An Over-the-Air (OTA) E-Band Radar Target Simulator for Automotive Radar Performance Evaluations

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***Abstract* — This paper presents an over-the-air (OTA) E-Band Radar target simulator (RTS) for automotive radar performance evaluations. The simulator is a single-sideband-modulation (SSM) based radar target simulator generating the Doppler shifts from the signals generated from the radar device under test (DUT) in the frequency range of 76 to 81 GHz. The simulator can simulate the target size, speed, and moving directions, receding or approaching, of the target so that the DUT radar system can be evaluated by the simulator for its system sensitivity, the accuracy of the speed, and the capability of detecting the moving direction of the target. In addition, with a calibrated signal delay of the simulator, the target simulator can be used for DUT radar system target distance (range) measurement accuracy evaluation. Inclusion of the simulator in an anechoic chamber with a 3D positioner further allows OTA radiation measurements at arbitrary angles. This setup is a cost-effective and practical system for automotive radar performance testing and evaluations in both laboratory and volume production environments.**

***Index Terms* — Millimeter-wave, E-Band, radar target simulator, single-sideband-modulator, automotive radar, doppler radar, ranging radar, FMCW, 3D positioner.**

I. INTRODUCTION

Automotive radar systems are rapidly becoming a critical component of advanced driver-assistance systems (ADAS) and autonomous vehicles, enabling reliable detection, tracking, and classification of objects under diverse environmental conditions. E-band (71–86 GHz) automotive forward-looking radar offers significant advantages for next-generation automotive sensing. Its wide bandwidth and small aperture size enables high range resolution, allowing precise discrimination of closely spaced targets in dense traffic environments. The shorter wavelength supports compact antennas and high-resolution beamforming, improving angular accuracy while reducing system size. E-band radars also provide enhanced Doppler sensitivity for accurate velocity measurement and better clutter rejection in complex urban scenarios. Collectively, these features make E-band radar well suited for advanced driver-assistance systems (ADAS) and autonomous vehicles, facilitating high-definition object detection and reliable performance under diverse driving conditions.

As the advancement of technology continues moving forward, the automotive radar developers and producers are seeking cost-effective radar target simulators for their development and production flows to accurately evaluate their radar performance under controlled and repeatable conditions. These simulators enable designers and testers to emulate real-world targets, velocities, and radar cross sections without the need for costly or potentially unsafe on-road experiments [1]–[3]. Industry wide, a variety of systems and solutions have been proposed, produced and established for E-band automotive radar system testing, employing different implementation techniques [4], [5].

In this paper, we present an over-the-air (OTA) E-band radar target simulator specifically designed for automotive radar performance evaluations. The proposed system is based on single-sideband-modulation scheme, which enables high-fidelity target emulation, including variable range, Doppler velocity, radar cross-section (RCS) characteristics, and moving target directions, thereby supporting comprehensive indoor testing of radar transceivers and signal processing algorithms. The architecture, design considerations, implementation details, and experimental validation are discussed, demonstrating the simulator's ability to replicate realistic automotive scenarios with repeatable, practical and accurate target metrics. Furthermore, by incorporating calibrated signal delay, the simulator supports evaluation of range detection accuracy of FMCW based radar systems for devices under test (DUTs). Experimental results obtained within a MilliBox MBX32 chamber further confirm the reliability and precision of the proposed approach. Owing to its cost-effectiveness and scalability, the simulator represents an effective solution for both laboratory research and large-scale production testing, as well as radar calibration for automotive manufacturers.

II. THE SIMULATOR TECHNICAL DESCRIPTIONS

It is well known that the relationship between the Doppler frequency and target speed is governed by the following equation:

$$F_d = \frac{2VF_{RF}}{C}\,cos\theta \qquad (1)$$

Where F_{RF} is the frequency of the transmitted signal from the DUT radar in Hz, C is the speed of light (3 x 10^8 meter/sec.), V is the target speed in travel in meters/sec., and Θ is the angle between the moving target and the radar beam. The two extremes are 1) no Doppler shift $Fd = 0$ when the moving target direction and radar beam are perpendicular ($\Theta=90°$) and 2) $F_d=2VF_{RF}/C$ when the moving target direction and radar beam are parallel or Θ is very small (0 to 10°).

The core technology implemented in the proposed radar target simulator is based on a single-sideband modulator (SSM). The simplified block diagram and signal flow are illustrated in Fig. 1. The radar signal transmitted by the device under test (DUT) is received at the antenna port and directed through a diplexer into the SSM. Depending on the I/Q phase configuration, the modulator shifts the incoming signal to either the upper or lower sideband and routes it back through the diplexer. The frequency-shifted signal is then re-radiated by the antenna, emulating a Doppler-shifted echo for the DUT to process.

Inside the DUT, this returned signal is mixed with the frequency of transmitter or local oscillator to produce an intermediate frequency (IF) equal to the applied modulation frequency. By adjusting the IF of the external function generator, the relative phase of the I and Q channels, and the routing attenuation, the simulator can emulate target velocity, motion direction, and radar cross-section (RCS). The required input modulation signal amplitude is ±10 Vp-p, typically.

The frequency of the applied I/Q signal directly corresponds to the simulated target speed, as it defines the Doppler shift frequency. Table 1 summarizes the relationship between IF frequency and target velocity at 79 GHz. The target simulator supports IF frequency settings from fractions of a hertz up to several gigahertz, enabling emulation of a wide span of target speeds. Consequently, simulation of different velocities from a few m/s up to hundreds of km/hr is achieved in a straightforward manner by simply tuning the I/Q frequency.

TABLE I
IF FREQUENCY VS. MOVING TARGET SPEED AT RF 79 GHZ

IF (Hz)	100	200	300	400	500
Speed (m/s)	0.19	0.38	0.57	0.76	0.95

In practice, the generation of a clean single-sideband (SSB) Doppler signal, as illustrated in Fig. 2, requires precise calibration of the I/Q input signals. Non-idealities in semiconductor devices and microwave circuitry introduce amplitude imbalance, phase error, and DC offsets that degrade sideband suppression. Although the theoretical condition assumes perfectly matched I/Q amplitudes with a ±90° phase shift, practical implementations demand fine-tuning of the I/Q amplitude, phase offset, and DC bias to achieve sufficient cancellation of the undesired sideband and ensure high spectral purity of the Doppler-shifted signal. While the Fig. 2 shows an upper-sideband (USB) scenario to emulate the approaching moving targets, the lower-sideband (LSB) setting of receding targets can be achieved by simply flipping the phase of the I/Q signal by 180°. The I/Q signals—with adjustable amplitude, phase, and DC offsets—are supplied by an external function generator, which is readily available today. Meanwhile, the ability to accurately simulate a low-speed target depends entirely on the short-term stability of the DUT's local oscillator, which in turn is inherently linked to the radar system's speed detection range.

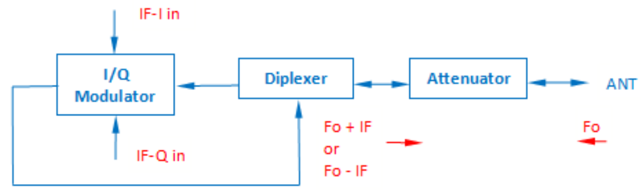

Fig. 1. Single-Sideband-Modulator (SSM)Based Target Simulator

To emulate target size, a programmable direct-reading attenuator is integrated into the radar target simulator. According to the radar range equation, the attenuator setting directly corresponds to the effective radar cross-section (RCS) and the associated detection sensitivity of the device under test (DUT). In particular, halving the effective detection range results in a 6 dB increase in attenuation, due to the round-trip signal propagation depicted in Fig. 1. The attenuator can be controlled either manually through a front-panel knob or remotely via a USB interface, thereby enhancing system flexibility for both laboratory testing and large-scale production environments.

A photograph of the E-Band radar simulator is shown in Fig. 3, where the programmable direct-reading attenuator provides precise and convenient control of the simulated target size. For more cost-effective implementations, the programmable attenuator may be replaced by a calibrated fixed-level setting model. Furthermore, by incorporating a standard gain horn, the simulator is readily configured for over-the-air (OTA) operation.

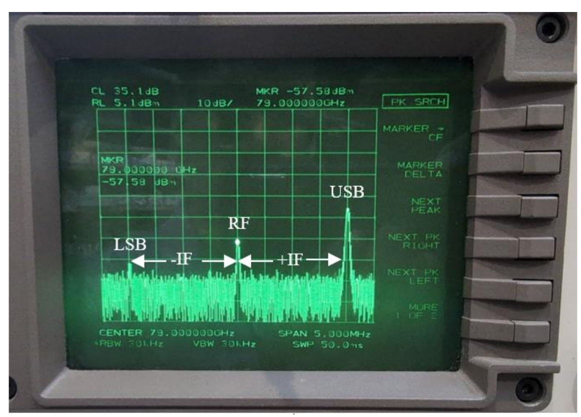

Fig. 2. Upper Side Band (USB) Doppler Signal

Fig. 3. Photograph of the E-Band Radar Target Simulator

If a radar system's sensitivity has been previously calibrated through on-road testing, the simulator's attenuator can be configured accordingly to establish a direct mapping between attenuation settings and DUT's detection sensitivity. This relationship can be recorded and maintained as a go/no-go threshold for production testing or laboratory evaluation. By referencing the attenuator settings to a calibrated radar unit, the relative sensitivity of a DUT radar system can be determined without performing actual road tests. Consequently, the simulator enables accurate, repeatable, and non-intrusive measurement of the DUT radar's sensitivity, providing a practical method for both R&D characterization and large-scale production quality assurance.

The S11 phase of the antenna port of the target simulator was measured using an E-band Vector Network Analyzer (VNA), as shown in Fig. 4. The group delay τ_g is obtained from the unwrapped S_{11} phase $\phi(f)$ according to

$$\tau_g = -\frac{1}{2\pi}\frac{d\varphi}{df} \qquad (2)$$

Where φ is in radians and f in hertz. The effective distance L is then calculated from the group delay as

$$L = \frac{c\tau_g}{2} \qquad (3)$$

Where c is speed of light and the factor of two accounts for the down-and-back travel time between the radar and the simulated target.

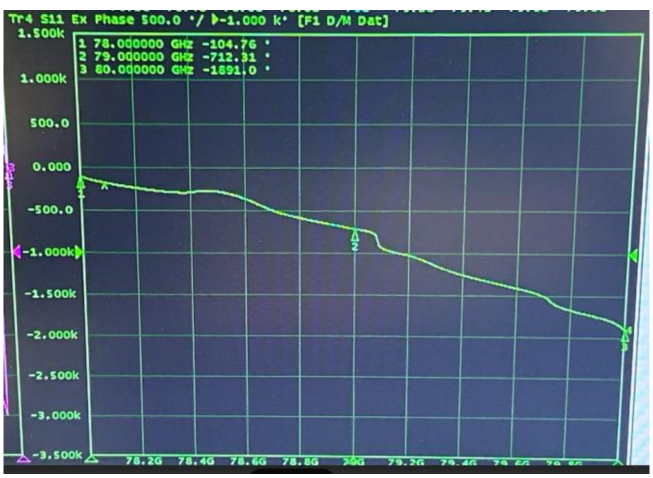

Fig. 4. Measured Phase Delay of the Simulator

From the above measured S11 phase, a group delay of τ_g = 2.48 ns was obtained with a corresponding distance of 0.372 m. Therefore, this distance should be added to the physical distance to determine the effective separation between the radar sensor and the virtual doppler target. To account for additional feature, such as, variable separation between the RTS and the DUT, a delay line or a controlled phase shift can be introduced between the RTS output and the antenna.

III. Over-the-Air (OTA) Evaluation

The radar system under test is a Texas Instruments E-band radar sensor evaluation board (model AWR1843AOPEVM). The evaluation board is an FMCW ranging sensor operating from 76 to 81GHz, capable of detecting both target distance and velocity. The AWR1843AOPEVM includes four receiver and three transmitter antennas on the package to provide a virtual MIMO array that can discriminate angle-of-arrival in elevation and azimuth. The radar sensor is running the default out-of-box (OOB) demo provided with the evaluation kit which allows adjustment of the radar chirping signal parameters to trade off the maximum range, range resolution, maximum velocity, and velocity resolution. The scene was chosen to optimize for short range and to provide good velocity resolution at lower maximum speed as shown in Figure 5.

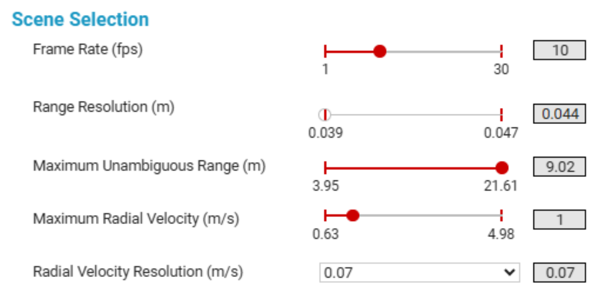

Fig. 5. TI 1843AOPEVM scene settings

Before mounting the simulator into the MilliBox MBX32R anechoic chamber for DUT radar performance evaluation, a bench-top open-air setup was assembled for functionality checking. As expected, the radar sensor is detecting many spurious objects at different distances due to the open-air environment.

Further evaluation of the radar sensor was performed by placing the radar target simulator inside a MilliBox MBX32 compact anechoic chamber and mounting the DUT on a GIM04X 3-axis positioner, as shown in Fig. 6. The chamber provides > 50dB of isolation in E-band and the positioner can move the DUT in azimuth, elevation, and polarization with an accuracy of < 0.1°.

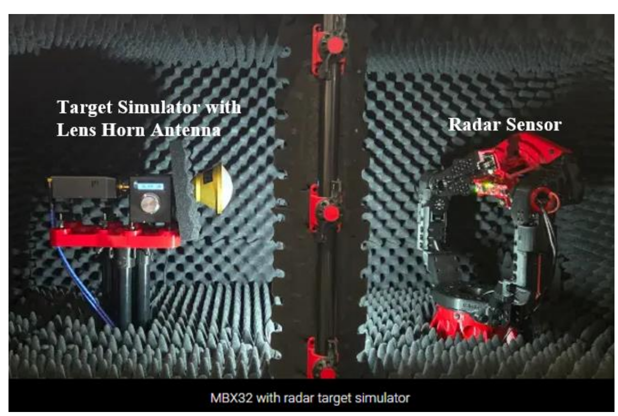

Fig. 6. MilliBox MBX32 Chamber with Radar Target Simulator

The effectiveness of the mmWave absorbers can be seen by testing the radar with the doors open and doors sealed shut and comparing the power vs. range profile for zero doppler (static objects) in Fig. 7. While the target is detectable in both cases, testing inside of a chamber greatly suppresses the spurious reflections and maximizes the dynamic range of the measurement system to get the true performance of the DUT.

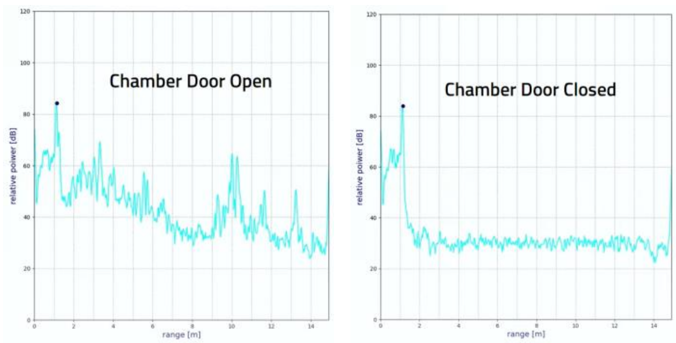

Fig. 7. Power vs. Range Profile Measured with the MBX32 Chamber

Using the 3-axis antenna positioner that can precisely rotate the radar sensor relative to the target simulator enables the radar to be characterized for its radiation pattern and polarization, beamforming accuracy, angle-of-arrival (AoA) estimation, and SNR coverage, to name a few. These types of tests allow for tuning of the chirp signal and detection algorithms to maximize the SNR and avoid blind spots and ghost objects.

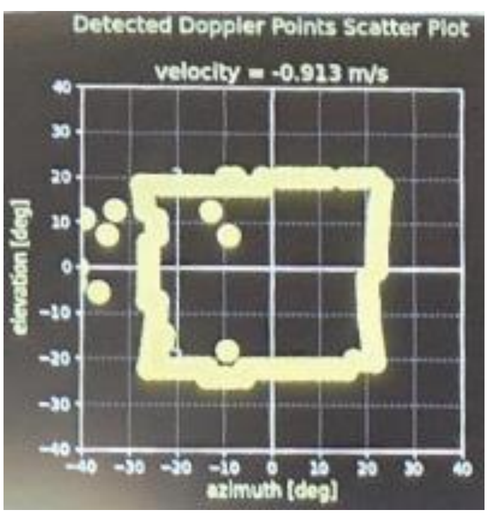

Fig. 8. Points Detected by Radar when Moving in a Square Pattern

As an example, Fig. 8 shows a test where the target simulator is set with an IF frequency equivalent to a doppler velocity of -0.9 m/s and the radar sensor board is moved in a square pattern of +/-20° in both azimuth and elevation. The figure shows that the radar has up to 8° error in AoA estimation at larger negative azimuth angles which could indicate inaccurate phase shifters, uncalibrated antenna gain, or insufficient virtual MIMO antennas. The accuracy of the external I/Q function generator is much better than the 0.07 m/s velocity resolution of the chirp signal, so the velocity test is limited by the DUT, not the RTS.

IV. Conclusion

The proposed system employs a single-sideband modulation (SSM) architecture to generate Doppler-shifted echoes in the 76 to 81 GHz band, enabling accurate emulation of receding and approaching targets. By adjusting the modulation parameters, the simulator can reproduce different target sizes, velocities, and motion directions, thereby allowing the (DUT) to be evaluated in terms of sensitivity, velocity estimation accuracy, and directional discrimination.

Furthermore, with the inclusion of calibrated signal delay, the simulator supports the assessment of range measurement accuracy, providing a comprehensive validation platform for automotive radar systems. Owing to its compact design, cost-effectiveness, and adaptability, the proposed simulator is suitable not only for research and laboratory characterization but also for large-scale production testing. This makes it a practical and scalable solution for advancing the reliability and performance of E-band automotive radar sensors.

The simulator was further included inside a MilliBox MBX32 anechoic chamber with 3D DUT positioner, and a Texas Instruments E-band radar sensor evaluation board with model number AWR1843AOPEVM was tested. This setup allows for a controlled environment to test over-the-air (OTA) radiation and ensure that the radar sensor satisfies the performance requirement in all directions.

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