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SUM AND DIFFERENCE MULTIPLE BEAM MODULATION TRANSMITTED BY MULTIMODE HORN ANTENNA FOR INVERSE MONOPULSE DIRECTION-FINDING

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Abstract—The sum and difference multiple channels were usually applied to the monopulse system only in a receiver. But this paper presents a technique of multiple beam modulation transmitted by the sum and difference multiple channels. The modulated field is designed as three chip signal vectors whose sum and whose differences are controlled by the gains of antennas, and the angle between the sum vector and the differential vector depends on the phase error between the channels so that the different microwave signals can be transmitted in the different directions. A receiver with single-antenna can extract azimuth and elevation with respect to the transmitter. Simulation results show that the proposed modulation system has been successfully designed to integrate digital communication with direction-finding in the way of the reverse monopulse.

1. INTRODUCTION

Monopulse technique is commonly used in modern radar and communication systems for tracking targets or communicating partners because of its angular accuracy [1]. A monopulse receiver uses the sum or the difference radiation patterns, simultaneously to receive the arrived signal. The angle of arrival with respect to the receiver is measured via computation of a variable named monopulse ratio, which is the ratio of the difference and the sum signals. But it is difficult for some missions where the transmitter may be designed large and complicated, whereas the receiver should be smaller and simpler [2]. In this case the inverse monopulse technique should be introduced. Although the inverse monopulse had been used in radar guidance systems, little information could be found about the integration of digital transmission and tracking. For communication systems, the inverse monopulse would deal with the problem of multiple access while sending signals with the multibeam antenna. With the development of multiple-input multiple-output (MIMO) systems, multiple antennas have the potential to dramatically improve the performance of communication and radar systems [3–14]. Moreover, transmitting signals with the sum and difference multibeams can modulate the spatial parameter into microwave field, which is convenient to extract azimuth and elevation information at the receiver with only an antenna. So this paper presents a technique of multiple beam modulation with the sum and difference beams for tracking systems such as communication, radar, guidance beacon and navigation.

Earlier work [15] has dealt with the concept of multiple beam modulation with a common phase center. Paper [16] introduces the technique of microwave space modulation transmitted by the four feed monopulse antenna. But both techniques can not be suitable for the antenna directional patterns without a phase center. It is fact that the multiple beam antenna without a common phase center is very universal and useful. For example, the multimode horn antenna is good characteristic of the sum and different beams, which is usually of small size to fit in the limited space and can work in microwave with higher frequency, but the multiple beam channels have a displaced phase center.Therefore, a goal of this paper is to design a modulation technique suitable for a multimode horn antenna.

Horn antennas are used in directly radiating arrays and also in feeds for reflector [17–22]. In directly radiating arrays it is highly desirable that the array elements have high aperture efficiency to maximize the gain for a given number of array elements. The multimode horn can improve the performance of the radiation patterns. Modern radar and communication systems have often included multimode horn feed or multimode horn antenna for searching and tracking purposes based on the principle of monopulse direction-finding. But the multimode antenna was used only at a receiver. To modulate the sum and the difference radiating patterns into microwave field, we transmit simultaneously with the sum beam and the two difference beams so that the synthesized signals can carry digital information and the directional information.

There are different interests in the fields of MIMO radar and MIMO communication. MIMO communication systems can realize a high data transmission overcoming the effect of fading in the wireless channel, while MIMO radar can provide a credible target detection and direction finding overcoming the degradations of the radar cross section fluctuations [3–14, 23, 24]. Besides radar, in other microwave systems such as guidance beacon, navigation systems and microwave measurement, the spatial parameter or the directional information is very important [25–28]. Therefore, it is possible and more useful to the systems with the exception of communication where the function of the spatial parameter modulation is enhanced and the capacity of data transmission is depressed.

The remainder of this paper is organized as follows. Section 2 introduces the relationships between the beams of antenna and the spatial parameters. The principle of multiple beam modulation is presented in Section 3. The differential demodulation of the data sequence is derived in Section 4. Noncoherent demodulations and coherent demodulations for the spatial parameters are designed in Section 5 and Section 6 respectively. Finally, the performances of the proposed modulation are investigated by computer simulation in Section 7.

2. CHOICE OF MODES FOR THE HORN ANTENNA

It is well known from the waveguide theory that at certain operating frequencies, electromagnetic wave propagates in a rectangular waveguides along with multiple modes such as transverse electric field TE_{mn}, and transverse magnetic field TM_{mn}. In monopulse radar systems the multiple mode fields have been used to receive the signal reflected from targets. But in this paper we utilize the multiple mode fields to transmit the spatial parameter.

The geometry and the coordinates of the rectangular horn antenna are shown in Figure 1. To analyze the radiation patterns for the multimode fields simply, we suppose that the far field radiates directly from the aperture. Similar to radar, the multiple modes have been chosen as follows:

Sum beam: TE_{10}, TE_{30}, TE_{12}/TM_{12}

H-plane difference beam: TE_{20}, TE_{22}/TM_{22}

E-plane difference beam: TE_{11}/TM_{11}, TE_{13}/TM_{13}

For the sum beam, the electric field in the aperture with the modes TE_{10}, TE_{30}, TE_{12}/TM_{12} can be excited as below [22],

$$E_{z\Sigma}(y,z) = \cos\frac{\pi y}{a} + k_{30}\cos\frac{3\pi y}{a} + k_{12}\cos\frac{\pi y}{a}\cos\frac{2\pi z}{b} \tag{1}$$

where $k_{30} = 0.4\exp(j\frac{\pi}{6})$, $k_{12} = 0.85\exp(-j\frac{5\pi}{36})$. If the reflection from the open terminal is neglected, the radiation pattern F_1 of the sum

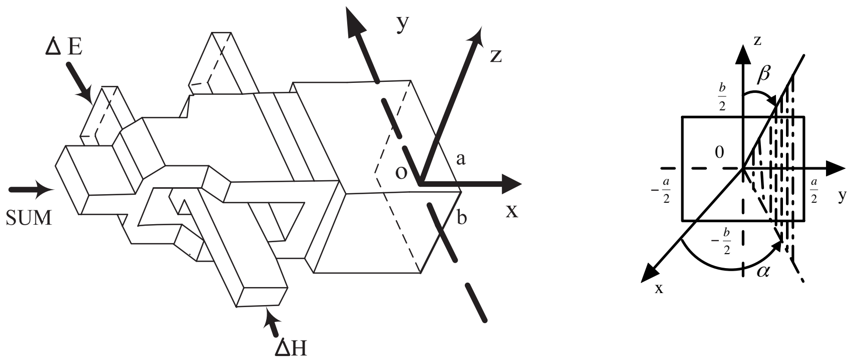

Figure 1. The coordinate system and the geometry of the rectangular horn antenna, where $a = 2.1\lambda$, $b = 1.9\lambda$, λ is a wavelength, α and β denote an azimuth angle and an elevation angle respectively.

beam in the far field can be derived as

$$\begin{aligned} F_1 \;=\; F_1(\alpha,\beta) = \frac{1}{1-(k_{30}/3)} \left\{ \left[\frac{\sin(\pi u)}{\pi u} + k_{12} \frac{\pi u \sin(\pi u)}{\pi^2 - (\pi u)^2} \right] \frac{\cos(\pi v)}{1-4v^2} \right. \\ \left. -3k_{30} \frac{\sin(\pi u)}{\pi u} \frac{\cos(\pi v)}{9-4v^2} \right\} \end{aligned} \tag{2}$$

where $u = \frac{b}{\lambda}\cos\beta$, $v = \frac{a}{\lambda}\sin\alpha\sin\beta$. From evaluating the function of F_1, it is found that the value of F_1 is a complex function, and can be denoted as $F_1 = |F_1|\exp\{j\theta\}$.

For H-plane difference beam, the electric fields with the modes TE_{20}, TE_{22}/TM_{22} on the aperture is represented as

$$E_{zH}(y,z) = k_{20} \sin\frac{2\pi y}{a} \left(1 + k_{22}\cos\frac{2\pi z}{b}\right) \tag{3}$$

where $k_{22} = 0.67$, k_{20} denotes an amplitude of H-plane different field, and can be adjusted so that the gain coefficient of F_2 equals to 0.38. The radiation pattern of H-plane difference beam is given as below.

$$F_2 = F_2(\alpha,\beta) = 0.38 \left[\frac{\sin(\pi u)}{1-4u^2} + k_{22} \frac{\pi u \sin(\pi u)}{\pi^2 - (\pi u)^2} \right] \frac{\sin(\pi v)}{1-4v^2} \tag{4}$$

For E-plane difference beam, the electric field with the modes TE_{11}/TM_{11}, TE_{13}/TM_{13} on the aperture is expressed as

$$E_{zE}(y,z) = k_{11} \left(\sin\frac{\pi z}{b} + k_{13}\cos\frac{3\pi z}{b} \right) \cos\frac{\pi y}{a} \tag{5}$$

where $k_{13} = 0.5$, k_{11} denotes an amplitude of E-plane different field, and can be adjusted so that the gain coefficient of F_3 equals to 1.5. The radiation pattern of E-plane difference beam is presented by

$$F_3 = F_3(\alpha, \beta) = 1.5 \left[\frac{u \sin(\pi u)}{1 - 4u^2} + k_{13} \frac{u \cos(\pi u)}{9 - 4u^2} \right] \frac{\cos(\pi v)}{1 - 4v^2} \qquad (6)$$

It should be explained that the functions of F_1, F_2, F_3 above have been uniformized and neglected a common term due to reflection from the open terminal because the ratios of $F_2/|F_1|$ and $F_3/|F_1|$ are important to convert the spatial parameters into the signal parameters. Figure 2 shows the relationship between $F_2/|F_1|$ and elevation angle, Figure 3 shows the relationship between $F_3/|F_1|$ and azimuth angle. Therefore, in next section, we will design the transmit signal to transform the parameters $F_2/|F_1|$ and $F_3/|F_1|$ into microwave fields.

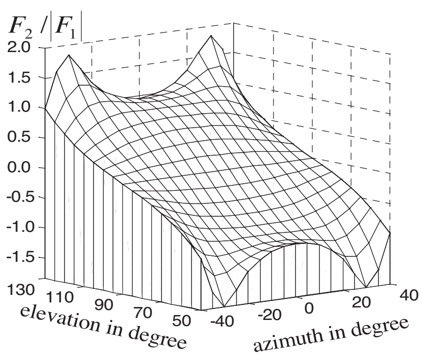

Figure 2. The relationship between $F_2/|F_1|$ and elevation.

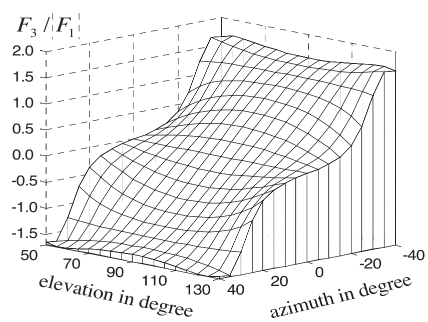

Figure 3. The relationship between $F_3/|F_1|$ and azimuth.

3. THE PRINCIPLE OF MULTIPLE BEAM MODULATION

For measurement of elevation and azimuth angles, a scheme of transmit system is designed as shown in Figure 4, which consists of data coders, an oscillator, time domain modulators, feeding components and a multimode horn antenna. Three-beams, named as the sum beam, the H-plane difference beam, the E-plane difference beam, are used as transmit channel. Every channel is fed by different modulation signal in time domain so that the synthesis of three channel electromagnetic fields is multiple beam modulation carrying the spatial parameters.

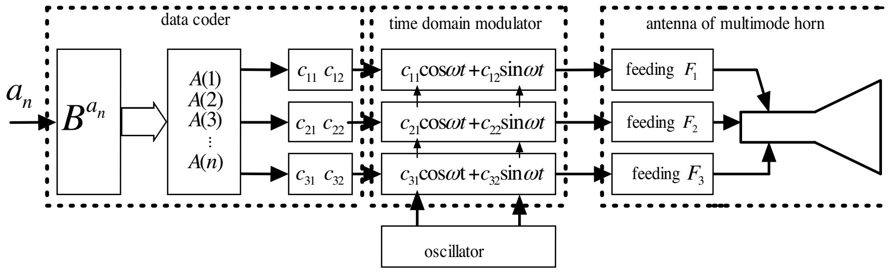

Figure 4. A scheme of transmit system with multiple beam modulation.

The feeding signal of every channel $s_j(t)$ could be designed as following:

$$s_j(t) = s_j(i,n,t) = c_{j1}(i,n)\cos\omega t + c_{j2}(i,n)\sin\omega t \tag{7}$$

where

ω is carrier radian frequency of transmit signal,
t denotes the time,
$c_{jl}(i,n) \in [-1,0,1]$ is the data information from the coder,
n denotes the nth frame signal,
$i = 1,2,3$ denotes the ith chip signal in the nth frame,
$j = 1,2,3$ denotes the jth channel or beam.

The signal $r(i,n,t)$ received at a single antenna is the synthesis of three channels, $r(i,n,t)$ is written as

$$r(i,n,t) = [F_1 \quad F_2 \quad F_3] \begin{bmatrix} c_{11}(i,n) & c_{12}(i,n) \\ c_{21}(i,n) & c_{22}(i,n) \\ c_{31}(i,n) & c_{32}(i,n) \end{bmatrix} \begin{bmatrix} \cos\omega t \\ \sin\omega t \end{bmatrix} \tag{8}$$

$$r(i,n,t) = X(i,n)\cos\omega t + Y(i,n)\sin\omega t \tag{9}$$

$$\begin{bmatrix} X(i,n) \\ Y(i,n) \end{bmatrix} = \begin{bmatrix} c_{11}(i,n) & c_{12}(i,n) & c_{21}(i,n) & c_{31}(i,n) \\ c_{12}(i,n) & -c_{11}(i,n) & c_{22}(i,n) & c_{32}(i,n) \end{bmatrix} \begin{bmatrix} |F_1|\cos\theta \\ |F_1|\sin\theta \\ F_2 \\ F_3 \end{bmatrix} \tag{10}$$

where the $X(i,n)$ and the $Y(i,n)$ are the equivalent baseband signals, and the complex signal $Z(i,n)$ equals to $X(i,n) + jY(i,n)$. In order to modulate F_1, F_2 and F_3 into the transmit signal, a time divided modulation scheme is designed similar to the conventional space-time code. The transmit signal is divided into the N frames, the nth frame is composed of three chips which are expressed by the six components $S(n) = [X(1,n) \quad Y(1,n) \quad X(2,n) \quad Y(2,n) \quad X(3,n) \quad Y(3,n)]^T$,

$$S(n) = A(n)H \tag{11}$$

where $H = [|F_1|\cos\theta \quad |F_1|\sin\theta \quad F_2 \quad F_3]^T$ is a matrix composed of the antenna radiation patterns, $A(n)$ is a matrix of modulation, whose iterative relationship is

$$A(n) = B^{a_n} A(n-1) \tag{12}$$

$$A(1) = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}$$

$$A(n) = \begin{bmatrix} c_{11}(1,n) & c_{12}(1,n) & c_{21}(1,n) & c_{31}(1,n) \\ c_{12}(1,n) & -c_{11}(1,n) & c_{22}(1,n) & c_{32}(1,n) \\ c_{11}(2,n) & c_{12}(2,n) & c_{21}(2,n) & c_{31}(2,n) \\ c_{12}(2,n) & -c_{11}(2,n) & c_{22}(2,n) & c_{32}(2,n) \\ c_{11}(3,n) & c_{12}(3,n) & c_{21}(3,n) & c_{31}(3,n) \\ c_{12}(3,n) & -c_{11}(3,n) & c_{22}(3,n) & c_{32}(3,n) \end{bmatrix}$$

where a_n is the data sequence to be transmitted, $a_n = 0$, 1, 2, 3; $A(1)$ is an initialization matrix. Figure 5 shows the signal constellation and the modulation relationship of the spatial parameters F_1, F_2 and F_3. The importance equations can be derived from (10):

1) The differential equation of the received signal phase $\psi(i,n)$,

$$\psi(i,n) = \psi(i,n-1) + 0.5\pi a_n, \quad i = 1,2,3; \tag{13}$$

2) The equations of spatial modulation,

$$|Z(1,n) + Z(2,n)| = |2F_1| \tag{14}$$

$$|Z(3,n) - Z(2,n)| = 2F_2 \tag{15}$$

$$|Z(1,n) - Z(3,n)| = 2F_3 \tag{16}$$

It is also obvious as shown in Figure 5 that the θ equals to the angle between the vector $[Z(3,n)-Z(2,n)]$ and the vector $[Z(1,n)+Z(2,n)]$. Therefore, the modulation signal is a multiple beam modulation which can transform the beam parameters, such as the gains and the error phase of beams, into the microwave signal. In the receiver, the scheme to demodulate the information noncoherently is very simple.

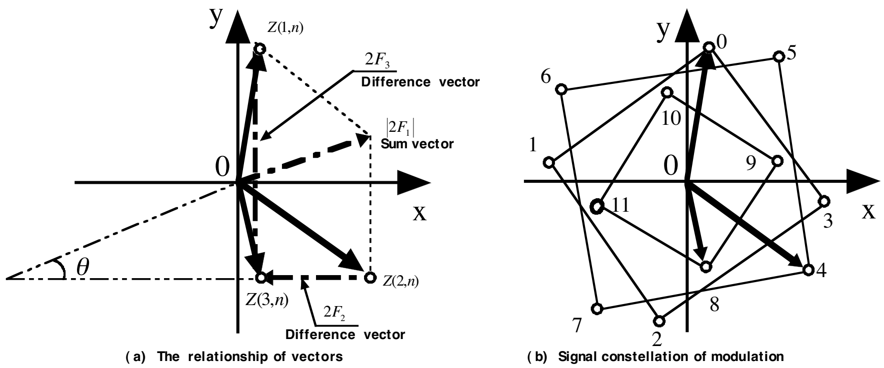

Figure 5. The modulation relationship of the spatial parameters.

4. DIFFERENTIAL DEMODULATION OF THE DATA SEQUENCE

The microwave field from the transmitter to the receiver will be introduced a delayed phase ϕ and an amplitude attenuation ρ. Then the received signal $V(i,n)$ is written in the equivalent baseband form

$$V(i,n) = \rho \exp(-j\phi) Z(i,n). \tag{17}$$

From (17) the differential relationship of the received signal is derived as follows

$$V(i,n) = \exp\{j0.5\pi a_n\} V(i,n-1). \tag{18}$$

Then the data signal $u(t)$ is estimated based on the theory of maximum likelihood estimation

$$\begin{aligned} u(t) &= \exp\{j0.5\pi \hat{a_n}\} \\ &= \frac{\begin{pmatrix} V(1,n)V^*(1,n-1)+V(2,n)V^*(2,n-1)+ \\ V(3,n)V^*(3,n-1) \end{pmatrix}}{\begin{pmatrix} V(1,n-1)V^*(1,n-1)+V(2,n-1)V^*(2,n-1)+ \\ V(3,n-1)V^*(3,n-1) \end{pmatrix}} \end{aligned} \tag{19}$$

Thus the data sequence $\hat{a_n}$ can be obtained when the signal $u(t)$ outputs from a decision device. It should be notice that the bit synchronization could accomplish by means of a frame synchronization code before the data information is demodulated.

5. NONCOHERENT DEMODULATION OF THE SPATIAL PARAMETERS

From the Eqs. (14)–(16) and Figure 5, the parameters of the beam directional patterns F_1, F_2 and F_3 can be estimated by

$$\hat{F}_1 = \frac{1}{2\rho}\left|V(1,n) + V(2,n)\right| \tag{20}$$

$$\hat{F}_2 = \frac{1}{2\rho}\left|V(3,n) - V(2,n)\right| \tag{21}$$

$$\hat{F}_3 = \frac{1}{2\rho}\left|V(1,n) - V(3,n)\right| \tag{22}$$

And the error phase between the beams θ is derived as

$$\hat{\theta} = \arccos\frac{[V(3,n) - V(2,n)] \bullet [V(1,n) + V(2,n)]}{|V(3,n) - V(2,n)|\,.\,|V(1,n) + V(2,n)|} \tag{23}$$

where the operation symbol "$\bullet$" denotes a point multiple of vectors, and the "$|X|$" denotes a module of the vector$X$.

6. CARRIER SYNCHRONIZATION AND COHERENT ESTIMATION OF THE SPATIAL PARAMETERS

The carrier phase in the receiver ϕ can be derived by the following equation.

$$\exp(-j\phi) = \frac{V(3,n) - V(2,n)}{|V(3,n) - V(2,n)|} \tag{24}$$

But the ϕ estimated from Equation (24) is not equal to the real carrier phase because there are four illegible values of ϕ, $\phi + 0.5\pi$, $\phi + \pi$, $\phi{+}1.5\pi$. In order to resolute the multiple values and to demodulate the spatial parameters coherently, a detail algorithm has been developed as follows:

Step 1: Directly calculate the absolute values $|F_1|$, $|F_2|$ and $|F_3|$ from the Equation (20)–(22) when $\rho = 1$;

Step 2: Derive the modulation matrix $A(n)$ from the data information received as the section 3 above.

Step 3: Let $S_V(n) = [X_V(1,n) \quad Y_V(1,n) \quad X_V(2,n) \quad Y_V(2,n) \quad X_V(3,n) \quad Y_V(3,n)]^T$, construct the transformation matrix of circumrotating coordinates $T(\phi_k)$, $\phi_k = \phi + 0.5k\pi$, $k = 0$, 1, 2, 3;

Step 4: For the different parameter k, find out the matrix of the spatial parameters H;

$$H = \left[A^T(n)A(n)\right]^{-1} A^T(n)T(\phi_k)S_V(n) \tag{25}$$

Step 5: Calculate F_1, F_2 and F_3 from H, find the optimal $k = k_{opt}$ so that the root mean square error (RMSE) of the F_1, F_2 and F_3 from H with respect to the results in step 1 can be minimum. Finally find out the F_1, F_2, F_3 and θ.

7. SIMULATION RESULTS

Figure 6 shows the performance of bit error rate (BER) versus signal-to-noise ratio (SNR). Simulations were performed under the following assumption:

1) a receiving method of demodulating differentially without estimating the channel parameters;
2) the systems in an additive white Gaussian noise (AWGN) channel,
3) three cases: the first is in the direction of $\alpha = 10°$ and $\beta = 100°$; the second is in the direction of $\alpha = 0°$ and $\beta = 90°$; and the third is in the direction of $\alpha = 15°$ and $\beta = 115°$.

It is fact that the performance of BER is deteriorated in the different direction because the total received power varies with the azimuth and the angle when the transmit power is constant. Therefore the curve B as shown in Figure 6 describes the referenced performance in the direction of beam center. The curve A and C denote the BER performances at the directions of ($\alpha = 10°$, $\beta = 100°$) or ($\alpha = 15°$,

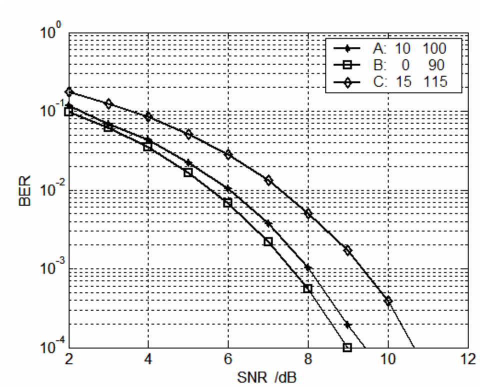

Figure 6. The performance of BER at the different directions.

$\beta = 115°$) respectively when the transmit power is the same as that of the curve B.

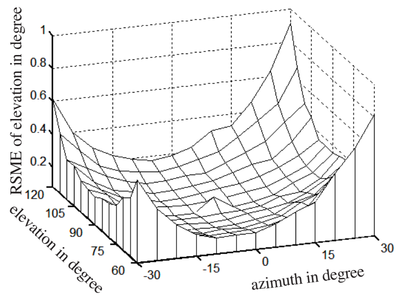

Figure 7. The RMSE of elevation in the different directions.

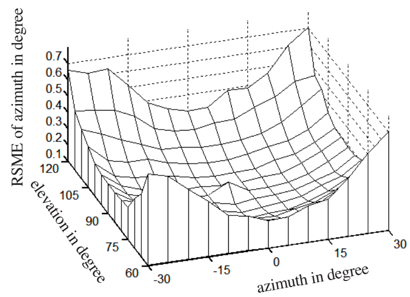

Figure 8. The RMSE of azimuth in the different directions.

Figures 7 and 8 show the root mean square error (RMSE) of the estimated directional angles in the AWGN channel when the SNR at a receiver in the beam center is 20 dB. In simulation we assume that the receiver can cumulate 64 frames to extract the azimuth angle and the elevation angle. The results show that the RMSE of direction-finding (DF) is small at the central axis of the antenna beam, and the farther distance from central axis is, the less accurate DF is achieved. Moreover, the dissymmetry of DF RMSE is visible regarding the central axis. The reason is due to two aspects: the one depends on the characteristics of $F_2/|F_1|$ and $F_3/|F_1|$; the other is variational in the received SNR. The received power is dissymmetric regarding the central axis, and less than that at the central axis. Therefore, the DF performance depands on the design of transmit signal and the property of F_1, F_2 and F_3. If a paraboloid reflector is used, the DF performance will be improved because the secondary radiation patterns from the reflector will have bigger ratios of the difference modes to the sum mode.

8. DISCUSSION AND CONCLUSION

The proposed sum and difference multiple beam modulation with multimode horn can convert the spatial parameter of antenna directional patterns into microwave signal. The receiver with a single antenna accomplishes communication and direction-finding easily in the beam-space. The systems with the multiple beam modulation can transmit different parameter signal in different directions, it is helpful to distinguish targets and estimate parameters in the bi-static or multistatic radar. The modulation technique can be applied into the system such as direction finding with a mini receiver, communication and tracking systems, radar, navigation and guidance beacon because the modulation has the advantage of the intuitionistic relationship between the signal vectors and the spatial parameters. Compared with space-time coding, however, the rate of bit transmission is decreased, but the function to transmit with spatial information is enhanced.

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