Wireless communication applications of the variable inclination continuous transverse stub array for Ku-band applications

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Abstract
A wideband and continuous beam steering variable inclination continuous transverse stub antenna array is presented in the communication. The proposed antenna consists of a continuous transverse stub (CTS) array and a line source generator (LSG). These two parts are designed and optimized separately. The LSG structure is generated by a Pillbox transition. The CTS array is composed of 20 radiating slots and is fed by a corporate-feed network. The corporate-feed network adopts a series-parallel hybrid structure to realize lower profile and high-efficiency performance. The relative rotation movement between the CTS array and the LSG generates a phase gradient on the radiation part such that the proposed antenna can obtain a continuous beam in the upper hemisphere. Based on the array synthesis encryption sampling technology theory, the relationship between the mechanical rotation angle and the beam direction is analysed and obtained. To validate the antenna concept, the antenna is fabricated and measured. The simulation and measurement results are in good agreement. Through the rotation of the CTS array, the designed antenna achieves a ±56° scan. The measured results show that the array can achieve an impedance bandwidth of 16% in Ku-band at the centre frequency of 12 GHz with 67% aperture efficiency. The proposed antenna has the characteristics of low profile, high efficiency, large coverage, and wideband, which is well suited for mobile satellite communication.

1 | INTRODUCTION

In recent years, the application of satellite services has been widely used in broadcast and information sharing networks such as digital broadcasting, television and the internet. Global positioning system and satellite services have high data rate and large data capacity, which are mostly working in the Ku-band [1, 2]. Many kinds of satellite communication (SATCOM) applications are created for a mobile environment such as cars, trains and airplanes. To satisfy the requirements of mobile platforms and reduce the impact of the environment, terminal antennas should have low-profile characteristics [3].

Unfortunately, the conventional mobile antenna systems, such as the classic parabolic system [4], the electromechanical scanning planar antenna array [5, 6] and the phased array [1], are not suitable for satellite service applications in mobile environments. For example, because of the high profile of the parabolic system, the wind resistance will affect the use of the antenna in the movement process. The structure of the electromechanical scanning planar antenna array is very complicated and the phased array antenna is very expensive and has large energy loss. Therefore, an antenna with high efficiency, high gain, low profile, low cost and beam scanning characteristics is needed for Ku-band mobile SATCOM system.

Continuous transverse stub (CTS) array [7] was proposed in the 1990s. Due to its good performance and stable manufacturing process, the CTS array is considered a good candidate for advanced antenna systems. The CTS array is with CTSs on the upper surface of the parallel plate waveguide (PPW). The transverse electromagnetic (TEM) mode planar wave is incident from the side of the PPW and radiated to the free space through the stubs [8, 9]. Radiation stubs have many advantages such as wideband, high radiation efficiency, low loss and compact structure. The CTS array is linearly polarized based on its radiation mechanism. Circular polarized operation can be achieved using a classical polarizer [10].
CTS multi-beam antenna based on a parabolic reflector has been reported in [11–13]. Although this kind of antennas has high performance and low cost, its size is very large due to the structure of the feeding network. A rotatable ridge waveguide slot array (RWSA) is used as a line source to feed a CTS array [14]. A beam-scanning capability of ±30° can be obtained by rotating the RWSA. In [15], a CTS array using a new line source generator is introduced. However, all the CTS arrays reported above are parallel feed, which causes a high profile. Variable inclination continuous transverse stub (VICTS) arrays with compact series-feed structures are proposed in [16–18]. Furthermore, a non-uniform slow-wave structure is reported in [19–20], but its beam direction varies with frequency.

A VICTS array based on CTS array technology is designed for the mobile SATCOM. The antenna consists of a CTS array and an LSG. A coplanar non-contact body allows the CTS array to rotate relatively, which has the advantages of low inertia, high mechanical flexibility, low cost and high efficiency. The motor torque is 1/5–1/10 of the reflector antenna, and it is easy to reach an angular velocity of over 600°/s. Thanks to its all-metal structure, the antenna can also work normally in harsh environments. Finally, the antenna is manufactured and measured. The simulation and measurement results are in good agreement. The proposed VICTS antenna will be a good candidate for future mobile SATCOM applications.

This work is organized as follows. Section 2 describes the antenna system. The structure of the antenna is introduced in Section 3. The prototype of the antenna and the comparison of the simulation and measurement results are described in Section 4. Finally, the conclusion is given in Section 5.

2 | VICTS ARRAY SYSTEM

The proposed CTS array system is shown in Figure 1. The system consists of two parts: (1) quasi-TEM LSG in the lower layer (pillbox transition) and (2) radiation part (CTS array). These two parts are individually mounted on a pair of rotatable concentric discs. The system does not have a phase shifter and the relative rotation of the two parts provides a phase gradient through the radiation part. Thus, a continuous beam can be generated in the upper hemisphere.

2.1 | Antenna mode of operation

Considering the LSG in the lower layer is fixed, the incident angle of the plane wave remains constant. And the upper CTS radiating part is rotated at an angle of \( \varphi_1 \), as shown in Figure 2. In a spherical coordinate system, the \( x \) and \( y \) components of the wavenumber \( k \) of the wave propagating in the PPW are given by [21]:

\[
k_x = \frac{2\pi}{\lambda_g} \sin \varphi_1
\]

(1)

where \( \lambda_g \) is the waveguide wavelength of PPW. In the spherical coordinate system \( x_0y_0z \), which is rotated together with the CTS array, the directional cosines are:

\[
\cos \theta_x = \sin \theta \cos \varphi_1
\]

(3)

\[
\cos \theta_y = \sin \theta \sin \varphi_1
\]

(4)

The phase relationship of the pointing angle of the main beam is given by:
\[ \cos \theta_x = \frac{k_x}{k_0} = \frac{\lambda_0}{\lambda_g} \sin \varphi_1 \] (5)
\[ \cos \theta_y = \frac{k_y}{k_0} = \frac{2\pi}{k_0d} \left( \frac{d}{\lambda_g} \cos \varphi_1 - 1 \right) = \frac{\lambda_0}{d} \] (6)

where \( d \) is the spacing of the periodic radiation slots. From the above formulas, the direction of the main beam is given by:

\[ \varphi_s = \tan^{-1} \left( \frac{\cos \theta_y}{\cos \theta_x} \right) \] (7)
\[ \theta = \sin^{-1} \left( \frac{\cos \theta_x}{\cos \varphi_1} \right) \] (8)

When the global coordinate system \( \text{xOy} \) attached to the PPW is put into consideration, it is worth mentioning that the angle \( \varphi_s \) should be increased by a rotation angle \( \varphi_1 (\varphi = \varphi_s + \varphi_1) \). So far, the corresponding relationship between the direction of the main beam and the rotation angle \( \varphi_1 \) can be obtained.

2.2 Antenna radiation pattern

VICTS array uses CTS as the radiation source, which can be approximated by a discrete point source. Based on array synthesis, point sampling of the CTS array was carried out. As shown in Figure 3(a), the VICTS array has \( M \) rows along the \( x \)-axis direction with a spacing of \( dx \), and \( N \) columns along the \( y \)-axis direction with a spacing of \( dy \). The \( +y \) direction is the propagation direction of the wave generated by LSG. An equivalent array of discrete point sources is used to describe the radiation characteristics of the VICTS array. The spacing of the equivalent radiation point sources increases (Figure 3(b)) with the relative rotation of the LSG and the CTS array. Due to the increase in spacing, the sampling points shown in Figure 3(b) cannot accurately describe the radiation characteristics of the VICTS array. So it is necessary to be encrypted. The row and column spacing of the discrete point sources can be represented by element spacing \( d \) and rotation angle \( \varphi \):

\[ d_x = d / \sin \varphi, \quad d_y = d / \cos \varphi \] (9)

The direction cosine of the observation vector \( P(r, \theta, \varphi) \) is defined as:

\[ u = \sin \theta \cos \varphi, \quad v = \sin \theta \sin \varphi \] (10)

And \( u_0 \) and \( v_0 \) are the locations in space at which constructive interference from all the array elements occurs.

When the method of encrypted sampling points is applied by \( Q \) times, the original spacing of sampling points is reduced to its \( 1/2^Q \) along the \( x_0 \) axis, as shown in Figure 3(c). By superposing all the sampling points’ radiation pattern, the array factor of the whole discrete array can be fully expressed as [22]

\[ AF \approx \frac{1}{2^Q MN} \frac{\sin[Mkd_x(u-u_0)/2]}{\sin[kd_x(u-u_0)/2]} \frac{\sin[Nkd_y(v-v_0)/2]}{\sin[kd_y(v-v_0)/2]} \]

As shown in Figure 4(a), the relationship between the scanning angle \( \theta \) and the rotation angle \( \varphi_1 \), because of the symmetrical antenna structure, the relationship between rotation angle and scanning angle is also symmetric.

Finally, the azimuth scanning of the beam is realized by rotating the VICTS system. The rotation angle \( \beta \) is shown in Figure 4(b). In this way, a continuous beam is generated in the upper hemisphere.

**Figure 3** The equivalent discrete point source array of VICTS array. (a) VICTS array with the rotation angle of \( \theta \), (b) VICTS arrays with the rotating angle of \( \varphi \) and (c) VICTS arrays with the rotation angle of \( \varphi \) and encrypted sampling points
3 | ANTENNA BUILDING BLOCKS

3.1 | Radiating part

When designing the VICTS radiating element, the height of PPW is fixed. The radiation energy can be controlled by adjusting the width of the stub. With stub growing wider, the radiation energy increases, but the matching condition becomes worse. If the reflection coefficient of the element is too high, the radiation pattern of the array will be affected. Therefore, we introduce a matching branch next to each stub, as shown in Figure 5. The matching branch is located after the stub, which is also connected with the PPW and shorted at the end.

To suppress the occurrence of grating lobes, radiation unit pairs are introduced to design the VICTS element. Thus, the periodic spacing of CTS units is reduced \( d = \frac{\lambda_g}{2} \), and the aperture efficiency can be improved. Then, a 10-element VICTS array is accomplished here. To achieve a high gain performance, all the elements are excited by signals with equal amplitude and phase. The height of the PPW is set to 8 mm, stub height \( l = 5 \) mm, radiating slot width \( B_r = 5 \) mm, and depth \( D_r = 5 \) mm. The VICTS element is optimized with ANSYS HFSS. Parameters after simulation optimization at 12 GHz are shown in Table 1. It is worth mentioning that the last radiating element (#10) is optimized to radiate the residual energy.

3.2 | Linear source generator

To guarantee the broadband characteristic of the antenna, we use a pillbox antenna as the LSG. As shown in Figure 6, the LSG consists of an H-plane horn and a pillbox transition. And the cylindrical wave generated by the H-plane horn is converted into the plane wave by pillbox transition. The H-plane horn and the pillbox transition are designed respectively here.

3.2.1 | Design of H-plane horn

The H-plane horn antenna consists of a uniform waveguide and a horn. It is used in the design as the feeding structure thanks to the characteristics of simple structure, low loss and low profile. And it is connected with a standard WR-75 rectangular waveguide. The final dimensions of the H-plane horn are shown in Figure 6(b).

| Table 1 Parameters for the proposed antenna |
|--------------------------------------------|
| Element | \( P_{rad} (%) \) | \( H \) (mm) | \( d \) (mm) | \( C \) (mm) | \( B_r \) (mm) | \( C_r \) (mm) |
|---------|----------------|-----------|------------|----------|-------------|-------------|
| #1      | 10.0           | 0.89      | 9.5        | 1.5      | 1.2         | 0.6         |
| #2      | 11.1           | 0.99      | 9.5        | 1.7      | 1.2         | 0.6         |
| #3      | 12.5           | 1.12      | 9.5        | 1.9      | 1.2         | 0.7         |
| #4      | 14.3           | 1.28      | 9.5        | 2.2      | 1.2         | 0.7         |
| #5      | 16.7           | 1.54      | 9.7        | 2.4      | 1.1         | 0.9         |
| #6      | 20.0           | 1.91      | 9.7        | 2.4      | 1.1         | 1           |
| #7      | 25.0           | 2.53      | 9.7        | 2.7      | 1           | 1           |
| #8      | 33.3           | 3.58      | 9.7        | 3        | 1           | 1.1         |
| #9      | 50.0           | 5.46      | 9.4        | 3.5      | 0.8         | 1.6         |
| #10     | 100            | 8.23      | 9.3        | 4        | 0.8         | 2           |

**Figure 4** Theoretical calculation. (a) The relationship between scanning angle \( \theta \) and rotation angle \( \varphi \) at frequency 12 GHz and (b) continuous beam is generated in the upper hemisphere

**Figure 5** E-plane cross-section of radiating element pairs
3.2.2 | Design of pillbox transition

The plane wave formed by the pillbox transition is used to excite the CTS array. Based on the theory of the front-feed parabolic reflector antenna, the geometric structure of the pillbox is analysed. As shown in Figure 6(b), the phase centre of the H-plane horn coincides with the focus F. According to the PO method, the electromagnetic waves transmitted from the horn will be reflected parallel to the OF axis by the paraboloid. So that the original cylindrical wave can be transformed into a planar wave.

The double-layer pillbox transition, which consists of two stacked PPWs coupled by a long slot of width 24.5 mm, provides the VICTS array a line source. The common metal plate between two stacked PPWs has a thickness of 1 mm. In the lower PPW, the cylindrical TEM mode transmitted by the H-plane horn is converted to a planar mode. Then, the plane wave is coupled into the upper PPW through the long slot. Finally, the desired line source is provided for the series-parallel hybrid CTS array. We design the pillbox transition following the guidelines provided in [11] and [23]. The focal distance of the pillbox transition is $f = 4.5\lambda_0 = 112.5$ mm, and the diameter of the aperture $D = 10\lambda_0 = 250$ mm. To improve the match condition, three-step transitions are applied between the upper PPW and the corporate-feed network.
4 | PROTOTYPE AND MEASUREMENTS

To verify the high efficiency and high angle beam scanning characteristics of the proposed VICTS antenna, the antenna is fabricated and measured. There is a good agreement between the simulation results and the measurement results. Figure 7 shows a photograph of the fabricated antenna. At the bottom, a Ku-band standard waveguide (WR-75) is connected with the LGS. The antenna has a planar structure with a total thickness of 42.4 mm (1.69 λ0).

Comparisons between the simulated and the measured performances are given below. All the simulations have been accomplished by ANSYS HFSS. The continuous rotating movement between the two components of the antenna ranges from −50° to 50°. Relying on the antenna’s symmetrical structure, its performance only needs to be measured at an angle of ϕ1 ranging from 0° to 50°, with a step of 10°.

4.1 | Scattering parameters

The reflection coefficient was measured using an Agilent N5230A. The simulated and measured reflection coefficients at the input port are shown in Figure 8. There is a good agreement between the simulation results and the measurement results. As Figure 8(b) shows, when ϕ1 = 0°, the measured −10 dB impedance bandwidth is 16% (11–12.9 GHz). When the antenna is rotated and ϕ1 ≠ 0°, the impedance bandwidth becomes a little less.

4.2 | Radiation patterns

The antenna is also measured in a microwave anechoic chamber environment. In a microwave anechoic chamber, the radiation characteristics of the antenna are measured by the plane near-field measurement method. Put the antenna is installed on the test bench. The tested antenna is a transmitting antenna, and the standard probe (WR75) receives the signal. Plane near-field measurement is a high-precision, multifunction, automatic measurement equipment. The antenna to be tested is erected on the test turntable with the antenna facing the sampling rack. Before testing the antenna to be tested, adjust each axis of the turntable to ensure that the antenna array plane is vertical to the ground and the antenna aperture is parallel to the scanning surface of the probe.

When ϕ1 = 0°, the simulated and measured radiation patterns in E- and H-planes at f = 12 GHz are shown in
Figure 9. Good agreements between measurement and simulation are obtained in both E- and H-planes. The measured 3 dB beamwidth is 5.2° and 6.8° in E- and H-planes, respectively. In the E-plane, the sidelobe level (SLL) is determined by the series-fed CTS radiating section and the matching branch. To achieve high-efficiency characteristics, a uniform amplitude in-phase design is used here, and the measured SLL is −14 dB. In the H-plane, the excitation provided by the pillbox transition could guarantee a good taper design, and the SLL is lower than −23 dB. The cross-polarization levels measured in the two planes are below −42 dB (peak-to-peak).

The simulated and measured scanning performance in the H-plane at the design frequency $f = 12$ GHz are shown in Figure 10. A delightful agreement is obtained between the simulated and measured results in the full scanning range. Figure 11 and 12 shows a comparison of the measured and theoretical beam directions $(\theta_m, \phi_m)$ varying with $\phi_1$. The theoretical beam directions are derived from the array synthesis.
the simulation.

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and 10 gain is also measured to obtain the gain of the designed antenna.
The measured gain and aperture area are shown in Figure 13, where the simulated gain is given for comparison.

5 | CONCLUSION AND DISCUSSION

A Ku-band flat VICTS array is proposed in this communication. The antenna has the advantages of low profile, wide-band and large coverage. Based on array synthesis encryption sampling technology, the relationship between the mechanical rotation and the beam pointing can be quickly predicted. The simulation and measurement results are in good agreement. The measured –10 dB impedance bandwidth is around 16% in the rotation range (0°–50°). In the H-plane, its scanning capability can be strengthened up to ±56°. At 12 GHz, the SLL of the E-plane is lower than –12.5 dB in the scanning range of ±56°. When φ₁ = 0° and φ₁ = 50°, the measured antenna gains are 30.1 dBi with 67.4% aperture efficiency and 22.3 dBi with 11.2% aperture efficiency. The high gain and high efficiency of the whole scanning range demonstrate the fantastic performance of the designed antenna.

The measured radiation performance of the VICTS at different rotating angle φ is summarized in Table 2. Table 2 shows the beam-scanning, SLL, gain and aperture efficiency. A comprehensive performance comparison between the reported works and the proposed antenna is shown in Table 3. All five antennas have beam scanning characteristics. Compared with the VICTS antenna designed in [18], the proposed antenna adopts the series-parallel hybrid feeding structure to broaden the impedance bandwidth. Considering the diameter of the whole aperture is 86 mm, the radiation efficiency of the antenna introduced in [18] is only 28%. The
The designed antenna improves the effective area of the aperture, resulting in a higher aperture efficiency. At the same time, the total thickness of the antenna is reduced to 1.69 * λ0 using the pillbox transition as the LSG.

The designed antenna is very suitable for mobile SATCOM applications, requiring wide bandwidth, large coverage and continuous beam scanning. Compared with an expensive and complicated phased array, it is a cost-effective solution for the problem of beam scanning. The proposed VICTS antenna will be a good candidate for future mobile SATCOM applications.

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**TABLE 3** Comparison between the reported works and the proposed antenna

| References | Antenna type | Bandwidth (GHz) | Fabrication complexity | Scanning angle (°) | Radiation efficiency |
|------------|--------------|-----------------|------------------------|-------------------|----------------------|
| [11]       | CTS          | 27.5–31         | Medium                 | −40~−40           | N/A                  |
| [14]       | WG-CTS       | 15.3–15.8       | Medium                 | −30~−30           | 60%                  |
| [18]       | VICTS        | 57–65           | High                   | −60~−60           | 28%                  |
| [20]       | WG-CTS       | 26–42           | High                   | −56.2~2           | 63%                  |
| This work  | VICTS        | 11–12.9         | Medium                 | −56~−56           | 67%                  |

**FIGURE 13** Simulated and measured realized gain versus the rotating angle $\phi_1$.