A Sparse Design for Aperture-Level Simultaneous Transmit and Receive Arrays

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Abstract: The aperture-level simultaneous transmit and receive (ALSTAR) system uses full digital architecture with an observation channel to achieve remarkably effective isotropic isolation (EII). However, the number of observation channels must be the same as the number of transmit channels, which increases the system’s complexity. To balance the system cost and performance of the ALSTAR, this paper proposes a joint design of sparse arrays and beamforming, which are achieved by a genetic algorithm and an alternating optimization algorithm, respectively. In the sparse design, we introduce beamforming technology to guarantee the EII while decreasing the corresponding elements of observation channel that contribute slightly to the EII. The simulation results are presented for a 32-element array that achieves 185.87 dB of the EII with 1000 W of transmit power. In the cases of sparsity rates at 0.875 and 0.75 (≥0.6), i.e., the number of observation channels decreases by 12.5% (2/16) and 25% (4/16), the reductions in EII do not exceed 1 dB and 3 dB, respectively. However, the EII decreases rapidly with a sparsity rate less than 0.25. Results demonstrate that our proposed joint design of sparse arrays and beamforming can reduce the system cost with little performance loss of EII.

Keywords: simultaneous transmit and receive; self-interference cancellation; sparse arrays; phased arrays

1. Introduction

The demand for multi-function phased arrays has rapidly developed in radar, communications, and electronic warfare. The simultaneous transmit and receive (STAR) [1] is an important application of digital phased arrays that could transmit and receive signals of the same frequency and time in the same environment and on the same system. The STAR system can significantly increase the throughput and band efficiency [2,3], operate simultaneously on multiple operating modes [4], has multiple pulse repetition intervals and continuous answering to interference [5], and joint multi-user systems [6,7]. In order to take full advantage of the STAR digital phased arrays, the isolation between transmitter and receiver must be enhanced.

Currently, many technologies have been implemented to improve isolation for the STAR system. Everett et al. [8] used digital transmit beamforming to reduce the self-interference received at the receiving antennas in a multi-antenna system. Qiu et al. [9] adopted a linear constrained minimum variance algorithm to optimize the beamforming, which provides at least 110 dB of isolation without affecting the target detection. Liang et al. [10] proposed a method to realize adaptive transmit beamforming together with digital self-interference cancellation (SIC). Zhang et al. [11] studied the coupling path characteristics of all spatial links between the transmit aperture and receive aperture, and used digital beamforming and digital SIC technology to improve the cancellation performance between transmit aperture and different receive position array elements [12].

In 2016, The MIT Lincoln Laboratory demonstrated that the aperture-level STAR (ALSTAR)
with digital beamforming and SIC technology was sufficient to achieve 163.9 dB of effective isotropic isolation (EII) over a 100 MHz instantaneous bandwidth in a 5 × 10 element digital phased arrays [13]. In [14], I. T. Cummings et al. further improved the theoretical study of the ALSTAR array. Theoretical results suggested that the isolation could reach 187.1 dB under the condition of 2500 W transmit power for the array with 25 transmit elements and 25 receive elements, while the noise floor only increased 2.2 dB. The author in [15] proposed an information-theoretic performance metric for a narrowband STAR imaging system. I. T. Cummings et al. also explored how to optimally divide the array into transmit and receive apertures by applying genetic algorithm (GA) [16]. Although there are various methods to improve the isolation between the transmitter and the receiver, the system cost and complexity must be considered in practical engineering.

For instance, in the signal model of the ALSTAR array, SIC is implemented by establishing the observation channel between the output of the power amplifier and the output of the receive beamforming. With the increase in the array elements, more observation channels are required, which greatly increases the cost and complexity of the system. Therefore, in a massive phased array with STAR function, it is crucial to reduce the system cost while maintaining good isolation performance. In the ALSTAR array, the digital cancellation method requires the observation channel to have the same performance as the receive channel while the cost of the receive channel is often higher than the one of the transmit channel. We propose a scheme with sparse arrays and beamforming to reduce some transmit channels and observation channels. Then, the purpose of reducing system costs and maintaining good isolation performance will be achieved.

Traditionally, sparse arrays were usually used for non-uniform array element spacing to reconstruct the desired radiation pattern. It used a smaller number of antenna elements to relieve the pressure of large-scale antenna element integration. Liu Y. et al. adopted the matrix pencil method (MPM) [17] in the sparse arrays to minimize the number of elements and enhance computation efficiency. Ning Liu et al., in [18], developed a joint Monte Carlo algorithm and particle swarm optimization (PSO) approach for sparse arrays synthesis. In [19], X. He et al. proposed a hybrid simulated annealing (SA) and PSO algorithm to numerically determine an optimal 4 × 4 multiple-input multiple-output (MIMO) array. This array achieved a lower peak side lobe level (PSLL) and narrower 3 dB beamwidth with 8 fewer elements compared to the corresponding 16-element uniform linear array (ULA). M. Lou et al. adopted the single pattern convex optimization (CO)-based synthesis and evaluated the system performance of the sparse arrays in mobile communication [20]. Further, they proposed a synthesis based on joint convex optimization (JCO) to construct a codebook for beamforming. Using half the number of antenna elements on a uniform array, the performance of a JCO-based sparse arrays was close to the one of a uniform array [21]. P. Pal et al., in [22], used GA for reducing the side lobe level (SLL) and imposing nulls at prescribed interfering directions to obtain the optimal radiation pattern of a linear adaptive antenna array. R. Rajamäki et al. in [23] designed a hybrid sparse planar array that attained the point spread function of a 17 × 17 element fully digital uniform square array using 78% fewer elements and 99% fewer transmit and receive front ends. Many research studies applied the sparse arrays to obtain lower SLL and optimal radiation pattern with a smaller number of array elements and lower array cost. However, few researchers focused on the effect of the sparse arrays on STAR. In [24], Samaiyar et al. explored the impact of the sparse arrays in isolation of STAR antenna array. They proposed a sparse arrays configuration that achieved an improvement in isolation of 20 dB compared to a uniform array. Their work with sparse techniques for STAR is similar to the one proposed in this work. However, our aim is to reduce the number of elements and system complexity in the case of little isolation reduction. Furthermore, they do not consider the effect of beam-formers on EII.

In this paper, we first introduce the sparse arrays into ALSTAR to reduce the number of elements of transmit and receive array and the number of observation channel. At the same time, it can ensure that the ALSTAR system has better isolation performance. We take the ALSTAR array with 16 transmit array elements and 16 receive array elements as an example,
and expound the specific application of sparse arrays and beamforming in ALSTAR array. Experimental results show that our scheme is very cost-effective for a very small reduction in isolation in exchange for a significant cut in the cost of the ALSTAR system.

The organization of this paper is as follows. In Section 2, we describe the signal propagation model of ALSTAR and sparse arrays design for ALSTAR. Section 3 discusses and analyses the performance with sparse ALSTAR arrays. Finally, the conclusion is provided in Section 4.

2. System Model

2.1. ALSTAR Architecture

Figure 1 shows the signal propagation model of the ALSTAR architecture. The symbol $x(t)$ means the digital baseband signal, the symbol $x_i(t) \in \mathbb{C}^{1 \times 1}$, $x_r(t) \in \mathbb{C}^{K \times 1}$, and $s(t)$ are the vector of transmitted signal, the vector of received signal and the signal of interest (SOI), respectively. The parameter $b_t \in \mathbb{C}^{J \times 1}$, $b_r \in \mathbb{C}^{K \times 1}$, and $b_c \in \mathbb{C}^{I \times 1}$ represent the vector of transmit beamforming, the vector of receive beamforming and the adaptive cancellation filter, respectively. $M \in \mathbb{C}^{K \times J}$ and $H_o \in \mathbb{C}^{I \times J}$ are the characteristic matrix of the coupled channel and the observation channel. $I$ and $K$ are the number of transmit channel and receive channel, respectively. The signal $x_i(t)$ at time index $t$ can be written as

$$x_i(t) = b_t x(t) + n_t(t),$$  

(1)

where $E[|x(t)|^2] = 1$. $n_t(t)$ is zero-mean complex additive white Gaussian noise. Its covariance matrix is $N_t = E[n_t n_t^H] = \text{Diag}(b_t b_t^H) / \eta_t$, the symbol $\eta_t$ is the dynamic range of transmit channel. The signal after receive beamforming can be expressed as

$$x_r(t) = b_r^H [M x_t(t) + s(t) + n_r(t)],$$  

(2)

where $n_r(t)$ is zero-mean complex Gaussian receiver noise with $N_r = E[n_r n_r^H] = \text{Diag}(E[r r^H]) / \eta_r + \sigma_r^2 I$. The symbol $\eta_r$ is the receiver dynamic range and $\sigma_r^2$ is the receiver thermal noise power. In the case of the ALSTAR, the final received signal after the cancellation can be expressed as

$$x_c(t) = x_r(t) - x_o(t),$$  

(3)
where \( x_o(t) \) is the reference signal after passing through the observation channel, and its expression can be noted as

\[
x_o(t) = b_c^H [H_o(x_i(t) + n_o(t))].
\] (4)

By assuming \( b_c^H = b_c^HM_{H_o}^{-1} \) and combining the Equations (2)–(4), \( x_c(t) \) can be expressed as

\[
x_c(t) = b_r^H[n_r(t) + s(t) - Mn_o(t)].
\] (5)

Obviously, the residual signals after cancellation are the receive channel noise, the observation channel noise, and the signal of interest. The signal \( n_o(t) \) is the additive white Gaussian noise, which obeys the normal distribution \( n_o(t) \sim N(0, N_o) \), and the parameter \( N_o \) is equal to \( Diag(b_t b_r^H) / \eta_r \). The ALSTAR cancellation strategy establishes an observation channel, introduces observation noise, and removes emission noise, thereby improving the EII in (6)

\[
EII = \frac{P_l G_r(\phi, \theta, b_r)q_r(\phi, \theta) q_r^H(\phi, \theta) b_r}{\bar{P}_n b_t^H M_{b_t} b_t},
\] (6)

where \( P_l \) represents the transmit power, \( P_n \) is the total residual noise in the receiver, \( G_t \) and \( G_r \) represent the total gain of the transmit array and receive array. The symbol \( g \) is the gain of a single element and \( M_{ld} \) is the covariance matrix of interference and noise. The \( q_t \) and \( q_r \) represent the steering vector of the transmit array and receive array, where \( q(\phi, \theta) = \exp\left( -j \frac{2\pi}{\lambda} (x \cos(\phi) \sin(\theta) + y \sin(\phi) \cos(\theta)) \right) \), \( x \) represents the distance from each element in the array plane to the \( x \)-axis, \( y \) represents the distance from each element in the array plane to the \( y \)-axis. The expression of \( G_t \) and \( G_r \) is as follows

\[
G_t(\phi, \theta, b_t) = \left( g(\phi, \theta) b_t^H q_t(\phi, \theta) q_t^H(\phi, \theta) b_t \right) / P_t,
\] (7)

\[
G_r(\phi, \theta, b_r) = g(\phi, \theta) b_r^H q_r(\phi, \theta) q_r^H(\phi, \theta) b_r.
\] (8)

2.2. Sparse Arrays Design for ALSTAR

In this paper, we develop the sparse arrays based on ALSTAR system with massive phased arrays. Due to the ability to reduce antenna elements, observation channel, and radio frequency (RF) chains, sparse arrays have the potential to provide lighter weight and significantly reduce the complexity of the baseband processor. In addition, since sparse arrays can relocate the antenna elements, it may provide better system isolation, transmit pattern, and receive pattern than the uniform array with the same number of antenna element. GA is a well-studied method of solving binary integer optimization problems in sparse arrays [25]. Therefore, GA based sparse arrays is used to optimize the transmit and receive arrays of ALSTAR, then the transmit and receive beamforming are optimized by using alternating optimization (AO) algorithm [14]. The binary symbols 1 and 0 of GA denote the retention and deletion status of array elements, respectively. According to the iterative optimization search mechanism of GA, the uniform planar array with \( N_T \) transmit elements and \( N_R \) receive elements is optimized to a sparse arrays with \( L_T \) transmit elements and \( L_R \) receive elements. The sparsity rate can be expressed as \( L_T / N_T \), \( L_R / N_R \). The symbol \( f_{id} \) indicates the working state of the corresponding array element, \( f_{id} = 1 \) indicates that the array element at this position is reserved, \( f_{id} = 0 \) indicates that the array element at this position is removed. Therefore, the vector \( f_{id} = (f_{i1}, f_{i2}, \cdots, f_{id}) \) represents the array state after sparse arrays optimization, \( d \) represents the number of transmit elements and receive elements in the uniform planar array. By taking EII as the
fitness function, the array geometry of the transmit and receive array is obtained. The fitness function is as follows

$$\max \left\{ P_t G_{t_{\text{sparse}}} (\phi, \theta, b_{t_{\text{sparse}}}) \cdot s_{t_{\text{sparse}}} q_{t_{\text{sparse}}} (\phi, \theta) q_{t_{\text{sparse}}} (\phi, \theta) b_{t_{\text{sparse}}} \right\},$$

$$s.t. \| b_{t_{\text{sparse}}} \|^2 = P_t, \| b_{r_{\text{sparse}}} \|^2 = 1.$$  \hspace{1cm} (9)

In Equation (9), the symbol $\max \{ \cdot \}$ represents the maximum value function of EII during sparse arrays optimization, the parameters $q_t$, $q_r$, $g$, and $M$ after sparse arrays optimization are expressed as follows

$$q_{t_{\text{sparse}}}/s_{t_{\text{sparse}}} (\phi, \theta) = q_{t/r} (\phi, \theta) \cdot f f_i,$$

$$s_{t_{\text{sparse}}}/s_{t_{\text{sparse}}} (\phi, \theta) = s_{t/r} (\phi, \theta) \cdot f f_i,$$

$$M_{t_{\text{sparse}}} = M \cdot f f_i f f_i^H.$$  \hspace{1cm} (10)

The symbol $G_t$ and $G_r$ after sparse arrays optimization are expressed as follows

$$G_{t_{\text{sparse}}} (\phi, \theta, b_{t_{\text{sparse}}}) = \left( s_{t_{\text{sparse}}} (\phi, \theta) \cdot \left( b_{t_{\text{sparse}}}^H q_{t_{\text{sparse}}} (\phi, \theta) q_{t_{\text{sparse}}}^H (\phi, \theta) b_{t_{\text{sparse}}} \right) \right) / P_t,$$

$$G_{r_{\text{sparse}}} (\phi, \theta, b_{r_{\text{sparse}}}) = s_{r_{\text{sparse}}} (\phi, \theta) \cdot \left( b_{r_{\text{sparse}}}^H q_{r_{\text{sparse}}} (\phi, \theta) q_{r_{\text{sparse}}}^H (\phi, \theta) b_{r_{\text{sparse}}} \right).$$  \hspace{1cm} (11)

GA is used for sparse arrays optimization of ALSTAR array. The flow chart of sparse arrays optimization operation is shown in Figure 2, and the algorithm flow is as follows:

1. Initializing a binary population that satisfies a certain sparsity rate.
2. The fitness of each individual in this population is calculated to determine whether the termination criterion is met, if the termination criterion is met, the operation is stopped and the optimal EII and individual are output as the optimization results.
3. If the termination criterion is not met, genetic operations of selection, crossover and mutation are performed on individuals in the population to ensure that the sparsity rate of each individual in the newly generated population remains unchanged.
4. For the evolved offspring population, the termination criterion is determined again, and the cycle continues until the termination condition is reached.

![Figure 2](image_url)

**Figure 2.** The flow chart of sparse ALSTAR arrays.
3. Experimental Results

In order to analyze the effect of the sparse arrays on the isolation between the transmit and receive arrays, we simulate the ALSTAR model with 16 Tx × 16 Rx uniform plane array in MATLAB software. Since the EII of the ALSTAR model is directly related to the characteristics of the coupling matrix and antenna gain, it is necessary to design phased arrays with high isolation and high gain. Subsequently, based on the designed phased arrays coupling matrix and the mode data of each element, the performance with sparse ALSTAR arrays is discussed and analyzed.

3.1. Phased Arrays Design

Equation (9) shows that the use of antenna elements with high-gain, low-coupling helps to improve the isolation between the transmit array and the receive array. In this paper, the improved U-shaped slot micro-strip patch antenna with high gain and low coupling characteristics is used as the antenna array element in the continuous wave radar scene. The configuration of the ALSTAR phase array is shown in Figure 3a. 8 array elements are evenly placed along the x-axis with a spacing of 0.5λ0, λ0 is the wavelength corresponding to the center frequency of the antenna in free space, and 4 array elements are evenly placed along the y-axis with a spacing of 0.5λ0, which constitutes the antenna aperture of the 32 array elements. In addition, the elements with 4 rows and 4 columns on the left of the array are defined as the transmit array, and the elements with 4 rows and 4 columns on the right of the array are defined as the receive array. The phased array is simulated in HFSS and its results are shown in Figure 3b–e. The EII is used to measure the isolation between the transmit array and the receive array. It can be seen from the simulation results that the center frequency of the antenna is 4.3 GHz, and its operating bandwidth is 100 MHz. The coupling between transmit array element #1 and each receive array element is less than −40 dB, and the maximum gain of the antenna reaches 5.5 dBi. The antenna has good low coupling and high gain characteristics.

![Array configuration and its performance](image-url)

**Figure 3.** Array configuration and its performance: (a) Array configuration; (b) Port reflection coefficient; (c) The coupling of the array element #1 to each receive array element; (d) The coupling of each transmit element to the array element #17; (e) The pattern of the array element #1 and the array element #17.
3.2. Performance Analyze with Sparse ALSTAR Arrays

In order to reveal the effect of ALSTAR array with sparse arrays, we conduct three experiments using only SIC, SIC-BF, SIC-BF-sparse arrays, and analyze the performance of ALSTAR under different sparsity rates. As described in Section 2.2, we incorporate this scheme into the measurement and optimization model of the ALSTAR array established by Equation (9). The antenna adopts the phased arrays designed above, and the array beams are scanned up to 70° from array normal. The system’s dynamic range of transmitter and receiver is set as 45 dB and 70 dB, respectively. The noise floor of the receive channel is −91 dB, which is obtained by the 100 MHz bandwidth channel with a 3 dB noise figure. The fitness function and the boundary range of the parameters are given in Section 2. The population size and number of iterations for GA are set to 30 and 100, respectively. The number of iterations for AO is 50. The experiment is duplicated 100 times independently utilizing the MATLAB software (Version: R2021a) to guarantee the reliability of experiment results. MATLAB is a commercial mathematical software developed by MathWorks, the founder is Cleve Barry Moler. Moreover, all comparative experiments are executed on a desktop PC with an Intel Core i7-8700 CPU processor @ 3.20 GHz, 16GB RAM, under the Windows10 64-bit OS, which is made by Microsoft of Washington. The manufacturer of Intel Core i7-8700 CPU is Asustek Computer Company in Shanghai.

The uniform plane array is partitioned as shown in Figure 3 into 16 transmit elements (left) and 16 receive elements (right). Figure 4 shows the performance realized across scan angles for SIC, SIC-BF and SIC-BF-sparse arrays with 1000 W of transmit power. As seen in Figure 4a, The SIC-BF achieves EII over 183 dB at beam scan angles (out to 30°), with an average isolation improvement of 43 dB compared to the SIC. At the sparsity rate of 0.75 and the scan angle of 0°, the EII of SIC-BF-sparse arrays is only reduced by up to 3 dB compared with the EII of the SIC-BF. The sparsity rate of 0.75 means that the number of ALSTAR observation channels is reduced by 25%. In addition, Figure 4a also shows the EII achieved across scan angles for the SIC-BF-sparse arrays at different sparsity rates. We noted that the EII decreases rapidly at the sparsity rate below 0.25, and reduces slowly at the sparsity rate above 0.6. Furthermore, Figure 5 shows the array configuration achieved under different sparsity rates for the SIC-BF-sparse arrays. The sparsity rate is 0.875, 0.75, 0.625, 0.5, 0.375, 0.25, and 0.125, respectively. Figure 4b–d show the noise power $P_n$, transmit total gain $G_t$, and receive total gain $G_r$ achieved across scan angles for the three cases. At the scan angle of 0°, the $P_n$ of SIC-BF and SIC-BF-sparse arrays is only 0.9 dB and 1.8 dB above the thermal noise floor, respectively, the improvement of 46.2 dB and 45.3 dB over the SIC. Within 30° of broadside, the reduction in $G_t$ and $G_r$ of the SIC-BF-sparse arrays with a sparsity rate of 0.75 is 1.5 dBi and 1.2 dBi compared to the SIC-BF, respectively. The far-field transmit and receive patterns of the SIC-BF-spare at sparsity rate of 0.75 are compared to the SIC’s and SIC-BF’s as shown in Figure 6. At the beam scan angle of 0°, Figure 6a,d shows that the peak directivity of transmit pattern $G_t$ and receive pattern $G_r$ for the three cases remains similar. The peak $G_t$ of SIC-BF-sparse arrays is 16.4 dBi, which is 3.2 dBi and 1.3 dBi lower than that of SIC and SIC-BF, respectively. Moreover, the SLL of SIC-BF-sparse is lower than that of SIC-BF. As shown in Figure 6b,c,e,f, at scan angles of −30° and 30°, the main beam is slightly broadened. The peak gain of transmit pattern $G_t$ and receive pattern $G_r$ deviates slightly, especially in the case of a scan angle of 30°. Compared with the SIC-BF, the peak gain of $G_t$ for SIC-BF-sparse array is reduced by 1.6 dBi at scan angle of −30° and by 3 dBi at scan angle of 30°. The peak gain of $G_r$ is reduced by 1.7 dBi at scan angle of −30° and by 2.2 dBi at scan angle of 30°, respectively. In addition, the peak directivity of the SIC-BF-sparse arrays for three scan angles remains the same as that of the SIC-BF. Obviously, the efficiency of sparse transmit array aperture and the efficiency of sparse receive array aperture remain consistent. It is further demonstrated that the sparse arrays can achieve great ALSTAR performance while reducing the number of transmit and receive array elements and observation channels.
Figure 4. Comparison of performance indicators of the system under sparse arrays: (a) The EII at different sparsity rates; (b) $P_r$ curves in SIC, SIC-BF, and SIC-BF-sparse with the sparsity rate of 0.75; (c) $G_t$ curves in SIC, SIC-BF, and SIC-BF-sparse arrays with the sparsity rate of 0.75; (d) $G_r$ curves in SIC, SIC-BF, and SIC-BF-sparse arrays with the sparsity rate of 0.75.

Figure 5. The uniform planar array and array configuration at different sparsity rates.
Figure 6. $G_t$ and $G_r$ curves of SIC, SIC-BF and SIC-BF-sparse arrays with sparsity rate of 0.75 in different scan angle at 4.3 GHz: (a) Scan angle of 0°; (b) Scan angle of 30°; (c) Scan angle of −30°; (d) Scan angle of 0°; (e) Scan angle of 30°; (f) Scan angle of −30°.

4. Conclusions

In this paper, a joint design of sparse arrays and beamforming is proposed to balance the system cost and performance of the ALSTAR. Sparse arrays and beamforming are used to reduce the corresponding observation channel by decreasing elements that contribute slightly to the EII. In sparse process, beamforming technology is introduced to maximize EII. Sparse arrays and beamforming are implemented by GA and AO, respectively. This work presents simulation results for an example 16 Tx × 16 Rx uniform planar array antenna based on the improved U-shaped slot micro-strip patch element. Experimental results show that when the sparsity rate is at 0.875 and 0.75, the reductions in EII do not exceed 1 dB and 3 dB, and the number of observation channel decreases by 12.5% (2/16) and 25% (4/16), respectively. Results also present that the EII decreases rapidly with a sparsity rate less than 0.25 while the EII declines slowly with a sparsity rate greater than 0.6. The array cost and system complexity of ALSTAR reduce by up to 40%. This is very cost-effective for a very small reduction in isolation in exchange for a significant cut in the cost of the ALSTAR system.

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