A Beamforming Method in UWB pulse Array based on Neural Network

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***Abstract*—In this paper, the principles and algorithm of array beamforming based on a realistic ultrawide-band (carrier free) pulse signal model is discussed firstly. Then an UWB pulse array beamforming method based on a radial basis function (RBF) neural network is presented. It can compensate the propagation delays accurately in each channel and form a narrow directivity beam in a desired direction. Compared with the method of employing FIR filter for delay steering in wideband beamforming, the RBF approach has its advantage in achieving arbitrary array response. The simulation results show that the beam formed by RBF has high gain main and very low sidelobe, in addition to rapid and accurate processing for the high parallelism and mapping ability of the neural network.**

I. INTRODUCTION

Over the last decade of the 20th century, the emerging ultrawide-band (UWB) impulse technology has found numerous applications in the commercial as well as the military sectors. The rapid technological advances have made it possible to implement impulse radar and impulse-radio communication. Space-time processing principle is also applicable to the technology of UWB system [1][2]. It promise further advancement in the operational capabilities of impulse radar to achieve long-range coverage, high capacity, and interference-free quality of reception.

In a UWB system, a Gaussian impulse waveform is often used [3]. For its very short duration, the resolution angle for the beam patterns is derived as a decreasing function of array size and frequency bandwidth, so it is of high resolution and penetration. However, the way of phase weighting for the received signal used in narrowband is not applicable, a substitute beamforming method is employing delay lines and FIR filters to compensate propagation delays in wideband and UWB system. In order to achieve electronic beamsteering for enhancing the received signal from a desired look direction, firstly the time-delay should be estimated correctly and then be compensated [4][5][6]. In this paper, a new beamforming method based on radical basis function (RBF) neural network is presented. The network is used to compensate the propagation delays of antenna channel and form main beam with narrow width in the desired direction after a slide correlation (SC) of the receive signal. Experimental results obtained with uniform linear array illuminated by UWB pulses train signal help to assess the usefulness of the proposed method.

II. PRINCIPLE OF UWB PULES ARRAY BEAMFORMING

A. Impulse-based transmission signal

The conventional technology of radar is based on the use of a sinusoidal carrier as a modulation waveform, which allows for the mathematically convenient complex representation of bandlimited signals on the theoretical side. For the emerging technology of impulse radio, the received signal *r(t)* is modeled by pulse trains with pulse position modulation (PPM) or pulse amplitude modulation (PAM):

$$r(t)=\sum_{n=-\infty}^{+\infty}\sum_{p=1}^{p}A_p\Omega(t-t_p-nT_r)+n(t) \tag{1}$$

where T_r is the pulse repetition interval (PRI) and $\Omega(t)$ is the pulse-shaping waveform. A commonly used pulse-shaping waveform based on Gaussian model is given as [7]:

$$\Omega(t)=\frac{E_0}{1-\alpha}\left\{\exp(-4\pi\left(\frac{t-t_0}{\tau}\right)^2)-\alpha\exp(-4\pi\alpha^2\left(\frac{t-t_0}{\tau}\right)^2)\right\} \tag{2}$$

We call it a Generalized Gaussian Pulse (GGP) signal. Here E_0 is the peak amplitude at the time $t=t_0$, τ is a nominal duration, and α is a scaling parameter. The time variation and autocorrelation function of the GGP with different values of α are plotted in Fig.1, Fig.2 respectively.

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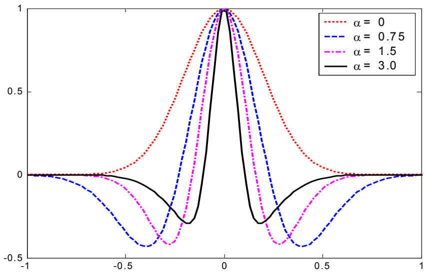

Figure 1. Normalized time variation

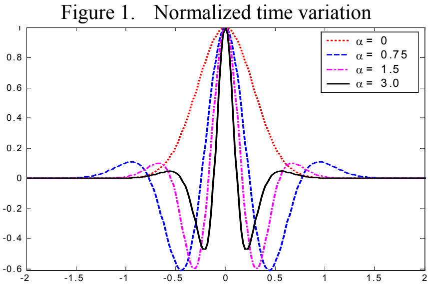

Figure 2. Autocorrelation function

B. *Impulse-based array beamforming*

The principle of array beamforming based on UWB (carrier free) signals is described in Figure 3 [6][7]. In this model, the beamforming system consists of a linear array of omnidirectional of M=2m+1 sensors uniformly spaced with interelement distance d. Each channel of the beamformer employs a slide correlator (SC) and a variable delay circuit (VDC) for temporal processing of the received signal. The array sensors are separated into two subarrays of equal size, and the output signals of each channel are summed to get the output of the array. Their difference is also used to compute the incident angle of coming signal to get the required delay quantities in a delay adjustment circuit (DAC). The VDC can be adjustable digital delay lines and FIR digital filters employed to compensate the propagation delay of each channel.

Take i=0 as a referenced point, the time delays of each array unit is a function of the incident angle ϕ and d:

$$\tau_i(\phi) = id\sin\phi / c = i\rho\sin\phi\cdot\Delta T/2m \quad (3)$$

where $\rho = 2md/(c\Delta T) = L\Delta f/c$ represents the ratio of the transmitted time of signal along the array to ΔT, named as the bandwidth of space frequency. To enhance the signal came from the angle ϕ_0, a time delay $\tilde{\tau}_i$ is exerted upon the received signals $\gamma_i(t) = \gamma(t-\tau_i(\phi))$. $\gamma(t)$ is the correlation function of $\Omega(t)$. When $\tilde{\tau}_i$ and ϕ_0 has such relations, then a main beam is formed in angle ϕ_0:

$$\tilde{\tau}_i/\Delta T = (i/2m)\rho\sin\phi_0 \quad (4)$$

Then we can obtain the maximum energy of array output. The propagation delay is compensated in this case. The array response is the sum able to be depicted using the error function:

$$y(t,\phi) = \sum_{i=-m}^{i=m}\gamma(t+\tilde{\tau}_i-\tau_i(\phi)) \quad (5)$$

The peak amplitude of the array output is defined as:

$$A(\phi) = y(0,\phi)/y(0,\phi_0) \quad (6)$$

The directive patterns of UWB pulse array is defined as the ratio of the output energy of array from angle ϕ and ϕ_0:

$$\tilde{W}(\phi) = \tilde{U}(\phi)/\tilde{U}(\phi_0) \text{ (where } \tilde{U}(\phi)=\int_{-\infty}^{\infty}[y(t,\phi)]^2dt\text{)} \quad (7)$$

The width of the main beam is a function of the size L of array and nominal bandwidth Δf : $\Delta\theta = Kc/\Delta f\cdot L$. For a narrowband array, d must be smaller than half of the wavelength of signal, which makes the realization of large array difficult. But UWB pulse array has no such limitation. The fewer antenna elements in UWB sparse array with same size can obtain same resolution of narrowband array.

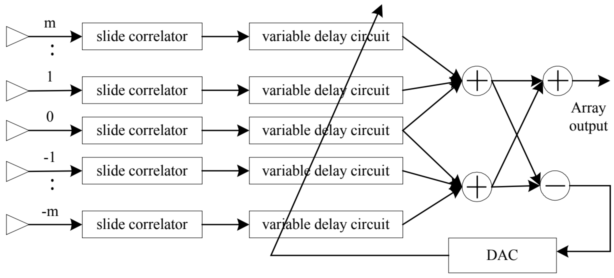

Figure 3. Principle of UWB pulse array beamforming

III. IMPULSE-BASED ARRAY BEAMFORMING USING NEURAL NETWORK

A. *Neural network with RBF function*

The multilayer perceptron (MLP) can realize a complex nonlinear mapping of the input to output by a combination of simple nonlinear function. The MLP with back Propagation (BP) algorithm is very efficient for function approximation in high dimensional spaces. But the BP-MLP is purely static and is incapable of processing the time information. BP network has a slow convergence and it tends to tap into the local minimum. However, another neural network with radial basis function (RBF NN) is derived form regular theory and has the optimal approximation ability for complex functions [8][9]. It takes the localized character of neurons into account and uses locally supported basis functions. An output is given only when the input is within the response area of neurons. It is consistent with the behavior of brain, so it is characterized with a good approximation. It has a faster learning speed compared the MLP with BP rule, and only part of the input space needs to be trained. The RBFNN is insensitive to the order of the appearance of the adjusted signals and hence more suitable for online for sequent adaptive adjustment.

A basic RBF network consists of three layers: the first layer takes an input; the second layer maps the input to a high dimension with nonlinear active function-radical basis function; the output layer is a linear layer, as shown in Figure 4. In this model, the number of nodes in input layer, hidden layer and output layer are L, J and K respectively.

We observe the processing of the input by the RBF network. When P samples $\mathbf{X}=[X_1,\ldots, X_P]$ (where $X_p=[x_{p,1},\ldots, x_{p,M}]^T$, $p\in[1,P]$) is input into the network and a Gaussian radical function is employed, then the output of the j-th node for the p-th sample of the hidden layer is:

$$z_{jp} = \Phi(\|X_p - C_j\|) = \exp[-\sum_{i=1}^{L}(x_{i,p}-c_{ji})^2/\sigma_{ji}{}^2] \qquad (8)$$

where c_{ji} and σ_{ji} are i-th component of the center and variance of the j-th radical function respectively. At last a linear network follows:

$$y_{ip} = w_{i0} + \sum_{j=1}^{L} w_{ij} z_{jp} \quad (i=1,..,K, p=1,..,P) \qquad (9)$$

where y_{ip} is the output of the i-th node for the p-th sample in the output layer, W_{ij} is the weight of the j-th hidden node to the i-th output one.

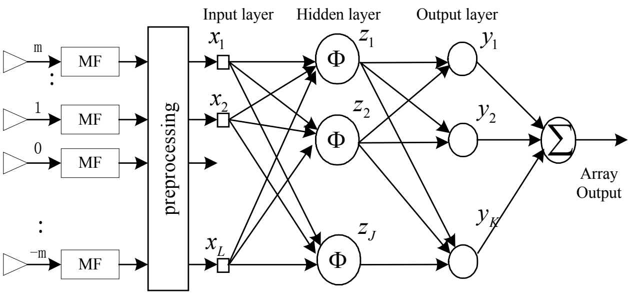

Figure 4. Beamformer of UWB pulse array based on RBFNN

B. A beamforming method of UWB pulse array based on RBF NN

It is known that neural network has universal approximation capability. The beamforming with neural network employment has been reported in conventional narrow band phased array. They utilize the approximation or optimization ability of neural network to solve the solution of optimal weight vector. But for UWB pulse array, the beamforming is often realized by propagation delay compensation. The available method cannot be reused in simple way. Reference [10] shows analogy of spatio-temporal processing between the biological neuron and digital spatio-temporal neural network system. Elemental unit of the spatio-temporal digital neuron is a TDL/FIR (time-delay-line/Finite Impulse response).

The presented method of delay adjustment in [6] is in principle. In fact it compute the delays directly according to the desired angle and it doesn't consider the noise, so it is not robust beamformer scheme of delay compensation. The beamformer for pulse array can be seen as a complicated nonlinear system with time delay. The input and output of beamformer can be regarded as nonlinear function of incident angle. So in this paper, RBF network is used to identify such a system, in another word, it is used to enhance the signal from the desired direction and suppress other interferes not in desired beam. The desired beampattern can be obtained by network learning of data sample. The beamformer structure of RBF network is shown as Figure 4 in which a RBF network follows a matched filter bank.

The training and working process is departed. Before the network begins to work, a training process is performed. The network input is output of match filter:

$$x_i(t) = \gamma_i(t-\tau(\phi)) \qquad i=1,2,...L \qquad (10)$$

And corresponding output is:

$$y_i(t) = \Gamma[x_i(t)] = \begin{cases} \gamma_i(t-\Delta), & \phi=\phi_d \\ 0 \quad , & \phi\neq\phi_d \end{cases} \qquad (11)$$

where Δ is fixed delay. Assume the incidence angle ϕ varies from -90^0 to 90^0, the training data are obtained by a uniform sampling spaced s. Each data sample is a received signal corresponding to angle sampled in angular field. If P sample number obtained, sensor number is M, snap number is N, then the input sample is a matrix with size M×N. Here we reshape sample matrix to one dimension sample with size MN×1. So the size of input layer and output layer of the RBFNN are both taken as MN.

Input the training samples into the network, and we adopt such a learning algorithm: firstly a self-organized feather maps (SOFM) clustering method is used to select the centers of the basis function, and then the radius of neurons are determined by $\sigma = D/\sqrt{2J}$, where D is the maximum distance of these selected centers.

For the weight of output layer, a recurrent least square (RLS) algorithm is used. Denote $W_k(n)=[w_{k0}(n),.., w_{kL}(n)]^T$ (k=1,..,K) and $\boldsymbol{Z}(n)=[z_0(n),.., z_L(n)]^T$ at the n-th iteration, then the k-th output unit is:

$$y_k(n) = \sum_{i=0}^{L} W_{ki}(n) z_i(n) = Z^T(n)\cdot W_k(n) \qquad (12)$$

Define such a weighted error function J:

$$\begin{aligned} J(n) &= \frac{1}{2}\sum_{i=1}^{n}\lambda^{n-i}\sum_{k=1}^{N}\varepsilon_k^2(n) = \frac{1}{2}\sum_{i=1}^{n}\lambda^{n-i}\sum_{k=1}^{N}(d_k(n)-y_k(n))^2 \\ &= \lambda J(n-1) + \frac{1}{2}\sum_{k=1}^{N}[d_k(n) - Z^T(n)W_k(n-1)]^2 \end{aligned} \qquad (13)$$

where λ is the weighted forget parameter which smoothes the effect of the foregoing samples little by little. d_k and y_k is the desired output and the real output of the k-th output node respectively. Denote $P(n) = \hat{R}^{-1}(n)$, RLS algorithm is as follows:

$$
\begin{aligned}
K(n) &= \frac{P(n-1)\cdot Z(n)}{\lambda + Z^T(n)\cdot P(n-1)\cdot Z(n)} \\
P(n) &= \frac{1}{\lambda}[P(n-1) - K(n)Z^T(n)P(n-1)] \\
\hat{W}_i(n) &= \hat{W}_i(n-1) + K(n)[d_i(n) - Z^T(n)\hat{W}_i(n-1)]
\end{aligned}
\tag{14}
$$

Train the network using (14). When the training process is completed, all the parameters of the RBF network are determined, so the network can work as a beamformer for the UWB impulse array.

IV. SIMULATIONS

In this section, we demonstrate the feasibility of UWB pulse array beamforming based on our constructed RBF neural network by applying it to a uniform linear array with element number M=11. The GGP signal used in the experiments has the nominal duration time $\Delta T = 2ns$, $T_r = 6ns$ sample period $T_s = 100ps$. Assume the incident signal comes from the angle 30^0. The snap number is 1000. We compare the performance of RBFNN-based beamformer with that of FIR filters. In the RBF, the training samples of the network are obtained by a uniform sampling of θ from -90^0 to 90^0 spaced s^0. Figure 5 gives the variation of network error with the iteration times in different s, from which we can see that more training samples we use, more fast of the convergence of the network. That is, a smaller s will lead to a rapider convergence. In the test a maximum iteration times 100 and s=10 is adopted. It means only 19 samples are used for learning.

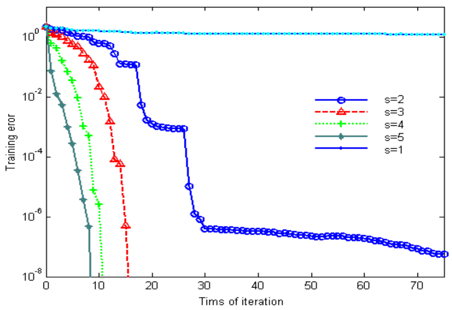

Figure 5. Convergence curves for different training samples

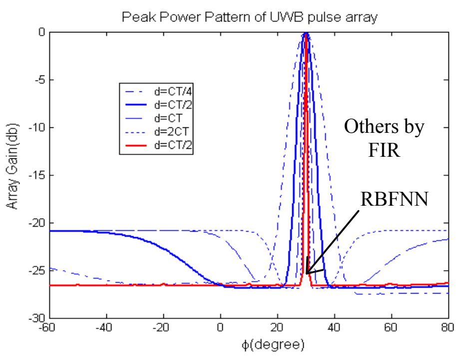

Figure 6. Peak power patterns without sidelobe

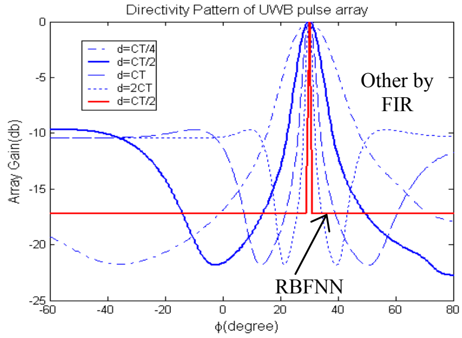

Figure 7. Energy pattern of UWB pulse array

Figure 6 shows the peak power directivity pattern employing FIR filter for delay compensation with different interelement spacing d=$C\triangle T/4$, d=$C\triangle T/2$, d=$C\triangle T$, d=$2C\triangle T$. And the trained RBF network with d=$C\triangle T/2$ is also plotted as a comparison .

Figure 7 gives the energy pattern of UWB pulse array of two different methods with different d. The results indicate that the presented method can smooth away the sidelobe of the classical filters. Moreover, it is characteristic of a fast and accurate processing.

ACKNOWLEDGMENT

The authors would like to thank for the financial support and the design facilities of National Lab. of Radar Signal processing, Xidian University.

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