A Beam-Forming Network for a Circular Switched-Beam Phased Array Antenna

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***Abstract*—This paper reports on the design and development of a dividing/phasing network for a compact switched-beam array antenna for land-vehicle mobile satellite communications. The device is formed by a switched radial divider/combiner and 1-bit phase shifters and generates a sufficient number of beams for the proper satellite tracking.**

***Index Terms*—Antennas for mobile satellite communications, beam-forming networks, phase shifters, switched-beam array antennas, variable power dividers.**

I. Introduction

A CIRCULAR switched-beam array with antenna elements located on a truncated cone is an attractive option of an electronically steered antenna for land-vehicle mobile satellite communications [1]. It is less complicated than a phased array and advantageous over a mechanically steered antenna, as it does not involve any mechanical movement of its parts. Its particular importance is for geographical regions with low look angles toward the satellite where a planar phased array performs poorly. In comparison with a phased array, a switched beam array usually features a larger size and profile. Hence, there is a lot of interest to make this array smaller. In order to reduce the size of the switched-beam array the number of antenna elements has to be reduced. For the Australian Mobilesat, or an equivalent system such the North American AMSC, the theoretical calculations show that an 8-element array with two elements active should provide an adequate gain. Beam formation for this antenna can be accomplished using an 8-way-2-elements-on switched radial divider/combiner, similar to that one presented for a 14-element array in [1]. Unfortunately, such a beam-forming network can generate only eight beams. This number is inadequate for the proper satellite tracking, as it would lead to signal outages during the hand over from one beam to an adjacent one. The number of generated beams can be increased from 8 to 24 by including 1-bit phase shifters at the peripheral ports of the radial divider. The design of such a dividing/phasing network is presented in this paper. This design is not restricted to satellite antennas. Also it should be found attractive in other applications such as smart antennas for mobile communication systems.

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II. Design

A. Switched Beam Phased Array Beam-Former

The basic configuration of the new dividing/phasing network for the compact 8-element switched beam array is shown in Fig. 1. The photograph of the developed network is shown in Fig. 2. The central part of this device consists of a coaxial central port and eight transmission lines distributed radially. In order to activate two and deactivate the remaining six output ports parallel PIN diode switches, located a quarter wavelength away from the central coaxial port, are used. When a switch produces a short circuit at its connection point it deactivates the transmission line, which appears as an open circuit at the 50 Ω central port. When the switch produces an open circuit, a quarter-wavelength long line connects the phase shifter and the antenna element to the central port of the radial divider/combiner. In order to provide a suitable impedance match between the two parallel active lines terminated in 50 Ω antenna elements to the 50 Ω central port, these lines have to feature characteristic impedance of 70.7 Ω.

B. Development of Switches and Phase Shifters

1) DPST Switch: The DPST switch is a pair of two adjacent parallel SPST PIN diode switches, which activate two adjacent antenna elements in the array. The performance of individual switches can be optimized using HP-EESof Touchstone. Each switch uses a PIN diode with a suitable biasing arrangement. In order to minimize the manufacturing cost a low-cost Phillips BA682 PIN diode is used. Normally, this diode is aimed for operation at 500 MHz. At 1.6 GHz, it features a large stray capacitance that leads to about 4 dB insertion loss in its off state making a very poor approximation of an open circuit. In order to extend its use to 1.6 GHz, an LC compensation technique is applied to tune out the stray capacitance [2]. When the stray capacitance is tuned out, the measured performances of the parallel switch are as follows: isolation $>$32 dB, insertion loss (IL) $<$0.2 dB, and return loss (RL) $>$25 dB over the frequency band from 1.4 GHz to 1.8 GHz.

2) 1-Bit Phase Shifter: As already mentioned, in order to obtain a smooth beam handover during the satellite tracking, 1-bit phase shifters, shown in Fig. 1, are included in the beam-forming network. In the present case, calculations reveal [3] that for the 8-way-2-elements-on switched beam array, a 50° phase shift bit is required. It can be realized using a loaded line phase shifter with two PIN diodes [2]. Similarly as for the parallel switches, LC compensated Phillips BA682 diodes are used to design this phase shifter. The measured performance of the developed device including RL, IL, and differential phase shift

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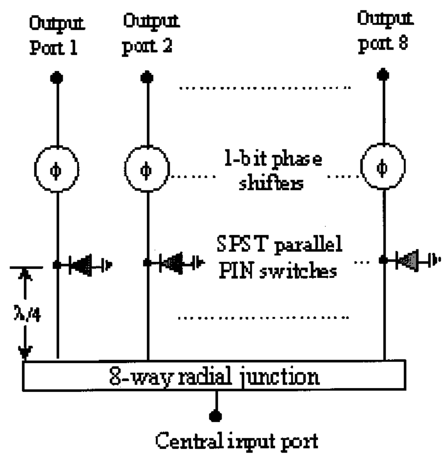

Fig. 1. Configuration of a variable dividing/phasing network for a compact 8-element switched-beam array.

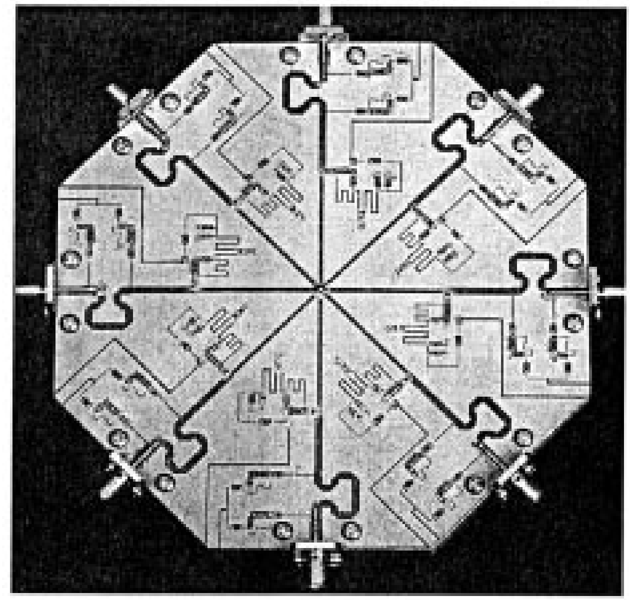

Fig. 2. Photograph of the developed variable dividing/phasing network including a switched radial divider/combiner and eight 1-bit loaded-line phase shifters.

($\Delta\phi$) is summarized as follows: RL >25 dB, IL <0.2 dB, and $\Delta\phi = 48° \pm 2°$ over the frequency band from 1.52 GHz to 1.68 GHz.

III. Prototyping and Measured Results

The photograph of the fully developed dividing/phasing network, including an 8-way-2-elements-on radial switch and eight 1-bit phase shifters, is shown in Fig. 2. In this case, the device includes SMA connectors at its peripheral ports, which are included to test its performance. When the network is incorporated in the array, the SMA connectors at the peripheral ports are eliminated and the lines are directly connected to microstrip patch antenna elements. This is done to reduce the manufacturing cost of the switched-beam array.

The circuit is activated using electronic drivers (not shown here), which supply suitable sequences of voltages via a 17-line ribbon cable to PIN diodes. DC +5 V (with 470 Ω current limiting resistor) and 10 mA current in the forward bias state and −15 V in the reverse bias state are used. The developed switch was tested when different two-element sub-arrays were activated. The measured results were: RL >10 dB, IL <1.5 dB, and Isolation <21 dB (between active and inactive ports) over the 7% Mobilesat frequency band centered at 1.6 GHz [see Fig. 3(a)]. The minimum IL (dashed lines) of the two active lines is very close to 4 dB. This value comprises 3 dB (for the ideal case) due to the 2-way dividing network, and about 1 dB loss due to the transmission lines, the switches and the phase shifters. The phase difference between the two active ports (one line with 50° phase shifter ON and another line with phase shifter OFF) is approximately $49° \pm 1.5°$ over the same frequency band [see Fig. 3(b)].

Following the satisfactory test results, the network was incorporated into an 8-element array [3]. The antenna elements are dual orthogonal feed aperture coupled circularly polarized circular patch antennas featuring gain of 8.5 dBi.

The elements are arranged into a cylindrical array of eight elements that are placed on a truncated cone with about 40° with regard to the horizontal plane. The developed array is 45 cm in diameter, 10 cm in height, and 3.5 kg in weight [3]. The complete antenna was measured in the University of Queensland's

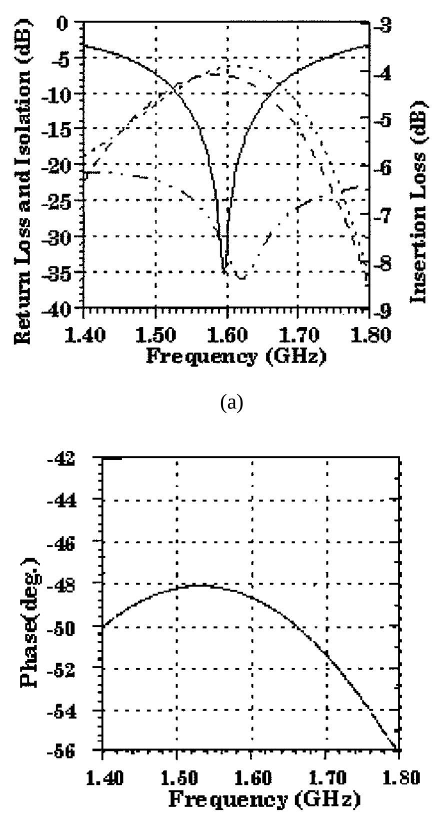

Fig. 3. (a) The measured results of the 8-way-2-element-on switch with two output ports always active: solid line (—) input return loss, dashed lines (- - - - - -) insertion loss of two active ports, and dashed-dotted line (—· ·—) isolation between active and inactive ports. (b) Phase difference between two activated output ports.

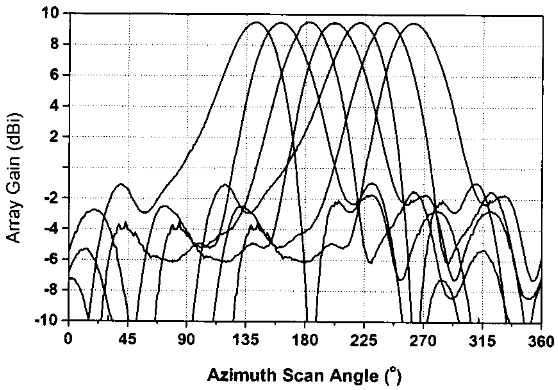

Fig. 4. Seven adjacent beams of an 8-element switched-beam phased array generated using the developed dividing/phasing network of Fig. 2.

Anechoic Chamber. Using the 50° phase shifters, each active pair of elements can generate a set of three beams: left (−50°, 0°), center (0°, 0°)—no phase shift between active elements and right (0°, −50°). As a result, a total of 24 beams can be generated from the 8-element cylindrical array. Seven such adjacent beam patterns produced by the antenna array are shown in Fig. 4. It can be seen that the antenna yields approximately 9 dBi gain and a smooth beam handover.

The outdoor experiments were performed in Brisbane, Australia where the satellite look angle was 59° toward Optus satellites. When connected to an NEC S1 transceiving terminal to communicate via Mobilesat, the handset reading indicated received signal levels between 8 and 9, meaning that a relatively strong signal was received. For this setting, the voice communication with a PSTN user was tested. A very good quality of voice communication in all the tests was recorded.

IV. Conclusions

This paper has reported on the design and development of a variable diving/phasing network for a compact 8-element switched-beam array antenna for use with the Australian mobile satellite communications system Mobilesat. The network is constituted by a switched 8-way-2-elements-on radial divider/combiner and eight 1-bit phase shifters. It is capable to generate 24 individual beams. It uses inexpensive substrates and low-cost UHF switching diodes and hence its manufacturing cost is very low. Indoor and outdoor trials have shown that this device functions very well.

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