A High Bandwidth Radar Target Simulator for Automotive Radar Sensors

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***Abstract*—In this paper, the construction of a modular target simulator for automotive radar sensors is described. Using a fully analog design, the simultaneous covering of all E-band automobile radar bands is possible. Static scenarios and moving targets with realistic parameters can be simulated.**

I. Introduction

Advanced driver-assistance systems make use of several sensors to gather information about a car's surroundings; the sensors include cameras, radar, lidar, and ultrasonic sensors. Radar sensors are advantageous because they are weather independent and can be mounted at a hidden position without affecting the car's design. In contrast, camera systems and human drivers have the same weather-related problems in bad weather, e.g., fog or heavy rain.

However, verifying that the radar sensors are operating in a correct manner is a challenging task. It is impractical to place real targets in front of a radar sensor because distances up to $250\,\mathrm{m}$ must be covered for long-range radar systems. Additional challenges include testing radar sensors with moving targets and the need for a reproducible test environment. With increasing use and integration of radar sensors, there is a growing demand for testing a sensor's functionality in various situations using radar target simulators. Radar target simulators are used to simulate targets at large distances; they are directly placed in front of the radar sensor typically inside a measurement chamber. Radar target simulators offer multiple benefits for developing radar-based driving assistance systems. These simulators are useful in the following areas: developing sensors; production in automotive supply industry; and the development and testing of driving assistance systems by the car manufacturer. Radar target simulators can be used in the after-sales market for testing driving assistance systems in maintenance and inspection without driving the car.

II. Automotive Radar

Automotive radar systems mainly use two frequency bands; one at approximately $24\,\mathrm{GHz}$ (K-band) and the other at $79\,\mathrm{GHz}$ (E-band). Historically, most sensors used the K-band because competitive E-band hardware was not available. Current systems still use K-band frequencies at the short range devices band ranging from 24 to $24.25\,\mathrm{GHz}$ for simple applications, e.g., side assist. However, most sensors are now using E-band frequencies because they provide higher bandwidth and, consequently, better range resolution, which is often needed. Two adjacent frequency bands are available within the E-band. A long-range radar (LRR) band can be used from 76 to $77\,\mathrm{GHz}$; a short-range radar (SRR) band may be used from 77 to $81\,\mathrm{GHz}$. However, global allocation of this SRR band is still in progress. This band will provide range resolution in the region of centimeters. Historically, a frequency band from 21.65 to $26.65\,\mathrm{GHz}$ in the K-band has been used for SRR. This bandwidth has been allocated for marketing new devices until 2018 and, consequently, is not interesting for any new designs [1].

III. Simulation of Radar Targets

A. Overview

To simulate a radar target, the transmitted signal of the radar device under test (DUT) must be transmitted back to the DUT with a given delay and amplitude. To accomplish this task, a receiving antenna is placed at a convenient distance from the DUT. After delaying the signal by a defined time interval it is transmitted back to the DUT using a transmitting antenna, which is usually located next to the receiving antenna. The well-known radar equation

$$\frac{P_\mathrm{r}}{P_\mathrm{t}} = \frac{G_\mathrm{t} G_\mathrm{r} \sigma \lambda^2}{(4\pi)^3 R^4} \tag{1}$$

is given in [2] wherein P_t and P_r describe the transmitted and received power, G_t and G_r describe the gain of the transmitting and receiving antennas, σ is the radar target cross section, λ is the wavelength and R is the maximum distance from the target to the radar for a radar target simulator setup.

The distance at which the DUT will detect the simulated target depends on the distance ρ between the antennas of the radar systems and the antennas of the target simulator as well as the delay τ of the target simulator between the receiving and transmitting antennas. For automotive radar systems, the propagation medium is air; it is assumed that propagation occurs in free space and with the speed of light c_0. Hence,

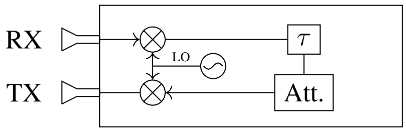

Fig. 1. A simple radar target simulator design.

the simulated target distance R as seen by the radar sensor is calculated according to Eq. 2.

$$R = \rho + c_0 \cdot \tau / 2 \tag{2}$$

Using Eq. 1 and assuming free space propagation between the radar sensor and the target simulator the simulated radar cross section σ can be derived. According to Eq. 3, the radar cross section depends on the simulated target distance R, the simulator distance ρ, the center frequency of the radar f_c, the overall attenuation α of one loop through the simulator as well as the gain G_{rx} and G_{tx} of the receiving and transmitting antennas, respectively.

$$\sigma = \frac{\alpha(\rho + R)^4 G_{rx} G_{tx} (c_0/f_c)^2}{4\pi\rho^4} \tag{3}$$

Fig. 1 shows the basic setup of a radar target simulator. It is beneficial to convert the frequency band used by the radar sensor to an intermediate frequency (IF) because the millimeter-wave frequencies used in automotive radar sensors are difficult to handle. Delay and attenuation can then be adjusted as required.

If necessary, a basic radar target simulator system can be extended to simulate more target properties. A target moving in a radial direction to the radar sensor will change its distance to the sensor and produce a Doppler frequency shift. The power received by the radar sensor will decrease with distance because a target usually does not significantly change its radar cross section. To simulate this behavior, the target simulator must have a mechanism to change the delay and attenuation introduced and introduce a frequency shift. The change in delay can be produced by switching between different cable lengths. A frequency shift can be produced by a chosen offset in the local oscillator (LO) frequency for the up- and down-converters. The change in attenuation can be achieved with a variable attenuator. If the radar sensor can measure the angle of the target and simulation of this target attribute is desired, either the sensor or the target simulator will have to be accordingly rotated.

B. Simulated Target Bandwidth

Automotive radar systems can use a bandwidth of up to $4\,\mathrm{GHz}$ in the $79\,\mathrm{GHz}$ SRR band; however, newly emerging sensors will likely only use parts of the available bandwidth. The adjacent LRR band provides a $1\,\mathrm{GHz}$ bandwidth. Therefore, in the foreseeable future, a simulation bandwidth of $5\,\mathrm{GHz}$ will adequately cover all bands simultaneously. For 24-GHz radar systems, there is a temporary allocation of a $5\,\mathrm{GHz}$ band available for SRR systems.

An automotive radar target simulator covering a bandwidth of $5\,\mathrm{GHz}$ is adequate for current and future sensors. As several sensors do not use the entire available bandwidth, using systems with less bandwidth is possible. However, LO frequencies of up- and down-converters must be adjusted for sensors using different operating frequencies.

C. Practical Approach

On a typical car journey, a radar sensor detects objects including other cars, road users, and characteristics of the road and objects next to the road. For the radar sensor, these objects are not necessarily single-point targets but may comprise many scattering centers that are detected as different radar targets. Then, it is the task of the processor inside the sensor to merge all these single targets detected by the sensor's low-level interface to a smaller number of larger objects. Lists of these higher-level objects are then transmitted to a management component that collects data from different sensors and provides further functionality [3].

A simulation of a real-world scenario by injecting generated target signals at the radar's operating frequency into the radar sensor is nearly impossible because such a scenario comprises many objects; however, in many cases, this is not needed. There is a need to evaluate single aspects of a sensor for production, development, and testing. Specifically, it is useful to verify the maximum specified target distance that the sensor can detect and to test a sensor's functionality under special conditions, e.g., an electromagnetic compatibility test. In many tests the simulation of a single target in one angle is sufficient so complicated test setups can be avoided. Furthermore, a minimal test case is easier reproducible because fewer components and parameters are needed.

For a radar target simulator, controlling the precise delay of the transmitted radar signal is important. Multiple approaches are feasible to achieve this. One approach is implementing the delay using the propagation delay of fixed cable lengths. Another approach is controlling the necessary delay in the digital domain using converters between analog and digital signals. An analog design was chosen for implementing a target simulator with a high bandwidth because the available components for conversion between digital and analog signals have limited bandwidth; in addition there is a latency that limits the minimum achievable simulation distance. The propagation delay for a returning signal from a target at a 10-m distance is $67\,\mathrm{ns}$. The maximum acceptable latency for a digital system is less than this value when considering the distance between the target simulator and the radar sensor as well as the delay of internal cables connecting the components inside the target simulator.

D. Implementation of the Delay Line

Coaxial cables are widely available at little cost for frequencies up to $18\,\mathrm{GHz}$ and beyond. However, cable attenuation may be an issue for long cables, particularly at high frequencies. Coaxial cables are not optimal for the realization of long delays, which are common for typical radar targets. Optical fibers are an alternative choice to coaxial cables. Converters from electrical to optical systems are readily available for bandwidths of a few GHz up to $40\,\mathrm{GHz}$. Converters use laser diodes as transmitters and photo diodes as receivers. The small size of optical fibers in comparison to coaxial cables is advantageous; despite the small size, optical fibers exhibit little loss. Optical fibers enable the integration of long delay lines within a decent space. Another advantage of optical fiber lines is their immunity to outside electromagnetic fields as well as their good stability over a range of temperature changes; these advantages result in stable simulated targets.

The simulation of multiple targets can be achieved by splitting and combining optical fibers; however, care is required to avoid interferences by coherent optical signals. Independent laser or photo diodes may be necessary. Changes in target distance can be realized by changing the active fiber segments using optical switches.

Optical fibers can be manufactured that provide greater than centimeter-scale precision, even for long fibers with lengths over $100\,\mathrm{m}$. This level of precision is acceptable for automotive applications especially for long distances where the exact target position is less important. Inaccuracies in fiber length can be precisely measured; therefore, the true delay is known and can be integrated into target simulation modeling and correction.

IV. A Practical Radar Target Simulation System

In this section, a practical implementation of an analog radar target simulator for 76 to $79\,\mathrm{GHz}$ is presented. The delay line was implemented using optical fiber cables. Moving targets can be simulated by controlling of optical switches in combination with fibers of different lengths. A Doppler frequency shift can be simulated by adding an offset to the up-converter's LO. Changing the reflected power of the simulated target via a variable attenuator to simulate a realistic target's behavior is possible while the simulated distance is changing. The detailed simulator setup is presented in the following sections.

A. RF Front-End

The RF front-end comprises two independent mixers; a down-converter and an up-converter. The LO inputs are connected to two programmable phase-locked loops (PLL), which are connected to the same reference oscillator. An LO frequency of approximately $75\,\mathrm{GHz}$ is used; this gives an intermediate frequency range of approximately 1 to $6\,\mathrm{GHz}$ for the full radar band. The up-converter LO frequency can be adjusted to higher or lower frequencies to generate a Doppler frequency shift. The RF side provides two E-band waveguide flanges where the transmitting and receiving antenna can be connected. The transmitted signal contains the LO frequency as well as the lower sideband. If these signals provide problems a waveguide filter can be added.

For some applications, the use of two separate antennas for receiving and transmission is problematic. In this case, a coupler can be added allowing the receiving and transmitting waveguide ports to be connected to a single antenna. Care is required for the isolation provided by the coupler and the match of the waveguide components because part of the up-converted signal will couple back to the receiver and produce unwanted additional targets in roughly twice the simulated distance. Additionally, in a simulation of the Doppler shift, the shifted LO frequency of the transmitter can couple to the receiver and produce unwanted mixing products. To overcome these problems, a waveguide filter at the up-converter HF port can be used. Additionally, a suppression of spurious emissions of the LO frequency and the lower sideband will be achieved.

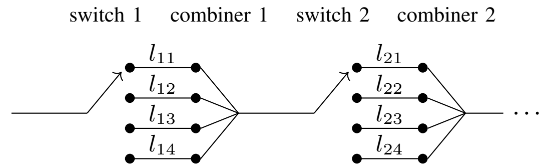

Fig. 2. Schematic layout of the adjustable delay line.

B. Adjustable Optical Fiber Delay Line

The delay line is implemented via fiber cables. An optical transceiver with a bandwidth of $4\,\mathrm{GHz}$ is currently used to convert electrical and optical signals and vice versa. Furthermore, an increase in the bandwidth to $6\,\mathrm{GHz}$ is planned to cover the full radar band. Optical fiber cables of different lengths are used as delay lines.

The system has been designed to be both cost-effective and modular. Fiber cables are relatively inexpensive but the transceiver and optical switches are expensive; consequently the use of switches has been minimized. Half of the switches can be avoided by replacing them with optical combiners. In this configuration, an n-port combiner adds an optical power loss of at least $3^{\mathrm{ld}\,n}\mathrm{dB}$. The delay line was designed to allow for the simulation of targets up to $87\,\mathrm{m}$. The step size was chosen as $30\,\mathrm{cm}$, which is equal to the cell size range of a sensor with a $500\,\mathrm{MHz}$ bandwidth. This has been proven to work well with commercial LRR sensors.

The design shown in Fig. 2 was achieved with four stages; each stage comprised one optical four-port switch and one optical four-port combiner. The delay of the optical fibers was chosen to provide a maximum switchable delay range while keeping the step size over the full distance range. The necessary fiber length l can be calculated for the switch in the kth stage and jth position with a step size s as follows:

$$l_{kl} = s \cdot 4^{k-1} \cdot (j-1) \tag{4}$$

For s equal to twice the minimum target step size, which is required in the delay line, the first stage requires electrical fiber lengths of $0\,\mathrm{m}$, $0.6\,\mathrm{m}$, $1.2\,\mathrm{m}$ and $1.8\,\mathrm{m}$. Accordingly, the lengths for the second stage will be $0\,\mathrm{m}$, $2.4\,\mathrm{m}$, $4.8\,\mathrm{m}$ and $7.2\,\mathrm{m}$.

The theoretical optical attenuation of this setup is $24\,\mathrm{dB}$ assuming loss-less switches and ideal combiners. As an effect of the optical modulation the resulting electrical attenuation

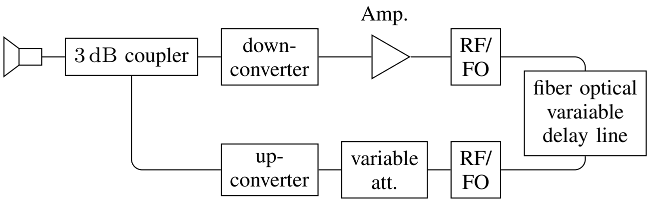

Fig. 3. Schematic layout of a complete analog radar target simulator.

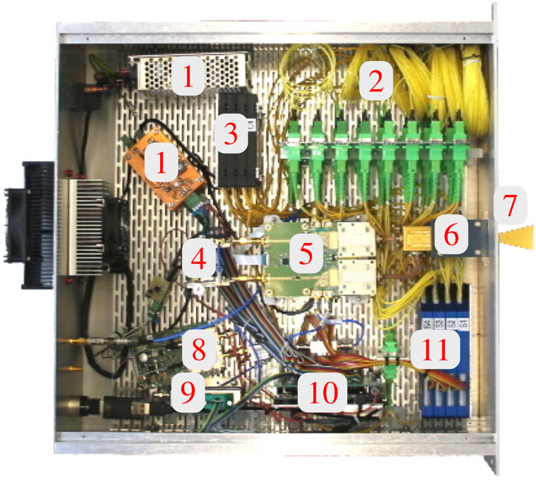

Fig. 4. Picture of the fully assembled radar target simulator, showing (1) power supply, (2) fiber delay line, (3) optical combiners, (4) PLL, (5) up- and down-converter, (6) coupler, (7) horn antenna, (8) optical transceiver, (9) programmable attenuator, (10) control logic, and (11) optical switches.

will be twice the value of the optical attenuation in dB. This must be considered while calculating the overall system attenuation.

C. complete target simulator setup

Fig. 3 shows the schematic of the full target simulator setup. Fig 4 shows a picture of the built device with descriptions of the used components. The device is able to simulate one target at a time. Static targets of different lengths in the range from 0 to 76.5 m can be simulated as well as dynamic targets moving within this range; this range excludes a fixed offset of about 10.5 m seen by the radar when the minimum length target is selected. To simulate real-life behavior, a Doppler shift was added that matched the movement pattern. For test purposes, a Doppler shift can also be added to a static target.

V. Measurements Results

Fig. 5 shows the measurement results of a simulated target at three different distances. The measurements were performed using a network analyzer and a distance of 1 m between the network analyzer antenna and radar target simulator antenna. The target distances have been set to the minimum and maximum available distances as well as a value in-between. At a distance of 1 m, the reflection of the horn antenna of the radar target simulator is seen. The further visible peaks correspond to the simulated targets.

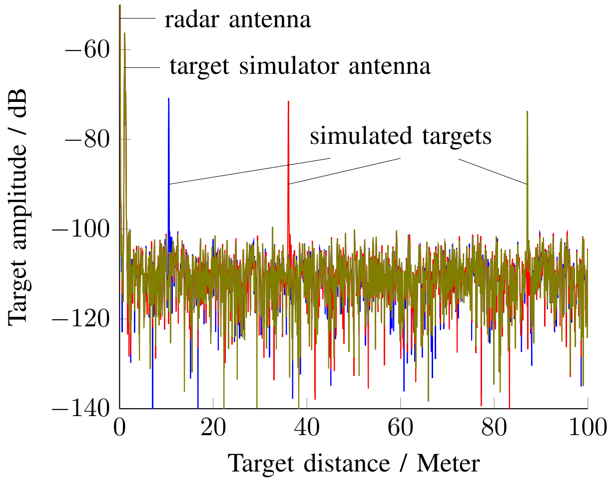

Fig. 5. Measurement results of simulated targets at 10.5 m (blue), 36 m (red), and 87 m (green). The measured bandwidth ranges from 76 to 79 GHz.

VI. Typical Applications

There are several applications for the simulation system described herein. Possible scenarios include quality assurance and measurement in production lines for radar sensors and the for development and verification of sensors, especially in hardware design. Further applications include providing sensor input data in electromagnetic compatibility measurements for a radar sensor. Other radar applications are possible because the design is not limited to automotive radar systems. However, for these applications, the desired parameters must be closely examined as they may differ from that of automotive radar systems. For example filling sensors for industrial tanks use radar technology and similar frequency bands. For these applications, sub-millimeter accuracy is an important parameter but the Doppler shift is less important.

VII. Conclusion

In this paper, the design for a radar target simulator for the 76 GHz and 79 GHz bands has been shown. Simulating a target in the range of 10.5 to 87 m with a step size of 30 cm is possible. The currently realized system provides a bandwidth of 76 to 79 GHz with an extension to 81 GHz planned; eventually, the full automotive frequency band is planned. To emulate the characteristic of a real moving target, a Doppler shift and a variation in received power were simulated in accordance with the change in distance. The design comprises entirely analog components; consequently, it is highly customizable and adaptable to many needs.

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