

Cognitive Tapered Slot Circular Array Antenna for Lunar Surface Communications

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Abstract—In this paper, we present the design of a cognitive tapered slot circular array (TSCA) antenna with multiple electronically switched sector beams for lunar surface communication. The circular array is capable of sensing the frequency, power, and direction of arrival of the RF signals. The design of the TSCA builds on our prior work on the development of a single TSA element with a balanced microstrip/coax feed. The measured return loss of the single TSA element shows wide bandwidth with good impedance match across the 5 to 35 GHz frequency range. Additionally, the single TSA has good radiation patterns. The single TSA serves as the building block for a four-element TSCA with multiple electronically switched sector beams for sensing and communications.

Keywords—Cognitive communications, Lunar surface communications, Tapered slot antenna, Circular array antenna, Cognitive antenna

I. INTRODUCTION

A robotic spacecraft on a mission to explore a planet and its moons in the outer solar system is separated from Earth based ground stations by vast expanse of space. Consequently, the signals transmitted by the spacecraft before reaching the ground stations are impacted by the ambient cosmic noise, cosmic microwave background radiation, solar wind, and Earth's fluctuating ionosphere. Hence, to ensure reliable communications throughout the duration of the mission, the radios onboard the spacecraft as well as at the ground stations have to autonomously adjust their settings and adapt to the changing environment. A radio equipped with a neural network can be trained to perform such tasks and is referred to as a cognitive radio [1]. Cognitive radio and its relation to software defined radio was first introduced in [2]. Since then, considerable developments and progress have been reported on cognitive radios; and recently NASA's Space Communications and Navigation (SCaN) program demonstrated the implementation of a cognitive engine algorithm on a testbed on the International Space Station [3]. The goal was to provide a baseline performance and potential of cognitive engine for communication systems.

NASA's human lunar exploration program plans to send astronauts to the surface of the Moon by 2024 and also establish sustainable exploration by the end of the decade. One of the goals of this program is to accomplish outstanding lunar science as outlined by the National Academies [4]. With this vision in mind NASA has established a Commercial Lunar Payload Service (CLPS) for delivering a variety of scientific instruments

and technology demonstrations to the lunar surface [5]-[7]. These instruments and demonstrations will help NASA gain valuable knowledge about the Moon and also prove new technologies prior to the landing of the astronauts.

A lunar surface network consisting of diverse nodes including landers, rovers, astronauts, science instruments/demonstrations, and towers for data communications are essential for the success of the above program [8]. Additionally, a lunar surface network based on wireless technologies is much more efficient than point-to-point communications [8]. However, the terrain profile of the lunar surface is highly irregular with craters and RF propagation models for lunar surface-to-surface links indicate high path loss [9]. In this context, a cognitive communication system architecture that works in unison with cognitive antennas to mitigate interference, share spectrum, and optimize the link performance is an enabling technology [10]-[12]. The advantage of using cognitive antennas is that it can sense the frequency, power level, and angle of arrival of the radio waves or RF signals and dynamically allocate bandwidth and/or adjust beam direction and directivity to optimize the spectral resources. Such capabilities would play a major role in enabling the autonomous collection of the science data from these surface instruments or assets.

In this paper, we present the design of a cognitive tapered slot circular array (TSCA) antenna with multiple electronically switched sector beams for the above communication requirements. The design feasibility presented in this paper builds on our prior work on the development of (1) a single TSA element with a balanced microstrip/coax feed and (2) a 16-element TSCA antenna with a sixteen-way microstrip power divider feed with omnidirectional radiation pattern [13]-[15]. These antennas are briefly described in Sections II and III below. The tapered slot antenna (TSA) belongs to a class of end-fire traveling-wave antennas; and in addition, being a printed antenna, the TSA has several advantages such as low profile, low mass, simple fabrication, suitability for conformal installation, and compatibility with mixed signal digital/microwave solid-state devices and integrated circuits. Furthermore, the TSA has wide bandwidth, moderately high gain, and almost equal E- and H-plane radiation patterns. Lastly, the capability to generate multiple electronically switched sector beams for cognitive antenna applications eliminate the need to mechanically steer the antenna and thus is an advantage while communicating with the above science instruments or assets dispersed over the lunar landscape.

II. SINGLE TAPERED SLOT ANTENNA (TSA) ELEMENT WITH ENDFIRE RADIATION PATTERN

A single TSA element with a balanced microstrip feed network is shown in Fig. 1 [13]. The single TSA is formed by gradually flaring the strip conductors of the balanced microstrip line feed on opposite sides of the dielectric substrate by an angle α with respect to the antenna axis. The feed system consisted of a conventional microstrip line on a dielectric substrate of thickness D with the ground plane tapered to a width equal to the strip width W to form a balanced microstrip line. The design frequency (f_0) is 18.0 GHz, and the corresponding free space wavelength is denoted as λ_0 . The dimensions of the TSA and the feed are summarized in Table I. The measured return loss (S_{11}) of the single TSA element is shown in Fig. 2 and is observed to have wide bandwidth with good impedance match across the 5 to 35 GHz frequency range. The endfire radiation from the TSA is linearly polarized and in the plane of the substrate, that is, the E-plane. The H-plane is orthogonal to the plane of the substrate. The measured E- and H-plane radiation patterns are shown in Fig. 3(a) and (b), respectively. The measured H-plane cross-polarized radiation is -16 dB below the co-polarized radiation at f_0 .

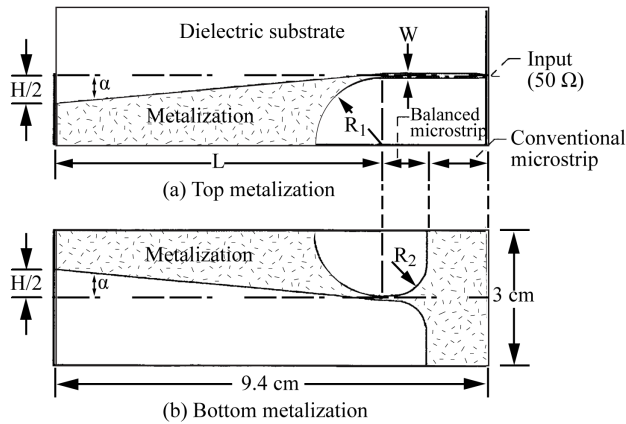


Fig. 1. Tapered slot antenna element and feed network.

TABLE I. SINGLE TAPERED SLOT ANTENNA ELEMENT AND FEED PARAMETERS

Variable	Value
Operating Frequency	18.0 GHz
Corresponding Free Space Wavelength	λ_0
Substrate Type, Permittivity, and Thickness (D)	RT/Duroid 5880, 2.2, 0.0508 cm
R1	$0.9 \lambda_0$
R2	$\lambda_0 / 2$
W	0.071 cm
H	$0.75 \lambda_0$
L	$4.3 \lambda_0$
α	5.3°

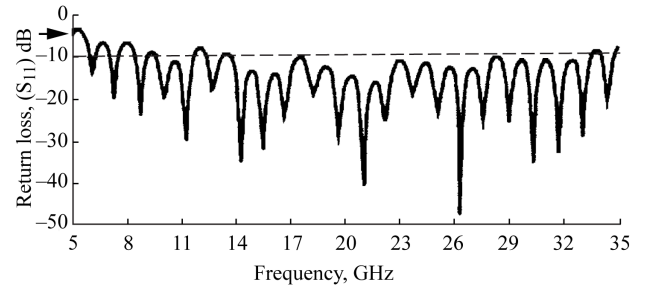


Fig. 2. Measured return loss at the coaxial input port.

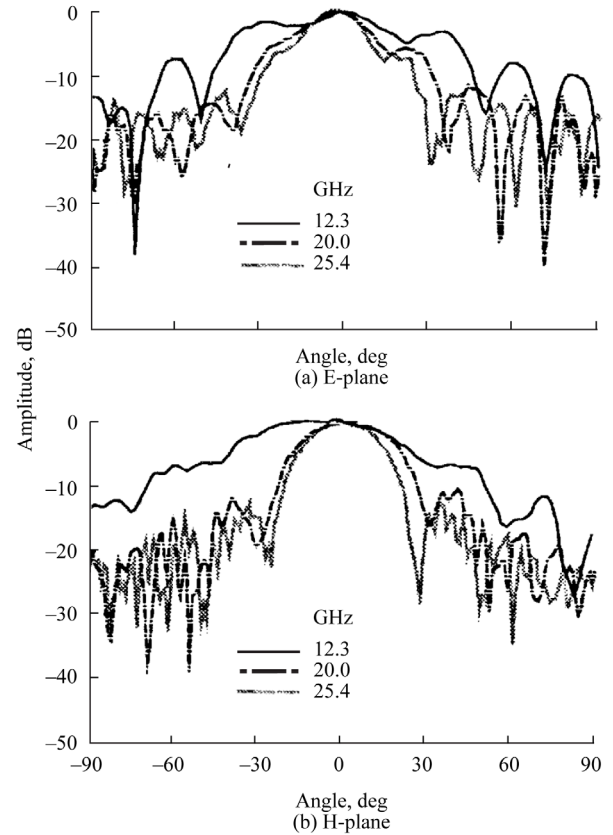


Fig. 3. Measured radiation patterns.

III. TAPERED SLOT CIRCULAR ARRAY (TSCA) ANTENNA WITH OMNI DIRECTIONAL RADIATION PATTERN

The circular array is composed of identical TSA elements equally spaced along the circumference of a circle. Additionally, each element is fed in equal amplitude and phase relative to the array center located at the origin of the coordinate system. The array generates an omnidirectional radiation pattern. A circular sixteen-element TSA array is shown in Fig. 4 [14]-[15]. The microwave power is surface launched by a modified OS-50 coaxial connector at the center to the input of the feed network. The feed network consists of a sixteen-way radial power splitter. The power splitter through a series of tee junctions and right-angle bends divides into sixteen radial output ports, which are electromagnetically coupled to the slotline feed of the sixteen TSAs as shown in Fig. 4. The TSA is formed by gradually flaring the width of the slotline. The TSCA and feed dimensions are also indicated in Fig. 4. The endfire radiation from the array

elements propagates along the z-axis as illustrated in Fig. 5(a). In addition, the endfire radiation is displaced in the elevation by an angle θ_1 when the array is placed above a copper ground plane as illustrated in Fig. 5(b). Furthermore, when a parasitic array is placed above the active array, the radiation is displaced even further by an angle θ_2 ($\theta_2 > \theta_1$).

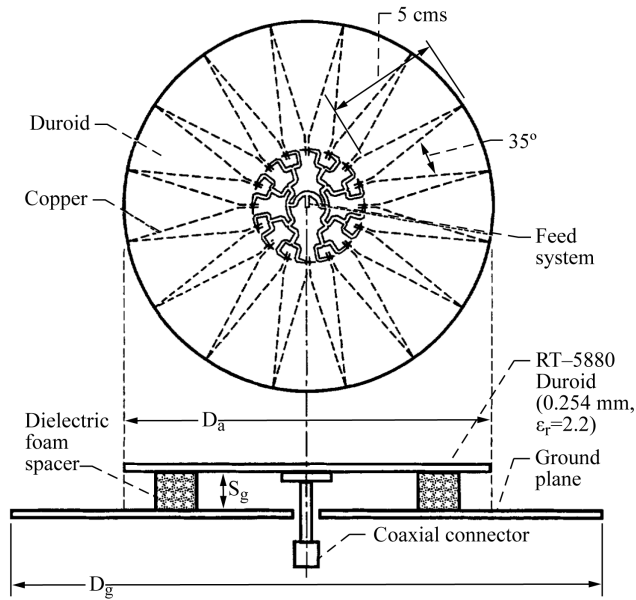


Fig. 4. Sixteen-element tapered slot circular array antenna. $D_a = 16$ cms, $D_g = 30$ cms and $S_g = 5$ mm ($0.286 \lambda_{01}$). λ_{01} is the free space wavelength at the center frequency of 18 GHz.

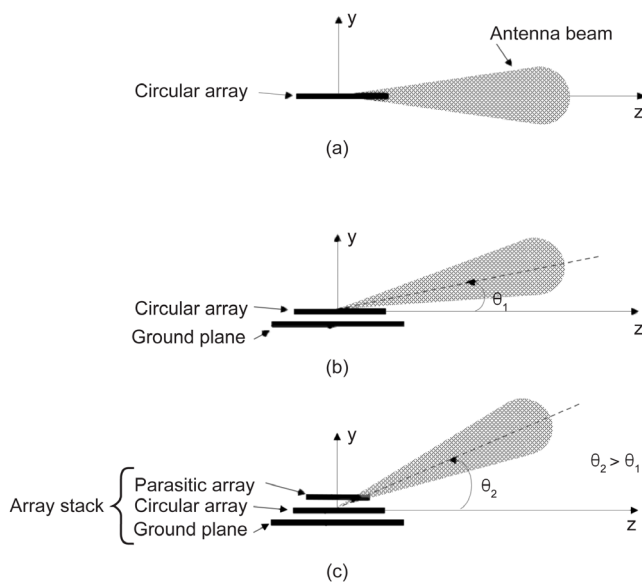


Fig. 5. Schematic illustrating the elevation beam orientation. (a) without a ground plane. (b) with a ground plane. (c) With a ground plane and a parasitic array.

The measured H-plane pattern of the array with and without a ground plane is shown in Fig. 6(a). In the presence of a ground plane the pattern is displaced by about 28° in the elevation. Because of this, the E-plane patterns measured by tilting the array in the elevation. Fig. 6(b) shows a typical peak pattern. The pattern in Fig. 6(b) however, shows the characteristics for only one quadrant of the array. Therefore, the measurement had to be repeated for the remaining three quadrants. This was done by rotating the array by 90° for each measurement. All four radiation patterns were similar to the first one. This demonstrates that the array is omnidirectional in the azimuth plane. The measured return loss of the array is better than 10 dB over the frequency range 18 to 20 GHz. The array has a gain of about 10 dB. The fabricated and characterized 16 element TSCA antenna with omni directional radiation pattern is shown in Fig. 7. The sixteen-element TSCA antenna placed above a copper ground plane and with a parasitic array on top is shown in Fig. 8.

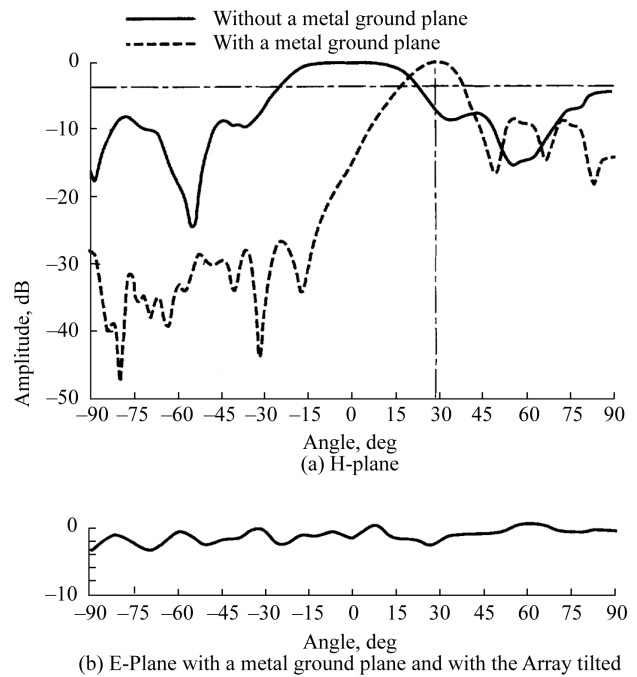


Fig. 6. Measured radiation pattern of the array at 19 GHz. (a) H-Plane. (b) E-Plane.

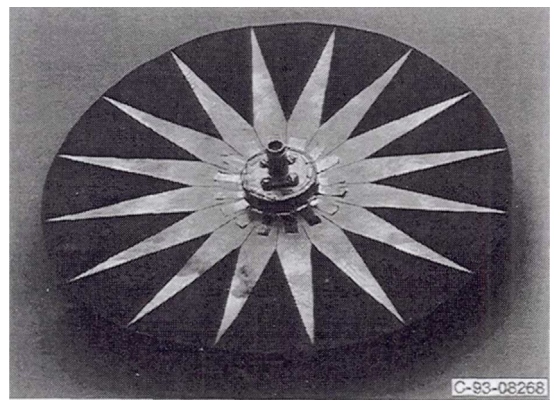


Fig. 7 Photograph of the sixteen-element tapered slot circular array antenna.

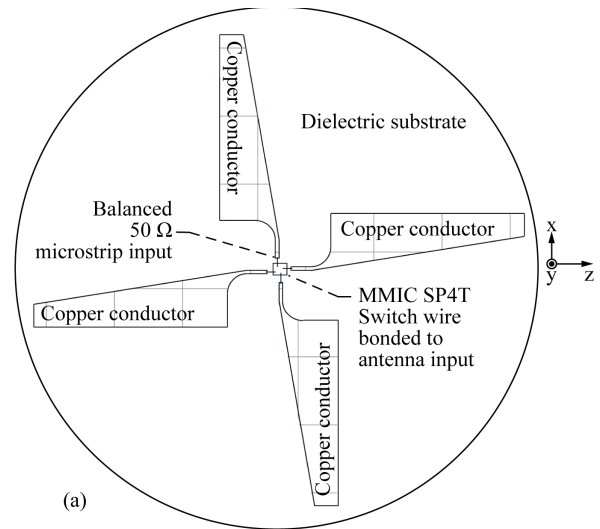


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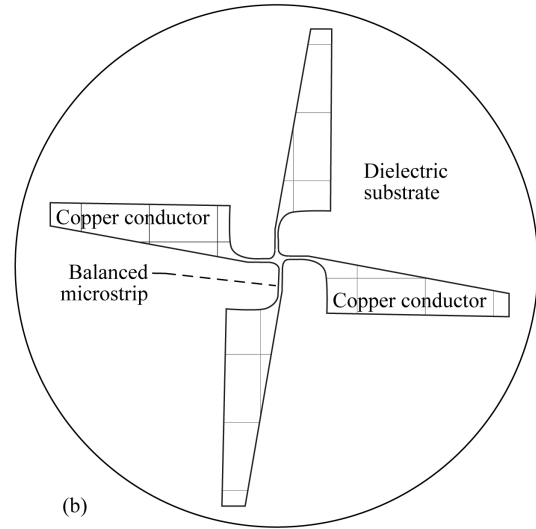
Fig. 8 Sixteen-element tapered slot circular array above a ground plane and with a parasitic array above

IV. TAPERED SLOT CIRCULAR ARRAY ANTENNA WITH SWITCHED SECTOR BEAMS

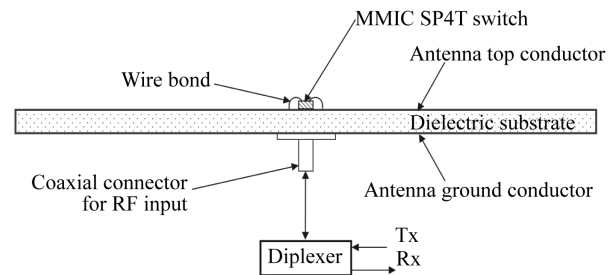
A four-element tapered slot circular array (TSCA) antenna with switched sector beams is shown in Fig. 9. In this array, the elements are arranged in a circle to realize a four-element circular array. The major difference between this array and the previous omnidirectional circular array is that the individual elements are not simultaneously excited, but rather sequentially excited or reconfigured in a time division manner to form four independent sector beams that point in the desired directions along the azimuth. The sector beams enable the cognitive antenna to sense the frequency, power level, and angle of arrival of the radio waves or RF signals [17]. Based on this input, the signal processing circuitry in the antenna controller can dynamically allocate bandwidth and/or adjust beam direction and directivity to optimize the spectral resources. Additionally, the TSA has an inherent advantage of wide bandwidth as demonstrated in our prior investigations [13]. Thus, the capability to dynamically reconfigure the TSA array's operating frequency and radiation pattern is possible, which enables improving the spectral efficiency of the cognitive radio. In the above array, the switching or reconfiguration is accomplished by a SP4T switch placed at the center. The switch is a gallium nitride (GaN) monolithic microwave integrated circuit (MMIC) based SP4T and couples the diplexer sequentially to any one of the TSA elements [16]. Such capabilities would play a major role in enabling the autonomous collection of the data from the science instruments placed over the lunar surface. The design can be extended or scaled to a multi-element TSA array with multi switched sector beams depending upon the application needs (Fig. 10). The modeling and simulation of the array performance using MiCIAN μ Wave Wizard EDA and CST Microwave Studio software tools are in progress [18] [19].



(a)



(b)



(c)

Fig. 9. (a) The switched four-element tapered slot circular array (TSCA) antenna top conductor side. (b) TSCA ground conductor side. (c) TSCA cross section.

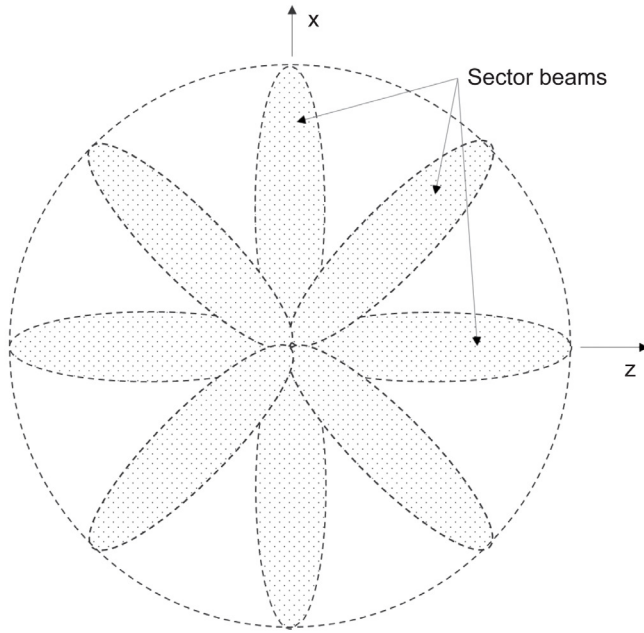


Fig. 10 Schematic illustrating switched multi-sector beams.

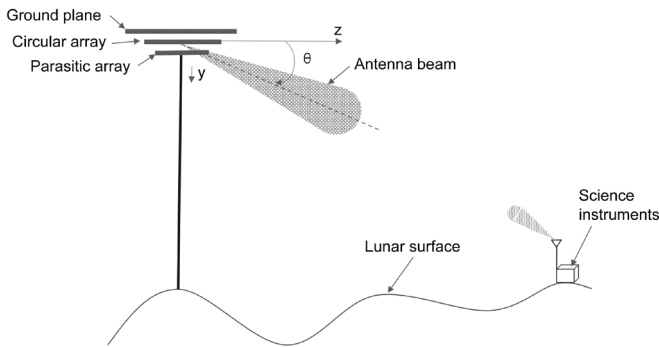


Fig. 11 Schematic illustrating the beam points direction when the array stack is inverted and elevated above the lunar surface.

V. COGNITIVE TAPERED SLOT CIRCULAR ARRAY (TSCA) ANTENNA WITH SWITCHED SECTOR BEAMS

Analogous to the antenna presented in Section III, the four-element TSCA antenna when placed above a ground plane and with a parasitic array on top can generate a beam displaced in the elevation. Such an antenna when inverted and elevated above the lunar surface can generate switched sector beams pointed in the downward direction. These beams are convenient for acquiring data transmitted by the science instruments dispersed across the lunar surface as illustrated in Fig. 11. The wide bandwidth of the TSA is an advantage because the frequency of operation, waveform, and data rates are different for each instrument since they perform different type of science (seismometer, spectrometer, UV/Visible camera, etc.) Additionally, these instruments can come from different sources such as, the Government (NASA), commercial, universities, laboratories, and international partners; and currently there are on acceptable interoperability standards for lunar surface communications.

Whether the cognition ability resides in the antenna or the antenna is part of a cognitive communication system depends on several factors. The location of the early science instruments/investigations and technology experiments delivered to the lunar surface will be known. Hence, the radio can instruct the antenna to point the beam at a given quadrant or sector. In which case very small amount of processing is required of the antenna controller and the cognition ability can reside on the software defined radio. Future payloads may include rovers, astronauts with hand-held instruments, and other mobile assets to broaden NASA's scope of knowledge. These assets may have to be found or re-discovered each time. The radio architecture can be simplified in this case by having the search conducted by the antenna. The radio would simply request to talk to a given asset and the antenna would be responsible for finding the asset. In such situations, the antenna controller has to perform significant amount of processing and it would be prudent to locate the cognition ability on the antenna. Finally, there is also the issue whether the antenna is compatible with a certain radio or is capable of working with a number of compatible radios. In the latter case, much more processing would be required by the antenna controller in order to achieve universal operation with many radio platforms.

VI. CONCLUSIONS

The design, fabrication, and characterization of a single TSA element with a balanced microstrip line feed and a sixteen-element circular array with a sixteen-way power divider as a feed has been briefly discussed. Additionally, the design of a four-element circular array with switched sector beams is presented. The circular array has applications in cognitive radios for lunar surface communications.

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