Performance of Thinned Antenna Arrays using Nonlinear Processing in DBF Radar Applications

Carsten Metz, Leif C. Stange, Arne F. Jacob and Ernst Lissel*

Institut für Hochfrequenztechnik, Technische Universität Braunschweig, Germany
*Volkswagen AG, Wolfsburg, Germany

***Abstract* — Efficient thinning techniques based on nonlinear multiplicative processing of antenna arrays are evaluated for high-resolution digital beamforming (DBF) radar. Operating mechanisms of such thinned arrays are introduced briefly together with a review of the scarce literature on this subject. Measurements implemented at 77 GHz with a synthetic aperture (SA) antenna setup are consulted to compare conventional and thinned array configurations with respect to imaging performance. Nonlinear processing systems show very attractive features allowing thinning rates on the order of 80 % with minor degradations in image quality.**

I. Introduction

Antenna arrays for high-resolution radar applications require large apertures in order to form a narrow beam. Conventional filled arrays with uniform interelement spacing in the range $0.5\lambda..\lambda$ (free space wavelengths) exhibit good performance with respect to gain and sidelobe level, but contain many elements to accomplish this. With larger aperture lengths the complexity of the feed networks rapidly grows beyond technically reasonable limits. In the majority of cases the aperture length is dictated by the beamwidth specification, but the high gain of a filled array may be dispensed with. A renewed interest in thinning techniques arises from the growing field of digital beamforming (DBF) arrays, since each antenna element is equipped with a dedicated but costly receiver module. Substantial reduction of the number of elements makes DBF potentially interesting for high volume consumer markets such as automotive radar.

Array thinning in a regular or periodic manner (regular overspacing) causes grating lobes to appear. Since the early 1960's thinning techniques have been developed applying various algorithms to aperiodic element placement. Lo stated that there would be no fundamental advantage of deterministic algorithms over random placement [1]. Optimization procedures were employed to yield improved sidelobe performance. Later, genetic search algorithms were proposed for selecting optimum element locations. One common problem of these techniques is that they become profitable and allow high thinning rates only for large arrays – on the order of 1000 λ and greater.

Nonlinear or multiplicative signal processing has been used in radio astronomy for a long time and to great advantage. Blommendaal [2] and Ksiensky [3] examined multiplicative interferometer-type systems for radar. A major advance was made by Davies and Ward [4], who introduced interdependent amplitude tapers for two constituent subarrays to synthesize a desired low-sidelobe radiation pattern. The thinning rates that can be achieved are on the order of 80 %. The experiments presented in [4] were conducted with analog receiver implementations and verified the basic concept, while radar measurements were not carried out.

Fig. 1 demonstrates the basic array setup used by Davies and Ward. The essential feature is the coincidence of the grating lobes in the pattern of the thinned subarray with pattern zeros of the filled subarray. Hence, the grating lobes are suppressed by the multiplication.

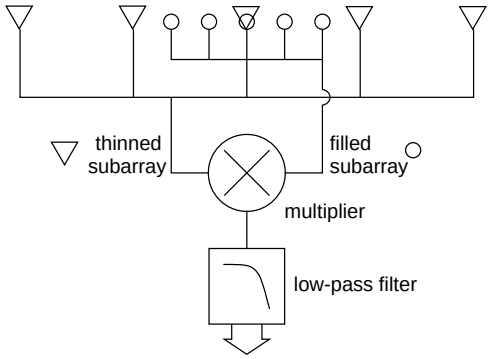

Fig. 1. Basic array arrangement used in [4]

Even higher thinning rates can be gained with low-redundancy offset array configurations, also proposed in [4]. This setup, with one half of the thinned subarray switched off, gives the same directional pattern in the far-field.

The objective of this paper is to compare DBF radar measurements obtained with conventional filled arrays to those obtained with multiplicative receiving systems, and thus extending the concept introduced in [4] to modern DBF applications. A fully digital signal processing is therefore developed which, in turn, allows near-field phase correction. The

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

measurements were done indoors at 77 GHz.

II. Experiment

A. Setup

In order to circumvent the fabrication of several complete antenna arrays, a special synthetic aperture (SA) antenna assembly was constructed. This way a large aperture array can be synthesized with only one physical antenna element by sampling the received field along the desired aperture. A linear carriage rail driven by a stepping motor serves as a mechanical support base for the assembly. Its usable length is 0.5 m. A vector network analyzer (HP8510C) was utilized as radar transmitter and receiver allowing accurate measurements of the transfer function. Rectangular W-band horn antennas were used for both transmit and receive operation. The instruments as well as the carriage feed are controlled by a computer running National Instruments' LabVIEW software. The whole setup is depicted in Fig. 2.

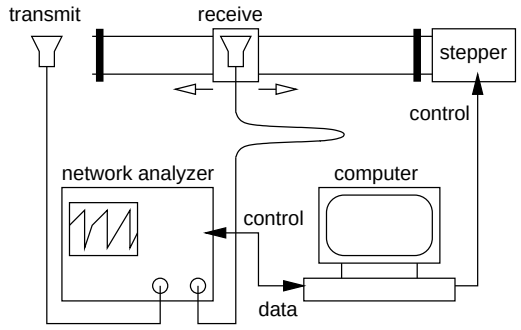

Fig. 2. Experimental setup

B. Data Processing

In contrast to the analog array processor used in [4] the processing employed here takes place in the digital domain after detection of the radar returns by the receiver. Beamforming and scanning is implemented in software.

Fig. 3 shows a functional block diagram of the processing path. After a measurement has been made, the frequency sweep data file is read and a virtual array consisting of subarrays and elements is created, stipulated by another input file. The software computes a range spectrum for each element by means of a Fast Fourier Transform (FFT). The range bins can then be processed successively by applying complex weighting factors and summing up the contributions of all elements. In the case of a multiplicative system the two subarray responses are finally combined according to the active power rule forming the time-averaged power. In this way a 2-D radar image of the illuminated scene forms and can be visualized using common data plotters.

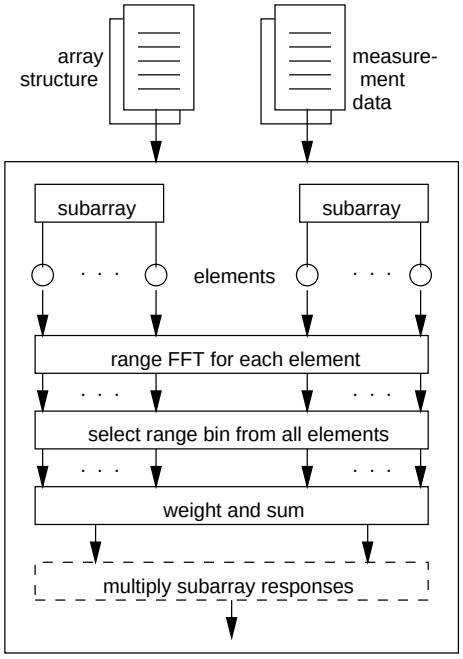

Fig. 3. Signal processing path

It should be noted that the radar images produced by the processing software are raw data. No post-processing, e.g. target detection or decision algorithms, are applied. The images to be presented in this paper show the echo intensity, normalized by the most intense target return.

To compensate for the errors induced by spherical phasefronts of near-field target returns the complex weighting factors have to be adjusted by additional correction terms. These correction phases depend on the location of the respective element within the aperture, the scanning angle and the focal distance of the targets to be imaged [5].

C. Synthesized Arrays

Three different array configurations were processed for comparison. Their parameters are compiled in Tab. I. All arrays exhibit nearly the same aperture length and beamwidth. The first array considered is a conventional 241-element filled array with a Chebyshev amplitude taper to yield a uniform sidelobe level of -25 dB. The thinned arrays (2 and 3) are low-redundancy offset type arrays with 67 (59 + 8) and 45 (29 + 16) elements, respectively.

III. Results

Fig. 4 shows the processed radar images as 2.5-D contour plots. The scenes captured constitute a corridor in our

No.	Filled (Sub)array		Thinned Subarray		Aperture	Beam-	Sidelobe	Thinning
	n.o.e.	el. spacing	n.o.e.	el. spacing	length	width	ratio	rate
1	241	2 mm	—	—	480 mm	0.42°	25 dB	0 %
2	59	2 mm	8	60 mm	478 mm	0.42°	22 dB	72 %
3	29	2 mm	16	30 mm	478 mm	0.42°	22 dB	81 %

TABLE I. Parameters of considered configurations (n.o.e.: number of elements)

building. Fig. 4 a-c and d-f correspond to two scenarios of artificial reflectors distributed throughout the room. The positions of real targets are designated in the topmost plots a and d, which are obtained with the fully filled array No. 1. Plots b and e show the images obtained with the thinned array No. 2, and plots c and f those from the thinned array No. 3 (cf. Tab. I).

The images from the thinned configurations exhibit a slightly higher background level that partly stems from the higher peak sidelobes of these arrays. The artifacts from the strong echos at a range of 5 m give a good indication of that. While some weak echos detectable in the image of the filled array drop to background level, most real targets can well be identified. Nevertheless the degradation of the images with higher thinning rates clearly emerges.

The second scenario with five closely spaced reflectors in one range bin must be considered more critical when multiplicatively processed, owing to complex multi-target responses [2, 3]. The larger corner reflector features two scattering centers appearing in all images. The returns of the smaller reflectors differ in intensity and exact angular position, but are evident in every plot. No degradation due to beam broadening can be observed in comparison to the fully filled array.

IV. Conclusion

In this paper nonlinear processing schemes applied to antenna array thinning were evaluated with respect to imaging performance. Arrays of moderate size, i.e. with an aperture length below $\sim 500\ \lambda$, can effortlessly be thinned by typically 80 % by nonlinear processing. Thinning rates up to 90 % are positively possible. Such rates are hardly reached with aperiodic arrays and definitely never obtained with random arrays. Compared to data processed by conventional fully filled arrays, the images from the thinned arrays show slight degradations in background level.

References

[1] Y.T. Lo, "A mathematical theory of antenna arrays with randomly spaced elements", *IEEE Trans. Ant. and Prop.*, vol. 12, pp. 257-268, 1964

[2] R. Blommendaal, "A note on multiplicative receiving systems for radar", *Jour. Brit. IRE*, vol. 28, pp. 317-325, 1964

[3] A. Ksienski, "Multiplicative processing antenna systems for radar applications", *Radio & Electron. Eng.*, vol. 29, pp. 53-67, 1965

[4] D.E.N. Davies and C.R. Ward, "Low sidelobe patterns from thinned arrays using multiplicative processing", *IEE Proc. Pt. F*, vol. 127, pp. 9-15, 1980

[5] B.D. Steinberg and H.M. Subbaram, "Microwave Imaging Techniques". Wiley & Sons Inc., New York, 1991

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

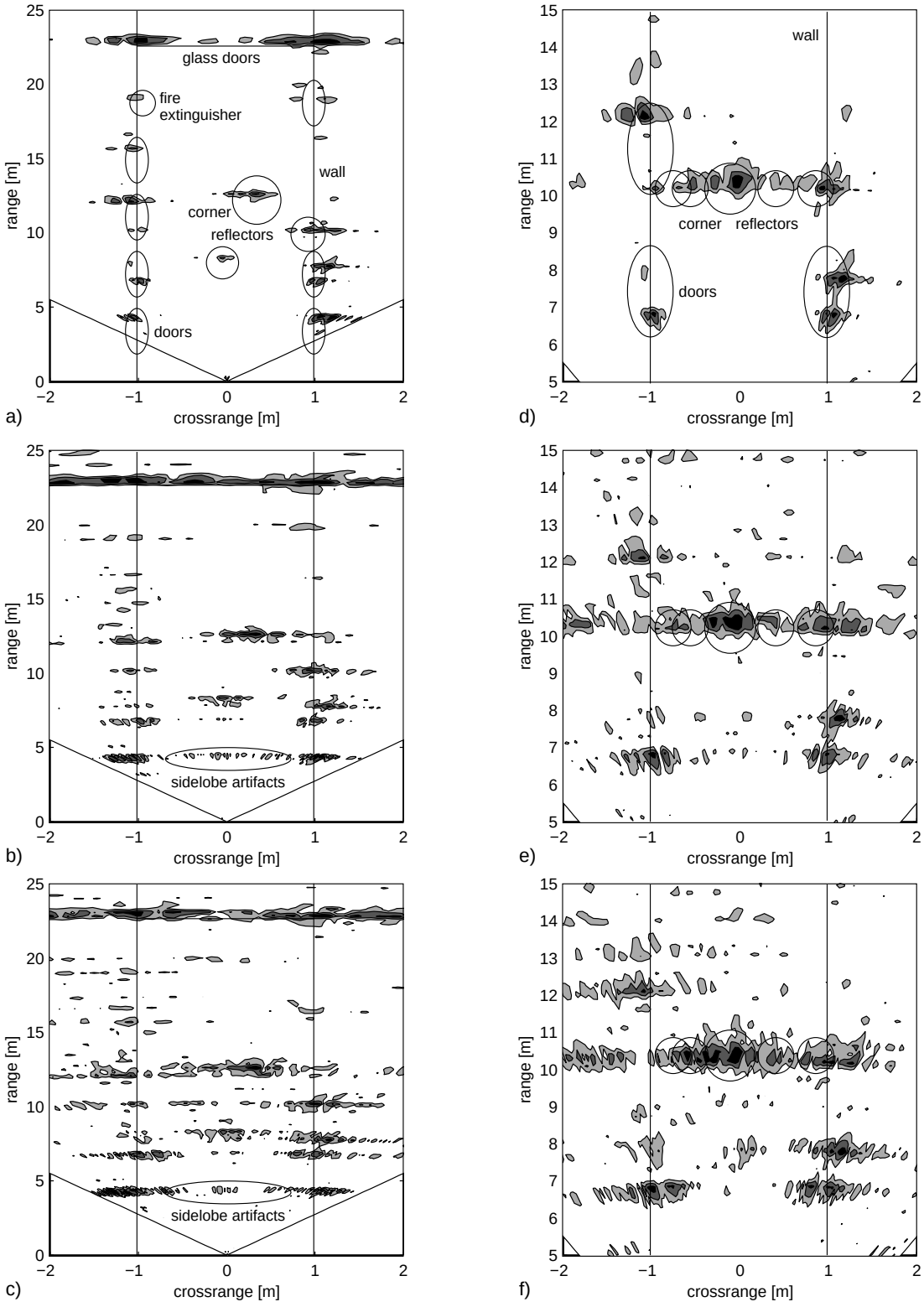

Fig. 4. Radar images: a-c: scenario 1, d-f: scenario 2

0-7803-6540-2/01/$10.00 (C) 2001 IEEE