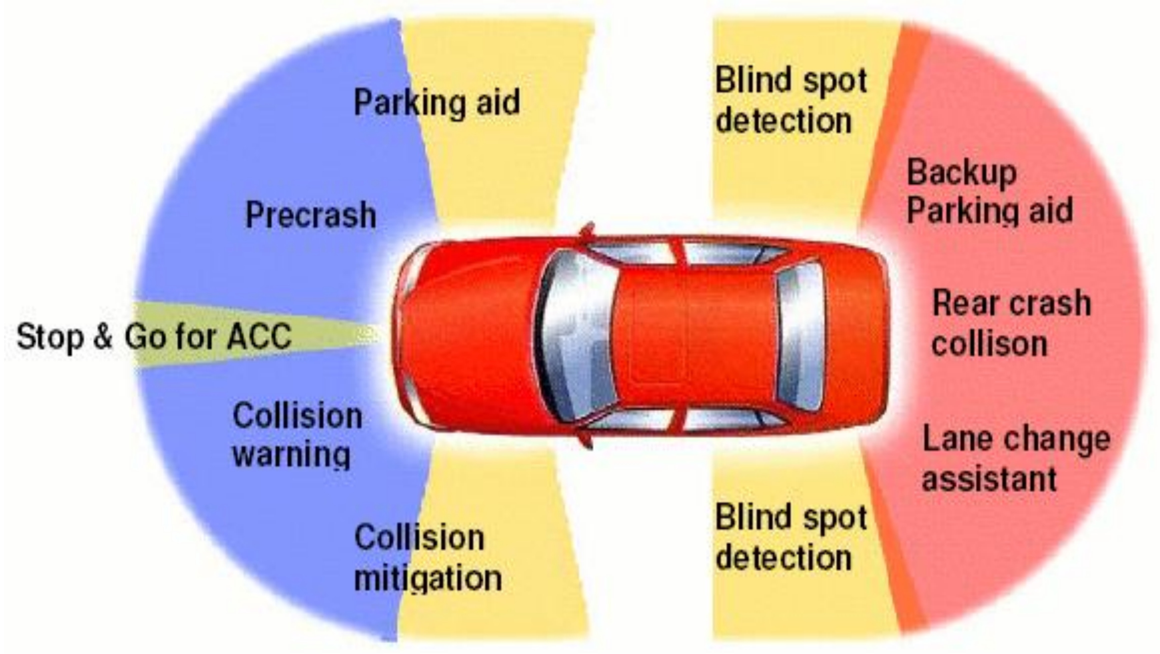

Figure 3: Short range radar and its safety applications. LRR functionality is also shown for ACC application

3.2 Long Range Radar

Automotive radar facilitates various functions which increase the drivers safety and convenience. Exact measurement of distance and relative speed of objects in front, beside, or behind the car allows the realization of systems which improve the drivers ability to perceive objects during bad optical visibility or objects hidden in the blind spot during parking or changing lanes. Radar technology has proved its ability for automotive applications for several years [11]

Long Range Radar is one of the radar types used in motor vehicles today. Typical LRR systems today show a maximum operation range of 150m for cars and motorcycles which is sufficient for most applications. Since the path prediction of the own vehicle based on e.g. steering angle and inertial sensors becomes more and more unreliable for far range over 150m, there is no point in further enhancement of a LRR range performance for frontlooking applications beyond this value. Typically, LRR sensor performance degrades for targets very close to the vehicle, resulting in a drop of range measurement stability and angular measurement accuracy. The range resolution of most long range radar systems on the market today comes close to the physical limits imposed by the sensor's transmit frequency bandwidth and usually is sufficient for long range applications but not for other applications. Lack in angular measurement accuracy and angular resolution - especially for multi target scenarios - is recognized as the most critical performance drawback of today's LRRs. [12]

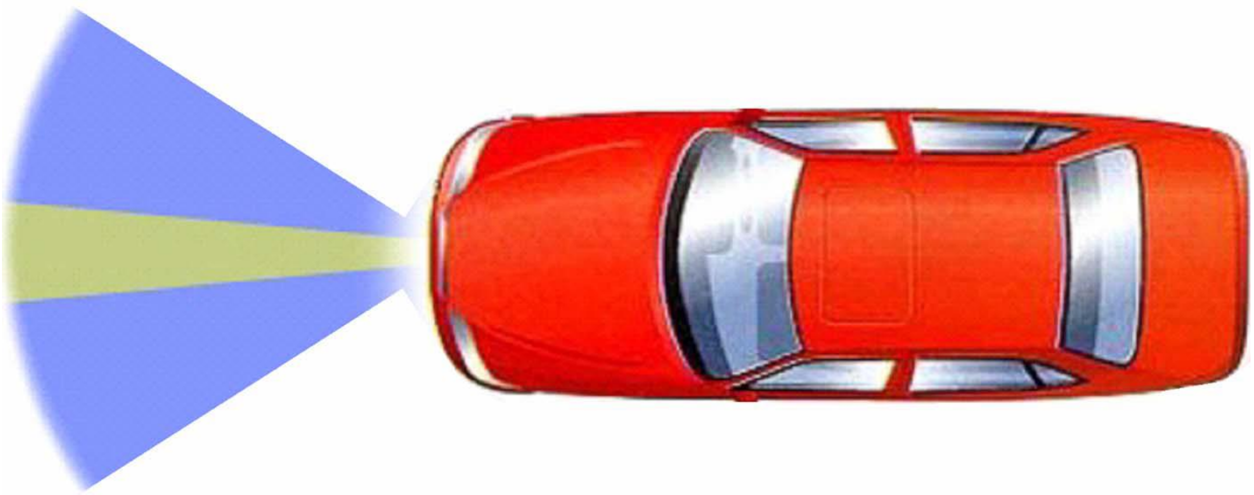

Figure 4: A vehichle equipped with LRR. These systems are forward mounted and serve for function such as ACC. [13]

3.3 Radar Designs for the Future

The transition for automotive radar from past frequency ranges is one of the biggest challenges and key aspects of future radar technologies. Current models for cars use a combination of LRR sensors operating at 77-79GHz and SRR operating at 24GHz to fully encompass all safety features (see Figure 3,5). For the future, automotive companies are working towards having LRR sensors as well as SRR sensors operating in the same frequency range of 79-81GHz, ultimately moving away from the 24GHz range.

For future systems it is necessary that the radar system has a sufficiently high resolution in the direction of propagation. It must be able to distinguish a person from other objects like containers or street lamps. Furthermore it has to be sensitive enough to detect a weakly reflecting obstacle in presence of a strong second reflector, for example a person standing in front of a wall. This would be beneficial for parking maneuvers in areas with many buildings and pedestrians. These and many other applications demand high resolution radar systems in the short and mid range area. It is a well known fact that high resolutions are better achievable in a higher frequency range. The step from 24 GHz to 79 GHz systems is still in progress but should be completed by 2022. [14]

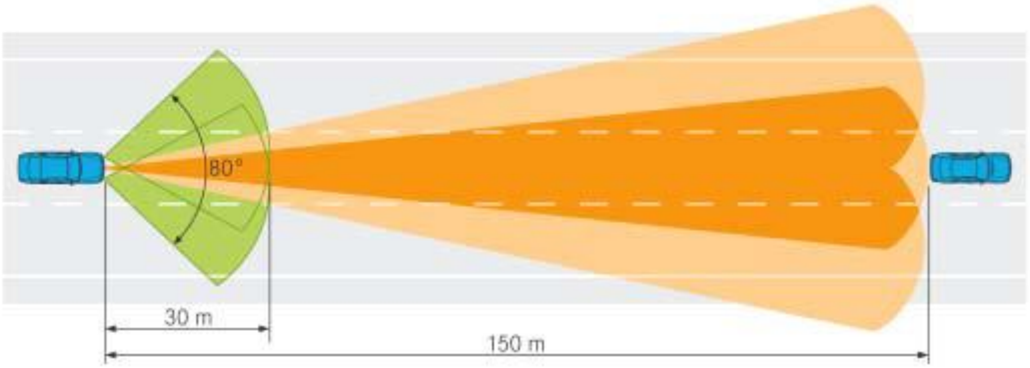

Figure 5: Automotive radar with SRR capability (green) and LRR capability (orange) with max range of detection of 15om. [13]

4. Waveform Design

Automotive radar systems have varying functions and one important attribute that lends to these differences is waveform choice for the system. The choice of waveform directly determines or is a major contributor to several fundamental radar system performance metrics. These include the signal-to-noise ratio (SNR) c, the range resolution DR, the Doppler (velocity) resolution DFD (Dv), ambiguities in range and Doppler, range and Doppler sidelobes, and range-Doppler coupling. These metrics are determined by such waveform attributes as the pulse duration, bandwidth, amplitude, and phase or frequency modulation. While all of these metrics are discussed, the primary emphasis is on SNR, range resolution, and Doppler resolution because these are the most fundamental drivers in choosing the waveform. [15]

4.1 Frequency Modulated Continuous Wave

Unmodulated continuous-wave (CW) radars transmit a signal with constant frequency. The lack of modulation of the source only allows for determination of the relative target velocity via the Doppler shift. Frequency modulated continuous-wave (FMCW) radar systems employ frequency modulation at the signal source to enable propagation delay measurements for determination of the distance to the target. Figure 4 shows a block diagram of an FMCW radar transceiver.[16]

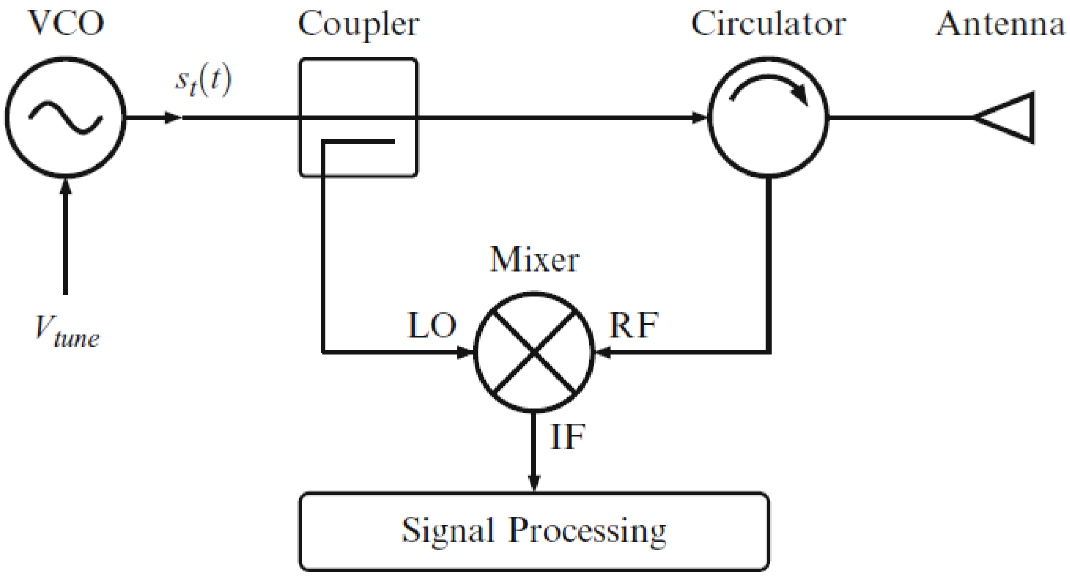

Figure 6

A voltage-controlled oscillator (VCO) forms the signal source that is modulatedas a linear frequency ramp by changing the tuning voltage *Vtune* of the VCO. Equation 2.6 gives the mathematical expression for a frequency modulation that uses up- and down-chirps of equal length *TP/*2 and bandwidth *B*. [16]

$$f_t(t) = f_0 + kt \qquad \text{with} \quad k = \frac{2B}{T_P} \tag*{4.1)}$$

The above modulation scheme yields a transmitted signal *st* of the form[17]

$$s_t(t) = A_t \cos\left(2\pi f_t(t) t\right) \tag*{4.2)}$$

$$= A_t \cos\left(2\pi f_0 t + 2\pi k t^2\right) . \tag*{4.3)}$$

A fraction of the signal is coupled to the receive mixer to act as the LO reference, while the other part is transmitted through the antenna. The backscattered signal

$$s_r(t-\Delta t) = A_r \cos\left(2\pi(f_0 + f_d)(t-\Delta t) + 2\pi k(t-\Delta t)^2\right) \quad 4.4)$$

with the propagation delay Δ*t* and a Doppler shift *fd* is received and translated into the baseband by means of a down-conversion mixer. Subsequently the intermediate frequency (IF) signal is digitized and the determination of target range and velocity is performed through a fast Fourier transformation (FFT).[16]

4.2 Frequency Shift Keying

Frequency shift keying (FSK) is one of several techniques used to transmit a digital signal on an analogue transmission medium. The frequency of a sine wave carrier is shifted up or down to represent either a single binary value or a specific bit pattern. The simplest form of frequency shift keying is called *binary frequency shift keying* (BFSK), in which the binary logic values one and zero are represented by the carrier frequency being shifted above or below the *centre frequency*. In conventional BFSK systems, the higher frequency represents a logic high (one) and is referred to as the *mark* frequency. The lower frequency represents a logic low (zero) and is called the *space* frequency. The two frequencies are equi-distant from the centre frequency. A typical BFSK output waveform is shown below. [17]

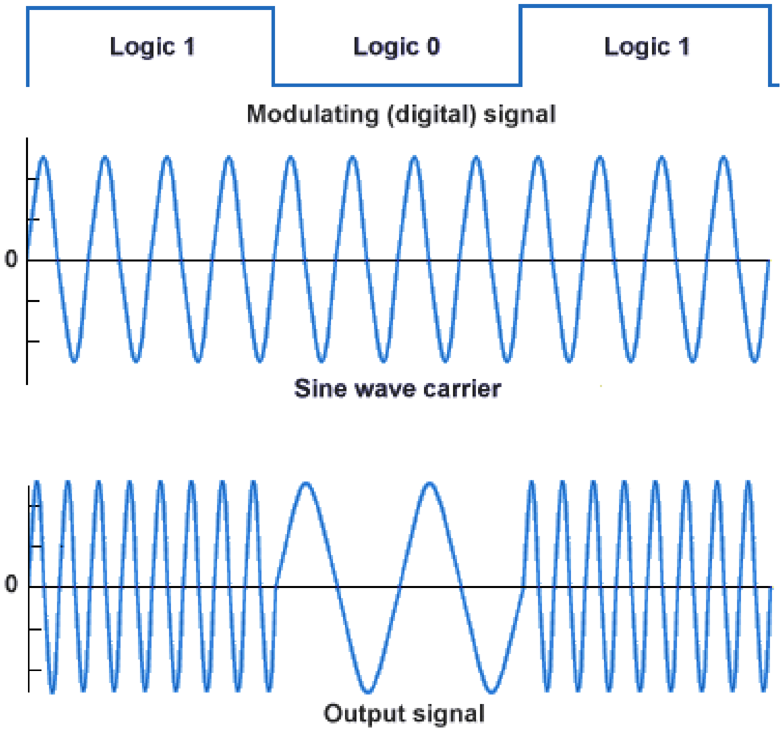

Figure 7: Binary Frequency Shift Keying (BFSK)

If there is a discontinuity in phase when the frequency is shifted between the mark and space values, the form of frequency shift keying used is said to be *non-coherent*, otherwise it is said to be *coherent*. In more complex schemes, additional frequencies are used to enable more than one bit to be represented by each frequency used. This provides a higher data rate, but requires more bandwidth (representing a group of two binary values, for example, would require four different frequencies). It also increases the complexity of the modulator and demodulator circuitry, and increases the probability of transmission errors occurring. [17]

4.3 Pulse Modulation

A pulsed-radar transmits modulated pulses at periodic intervals of time (i.e., a train of modulated pulses) as illustrated in Fig. 8. Range is readily extracted by measuring the time delay between the instants of pulse transmission and reception. Object velocity can be determined by measuring the rate of change of range, or by employing a bank of Doppler filters. Pulse radar waveforms are characterized by three main parameters: (a) pulse-width, τp (b) carrier frequency, f0 and (c) pulse repetition frequency, prf. The prf must be chosen to avoid range and Doppler ambiguities and to maximize average transmitted power. Range ambiguity decreases with decreasing prf, while Doppler ambiguity decreases with increasing prf. Radars with high prf are usually called pulsed Doppler radars. Intentional pre-determined jitter is sometimes introduced in the prf in order to avoid blind speeds and range and Doppler ambiguities. In a pulsed-radar, the transmitter (TX) and the receiver (RX) essentially operate in a time-duplexed manner, and hence a high dynamic range can be attained. Although a complex timing engine with delay circuitry is required, pulsed radar is the simplest architecture to implement. [18]

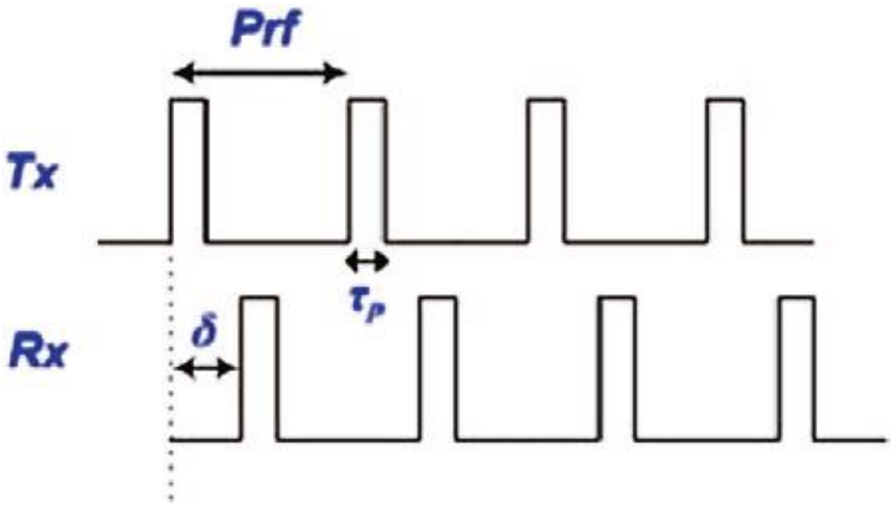

Figure 8: Typical transmit and receive waveform envelopes in a pulsed-radar

Conclusion

With vehicle accidents lending to one of the leading causes of death in the U.S., vehicle safety has become a very important area of research. To combat these accidents, significant headway has been made towards vehicle safety features. The most vital of active crash prevention comes from automotive radar and the functionalities that they serve. From crash mitigation to automatic cruise control(ACC), automotive radar have been a major key for vehicle safety and comfort. As of today most automotive radar systems types come in the form of short range radar (SRR) or long range radar (LRR) operating at 24GHz and 76GHz respectively. While SRR serves the purpose of safety mitigation, LRR controls features such as ACC.

In the future, automotive radar will be shifted towards operation in the 77-81GHz range, and previous 24GHz operation will be phased out. This phasing of the 24 GHz operation range is due to operation of other radio systems such as radio astronomy stations, earth exploration satellites and other satellite services at this frequency and range. And with the requirement for all cars made to have radar systems by 2025 (according to the EURO NCAP requirements), it becomes quite clear that operating in this range can lead to much interference. [5, 6] This is a requirement set by the ECC by 2022, and will lend to new changes in automotive radar technologies. One of the biggest drawbacks facing current systems is shifting SRR capabilities towards the new allocated range. The biggest reason for this issue comes from the amount and accuracy of information coming from radar systems operating at higher frequencies and lower bandwidths. With lower frequencies and bandwidths, the range and angular resolution of these systems are compromised and as a result, valuable information is lost that could be used for functionalities such as crash mitigation. These are features that were dealt with coherently in the 24GHz range, but are something that needs to be addressed in the future as we move towards a new allocated frequency range.

References

1. Wenger, J. (2005). Automotive Radar – Status and Perspectives, 21–24.
2. Gresham,Ian. (2014) Automotive Radar Solutions, Anikiwave.Web.02 Feb. 2016.
3. Brizzolara,David. (2013) Future Trends for Automotive Radars: Towards the 79GHz Band, *ITU News*. Web. 2 Feb. 2016.
4. Issakov, V. (2010). Microwave Circuits for 24 GHz Automotive Radar in Silicon-based Technologies, 5–19.
5. (2014) A radar for your Car-Digitial Agenda for Europe-European Comission, *Digital Agenda for Europe*.European Comission, Web. 02 Feb. 2016.
6. Bloecher, H., Sailer, A., Rollmann, G., & Dickmann, J. (2013). Radio Science 79 GHz UWB automotive short range radar – Spectrum allocation and technology trends increased doppler (Electronic Communications Committee of the • higher angular resolution with CEPT) adopted decisions using 24 GHz spectrum in Europe until July 1 (December 2009), 61–65.
7. Basics, B. R. (2009). Radartutorial, 1–18.
8. Chang,K (2000) Wireless Communication Systems in RF and Microwave Wireless Systems, John Wiley & Sons, Inc.
9. Akihiro Kajiwara (2011). Ultra-Wideband Automotive Radar, Advances in Vehicular Networking Technologies, Dr Miguel Almeida (Ed.)
10. Bloecher, H., Sailer, A., Rollmann, G., & Dickmann, J. (2013). Radio Science 79 GHz UWB automotive short range radar – Spectrum allocation and technology trends increased doppler (Electronic Communications Committee of the • higher angular resolution with CEPT) adopted decisions using 24 GHz spectrum in Europe until July 1 (December 2009), 61–65.
11. Wengerl, J. (1998). Automotive mm-wave, 1–7.
12. Rasshofer, R. H., & Naab, K. (n.d.). 77 GHz Long Range Radar Systems Status , Ongoing Developments and Future Challenges, 2–5.
13. Wenger, J. (n.d.). RF-Applications in Vehicles – Today and Tomorrow Automotive Applications of RF- Technology, 1–18.
14. Mike, K., Gumbmann, F., & Sch, J. (2010). Considerations for Future Automotive Radar in the Frequency Range Above 100 GHz, *8*(c), 284–287.
15. Waveforms, R. (n.d.). Radar Waveforms 4.1.
16. Kissinger, Dietmar (2012) Millimeter-Wave Receiver Concepts for 77 GHz Automotive Radar in Silicon-Germanium Technology, 9-19
17. Frequency Shift Keying(FSK), *TechnologyUK*, N.p.,n.d. Web. 02 Feb. 2016
18. Jain, Vipul, Heydari, Payam (2013) Automotive Radar Sensors in Silicon Technologies, 5-11