HF superdirective smart antenna system for interference suppression

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Abstract: In this work, Wuhan University has proposed a vehicle mounted HF smart antenna system, which is used for anti-interference communication. Compared with existing work, the novelty of this work is as follows: 1. Propose a IF-based DBF hardware architecture, which has better stability and is easier to achieve channel expansion; 2. Verify the performance and limitation of existing superdirective beamforming method via field tests. 3. Propose and verify an effective anti-interference method by nulling technology. The experimental results prove that the system has good anti-interference performance.

Keywords: smart antenna, compact array, superdirective beamforming, anti-interference, HF

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

The concept of smart antennas has been proposed since 1990s. But it does not really enter into practical stage until the emergence of high-speed analog-digital (ADC) devices and digital signal processors (DSPs) in recent years. Smart antenna systems estimate the direction of arrival (DOA) through cer-
tain criteria and can automatically adjust the radiation pattern of array. The system can make the main lobe of antenna array point towards the signal-of-interest (SOI) while directs the side lobe or nulls in the directions of signal-not-of-interest (SNOI), which can improve signal-to-interference-plus-noise ratio (SINR). Therefore, they have been widely applied in radar, sonar, mobile and satellite communication.

Short-wave communication owns inherent advantages compared to other communication means. Because of its unique transhorizon propagation mode, ground wave and sky wave, it can achieve long-distance communication without relay network. The equipment is relatively simple and flexible, which can be placed in car, ship and plane. Its disadvantages are also obvious. Crowded frequency band and various background noise makes it hard to choose a high quality channel. Multipath effect and energy attenuation caused by topography and atmospheric environment also influences receiving performance. Smart antenna technology can help to overcome these problems for its excellent properties mentioned above. However, array aperture is the main obstacle affecting its application. Most current smart antenna systems require a half-wavelength aperture array based on the demand for optimal directive gain. For high frequency (HF) array, it will occupy a large setting up area. Besides, the huge arrays may be attacked by enemies in time of war because of its easily identifiable characteristics. If we use small aperture array to achieve a high directive gain which is comparable with the conventional array, it will be very attractive. To achieve this goal, superdirective array synthesis concept is proposed [1]. However, so far most studies are limited to theory simulation. The practical effect is rarely verified and there is no precedent of applying it into short-wave communication. The Codar company once used this technology to develop a compactly spaced HF radar system for oceanographical remote sensing [2]. However, this system adopts classic superdirective method [3]. In order to avoid pattern distortion, array error needs to be strictly controlled. In paper [4], a constrained optimal directive gain (CODG) method is proposed. It enhances the acceptance of superdirective beamforming in actual HF array, which allows some degree of amplitude and phase errors. But under high-power interference environment, it can not afford enough inhibitory effect. In paper [5], a superdirective digital beamformer is designed. Its experiment results are based on hardware simulation, which is lack of field data verification. On these basis, we further propose a novel HF smart antenna system. Compared with existing work, we make the following innovative work: 1. The novel IF-based DBF hardware architecture is more stable and easier to achieve channel expansion than conventional analog domain architecture [6, 7]; 2. We verify the performance and limitation of existing superdirective beamforming method via field tests. 3. An effective anti-interference method by nulling technology is proposed. The field tests confirm that the system has better anti-jamming ability, compared with previous method.
2 System architecture

Fig. 1. System block diagram.

As the Fig. 1 shows, the system adopts advanced software-defined radio (SDR) architecture. All signal processing is done in intermediate frequency (IF). System can operate in two modes: simple array mode and full array mode. In simple mode, 5 short vertical dipole antennas are used. To enhancing the communication quality, the small array can rise 10 meters by lift rod. The antenna located in the center of circular array is used for array calibration and signal call. In full array mode, up to 16 reconfiguration receiving channels can be used, usually applied in large immovable array. Except for the antennas, the system consists of analog receiver, base-band signal processing board, short-wave radio, transmitter, frequency synthesizer and mode controller.

Analog receiver array adopts two-stage frequency conversion mode, converting radio frequency (RF) into low IF. Comparing with the single-stage frequency conversion mode, it can effectively improve the image rejection ratio. IF signals are digitized by analog-to-digital converters (ADCs). Then, decimation and filtering processing is done, moving the IF signals to 125KHz baseband. The low-rate data flow will be transferred into direction of arrival (DOA) and digital beamforming (DBF) function modules at the same time, which is used for azimuth estimation and digital beamforming. Digital signal processors (DSPs) are responsible for calculating the azimuth information and weight vectors and then send the weight coefficients to beamforming networks (BFNs) in field programmable gate array (FPGA). Digital up converters (DUCs) will reconstruct the beamformed signals to RF for short-wave radio. Short-wave radio adopts half-duplex communication. In receiving end, it selects the desired channel by beam switches. In transmitting end, 100 watt transmitter will send the amplified signal to the center antenna through antenna tuner. When working in calibration mode, transmitter will be bypassed and radio signal is directly routed to center antenna as calibration source. Frequency synthesizer generates two local oscillator (LO) signals for analog receiver array and one system clock for data acquisition and processing board. In order to get high frequency resolution while reducing the band spurious,
it adopts the architecture of direct digital frequency synthesizer (DDS) driving phase locked loop (PLL). Mode controller accepts the instructions from personal computer (PC) and initializes all function modules when power on.

3 Superdirective beamforming

3.1 Existing method

Superdirective beamforming algorithms are dedicated to small aperture arrays (i.e. the array element space is much less than half wavelength), which can achieve better directive gain than conventional methods [4, 5]. However, practical array antennas always have certain amplitude and phase errors even after correction. Classic superdirective beamforming does not consider this point, which makes it extremely sensitive to array perturbation, resulting in poor receiving performance. Although the diagonal loading method can improve the robustness, it does not establish direct contact with the sensitivity of array, which makes it hard to choose a proper loading value. CODG method is more suitable for actual array. It introduces a parameter $K$ called sensitivity factor, which is used to control the robustness of array. For a uniform circular array, we assume the steer vector of main lobe direction as $a(\theta_m, \varphi_m)$, and the desired weight vector is assumed as $w$. The sensitivity factor $K$ denotes as:

$$K = \frac{w^H w}{w^H N w}$$

in which $N = a(\theta_m, \varphi_m) a^H (\theta_m, \varphi_m)$. $[\cdot]^H$ denotes conjugate transpose. The corresponding weight vector $w$ should subject to the following constraints:

$$\min_w w^H Rw, \quad w^H a(\theta_m, \varphi_m) = 1, \quad \|w\| = K$$

where $R = \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi \sin \theta a(\theta, \varphi) a^H (\theta, \varphi) d\theta d\varphi$. The method of selecting $K$ value and the whole derivation procedure can be found in paper [4]. Here, we directly give out the formula:

$$w = \frac{(R + \hat{\lambda} I)^{-1} a(\theta_m, \varphi_m)}{a^H(\theta_m, \varphi_m)(R + \lambda I)^{-1} a(\theta_m, \varphi_m)}$$

where $\hat{\lambda}$ is the lagrange multiplier, which can be calculated in numeric method. Paper [5] introduces its hardware solution.

3.2 Anti-interference method

In practical electromagnetic environment, the suppression effect of CODG method is not enough when the power of interference is much larger than desired signal. Therefore, it is meaningful to form deep nulls in the interference direction. Assuming the interference signal number is $P$ and the steer vector of corresponding direction is $a(\theta_i, \varphi_i), i = 1, 2, \cdots, P$. The constraints to provide direction control can be written as:

$$w^H a(\theta_m, \varphi_m) = 1, \quad w^H a(\theta_i, \varphi_i) = \epsilon_i, \quad i = 1, 2, \cdots, P$$


where $\epsilon_i$ is minimum value for controlling the null depth. The constraints above can be written in matrix form as:

$$CHw = g$$  \hfill (5)

where $C = [a(\theta_m, \varphi_m), a(\theta_1, \varphi_1), \ldots, a(\theta_P, \varphi_P)], g = [1, \epsilon_1, \ldots, \epsilon_P]^T$. $[.]^T$ represents the transpose of vector. Considering the array uncertainty, multi-point constraint approach can be applied to broaden null. To be specific, we can locate several closely spaced null points in interference region. Using five-element array as example, if SOI direction is from $(\theta_m, \varphi_m)$, SNOI is from $(\theta_1, \varphi_1)$, under single-point constraint approach, the matrix $C$ can be easily written as $C = [a(\theta_m, \varphi_m), a(\theta_1, \varphi_1)]$ and corresponding $g = [1, 0]^T$. Under multi-point constraint approach, we can further add two adjacent null points in SNOI direction. The distance $(\Delta \theta, \Delta \varphi)$ between null points determines the width of null region. Thus, matrix $C$ can be denoted as:

$$C = [a(\theta_m, \varphi_m), a(\theta_1 - \Delta \theta, \varphi_1 - \Delta \varphi), a(\theta_1, \varphi_1), a(\theta_1 + \Delta \theta, \varphi_1 + \Delta \varphi)]$$  \hfill (6)

The corresponding $g = [1, \epsilon_0, \epsilon_0]^T$. By multiple simulation tests, we find that, in order to obtain an effective solution $w$, $(\Delta \theta, \Delta \varphi)$ can not be set too small and $\epsilon_0$ should be larger than 0. Actually, compared with single-point constraint approach, although null width is broaden, it also sacrifices some anti-jamming performance, which will be verified by the following field experiment.

Based the analysis above, the method based on nulls forming is:

$$\min_w w^H R w, \quad C^H w = g,$$  \hfill (7)

The expression can be solved by Lagrange multiplier method. The target function can be constructed as:

$$L = w^H R w + \hat{\lambda}^H (C^H w - g) + (C^H w - g)^H \hat{\lambda}$$  \hfill (8)

where $\hat{\lambda}$ is $P+1$ dimension Lagrange column vector. Taking its gradient with respect to $w$ and making $\nabla_w(L) = 0$, we get:

$$w = -R^{-1}C\hat{\lambda}$$  \hfill (9)

Inserting (9) into the equation $C^H w = g$ leads to:

$$\hat{\lambda} = -\left(C^H R^{-1}C\right)^{-1} g$$  \hfill (10)

Thus, the formula (9) can be rewritten as:

$$w = R^{-1}C \left(C^H R^{-1}C\right)^{-1} g$$  \hfill (11)

Equation (11) is the final weight formula of anti-interference method.
Fig. 2. (a) Field test environment. (b) Layout of antenna array.

Fig. 3. (a) Beam pattern. (b) Original base-band spectrum. (c) The spectrum by CODG method ($K = 0.25$). (d) The spectrum by single-point constraint. (e) The spectrum by multi-point constraint.

4 Field experiment validation

A compact 5-element circular array is designed for field experiment. Fig.2(b) shows its layout. Antenna element adopts 2-meters long verticle dipole. The array radius is 4 meters. The hardware system can receive the five elements’ signal and implement beamforming via given weight value. The whole working principle of hardware has been introduced in section 2. Here, a detailed
description of the experimental process is as follows. Assuming the system working frequency is 20.901MHz and interference frequency is 20.899MHz. Firstly, we use center antenna as calibration source, and collect snapshot data from 5 antenna elements for amplitude and phase errors estimation. Then, turn off the calibration source and dispose two handheld radio stations in point E and point F respectively. Record the latitude and longitude of these two radiation sources by globe position system (GPS), which have been marked in fig.2(a). By computation, the E point is 103°, north by east, and the F point is 235°, north by east. Set point E as SOI and radiation frequency is 20.901MHz. Set point F as SNOI and radiation frequency is 20.899MHz. They are all unmodulated continuous wave signals. Adjust the radiation power of point E and F, making the SNOI power from point F is much larger than SOI from point E. Upload received baseband data from single antenna to PC and analyze its spectrum. Its original spectrum is as fig.3(b) shows, our goal is to inhibit or even eliminate SNOI while keeping SOI signal undistorted. In implementation, we use different weight vectors in DBF modules and upload beamformed signals from respective DBF output end to PC for spectrum analysis.

For CODG method, we just need to steer its mainlobe towards the SOI direction and use its sidelobe to suppress SNOI. The output spectrum is showed in fig.3(c). The SNOI reduces power of 11.1dB. For nulling method, under single-point constraint, we make \( g = [1,0]^T \). As we can see in fig.3(d), the SNOI reduces power of 22.5dB. Under multi-point constraint, we make \( g = [1,10^{-2},10^{-2},10^{-2}]^T \) and \( (\Delta \theta, \Delta \varphi) = (0^\circ, 10^\circ) \). In fig.3(e), the corresponding power inhibit amount is 19.5dB. Obviously, the nulling methods acquire better anti-jamming performance than CODG method. We simulate their beampatterns in fig.3(a). Nulling beampattern 1 denotes single-point constraint method and nulling beampattern 2 denotes multi-point constraint method. Their weight vector values are listed in table.I.

| Antenna | \( w_1 \) | \( w_2 \) | \( w_3 \) |
|---------|---------|---------|---------|
| 1       | 0.3019 + 0.0483i | 0.3494 + 0.0319i | 0.3225 - 0.0760i |
| 2       | -0.1521 + 0.1056i | -0.2795 + 0.0675i | -0.0702 + 0.2178i |
| 3       | 0.1884 + 0.1579i | 0.2828 + 0.1084i | 0.1709 + 0.1128i |
| 4       | 0.0753 - 0.1734i | 0.0582 - 0.1208i | 0.0894 - 0.0711i |
| 5       | -0.0895 - 0.1345i | -0.0950 - 0.1403i | 0.0991 - 0.1801i |

(\( w_1 \):CODG method. \( w_2 \):single-point constraint. \( w_3 \):multi-point constraint.)

5 Conclusion
In this work, a superdirective smart antenna system based on compact circular array with radius of only 4 meters is proposed. By adopting novel nulling
beamforming method, system acquires better interference suppression effect. Therefore, it provides a good solution for vehicle mounted high-quality short-wave communication. Meanwhile, in field experiments, we also find some work yet to be improved. Because of the deviation of azimuth estimation (within 5° measured by statistical average), in order to get more perfect anti-interference effect, we still need to properly adjust the position of nulls in the vicinity of estimated azimuth. Consequently, a smarter anti-interference method is worthy of further study.

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