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Analysis of Fixed Weight Beamforming to Enhance the Desired Signal Using Smart Antenna in Wireless Communications

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Abstract: Smart antenna systems plays an important role in wireless communications systems. This study begins with a heuristic approach about the optimization of Signal-to-Interference Ratio (SIR) to enhance the received signal and minimize the interfering signals in wireless communications. After that, the approach for improvisation of SIR of a desired signal is extended for a specified condition and for its formulation requires noise to be added in the system in this study. In this study, a rigorous derivation of the Signal-to-Interference Ratio (SIR) maximization is derived by considering a general non adaptive conventional or traditional narrowband array and finally the limitations of non-adaptive or fixed beamforming approach to enhance the desired signal.

Key words: Beamforming, fixed weight vector, wireless communications, signal-to-interference ratio, smart antenna, array of elements

INTRODUCTION

Over the decade, demands for better quality and new value-added services on the existing wireless communication infrastructures have risen beyond all expectations. It is estimated that half a billion handsets will be put into the context of the third generation system, which will provide an up to 2 MB bandwidth for each user. The most challenging demands are: the need to increase the spectrum efficiency and the system capacity of the current wireless networks. These demands have brought technological challenges to service providers. Due to the ability of suppressing interference and combating against fading and providing new services, the adaptive array antennas or so called smart antennas have become one of the key technologies to realize 3rd Generation (3G) and even 4th Generation (4G) wireless communications. We start with a brief introduction about one criterion, which can be applied to enhancing the received signal and minimizing the interfering signals is based upon maximizing the Signal-to-Interference Ratio (SIR) is given by Litva and Kowk-YeungLo (1996) and Monzingo and Miller (1980) in wireless communication systems. We will present different conditions and considerations to improve the desired signal strength through the optimization of (SIR) with the smart antenna technologies in the wireless communications. After that by taking the general non-adaptive narrowband array, the derivation for maximization of Signal-to-Interference Ratio (SIR_{max}) is derived and with their respective array patterns, comparison is made.

Maximum signal to interference ratio: The optimization of Signal-to-Interference Ratio (SIR_{max}) is 1 criterion to enhance the received signal and minimizing the interfering signals by placing nulls at their angles of arrival. Assume that the 3 element array with one fixed known desired source and 2 fixed undesired interferers and all signals are assumed to operate at the same carrier frequency as shown in Fig. 1.

The array vector is given by:

$$\bar{\alpha} = \left[e^{-jkd\sin\theta} \;\; 1 \;\; e^{jkd\sin\theta} \right]^T \tag{1}$$

And the array weights yet to be determined are given by:

$$\bar{w}^H = [w_1 \;\; w_2 \;\; w_3] \tag{2}$$

So, the general total array output is given as:

$$y = \bar{w}, \bar{\alpha} = w_1 e^{-jkd\sin\theta} + w_2 + w_3^{\,jkd\sin\theta} \tag{3}$$

The array output for the desired signal is represented as y_s and the array output interfering or undesired signals

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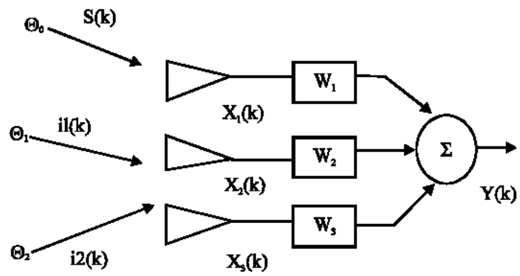

Fig. 1: Three-element array with desired and interfering signals

are represented as y_1 and y_2, respectively. Since, there are three unknown weights, there must be three conditions satisfied as:

Condition 1:

$$y_3 = \bar{w}^H, \bar{\alpha}_0 = w_1 e^{-jkd \sin\theta} + w_2 + w_3 e^{jkd \sin\theta_0} = 1 \quad (4)$$

Condition 2:

$$y_1 = \bar{w}^H, \bar{\alpha}_1 = w_1 e^{-jkd \sin\theta_1} + w_2 + w_3 e^{jkd \sin\theta_1} = 0 \quad (5)$$

Condition 3:

$$y_2 = \bar{w}^H, \bar{\alpha}_2 = w_1 e^{-jkd \sin\theta_2} + w_2 + w_3 e^{jkd \sin\theta_2} = 0 \quad (6)$$

Condition 1 demands that $y_3 = 1$ for the desired signal, thus allowing the desired signal to be received without modification and condition 2 and 3 rejects the undesired interfering signals given by Godara (2004). These conditions can written in matrix form as:

$$\bar{w}^H, \bar{A} = \bar{u}1^T \quad (7)$$

Where,

$$\bar{A} = [\bar{\alpha}_0 \ \bar{\alpha}_1 \ \bar{\alpha}_2]$$

is a matrix steering vectors and $\bar{u}_1 = [1 \ 0 \ ... \ 0]^T$ is a Cartesian basis vector. One can invert the matrix to find the required complex weights w_1, w_2 and w_3 by using

$$\bar{w}^H = \bar{u}1^T, \bar{A}^{-1} \quad (8)$$

One consideration in estimation of weights: The Cartesian basis vector in Eq. 8 indicates that the array weights are taken from the 1st row of $\bar{A}^{-1}$. This development is predicated on the fact that the desired signal and the total interfering signals make $\bar{A}$ an invertible square matrix. It is notice that $\bar{A}$ must be an N×N matrix with N-array elements and N-arriving signals. In the case, where, the number of interferers is <N-1, where, N indicates the number of array elements, this needs to modify the Eq. 8 and this modified equation is given by Godara (1997), which is an estimation of weights. However, this formulation requires noise to be added in the system because the matrix invertion will be singular otherwise.

Using this method we have

$$\bar{w}^H = \bar{u}1^T, \bar{A}^H (\bar{A}, \bar{A}^H + \sigma_n^2 \bar{I})^{-1} \quad (9)$$

where:

- $\bar{u}1^T$ = The cartesian basis vector whose length equals to the total number of sources
- σ^2_n = The noise variance

MATERIALS AND METHODS

Traditional narrowband array: Figure 2 shows one desired signal arriving from the angle Θ_0 and N inteferers arriving from angles Θ_1, ... Θ_N. The signal and the interferers are received by an array of M elements with M potential weights. Each received signal at element m also includes additive Gaussian noise. Time is represented by the kth time sample. Thus, the weighted array output y can be written as:

$$y(k) = \bar{w}^H, \bar{x}(k) \quad (10)$$

Where,

$$\bar{x}(k) = \bar{\alpha}_o s(k) + [\bar{\alpha}_1 \ \bar{\alpha}_2 ... \bar{\alpha}_N] \begin{bmatrix} i_1(k) \\ i_2(k) \\ \vdots \\ i_N(k) \end{bmatrix} + \bar{n}(k) = \bar{x}_3(k) + \bar{x}_i(k) + \bar{n}(k) \quad (11)$$

with

$$\bar{w} = [w_1 \ w_2 ... w_M]^T$$

are array weights, $\bar{x}_3(k)$ is a desired signal vector,

- $\bar{x}_i(k)$ = An interfering signals vector
- $\bar{n}(k)$ = Zero mean Gaussian noise for each channel,
- $\bar{\alpha}_i$ = M-element array steering vector for the Θi direction of arrival

We can rewrite the Eq. 10 using the expanded form of Eq. 11 as:

$$y(k) = \bar{w}^H, [\bar{x}_3(k) + \bar{x}_i(k) + \bar{n}(k)] = \bar{w}^H, [\bar{x}_3(k) + \bar{u}(k)] \quad (12)$$

where is undesired signal.

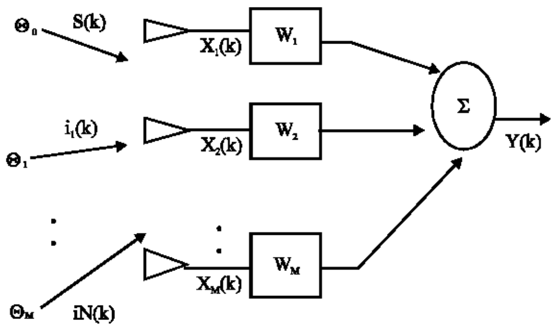

Fig. 2: Traditional narrowband array

It is initially assumed that all arriving signals are monochromatic and the total number of arriving signals N+1 ≤M. So that the arriving signals are time varying and thus, our calculations are based upon k-time snapshots of the incoming signal. Obviously, if the emitters are moving, the matrix of steering vectors is changing with time and the corresponding arrival angles are changing. Unless otherwise stated, the time dependence will be suppressed in Eq. 11 through 12.

Derivation for maximum SIR: The basic sidelobe canceling scheme works through an intuitive application of the array steering vector for the desired signal and interfering signals. However, by formally maximizing the SIR, we can derive the analytic solution for all the arbitrary cases.

We can calculate the array correlation matrices for both the desired signal ($\bar{R}_{ss}$) and the undesired signal ($\bar{R}_{uu}$). Since, we do not generally know the statistical mean of the system noise, it is best to label all $\bar{R}$ matrices as correlation matrices. If the process is ergodic and the time average is utilized, the correlation matrices can be defined with the time average notation as $\hat{R}_{ss}$ and $\hat{R}_{uu}$.

The weight array output power for the desired signal is given by:

$$\sigma_3^2 = E[|\bar{w}^H, \bar{x}_3|^2] = \bar{w}^H, \bar{R}_{ss}, \bar{w} \tag{13}$$

where,

$$\bar{R}_{SS} = E[\bar{x}_3 \bar{x}_3{}^H]$$

is a signal correlation matrix.

The weighted array output power for the undesired signals is given by:

$$\sigma_u^2 = E[|\bar{w}^H, \bar{u}|^2] = \bar{w}^H, \bar{R}_{uu}, \bar{w} \tag{14}$$

Where, it can be shown that

$$\bar{R}_{uu} = \bar{R}_{ii} + \bar{R}_{nn} \tag{15}$$

With

$\bar{R}_{ii}$ = Correlation matrix for interferers
$\bar{R}_{nn}$ = Correlation matrix for noise

The (SIR) is defined as the ratio of the desired signal power to the undesired signal power as:

$$\text{SIR} = \frac{\sigma_3^2}{\sigma_u^2} = \frac{\bar{w}^H, \bar{R}_{ss}\bar{w}}{\bar{w}^H, \bar{R}_{uu}\bar{w}} \tag{16}$$

The SIR can be maximized in Eq. 16 by taking the derivative with respect to $\bar{w}$ and setting the result equal to zero Harrington (1968). Rearranging terms, we can derive the following relationship as:

$$\bar{R}_{ss}, \bar{w} = \text{SIR}, \bar{R}_{uu}, \bar{w} \tag{17}$$

or

$$\bar{R}_{uu}^{-1}\bar{R}_{ss}, \bar{w} = \text{SIR}, \bar{w} \tag{18}$$

Equation 18 an eigenvector equation with SIR being the eigenvalues. The maximum SIR (SIR_{max}) is equal to the largest eigenvalue λ_{max} for the Hermitian matrix $\bar{R}_{uu}^{-1}\bar{R}_{ss}$. The eigenvector associated with the largest eigenvalue is the optimum weight vector $\bar{w}_{opt}$. Thus,

$$\bar{R}_{uu}^{-1}\bar{R}_{ss}, \bar{w}\text{SIR} = \lambda_{max}, \bar{w}_{opt}. = \text{SIR}_{max}, \bar{w}\text{IR} \tag{19}$$

Since, the correlation matrix is defined as:

$$\bar{R}_{ss} = E[|s|^2]\bar{\alpha}_0, \bar{\alpha}_0^H,$$

We can pose the weight vector in terms of the optimum Wiener solution.

$$\bar{w}\text{SIR} = \beta.\bar{R}_{uu}^{-1}, \bar{\alpha}_0 \tag{20}$$

Where,

$$\beta = \frac{E[|s|^2}{\text{SIR}_{max}}\bar{\alpha}_0^H, \bar{w}\text{SIR} \tag{21}$$

RESULTS AND DISCUSSION

If the desired signal is arriving from $\theta_0 = 0°$ while, θ_1 = -45° and θ_2 = 60°, the necessary weights can be calculated by substituting these data in Eq. 20 as:

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} 0.28-0.07_i \\ 0.45 \\ 0.28+0.07_1 \end{bmatrix}$$

and the array factor can be plotted as shown in Fig. 3.

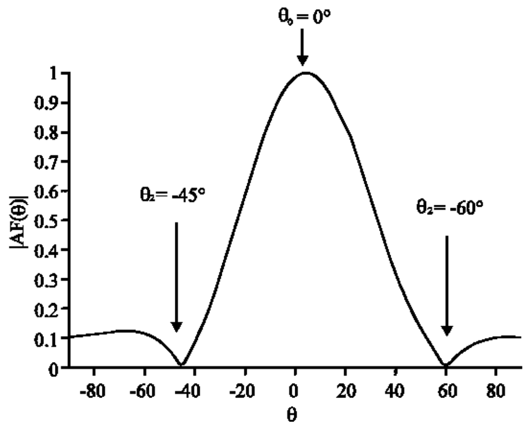

Fig. 3: Sidelobe cancellation pattern

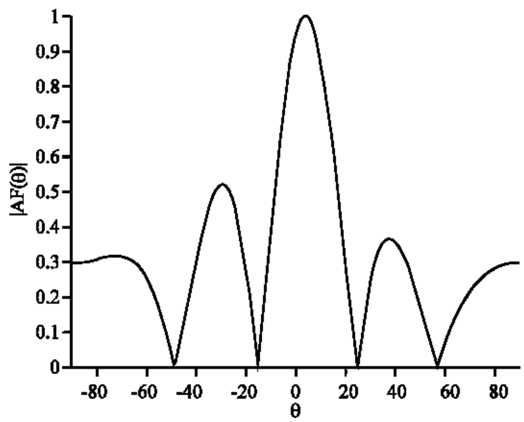

Fig. 4: Array pattern with approximate nulls at -15° and 25°

The Cartesian basis vector in Eq. 8 indicates that the array weights are taken from the 1st row of $\bar{A}^{-1}$. From this analysis, we can predicated that the desired signal and the total of the interfering signals make $\bar{A}$ an invertible square matrix. $\bar{A}$ must be an N×N matrix with N-array elements and N-arriving signals.

In the case, where, the number of interferers is less than N-1, where N is number of array elements, which needs to modify the Eq. 8 and this modified equation gives an estimation of weights. However, this formulation requires noise to be added in the system because the matrix inversion will be singular otherwise. Using this method we can get the modified equation as shown as Eq. 9.

For N = 5-element array with element spacing d = λ/2, the desired signal arriving at θ = 0° and 1 interferer arrives at -15° while, the other interferer arrives at +25°. If the noise variance is σ^2_n = 0.001, by using the array weight estimation found in Eq. 9, we can find the array weights. The matrix of the steering vectors is given as:

$$\bar{A} = [\bar{\alpha}_0 \; \bar{\alpha}_1 \; \bar{\alpha}_2]$$

Where,

$$\bar{\alpha}_0 = [1\,1\,1\,1\,1]^T$$

And

$$\bar{\alpha}_n = [e^{-j2\pi\sin\theta_n} \; e^{-j\pi\sin\theta_n} \; 1 \; e^{j\pi\sin\theta_n} \; e^{j2\pi\sin\theta_n}]^T$$

where, n = 1, 2. Since, only 3 sources are present, $\bar{u} = [1\,0\,0]^T$. By substituting these data in Eq. 9, we can get:

$$\bar{w}^H = \bar{u}_1^T, \bar{A}^H (\bar{A}, \bar{A}^H + \sigma_n^2 \bar{I})^{-1} = \begin{bmatrix} 0.26 + 0.11_i \\ 0.17 + 0.08_i \\ 0.13 \\ 0.17 - 0.08_i \\ 0.26 - 0.11_i \end{bmatrix}^T$$

The plot of this array factor is shown in Fig. 4.

The advantage of this method is that the total number of sources can be less than the number of array elements.

The basic sidelobe canceling scheme works through an intuitive application of the array steering vector for the desired signal and interfering signals. However, by formally maximizing the SIR, we can derive the analytic solution for all arbitrary cases which is described in this study.

For N = 3-element array with spacing d = 0.5λ has a noise variance σ^2_n = 0.001, a desired received signal arriving at θ_0 = 15° and 2 interferers arriving at angles θ_1 = -30° and θ_2 = 45°. Assume that the signal and interferer amplitudes are constant. So, to calculate SIR_{max}.

We can get normalized weights from Eq. 19. Based upon the incident angles of arrival for the desired signal and interferers along with the array vector $\bar{\alpha}$, we can find the correlation matrices of the and undesired signals as:

$$\bar{R}_{ss} = \begin{bmatrix} 1 & i & -1 \\ -i & 1 & i \\ -1 & -i & 1 \end{bmatrix}$$

and

$$\bar{R}_{uu} = \begin{bmatrix} 2.001 & -0.61-0.20i & -1.27-0.96i \\ -0.61+0.20i & 2.001 & 0.61-0.20i \\ -1.27+0.96i & -0.61+0.20i & 2.001 \end{bmatrix}$$

The largest eigenvalue for Eq. 19 is given as $SIR_{max} = \lambda_{max}$ = 679. The array weights are arbitrarily normalized by the center weight value.

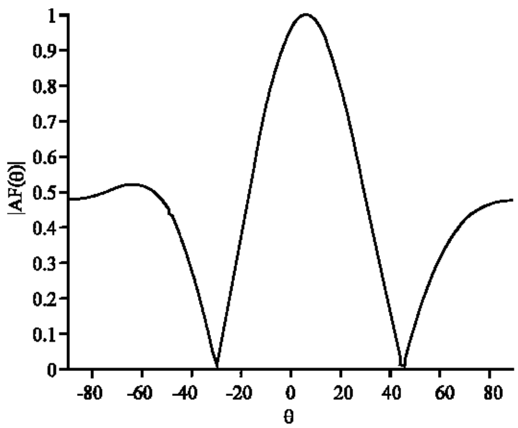

Fig. 5: Maximum SIR beamforming

Thus,

$$\bar{w}_{SIR} = \begin{bmatrix} 1.48+0.5i \\ 1.48-0.5i \end{bmatrix}$$

The derived pattern is shown in Fig. 5.

CONCLUSION

The applications with these fixed beamforming approaches are limited because these approaches are assumed to apply to fixed arrival emitters. If the arrival angles don't change with time, the optimum array weights won't need to be adjusted. However, if the desired arrival change with time, it is necessary to devise an optimization scheme that operates on-the-fly so as to keep recalculating the optimum array weights.

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