High Gain Planar Antenna Arrays for Mobile Satellite Communications

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Abstract — Two large and low profile panel antenna arrays used as receiving and transmitting antennas for mobile satellite communications are described. The receiving and transmitting arrays have overall dimensions of 120×20.7×1.3 cm³ and 107.5×20.4×1.7 cm³, respectively, and exhibit high gains and adequate efficiencies due to integrated array designs. For the receiving panel array, a method using a number of high efficiency sub-arrays combined with a novel active integrated global feed network is proposed. For the transmitting panel array, a number of high efficiency sub-arrays together with a novel compact waveguide feed network is employed. Based on the above techniques, two large panel antenna arrays were successfully developed. We present detailed designs of the sub-arrays, the passive and active feed networks, and the vertical transitions. Simulated and experimental results show that the designed receiving and transmitting panel arrays achieve measured gains and efficiencies of 34.1 dBi, 48.2% and 33.5 dBi, 36.3%, respectively, in each band, which indicates that the proposed antenna panels are good candidates for future satellite communications applications.

Index Terms — mobile satellite communications, antenna array, feed network, ridge waveguide, vertical transition

I. INTRODUCTION

Owing to the demand of users on the move, the popularity of mobile satellite communication systems has increased steadily in recent years. The antennas of such systems are usually mounted on the top of vehicles so they must meet low profile requirements, while maintaining good electric performance including high gain, wideband, and low cross polarization. Steerable reflector or lens antennas with high gain and high aperture efficiency have been studied extensively in the past and successfully applied to many systems [1-5]. However, they tend to be large in volume and have too high a profile for many applications especially where high speed motion is involved. In contrast, flat panel antenna arrays can provide much lower profile and greater agility and, therefore, they have attracted attention in the design of mobile communication terminals. Generally speaking, the configuration of the element and feed network is a key part in a panel antenna design. Microstrip antennas have been extensively employed as the array element due to the advantages of compact size and ease of fabrication. To improve their performance, numerous techniques have been introduced such as using air substrate or cavity backed patches to raise antenna gain [6-8], using parasitic patches [9] or U-shaped slots embedded on the patch [10] to expand the bandwidth, and employing metamaterial [11] or multilayer substrates [12] to increase the radiation efficiency, to name just a few. Other types of elements employed for mobile satellite applications include printed dipoles [13-15], the quasi-Yagi [16], the Vivaldi antenna [17], the dielectric resonator antenna (DRA) [18], the comb-line antenna [19], the curl antenna [20] and the spiral antenna [21].

The radiation efficiency of an array antenna is normally much lower than that of a reflector antenna of comparable dimensions, especially when the antenna radiation aperture becomes very large as the insertion loss in the feed network becomes significant [22]. To alleviate the problem, much effort has gone into reducing loss such as employing low-loss waveguide in the design of the feed network [23-25]. To reduce the overall height of the antenna and simplify the transition from waveguide to antenna, the waveguide can be replaced by SIW (substrate integrate waveguide) as reported in [26-27]. A commercial product from Raysat Antenna System Company reported in [28] employed slot coupled antennas and a stripline feed network, of which the structure was in a “sandwich” form to reduce power dissipation. Active combination of sub-arrays is another way to compensate for the insertion loss at the price of cost. A Ku band phased array system for mobile satellite reception was reported in [29], where the antennas distributed in 17 sub-arrays were combined through a series of active components with a smart beamforming algorithm [30]. To reduce the number of active and controlled components, the receiver in [31] used the hybrid operation mechanism with a 45° inclination of the antenna array. Recently, the huge potential of LTCC technology in array designs was shown in [32-33], but...
II. ANTENNA IMPLEMENTATION

2.1 Antenna

Figure 2. The simulated S parameters of element.

In order to achieve high gain and dual polarization requirements, a stacked antenna structure is selected. Figure 1 shows the configuration of the proposed dual-polarized element, which consists of three substrate layers. All substrates have the same dielectric constant $\varepsilon_r=2.55$ and thickness $h=0.762\text{mm}$. The upper square patch with a side length of $a_1$ is printed on the upper substrate while the lower square patch with a side length of $a_2$ is on the middle substrate, where the distance between these two substrates is $h_0$. Two microstrip lines are employed to generate horizontal and vertical polarizations, respectively. They are separated by the ground plane to reduce the mutual coupling.

Based on the above antenna configuration, two antenna elements are designed to operate in 12.25-12.75GHz for the receiving band (R-antenna) and 14-14.5GHz for the transmitting band (T-antenna) respectively. The performance of the antennas was evaluated with CST MWS software. The simulated S parameters of the two antennas are shown in Figure 2. In the operating bands, the reflection coefficients of the two polarizations are less than -15dB, the isolation is greater than 20dB, and the gain is greater than 8dBi. The parameters of the antenna element are optimized to produce a good impedance matching and a high gain. The final optimized geometries of the R- and T-antenna are listed in Table I.

| TABLE I Optimized Parameters of the Elements |
|---------------------|-----|-----|-----|
|                     | $a_1$ | $a_2$ | $h$  | $h_0$ |
| R-antenna (mm)      | 3.4  | 3.4  | 0.762| 1     |
| T-antenna (mm)      | 3    | 3    | 0.762| 1.2   |

The feed network inside the sub-array is realized in the microstrip form. In the $2 \times 2$ sub-array design, an anti-phase technique is utilized, where two adjacent antenna elements are mirrored and the out-phase component is produced with a microstrip line. This technique is known to be effective for suppressing the cross-polarization radiation in the main-beam [34-37]. To reduce the microstrip line’s parasitic radiation, we adopt the concept reported in [38], where circular arc lines were used instead of right angle lines in the network.

Owing to the space constraint on vehicle roof-tops, the number of the antenna elements one can employ in the array is limited, which imposes restrictions on the gain of the antenna array. On the other hand, a high gain is required to maintain the link budget. Therefore, the challenges in the design of antennas for mobile satellite communication is to increase the efficiency of the array and at the same time maximize the antenna gain in a limited space. This is the main focus of the reported work.

We report in this article the design and experimental results of high gain and high efficiency stacked patch microstrip antenna arrays for receiving and transmitting in mobile satellite communications. They are fixed beam antennas for mechanical scanning. A high efficiency sub-array combined with a novel active global feed network is adopted in the receiving panel, while in the transmitting panel, a high efficiency sub-array is combined with a compact waveguide feed network. The configuration of the sub-array is based on a stacked microstrip patch antenna, in which a key feature is the microstrip feed network that assists to enhance gain and also has a vertical transition to allow the antenna to be integrated closely with RF components at the rear of the receiving panel. The active global feed network has been optimized to reduce insertion loss, to effectively eliminate the non-uniformity of sub-arrays, to increase isolation and to maintain compactness. In addition, a novel folded miniaturized ridge waveguide has been adopted in the transmitting panel, in which a coupling probe from waveguide to microstrip is designed to connect the waveguide to the antenna. Both the antenna panels have a low profile of less than 21cm, thus making it suitable for small mobile satellite communication terminals.

The remainder of the article is organized as follows. In Section 2, the configuration of the antenna is described where the commercial software package CST Microwave Studio (CST MWS) is employed to evaluate the performance. Based on the designed sub-arrays, the receiving and transmitting antenna panels are described in Section 3 and Section 4, respectively, where we focus on the design of the global feed network and its integration with the antenna sub-arrays. Finally, concluding remarks are made in Section 5.
Figure 4. Aperture efficiency of sub-array with different elements.

Figure 5. The simulated reflection and isolation results of the 48-element sub-array.

Figure 6. Vertical transition (a) structure, and (b) simulated S parameters.

Figure 7. Antenna panel with active synthesis.

2.2 Sub-array Distribution

Before a global feed network is added to the sub-arrays to form the final panel, the dimension of the sub-array must be considered carefully. Due to loss in the dielectric and also parasitic radiation, the feed network efficiency of the sub-array decreases as the number of elements increases. In Figure 4, the simulated efficiencies of sub-arrays with various numbers of elements are shown, taking into account the effect of the feed network. When the scale of the sub-array is small, such as 24-element or 48-element, the radiation efficiency is high, around 80%. However, the aperture efficiency reduces quickly to 70% and below once the number of elements exceeds 48 when the power loss in the feed network becomes higher. On the other hand, if the sub-array element number is too small, the global feed network becomes very complicated. Making the tradeoff between the efficiency and the overall system simplicity, we selected a 48-element sub-array to form the large panel array. The final designed feed network is based on the previously mentioned 2x2 feed networks, where both parallel and serial feeding techniques are employed to ensure the compactness of the feed network. The simulated result of the 48-array is shown in Figure 5. The reflection coefficient is maintained below -15dB, and the isolation improves to > 30dB.

2.3 Vertical Transition

The output of the sub-array is connected to RF components (LNA or waveguide) mounted at the rear of the array. One approach of realizing the connection is to employ side-feeds, but this requires an extra microstrip line extending to the edge of the substrate. Furthermore, a side mounted connector will increase the height of the antenna panel.

A possible alternative approach is to use a vertical transition. Mousavi, et al. [29] describe a simple transition that goes from the microstrip line to the C-CPW (conductor-back coplanar waveguide) and then to the coaxial line for the input port of LNA. This approach is not suitable for our design due to two reasons: firstly, a two-stage transition is required in the coaxial line for impedance matching; secondly, the soldering of the probe to the CPW is difficult since they are on the same side of the substrate. With these limitations in mind we adopted the vertical transition from the microstrip line to the CPW as shown in Figure 6.
Two arc stubs are loaded at the end of the coaxial line, with a section of the substrate removed. The stub length is slightly greater than the thickness of the substrate, so that the coaxial line can be inserted into the substrate and soldering is easily performed at the other side of the substrate. A parasitic capacitance effect can occur between the signal line and the outer shield, resulting in an increased reflection coefficient, but this can be reduced by properly selecting the width of the stubs. The insertion loss obtained by simulation is less than 0.3dB. Compared with the side-feed technique, the novel vertical transition simplifies the structure and avoids use of an extra section of the microstrip line.

### III. ACTIVE RECEIVING ARRAY

Based on the sub-array designed in Section 2, a panel design that is suitable for satellite reception in the band 12.25-12.75GHz is described in this section. Since the 16 sub-arrays are collinear, making the radiation aperture dimensions larger than $5\lambda_0$ (where $\lambda_0$ is the wavelength at the center frequency), active combination is used to compensate for the insertion loss in the global feed network, as shown in Figure 7. There are three challenges in this approach. Firstly, the connections between RF components and sub-arrays can cause further insertion loss and must be taken care of. Secondly, due to a number of factors such as fabrication imperfections, the outputs of different signal chains may not have the same phase, which affects the panel’s efficiency. Thirdly, the power coupling between each sub-array through the feed network may pose a serious threat to the active components and should be suppressed by some isolation units.

In the schematic shown in Figure 7, all arrows in the block diagram indicate connections. The conventional method realizes the connection through the standard SMA connectors (male or female), in which several defects exist:

1. The single arrow before the LNA in Figure 7 requires four SMA connectors, and their losses will reduce the radiation efficiency. Also, the connectors make the system bulky and increase its cost.

2. A total of 32 soft coaxial lines connected to the power combiner at the rear of the panel will increase the complexity of the structure, as well as the cost. Moreover, the stacked winding coaxial lines can potentially introduce cross talks.

3. The phase adjustment can only be performed by selecting coaxial lines of different lengths, which is another source of cost.

To avoid the problems mentioned above, one solution is to locate the LNAs, the output ports of the sub-arrays, and the global feed network on the same substrate and all connections/transitions are in planar circuit form as described below.

The LNAs are fabricated on the Rogers substrate with its ports in CPW form. To connect with the sub-arrays, the vertical transition described in Section 2.2 is applied once again in an inverse sense that is from the CPW to the coaxial line. The outputs of the LNAs are gradually transitioned to the microstrip line. All the ports are tuned to match to 50Ω impedance, so they can be connected directly.

The global network consists of microstrip and coaxial lines instead of the soft coaxial line, and the coaxial line is embedded in the substrate and the aluminum board. The transition between the microstrip and the coaxial line is realized by a section of CPW with its ground gradually expanded. The integration is shown in Figure 8. It can be seen that no standard connector, such as SMA, is used, and the feed network is printed on the substrate, making it very compact and easy for integration.

Another advantage of a microstrip global feed network is that the phase adjusting and the isolation units can be fabricated conveniently nearby. Although the performance of the sub-array and its connection to the global network has been optimized, the array panel may not reach its peak gain unless the phases of the sub-arrays are aligned. As mentioned before, the phase difference can be tuned by selecting coaxial lines of different length, or even using phase shifters. But the latter increases the loss and cost, and the precision is limited.

To overcome this difficulty, a defected microstrip structure is used for phase adjustment, which is easily applied in the available global network and has a high precision. It is inspired
TABLE II THE GAIN/LOSS OF THE COMPONENTS IN THE RECEIVING ARRAY

<table>
<thead>
<tr>
<th>Components</th>
<th>16 sub-arrays (dBi)</th>
<th>Vertical Transition (dB)</th>
<th>LNA (dB)</th>
<th>Combiner (dB)</th>
<th>Coaxial line (dB)</th>
<th>Active Array (dBi)</th>
<th>Passive Array (dBi)</th>
<th>Aperture radiation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>---</td>
<td>---</td>
<td>18.5</td>
<td>-6.3</td>
<td>-0.2</td>
<td>46.1</td>
<td>34.1</td>
<td>48.2%</td>
</tr>
<tr>
<td>Simulated</td>
<td>23+12</td>
<td>-0.25</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>34.75</td>
<td>55.9%</td>
</tr>
</tbody>
</table>

Figure 11. The assembled receiving panel antenna.

Figure 12. The farfield pattern of panel (a) horizontal polarization (b) vertical polarization.

by the idea that a slot in the microstrip line causes a phase delay. As shown in Figure 8, a series of C-shaped slots are etched in the microstrip line. The simulated phase delay values with different numbers of slots are also shown in Figure 9. It is seen that for a specific geometry one slot can provide about 3° phase delay, which means that 8 slots can provide a phase range of 24°. In the phase tuning process, slots are etched in the global feed network in advance. The channel phase is finely-tuned through filling up the slots by soldering according to the calibration method reported in [39] to realize the phase of each channel. The total insertion loss for 8 C-slots is about 0.3dB.

An isolation unit is required to prevent the coupled power from causing self-oscillation in the active components. In the receiving panel global network, the isolation is realized with a few isolation resistors in the power combiners, as shown in Figure 10. The resistor is loaded in the T-shaped combiner, where a small slot is open at the impedance transformer. This is based on the conventional structure of a Wilkinson power divider, with some modification so that it provides a good isolation and a compact size. The measured isolation between the two input ports is >20dB.

The final assembled receiving panel antenna is shown in Figure 11, with the sub-array and global feed network integrated on an aluminum board. The dimension of the panel is 120cm×20.7cm. The measured radiation patterns in the azimuth plane at 12.5GHz are shown in Figure 12.

It is seen that the first side-lobe on both sides of bore sight are about -14dB relative to beam peak. The cross-polarization level for both polarizations is <30dB. There are some far outside-lobes with a level of about -20dB for the H-polarization, which are probably due to the microstrip feed networks for the sub-arrays. These networks are printed on the same side as the patch antennas.

Based on the block diagram in Figure 13, a loss budget is given in Table II. The gain of the receiving panel array is measured by comparing with a standard horn, where the gain is recognized as the gain of the active array. Since the loss of the feed network and the coaxial line can be compensated for by the LNA for the active array, the estimated gain of the passive receiving panel array is about 34.1dBi. The simulated gain of sub-array is about 23dBi and the loss in the vertical transition is...
about 0.25dB, so the simulated gain of the passive receiving panel array is about 34.75dBi. The slight difference between the simulation and measurement results is mainly due to the inconsistency of different channels and test inaccuracies.

The antenna aperture efficiency is calculated from

\[
\eta_{\text{eff}} = \frac{G_{\text{measured}}}{G_{\text{max}}} \quad (1)
\]

where \(G_{\text{measured}}\) is the measured gain of the panel array and \(G_{\text{max}}\) is the maximum gain for a prescribed aperture area \(A\) [40] defined as

\[
G_{\text{max}} = \frac{4\pi A}{\lambda^2} \quad (2)
\]

A comparison with some available commercial satellite communication systems for comparable applications, from Raysat and TracStar, is summarized in Table III. The StealthRay2000/3000 series antenna contains three receiving antenna panels, which are combined using phased array techniques. From their patent description[41], the elements spacing is estimated to be about 0.8 \(\lambda_0\), the length of the three panels are 70cm, 70cm and 60cm, and the width is 8cm. The total aperture area is estimated to be 1600(70x8x2+60x8)cm², so the aperture efficiency is calculated to be about 26%. As the detail configuration of antennas RaySat-E7000 and TracStar450M is unavailable in the open literature, no estimate of the efficiency is given here. However, we estimated the efficiency of StealthRay2000, based on the antenna gain and aperture area, which is given in Table III for comparison with the proposed receiving panel antenna array.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>COMPARISON WITH AVAILABLE PRODUCTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product model</td>
<td>Dimensions (cm)</td>
</tr>
<tr>
<td>StealthRay 2000</td>
<td>115x90x15</td>
</tr>
<tr>
<td>StealthRay 3000</td>
<td>115x90x18</td>
</tr>
<tr>
<td>RaySat E7000</td>
<td>Φ130.0x30.0</td>
</tr>
<tr>
<td>TracStar i450M</td>
<td>Φ114.3x29.2</td>
</tr>
<tr>
<td>Proposed receiving panel</td>
<td>Φ130.0x23.0</td>
</tr>
</tbody>
</table>

IV. TRANSMITTING ARRAY

The transmitting array is designed to operate in the band of 14-14.5GHz. The antenna panel consists of 16 sub-arrays which are collinear. To obtain high gain and high efficiency, we adopted the high efficiency sub-arrays combined with a compact waveguide feed network. However, similar to the receiving panel, one challenge is the connection between the sub-arrays and the waveguide. Additional challenges include the design of a compact waveguide feed network which can be accommodated by the low profile antenna panel, and the nonconformity of sub-arrays. Facing the first challenge, a novel microstrip coupling probe which integrates the port of the sub-arrays with the waveguide directly is proposed, thus avoiding the need for connectors or transitions and making the system easier to integrate. The structure is illustrated in Figure 14(a).

An inverted trapezoidal window is opened in the ridge waveguide, as shown in Figure 14(a). The fan-shaped coupling probe is printed on a small substrate with its width gradually increasing to the 50Ω to match to the microstrip line. A coupling probe is inserted into the trapezoidal window on the wall of the waveguide, and the input power from the ridge waveguide is transmitted into the microstrip line through coupling. The sub-arrays are connected to the microstrip line through vertical transitions in a similar fashion to the receiving antenna. The reflection coefficient and insertion loss of the connection predicted by simulation are shown in Figure 14(b). The loss is about 0.25dB within the band. In addition, the phase adjusting unit developed for the receiving antenna is applied to the microstrip line in the coupling probe, where a serial of C-shaped slots are opened. In this way, the problem of nonconformity between the sub-arrays is solved without increasing system cost.

In the waveguide network design, we employed a miniaturized folded ridge waveguide network [42]. “Folded” here refers to bending or cascading the waveguides, aiming at minimizing the stretching directions of the dividers. Figure 15(a) shows the structure of ridged waveguide H-junction which is folded. The power transition is realized through a slot coupling, a structure developed by our group for wideband operation [42].
TABLE IV. THE GAIN/LOSS OF THE COMPONENTS IN THE TRANSMITTING ARRAY

<table>
<thead>
<tr>
<th>Components</th>
<th>Antenna Sub-array(dBi)</th>
<th>Vertical transition(dB)</th>
<th>Microstrip to waveguide Transition(dB)</th>
<th>Divider (dB)</th>
<th>Coaxial line(dB)</th>
<th>Passive Array(dBi)</th>
<th>Aperture radiation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>23.5+11.8</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-0.3</td>
<td>33.5</td>
<td>36.3%</td>
</tr>
<tr>
<td>Simulated</td>
<td>23.7+12</td>
<td>-0.25</td>
<td>-0.25</td>
<td>-0.7</td>
<td>-0.2</td>
<td>34.3</td>
<td>43.5%</td>
</tr>
</tbody>
</table>

Each of the 1 to 16 power dividers consists of several H-junctions. The height of the ridge waveguide network is 12.03mm, making it very compact to be attached to the back of the antenna panel. This network was tested using an Agilent 8722ES vector network analyzer and the measured results are shown in Figure 15(b). Within the operating band, it is seen that the reflection coefficient is almost below -15dB, except at isolated frequency points, and the average insertion loss is 0.9dB.

The backside of the transmitting antenna panel array is shown in Figure 16. The transmitting antenna was tested on an outdoor range. The far-field patterns obtained in the azimuth plane at 14.25GHz are given in Figure 17. The first side lobe is at about -12dBi relative to beam peak, which is slightly higher than the simulated one of -14dBi. This may be caused by the nonconformity of the sub-arrays and the imperfect fabrication of waveguides, as well as the test environment. By comparing the gain against a standard horn it was found that the transmitting antenna array has a gain of about 33.5dBi at 14.25GHz, and the corresponding aperture efficiency is 36.3%.

The small difference between them is likely due to fabrication error in the
components and their mechanical tolerance as well as inconsistence in the different channels.

To our knowledge, up to now, full passive panel antenna arrays at Ku band with an aperture length larger than 50λ₀ have not been reported in the open literature. Similarly to the receiving antenna, the proposed transmitting panel array is also compared with the available panel array products from different companies, as shown in Table V.

The StealthRay2000/3000 series contains one antenna panel for transmitting. Assuming the elements spacing is about 0.8λ₀, the size of the panel is 47cm×7cm, from which the aperture efficiency can be estimated to be about 53%. The present transmitting antenna has a lower efficiency but it should be noted that the antenna aperture area available is much greater than that of the StealthRay’s. The dimensions of the RaySat-E7000 and TracStar i450M antennas are unknown. They have higher gains but also have a greater height.

Both panel arrays are separated by about 40cm in the system, as shown in Figure 19. Figure 20 shows the simulated isolation between transmitting and receiving panel arrays, which is > 55dB. In addition, since the transmitting and receiving bands are separated by 1.25GHz, the PA and LNA can be chosen to have a good out-of-band suppression. No additional filter is used in the developed panel arrays.

V. CONCLUSION

The design of two high gain and high efficiency Ku-band antenna arrays for mobile communications is presented. One is used for transmitting and the other for receiving. The architecture of the antenna panels and the feed network have been optimized to reduce the feed loss caused by the large aperture dimensions. In particular, it is shown that, in the receiving array, the proposed vertical transition can reduce the insertion loss by avoiding the use of RF connectors. The defected microstrip structure can effectively compensate for the phase error to improve the combination efficiency. Whilst in the transmitting array, a folded miniaturized ridge waveguide has been adopted to improve the bandwidth of the feed network, and the microstrip coupling probe is used for connecting the waveguide and the antenna. The measured gain of the receiving and transmitting arrays at the center frequency of each band are 34.1dBi and 33.5dBi while the aperture efficiencies are 48.2% and 36.3%, respectively. Compared with similar antenna arrays, either better aperture efficiency or higher gain is achieved, which validated the effectiveness of proposed design method. Also, the system loaded with the proposed antenna panel has a low profile of 23cm, which is lower than the RaySat E7000 (whose height is 30cm) and TracStar i450M (whose height is 29.2cm) at a comparable gain; hence they are attractive for mobile satellite communication applications. The transmitting array has a lower efficiency than the receiving array since the gain was reduced by the insertion loss caused by minor fabrication and assembly errors, while in the receiving array the loss is alleviated by the active amplifiers. Therefore, in future work on large antenna array design, higher precision and more integrated fabrication process will be pursued to increase the gain of the array. In particular, in an active array design, the antenna can be regarded as a part of the active circuit so they can be integrated to achieve a significant improvement in performance.

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