Digital True Time Delay for Pulse Correlation Radars

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Digital True Time Delay for Pulse Correlation Radars

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***Abstract*—A novel concept for digital true time delay pulse correlation radars using digital programmable delay lines and monolithically integrated radar front-ends is investigated. The effects of quantization errors on side lobe level and deviation of beam direction due to the digital true time delay lines are evaluated by numerical simulations based on the performance of commercially available time delay units.**

To verify the simulation results, a compact 26 GHz active electronically steered linear antenna array consisting of 8 elements has been realized, which provides beamforming in both transmit and receive path. Measurement results and design details of this steerable radar sensor are presented in the experimental part of this paper.

I. Introduction

The flexibility to point the antenna beam in any direction at any time is the most important advantage of active electronically steered antenna arrays [1]. The beam steering can either be done with phase shifters or with true time delays. Phase shifters are typically frequency-dependent and hence limit the bandwidth due to beam squint. A large bandwidth, however, is crucial for good range resolution.

This bandwidth restriction can be eliminated by using true time delays instead of phase shifters creating benefits for industrial short range sensors with high range resolution. If true time delays are implemented as switched sections of transmission lines in the transmit and/or receive path at RF frequencies, these units require large chip or PCB area and suffer from insertion loss of the switches making them impractical for many applications [2].

Regarding the commonly used principle for pulse radar front-ends in level measurement based on correlation [3], also termed as sequential sampling pulse radar [4], these disadvantages can be overcome. Instead of delaying the high frequency signals, the required time delay units for beam-steering can be realized as baseband digital circuits delaying the trigger-signals of the transmit (TX) and local oscillators (LO) according to the desired beam direction.

The combination of pulse correlation radars (PCR) and true time delay units results in a low complex imaging radar with high bandwidth. The simple data analysis of the pulse correlation radar with low sampling rates remains unchanged. By programming digital delay lines the beam direction can be steered, complementing the range information by the angular information.

In Section II the novel concept for beamforming is presented. In Section III the effects of quantization errors and their influence on side lobe level and deviation of beam direction are discussed. In Section IV a realization of the true time delay beamformer based on pulse correlation radar ASICs and commercially available delay lines is presented. In Section V the simulation results are verified by measurement results.

II. System Concept

The block diagram in Fig. 1 illustrates the system configuration of a single transmitter-receiver (TR) module of this concept. It can be subdivided into

- time delays,
- pulse correlation radar,
- antenna,
- bandpass amplifier.

The functional principle of a pulse correlation radar is based on two slightly different pulse repetition frequencies f_{PRF1} and f_{PRF2} which trigger the TX and LO oscillators whereby their pulses drift apart from each other and so the measurement range is sequentially sampled. If the time difference between the activation of these oscillators corresponds to the time of flight caused by a target, LO and the reflected pulse arrive at the mixer inputs at the same time. Consequently the result of the multiplication is maximum. Thus, to evaluate the time of flight or distance, the maximum of the mixer output has to be detected.

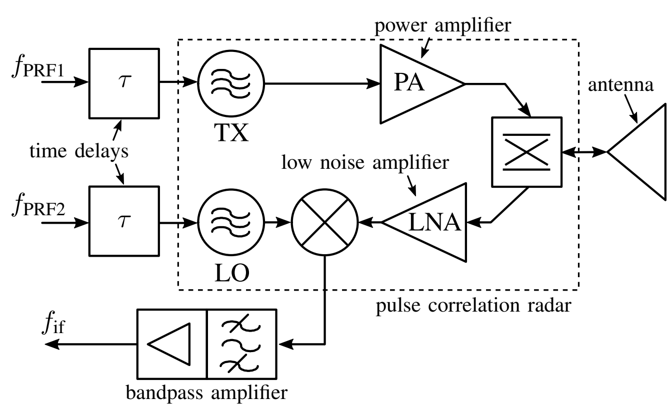

Fig. 1. Concept of a TR module consisting of a pulse correlation radar, digital programmable time delay units to individually delay the pulse repetition signals for transmit and receive, an antenna, and a bandpass amplifier.

By connecting several TR modules with common pulse repetition signals and individually delaying them, the beam can be steered in a predetermined direction. This can be done in transmit and/or receive path. Fig. 2 illustrates the principle for beamforming in the transmit path.

III. Quantization Errors

The quantization errors due to the digital delays will result in an increased side lobe level and a deviation of the beam direction [2]. According to Fig. 2, the delay time between each antenna can be calculated with

$$\tau_{n+1} - \tau_n = \Delta\tau = \frac{d_x \sin\theta_0}{c_0} \qquad n{=}1{,}2{,}3 \tag{1}$$

where c_0 is the speed of light, d_x the element spacing, and θ_0 the desired beam direction with respect to the boresight direction [5]. Tab. I shows the required time delays for an 8-element array with an element spacing of d_x=7 mm. The required time delays for this configuration are in the double-digit picoseconds range. At the time of this writing, there are time delays commercially available with a resolution τ_{LSB} of 3.3 ps, 5 ps, and 10 ps leading to considerable quantization errors. Errors due to imperfect components e.g. etching tolerances, different propagation times, or temperature dependencies are not considered here.

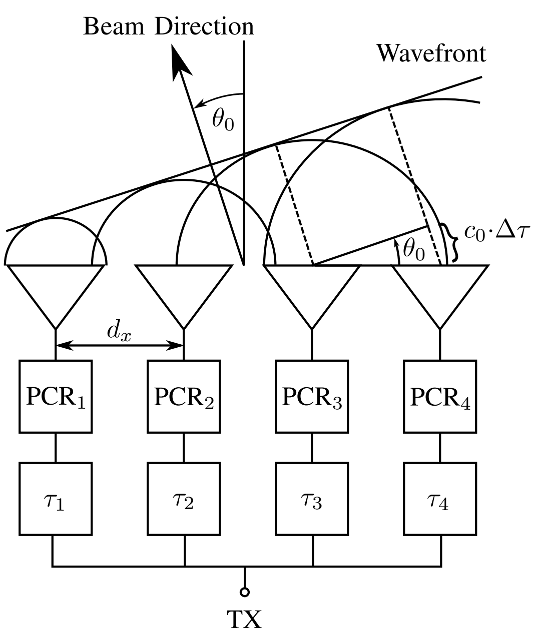

Fig. 2. Huygens' principle to illustrate TX-beamforming for a 4-element active electronically scanned array consisting of pulse correlation radar front-ends and digital time delays fed with a common transmit pulse (with $\tau_1>\tau_2>\tau_3>\tau_4$).

TABLE I
Required time delays in ps for an 8-element array with an element spacing of d_x=7 mm for a desired beam direction θ_0.

θ_0	EL0	EL1	EL2	EL3	EL4	EL5	EL6	EL7
15°	0.00	6.04	12.09	18.13	24.17	30.22	36.26	42.30
25°	0.00	9.87	19.74	29.60	39.47	49.34	59.21	69.08
35°	0.00	13.39	26.79	40.18	53.57	66.96	80.36	93.75

The increase of the side lobe level and the deviation of beam direction can be simulated using the group factor [2] of a linear array with N elements

$$\underline{F}_G(\theta) = \sum_{n=1}^{N} a_n \mathrm{e}^{\mathrm{j}k_0 n d_x(\sin\theta - \sin\theta_0)} \tag{2}$$

and replacing the required delay time (1) with the quantized delay time of each element, where a_n is the amplitude, and k_0 the free-space wave number.

Fig. 3 illustrates the radiation pattern of a uniformly illuminated 8-element array with an element spacing of d_x=7 mm, at a frequency of f_0=25.25 GHz and a desired beam direction of θ_0=15°. The side lobe level of an ideal uniform illuminated array of about −13 dB serves as reference. As can be seen, the different quantizations clearly influence the side lobe level. Despite the massive quantization, the side lobe suppression is sufficient for an application in industrial level measurements, considering the fact that the suppression in transmit and receive path in the real system doubles.

Furthermore, there is a dependency between the desired beam direction and the side lobe level due to the quantization stages. Fig. 4 illustrates the maximal side lobe level depending on the desired beam direction. If the required time delay corresponds to a multiple of the resolution τ_{LSB}, a side lobe level suppression comparable to the ideal case can be achieved.

Due to the quantization, the beam direction cannot be steered continuously resulting in beam direction errors. These possible beam directions are not equidistantly distributed. But regarding a system with 8 elements and 13° beam width, there are enough steps with low side lobes to scan and interpret the scenery, regardless of the small beam direction deviations. To improve the angular resolution, a trade-off must be made between element spacing and maximum steering angle and/or number of elements and additional hardware.

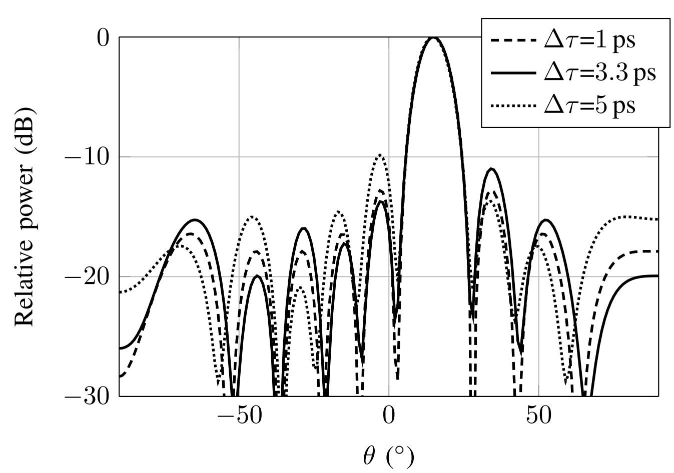

Fig. 3. Radiation characteristics of a uniformly illuminated 8-element array with quantized time delays (f_0=25.25 GHz, d_x=7 mm, θ_0=15°).

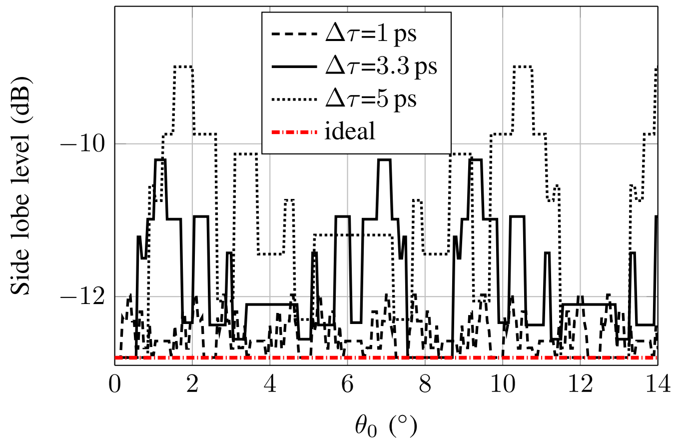

Fig. 4. Maximal side lobe level of a uniformly illuminated 8-element array with quantized time delays depending on the desired beam direction and of an array with ideal time delays (f_0=25.25 GHz, d_x=7 mm, θ_0=15°).

IV. True Time Delay Beamformer

As per block diagram shown in Fig. 1, a 26 GHz true time delay beamformer has been developed. Commercially available 2-channel time delays have been used as delay lines [6]. They have a resolution of τ_{LSB}=5 ps and can be programmed via a 3-wire interface. The radar front-ends were available as monolithically integrated RF-circuits, whereby a low-cost imaging sensor could be realized.

The developed beamformer consists of 8 TR modules, which are connected as shown in Fig. 5. Since the delay lines for the transmit and receive paths are placed in front of the pulse correlation radar, the output signal of each TR module is simply summed up by an operational amplifier. The sum signal is amplified with a logarithmic detector before it is digitalized by a 1-channel 20 kHz ADC with 12-bit resolution. The data acquisition needs not to be changed independently of the number of connected TR modules, since only one single envelope curve is recorded per beam direction.

Fig. 6 shows a photo of the hardware setup of the digital true time delay pulse correlation radar. The pulse repetition frequencies are yet provided by a functional generator, and the beam-steering is controlled by a computer via a USB2SPI interface. After data acquisition a 2-dimensional radar image is generated from the envelope curves.

In the later application it could be sufficient to scan only a few different angles to achieve benefit in comparison to the prevailing industrial level measurement sensors with fixed beam.

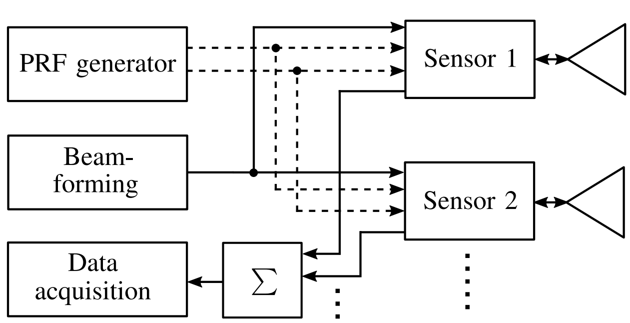

Fig. 5. Block diagram of the true time delay beamformer consisting of 8 TR modules, a PRF generator and a computer for beam-steering and data acquisition.

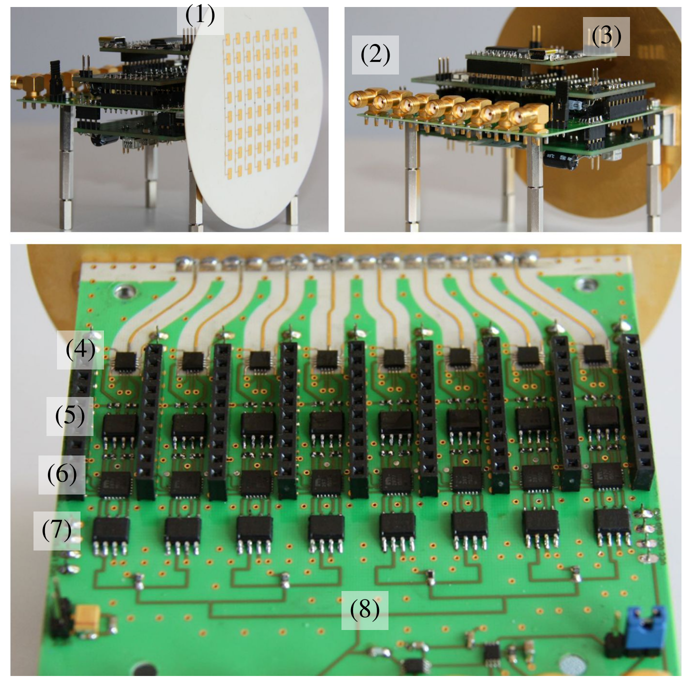

Fig. 6. Photos of the 26 GHz digital true time delay pulse correlation radar with 8 channels and an element spacing of d_x=7 mm distributed on four stacked boards. (1) 8x8-element patch antenna, (2) connectors to PRF generator and for data acquisition, (3) USB2SPI interface for programming the time delays, (4) pulse radar ASIC, (5) 2-channel LVDS receiver, (6) 2-channel digital programmable time delay, (7) 2-channel LVDS driver, and (8) distribution network.

V. Experimental Results

To verify the simulation results, the radiation pattern of the beamformer has been measured. For this purpose, the transmit and receive radiation patterns were recorded successively in a bistatic arrangement. As already mentioned, in radar applications the beam is steered in both transmit and receive path resulting in twice the side lobe suppression.

Fig. 7 shows the simulation and measurement results for TX-beamforming with a desired beam direction of θ_0=15°, proving the feasibility of this concept. The difference between simulation and measurement can be explained by propagation delays of LVDS driver and LVDS receiver units used for converting the trigger signal from single-ended to differential in front and vice versa after the differential time delay circuits. Due to the coarse resolution of the time delay units, a slightly different propagation delay between the 8 channels could not be fully compensated, resulting in an additional error leading to an increased side lobe level and a deviation of the beam direction.

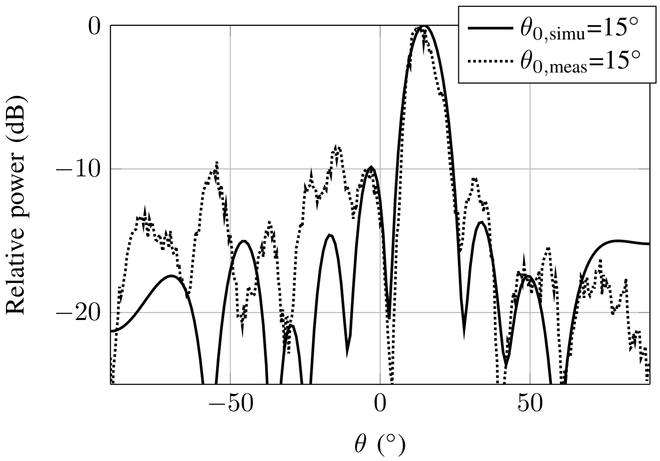

Fig. 7. Comparison between simulation and measurement for TX-beamforming with a desired beam direction of 15° and a uniformly illuminated 8-element array (f_0=25.25 GHz, d_x=7 mm, θ_0=15°).

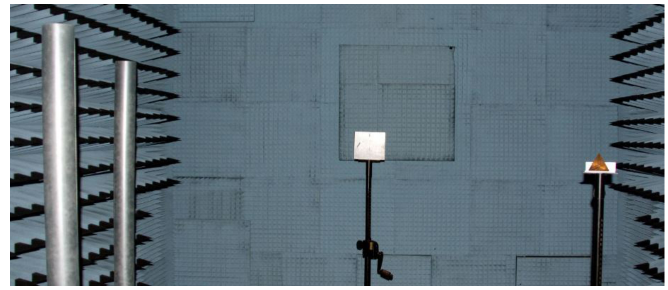

Fig. 8. Measurement setup with two metal tubes at radial distances of 2.45 m and 3.78 m on the left-hand side, a metal plate at the center with a distance of 4.96 m and a corner reflector at a radial distance of 3.09 m on the right-hand side as targets.

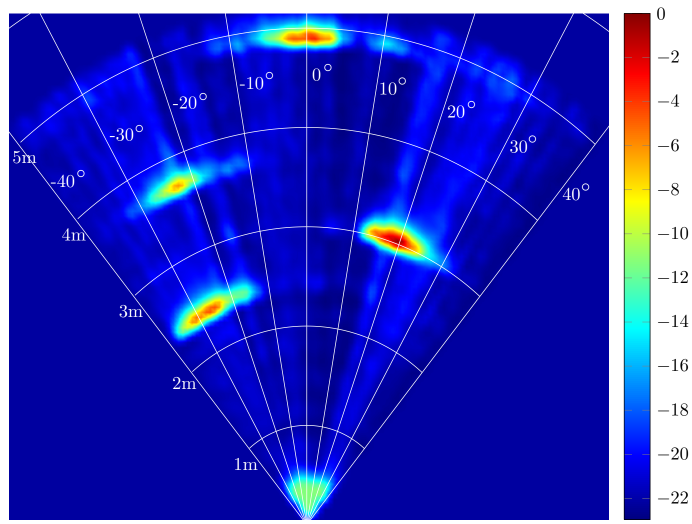

Fig. 9. 2-dimensional radar image of the measurement setup shown in Fig. 8 generated from 81 single envelope curves. The relative power is given in dB.

To generate a 2-dimensional radar image, the beam was steered in discrete steps of $\Delta\theta_0$=1° from θ_0=−40° to θ_0=40°. For each beam direction, an 1-dimensional measurement data set (envelope curve) was recorded. Following this, the single envelope curves were merged into one 2-dimensional image as function of the beam direction. The time to record a single envelope curve is determined by the pulse repetition frequencies and takes approximately 90 ms. By comparison, the time it takes to program the time delay units (13 µs) is negligible. Thus the scan time for a two-dimensional image consisting of 81 single measurements takes at least 7.3 s.

Fig. 8 shows the measurement setup with some targets: two metal tubes at radial distances of 2.45 m and 3.78 m, a metal plate at the center with a distance of 4.96 m, and a corner reflector at a radial distance of 3.09 m on the right-hand side.

The corresponding 2-dimensional radar image generated from 81 single envelopes is shown in Fig. 9. The radial distance of the four targets can be mapped quite accurately. With this system configuration a range resolution of 10 cm could be achieved. The limiting factor for range resolution was the minimum settable pulse length of the pulse correlation radar ASIC of approximately 650 ps. Due to the small number of 8 elements, the angular resolution is roughly 13°, resulting in a large lateral expansion of the targets.

VI. Conclusion

It has been successfully demonstrated, that this concept of digital true time delay pulse correlation radar can be applied to generate 2-dimensional radar images with high range resolution. With this simple system configuration consisting of pulse radar ASICs and commercially available time delays, an imaging sensor was realized, which offers benefits over the prevailing level measurement methods in process automation with low refresh rates, for example by scanning several different angles to increase the measurement reliability. It was shown, that the quantization errors by the time delays mainly influence the side lobe level and that the slight deviation of beam direction has not to be considered for this application.

A further improvement of this system could be the integration of the time delay elements into the pulse correlation radar ASIC. Thus the power consumption and the temperature dependency could be reduced and moreover the LVDS drivers and receivers for signal conversion are no longer required, whereby the image quality could be increased.

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