STOCHASTIC OPTIMIZATION OF LINEAR ARRAYS FOR PULSE-ECHO IMAGING SYSTEMS

Gabriella Cincotti[1], *Giovanni Cardone*[2], *Paul D Fox*[3], *Paola Gori*[1] *and Massimo Pappalardo*[1]

[1]University of Roma TRE, Electronics Department
via della Vasca Navale 84, I-00146 Roma Italy, e-mail:g.cincotti@uniroma3.it
[2]CRS4-Center for Advanced Studies, Research and Development in Sardinia
VI Strada Ovest Z.I. Macchiareddu, C.P. 94, I-09010, Uta, Cagliari Italy
[3]University of Oslo, Department of Informatics
P.O. Box 1080 Blindern, N-0316 Oslo Norway

ABSTRACT

We apply the simulated annealing optimization algorithm to linear arrays to be used in ultrasound imaging systems under wide-band operation. We address the optimization problem of both dense and sparse wide-band arrays. In the first case, we compare the optimized beam pattern with that obtained with a classical shading function. In the latter case, we consider either the optimization of the layout (element positions and weights) or the optimization of only element positions of sparse arrays which generate a beam pattern with minimum side-lobe level. We show that an about -7-dB further reduction of the side-lobe level can be achieved with a wide-band sparse array optimization, with respect to a narrow-band optimization. The performances of the optimized arrays are verified on some phantom images.

1. WIDE BAND ARRAY OPTIMIZATION

The problem of designing non uniformly spaced arrays that generate a desired Beam Pattern (BP) has been widely studied over the last 30 years. The basic motivation of their investigation is that sparse aperiodic arrays provide a higher resolution, compared with periodic arrays with the same number of elements, since the array aperture can be enlarged by spacing elements more than $\lambda/2$. Unlike the main-lobe width and antenna gain, which are quite independent from the array configuration, the side-lobe level is heavily influenced by the element positions and weights. A large number of different optimization strategies have been proposed; the majority of which investigate the properties of sparse arrays under Narrow Band (NB) excitation. In medical imaging, as well as in high-resolution sonar imaging, Wide Band (WB) arrays which transmit ultrasound pulses shorter than a few cycles of the nominal frequency, are commonly used to enhance the axial resolution. The increase of the bandwidth smears the side-lobe peaks out in the time, since the acoustic pressure energy transmitted in the directions far from the main-lobe arrives over a longer time interval. NB and WB BPs are comparable only in the neighbourhood of the focal point, where the WB ultrasonic pulses interfere. Therefore, in an optimization process, where the goal is the best achievable performance, the NB analysis can lead to unsatisfactory results.

We address here the optimization problem of WB linear arrays to be used in pulse-echo imaging systems. To form a comparison with the NB case, the BP of a WB array is determined finding the maximum over time of the transient acoustic field at each angular direction. The maximum projection method loses information regarding the temporal waveform of the BP, but preserves the maximum angular side energy that would produce artifacts [1]. The evaluation of the BP constitutes the major computational load in the optimization procedure and a fast, but accurate, numerical algorithm has been implemented.

Unlike traditional optimization methods, which usually converge toward a global minimum only if the starting point is close to solution, Simulated Anneal-

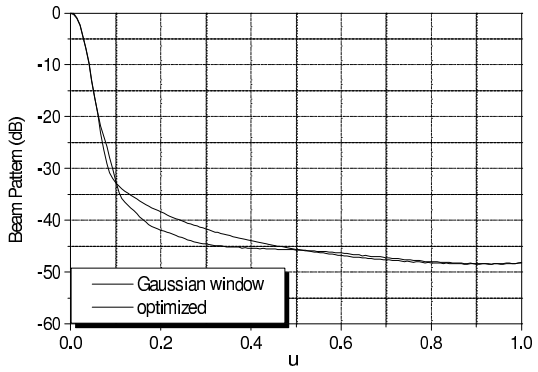


Figure 1: BPs of an optimized WB dense array and a Gaussian windowed array. The arrays consist of 50 elements $\lambda/2$ spaced.
$u = \sin\Box - sin\Box_0$, where $\Box$ is the observation angle and $\Box_0$ is the steering angle.

ing (SA) algorithm has been demonstrated to be able to solve optimization problems with a large number of extrema, because its random-search character helps to escape from local minima [2]. In particular, SA has been used in sparse array optimization, under NB excitation [3].
We apply the SA algorithm to both WB dense and sparse arrays which generate a desired beam pattern. For a dense array, the goal is to minimize the side-lobe energy by varying the element weights. For a sparse array, we consider both the optimization of the complete layout (weights and positions) and the optimization of only element positions.
The beam properties of the optimized arrays are evaluated on some synthetic phantoms.

1.1 Dense array

We address here several different optimization problems and in all of them, we $\Box$x the element positions on a $\lambda/2$ grid. We start with the minimization of the side-lobe level by only varying the element weights of a dense (uniformly spaced) array. It is well known that aperture tapering reallocates energy from the side-lobe region into the main-lobe region, enhancing the contrast resolution at the cost of a loss of detail resolution. By applying the SA algorithm to a WB dense array constituted by 50 elements over 25λ, we obtain the BP presented in Figure 1. In the same $\Box$gure the BP corresponding to a Gaussian windowed WB array is plotted; it is evident that the proposed optimization method yields a lower BP level in almost the whole side-lobe region, whereas the main-lobe widths are practically the same. In fact, classical window functions may result not completely satisfactory in shaping the BP of WB arrays; on the contrary, an appropriate WB optimization process yields better results, since it takes into account the effect of the partial superposition of the transmitted acoustic pulses for large observation angles, where the acoustic beam spreads out in time.

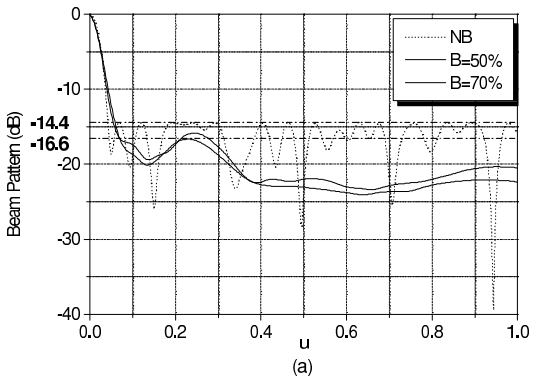
1.2 Sparse array

1.2.1 *Optimization of weights and positions*

We now study the optimization of both element weights and positions of a sparse array. To demonstrate that some results obtained in a NB array synthesis are not completely satisfactory under WB operation, we consider the array analyzed in [3]. The optimized BP for NB excitation is plotted in Figure 2(a), and it is, to the best of our knowledge, the best result for this problem in literature. Starting from the optimized layout derived by Trucco et al., we compute the corresponding BP for WB excitation and, in the same $\Box$gure, the BPs corresponding to 50% and 70% bandwidth are plotted. It is evident that the main-lobe width remains practically unchanged, but the side-lobe level decreases under WB operation. We then apply the SA algorithm to the same WB sparse array and the optimized BP is plotted in Figure 2(b). Remark that with a WB optimization process, a -6.8dB further reduction of side-lobe level (from -16.6dB to -23.4dB) is achieved, whereas the main-lobe widths are very similar.

1.2.2 *Optimization of positions only*

Since the amplitude tapering reduces the Signal-to-Noise Ratio (SNR), we study the optimization of only the element positions of the same WB linear array considered above, constituted by 24 elements uniformly excited, distributed over a 25λ aperture. The realtive bandwidth is $\Box$xed to 80%. The optimized BP and the array layout are plotted in Figure 3(a) and (b), respectively. Comparing Figure 3(a) with Figure 2(b), it is evident that the sparse array uniformly excited yields to a lower side-lobe level, with respect to the amplitude tapered sparse array. This result shows that the side-lobe level of a WB sparse array



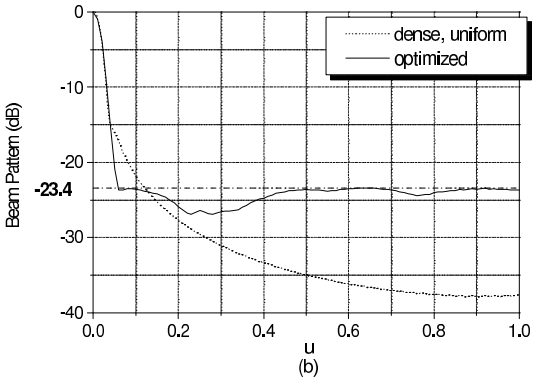
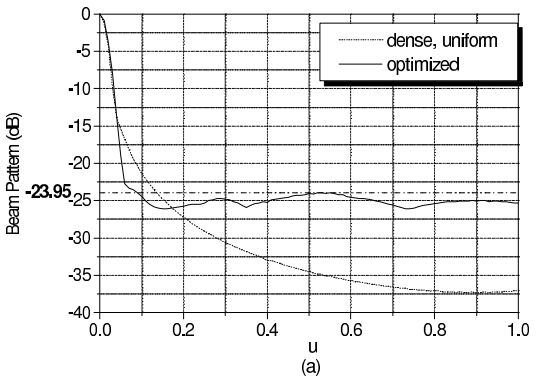


Figure 2: Optimization of a sparse array constituted by 24 elements over 25λ.
a) Best known result in literature obtained from a NB optimization. The BPs under NB and WB excitations are plotted.
b) WB optimization of a 70% bandwidth array.

is highly influenced by the number of active elements as well as their position; on the contrary, the amplitude tapering can raise the side-lobe level, and this effect is more evident as the sparseness and the relative bandwidth of the ultrasound pulse are increased. (see [1]).

2. PHANTOM IMAGES

The beam properties of the optimized sparse array are evaluated using the ultrasound simulator FIELDII by Jensen [4]. We consider a 2.5 MHz phased array, with relative bandwidth 70% and 0.25-mm element spacing; moreover, only one focus was used in transmission, whereas the array was dynamically



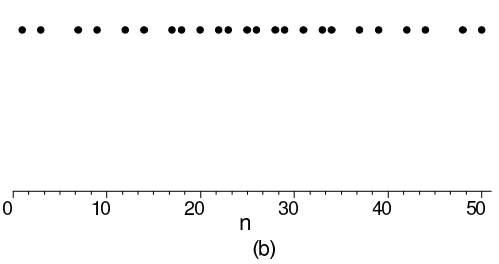


Figure 3: Minimization of the side-lobe level for a sparse array constituted by 24 elements over 25λ. All the elements are uniformly excitated.
a) Optimized BP of a 80% bandwidth array.
b) Array layout.

focused in reception. Each image is logarithmically compressed and displayed at 40-dB dynamic range. Figure 4 shows two images of a phantom constituted by 11 wire target uniformly spaced, obtained by using two different array geometries: in Figure 4(a) we used the dense 50-elements array, whereas in Figure 4(b) we used the optimized sparse array constituted by 24elements over the same aperture 25λ.
Figure 5(a) shows the image of the tissue equivalent phantom obtained using a dense 50-elements image, whereas the image of Figure 5(b) was achieved with the optimized sparse 24-elements array. Therefore, we can conclude that the two arrays con□gurations give a quite similar detail resolution, but a lower contrast resolution is achieved with the sparse array.

3. CONCLUSIONS

The proposed optimization method is shown to work e□ciently, for both WB dense and sparse arrays to be

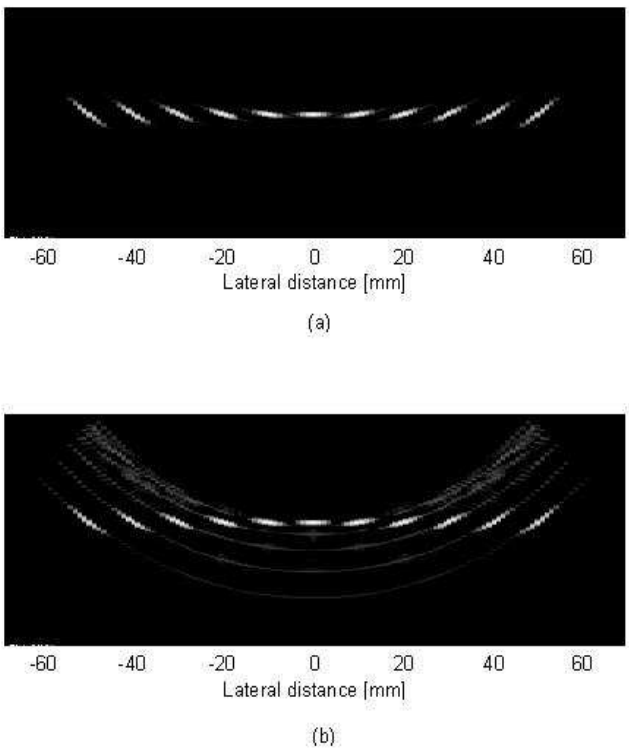


Figure 4: Images of a wire targets phantom.
a) Dense 50-elements array.
b) Sparse 24-elements array.

used in pulse-echo imaging systems. Since the peaks from side or grating lobes smear out in time, when short pulse excitation is used, better results can be achieved with a WB optimization process, with respect to NB optimization. Furthermore, it has been verified that amplitude tapering can limit the performances of large bandwidth sparse arrays, since it can raise the side-lobe level.

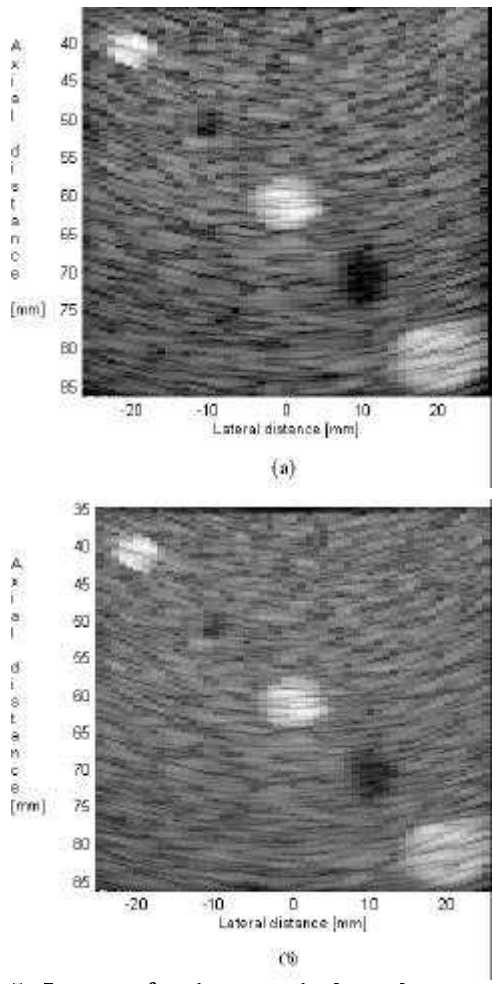


Figure 5: Images of a tissue equivalent phantom.
a) Dense 50-elements array.
b) Sparse 24-elements array.

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Acknowledgements

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