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Beamspace Adaptive Array Antenna for Broadband Signals

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1. Introduction

Tapped-delay-line circuits are used for (digital) beamforming networks and adaptive array antennas for broadband signals [1]-[3]. In this case, the number of adaptive weights of an element space adaptive array increases considerably as the number of sensor elements and taps is increased. On the other hand, beamspace adaptive array antennas have the advantage that they can acquire desired signals and suppress interference with fewer adaptive weights [4]-[6]. However, they are difficult to apply to broadband signal processing.

In this paper, we propose a beamspace adaptive array antenna for broadband signals. The proposed structure fully displays the above stated advantage. The proposed beamspace adaptive array antenna has only a few adaptive weights, which is considerably less than an element space adaptive array with tapped-delay-line circuits. We prove by computer simulation that interference suppression of the proposed beamspace adaptive array antenna is as good as that of the element space adaptive array and that it has the property of much faster convergence.

2. Beamspace Adaptive Array Antenna for Broadband Signals

2.1 Proposed Structure of the Beamspace Adaptive Array Antenna for Broadband Signals

Figure 1 shows the proposed beamspace adaptive array antenna for broadband signals. In this structure, a digital multibeam network that can pass the broadband signal is used instead of FFT. Tapped-delay-line circuits are used for the broadband DBF networks with fixed weights $a_{i,n,l}$ of which the digital multibeam network is composed. A few adaptive weights w_n follow the beam selector. Although computational complexity in the digital multibeam network is increased, this structure has considerably fewer adaptive weights than an element space adaptive array with tapped-delay-line circuits.

In order to suppress the broadband interference signals by a linear combination of selected broadband beams, the following conditions are necessary:

- Each broadband DBF network has the same phase characteristics;
- The beam pattern of each broadband DBF network is nearly independent of frequency, not only for the main beam, but also for the pattern of every angle.

In the next section, we will give a brief description of the methods for calculating the weights $a_{i,n,l}$ that satisfy the above requirements.

When a constant modulus algorithm (CMA) is applied to the beamspace adaptive array antenna shown in Fig. 1, the adaptive weights are updated according to the following equations:

$$W^{(m+1)} = W^{(m)} - \mu z(m)\left\{|z(m)|^2 - \sigma^2\right\}Y^*(m) \qquad (1)$$

$$W^{(m)} = \left[w_1^{(m)}, w_2^{(m)}, \cdots, w_b^{(m)}\right]^{\mathrm{T}} \qquad (2) \qquad\qquad Y(m) = \left[y_{i_1}(m), y_{i_2}(m), \cdots, y_{i_b}(m)\right]^{\mathrm{T}} \qquad (3)$$

$$y_i(m) = \sum_{n=0}^{N-1}\sum_{l=0}^{L-1} a_{i,n,l}x_n(m-l) \qquad (i=0,1,\ldots,I\text{-}1)\ (4) \qquad\qquad z(m) = \sum_{k=1}^{b} w_k^{(m)} y_{i_k}(m) = W^{(m)\mathrm{T}}Y(m) \qquad (5)$$

where each $w_k^{(m)}$ is the adaptive weight value at the time=m, $\{i_1, i_2, \ldots, i_b\}$ is the set of the selected beam numbers, μ is a step size parameter, and σ is the desired modulus value. The adaptive algorithm is not limited to the CMA.

2.2 Design Method of the Broadband DBF Networks

A brief description of the design method is given here. The term "design" means calculating the fixed weights $a_{i,n,l}$.

The broadband DBF network #i (i=0, 1, ..., I-1) can be regarded as a two-dimensional digital filter (2D-DF). The frequency response of this 2D-DF is

$$G_i(F_1, F_2) = \sum_{n=0}^{N-1}\sum_{l=0}^{L-1} a_{i,n,l}\,e^{-j2\pi F_1 l}e^{j2\pi F_2 n}, \qquad (6)$$

$$F_1 = (f - f_c)/f_s, \qquad (7) \qquad\qquad F_2 = (d\sin\theta/c)(f_s F_1 + f_c), \qquad (8)$$

where F_1 and F_2 are normalized temporal frequency and normalized spatial frequency, respectively.

Assuming that the main beam direction is θ_0, the passband region of the 2D-DF is the hatched area on the F_1-F_2 plane shown in Fig. 2, where θ_0 =40°, f_s=0.2f_c, and d=0.45λ_c. The stopband region is the outside of the hatched area. The "magnitude contour" of the 2D-DF is required to run along the line of Eq. (8) on the F_1-F_2 plane in order for the beam pattern to be nearly independent of frequency including sidelobe characteristics, because θ=constant is mapped to Eq. (8) on the F_1-F_2 plane. (The group of slanted lines of Fig. 2 shows Eq. (8)

as the parameter θ.) Such 2D-DFs can be obtained by a spectral transformation of Eq. (9) to one-dimensional zero-phase FIR narrow-band lowpass digital filters. Equation (9) is the ideal transformation.

$$F = \frac{F_2}{(f_s/f_c)F_1 + 1} - F_{2shift}, \quad F_{2shift} = (d/\lambda_c)\sin\theta_0 \tag{9}$$

The weights $a_{i,n,l}$ are obtained from the impulse response of the transformed 2D-DF. Both the number of array elements N and the number of taps L are limited to being odd.

Figure 3 shows the antenna pattern of the broadband DBF network designed by the above method, where θ_0 =56°, f_s=0.2f_c, and d=0.45λ_c. We assume that each antenna element has an omnidirectional pattern and no mutual coupling. All antenna patterns nearly agree irrespective of frequency.

3. Simulation

Here, we will apply the CMA to the adaptive algorithm.

3.1 Conditions of Simulation

Table I gives the radio environment. There are two interference signals. Signal power is defined for I and Q signals at the input of the beamforming network per one element. These three signals are not coherent with one another.

We assume that each antenna element has an omnidirectional pattern and no mutual coupling. Linear-uniform array is also assumed. Table II gives the bandwidth of signals used in the computer simulation, where f_c and λ_c are carrier frequency and wavelength, respectively. As shown in Table II, we examine three kinds of bandwidths. Element distance is set to the almost same value as half of the wavelength corresponding to the maximum frequency of the RF signal in order that the main beam pattern and the frequency characteristics of the broadband DBF networks do not deteriorate when the main beam direction is near endfire.

Table III gives other parameters. The multiple beamformer does not form orthogonal beams. The step size parameter μ is set so that standard deviation of the desired output signal can become about 0.5 dB after convergence. We select 6 beams according to decreasing order of the power of the multibeam network output. Initial weight value is set to 0.1 for the weight corresponding to the output of the multibeam network with maximum instantaneous power and 0 for the rest. For comparison, we also examine the performance of an element space adaptive array with tapped-delay-line circuits that have 7 taps.

The number of adaptive weights is:

Beamspace structure, 6; element space structure, 17×7=119.

Table I Radio environment used in computer simulation

	Direction of arrival	Power (relative to noise)	Kind of signal
Desired signal	25°	20 dB	random FM
Interference 1	35°	17 dB	random FM
Interference 2	-50°	16 dB	random FM
Noise	—	0 dB	white Gaussian

Table II Bandwidth of signal

	Case 1	Case 2	Case 3
Bandwidth of desired signal	$0.08f_c$	$0.16f_c$	$0.24f_c$
Bandwidth of interference 1 and 2	$0.08f_c$	$0.16f_c$	$0.24f_c$
Sampling frequency f_s	$0.1f_c$	$0.2f_c$	$0.3f_c$
Distance of elements d	$0.47\lambda_c$	$0.45\lambda_c$	$0.43\lambda_c$

Table III Other parameters

Number of antenna elements N	17
Number of multiple beams I	15 (main beam direction 0°, ±7°, ±15°, ±24°, ±34°, ±45°, ±56°, ±70°)
Number of taps of the broadband DBF network L	17
Desired modulus value σ	10.0

3.2 Results

The improvement factor (IMF) is used as index of the performance of interference suppression. IMF is defined as

$$IMF = (S/I)_{out} / (S/I)_{in}, \tag{10}$$

where $(S/I)_{in}$ is the desired signal to interference power ratio at the input of the adaptive array per one element and $(S/I)_{out}$ is the desired signal to interference power ratio at the output of the adaptive array. Table IV gives the IMF. Although the proposed broadband beamspace adaptive array antenna has much fewer weights than the element space adaptive array, the performance of interference suppression of the former is as good as the latter.

Figure 4 shows the antenna pattern and the frequency characteristics of the broadband beamspace adaptive array after 4000 iterations for case 2. It is observed that a broadband null is formed in the interference signal directions of 35° and -50°. The null levels are more than 30 dB lower than the main beam level.

Figure 5 shows the convergence characteristics of the broadband beamspace adaptive array and the element space adaptive array for case 2. This is the relative instantaneous power of output signals of the adaptive array antenna. Clearly, convergence of the beamspace adaptive array is faster than the element space adaptive array. The reason why convergence of the beamspace adaptive array is faster is that broadband beams have already formed in the multiple beamformer and they are controlled by a few adaptive weights.

Table IV Improvement factor

	Case 1		Case 2		Case 3	
DOA of interference	35°	-50°	35°	-50°	35°	-50°
Broadband beamspace structure	38.4 dB	38.1 dB	35.1 dB	34.9 dB	33.0 dB	36.0 dB
Element space structure (tapped delay line)	34.4 dB	35.8 dB	34.7 dB	37.0 dB	31.6 dB	33.2 dB

4. Conclusions

We have proposed a beamspace adaptive array antenna for broadband signals. The proposed adaptive array has only a few adaptive weights that follow a broadband digital multibeam network and a beam selector. We have briefly described the required characteristics and the design method for the broadband DBF networks of which the multibeam network is composed.

Finally, we have shown by computer simulation that the performance of interference suppression for the proposed beamspace adaptive array antenna is as good as that of an element space adaptive array and that it has much faster convergence.

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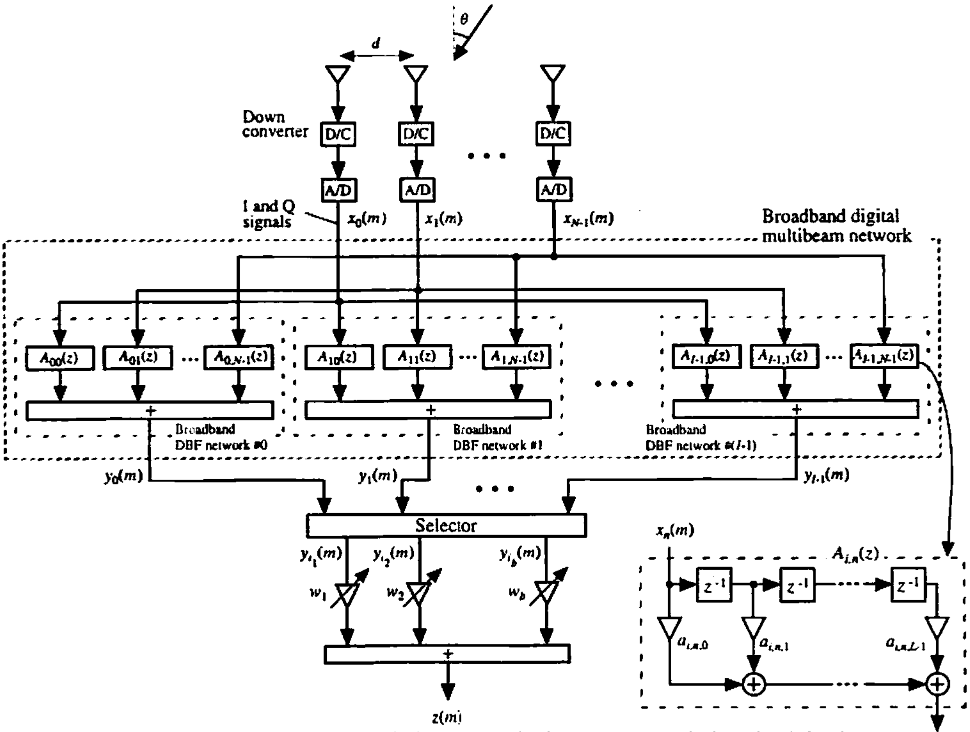

Fig. 1. Proposed structure of the beamspace adaptive array antenna for broadband signals.

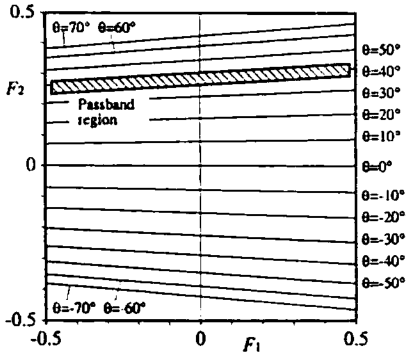

Fig. 2. Passband region on the F_1-F_2 plane for the broadband DBF network. Main beam direction is 40°.

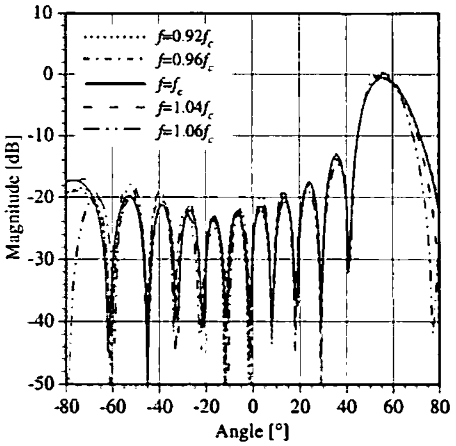

Fig. 3. Antenna pattern for the designed broadband DBF network. Main beam direction is 56°.

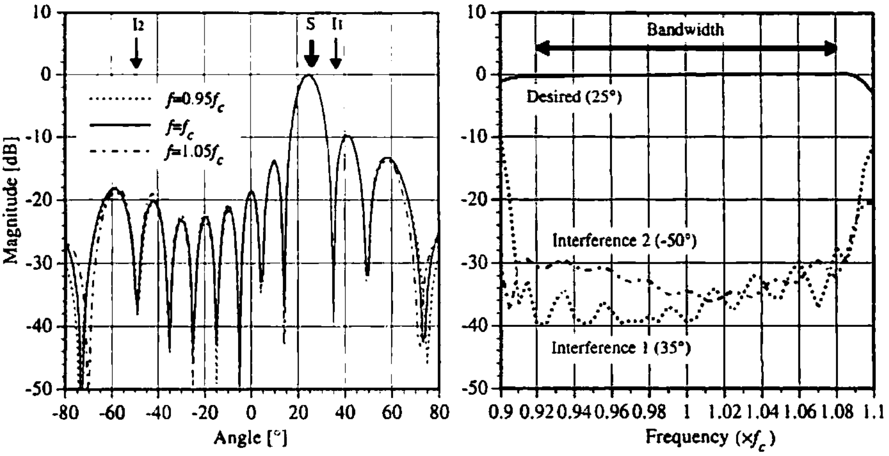

Fig. 4. Antenna pattern (left) and frequency characteristics (right) of the proposed broadband beamspace adaptive array (case 2, after 4000 iterations).

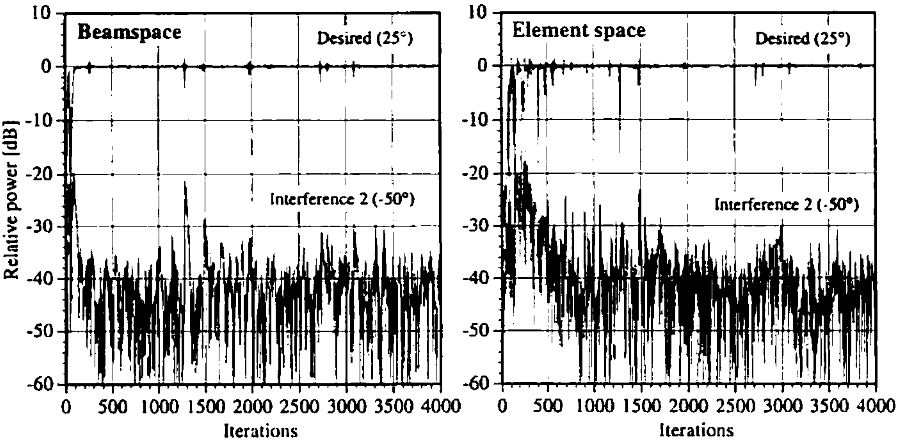

Fig. 5. Convergence characteristics for the proposed broadband beamspace adaptive array (left) and the element space adaptive array (right).