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Multipath Separation-Direction of Arrival (MS-DOA) with Genetic Search Algorithm for HF channels

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Abstract

Direction-of-Arrival (DOA) defines the estimation of arrival angles of an electromagnetic wave impinging on a set of sensors. For dispersive and time-varying HF channels, where the propagating wave also suffers from the multipath phenomena, estimation of DOA is a very challenging problem. Multipath Separation-Direction of Arrival (MS-DOA), that is developed to estimate both the arrival angles in elevation and azimuth and the incoming signals at the output of the reference antenna with very high accuracy, proves itself as a strong alternative in DOA estimation for HF channels. In MS-DOA, a linear system of equations is formed using the coefficients of the basis vector for the array output vector, the incoming signal vector and the array manifold. The angles of arrival in elevation and azimuth are obtained as the maximizers of the sum of the magnitude squares of the projection of the signal coefficients on the column space of the array manifold. In this study, alternative Genetic Search Algorithms (GA) for the maximizers of the projection sum are investigated using simulated and experimental ionospheric channel data. It is observed that GA combined with MS-DOA is a powerful alternative in online DOA estimation and can be further developed according to the channel characteristics of a specific HF link.

Keywords: Ionosphere; HF channel; Direction of Arrival (DOA); Direction Finding (DF); Multipath Separation and Direction of Arrival (MS-DOA) Estimation; Genetic Algorithm (GA)

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1. Introduction

HF links between 3 and 30 MHz provide a very secure and ever available channel for long distance communication. The transmitted signals are reflected from the ionosphere and can reach to thousands of kilometers without being able to be detected by other users. Yet, being spatially and temporally varying and dispersive, ionospheric channels can cause various degrading effects on the transmitted signals that require a wide bandwidth and increased bit rates. The problem is more complicated by the multipath and polarization fading phenomena (Goodman, 1992). Thus, for proper recovery of the transmitted signals, the modes and multipath components need to be successfully separated at the receiver. There have been various efforts to separate the modes and overcome the degrading effects of fading including diversity techniques in angle of arrival (AOA), polarization, frequency and time, RAKE receivers designed to counter the effects of multipath fading by using several correlators each assigned to a different multipath component resulting in a high signal-to-noise ratio (Proakis, 1995), polarization separation (Afraimovich et al., 1999), adaptive DF eigenstructure methods such as MUltiple Signal Classification (MUSIC) (Schmidt, 1986) and algebraic methods (Van Der Veen, 1998). As discussed in detail in Arikan et al. (2003) all of these methods have advantages and disadvantages in various kinds of applications, yet it is being widely observed that for deter-

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ministic source separation and direction of arrival estimation, algebraic methods have certain advantages over the adaptive techniques (Arikan et al., 2003).

Multipath Separation-Direction of Arrival (MS-DOA) is a blind source estimation technique that can separate the multipath modes successfully and find their arrival angles with high accuracy (Arikan et al., 2003). In MS-DOA, both the array output vector and incoming signal vector are expanded in terms of a basis vector set. A linear system of equations is formed using the coefficients of the basis vector for the array output vector, the incoming signal vector and the array manifold. The angles of arrival in elevation and azimuth are obtained as the maximizers of the sum of the magnitude squares of the projection of the signal coefficients on the column space of the array manifold. Once the array manifold is estimated then the incoming signals can also be determined using the basis vectors and signal coefficients. For certain array configurations, the search for maximizing angles can be eliminated by using closed form solutions of the constructed linear system (Yilmaz et al., 2000). The angular resolution with typical array apertures can get as low as 0.2° without the help of any preprocessing techniques. For homogeneous arrays, the number of antennas that are required in the array has to be one more than the number of incoming signals. The developed technique also allows the user to recover the multipath signals with very high accuracy. When there are more than one mode impinging on the array or when the region of interest is not restricted, the search for the maximizer of the projections with brute force requires a time interval that inhibits the use of MS-DOA for online signal and angle estimation. Therefore, in this study, we developed the use Genetic Algorithm (GA) as an alternative search routine that can operate online for multiple direction of arrival estimation.

GA forms a major group of nonlinear search algorithms based on the mechanics of natural selection and natural genetics. GA differ from traditional search methods in various aspects such as the GA work with coded parameter set, not with the parameters themselves; search for a population of points, not with a single point; use an objective function, not derivatives; and use probabilistic transition rules, not deterministic ones. GA can be adapted to work with multiple parameter problems easily and search for all the parameter optimizers at the same time. There are various efforts in the literature where GA is used directly for DOA or it is used together with other methods for fast optimization of objective function in arrival angle estimation (Goldberg, 1989; Varlamos and Capsalis, 2004; Li and Lu, 2004; Man et al., 1996).

In this study, the MS-DOA is combined with GA to provide fast and accurate estimates for arrival angles and the technique is tested on simulated and experimental data. The results are compared with those from plain MUSIC that is widely used as a DOA estimator for its ease in implementation and speed in convergence. It is observed that MS-DOA with GA has superior performance over plain MUSIC for HF multipath separation and arrival angle estimation.

In Section 2, a brief overview of MS-DOA technique is provided. Section 3 is a summary of GA algorithm and how it is implemented for the given problem. In Section 4, plain MUSIC is discussed and Section 5 includes the performance comparison of the methods for simulation and experimental data.

2. Brief review of MS-DOA

In this section, brief review of the incoming signal model, sensor array model and MS-DOA algorithm are provided. A more detailed explanation is given in Arikan et al. (2003).

Consider K incoming signals are impinging on an L element array of sensors. Let $\mathbf{r}_1$ denote the position vector of the reference sensor. The time delay introduced on the lth element $(1 \leqslant l \leqslant L)$ by kth$(1 \leqslant k \leqslant K)$ incoming signal can be given by $\gamma_l(\theta_k, \phi_k)$ where

$$\gamma_l(\theta_k, \phi_k) = \frac{\mathbf{r}_l}{c} \cdot \hat{v}(\theta_k, \phi_k) \tag{1}$$

and $\mathbf{r}_l$ is the position vector of lth sensor; $\hat{v}$ is the unit vector in the direction of kth signal and c is velocity of light in vacuum. The demodulated baseband output of reference sensor is given by $y_k(t)$ and $x_l(t)$ denotes the output signal of the lth sensor due to K impinging signals as

$$x_l(t) = \sum_{k=1}^{K} y_k(t) e^{jw_0 \gamma_l(\theta_k, \phi_k)} \tag{2}$$

Following a down-conversion stage, the baseband output of the sensors are sampled with Nyquist rate and the receiving antenna system can be expressed as a linear system of equations. The measurement model of the signals can be given in

$$\mathbf{X} = \mathbf{Y}\mathbf{A}^{\mathbf{T}} \tag{3}$$

where

$$\mathbf{X} = [\mathbf{x}_1 \ldots \mathbf{x}_l \ldots \mathbf{x}_L] \tag{4}$$

$$\mathbf{Y} = [\mathbf{y}_1 \ldots \mathbf{y}_k \ldots \mathbf{y}_K] \tag{5}$$

and

$$\mathbf{A} = \begin{bmatrix} A_1(\mathbf{a}_1) & \ldots & A_1(\mathbf{a}_K) \\ \vdots & \ldots & \vdots \\ A_L(\mathbf{a}_1) & \ldots & A_L(\mathbf{a}_K) \end{bmatrix} \tag{6}$$

denotes the array manifold. Here, $A_l(\mathbf{a}_k) = e^{jw_0 \gamma_l(\theta_k, \phi_k)}$ and $\mathbf{a}_k = [\theta_k, \phi_k]^T$. Since x_l's are linear combinations of y_k's, the rank of $\mathbf{X}$ can be at most K (Arikan et al., 2003). This implies that K basis vectors are necessary and sufficient to represent the measurement vector. In determining the basis that spans the column space, Singular Value Decomposition (SVD) is used (Haykin, 1989). SVD is used to determine the number of impinging waves on the receiving array by checking the number of significant singular values as follows:

$$\mathbf{X} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathbf{H}} \tag{7}$$

where the superscript H denotes the Hermitian operator throughout the text and

$$\mathbf{U} = [\mathbf{u}_1 \dots \mathbf{u}_l \dots \mathbf{u}_L] \tag{8}$$

and

$$\mathbf{V} = [v_1 \dots v_k \dots v_L] \tag{9}$$

Here,

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & 0 & \dots & 0 \\ 0 & \sigma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_L \end{bmatrix} \tag{10}$$

An effective set of basis vectors can be chosen corresponding to the significant singular values as

$$\mathbf{U}_{\mathbf{eff}} = [\mathbf{u}_1 \dots \mathbf{u}_l \dots \mathbf{u}_K] \tag{11}$$

and

$$\mathbf{V}_{\mathbf{eff}} = [v_1 \dots v_k \dots v_K] \tag{12}$$

Then $\mathbf{X}$ can be written as

$$\mathbf{X} = [\mathbf{u}_1 \dots \mathbf{u}_l \dots \mathbf{u}_K][\mathbf{X}_1 \dots \mathbf{X}_k \dots \mathbf{X}_K]^T \tag{13}$$

and

$$[\mathbf{X}_1 \ \dots \ \mathbf{X}_k \ \dots \ \mathbf{X}_K]^T = \underbrace{\begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_K \end{bmatrix}}_{\Sigma_{\text{eff}}} \mathbf{V}^H_{\text{eff}}. \tag{14}$$

and Σ_{eff} denotes the singular value matrix which holds the K most significant singular values. By using above derivations the linear system of equations can be rewritten as

$$\underbrace{\begin{bmatrix} \mathbf{A} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{A} & \cdots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{A} \end{bmatrix}}_{\mathbf{A}_g} \underbrace{\begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \\ \vdots \\ \mathbf{Y}_K \end{bmatrix}}_{\mathbf{y}_g} = \underbrace{\begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_K \end{bmatrix}}_{\mathbf{x}_g} \tag{15}$$

For the optimum solution of the above set of equations, the following least squares cost function is defined as

$$J(\mathbf{a}_1; \dots \mathbf{a}_K; \mathbf{y}_g) = \|\mathbf{A}_g\mathbf{y}_g - \mathbf{x}_g\|^2 \tag{16}$$

where $\|.\|$ denotes the $\mathscr{L}2$ norm (Arikan et al., 2003). By using this cost function and writing for all components as a summation

$$J(\mathbf{a}_1; \dots \mathbf{a}_K; \mathbf{y}_g) = \sum_{k=1}^{K} \|\mathbf{A}\mathbf{Y}_k - \mathbf{X}_k\|^2 \tag{17}$$

We investigate the values $\mathbf{a}_k$ and $\mathbf{y}_g$ which will minimize J. Because of the orthogonality property of the least squares cost function, the individual J_k's are minimized when the projection of $\mathbf{X}_k$'s onto the range space of $\mathbf{A}$ are maximized. The projections are defined as

$$\mathbf{P}_k(\mathbf{a}_k) = \mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{X}_k \tag{18}$$

where $1 \leqslant k \leqslant K$. Therefore, the optimal solution can be obtained as the maximizer of the following function $\mathscr{M}$:

$$\mathscr{M}(\mathbf{a}_1; \dots; \mathbf{a}_K) = \sum_{k=1}^{K} \|\mathbf{P}_k\|^2. \tag{19}$$

Once the arrival directions are estimated as the maximizer of $\mathscr{M}$, then $\mathbf{Y}_k$'s can be obtained as

$$\mathbf{Y}_k = (\mathbf{A}^H(\tilde{\mathbf{a}}_1; \dots; \tilde{\mathbf{a}}_K)\mathbf{A}(\tilde{\mathbf{a}}_1; \dots; \tilde{\mathbf{a}}_K))^{-1}\mathbf{A}^H(\tilde{\mathbf{a}}_1; \dots; \tilde{\mathbf{a}}_K)\mathbf{X}_k \tag{20}$$

The computed $\mathbf{Y}_k$'s, the output signals of the reference antenna for the kth mode, are then inserted into Eq. (20) to obtain $\mathbf{Y}$. Thus, with MS-DOA algorithm, not only the arrival angles of the incoming signals are estimated but also the incoming signals themselves at the output of the reference antennas are determined. The search for the maximizers can be performed either by brute force (optimum solution but has higher computational time) or by a suboptimum but fast nonlinear search algorithm such as Genetic Search as discussed in the next section.

3. Implementation of GA

Genetic Algorithms (GA) are search algorithms based on the mechanics of natural selection and natural genetics and they differ from traditional search methods (Goldberg, 1989). GA has the ability of solving multiple parameter problems. The parameters of the GA are usually converted to binary form according to the provided translation procedure which is called a chromosome. The combination of one set of parameters forms a gene. Thus, the algorithm uses these genes in the operation. Every gene has a fitness values according to the objective function (Goldberg, 1989; Man et al., 1996). In the application of GA for DOA problem, a number of different paths can be taken in the choice of the objective function, initial population, crossover and mutation and the termination of the algorithm. In DOA applications, the optimization is performed on the real values of the parameters to be searched instead of converting them to binary form which is called the floating point representation.

The operating steps of the Genetic Algorithm combined with MS-DOA is as follows:

(1) Initialization of the population
Initial population in DOA applications are formed by sets of possible angle values in elevation and azimuth. In most DOA problems, a pre-estimator is used to determine the range of the initial population (Li and Lu, 2005). In this study, a plain MUSIC algorithm is used for a rough estimate of region of interest. Each possible solution set in the initial population is defined by column vectors of containing the real valued floating point representation of elevation and azimuth angles

$$\mathbf{P}_n = [\theta_{1n}\phi_{1n} \ldots \theta_{kn}\phi_{kn}]^T \tag{21}$$

Initial population **P** is composed of these column vectors, where N denotes the population size:

$$\mathbf{P} = \begin{bmatrix} \begin{bmatrix} \theta_{11} \\ \phi_{11} \end{bmatrix} & \begin{bmatrix} \theta_{12} \\ \phi_{12} \end{bmatrix} & \cdots & \begin{bmatrix} \theta_{1N} \\ \phi_{1N} \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \theta_{k1} \\ \phi_{k1} \end{bmatrix} & \begin{bmatrix} \theta_{k2} \\ \phi_{k2} \end{bmatrix} & \cdots & \begin{bmatrix} \theta_{kN} \\ \phi_{kN} \end{bmatrix} \end{bmatrix} \tag{22}$$

(2) Ranking
Members of the population are sorted according to their fitness values. The fittest solution sets have higher rank and more closer to the desired solutions.

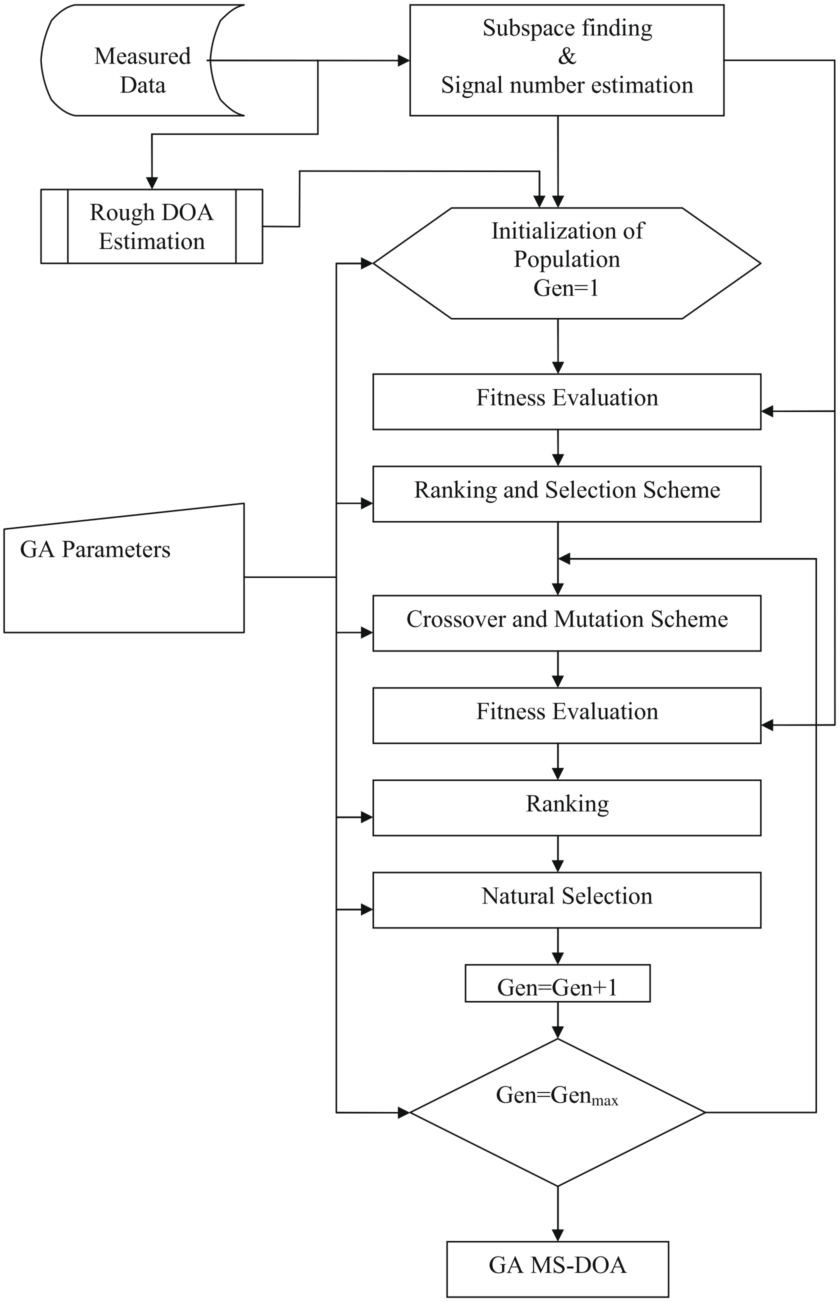

Fig. 1. The flowchart of Genetic Algorithm as search routine for MS-DOA.

In this study, the objective function or the fitness function is chosen as the minimizer of the cost function in Eq. (16) and thus the maximizer of the sum of the projections in Eq. (20).

(3) Production of next generation by using parents: mating scheme
Mating scheme is a the most important part of the GA for the offsprings that have the best fit for the objective function are determined and ranked. There are various methods for mating schemes that include the crossover, mutation and selection routines. In this study, the Emperor Selective Scheme (EMS) is used to select the parents which are qualified to mate with each other. Crossover operation generates new offsprings from their parents. Crossover is usually carried out on the binary coded chromosomes but in this problem the chromosomes are defined by floating point representation and the crossover is performed on the real values of the angles (Yeo and Lu, 1999; Li and Lu, 2005; Man et al., 1996). Here, Extrapolation Crossover (EPX) technique is used on the real valued chromosomes. EPX is based on the generation of new offsprings according to the range defined by two parents. EPX takes two parents, P1 and P2, to produce two offsprings, C1 and C2, that lie outside the range, a, of the two parents. The offsprings have equal probability to lie within the range a, extended in both directions from P1 and P2. C1 will then lie on the same side as P1 and C2 on the same side as P2. The range, a, of the parents is defined by $\delta = (\mathrm{P2}, \mathrm{P1})$ where $\mathrm{P2} > \mathrm{P1}$ and $\mathrm{C1} = \mathrm{P1} + a\delta, \mathrm{C2} = \mathrm{P2} + a\delta$. Here δ is a random number chosen between 1 and 2. For the given DOA application, the optimum value of δ is set to 1.5 to have the maximum extrapolation (Yeo and Lu, 1999). Mutation is used to guarantee the variation of the populations. By using this operator the algorithms are prevented from approaching the local maxima instead of the global maxima. As in crossover operators, mutation is normally performed on binary coded forms of the chromosomes. In this study, the mutation is carried out on real valued chromosomes by inserting a new solution set into the population.

(4) Elitism property
The convergence of GA can be improved by keeping some of previous population to next generation. Keeping some of fittest parents of previous population and inserting them into the new generation is called the elitism property (Goldberg, 1989; Man et al., 1996). In this study, 0.1 percent of the initial population is considered to be the elite population and kept for next generation.

(5) Termination criteria
Termination criteria defines the quality of the selected or optimized population where the algorithm must stop. In most applications, the termination criteria is defined by the probability of being close to the desired value. In DOA applications, the termination criteria is usually determined by the convergence of the solution set and the angles that satisfy the fitness function for a number of generations (Li and Lu, 2004; Varlamos and Capsalis, 2004). The solution sets that are considered as best parents for the upcoming selection routine are observed and if the fitness of the new offspring set does not improve the original parent set, then it can be determined to terminate the search algorithm. For the given problem scenario, the optimum termination is determined over the simulated channel signals for various ionospheric parameters.

An outline of the above described GA algorithm as the search routine for the MS-DOA is summarized in Fig. 1.

4. Plain MUSIC

Adaptive Direction Finding (DF) algorithms are more commonly used to separate the signals arriving on to the antenna array from various directions. All the modes exiting the ionosphere arrive to the receiving antenna with different elevation and azimuth angles. Adaptive DF algorithms are used to determine these arrival angles and thus separate the signals accordingly. Although various methods are reported in the literature for separation of multipath signals (Godara, 1997), eigenstructure methods such as MUltiple Signal Classification (MUSIC) (Schmidt, 1986), CLOSEST (Buckley and Xu, 1990) and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) (Roy and Kailath, 1989) are widely used since they can separate the angles with high resolution. Although these techniques are advantageous over the classical DF methods, with typical homogeneous array apertures, the algorithms fail to distinguish signals which are highly correlated (like multipath signals) and the resolution capability may be a couple of degrees (Godara, 1997; Pillau, 1989; Roy and Kailath, 1989). In order to cope with these disadvantages, preprocessing techniques like forward–backward smoothing are employed (Godara, 1997; Pillau, 1989). Yet, in order to use these preprocessing methods, the number of antennas that are utilized in the receiving array has to be doubled and also the computational complexity increases (Pillau, 1989).

Regardless of its shortcomings in separation of highly correlated multipath signals, MUSIC is one of the widely used DOA algorithms due to its ease in implementation and application. Unlike the MS-DOA algorithm as discussed in Section 2, the MUSIC algorithm operates on the estimated correlation matrix of the received source signals as

$$\mathbf{R}_{\mathbf{x}} = \mathscr{E}\left\{\mathbf{x}_n \cdot \mathbf{x}_n^H\right\} \tag{23}$$

where $\mathscr{E}$ is the expectation operator; superscript H denotes the Hermitian; and

$$\mathbf{x}_n = [\mathbf{x}_1(n) \ \ldots \ \mathbf{x}_l(n) \ \ldots \ \mathbf{x}_L(n)]^T \tag{24}$$

is the received antenna outputs at time sample n. Note that, in practice, the expectation operator is replaced by time averaging on a recent block of array outputs. Therefore, in MUSIC, the signal and noise subspaces are separated based on their differences in the power spectral domain. Such a treatment provides robust estimates to the direction of arrivals of impinging signals when the SNR is above a certain threshold and the impinging waveforms are not strongly correlated (Godara, 1997).

For additive noise in the channel, the eigenvectors of the correlation matrix should be separated into signal subspace and noise subspace. The Akaike Information Criterion (AIC) is a widely used measure for the ranking of eigenvalues. The MUSIC spectrum is computed by first forming a steering vector $\mathbf{s}(\theta,\phi)$ for all θ and ϕ angles as

$$\mathbf{s}(\theta,\phi) = [e^{j2\pi f_0 \tau_1(\theta,\phi)} \dots e^{j2\pi f_0 \tau_I(\theta,\phi)}] \tag{25}$$

and the matrix containing the eigenvectors of noise subspace $\mathbf{U}$ as

$$P_{MU}(\theta,\phi) = \frac{1}{|\mathbf{s}^H\mathbf{U}|^2} \tag{26}$$

The peaks of $P_{MU}(\theta,\phi)$ correspond to estimated DOA angles corresponding to the peaks of signal subspace. The outline of MUSIC algorithm as it is implemented in this study is provided in Fig. 2.

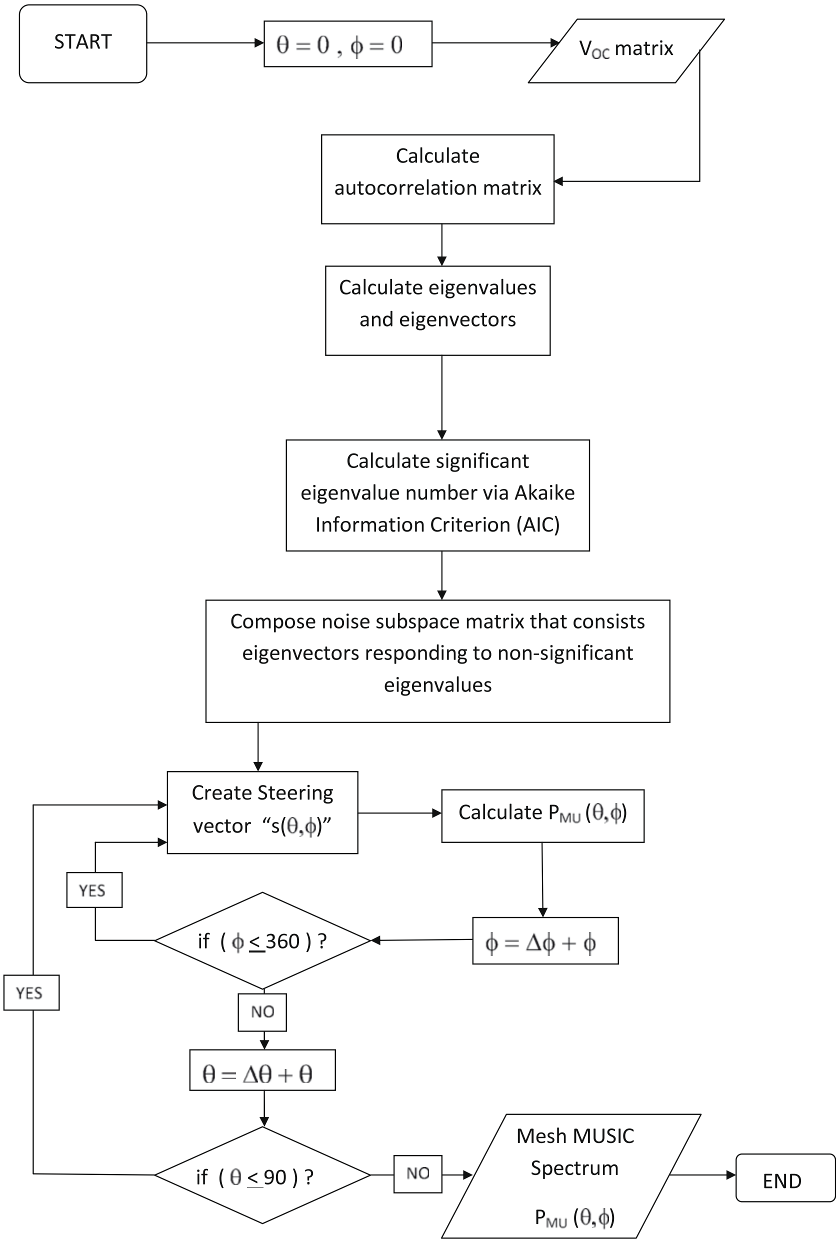

Fig. 2. The flowchart of MUSIC algorithm for DOA estimation.

5. Results

In this section, the performance of MS-DOA with GA is compared with Plain MUSIC algorithm both for simulated and experimental data. As discussed previously in this paper, MUSIC is the most commonly used Direction Finding (DF) method in the literature for high resolution spatial analysis due to its ease in implementation (Rogier et al., 1991). In spite of its drawbacks for HF DOA estimation, it forms a basis of comparison with other methods. For simulated data, the performance is based the root-mean-square-error (RMSE) for the following parameter set: ionospheric channel condition, receiver array type, receiver antenna type and signal-to-noise ratio (SNR). The RMSE is defined as

$$RMSE_{n_p} = \sqrt{\frac{1}{N_t}\sum_{n_t=1}^{N_t}[(\theta_{0,n_p}(n_t) - \theta_{e,n_p}(n_t))^2 + (\phi_{0,n_p}(n_t) - \phi_{e,n_p}(n_t))^2]} \tag{27}$$

where $RMSE_{n_p}$ is the RMSE for path n_p; N_t is the total number of trials for each simulation scenario and n_t is the trial index; $\theta_{0,n_p}(n_t)$ and $\phi_{0,n_p}(n_t)$ denote the original elevation and azimuth angles for the path n_p and trial n_t in the simulations, respectively; and $\theta_{e,n_p}(n_t)$ and $\phi_{e,n_p}(n_t)$ denote the estimated elevation and azimuth angles for the path n_p and trial n_t in the simulations, respectively. The channel simulations are done for various ionospheric conditions including good, moderate and poor ionosphere. The ionospheric channel simulations and forming of scenario sets are defined in detail in Arikan et al. (2003) and Arikan and Arikan (2003). For the time varying HF channel impulse response used in the simulation program is based on the model proposed in Watterson et al. (1970) where a Finite Impulse Response (FIR) filter is used to generate tap coefficients in delay for each sampling interval in time. The parameter set for simulation is obtained from the document (ITU-R, 1992). In the modified Watterson model implemented in this manuscript, we have multiplied the tap coefficients with a spread function and superposed the spread functions with appropriate time delays at the filter output. The summary of the parameters of the modified Watterson model for ‘good’, ‘moderate’ and ‘poor’ ionospheric conditions are provided in Table 1 of Arikan and Arikan (2003). The amount of delay spread for good, moderate and poor conditions extends as 2, 4 and 6 pulses, respectively. 1-D linear antenna arrays, and $2 \times 2, 3 \times 3$, and 5 element V shaped 2-D arrays are included in the simulations. The receiving antennas are chosen from widely used HF antennas such as vertical dipole, horizontal dipole, crossed loop and tripole.

Differentiating closer modes is a challenge when the angle separation and SNR are low due to the correlation of modes from the same origin. Thus, the first performance criterion for a DOA algorithm is how well it can differentiate the incoming signals for various SNRs. The separation of angles of the incoming signals, whether they are correlated or not, number and configuration of the receiving antennas and SNR are some of the factors that are effective in the performance of the DOA algorithms. When the RMSE errors for various scenarios are compared, it is observed that the linear array produces major ambiguity when signals arrive both from elevation and azimuth for MUSIC. The best performance is obtained when the array aperture increases from 1-D to 2-D and also wider the array aperture, lower SNR signals can be resolved with plain MUSIC without any preprocessing. Antennas that can receive from both polarizations such as crossed loop and tripole have higher performance compared to vertical or horizontal dipole arrays. When ionospheric conditions change from good to poor, large array apertures with 5 to 9 tripole antennas can keep their performance for SNR levels lower than 15 dB. Yet, for antenna arrays with a minimum number of antennas and smaller apertures, the performance degrades significantly for poor ionospheric conditions.

The parameters of GA such as the size of the initial population, percent of elitism, number of runs for convergence are optimized using various ionospheric conditions, array sizes and antenna types. When the MS-DOA with GA is

Table 1
The estimation of arrival angles for elevation and azimuth in degrees for 4.636001 MHz on May 02, 2003 between 23:03:19 and 23:24:19.

Time	MUSIC		MS-DOA with GA			
	Path 1		Path 1		Path 2	
	Elevation	Azimuth	Elevation	Azimuth	Elevation	Azimuth
23:03:19	25.7	194.8	29.5	196.5	35.9	195.7
23:06:19	20	117	28.9	194	34.7	193.6
23:09:19	25.1	195.6	27.9	196	33	194.7
23:12:19	32.9	196.3	26.3	196	32.4	195.6
23:15:19	42.9	197.4	26.5	196.8	34.8	195.2
23:18:19	27.5	195.3	27.5	196.1	33.6	195
23:21:19	30.2	194.8	28.7	195	34.7	194.8
23:24:19	29.3	195.7	28.8	194.8	33.5	194.7
Mean	29.2	185.9	28	195.7	34.1	194.9
Median	28.4	195.5	28.3	196	34.2	194.9

compared with MS-DOA with brute force search, it is observed that if the initial search space is narrowed down and only a limited number of paths (one or two) are received, then the MS-DOA estimates the arrival angles with higher accuracy and a computation time comparable to GA search. Yet, when the number of signals impinging on the array increases, the required computational time for brute force search grows exponentially with each path. MS-DOA with GA, on the other hand, is capable of producing reasonable estimates with a computational time that can be implemented on-line.

The performance of the two methods are compared with respect to an average scenario where for good ionospheric conditions the computational time is similar to each other. Figs. 3–5 denote the comparison of RMSE for SNR varying from 0 dB to 40 dB. The scenarios are formed for good ionospheric conditions for a and b subplots and poor ionospheric conditions for *c* and *d* subplots. The subplots *a* and *c* denote the RMSE from path 1 and subplots *b* and *d* are the RMSE for path 2. A 2×2 planar array with crossed loop antennas is implemented. For all figures, 20 trials are run for each scenario and the incremental step size in search was 0.1° in both elevation and azimuth. In Fig. 3, the signals arrive from angles $[35°, 125°]$ for path 1 and $[36°, 123°]$ for path 2. This scenario demonstrates a case where the angles of arrival are very close to each other both in elevation and azimuth. It is observed from Fig. 3 that plain MUSIC cannot resolve signals in elevation and azimuth for SNR lower than 25 dB, yet although RMSE increases, MS-DOA with GA can resolve them even for 0 dB SNR. In Fig. 4, the signals arrive from angles $[36°, 125°]$ for path 1 and $[32°, 125°]$ for path 2. This scenario demonstrates a case where the angles of arrival is the same for azimuth and they are widely separated in elevation. For this case plain MUSIC can not resolve signals in elevation and azimuth for SNR lower than 25 dB for good ionosphere and 28 dB for poor ionosphere, due to the fact that MUSIC can not resolve with high accuracy in elevation. Again, although RMSE increases, MS-DOA with GA can resolve the two paths and estimate arrival angles for both elevation and azimuth even for 0 dB SNR. In Fig. 5, the signals arrive from angles $[36°, 122°]$ for path 1 and $[36°, 126°]$ for path 2. This scenario demonstrates a case where the angles of arrival is the same for elevation and they are widely separated in azimuth. For this case plain MUSIC can not resolve signals in elevation and azimuth for SNR lower than 15 dB for both good and poor ionosphere. The RMSE performance is better compared to two previous scenarios due to the fact that MUSIC can resolve with higher accuracy in azimuth. MS-DOA with GA can resolve the two paths and estimate arrival angles for both elevation and azimuth even for 0 dB SNR with lower RMSE compared to two previous scenarios.

For the application of plain MUSIC and MS-DOA with GA to experimental data, the data set from a high latitude path is chosen. The data set is provided by Dr. E.M. Warrington from University of Leicester, UK. The HF

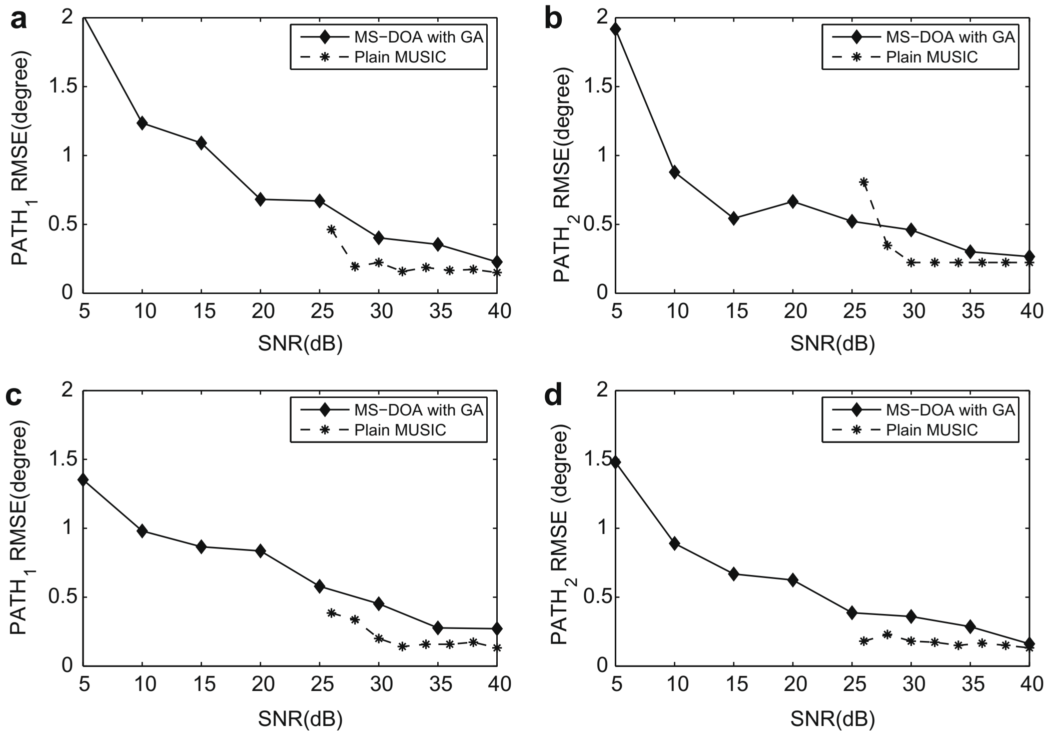

Fig. 3. RMSE versus SNR for 2×2 planar array with crossed loop antennas for good ionosphere (a) path 1, (b) path 2; and for poor ionosphere (c) path 1, (d) path 2 with arrival angles $[35°, 125°]$ for path 1 and $[36°, 123°]$ for path 2.

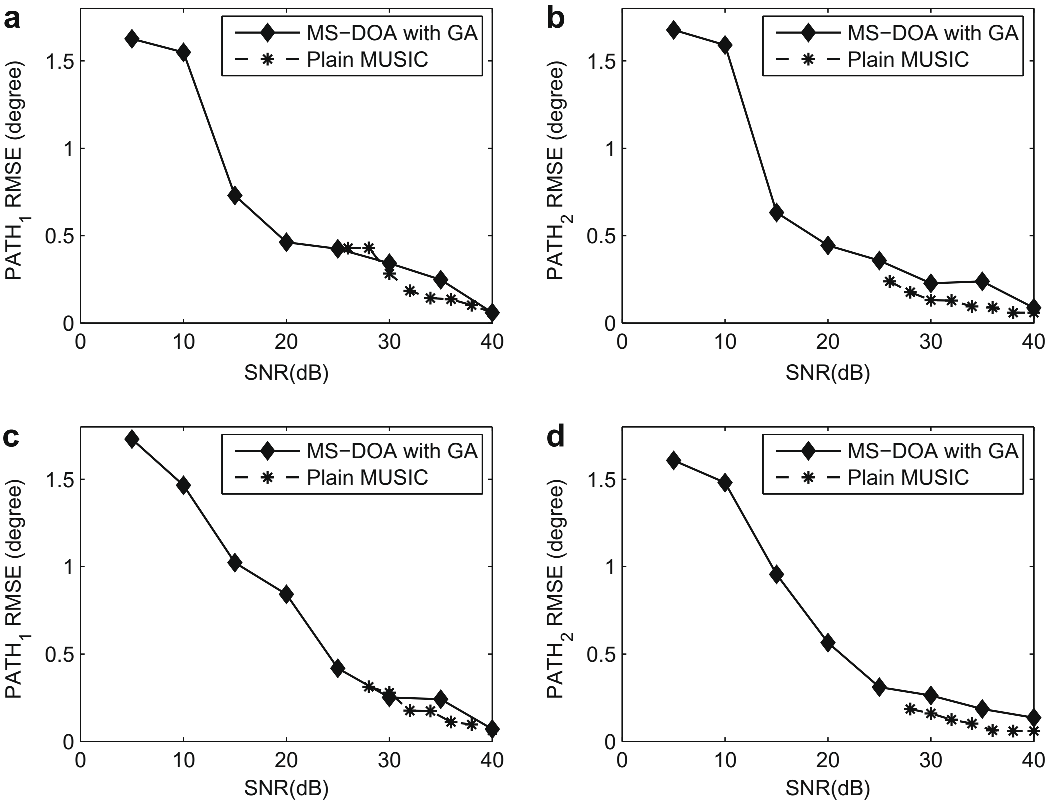

Fig. 4. RMSE versus SNR for 2 × 2 planar array with crossed loop antennas for good ionosphere (a) path 1, (b) path 2; and for poor ionosphere (c) path 1, (d) path 2 with arrival angles [36°, 125°] for path 1 and [32°, 125°] for path 2.

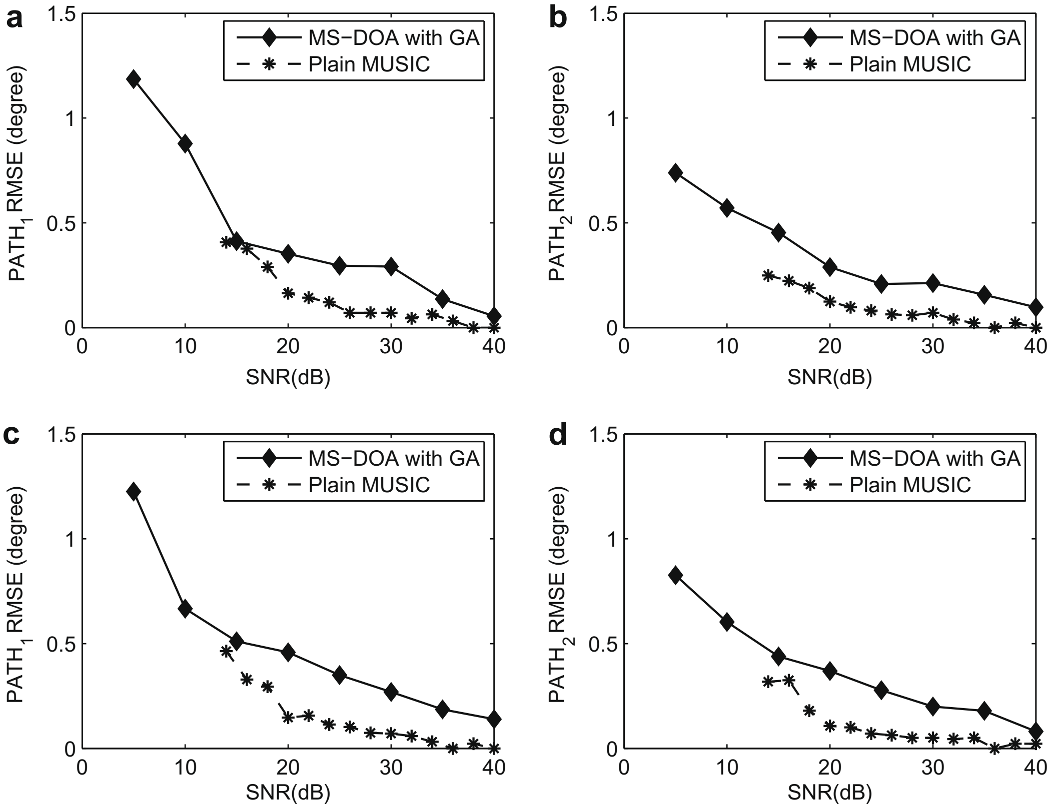

Fig. 5. RMSE versus SNR for 2 × 2 planar array with crossed loop antennas for good ionosphere (a) path 1, (b) path 2; and for poor ionosphere (c) path 1, (d) path 2 with arrival angles [36°, 122°] for path 1 and [36°, 126°] for path 2.

transmitter is located at Uppsala, Sweden and the receiver array is at Kiruna, Sweden. The receiver array is formed of 6 antennas, distributed inhomogeneously in a circular array. Out of this set of 6 antennas, only 5 antennas are calibrated and used in the DF problem. The transmitted signals are Barker-13 coded BPSK pulses modulated at 1667 baud with a repetition rate of 55 coded pulses per second. Signal duration is 2 s. The carrier frequency is changed every 30 s. The frequencies are repeated every 3 min. The details of the transmitted signal are provided in Siddle et al. (2004) and the receiver array is given (Warrington et al., 2000). Due to the structure of the HF link, only the signals at 4.63 MHz and 6.95 MHz proved to be useful in the analysis. The antenna output signals are normalized with respect to their $\mathscr{L}2$ norm before they are introduced to the DF algorithms. The estimates of arrival angles for

Table 2
The estimation of arrival angles for elevation and azimuth in degrees for 6.953 MHz on May 02, 2003 between 23:00:49 and 23:24:49.

Time	MUSIC		MS-DOA with GA			
	Path 1		Path 1		Path 2	
	Elevation	Azimuth	Elevation	Azimuth	Elevation	Azimuth
23:00:49	30.8	196	33.4	193.1	36.5	194.8
23:03:49	31.7	196.5	33	193.2	37.1	194.3
23:06:49	31.9	195.7	33.4	194	37.2	195.6
23:09:49	32.6	195.3	33.7	194.2	37.8	195.7
23:12:49	33	195.2	33.3	193.5	37.4	195.3
23:15:49	33.3	197.4	32.6	194.6	36.5	196
23:18:49	32.4	196.1	33.4	194.3	37.9	196.2
23:21:49	32.3	196.3	32.9	194.4	36.7	196.1
23:24:49	32.8	195.8	32.3	194.2	36.3	195.6
Mean	32.3	196	33.1	193.9	37	195.5
Median	32.4	196	33.3	194.2	37.1	195.6

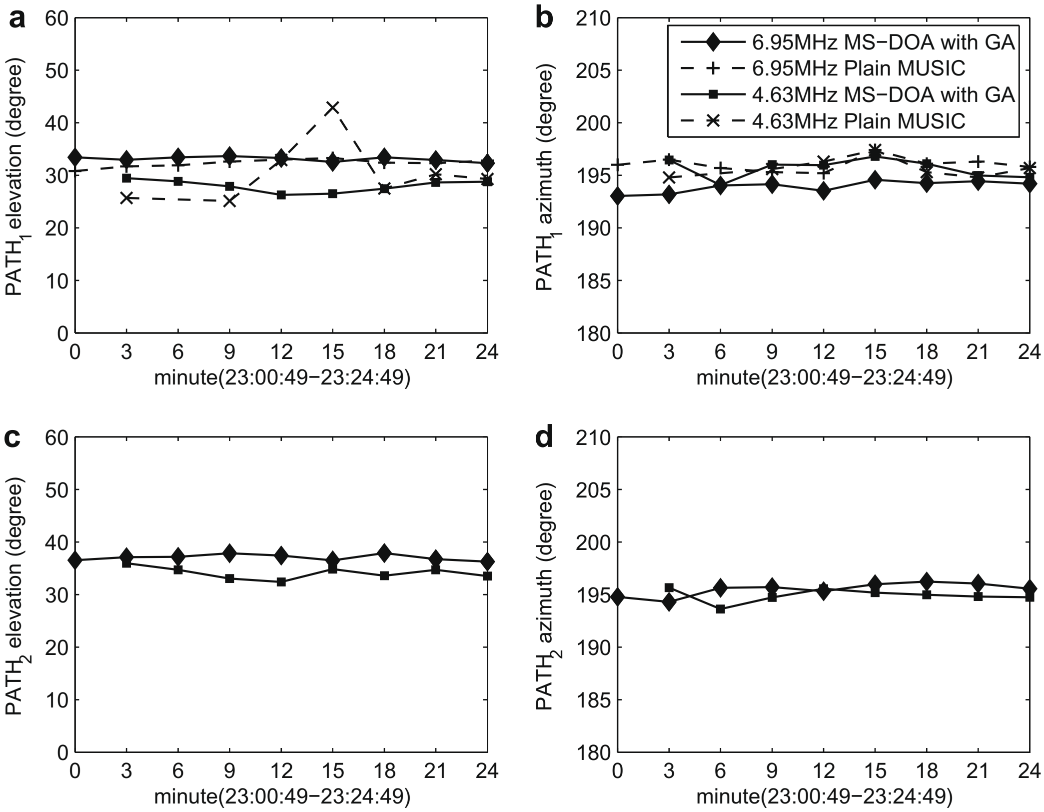

Fig. 6. Estimation of arrival angles for MS-DOA with GA and MUSIC for two frequencies for path 1 (a) elevation, (b) azimuth; for path 2 (c) elevation, (d) azimuth.

the test cases for 4.636001 MHz between 23:03:19 and 23:24:19 are provided in Table 1 on May 2, 2002. Here, the numbers denote the hour, the minute and the seconds, respectively. On May 2, 2002, at 2300 UT, sunspot number was 86, Kp index was 2+, Ap index was 9 and Dst index was −17. The approximate distance between the Uppsala and Kiruna is 886 km and Uppsala is 193° from the local north of Kiruna in the azimuth. The elevation of multipath components for both frequencies are expected to be between 20° and 40° according to the results in Siddle et al. (2004).

The estimates of arrival angles for the test cases for 6.953 MHz between 23:00:49 and 23:24:49 are provided in Table 2. Here, the numbers denote the hour, the minute and the seconds, respectively.

As it might be readily observed from Tables 1 and 2, for both frequencies, Plain MUSIC is able to detect only one path, yet for MS-DOA with GA, two paths are estimated. The estimate of the MUSIC in one path corresponds to the first path estimated with MS-DOA. The mean and median of the angles during the estimation interval are also provided in the tables. With MS-DOA estimates, both the mean and the mean are close to each other for all paths indicating a consistency and robustness in the estimates. When the two paths estimated are compared, it is also observed that the two paths are very close to each other in azimuth and they are separated with couple of degrees in elevation. The mean estimates for the arrival angles are in very well accordance with the expected azimuth and elevation angles. The angle spread is larger in MUSIC than MS-DOA with GA for both frequencies. The estimates are also provided in Fig. 6 for easier viewing. In Fig. 6a and b, the estimates for the arrival angle in elevation and azimuth, respectively, are provided for the first path and for the two frequencies. The first path is estimated by both MUSIC and MS-DOA with GA. In Fig. 6c and d, the elevation and azimuth estimates for the two frequencies are given for path 2. The second path is only estimated by MS-DOA with GA. From the analysis of both simulated and experimental data, it can be observed that MS-DOA with GA provides a powerful alternative in direction of arrival and multipath separation problems in HF links.

6. Conclusion

In this paper, Multipath Separation-Direction of Arrival (MS-DOA), is combined with Genetic Algorithm to estimate arrival angles in elevation and azimuth for signals incoming from various ionospheric paths. The signals at the output of the reference antenna can also be identified with high accuracy. In MS-DOA, both the array output vector and incoming signal vector are expanded in terms of a basis vector set. A linear equation is formed using the coefficients of the basis vector for the array output vector and the incoming signal vector and the array manifold. The angles of arrival in elevation and azimuth which maximize the sum of the magnitude squares of the projection of the signal coefficients on the range space of the array manifold are the required separation angles. Once the array manifold is estimated then the incoming signals can also be determined using the basis vectors and signal coefficients. The search for maximizing angles can be eliminated by solving the above mentioned system in closed form for certain antenna configurations; it can performed by brute force checking each possible angle pair in the search space; or by a nonlinear search algorithm like Genetic Search. The performance of the MS-DOA is a function of the array configuration and number of antennas in the receiving array. As the number of receiving sensors increase the performance of the MS-DOA improves. The optimum array configuration should be determined according to the statistical structure of the desired HF link. In this paper, the performance of MS-DOA with GA is compared with plain MUSIC, for both simulation and experimental data. According to our analysis, MS-DOA with GA provides very accurate estimates of arrival angles both in elevation and azimuth even at low SNRs and small angle separations. With MS-DOA, it is also possible to estimate the incoming signals at the output of the reference antenna successfully. This feature is not available in MUSIC. Thus, MS-DOA provides significant improvement over MUSIC algorithm with ease in implementation and shortened search time. MS-DOA with GA proves itself as a very powerful alternative in arrival angle estimation and multipath separation.

Acknowledgments

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