A NOVEL BUTLER MATRIX BASED BEAM FORMING NETWORK ARCHITECTURE FOR MULTIPLE ANTENNA BEAM STEERING

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1. Introduction

The next generation Japanese communication satellite will cover the service area, e.g., the main islands of Japan and its archipelago, by multiple spot beams. It will offer direct bidirectional links between the geostationary satellite and low-cost very small earth stations/handy terminals, for the advanced personal communication service. Large deployable reflector antennas with diameters exceeding ten meters [1] fed by active phased array antennas will be used by the satellite borne antenna system to obtain an equivalent isotropically radiated power (e.i.r.p.) some one hundred times higher than the level achieved by present satellite technology.

Multiple beam phased array antennas will be adopted for the following advantages. First, the radiated microwave (MW) power level can be enhanced by simply increasing the number of antenna elements through spatial power combining. Second, the system works efficiently even if traffic imbalances exist among the beams, because the MW signals to the different beams are combined and are commonly amplified by an array of high power amplifiers (HPAs). Third, the phased array tolerates HPA failure.

A Butler matrix is one type of beam forming network (BFN) for multiple beam phased array antennas. Although the configuration of the circuit is very simple and the circuit is ideally lossless, it has not been widely used for multibeam forming because it can only generate beams with fixed spacing.

This paper introduces a novel BFN configuration that permits antenna beam steering using the Butler matrix. The prototype circuit for a 7-beam, 8-element phased array is fabricated, and its transmission characteristics examined. This paper describes the configuration and performance of the circuit.

2. Configuration of the Proposed BFN and its Principle of Operation

A Butler matrix is suitable as the BFN for fixed multiple beam linear phased array antennas [2]. It has multiple MW input/output ports, and consists of a hybrid array and a fixed phase shifter array. The input MW signals are divided by the hybrids and distributed to all the output ports; the appropriate phase shifts are set as the signal propagates through the circuit. The strengths of the output signals are equal, and have constant phase difference among the adjacent output ports. Feeding the MW signal to a different input port induces a different amount of phase shift among the output ports. For an eight-element Butler matrix, eight different constant phase shifts, say, $\pm\pi/8$, $\pm3\pi/8$, $\pm5\pi/8$ and $\pm7\pi/8$ are obtained. These phase differences stimulate radiations at certain angles in space. The eight antenna beam patterns generated by the eight-element Butler matrix, named 4L, 3L, 2L, 1L, 1R, 2R 3R, and 4R are shown in Fig. 3 as the dotted lines. The calculations for these plots assumed that the array elements were equi-spaced in half-wavelength and isotropic.

The proposed configuration basically feeds several input ports simultaneously. Assume that an MW signal is divided and is simultaneously fed in phase to two input ports associated with two adjacent antenna beams. Assuming that the phase differences introduced by the two ports $\Delta\phi_1$ is and $\Delta\phi_2$, the phase difference so created will be between $\Delta\phi_1$ and $\Delta\phi_2$. The amount of phase difference can be controlled by weighting the strengths of the two signals. Consequently, we can control the antenna beam direction between the two directions of the two input ports. The beam direction shifts according to the ratio of the strength of the two input signals.

Fig. 1(a) illustrates the configuration of the BFN that realizes the above concept. The BFN consists of two parts: the 'beam steering circuit (BSC)' and the Butler matrix. The BSC consists of an array of variable power divider (VPD) and power combiners. The VPD arbitrarily weights the input MW signals . The outputs of adjacent VPDs are combined by the power combiner (PC) and input to the Butler matrix. An example of the VPD configuration being applied an interferometer is illustrated in Fig. 1(b). By changing the variable phase shifter (VPS) from 0 to 180 degrees, we can arbitrarily set the ratio of the two output signal levels. Note that phase difference of the two output ports is always zero. Between the BSC and the Butler matrix, an array of fixed phase shifters (PSs) is installed. The values of the PSs are adjusted so that absolute phase shifts for the different input port coincide at the center of the antenna's aperture.

3. Performance of a Fabricated BFN

A BFN for a 7-beam, 8-element phased array was fabricated using MW components, such as hybrids, power dividers and mechanical VPSs; connections were made by semi-rigid coaxial cables. The lengths of the cables were precisely adjusted to provide certain amounts of phase shift. The circuit was designed for the center frequency of 2.5 GHz.

3.1 An Interferometer Variable Power Divider

The performance of the BSC was measured. The results for the third input port are illustrated in Fig. 2 as an example. When the VPS in the VPD was set to 0.5 a.u., all input power is passed to the first output port. The ratio of strength of the two signals was less than -37 dB. The levels of two outputs are equal when VPS is set to 12.5 a.u. When VPD is set to 24 a.u., all input power was sent to the second output port. The phase difference between the two output ports is zero. One a.u. equals 7.5 degrees.

3.2 Butler matrix

The 8 by 8 Butler matrix was fabricated, and its 64 forward transmission coefficients were measured. The matrix was evaluated in terms of excess losses and the deviation of the amplitudes and phase from the designed values. The worst case amplitude and phase deviation were 0.4 dB (defined max. to min.) and -1.6/1.8 degrees, respectively. The excess loss for respective input ports ranged from -0.56 to -0.67 dB.

3.3 Antenna Array Factor

The BSC and the Butler matrix were combined, and the forward transmission coefficients were measured as a function of the phase shift set by the VPS in the BSC. The antenna array factors were calculated from the measured forward transmission coefficients. The transmission coefficients of the third input port were used in the calculations and the results plotted in Fig 3. From the figure, it is observed that beam direction changes from the angle of 1L towards the 2L beam as the phase shifts were increased by the third VPS. The absolute level of the antenna gain calculated using measured coefficients was slightly lower (about -1.3dB) than the theoretical value, which is due to the actual loss in the BFN.

The shape of the array factor was precisely analyzed. The relative maximum gain and the beam direction are plotted in Fig. 4 (a), and the first sidelobe level and half beam width are plotted in Fig. 4 (b), as a function of the phase shifts set by the VPS. The theoretical values are also plotted as the solid and dotted lines. Excellent agreement was achieved between the two results. The maximum gain slightly changes with VPS changes. When VPS was set to 12.5 a.u. (90 degrees), the minima was -0.9 dB. The worst case first sidelobe level is -11.7 dB when VPS was set at zero; the minima was -23.9 dB when the VPS was set to 12.5 a.u. We found that the first sidelobe level is improved compared to when only the Butler matrix was used.

4. Conclusion

A novel BFN configuration for multiple beam phased array antennas based on the Butler matrix was presented. A VPD array was attached to the input ports of a Butler matrix to realize multiple antenna beam steering. A 7-input, 8-output circuit was fabricated and its performance tested. The transmission coefficients were measured, and antenna array factors were calculated. Excellent agreement was achieved between the theoretical and measured values. The antenna beam steering function realized by the circuit was confirmed. The worst case excess loss of the circuit was very small at only -4.4 dB, which included the intrinsic signal loss of 3 dB. The circuit is a promising candidate for satellite borne multiple phased array beam forming networks for the following reasons. i) The circuit is inherently very simple; ii) each antenna beam can be steered by a single VPS, and it significantly reduces the complexity of the antenna beam control circuit.

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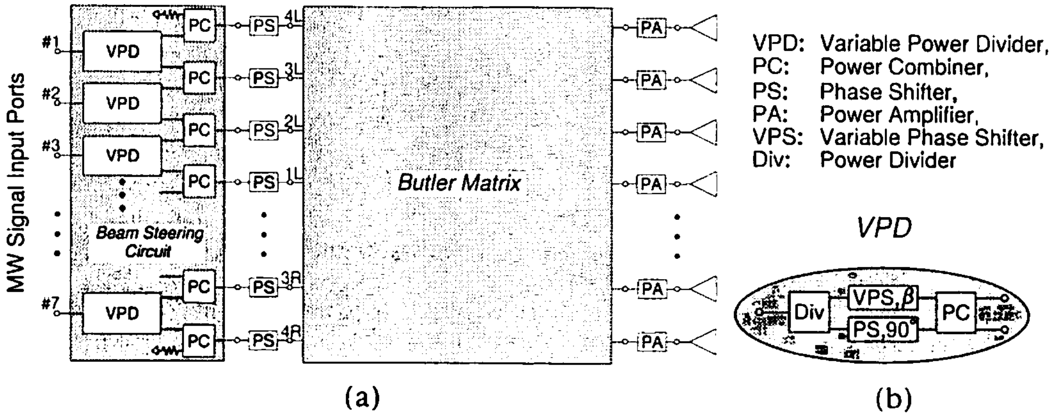


Fig. 1 (a) Proposed BFN configuration for multiple antenna beam steering
(b) Configuration of the variable power divider (VPD)

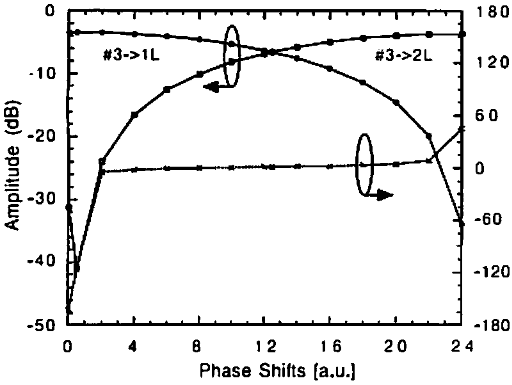


Fig 2. Transmission characteristics of the variable power divider

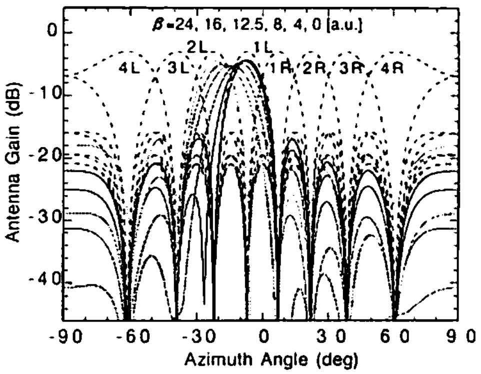
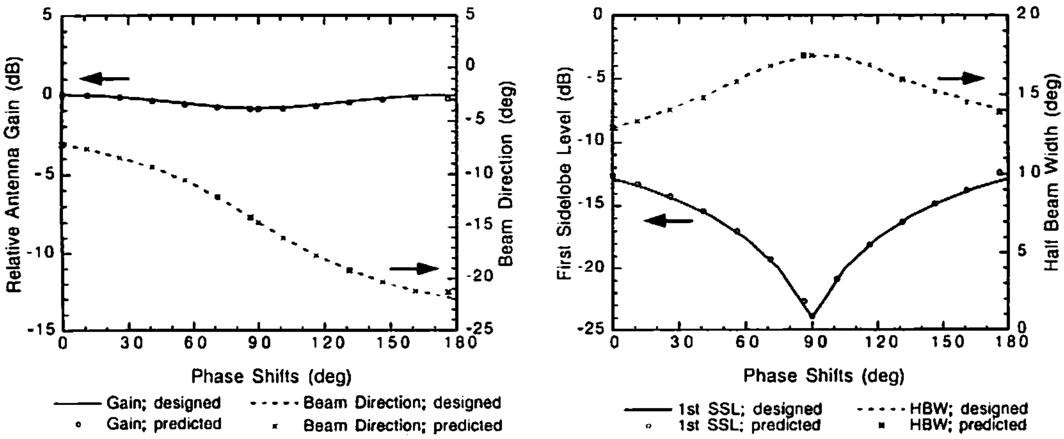


Fig. 3 Calculated array factor. Measured transmission coefficients were used.



(a) Relative antenna gain beam direction

(b) Half beam width and first sidelobe level

Fig. 4 Characteristics of the calculated antenna pattern