Power Allocation Optimization of A Conformal Antenna Array for Satellite Applications

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***Abstract*—A power allocation optimization method of a conformal antenna array is proposed for L-band low Earth orbit (LEO) satellite applications. For a required effective isotropic radiated power (EIRP), the power consumption of the RF payload with optimized power allocation for antenna elements is greatly reduced, namely, up to 52% reduction compared with the one with single antenna excitation.**

***Index Terms*—LEO, power, conformal antenna array, payload, MIMO.**

I. INTRODUCTION

To meet the fast growth in demand for data services, environmental monitoring and overhead imagery, the number of low Earth orbit (LEO) satellites and related services have rocketed up. Due to the altitude limitation, the communication time of a LEO satellite to a ground station is limited. An inter-satellite link between a LEO satellite and a geosynchronous orbit (GEO) satellite or a medium Earth orbit (MEO) satellite is desired to increase the data transmission capabilities of LEO satellites, where the LEO satellite can transmit the data to the ground station anywhere/anytime via the GEO satellite as illustrated in Fig.1 [1]. In such satellite relay system, the LEO satellite is always required to direct to the GEO satellites for establishing a reliable transmission link, a conventional auto-tracking dish antenna with mechanical rotating structure is not suitable for the LEO satellite because of the size constraint. Instead, an electrical beam steering array antenna is more desirable. Furthermore, a conformal antenna array with wide coverage (±90° or more) is of more significance [2-5].

From operation point of view, the LEO satellite is expected to transmit data to GEO satellite anytime. The data transmission time period is much dependent on the power consumption of the RF payload. However, due to the size limitation, the capacity of the solar-power system of a LEO satellite, in particular, a CubeSat, is limited. The power shortage limits the operation time period of a LEO satellite severely, and therefore any power efficient solution/configuration is preferred for LEO satellite payload designs.

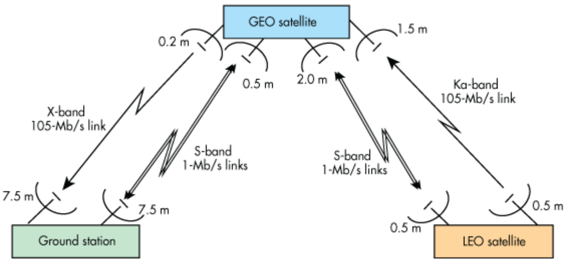
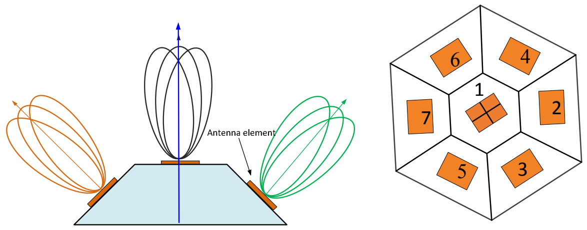


Fig. 1. The inter-satellite communication between LEO and GEO [1].

Unlike a conventional planar antenna array, the gain of each antenna element of a conformal antenna array is different at a specified direction, which offers the opportunity for optimizing power allocation for each antenna elements and thus reduce the total power consumption of the RF payload. Similar to the optimization of power allocation in Multiple-Input-Multiple-Output (MIMO) system with water-filling algorithm [6], the LEO-to-GEO link with a conformal antenna array on LEO satellite can be considered as a Multiple-Input and Single-Output (MISO) system and the optimization of the power allocation for power consumption reduction can be carried out accordingly.

II. BEAM STEERING CONFORMAL ANTENNA ARRAY

A compact beam steering L-band conformal antenna array for a LEO satellite is shown in Fig. 2. Seven meta-surface based wideband circularly polarized antenna elements are positioned on a truncated cone, a 6-bit phase shifter is connected to each antenna element for beam steering.



(a) (b)

Fig. 2. The L-band conformal antenna array; (a) cross-sectional view and (b) top view

With proper phase configuration, the antenna array is able to provide a full semi-spherical coverage of θ=±90° with antenna gain of greater than 5 dBic.

III. PRINCIPLE OF POWER ALLOCATION OPTIMIZATION

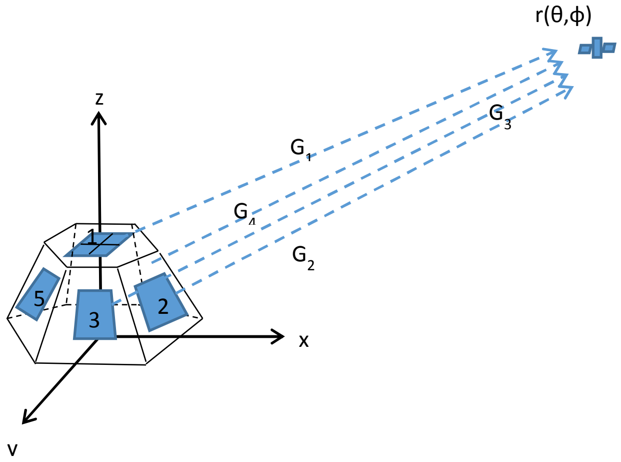


Fig. 3. The LEO and GEO link.

Fig. 3 shows the LEO and GEO link where GEO satellite is at a specified location of r(θ, φ). The electric-field intensity of the nth antenna can be defined as Eq. 1 [7].

$$E_{antn}\,(r,\theta,\varphi) = \sqrt{\frac{2\eta P_n G_n}{4\pi r^2}} \tag{1}$$

where, η: intrinsic impedance of the medium

P_n: input power of the nth antenna element

G_n: gain of the nth antenna element

To meet the required signal-to-noise ratio (SNR) for a specific link budget, the effective isotropic radiated power (EIRP) of the LEO satellite should be greater than a certain level, and the related electric-field intensity, E_{req} can be described as in Eq. 2.

$$E_{req} = \sqrt{\frac{2\eta EIRP_{req}}{4\pi r^2}} = E_{ant\,1} + E_{ant\,2} + \cdots + E_{antn} \tag{2}$$

From (1) and (2),

$$\sqrt{EIRP_{req}} = \sqrt{P_1 G_1} + \sqrt{P_2 G_2} + \cdots + \sqrt{P_n G_n} \tag{3}$$

n: element number of the conformal antenna array

The total input power of the conformal antenna array can be calculated by Eq. 4 as below.

$$P = P_1 + P_2 + \cdots + P_n \tag{4}$$

The Lagrange function of Eq. 4 is expressed as below.

$$\mathcal{L}(P_1, P_2, \dots, P_n, \lambda) = P_1 + P_2 + \cdots + P_n + \lambda(\sqrt{P_1 G_1} + \sqrt{P_2 G_2} + \cdots + \sqrt{P_n G_n} - \sqrt{EIRP_{req}}) \tag{5}$$

λ: Lagrange multiplier

The gradient of Eq. 5 is expressed as given below.

$$\nabla_{P_1,P_2,\dots,P_n,\lambda}\mathcal{L}(P_1, P_2, \dots, P_n, \lambda) = \left(\frac{\partial\mathcal{L}}{\partial P_1}, \frac{\partial\mathcal{L}}{\partial P_2}, \dots, \frac{\partial\mathcal{L}}{\partial P_n}\right) = 0 \tag{6}$$

From Eq. 6, the optimized input power of each antenna can be defined as given below in Eq. 7.

$$\begin{aligned} P_1 &= EIRP_{req}\frac{G_1}{(G_1 + G_2 + \cdots + G_n)^2} \\ P_2 &= EIRP_{req}\frac{G_2}{(G_1 + G_2 + \cdots + G_n)^2} \\ &\quad\vdots \\ P_n &= EIRP_{req}\frac{G_n}{(G_1 + G_2 + \cdots + G_n)^2} \end{aligned} \tag{7}$$

The simulated gain of antenna elements 1 to 7 at 1.6 GHz at $\theta = 60^{\circ}$, $\varphi = 0^{\circ}$ are listed in Table I. The Ant 2 shows the greatest gain of 6.27 dBic and the Ant 7 features the smallest gain of -9.36 dBic. Assume the required $EIRP_{req} = 40$ dBm, the input power for single antenna element and the combinations, namely, 1 to 7, 1+2, 1+2+3, 1+2+3+4, 1+2+3+4+5, 1+2+3+4+5+6 and 1+2+3+4+5+6+7 are calculated and tabulated in Table I. Taking the input power of the single antenna element, Ant 2, that is with the highest gain, as a reference, $P_2 = 33.73$ dBm, the relative power consumption ratio of the different antenna elements as well as the combinations are also given in Table I.

For single antenna element, it is obviously the excitation of the Ant 2 offers the lowest power consumption since it is with the greatest gain at $\theta = 60^{\circ}$, $\varphi = 0^{\circ}$. Compared with Ant 2, all the other antenna elements need much higher input power to achieve identical EIRP. On the other hand, the combined configuration with multiple antenna elements excitation requires less input power for same EIRP and therefore achieves power consumption reduction. For example, the configuration of antenna elements 1+ 2+ 3 is able to reduce the power consumption by 40%. The combinations with more antenna elements can reduce the power consumption further, while it is worth to note that the configuration with all antenna elements is not applicable from system point of view. First, switching on those low gain antenna elements may increase the power consumption of the whole system because the power-added efficiency (PAE) is reduced when the output power of the power amplifier (PA) is reduced and the unavoidable driving stage power consumption of the power amplifiers cannot compensate the little contribution of the antenna elements to the array. Second, a transmitting antenna is generally required to meet a regulated pattern profile, which limits the selection of the antenna elements as well.

IV. MEASUREMENT RESULTS

The photo of L-band conformal antenna array is shown in Fig. 4. The meta-surface based circularly polarized conformal phase array antenna targets to offer a semi-spherical coverage with combined antenna gain of greater than 5 dBic at L-band of 1.5-1.7 GHz. The measurement set-up is illustrated in Fig. 5. Fig. 5(a) shows the schematic configuration of the antenna array, two 5-bit 15-dB digital attenuators and a 6-bit digital phase shifter are applied to adjust the input power and phase of each antenna element respectively. Fig. 5(b) exhibits the measurement system configuration. The conformal antenna array is used for transmitting signal and connected to a signal generator. A horn antenna is for receiving and connected to a spectrum analyzer. A low noise amplifier (LNA) is utilized to enhance the dynamic range of the measurement systems. The conformal antenna array is positioned on a turntable so that a specific direction can be tuned automatically by a turntable controller. All the measurements are carried out at 1.6 GHz in a full anechoic chamber. In the measurement, only the Ant 1 to Ant 4 are considered to be the array combination. The other antenna elements, namely, Ant 5 to Ant 7, are not excited as the gains of the antenna elements are less than -5 dBic at $r(60^{\circ}, 0^{\circ})$. The measured gains of Ant 1 to Ant 4 at 1.6 GHz are listed in TABLE II. Note that the measured gains of the antenna elements are slightly different from the simulations because the mutual couple effect between the antenna elements is not accounted in the simulation.

The lowest gain is 0.2 dBic of the antenna 1, and its input power of -33.18 dBm when the attenuation of the two digital attenuators are set to zero. Thus the $EIRP_{req}$ is set to -32.98 dBm to make use of the digital attenuators of the other higher gain antenna elements (2 to 4) to modify their input powers. Based on the preset $EIRP_{req}$, the particular antenna element combinations as described in Table I were measured and the measurement results are listed in Table II, the power consumption performance is compared with the highest gain antenna element, antenna 2.

V. CONCLUSION

A power allocation optimization method for the conformal antenna array at the L-Band for LEO satellite has been studied and validated by measurements. Based on the simulated and measured results, it is concluded that the combined antenna element configuration is able to achieve a specific EIRP with less input power and thus reduce the power consumption. Compared with the single element excitation, the power consumption of the optimized combined configuration features a reduction up to 52%, which will be great promising for small/micro-satellite and CubeSat systems.

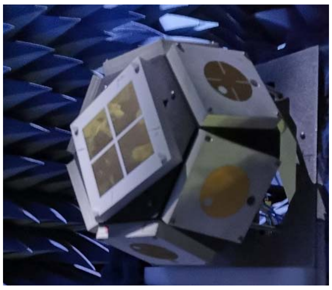


Fig. 4. L-Band conformal antenna array prototype in anechoic chamber.

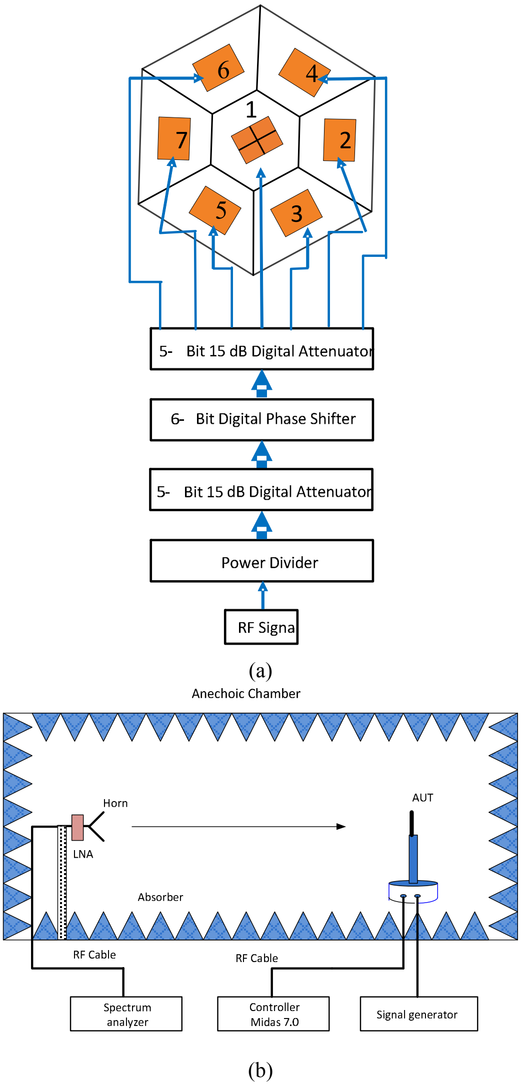


Fig. 5. The measurement setup, (a) Schematic configuration of the antenna array and (b) measurement system configuration.

REFERENCES

[1] V. Sambasiva Rao, “Extend LEO Downlinks with GEO Satellites,” *Microwave and RF*, Nov 30, 2016.

[2] N. Karmakar and M. Bialkowski, “A compact switched-beam array antenna for mobile satellite communications,” *Microwave and Optical Technology Letters*, vol. 21, no. 3, pp. 186–191, 1999.

[3] N. Karmakar and M. Bialkowski, “A low cost switched beam array antenna for L-Band land mobile satellite communications in Australia,“ *Proc. IEEE Vehicular Technology Conf.* 1997, pp. 2226–29, 1997.

[4] Q. Wang, M. Lecours, and C. Vergnolle, “Optimization of switches for radial satellite antenna array applications,“ *Sixth Int. Mobile Satellite Conference*, Ottawa, Canada, pp. 393–397, June 1999.

[5] S. Jellet, M. Bialkowski, and R. Varnes, “An L-band vehicle mounted cylindrical array for satellite communications,“ *IEEE ICCS*, pp. 710–14, Singapore, India, 1994.

[6] A.F. Molisch, *WIRELESS COMMUNICATIONS, 2nd Edition*, 2011 John Wiley & Sons Ltd.

[7] C.A. Balanis, *Antenna Theory: Analysis and Design, 3th Edition*, John Wiley & Sons, Inc., 2005.

TABLE I. SIMULATED GAIN AND INPUT POWER OF ELEMENT 1 TO 7 AND COMBINATIONS @ $\Theta = 60^{o}$, $\Phi = 0^{o}$

EIRP= 40dBm

Antenna Elements and Combination	**Gain (dBic)**	**Input Power (dBm)**								**Power Consumption (%)**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**Sum**	
1	1.55	38.45							38.45	296.5
2	6.27		33.73						33.73	100.0
3	1.33			38.67					38.67	311.9
4	1.93				38.07				38.07	271.6
5	-5.59					45.59			45.59	1534.6
6	-5.29						45.29		45.29	1432.2
7	-9.26							49.26	49.26	3572.7
1+2		26.5	31.2						32.5	75.3
1+2+3		24.6	29.3	24.4					31.5	59.8
1+2+3+4		22.9	27.6	22.7	23.3				30.7	49.8
1+2+3+4+5		22.6	27.3	22.4	23.0	15.5			30.5	47.5
1+2+3+4+5+6		22.3	27.0	22.1	22.7	15.2	15.5		30.4	46.5
1+2+3+4+5+6+7		22.2	26.9	22.0	22.6	15.1	15.4	11.4	30.3	45.4

TABLE II. GAIN AND INPUT POWER OF ELEMENT 1 TO 4 AND COMBINATIONS @ $\Theta = 60^{o}$, $\Phi = 0^{o}$

Antenna Elements and Combination	**Gain (dBic)**	**Input Power (dBm)**					**Power Consumption (%)**
		1	**2**	**3**	**4**	**Sum**	
1	0.2	-33.18				-33.18	571.5
2	7.78		-40.75			-40.75	100.0
3	4.01			-36.99		-36.99	237.7
4	4.87				-37.85	-37.85	195.0
1+2		-49.7	-42.2			-41.5	84.1
1+2+3		-52.4	-48.6	-44.8		-42.8	62.4
1+2+3+4		-54.8	-51	-47.2	-50.1	-44.0	47.3