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TDL-based Wideband Beamforming for Radio Sources Close to the Array Endfire

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ABSTRACT

Uniform linear array (ULA)-based tapped-delay line (TDL) structure has good performance metrics when the signal sources are located at the middle angles. It offers poor performance when the signal sources are close to the array endfire. In this paper, a new approach is proposed which offers higher performance and desired beamforming on TDL structure when the wideband uncorrelated radio sources are close to the array endfire. This new TDL structure is based on Shirvani-Akbari array (SAA). Numerical results of this investigation show that both ULA-based and SAA-based TDL structures have the same performance where the signals of interest located at the middle angles. But, where the signals are close to the array endfire, the SAA-based TDL structure has much higher performance. In order to find a good comparison, the absolute array factor (AF) in center frequency for different angles and three well-known performance metrics, normalized mean square error (NMSE), signal to interference plus noise ratio (SINR) and bit error rate (BER) are evaluated for both ULA-based and SAA-based TDL structures.

1. INTRODUCTION

Antennas are classified as either single element antennas or array antennas (multi element). Single element antennas are either omni-directional or directional. Omni-directional antennas have equal gain in all directions and are also known as isotropic antennas. Directional antennas have maximum gain in the desired directions and less one in the other directions. Antenna array is an arrangement of many individual antennas which are placed in space and phase such that the contribution of individual antennas will be added in one desired direction and be cancelled in other directions [1]-[4].

The antenna arrays are used to generate electronically steerable antenna patterns. The desired signal reception is maintained by steering the main beam. Spacing between array elements is an important factor in designing antenna arrays. The adaptive antenna array adjusts their pattern automatically to signal environment to reduce interference. Such system is named as smart antenna [5], [6].

A smart antenna system combines multiple antenna elements with a signal processing capability to optimize its radiation pattern automatically in response to the signal environment [7]. The digital signal processing (DSP) unit controls radiation parameters of the antenna. The direction of arrival (DOA) estimation algorithms tracks the signal received from the user.

The radiation pattern is adjusted to place nulls in the direction of Interferers and Maxima in the direction of the desired user or users [8], [9].

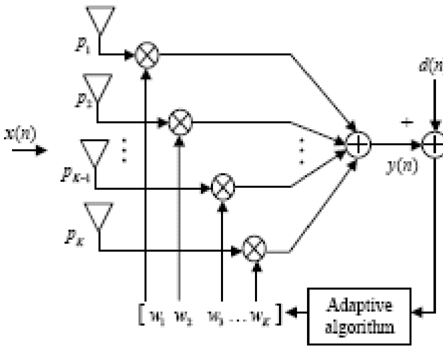

Figure 1: Adaptive Beamforming System [7].

Smart antenna system is proposed as a promising solution that can significantly increase the data rate and improve the quality of received signal in wireless communication systems. It enables the main beam to be directed towards a specific user, while the nulls are adjusted towards the interferers, that need to achieving the optimal weights of antenna elements dynamically which is called beamforming [10], [11]. Beamforming is the process by which phase shifts are introduced to an array of antennas in order to achieve a desired beam pattern. An example of a time-domain processing beamformer is shown in Fig. 1.

The sampled signal from each antenna is combined to determine the output signal. By varying the weights for each branch, we can increase or decrease the strength of signals arriving from different angles [12], [13].

In [14], [15], the impact of signal bandwidth on the beamforming and performance of a smart antenna system were investigated. It is clear that, as the signal bandwidth increases, the interference rejection and the ability to form main beam in the desired direction cannot be achieved successfully using the existing narrowband weighting schemes. So, a concept of finite impulse response (FIR)-based beamforming has been modeled for broadband antenna arrays [16].

Recently broadband beamforming has found many applications in various areas ranging from sonar and radar to wireless communications. Therefore, we need use suitable structures for this case of beamformers. Traditional adaptive broadband beamformer usually employs tapped-delay lines (TDLs) or linear transversal filters with adaptive coefficients to generate appropriate beam patterns for suppressing undesirable interference. This type of beamformer usually requires considerable number of adaptive coefficients resulting in a rather long convergence time and high implementation complexity.

Generally, we will need a series of tapped delay-lines or FIR or infinite impulse response (IIR) filters in its discrete form to process each of the received signals which can form a frequency dependent response for each of the received broadband sensor signals to compensate the phase difference for different frequency components [17], [18].

In [19], authors focused on two ULA-based SDL and TDL beamforming structures, appropriate for wideband radio signals. They evaluated the performance of sensor delay line (SDL) and TDL structures based on normalized mean square error (NMSE) and signal to interference plus noise ratio (SINR) criteria in the case of uncorrelated sources.

In addition, the effect of the bandwidth, signal to noise ratio (SNR) and the number of branches were investigated. It was shown that the ULA-based SDL structure offers higher performance, lower NMSE and higher SINR, than ULA-based TDL structure in similar conditions. Simulations show that by increasing the SNR, NMSE will be decreased and the SINR will be converged faster.

Moreover, increasing the bandwidth is the reason for decreasing the performance. Furthermore, increasing the number of SDL or TDL branches will increase the performance. In contrast, the system will be more complicated. The number of TDLs and SDLs has an optimum amount that in these simulations the optimum number is N= 10.

The conventional ULA is the most common array geometry for smart antenna systems and array signal processing. Beside great advantages, the ULA does not perform uniform for all angles in the spatial spectrum and cannot detect or resolve close sources located at endfires, accurately. In [20], a new ULA-based array geometry is proposed and presented which can remove this drawback by keeping the simplicity in implementation and analysis. Numerical evaluation is done on the resolution of both ULA and proposed array (PA), named as Shirvani-Akbari array (SAA), geometries via two well-known angle of arrival (AOA) estimation algorithms. Simulation results show that the proposed array resolves narrowband signal sources located at close angles to the array endfire accurately, while having a good resolution in the other directions.

In this investigation, SAA is applied for TDL-based wideband beamformer for finding higher performance where the signal sources are close to the array endfire.

The rest of this paper is organized as follow. The broadband beamforming by ULA-based TDL structure is reviewed in section 2. In addition, the various structures for SAA are studied in this section. Comparative results are reported in section 3.

All simulation results are compared based on three well-known performance criteria, Array factor (AF), NMSE, SINR and bit error rate (BER). Finally, section 4 concludes this paper.

2. TDL STRUCTURE

A. ULA-based TDL Structure

In TDL structure, the received array signals will be processed in the temporal domain by using delays, which is equivalent to applying a FIR filter to each of received signals. Then, array can form a frequency dependent response for each of the received broadband sensor signals to compensate the phase difference for different frequency components. Fig. 2, shows the general TDL structure for broadband beamforming, in which J is the number of delay elements associated with each of the M sensor channels. The beamformer with such a structure samples the propagating wave field in both space and time [17, 19].

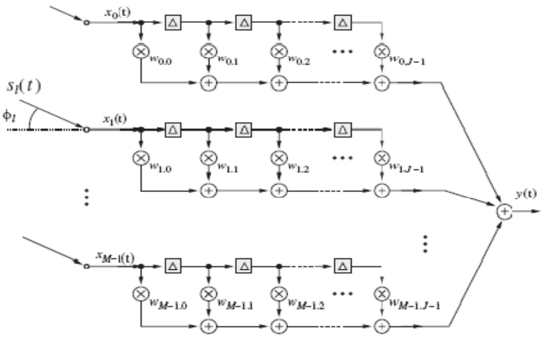

Figure 2: A ULA-based broadband beamforming TDL structure [18].

The output signal y(t) can be written as:

$$y(t) = W^T X(t) \tag{1}$$

$$W = \left[w_{0,0}, \dots w_{M-1,0} \dots w_{0,J-1} \dots w_{M-1,J-1}\right]^T$$
$$X = \left[x_{0,0}(t) .. x_{M-1,0}(t) \dots x_{0,J-1}(t) \dots x_{M-1,J-1}(t)\right]^T \tag{2}$$

AF as a function of the signal angular frequency and the direction of arrival angle can be expressed as

$$P(\omega,\theta) = \sum_{m=0}^{M-1}\sum_{k=0}^{J-1} w_{m,k} e^{-j\omega(\tau_m + kT_s)} \tag{3}$$

where Ts is the delay between adjacent taps of the TDLs and τ_m is the spatial propagation delay along the x-axis.

For a uniformly spaced linear array with an inter-element spacing d, we have $\tau_m = m\frac{d}{c}\cos\theta$.

B. A New SAA-based TDL Structure

In this section, SAA configuration is proposed for wideband TDL beamformer to find higher performance with respect to ULA especially for endfire angles. SAA configuration changes the location of two border array elements of ULA to top and bottom of the array axis. The ULA and three various structures of SAA are shown in Fig. 3 [18]. The structure of the array, impress the array steering vector and also the performance of adaptive beamformer. Array factor for SAA structure can be expressed as a function of signal angular frequency ω and the direction of arrival angle θ:

$$p(\omega,\theta) = \sum_{m=0}^{M-1} f(\omega,\theta) \tag{4}$$

$$f(\omega,\theta) = \begin{cases} \sum_{k=0}^{J-1} w_{m,k} e^{-j\omega(\mathrm{\tau_m} + \mathrm{kT_s})} & ,1 \le m \le M-2 \\ \sum_{k=0}^{J-1} w_{m,k} e^{-j\omega(\mathrm{\tau_m} + \mathrm{kT_s} + T_e)} & ,m = 1 \\ \sum_{k=0}^{J-1} w_{m,k} e^{-j\omega(\mathrm{\tau_m} + \mathrm{kT_s} - T_e)} & ,m = M-1 \end{cases} \tag{5}$$

$\mathrm{\tau_m}$ and $\mathrm{T_s}$ are the same as the previous section. $\mathrm{T_e}$ is the spatial propagation delay along the y-axis. For an ULA with an inter-element spacing d , we have

$$\mathrm{T_e} = \frac{\mathrm{d}}{\mathrm{c}}\sin\theta \tag{6}$$

It is assumed that the middle sensor position is set as the phase reference point. The AF for other structures of SAA-based TDL beamformer can be written, simply.

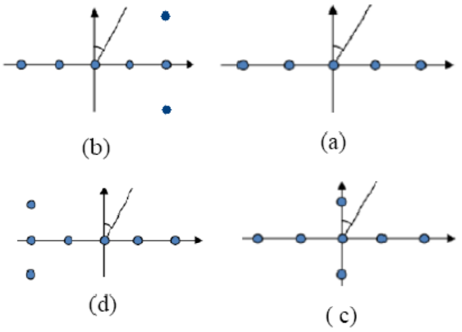

Figure 3: ULA and Shirvani-Akbari array configurations [20].

C. Some Assumptions

In the above formulations, all signals are supposed impinge from the direction $\theta = \frac{\pi}{2}$. This means that all signals are on the same plane. The coefficients (weights) for TDL structure can be determined in different ways. Here, we use the case for which a reference signal $r(t)$ is available and the weights are adjusted to minimize the mean square error between the beamformer output $y(t)$ and the reference signal $r(t)$ as shown in Fig. 4.

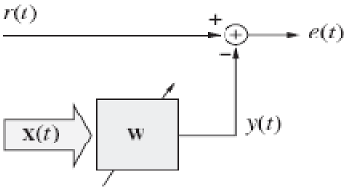

Figure 4: Reference signal-based beamformer.

It is a classical adaptive filtering problem and can be solved by existing adaptive algorithms such as the least mean squares (LMS) or recursive least squares (RLS) algorithms. In our simulations, normalized least mean square error (NLMS) algorithm is used and the learning curves of NMSE, BER and SINR versus iterations are represented. The formulation of SINR is as follow:

$$SINR = \frac{P_S}{P_N} \tag{7}$$

where P_S is the mean output power due to the desired signal and P_N is the mean power at the output of the array contributed by random noise and unwanted interferences that is:

$$P_N = P_n + P_i \tag{8}$$

$$\left.\begin{aligned} P_s &= w^H R_s w, \\ P_n &= w^H R_n w, \\ P_i &= w^H R_i w \end{aligned}\right\} \tag{9}$$

where R_S, R_i and R_n are the array correlation matrices due to the signal source, unwanted interference, and random noise, respectively.
Then, the SINR can be written as:

$$SINR = \frac{w^H R_S w}{w^H R_n w + w^H R_i w} \tag{10}$$

3. SIMULATION RESULTS

In this section, the conventional TDL structure is compared with the proposed SAA-based TDL. In this investigation, M=N=15. A desired signal and two interferences are considered. All signals have a bandwidth of [0.4π; π].

The signal to interference ratio (SIR) is about −20 dB and the SNR is about 20 dB. Weighting is based on NLMS algorithm considering step size 0.03.

Fig. 5 shows the absolute AF, NMSE, SINR and BER in center frequency for TDL structures based on four array geometries of Fig. 3, when the signal of interest and interferences are located at $\theta = 0^\circ, 30^\circ, -30^\circ$, respectively.

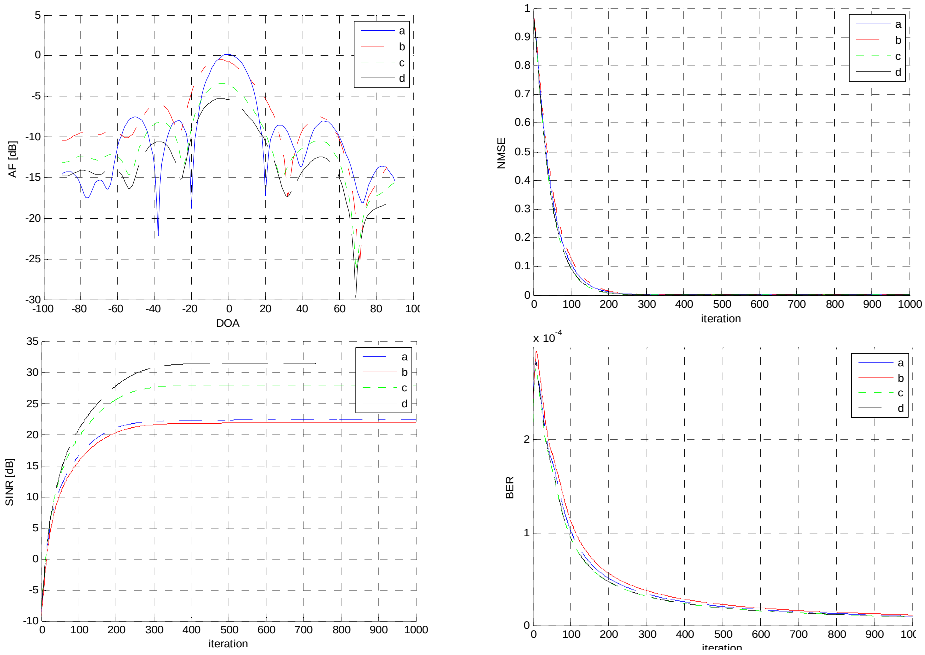

Figure 5: Performance metrics of different TDL structures where signal of interest and interferences are located at $\theta = 0^\circ, 30^\circ, -30^\circ$

As depicted in this figure, SAA-based TDL structure offers higher performance than ULA-based one, even where the signals are located at the middle angles.

Fig. 6, illustrates the performance metrics, when the signal of interest is close to array endfire, at $\theta = 85^{\circ}$, and interference signals are located at $\theta = 30^{\circ}, -30^{\circ}$. In this case, SAA-based structure shows much higher performance compared to conventional TDL structure.

Furthermore, Figures 7, 8 show the performance metrics, absolute AF, NMSE, SINR and BER in center frequency for different TDL structures. In Fig. 7, the signal of interest is located at $\theta = 0^{\circ}$ and interferers are close to the array endfire ($\theta = 85^{\circ}, -85^{\circ}$). In Fig. 8, one of the interference signals is located at $\theta = 5^{\circ}$ close to the desired one. The desired signal is close to the array endfire, at $\theta = 85^{\circ}$ and one of the interferers is located close to the desired one, at $\theta = 80^{\circ}$.

4. CONCLUSION

Recently, adaptive array antenna has been widely considered to improve the quality of wireless radio signals and manage radio resources. In this investigation, we focused on TDL beamforming structure.

The main goal of this work was to improve the performance of TDL-based wideband beamforming for uncorrelated signals.

It was done considering new proposed array geometry, named as Shirvani-Akbari array (SAA).

The performance of both ULA-based and SAA-based TDL structures considering AF, NMSE, BER and SINR was evaluated for wideband uncorrelated sources on various angles of arrival.

Simulations showed the following results:

- When the signals of interest are located in the middle angles, the SAA-based TDL structure has the same performance as ULA-based TDL structure.
- When the signals of interest are close to the array endfire, the SAA-based TDL structure has much higher performance than conventional ULA-based TDL structure.
- When the angular difference between the desired signal and the interference one is much low, in the middle angles, the performance metrics are much higher for both conventional and new proposed TDL structure.
- For close signals at the endfire, SAA-based TDL structure offers higher performance than conventional ULA-based structure.

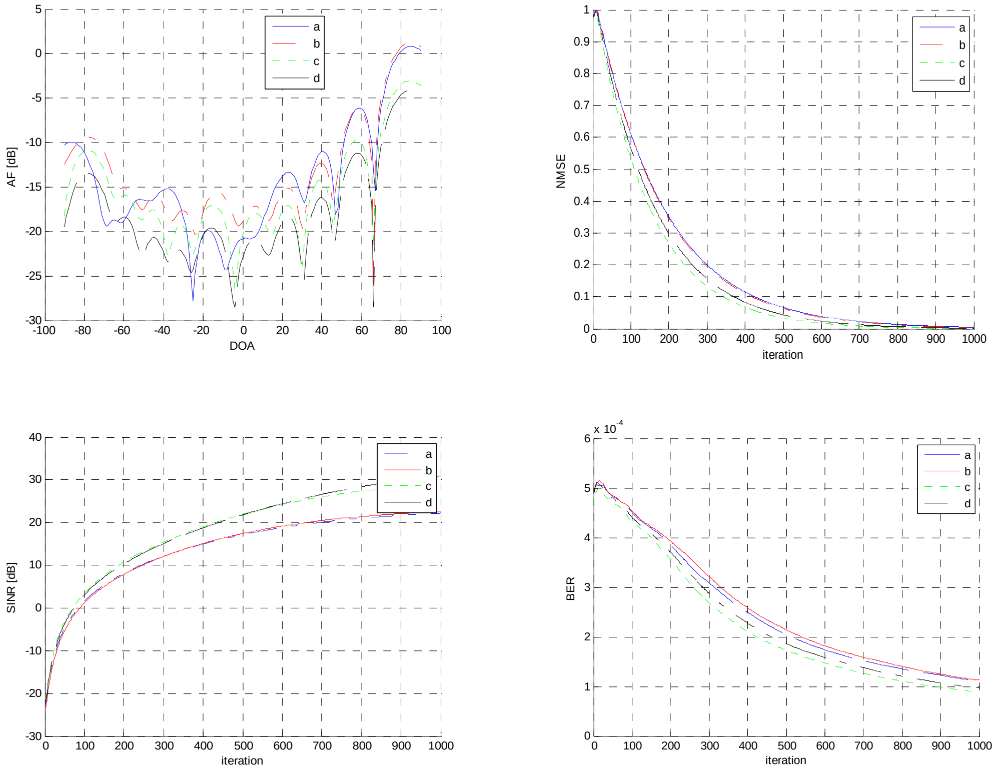

Figure 6: Performance metrics of different TDL structures where signal of interest and interferences are located at $\theta = 85^{\circ}, 30^{\circ}, -30^{\circ}$.

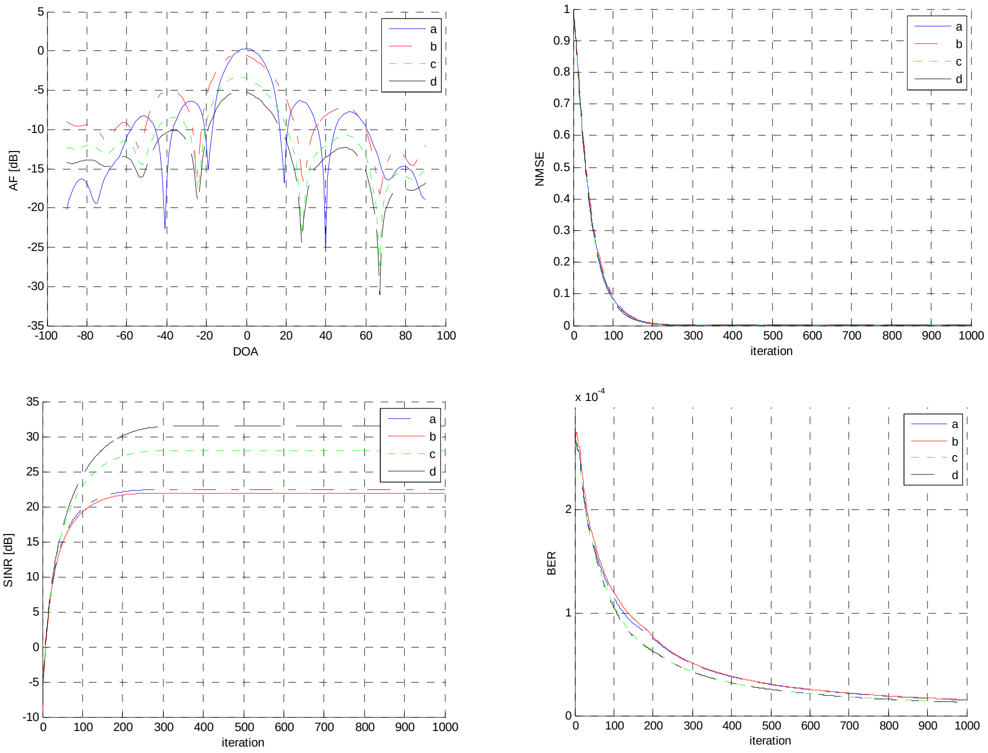

Figure 7: Performance metrics of different TDL structures where signal of interest and interferences are located at $\theta = 0^{\circ}, 85^{\circ}, -85^{\circ}$

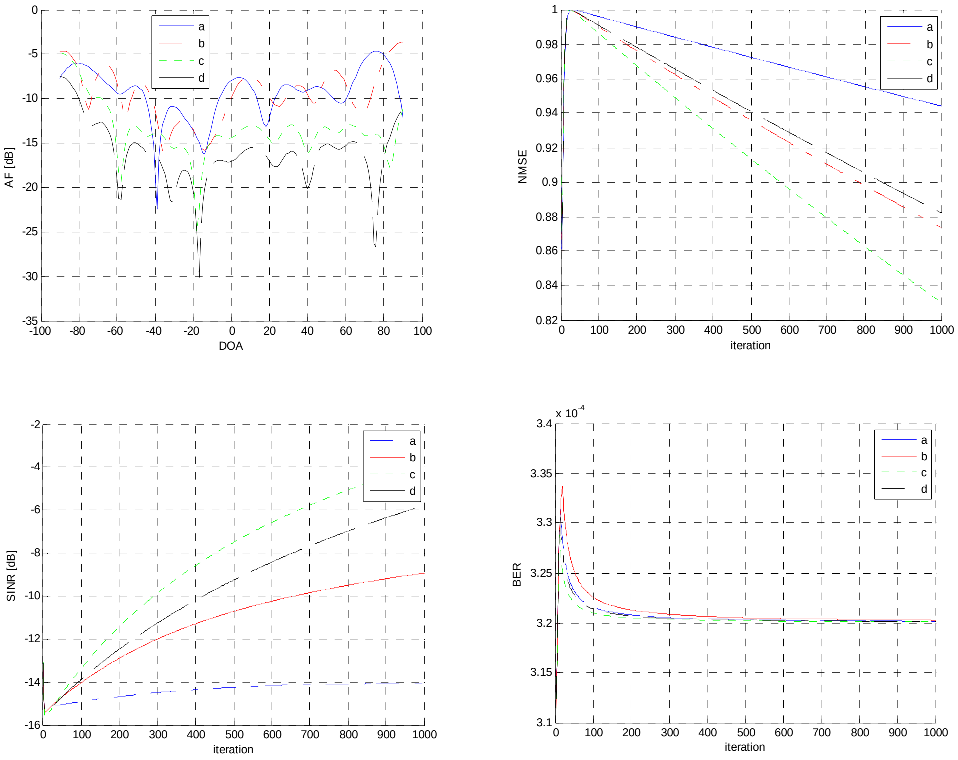

Figure 8: Performance metrics of different TDL structures where signal of interest and interferences are located at $\theta = 85^{\circ}, 80^{\circ}, -30^{\circ}$

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