

Design Optimization of Miniature Vehicle Radar Design Using Ultra-Wideband (UWB) Technology



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ABSTRACT The optimization of Radar Cross-Section (RCS) using Animation-Based Visualization techniques for miniature Ultra-Wide band (UWB) vehicle radars is presented in this study. The radar is designed to enhance detection of static and dynamic road hazards, such as animal carcasses or debris, with a range of up to 1 kilometre. The optimization methodology was centered on striking a balance between RCS reduction, power efficiency, and detection accuracy. With a spatial precision of roughly one meter, the UWB technology broadcasts small pulses while using little power. According to simulation results, detection is effective up to 1000 meters, and the amplitude of the received signal decays exponentially with distance, which is consistent with the behavior of theoretical route loss. For instance, the system's range-dependent sensitivity is confirmed when the signal amplitude decreases from 5.06 mV at 100 meters to 1.45 mV at 1000 meters. These findings indicated the critical role of pulse modulation, adaptive beam steering, and intelligent power management in maintaining reliable detection in dynamic environments. The optimized radar system demonstrates strong potential for integration into Advanced Driver-Assistance Systems (ADAS), contributing to enhanced vehicle safety and autonomy. Future research will investigate real-time adaptation strategies and validation in diverse environmental scenarios to further improve performance.

KEYWORDS: UWB, ADAS, Optimization Techniques, Radar system

I. INTRODUCTION

In modern autonomous vehicles, collision prevention depends heavily on the ability to detect objects far in advance. Conventional vehicle radar systems primarily address short-range detection, which limits their effectiveness for high-speed driving and obstacle avoidance. Ultra-Wideband (UWB) radar technology offers significant improvements in terms of range, resolution, and power efficiency. However, reducing the radar's size while maintaining performance presents design challenges, making optimization techniques essential. Radar is widely used to detect moving objects in the sky. Current radar technology utilizes a pulse signal being sent in a single shot to detect objects in the sky (Cheraghinia et al., 2024). The transmitted pulse is converted into electromagnetic wave that propagates towards the target, where it scatters upon impact. A portion of the reflected signal is received by the system. Repeated transmissions enable continuous distance tracking and real-time display Noori *et al.*, 2021).

In this research, UWB (Ultra-Wideband) technology is employed in the design of vehicle radar to detect objects on the road. The UWB system converts the carrier signal into a digital pulse (Yang et al., 2008). The radar transmitter emits a single UWB pulse per cycle to detect objects via the directional antenna. In this vehicular application, the antenna is electronically steered, and a pulse is transmitted at every 50° increment of its angular sweep of the transmitter and receiver

(Zhou et al., 2020). At a 50° angle of rotation, the radar sends the pulse approximately four times from 0° to 180° and another four times from 180° back to 0°. The pulse is continuously sent from 0° to 180° and back to 0°. Similarly, the pulse is received after being sent from the transmitter. To demonstrate the operation of the radar, this research proposes using MATLAB to model the radar system that operates using UWB technology.

MATLAB was chosen for this research because it provides specialized toolboxes with built-in functions for radar waveform generation, target detection and RCS analysis.

II. REVIEW OF FUNDAMENTAL CONCEPTS

UWB radar technology is characterized by wide bandwidth, short pulses, high precision and low power consumption. This has made it suitable for different applications (Zhu et al. (2021), Noori et al. (2021), Engels et al. (2021) Chen Y et al. (2022)). Most UWB radars are primarily used in medical applications to detect breathing and the presence of humans. The detection range for these radars is typically short, about 1 to 5 meters. However, there have also been studies that explore the use of UWB technology for vehicle radar systems. These studies are documented in papers published by Zhao et al. (2023), Hamaguchi et al. (2005), Cheraghinia et al. (2024). For vehicle radar systems utilizing UWB technology, the detection range remains limited, often

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less than 10 meters. These systems are primarily designed to detect pedestrians crossing the road and are frequently used in autopilot or cruise control systems. Such radars can be improved to detect objects at greater distances, such as beyond 10 meters, 100 meters, or even up to 1 kilometer or more. Bhatta and Priya (2017) highlight that the power required for a radar to detect distant objects typically ranges from 1 kW to 5 kW. Their findings indicate that increasing radar power enables the electromagnetic pulse to travel greater distances. Alongside power, the antenna is a critical factor in improving pulse directivity. For effective operation, radar systems require directional antennas for both transmission and reception. Modern radar designs often position the transmitting and receiving antennas side by side or integrate them into a single unit, ensuring that both antennas rotate simultaneously during operation.

UWB technology is characterized by its broad frequency range. A frequency spectrum classified as UWB is defined by its large fractional bandwidth typically greater than 20% of the center frequency or exceeding 500 MHz of absolute bandwidth. This is achieved by transmitting extremely short-duration pulses that inherently span a wide frequency range. A pulse that is narrow in the time domain will have a wide bandwidth in the frequency domain. This inverse relationship can be illustrated through the Fourier transform. Figure 1 depicts the Fourier transforms of pulses with varying durations in the time domain and their corresponding bandwidths in the frequency domain.

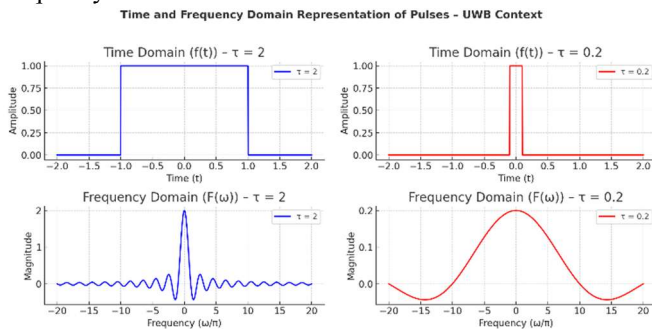


Figure 1. Time-Frequency Representation of UWB

As seen in Figure 1, when the pulse width narrows, the bandwidth in the frequency domain increases. The frequency domain representation of the pulse in the time domain is a Sinc function. Since Fourier transform theory relates with the UWB concept, it implies that to achieve a wide bandwidth, the pulse in the time domain must be shorter. In radar systems, the carrier is a high-frequency sinusoidal signal that can be modulated to carry information. UWB systems transmit short-duration pulses that inherently occupy a wide frequency band.

In analogue communication systems, information is typically modulated onto a carrier, which can then be shaped into a pulse for transmission, then compressed into a pulse before transmission. This process is complex and can sometimes result in signal distortion during the conversion of signals into a pulse.

A. Radar Theory

Radar is a device used to detect objects. The basic concept was explained in the introduction. This section will explain how radar works to detect objects. Figure 2 illustrates a radar system used to detect a moving object in the sky, while Figure 3 shows an on-road radar system used to detect vehicles.

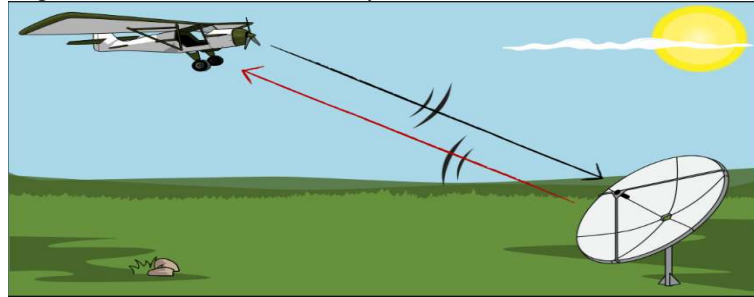


Figure 2. Basic radar used to detect an object on the sky (Hill, 2008)

Note that the detection of object in the sky and detection of moving object on the land using the same concept, but the processing method may be different.

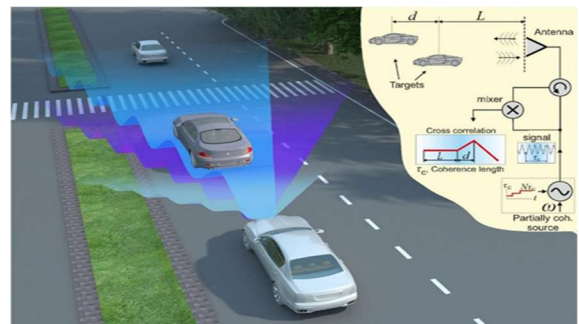


Figure 3(a): Short distance radar system to detect front car

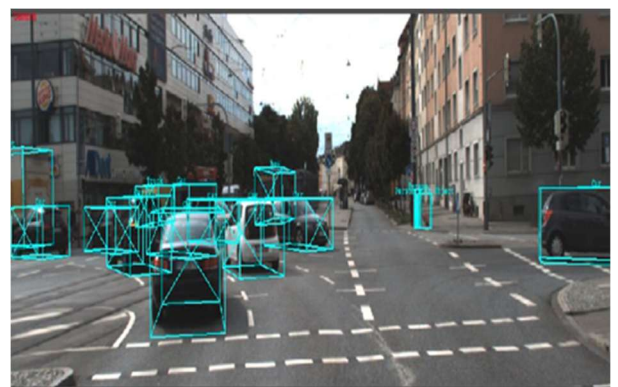


Figure 3(b): Image processing method to detect moving object on the road

Figure 3: Radar system in the land vehicle (Merrill and Skolnik, 1962)

Figure 2 illustrates how a radar emits a single pulse of radio waves aimed at an object in the sky. Upon striking the object, the pulse scatters, generating multiple reflected waves around it. These reflected waves travel back to the radar's receiver, which amplifies the signal and records the reception time of the pulse. The radar system records the timestamp of pulse transmission and reception to compute the round-trip propagation delay. This time delay, denoted as Δt , is used to estimate the range R to the target using the relation (Leach et al., 1986):

$$\Delta T = T_R - T_T \quad (1)$$

Where T_R = receive time in second

T_T = transmit time in second

To know the distance of object toward the radar station, equation 1 was multiply with speed of light, c given as:

$$d = \Delta T \times c \quad (2)$$

$$d = \Delta T \times 300 \times 10^6 \text{ m/s} \quad (3)$$

Where d is distance

$$c = 300 \times 10^6 \text{ m/s} = \text{speed of light}$$

To show the object closed to the radar station, a polar plot is used. Figure 4 shows the common radar screen with polar plot used to determine the position of the object near to the radar station.

Figure 4 shows some detected object that are represented as red dots for a radar station. As can be seen from equation 3, time is dynamically changing and this causes the distance of the red dot plotted to change also. Therefore, the red dot keeps moving in the screen.

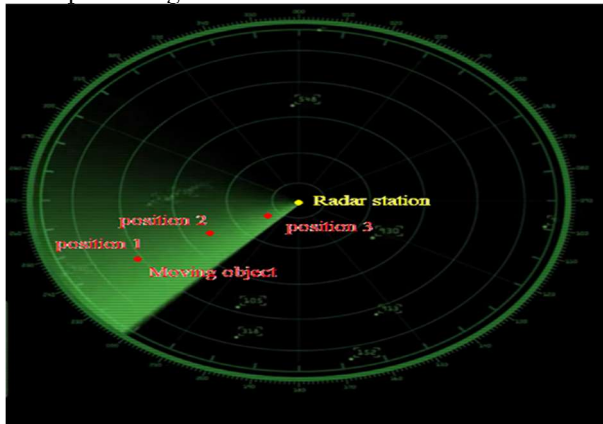


Figure 4: Commonly used radar screen (Li and Kiang, 2004)

In summary, once the distance of an object is known, the radar processor will quickly plot the location in the radar screen. This will show the distance of an object toward the radar station.

For the case of radar used in land vehicle, the concept is almost the same but the radar has to be modified in such a way that the size of the antenna and transceiver system are reduced. Apart from that, the antenna rotation has to be 180°

instead of 360° . This is because the radar used in the land vehicle is to detect the front object only and it has to be very far. If the processing of detected object using image processing method like the one show in Figure 3, then the radar cannot detect a far object. The image processing method can identify the object nearby the vehicle whether they are vehicle or static object. Advanced object detection can be enhanced using artificial intelligence (AI) technologies, which enable on-screen identification and classification of detected objects. However, this study does not employ image processing techniques, as such methods are generally ineffective for detecting distant objects. Moreover, front-facing object detection using image processing is already well-established in commercial applications, with several free implementations available on Android platforms (Gyorödi et al., 2017). Radar (Radio Detection and Ranging) is an electronic system that operates on the principle that high Radio Frequency (RF) signals reflect off conductive objects (Gyorödi et al., 2017). Typical targets include aircraft, missiles, ships, and vehicles. In radar operation, a signal is transmitted toward a target, and the reflected signal, known as an echo, is detected by the radar system (Li and Kiang, 2004).

This mechanism enables the determination of the target's range (distance), azimuth (direction), and sometimes its elevation (height above the horizon). Accurate distance measurement relies on the known speed of radio signal propagation.

In radar systems, distances are often measured in nautical miles instead of statute miles, where one nautical mile is approximately 6076 feet (Leach et al., 1986). Radio signals travel at a speed of 162,000 nautical miles per second. A radar mile, a unit specific to radar, equals 6000 feet. For context, a radio signal takes 5.375 microseconds to travel one statute mile and 6.18 microseconds to cover one nautical mile.

Since the radar signal must travel to the target and back, the total distance covered is double the target range. For instance, if a target is one nautical mile away, the signal takes 6.18 microseconds to reach the target and another 6.18 microseconds to return, totalling 12.36 microseconds from transmission to echo reception. The distance to a target is determined using the following formula (Li and Kiang, 2004):

$$D = \frac{T}{12.36} \quad (4)$$

In the formula, D represents the distance from the radar unit to the target in nautical miles, and T is the total time elapsed in microseconds (μs) between the signal's transmission and reception. For shorter distances, the yard is commonly used as a unit of measurement. Given that a radio signal travels 328 yards per microsecond, the distance to the target in yards can be determined using the following equation:

$$D = \frac{328T}{2} = 164T \quad (5)$$

A time measurement of $5.6\mu s$ corresponds to a distance of 914.8 yards. For strong reflections or echoes from distant objects, the radar signal's wavelength must be smaller

than the size of the target. If the wavelength is longer than the target's size, only a small fraction of the signal's energy will be reflected back. Higher radar frequencies, which correspond to shorter wavelengths, generally result in increased reflected energy from a target. For efficient reflection, the target's characteristic dimension should be at least one-quarter of the radar wavelength. When the wavelength is significantly shorter than the target size, the radar system achieves enhanced resolution and better definition, potentially capturing the object's shape with greater fidelity. Although basic object detection may only require coarse reflection, the use of shorter wavelengths enables high-resolution imaging and structural characterization.

The concept of Radar Cross Section (RCS) quantifies a target's effective reflectivity and is expressed in square meters. RCS represents the equivalent area that would intercept and scatter the incident radar signal back to the receiver. When a target's size exceeds approximately ten times the radar wavelength (λ), its RCS becomes relatively stable and independent of small changes in λ . RCS is influenced by several factors, including the target's size, geometry, material composition, aspect angle, and orientation. A larger RCS corresponds to stronger backscattered signals, improving detection range and enhancing the likelihood that the return signal exceeds the ambient noise floor.

The material composition of the target also plays a crucial role in the strength of the reflected signal (Gyorödi et al., 2017). Metallic surfaces are particularly effective at reflecting radar signals, though other materials may also contribute to reflections to varying extents. Some objects, however, absorb radar waves, significantly diminishing the reflected signal.

For example, the U.S. Air Force's F-117 stealth fighter, which has a physical cross section of around 1 square meter, is specifically engineered to deflect and absorb radar signals, minimizing its radar visibility (Leach et al., 1986). The aircraft's surfaces are designed with angled geometry, causing radio signals to deflect away from the radar unit rather than reflecting back, thereby minimizing or completely eliminating the energy received. Moreover, the aircraft is coated with materials that absorb radio waves, further reducing its radar cross section to resemble that of a small bird. The combined factors that determine the strength of the signal reflected from a target are encapsulated in the radar equation (Leach et al., 1986).

$$P_r = \frac{P_t G \sigma A_e}{(4\pi)^2 R^4} \quad (6)$$

Where P_r is received power, A_e is effective area of receiving antenna, G is antenna gain, R is range or distance to target and σ is cross section of target.

The relationships among the variables are generally simple to understand. However, since the received power diminishes with the fourth power of the distance to the target, it is not surprising that radar range is often limited. It's important to highlight that the radar equation doesn't consider the signal-to-noise (S/N) ratio, making low-noise receiver front ends essential for effective target detection.

As radar operates at microwave frequencies, it depends on line-of-sight communication, meaning it cannot detect objects beyond the horizon. Although objects do not need to be directly visible, they must fall within the line-of-sight range for detection. The connection between range, azimuth, and elevation can be depicted by a right triangle, as shown in Figure 5. In this example, assume the radar is ground-based and intended for aircraft detection. The distance between the radar and the aircraft forms the hypotenuse of the right triangle, with the angle of elevation representing the angle between the hypotenuse and the baseline, a line tangent to the Earth's surface at the radar's position.

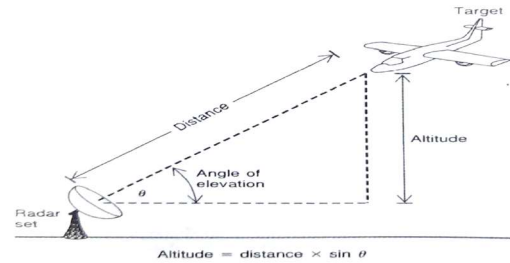


Figure 5: The trigonometry of radar (Leach et al., 1986)

Altitude is determined by the angle of elevation, where a higher angle of elevation corresponds to a greater altitude. By knowing both the range and the angle of elevation, altitude can be computed using basic trigonometric techniques. Another critical factor in detecting a distant object is understanding its direction relative to the radar system. For a fixed, land-based radar station, the direction is usually expressed as a compass bearing in degrees, where true north is 0° or 360° , east is 90° , south is 180° , and west is 270° . When the radar is installed on a moving platform, like an aircraft or ship, the azimuth is given as a relative bearing, based on the forward direction of the vehicle. In this case, straight ahead is 0° or 360° , directly to the right is 90° , directly behind is 180° , and directly to the left is 270° . To accurately detect the direction of a distant object, a highly directional antenna is essential. An antenna with a narrow beam width captures signals within a limited angular range (Leach et al., 1986). The narrower the beam width, the more accurately the radar can determine the object's precise bearing. Since most radar systems operate within the microwave range, it is relatively straightforward to achieve highly directional antennas.

Common configurations include horn antennas with parabolic reflectors, which can achieve beam widths of less than 1° . These antennas typically rotate continuously through 360° . The same antenna is used for both transmitting the original signal and receiving the reflected echo. The radar system's circuits are calibrated to ensure the direction the antenna is facing is accurately known. Once the echo is received, it is compared to the calibrated values, enabling precise determination of the direction. The radar's ability to calculate the altitude of a distant target depends on the vertical beam width of the antenna. The antenna may scan vertically while also measuring the object's distance. When the object is detected, the antenna's vertical angle is recorded, and the actual altitude is then computed.

Radar systems are typically classified into two main types: pulsed and continuous wave (Li and Kiang, 2004). Within these categories, there are various subtypes. The pulse radar is the most commonly used type of radar system (Gyorödi et al., 2017). In this system, signals are transmitted in short bursts or pulses, as shown in Figure 6. The duration or width of these pulses is very short, ranging from less than 1 μ s to several microseconds, depending on the specific application.

The time interval between successive pulses is known as the pulse repetition time (PRT). Once the PRT is determined, the pulse repetition frequency (PRF) can be calculated using the following formula (Li and Kiang, 2004):

$$PRF = \frac{1}{PRT} \quad (7)$$

For example, if the pulse repetition time (PRT) is 150 μ s, the pulse repetition frequency (PRF) would be the reciprocal of 150 μ s, which equals 666.7 Hz. The ratio of the pulse width to the PRT is known as the duty cycle, and it is usually expressed as a percentage:

$$Duty\ cycle = W \times \frac{100}{PRT} \quad (8)$$

The echo is received during the time interval between the end of one transmitted pulse and the beginning of the next pulse, as shown in Figure 6.

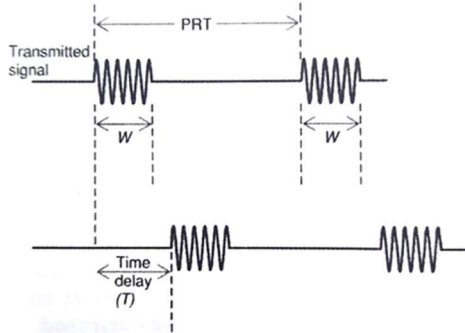


Figure 6: Pulsed radar signal [14]

According to research by Bhatta and Priya (2017), the estimated power required for a radar to detect distant objects ranges from about 1kW to 5kW. The research shows that increasing the power used by the radar allows the electromagnetic pulse to travel further. Not only is power important, but the antenna also plays a crucial role in enhancing the directivity of the pulse. The radar antenna must be a directional antenna for both the transmitting and receiving systems. In modern radar antenna design, the transmitting and receiving antennas are often placed side by side or integrated into a single unit, so that when the transmitting antenna rotates, the receiving antenna rotates along with it.

B. A Review of UWB Transmitter

This section outlines the types of Ultra-Wideband (UWB) transmitters used to generate UWB pulses for communication, noting that while different designs exist, they share common conceptual elements with variations in components. It includes a summary of these typical components, which are useful for UWB transmitter modelling in MATLAB. Figures 8 to 11 illustrate four UWB transmitter types from research sources, with Figure 8 detailing a transmitter that receives a TTL-generated digital pulse, features a driver circuit for the SRD, and has a high-frequency pulse-forming circuit.

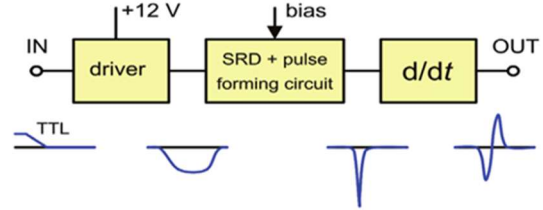


Figure 7: General block diagram of UWB transmitter [15]

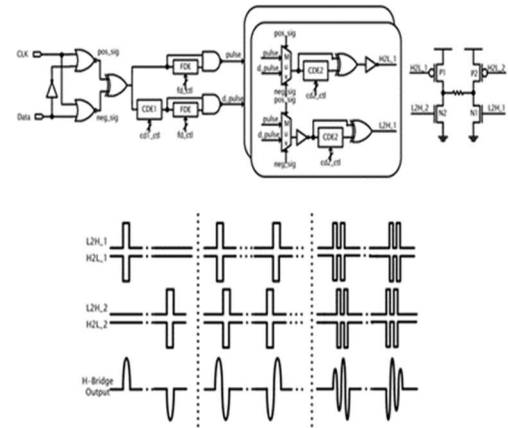


Figure 8: Detail of the UWB transmitter system using logic gates(Kozlov et al., 2022)

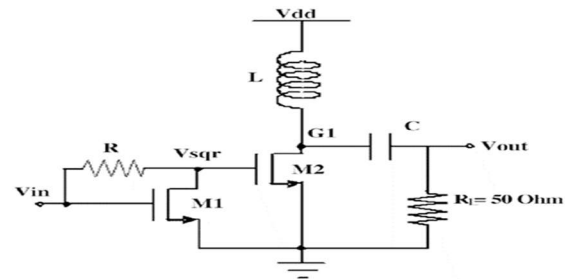


Figure 9: Simplify UWB transmitter (Coleman, 1945)

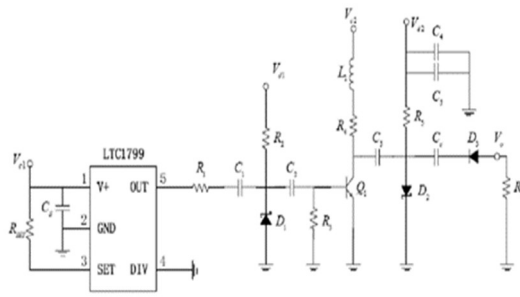


Figure 10: UWB transmitter using LTC 1799 IC (De Maio and Greco, 2016)

This section explains the workings of various UWB transmitter designs and their component roles. Due to the SRD circuit's biasing trigger, the input pulse has a brief, intense negative phase. A differentiator circuit showing logic gates that produce HIGH and LOW pulses, which are multiplexed into positive and negative UWB pulses is shown in Figure 8. An H-bridge MOSFET circuit then converts these into a high-frequency analog pulse for antenna transmission.

In Figure 9, MOSFETs M1 and M2, along with a resonant LC circuit and impedance-matching resistors, help radiate UWB pulses. Figure 10 introduces the LTC1799 IC for simplified pulse generation, with frequency control and digital-to-analogue conversion using diode and transistor circuits to maintain output consistency.

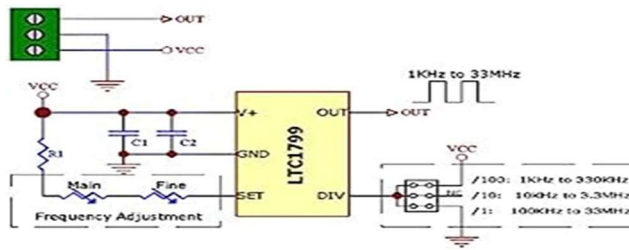


Figure 11: Test of LTC1799 IC to produce series of pulse (Linear Technology, 2016)

In summary, literature on UWB transmitters highlights the need for an initial logic circuit to generate pulse series, which are then converted into an analog equivalent to enable transmission as radio waves. Amplifier and tank circuits are essential for signal amplification and resonance. Ultimately, the UWB transmitter outputs a high-frequency analog pulse with a narrow bandwidth, effectively representing the original digital pulse.

C. Review of UWB Receiver

UWB receivers, illustrated in Figures 12 to 15, are designed to receive, process, and display information from UWB signals. While there are various designs, they generally share similar circuit blocks and system structures within the UWB receiver setup.

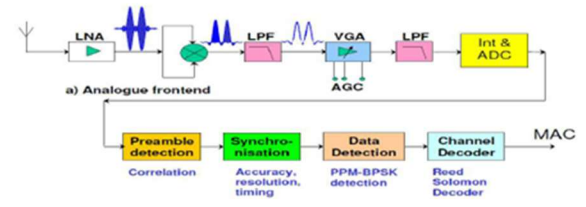


Figure 12: UWB receiver block diagram (Skapa and Pola, 2016)

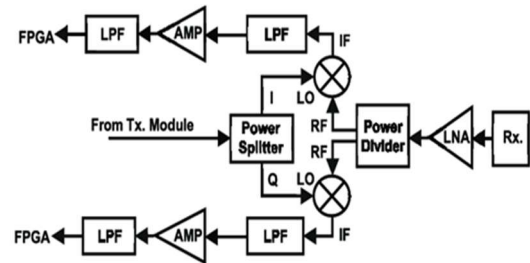


Figure 13: UWB receiver (Kumar and Parameshachari, 2023)

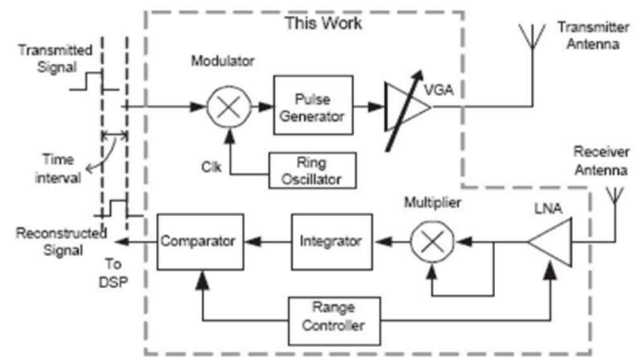


Figure 14: Radar transceiver circuit using UWB technology (Kuhn et al., 2010)

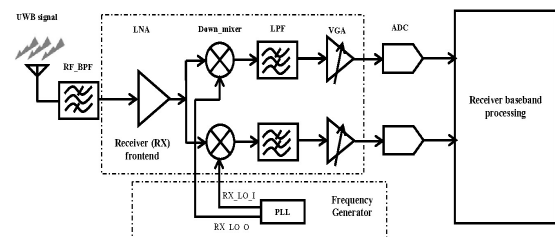


Figure 15: UWB Radar receiver block (Crepaldi et al., 2006)

The UWB receiver circuitry, depicted across Figures 12 to 15, involves several stages for signal processing. Figure 12 shows the key components: an LNA for signal amplification, a low-pass filter (LPF) for noise reduction, and an ADC to digitize the output. Once digitized, the signal undergoes preamble detection, synchronization, data detection, and channel decoding to extract information. Figure 13 adds a power divider to split the signal into I and Q components,

which are independently amplified and filtered before processing in an FPGA.

Figure 14 introduces a radar transceiver with a receiver circuit that multiplies the signal to decode it and uses an integrator and comparator to produce a digital output for DSP processing.

Lastly, Figure 15 shows a UWB receiver that splits the signal into I and Q channels, processes the I signal through an ADC, and manages phase alignment in the Q channel via a PLL. A frequency generator ensures synchronization, comparing the incoming and transmitted UWB signals to confirm the correct reception.

D. REVIEW OF RELATED LITERATURES

Table 1 summarizes the outcome of critical analysis of related literatures. The review focused on application, detection range, power consumption, signal processing

technique and limitation. From the existing literatures reviewed, the notable limitations include limited optimization and AI integration, short range and lack of adaptive beam control, manual power tuning and so on. This study aims to explore optimization techniques that enhance UWB radar's detection capabilities, extend operational range, and maintain compactness suitable for automotive integration. Key areas of focus include power management, pulse modulation, and radar cross-section minimization.

Table 1: Comparative Review of UWB Radar Systems for Vehicular Applications

Study	Application Focus	Detection Range	Power Consumption	Signal Processing Techniques	Limitations
Zhao et al. (2023)	Pedestrian detection	<10 meters	~500 mW	Basic threshold detection	Short range, no adaptive beam control
Hamaguchi et al. (2005)	Lane change assistance	~5 meters	~1 W	FMCW with analog filtering	Outdated modulation, lacks power control
Cheraghinia et al. (2024)	Urban object recognition	10 meters	~1.2 W	MATLAB-based pulse compression	No real-time optimization or AI integration
Bhatta & Priya (2017)	Long-range radar	>100 meters	1–5 kW	Manual power tuning	Unsuitable for compact vehicle deployment
Proposed Study	ADAS radar optimization	100–1000 meters	<1 W	Adaptive beamforming, AI control	Aims to combine low power with long range

III. MODELLING OF RADAR SYSTEM

This section details the modelling of a radar system aimed at detecting vehicles on the road using MATLAB, focusing on the development of a UWB radar system for automotive applications. The radar chosen is a long-range UWB radar operating at a centre frequency of 77 GHz, capable of distinguishing objects that are at least 1 meter apart and tracking targets with closing speeds of up to 230 km/h.

Key parameters for modelling include the object's position, speed, beam angle, error signals, direction, and distance from the UWB radar unit. The object's position is crucial for computing the distance, which must be updated with every movement. The beam angle determines the radar's coverage, with a narrow beam providing accurate single-object detection and a wider beam detecting multiple vehicles but being more prone to noise.

A. System Model in MATLAB

The UWB radar system is modelled using MATLAB Simulink to facilitate performance testing and optimization adjustments. MATLAB was selected for its communication library block set, which enables precise modelling of radar parameters such as pulse timing, transmission range, and radiation.

The initial step involves determining an equivalent model for the radar system, onto which the UWB concept will be applied. Previous studies have introduced various equivalent radar models, with an example illustrated in Figure 17. This model serves as a foundation for incorporating UWB technology into radar system design.

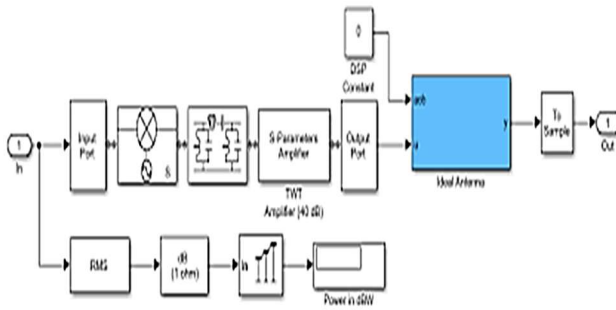


Figure 16: Equivalent model of radar system modelled using Simulink in MATLAB (Source: MATHWORK)

After establishing and designing the radar system model, the UWB system is modeled and integrated with it to form a complete UWB radar system for object detection. The final phase includes running simulations, analyzing results, and, if beneficial, creating animations. These animations would visually depict object placement and detection by the radar, aiding in model design and validation.

B. Design and Improvement of the UWB Radar Modelling

This section presents the modified and improved version of the UWB radar modelling system. The complete design is shown in Figure 17.

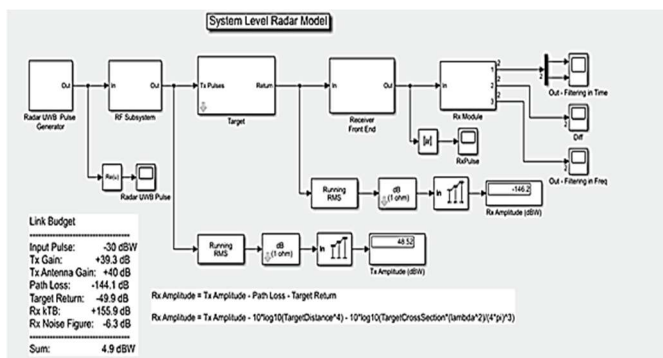


Figure 17: The new model and design of the UWB radar system

The model shown in Figure 17 is very similar to the one shown in Figure 16, except that the link budget is added to describe the radar signal propagation under virtual conditions. Let's examine each block and understand the designed model. On the far left is the radar UWB pulse generator. This block is crucial because it generates the UWB pulse.

Pulse Generation and Beam Control: The UWB pulse generator block in Simulink is set to generate discrete, narrow pulses optimized for vehicle radar systems. These pulses, sent at intervals of 50° , enable the radar to scan effectively from 0° to 180° and back, covering a comprehensive field of view. Each pulse's transmission and reception times are critical for calculating object distance and signal processing accuracy.

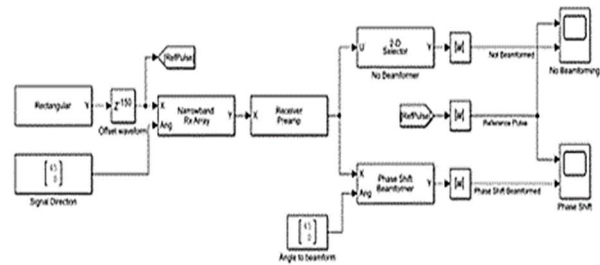


Figure 18: Beam forming for the antenna

Figure 18 is a proposed beam forming antenna block design for the UWB antenna. Notice the components in the beam forming antenna. The components build up the beam antenna are rectangular pulse, signal direction, offset waveform, reference pulse, narrow band array, phase shift, and angle to beam form. The beam forming antenna is important because it will direct the UWB signal in one direction for scanning purposes.

There are two scopes connected at the output of the beam forming antenna. The scopes are used to monitor waveforms formed by the beam. The result of the waveform should be the spectrum, which will be shown in the results section.

Optimization of Radar Cross-Section: The radar cross-section is reduced by adjusting the antenna configuration and transmission power, minimizing signal scatter and enhancing target detection. Adjustments to the radar's effective radiated power are made in MATLAB by tuning the S-parameter amplifier for improved gain.

IV. RESULTS

In the UWB pulse transmission and reception simulations conducted in MATLAB Simulink, optimized pulse timing has proven effective for object identification within a 1-kilometer range. By generating controlled, narrow pulses, the radar achieves high signal accuracy and consistent object detection across a 0° to 180° scanning range, as shown in the radiation patterns of the Simulink model. Figure 19 displays the generated UWB pulse, characterized by equal amplitude and periodicity.

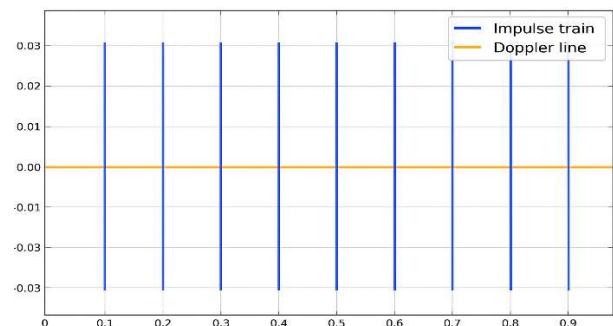


Figure 19: Simulation results for UWB signal

The UWB pulse is generated every 0.1 seconds, creating a pulse train over a 1-second duration to detect objects via the channel. The blue pulse is extremely narrow, with a nearly negligible width and amplitudes of ± 0.03 . This pulse, output from the UWB generator, is then multiplied by the carrier frequency, resulting in the UWB pulse shown in Figure 19.

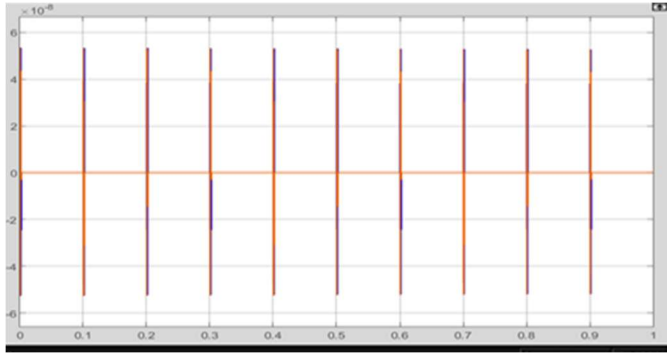


Figure 20: The UWB pulse in time domain added with carrier frequency signal

The graph describes two figures related to Ultra-Wideband (UWB) signals. Figure 20 illustrates the UWB pulse in orange and the UWB carrier in blue, highlighting that the carrier has a higher amplitude than the pulse. Figure 21 shows the UWB beam signal resulting from the beamforming process, indicating that at 150ms, the beam reaches an amplitude of approximately 1.3 in normalized units. Additionally, it notes that the UWB signal's waveform has a small amplitude due to the object being 4000 meters away from the transmitter.

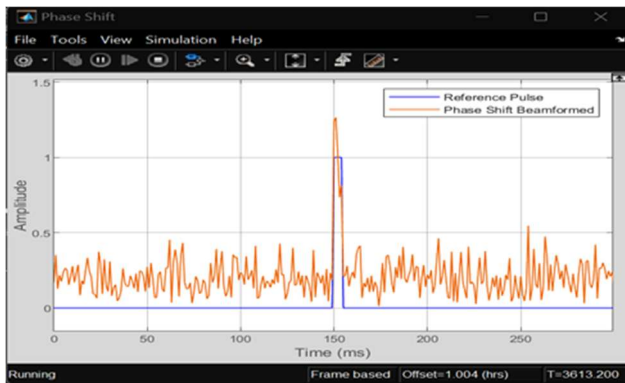


Figure 21: Simulation results when the UWB signal added with noise

The graph explains that the results in Figures 20 and 21 pertain to a target located 4000 meters away. It indicates that altering the distance will affect the waveform in Figure 20. The following section will present several cases demonstrating how the UWB received signal changes as the distance varies from 100 meters to 4000 meters, specifically without any noise in the channel.

Radar Cross-Section and Signal Reflection: Optimization of radar cross-section parameters yielded a significant reduction in signal scatter. As simulated in MATLAB, the adjustment of S-parameter amplifiers minimized the radar cross-section while maintaining the effective radiated

power required for clear signal reflection. The cross-section reduction also improved detection accuracy at longer ranges by mitigating interference.

Power Efficiency and Range Extension: Power management settings, including gain normalization to 1mW, demonstrated an efficient power-to-distance ratio. The radar system's ability to detect objects at approximately 1 kilometre was maintained even under reduced power conditions, with no substantial loss in detection quality. Results indicate a balanced design between power efficiency and effective range, essential for real-world vehicle applications.

A. Simulation Results with Object Varies Distance

Figure 22 shows the simulation results when the target distance is varies from 100 m to 4000 m. Note that random distances are selected to see the signal changed.

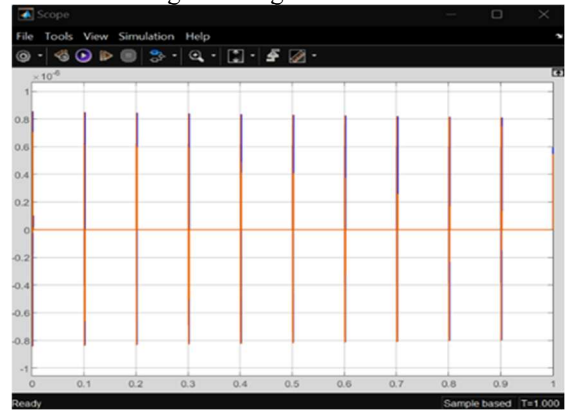


Figure 22 (a) Object detected when it is at 100m from the transmitter

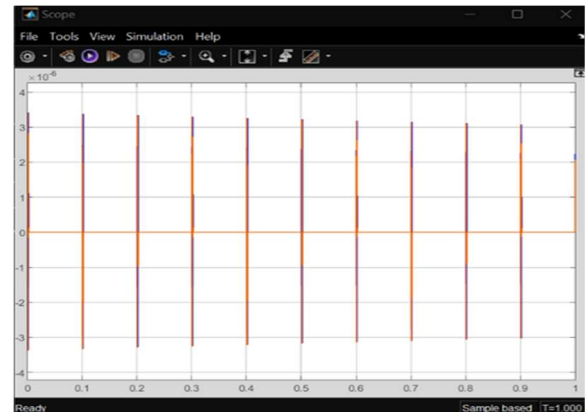


Figure 22 (b) Object detected when it is 500m from the transmitter

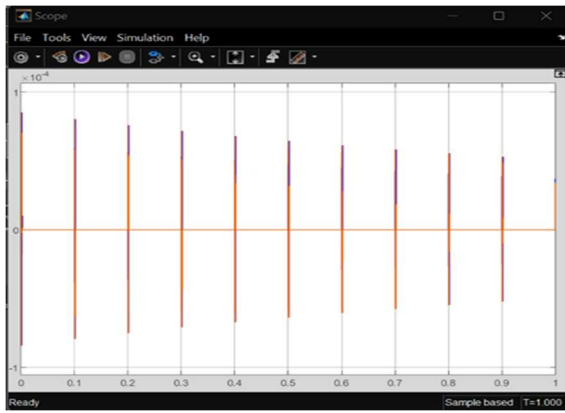


Figure 22(c) Objected detected when it is at 1000m from the transmitter

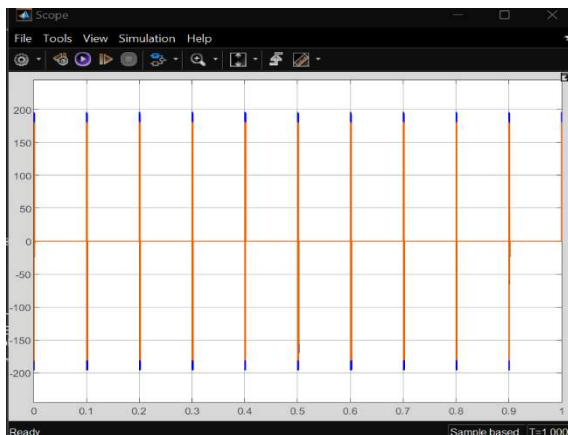


Figure 22 (d) Objected detected when it is at 4000m from the transmitter

Figure 22: The UWB signal changed when the object is varies from 1000m to 4000m

When the target is at far distance, the UWB amplitude is very small. The amplitude typically in micro range. On the other hand, if the target is very close to the transmitter, the amplitude is very large, typically in milli range as seen in Figure 22 (a). Compiling the results and performing simulation tests, table 2 shows the results of UWB signal amplitude versus the distance.

Table.2: UWB signal received without noise versus the distances

Distance (m)	Amplitude of UWB (mV)
100	5.06
500	3.22
1000	1.45
1500	0.67
2000	0.35
2500	0.21
3000	0.16
3500	0.08
4000	0.02

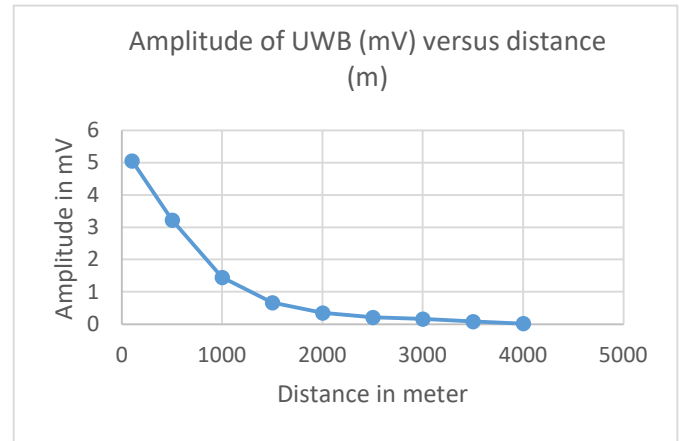


Figure 23: The plot for table 1

The received UWB signal's amplitude clearly shows an exponential decrease with increasing propagation distance, as seen in Figure 23. This trend is in line with the features of free-space path loss, where energy dispersion and attenuation cause the signal strength to drastically decrease with distance. Table 2 sheds quantitative light on this pattern by demonstrating that the received signal amplitude is 5.06 mV at 100 meters and gradually decreases to 0.02 mV at 4000 meters.

The UWB pulse is significantly degraded by distance alone, even without additional noise, highlighting the intrinsic restriction placed on long-range detection by propagation losses. Interestingly, after 1000 meters, the amplitude drops below 1 mV, reaching 0.67 mV at 1500 meters before sharply decreasing. This suggests that either signal amplification, antenna gain improvement, or sophisticated signal processing methods like matched filtering or pulse integration would be required for realistic radar applications in order to retain detection reliability beyond 1000 meters.

The simulation results validate the effectiveness of the proposed UWB model in detecting objects up to 1000 meters with acceptable signal strength, which aligns with the design objective of extending UWB radar capability beyond typical short-range applications (≤ 10 m). These findings also support the notion that radar system performance must be carefully engineered to account for signal attenuation over distance, especially when targeting long-range vehicular or environmental sensing scenarios.

V. CONCLUSIONS

An optimized UWB radar model for applications involving small vehicles was provided in this work, with a focus on compact design, low power consumption, and increased detection range. The system's ability to detect objects from 100 to 1000 meters was validated using simulations, which also showed that the signal amplitude decreased predictably with distance. Even in situations with low visibility, the radar can accurately detect stationary road dangers by combining narrow pulse creation with effective power control. These results provide a useful basis for smarter and safer car technologies like ADAS. Future research will concentrate on adaptive strategies and real-world hardware implementation to enhance performance in challenging driving situations.

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