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The Effect of Missing Elements on the Performance of D^3LS STAP Approach using Real Antenna Elements

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ABSTRACT
Space Time Adaptive Processing (STAP) applied on signal received from different configurations of real elements using D3LS (Direct Data Domain Least Squares). We will discuss the impact of each typical element-missing on the performance of this approach and the precision of the estimated strength of the SOI. We are interested in five different antenna configurations which are uniform linear equal spaced array, exponential spaced linear array, semicircular array, sinusoidal spaced array and planar array. The mutual coupling between real elements will affect on the estimation of complex amplitude of Signal of Interest (SOI). It is necessary to use a transformation matrix to compensate for the strong mutual coupling that exists between the antenna elements. Then, we will apply D3LS STAP on the compensated voltages. Numerical simulations are done using the three main methods of D3LS namely the forward, backward, and the forward–backward methods.

General Terms
Adaptive signal processing algorithm, preprocessing technique

Keywords
Direct Data Domain Least Squares (D^3LS), Space Time Adaptive Processing (STAP)

1. INTRODUCTION
In reality, some antenna elements may not work when they powered off or destroyed. Therefore, a question is naturally raised: does STAP based on D^3LS approach still work in such a case and how does it work? [1]. this paper will introduce the effect of missing elements on the performance D^3LS STAP and the precision of the estimated strength of the SOI. Initially, EM principles are applied to compensate for the effects of mutual coupling including the effect of nonuniformity in spacing between the antenna elements. This EM processing technique transforms the voltages that are induced in the non-uniformly spaced array containing real elements due to all incoming signals to an equivalent set of voltages that will be produced in a ULVA containing isotropic point radiators by the same set of incident signals [4].

Once the compensated voltages are obtained, we can apply STAP based on D^3LS approach [2]. For airborne radars, the detection of moving targets is a primary objective. During detection, the radar encounters the effect of strong interference which will affect on the estimation of signal. If the radar platform is stationary, the effect of the interference can easily be removed. However, when the platform is nonstationary, the space-time adaptive processing (STAP) has been developed to address these applications [8]. STAP is carried out by performing two-dimensional (2-D) filtering on signals that are collected by simultaneously combining signals from the elements of an antenna array (the spatial domain) as well as from the multiple pulses from a coherent radar (the temporal domain). The Direct Data Domain Least Squares (D^3LS) approach developed earlier for spatial adaptive processing is extended to deal with the STAP scenario. D^3LS process the data dealing with each space–time snapshot individually [9].

In this paper, five different kinds of antenna configurations are used: Uniform Linear Equal Spaced Array (ULESA), Exponential Spaced Linear Array (ESLA), a Semicircular Array (SCA), Sinusoidal Spaced Array (SSA), and Planar Array. D^3LS STAP will be applied on the measured voltages from these configurations.

2. SYSTEM MODEL
Assume that U+ 1 source impinge on an array of real elements antenna from distinct azimuthal directions $\varphi_0,.....,\varphi_U$. So in addition to SOI there are U undesired signals. We will deal with five array configurations of real elements and each configuration consists of N elements. In ESLA the distance between elements is set to

$$D_n = d\,\exp(n\delta) \qquad n = 1,2,.....,N-1 \tag{1}$$

where d is the distance between elements in the virtual array and δ is a constant.

Single snapshot of the voltages represents a $N\times1$ vector of phasor voltages $[x(t)]$ received by the elements of the actual array at a particular time instance t and can be expressed by

$$[x(t)] = \begin{bmatrix} x_0(t) \\ x_1(t) \\ \vdots \\ x_{N-1}(t) \end{bmatrix} = \sum_{u=0}^{U} s_u(t)[a(\varphi_u)] + [\zeta(t)] \tag{2}$$

where $s_u(t)$ denotes the signal at the elements of the array from the u^{th} source, for $u = 0,....,U$. $[a(\varphi)]$ denotes the steering vector of array toward the azimuth direction φ and

$\left[\zeta(t)\right]$ denotes the noise vector at each of the loaded antenna elements.

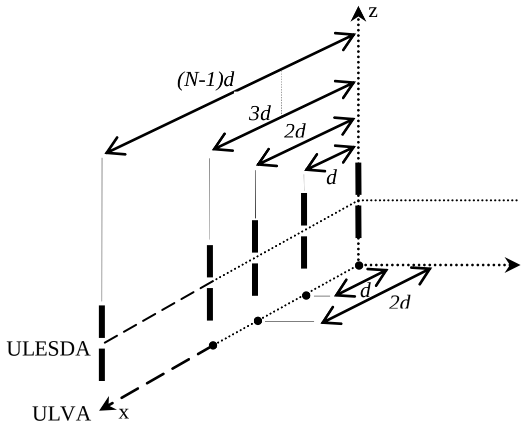

Fig.1 Geometry of ULESA and its equivalent ULVA

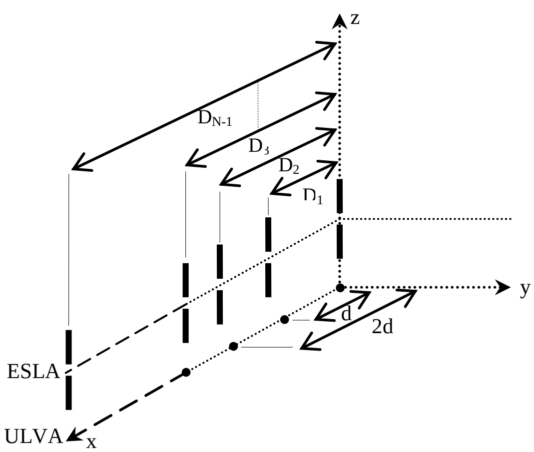

Fig.2 Geometry of ESLA and its equivalent ULVA

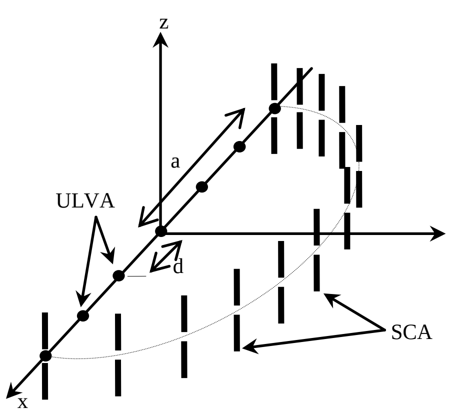

Fig.3 Geometry of SCA and its equivalent ULVA

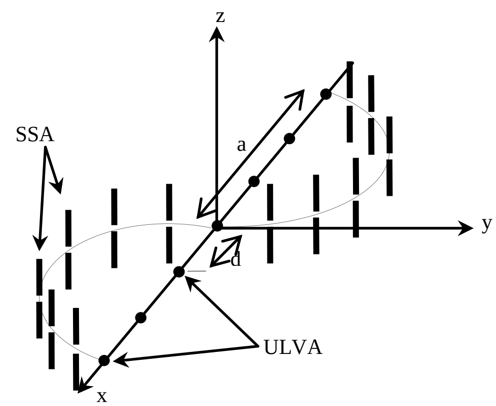

Fig.4 Geometry of SSA and its equivalent ULVA

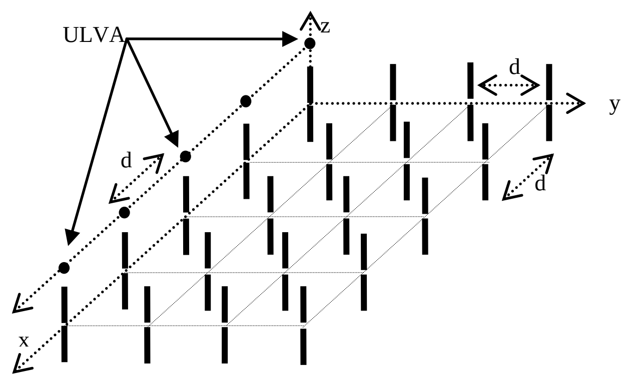

Fig.5 Geometry of planar array and its equivalent ULVA

By using a matrix representation (2) becomes

$$\left[x(t)\right] = \left[A(\varphi)\right]\left[s(t)\right] + \left[\zeta(t)\right] \qquad (3)$$

Where $[A(\varphi)]$ of size $N \times (U+1)$ referred to as the array manifold corresponding to each one of the incident signals of unity amplitude and is represented by

$$\left[A(\varphi)\right] = \left[a(\varphi_0), a(\varphi_1), \ldots\ldots, a(\varphi_U)\right] \qquad (4)$$

In practice, the induced voltages in the real array are contaminated by the effects of the mutual coupling between the elements of the array which will undermine the performance of a conventional adaptive signal processing algorithm [4]. The preprocessing technique that transforms the actual induced voltages to a set of voltages that would be induced in an ULVA consisting of omnidirectional isotropic point radiators is used in oreder to get the transformation matrix. This technique is discussed in [2, 3, 7]. The compensated voltages $\left[x_c(t)\right]$ will then be given by

$$[x_c(t)] = [\Im][x(t)] \qquad (5)$$

Where $\left[\Im\right]$ is the best fit transformation matrix.

3. D^{3}LS STAP APPROACH

There is a Doppler shift (f_d) in the received signal With M pulses received by a single antenna element due to the motion of antenna platform [5,8]. So, the system processes M coherent pulses at a constant pulse repetition frequency (f_r). The compensated voltages are now applied to the STAP processor as shown in Fig.6 [9].

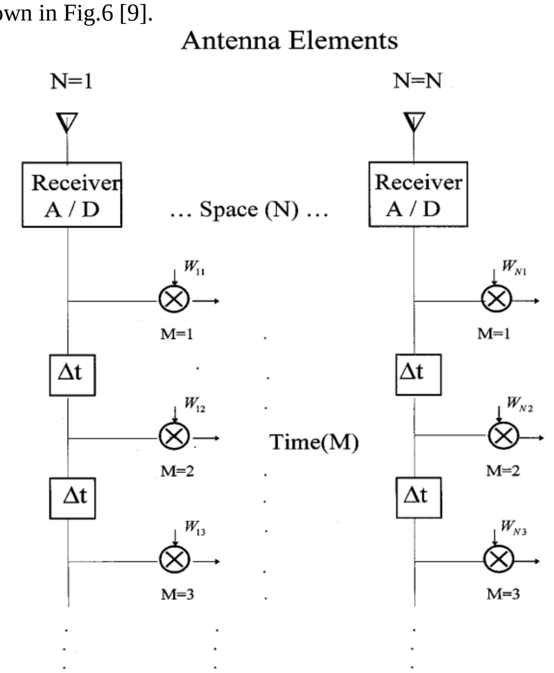

Fig.6 Data collection system

The D^{3}LS method has three different formulations namely the forward, backward, and the forward–backward methods.

3.1 Forward Method

The D^{3}LS method uses a single space-time snapshot of the data received by the array antenna in order to generate a cancellation matrix that contains only the interference and noise in the received data. Then, the weight vector that forces this matrix to be zero will be determined. By putting an additional constraint row for the SOI, the weight vector preserves the SOI gain while canceling the interference and noise in the data [8]. To generate the cancellation matrix, the element-to-element offset of the SOI in space and time, respectively, are defined as [6, 9]

$$Z_1 = \exp(j2\pi \frac{d}{\lambda} \cos\phi_s) \tag{6}$$

$$Z_2 = \exp(j2\pi \frac{f_d}{f_r}) \tag{7}$$

where ϕ_s and λ are the angle of arrival and the wavelength for SOI and d is antenna spacing. Thus we can form three cancellation equations from the received signal and its adjacent data as follows:

$$X_{m,n} - X_{m,n+1} Z_1^{-1}, \tag{8}$$

$$X_{m,n} - X_{m+1,n} Z_2^{-1}, \tag{9}$$

$$X_{m,n} - X_{m+1,n+1} Z_1^{-1} Z_2^{-1} \tag{10}$$

By setting the number of weights to be $N_a N_p$ according to [6], the cancellation matrix for (8) can be formed as

$$\begin{bmatrix} x_{1,1} - x_{1,2} z_1^{-1} & x_{1,2} - x_{1,3} z_1^{-1} & \cdots & x_{1,N_a} - x_{1,N_a+1} z_1^{-1} \\ x_{2,1} - x_{2,2} z_1^{-1} & x_{2,2} - x_{2,3} z_1^{-1} & \cdots & x_{2,N_a} - x_{2,N_a+1} z_1^{-1} \\ \vdots & \vdots & & \vdots \\ x_{N_p,1} - x_{N_p,2} z_1^{-1} & x_{N_p,2} - x_{N_p,3} z_1^{-1} & \cdots & x_{N_p,N_a} - x_{N_p,N_a+1} z_1^{-1} \end{bmatrix} \tag{11}$$

In the same way, the cancellation matrix for (9) and (10) can be generated in the same manner. We have to know that (8) corresponds to spatial difference, (9) corresponds to temporal difference, and (10) corresponds to spatial-temporal difference of the received signal. Once three different cancellation matrices have been generated, we will arrange the elements of each cancellation matrix as a row vector of dimension $1 \times N_p N_a$ by putting each row side by side. We call this row as a cancellation row. Now, we have generated three cancellation rows. To find a weight vector, we need to generate the total of $N_p N_a - 1$ row vectors. To preserve the SOI from being canceled by the weight vector, we left 1 row for gain constraints along target direction as follows [10].

$$\begin{bmatrix} 1 & z_1 & z_1^2 & \cdots & z_1^{N_a-1} & z_2 & z_1 z_2 & z_1^2 z_2 & \cdots & z_1^{N_a-1} z_2 & z_2^2 & z_1 z_2^2 & \cdots & z_1^{N_a-1} z_2^{N_p-1} \end{bmatrix} \tag{12}$$

After we put all cancellation and constraints rows, we obtain a cancellation matrix [T] of dimension $N_p N_a \times N_p N_a$ and the weight vector, W, which cancels the interference and maintain the SOI can be found by solving the following equation:

$$[T][W] = [C \quad 0 \quad \cdots \quad 0]^T_{N_a N_p \times 1} \tag{13}$$

where C is a look-direction gain SOI. After obtaining W, the signal amplitude, $\hat{\alpha}$, can be estimated from[8]

$$\hat{\alpha} = \frac{1}{C} \sum_{m=1}^{N_p} \sum_{n=1}^{N_a} W[(N_a \times m - 1) + n] \, X_{m,n} \tag{14}$$

3.2 Backward Method

The weight vector can also calculated in a backward direction; where the equations (8)-(10) are generated in the reverse order with complex conjugate starting from X_{N_p,N_a} [6,10]. The cancellation equations for backward method are as follows.

$$X^*_{m,n} - X^*_{m,n-1} Z_1^{-1}, \tag{15}$$

$$X^*_{m,n} - X^*_{m-1,n} Z_2^{-1}, \tag{16}$$

$$X^*_{m,n} - X^*_{m-1,n-1} Z_1^{-1} Z_2^{-1} \tag{17}$$

Where * denotes the complex conjugate of the data. We, then, simply obtain a similar cancellation matrix as in (11) in a similar fashion for the forward method with the reversed order of the conjugated data. Once $N_p N_a - 1$ cancellation rows have been generated, the look-direction constraint in (12) will be added to obtain a square matrix [B] of size $N_p N_a \times N_p N_a$ .The weight vector can be obtained by solving the following equation [8]

$$[B][W]=\begin{bmatrix}C & 0 & \cdots & 0\end{bmatrix}^T_{N_aN_p\times 1} \qquad (18)$$

After obtaining W, the signal amplitude can be estimated from

$$\hat{\alpha}=\left[\frac{z_1^{N_a-1}z_2^{N_p-1}}{C}\sum_{m=1}^{N_p}\sum_{n=1}^{N_a}W\left[(N_a\times m-1)+n\right]X^*_{N_p-m+1,N_a-n+1}\right]^* \qquad (19)$$

3.3 Forward-Backward Method

To increase the number of degrees of freedom of the system, one need to use the forward-backward method that can be generated by putting both of the cancellation matrices from forward and backward directions together when calculating the weight vector. And the target signal complex amplitude can be estimated by either forward or backward direction. This increases the number of degrees of freedom and the accuracy of the system [10]. In the next section, the performance of the three methods will be shown via numerical simulations.

4 SIMULATION RESULTS

4.1 The performance of ULESDA

An array of equal spaced dipole is used as shown in Fig.1. Consider the SOI arriving from $\varphi_s=100^o$ and one jammer stronger than the SOI by 47dB arriving from 50^0 impinging on 12 elements. The performance of three cases of antenna distribution will be investigated. The first case when there is no element missing, the second case when the 4^{th} element is missing, and the third case when the 4^{th} and 8^{th} elements are missing. Due to the use of real elements, there will be coupling effect on the performance. So, the preprocessing technique is used firstly by transforming the actual set of voltages to another set generated form ULVA of isotropic point sources. The output SINR is used as an indicator of the accuracy of SOI estimation and is defined as [1]

$$\text{SINR}=20\log\left|\frac{s}{s-s_e}\right| \qquad (20)$$

where s and s_e are the exact and the estimated amplitude of the desired signal respectively.

Fig.7, Fig.8, and Fig.9 show the performance of the forward, backward, and forward backward methods respectively for the three cases of antenna distribution.

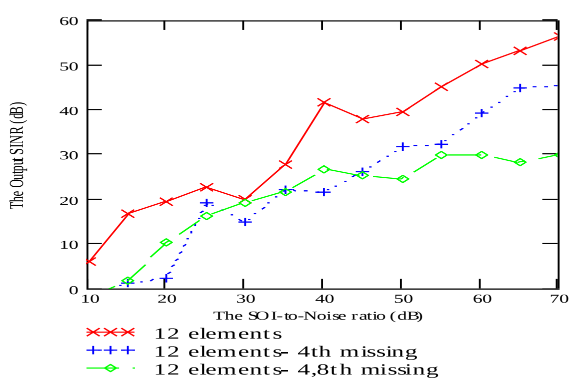

Fig .7 The output SINR of the forward method for the three cases using ULESDA

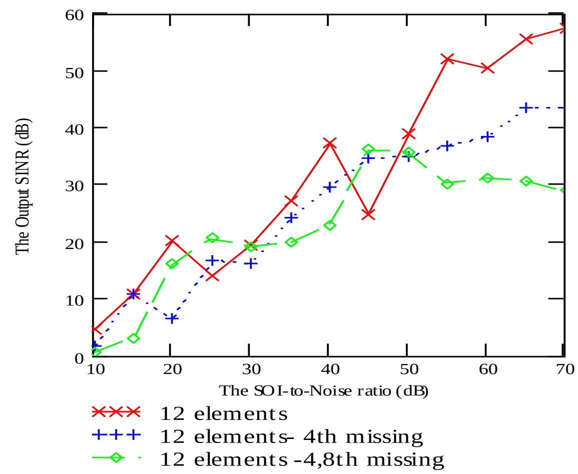

Fig.8 The output SINR of the backward method for the three cases using ULESDA

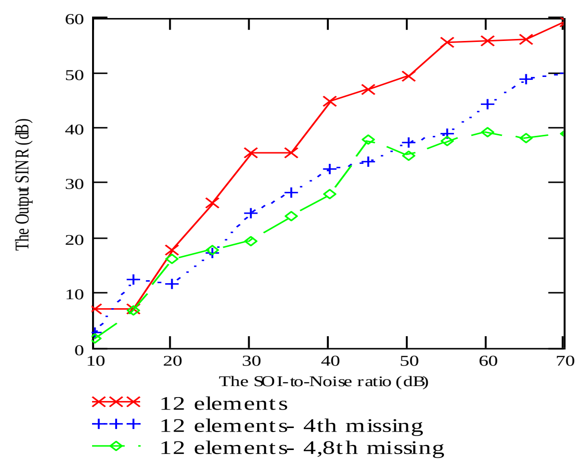

Fig.9 The output SINR of the forward-backward method for the three cases using ULESDA

The performance shown in the three figures is clear since the output SINR is degraded as the number of missing elements increases especially in the large input SNR. It is obvious that the performance of forward backward method better than forward and backward methods for the three cases of antenna distribution and the average performance of forward method and backward method are almost the same.

4.2 The performance of ESLA, SCA, and SSA

Consider an array of 12 elements is used. The elements are distributed in three different forms: Exponential Spaced Linear Array (ESLA), Semicircular Array (SCA) and Sinusoidal Spaced Array (SSA). Each element of the array is identically point loaded at the center. The dipoles are z-directed of length $L=\lambda/2$ and placed as shown in Fig.2, Fig.3, and Fig.4 respectively.

Consider the SOI arriving from $\varphi_s=100^o$ and one jammer stronger than the SOI by 47dB arriving from 50^0 impinging on the three arrays. The performance of three cases of antenna distribution will be investigated. The first case when there is no element missing, the second case when the 4th element is missing, and the third case when the 4th and 8th elements are missing. The preprocessing technique is used to compensate for the lack of nonuniformity in the real array contaminated by the mutual coupling effects. This is done by transforming the actual set of voltages to another set induced form ULVA of isotropic point sources consisting of 7 elements.

Fig.10, Fig.11, and Fig.12 show the performance of the first, second, and third cases respectively using ESLA, SCA, and SSA.

As shown from Fig.10, Fig.11, and Fig.12, there is no great difference between the three cases for all configurations except the performance of SCA is degraded slowly with each missing element and the performance of SSA is beginning to degrade obviously after the second case.

It can be seen that the performance of ESLA is going to be better over SCA and SSA with each missing element although it was not good enough in the first case.

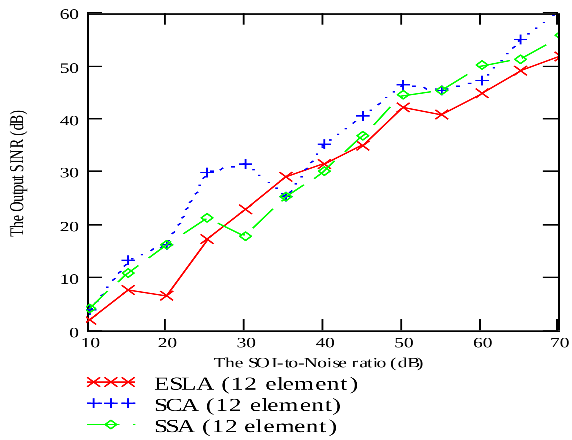

Fig.10 The output SINR for the first case using ESLA, SCA, and SSA

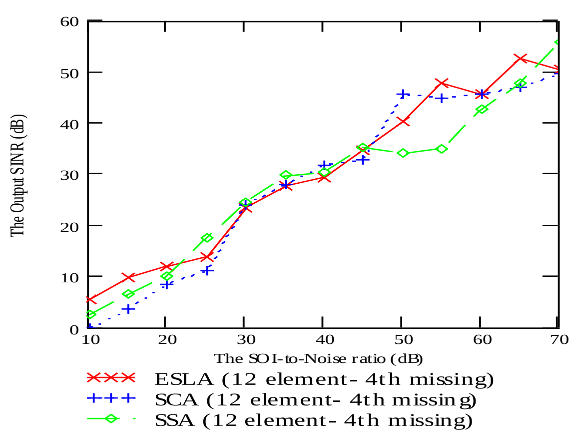

Fig.11 The output SINR for the second case using ESLA, SCA, and SSA

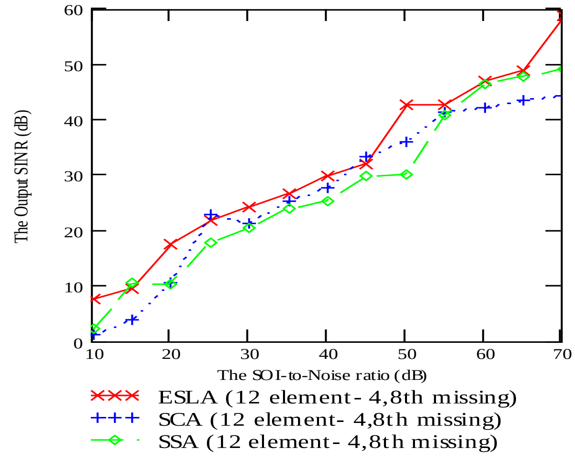

Fig.12 The output SINR for the third case using ESLA, SCA, and SSA

4.3 The performance of planar array

Consider the SOI arriving from $\varphi_s = 100^o$ and one jammer stronger than the SOI by 47dB arriving from 50^0 impinging on 5×4 elements of planar array each of $L = \lambda/2$, $d_x = d_y = \lambda/2$ as shown in Fig.5. The elements are distributed as 5 along x-axis and 4 along y axis. The set of voltages induced in the planar array is transformed to another set of voltages would be induced in a ULVA of isotropic point radiators along x-axis consisting of 5 elements in order to eliminate the mutual coupling between elements. This is done by using transformation matrix. The performance of three cases of antenna distribution will be investigated.

The first case when there is no element missing, the second case when two elements are missing, and the third case when four elements are missing.

Fig.13, Fig.14, and Fig.15 show the performance of the forward, backward, and forward backward methods respectively for the three cases of antenna distribution of the planar array.

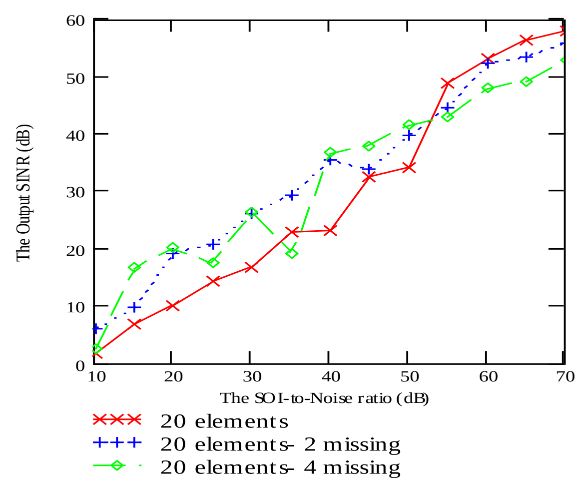

Fig.13 The Output SINR of the forward method for the three cases using planar array

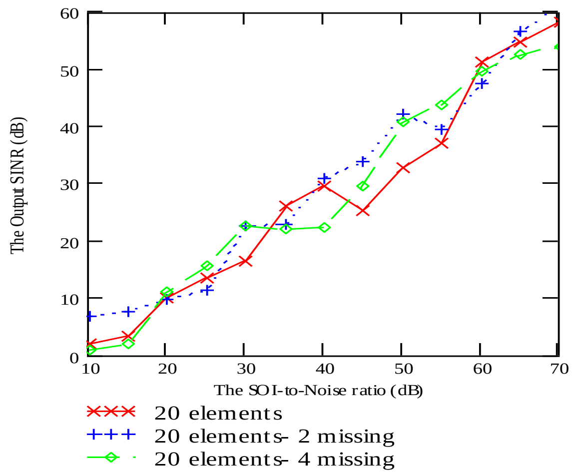

Fig.14 The Output SINR of the backward method for the three cases using Planar array

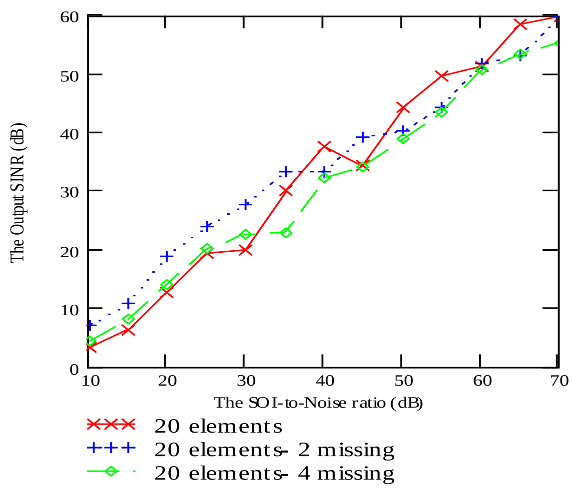

Fig.15 The Output SINR of the forward-backward method for the three cases using planar array

It is obvious from Fig.13, Fig.14, and Fig.15 that the average performance of the three cases of antenna distribution is comparable for each method with no great difference and the performance of forward backward method is better than the forward and the backward methods.

5 CONCLUSION

A D^3LS STAP approach applied on signals received by ULESA, ESLA, SCA, SSA and planar array. We use only single snapshot in order to null the interference signal and to maintain the main beam directed towards SOI. The effect of missing elements on the performance of D^3LS STAP and on the precision of the estimated strength of the SOI is investigated. The performance of ULESA is degraded rapidly with each missing element while the performance of ESLA, SCA, SSA, and planar array is good. The reason for that is the number of elements in ULVA since the number of isotropic point radiators is always lower than the number of real elements in all configurations except ULESDA.

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