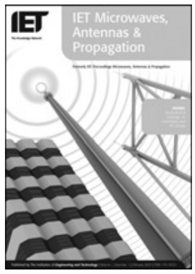
Published in IET Microwaves, Antennas & Propagation
Received on 9th December 2007
Revised on 11th March 2008
doi: 10.1049/iet-map:20070311



ISSN 1751-8725

# Theoretical and experimental study on a partially driven array antenna with simplified dipole elements

M. Okumura[1] T. Imura[2] Y. Kamata[3] N. Kamo[4]
A. Sugawara[3] T. Takano[5]

[1]East Japan Railway Co., 2-2-2 Yoyogi, Sibuya-ku 151-8578, Japan
[2]University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[3]Japan Aerospace Exploration Agency, 3-1-1 Yoshino-dai, Sagamihara 229-8510, Japan
[4]NTT docomo, 449-1 Minami-ohhata, Niigata 951-8107, Japan
[5]Nihon University, 7-24-1 Narashino-dai, Funabashi 274-8501, Japan
E-mail: ttakano@isas.jaxa.jp

**Abstract:** A novel design is proposed to reduce the number of driven elements by replacing them with passive elements or wires in an array antenna. The study is based on the analysis of electromagnetic wave fields by considering of the coupling between the half-wavelength dipoles. An array antenna of two driven elements and two passive elements is considered as a model. After optimising the element arrangement, the antenna gain can match that of the equivalent four-driven element case. The simulation result is confirmed by an experiment that uses dipoles with simplified matching technique. Feeding networks in a high-power radiating system are analysed in terms of the length and matching of feed lines, and the number of amplifiers.

## 1 Introduction

An array antenna (AA) of a broadside type has excellent features in its extension from a radiating element to a large aperture in order to obtain a higher gain or a shaped radiation pattern. The AA is widely used in relatively simple systems. Especially, a phased-array antenna (PAA) has a significant capability of beam scan in addition to the features of an AA, and is used widely in radars [1, 2], or satellite tracking [3]. The PAA is attractive because of the beam agility for the fields of satellite communications and broadcast reception [4, 5], remote sensing [6] and is put into actual utilisation in communication systems although in small numbers [7, 8]. Also, the PAA is assumed to be a possible scheme to realise quite a large aperture and beam agility for microwave power transmission systems (MPTS) [9, 10]. The problem of PAA is the complexity of an antenna in comparison with other kinds of antennas, such as a reflector antenna with a mechanical scanning capability. In a PAA, the array aperture should be divided by a number of radiating elements. And each element should be attached with the associated electronic circuit such as a phase shifter and an amplifier if necessary, and should be connected through a feeding network to a single signal source in a transmission case or to a single detector in a reception case, respectively. As the elements in an AA increases, more feed circuits are required. Accordingly, the whole system becomes more complex. Up to now, many attempts to use PAA in communications have been studied to make an advanced radio communication system because of the agility of beam scan, but almost all have failed. The reasons might be its disadvantages in: (1) cost, (2) weight and size, (3) power consumption.

Recently, several new attempts were proposed to overcome the above-mentioned disadvantages of PAA and to put them to practical applications. A thinning technique or a sparse array was studied because the antenna gain decreases less than the thinning ratio, namely the ratio of the driven elements to the original and total elements [11–13]. Another attempt is to


© The Institution of Engineering and Technology 2008

realise the desired field distribution on an array aperture by using the identical elements and electronics [14]. The elements are allocated on the aperture with periodic spacings. Accordingly, the radiation pattern is improved with a slight gain reduction from the maximal gain obtained with the same number of elements. In these cases, all elements should be fed and the antenna gain is almost limited by the number of elements.

In order to solve the above-mentioned disadvantages of PAA, a novel way is proposed to simplify the structure of a broadside AA by replacing driven elements with passive elements, which are actually conducting rods or wires. Accordingly, the number of driven elements can be reduced to a half, so that the associated electronic circuits and feed networks can be omitted to a half. This scheme may be called a partial drive technique, and effective to eventually realise a practical PAA. One may recall this as a way of using passive elements or omitted elements in a large AA; a thinning technique that is used to moderate side lobes in the AA pattern. In the thinning technique, however, only a few percent of the elements are omitted. And as the passive elements are terminated, the antenna gain is almost reduced according to the thinning ratio. Instead, the partial drive is a more aggressive way of element reduction using the coupling effect.

The coupling effects were analysed, mostly for the purpose of reducing or compensating the coupling [15–17]. But there were also several examples to positively utilise the coupling effects. For example, Yagi-Uda antenna utilises a driven element and the associated passive elements which are called reflectors and directors, although the radiation direction is an endfire type [18]. Also, an endfire AA with three dipole elements was attached with two coupled passive elements on both sides [19]. A microstrip array with one driven element and four passive elements was proposed [20]. These cases are not appropriate to be applied to ultra-large antennas because of three-dimensional structures. Also, a broadside array with one driven element and two passive elements (suppressors) on both sides was analysed where each element is a half-wavelength dipole [21]. The gain was improved to 7.06 dBi when the separation between the driven and passive elements is 0.65λ (λ is the wavelength in free space). The objective is to lead to a five-element AA to improve a Yagi-Uda array by adding suppressors. This configuration of the array is not appropriate to cover a wide area by recursive installation. Coupling effects are also quite important to predict the impedance and radiation characteristics of a PAA. For that purpose, the mutual admittance matrix was derived from the small array ignoring the coupling beyond the size of the small array [22].

In this work, an AA with a partial drive is first investigated from the viewpoint of the current distribution on all elements and the radiation pattern using the method of moment. We assume a radiating system where only half elements are driven. In order to confirm the simulation results, an experiment was carried out using the same AA model at 2.0 GHz. A novel matching technique is applied to dipoles with more convenience than a conventional balance-to-unbalance transducer (balun) [23, 24]. Finally, the connections between microwave power generators and radiator elements, and the allocation of microwave amplifiers have been compared between the partially and fully driven cases.

The purpose of this paper is to show the concept of the partial driving technique to reduce the number of driven elements, and to confirm its validity through simulation and experiment. Therefore we treat only one configuration of a unit cell without a reflector [25]. The study of a PAA is important from the viewpoint of element-coupling, but is not included in this paper owing to space constriant.

## 2 Analysis antenna model

### 2.1 Antenna configuration

The antenna model for analysis is shown in Fig. 1. Driven elements are located on a line in the same direction with a separation, $2S$. On both sides of the line, passive elements are located parallel to the driven elements with a separation $d$ from the center line. The passive elements are not terminated, but are shortened to be simple wires. This rhombic arrangement of elements is considered to be a basic unit for the study on a triangular arrangement, which is adopted in conventional AA to suppress grating lobes.

The length of each element is assumed to be geometrically one-half wavelength of the microwave at 2.0 GHz, which is fed from an oscillator. The separation $2S$ is changed from 0.55λ, 0.75λ and 1.0λ.

The driven elements generate the electric field lines which reach the passive elements. Accordingly, the current is induced on the passive elements and re-radiates the field to space. By adjusting the parameters $2S$ and $2d$, the phase of the re-radiated field can be matched with that of the

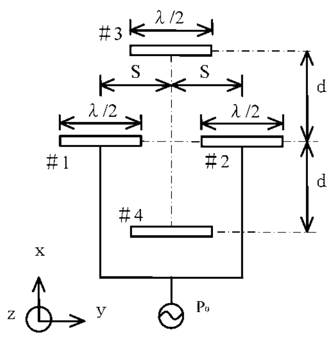



**Figure 1** *Antenna model with configuration parameters 2S and d*

No. 1 and No. 2: driven elements; No. 3 and No. 4: passive elements



© The Institution of Engineering and Technology 2008

radiated field by the driven elements. Preferably, the radio wave should be radiated in $z$-direction.

### 2.2 Analysis tool

The analysis is carried out using the moment method. The element radius is assumed to be 0.005λ, and each element is divided into 24 parts of equal length. A microwave voltage from the oscillator is given in the infinitesimal gap at the center of each driven element, which is 0.5 V in the same phase in this calculation. The current and electric field on each element is expressed by the Pocklington integral equation.

Solving the equation, we obtain the current distribution on the elements from which the antenna radiation pattern and gain can be derived. This procedure is realised using the IE3D software [26].

## 3 Analytical results

### 3.1 Gain against configuration

Antenna gain was calculated at the boresight (in the $z$-direction) at a far distance for several sets of parameters, $2d$ and $2S$. The computational results are shown in Fig. 2. The gain changes almost periodically with $2d$ with a period of 2λ. The dependence on $2S$ is not significant. At the abscissa, $2d$ of about 1.2λ with the parameter $2S$ of 0.75λ, the gain is at a maximum of 8.6 dBi.

The fully driven AA with the same element arrangement was also analysed for comparison purpose using the moment method to obtain the antenna gain of 10.3 dBi. The antenna gain in the case of partial drive is 1.7 dB lower than that of full drive. But the gain of four driven elements without coupling should be theoretically $2.2 + 6.0 = 8.2$ dBi; we can say that the gain is almost recovered even if the two elements are not driven. At $2d$ of 2.0λ with $2S$ of 0.75λ, the gain is at a minimum of 2.1 dBi.

The current distributions on both the driven and passive elements are important to determine the radiation characteristics, and have been calculated in the partially driven AA in Fig. 1. The current amplitude has a

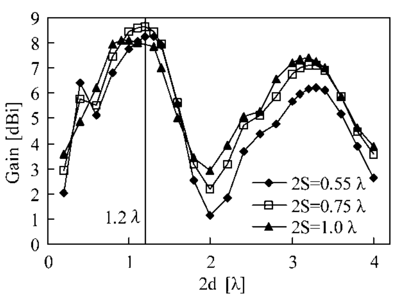



**Figure 2** *Calculated results for gain versus the arrangement of the elements for the case of partial feeding*

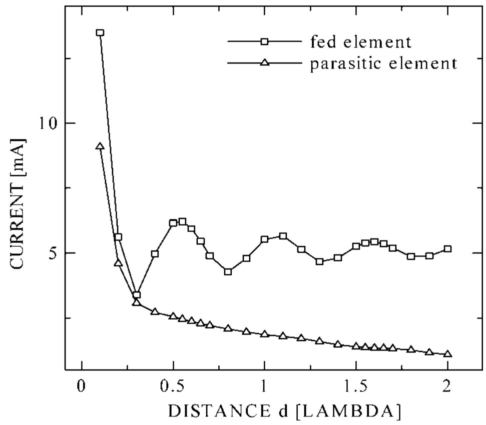



**Figure 3** *The calculated current amplitude at the center of each element ($2s = 0.75\lambda$)*

sinusoidal distribution on an element. The amplitude at the center is plotted against $d$ in Fig. 3. The current with $d$ increasing oscillates and approaches a constant value on a driven (fed) element, and decreases monotonically on a passive (parasitic) element. At the best parameter $d$ of 0.6λ, the current values are 7.0 and 2.4 mA for driven and passive elements, respectively.

The phase distribution of the current on the elements was analysed. The results for the maximum gain case with $2S = 0.75\lambda$ and $2d = 1.2\lambda$ are shown in Fig. 4*a* with the coordinate origin at the center of the element. The phase difference between the driven elements and the passive elements is only 10–20°. It is interpreted that in this allocation the radiated wave from the driven element propagates to the passive element and the phase rotates by 180° because of the propagation and proximity coupling effects between the elements. Accordingly, the current on the passive element flows in the same phase with that on the driven element.

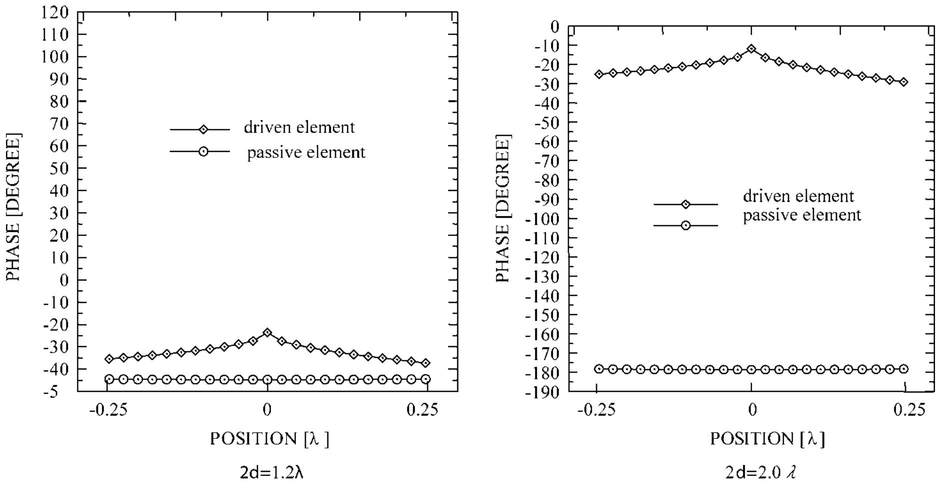
The results for the minimum gain case with $2S = 0.75\lambda$ and $2d = 2.0\lambda$, are shown in Fig. 4*b*. The excitation phase of the passive element is 180° out-of-phase from the driven element, as is deemed to be the cause of the gain degradation.

The current distribution on each element is not much affected by the parameter $2S$, as is expected from Fig. 2.

### 3.2 Radiation patterns

The radiation pattern in the case of the maximal gain in Fig. 2 was calculated. The thin lines in Fig. 5*a* and 5*b* show the calculated radiation patterns in the E-plane ($y$–$z$ plane) and the H-plane ($z$–$x$ plane), respectively, together with the experimental results drawn in the thick lines. The two main beams appear at 0 and 180° because of the antenna topology employed only for simplification purpose. The patterns in both planes are symmetrical with respect to the angle 0°. The gain is 8.6 dBi at the two bore sight angles of 0° and 180° in both the E-plane and the

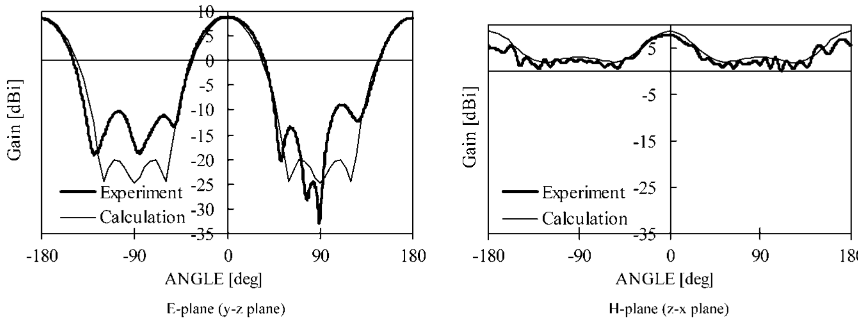

© The Institution of Engineering and Technology 2008
doi: 10.1049/iet-map:20070311




*a*          *b*

**Figure 4** *Phase of the calculated current on each element (2S = 0.75λ)*

*a* 2*d* = 1.2λ
*b* 2*d* = 2.0λ




*a*          *b*

**Figure 5** *Calculated and experimental radiation patterns at the maximum gain condition (2S = 0.75λ, 2d = 1.2λ)*

*a* E-plane (*y*–*z* plane)
*b* H-plane (*z*–*x* plane)

H-plane. The side lobes occur at $\pm 56^\circ$ with $-20$ dBi in the E-plane, but are high with 2.9 dBi around $\pm 90^\circ$ in the H-plane.

The radiation pattern in the case of minimal gain is shown in Fig. 6 only for the E-plane, which is much more significant than H-plane. As the phase of the currents on the driven and passive elements is almost reversed as shown in Fig. 4*b*, the gain at the boresight is quite low to form a dip between sidelobes.

### 3.3 Impedance

The input impedance seen at the center of each driven element in Fig. 1 was calculated using the moment method. The result is $76.1 + 31.2\,\mathrm{j}\Omega$ for each. As the impedance of an isolated half wavelength dipole is $73 + 42.5\,\mathrm{j}\Omega$, the coupling effect to the impedance is quite small.

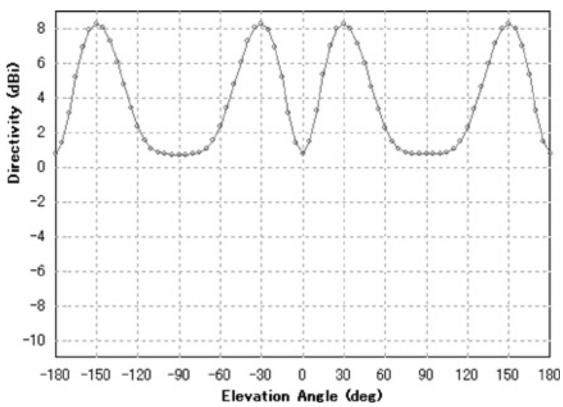



**Figure 6** *Calculated radiation pattern at the minimum gain condition*
(2*S* = 0.75λ, 2*d* = 2.0λ)


doi: 10.1049/iet-map:20070311
© The Institution of Engineering and Technology 2008

The impedance in the case of full drive with the same element arrangement was calculated to be $59 + 28\,j\Omega$ for each of No. 1 and No. 2 elements, and $59 + 33\,j\Omega$ for each of No. 3 and No. 4 elements. It is, therefore, concluded that the impedance in a partial drive case is less affected by coupling than that in a full drive case.

# 4 Experimental setup

## 4.1 Total antenna configuration

Fig. 7 shows the configuration of the AA used for the experiment. Two driven elements (Nos. 1 and 2) and two passive elements (Nos. 3 and 4) are located on the crossed lines, respectively, and arranged in the same direction. They are fixed in foamed plastic to simulate free space. The driven elements are driven in the same phase through the coaxial cables and a power divider. The isolation of the power divider is 20 dB.

The passive elements are made of brass which is 2.0 mm in diameter and 75.0 mm or a geometrical half-wavelength at 2.0 GHz in length. The distance $2S$ between No. 1 and No. 2 is changed to $0.55\lambda$ (82.5 mm), $0.75\lambda$ (112.5 mm), and $1.0\lambda$ (150.0 mm). The distance $2d$ between No. 3 and No. 4 is changed from $0.4\lambda$ (60.0 mm) to $3.2\lambda$ (480.0 mm) with a step of $0.4\lambda$.

## 4.2 Driven element

Fig. 8 shows a driven element used for the experiment, which is actually an electrical half-wavelength dipole. The driven element is made of a semi-rigid coaxial cable, which is erected from the connector and bent to the right by 90°. The outer conductor of the coaxial cable is stripped-off in the horizontal part of a quarter wavelength. A copper wire, which is a quarter wavelength in electrical length, is welded to the horizontal part of the coaxial cable to form an electrical half wavelength in total length. The diameters of the outer and inner conductors of the coaxial cable are 2.2 mm and 0.51 mm, respectively. The relative dielectric constant of the internal insulator is 2.1. The diameter of the copper wire is 2.0 mm.

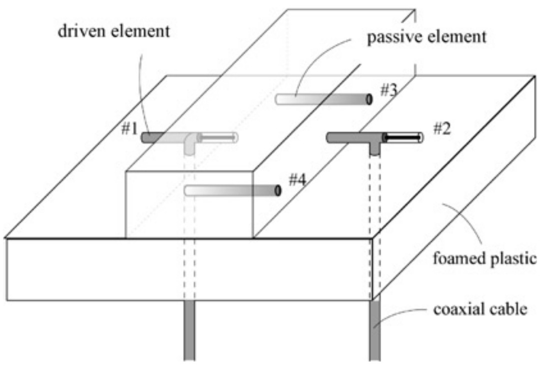



**Figure 7** *Configuration of the antenna under experiment*

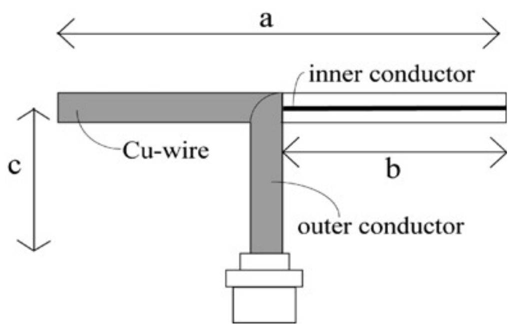



**Figure 8** *Configuration of a driven element with simplified matching*

The outer conductor of the horizontal coaxial cable is stripped-off, and its edge is a feeding point to the element. In this case, the feed point is the center of the driven element. This matching technique is quite effective and easy to be made in comparison with a conventional technique using a balun.

In Fig. 8, $a$ is the total length, $b$ the length of the inner conductor and $c$ the height from the connector. The parameters of the driven elements are summarised for two samples in Table 1. As the elements were made by hand, each size value shows a much larger difference between all samples than the least significant digit in Table 1.

Fig. 9 shows the measured return loss of a driven element, no. 2 in this case. The return loss at 2.0 GHz is −18 dB and −17.1 dB for No. 1 and No. 2 elements, respectively.

Fig. 10 shows the measured radiation pattern of the driven element, No. 2 in this case. The maximum gain is 2.5 dBi and the half-power beam width is 70°. In the case of a half wavelength dipole in free space, the maximum gain is 2.15 dBi and the half-power beam width is 78°. Consequently, the directivity of this driven element is higher than that of a half wavelength dipole in free space.

**Table 1** Parameter of the driven element

| | No. 1 (mm) | No. 2 (mm) |
|---|---|---|
| a | 65.38 | 66.05 |
| b | 32.93 | 32.61 |
| c | 28.71 | 28.10 |

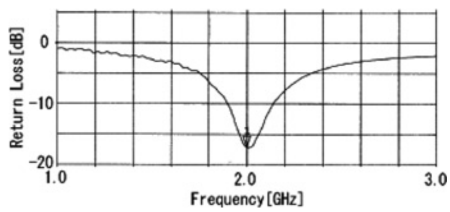



**Figure 9** *Measured return loss of the driven element*


© The Institution of Engineering and Technology 2008
doi: 10.1049/iet-map:20070311

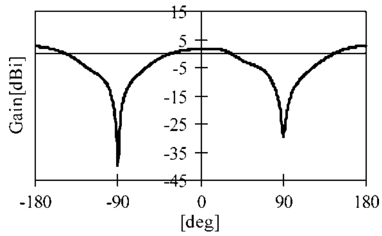



**Figure 10** *Measured radiation pattern of the driven element*

The radiation pattern is not symmetrical with respect to the boresight of 0°. This is characteristic in a dipole with simplified matching shown in Fig. 8 because of the asymmetrical structure.

# 5 Experimental results

## 5.1 Gain against configuration

The antenna gain was measured by comparing with a standard dipole antenna. The gain change for the distance between two driven elements $2S$ and the distance between passive elements $2d$ is shown in Fig. 11. The gain periodically changes with a period of $2\lambda$, just as for the calculations.

The gain is highest at $2d = 1.2\lambda$ with any $2S$ and at $2S = 0.75\lambda$ with any $2d$. Consequently, at $2S = 0.75\lambda$ and $2d = 1.2\lambda$, the maximum gain can be obtained as 8.7 dBi, which is almost the same as 8.6 dBi obtained in the calculation.

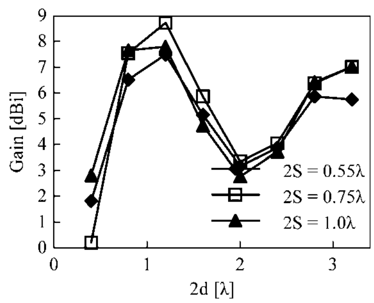



**Figure 11** *Measured gain against the arrangement of the elements for the case of partial feeding*

With $2S = 0.75\lambda$, the minimum gain is obtained as 3.3 dBi at $2d = 2.0\lambda$.

## 5.2 Radiation pattern

The thick lines in Fig. 5 show the measured radiation patterns for $2S = 0.75\lambda$ and $2d = 1.2\lambda$ at which the maximum gain can be obtained. The maximum gain is obtained at $\pm 180°$ and $0°$ in the E-plane. The radiation pattern in H-plane is symmetrical with respect to the angle $0°$, but that in E-plane shows a significant asymmetry. These characteristics are attributed to structural asymmetry of the driven element as explained in relation to Fig. 10.

The experimental result agrees well with the calculated result around the main lobe. In the E-plane, the half-power beam width is $\pm 22°$ in the experiment. It is indicated that the side lobe is suppressed less than $-10$ dBi.

According to Fig. 5*b* in the H-plane, the measured pattern agrees with the calculation result in general. However, ripples appear at angles beyond $110°$ and $-130°$ in the experiment, and degrade the measurement accuracy of the antenna gain. The cause is inferred to be cables and the feeding circuit behind the foamed plastic.

# 6 Impact of partial drive to system design

Possible circuits to feed microwave to each radiator element are shown for the partially driven and fully driven cases in Fig. 12*a* and 12*b*, respectively. The first advantage of a partial drive over a full drive is the smaller number of radiating elements. The passive elements are simple metal wires, and need no matching structure.

The second advantage is the shorter length of feed lines. In Fig. 12*b*, the lengths should be equal from the oscillator to four radiator elements although the lines to elements No. 3 and No. 4 are drawn for simplification purpose and the lengths are incorrect. Therefore, the line length in Fig. 12*a* is reduced to a half in this case.

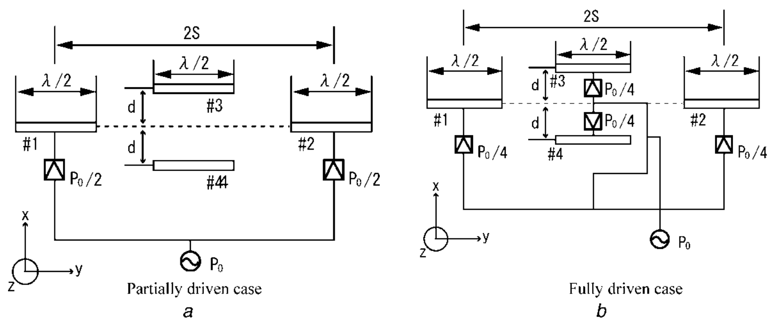



**Figure 12** *Feeding circuit*

*a* Partially driven case
*b* Fully driven case


© The Institution of Engineering and Technology 2008

The third is the simplification of the line network. At a branch point, the width of the upper-stream line should be double that of the lower-stream lines for good impedance matching. Therefore the complexity is much reduced according to the number of branch points. Also, the chances of a circuit cross-over are apparently reduced greatly.

The fourth is to reduce the number of associated electronic components. A driven element needs an amplifier and a phase shifter in a PAA. Two sets of amplifiers and phase-shifters are sufficient in the partially driven case although four sets are required in the fully driven case. In an active PAA, the electronic components are integrated with a radiator element and occupy most part of the total cost. Therefore the fourth advantage is quite valuable.

## 7 Conclusions

The AA model with two driven elements and two passive elements has been adopted for the study of the 50% partial drive technique as the simplest example. The simulation result shows that the maximum gain is 8.6 dBi ($2S = 0.75\lambda$, $2d = 1.2\lambda$). This antenna gain with the optimised configuration for desired coupling between elements is almost the same as that in the case where all elements are driven.

Experiment has been carried out to verify the simulation results using dipoles with simplified matching technique in the same AA model with two driven elements and two passive elements. The antenna gain and radiation pattern agree well with the analysis and experiment results. The maximum gain in the experimental result is 8.7 dBi ($2S = 0.75\lambda$, $2d = 1.2\lambda$).

It has been concluded in an AA with small resonant radiators that the driven elements can be replaced with passive elements by utilising the coupling between elements. In the case of a dipole array, the shorted passive elements are only wires. By reducing the number of driven elements, the feeding circuits from a microwave oscillator to the elements can be greatly simplified. The matching between the connected feed lines could be improved. The number of microwave amplifiers and phase-shifters can be reduced.

The analytical and experimental results may be easily extended to a larger AA by assuming the used model as a unit. This technique can be applied to various kinds of antenna shapes, and can be extended to a PAA. Therefore it is concluded that a partial drive technique is effective in reducing the cost of AA, especially an active PAA.

## 8 Acknowledgment

This work was partly supported by the Ministry of Internal Affairs and Communications. The authors thank Mr. K. Kumamaru for his cooperation in the experiment.

## 9 References

[1] RUDGE A.W., MILNE K., OLVER A.D., KNIGHT P. (EDS): 'The handbook of antenna design' (Peter Peregrinus Ltd, IEE Press, 1986)

[2] HEMMI C., DOVER R.T., GERMAN F., VESPA A.: 'Multifunction wide-band array design', *IEEE Trans. Antenna Propag.*, 1999, **47**, (3), pp. 425–431

[3] SILVERSTEIN D.J., ASHE M., KAUTZ G.M., WHEELER F.W., JACOMB-HOOD A.: 'A system for determining orientation and attitude of a satellite borne active phased array', *IEEE Trans. Aerospace Electron. Syst.*, 2002, **38**, (1), pp. 2–12

[4] BAGGEN R., VACCARO S., LLORENS DEL RIO D.: 'Design considerations for compact mobile Ku-band satellite terminals'. The Second European Conference on Antennas and Propagation, Edinburgh, UK, November 2007 Tu2.8.9

[5] JEON S.I., KIM Y.W., OH D.G.: 'A new active phased array antenna for mobile direct broadcasting satellite reception', *IEEE Trans. Broadcast.*, 2000, **46**, (1), pp. 34–40

[6] TANNER A.B., WILSON W.J., LAMBRIGSTEN B.H., DINARDO S.J., BROWN S.T., KANGASLAHTI P.P., GAIER T.C., RUF C.S., GROSS S.M., LIM B.H., MUSKO S.B., ROGACKI S., PIEPMEIER J.R.: 'Initial results of the geostationary synthetic thinned array radiometer (GeoSTAR) demonstrator instrument', *IEEE Trans. Geosci. Remote Sens.*, 2007, **45**, (7), pp. 1947–1957

[7] SCHUSS J.J., UPTON J., MYERS B., SIKINA T., ROHWER A., MAKRIDAKAS P., FRANCOIS R., WARDLE L., SMITH R.: 'The IRIDIUM main mission antenna concept', *IEEE Trans. Antennas Propag.*, 1999, **47**, (3), pp. 416–424

[8] TANAKA S., HARADA A., SAWAHASHI M., ADACHI F.: 'Experiments on coherent adaptive antenna array diversity for wideband DS-CDMA mobile radio', *IEEE J. Select. Areas Commun.*, 2000, **18**, (8), pp. 1495–1504

[9] HANLEY G.M.: 'Satellite power systems (SPS) concept definition study: Vol. I-executive summary' (NASA, CR-3317, 1980)

[10] MATSUMOTO H.: 'Research on solar power station and microwave power transmission in Japan: review and perspectives', *IEEE Microwave Mag.*, 2002, **3**, (4), pp. 36–45

[11] STANGE L.C., METZ C., LISSEL E., JACOB A.F.: 'Multiplicatively processed antenna arrays for DBF radar applications', *IEE Proc. Microwaves, Antennas Propag.*, 2002, **1490**, (2), pp. 106–112

[12] BUCCI O.M., D'URSO M., ISERNIA T.: 'Some facts and challenges in array antenna synthesis'. Proc. 19th Int.


© The Institution of Engineering and Technology 2008
doi: 10.1049/iet-map:20070311

Conf. Applied Electromagnetics and Communications, Dubrovnik, Croatia, September 2007, pp. 19–22

[13] CAILLE G., CAILLOCE Y., GUIRAUD C., AUROUX D., TOUYA T., MASMOUSDI M.: 'Large multibeam array antennas with reduced number of active chains'. The Second European Conference on Antennas and Propagation, Edinburgh, UK, November 2007 Tu1.8.1

[14] TOSO G., MANGENOT C., ROEDERER A.G.: 'Sparse and thinned arrays for multiple beam satellite applications'. The Second European Conference on Antennas and Propagation, Edinburgh, UK, November 2007 Th2.2.6

[15] FREDRICK J.D., YUANXUN W., ITOH T.: 'Smart antennas based on spatial multiplexing of local elements (SMILE) for mutual coupling reduction', *IEEE Trans. Antennas Propag.*, 2004, **52**, (1), pp. 106–14

[16] HUI H.T.: 'A practical approach to compensate for the mutual coupling effect in an adaptive dipole array', *IEEE Trans. Antennas Propagation*, 2004, **52**, (5), pp. 1262–9

[17] D'ELIA G., SOLDOVIERI F., DI MASSA G.: 'Mutual coupling compensation in a power synthesis technique of planar array antennas', *IEE Proc. Microwaves, Antennas Propag.*, 2000, **147**, (2), pp. 95–99

[18] RUDGE A.W., MILNE K., OLVER A.D., KNIGHT P.: 'The handbook of antenna design' (IEE, Peter Peregrinus Ltd, London, 1986), Vols 1 and 2

[19] ZIMMERMAN M.L., LEE R.Q.: 'Mutual coupling effects for small microstrip array antennas', *IEEE AP-S Int. Symp. Digest*, 1993, **3**, pp. 1382–1385

[20] LEGAY H., SHAFAI L.: 'A new stacked microstrip antenna with large bandwidth and high gain', *IEEE AP-S Int. Symp. Digest.*, 1993, **2**, pp. 948–951

[21] HARTANTO A., SUZUKI T.: 'An improvement of parasitic dipole array using suppressor elements', *IEEE Trans. Antenna Propag.*, 1991, **39**, (9), pp. 1434–1436

[22] KISHK A.A.: 'Prediction of large array characteristics from small array parameters'. The Second European Conference on Antennas and Propagation, Edinburgh, UK, November 2007 Th2.5.9

[23] THUNVICHIT A., TAKANO T., KAMATA Y.: 'Ultra low profile dipole antenna with a simplified feeding structure and a parasitic element', *IEICE Trans. Commun.*, 2006, **89-B**, (2), pp. 576–580

[24] THUNVICHIT A., TAKANO T., KAMATA Y.: 'Characteristics verification of a half-wave dipole very close to a conducting plane with excellent impedance matching', *IEEE Trans. Antenna Propag.*, 2007, **55**, (1), pp. 53–58

[25] KAMO N., SUGAWARA A., TAKANO T.: 'Optimization of a half-wave length array with passive elements'. Proc. IEICE Society Conference, 2003, B-1-80, p. 80

[26] 'IE3D User's Manual, release 11.5' (Zeland Software, Inc., Freemont, CA, May, 2002)


doi: 10.1049/iet-map:20070311
© The Institution of Engineering and Technology 2008

Copyright of IET Microwaves, Antennas & Propagation is the property of Institution of Engineering & Technology and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.