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Design of polyrod antenna having isoflux radiation characteristic for satellite communication systems

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ABSTRACT

In satellite communication, link margin and therefore antenna radiation characteristics are key factors to ensure providing a robust communication link between space and ground segment. For telemetry/telecommand and payload data transfer, isoflux antennas are employed widely in satellite communication systems to direct electromagnetic wave efficiently. To decrease complexity and manufacturing cost, simple antenna structures are preferred. In this study, after a detailed literature survey, a polyrod antenna has been designed to use in the space segment of Low Earth Orbit satellite communication subsystem. The proposed polyrod antenna has maximum gain at about 60^0 elevation angle of the antenna. Moreover, its impedance bandwidth is 750MHz (11%) that is fairly adequate to use in high data rate transmitters. By using CST Microwave Studio™ which is a commercially available 3-D electromagnetic time-domain solver, directivity, gain, axial ratio for elevation plane at X-Band, and return loss characteristic have been presented. Based on the obtained results, the designed polyrod antenna can be used where a conical shaped beam radiation pattern is needed.

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1. Introduction

Communication systems on satellites take on various tasks. Those are telemetry/telecommand (TM/TC) transmit and receive tasks, payload data transfer to a ground station, inter-satellite communication, broadcasting service, mobile communication service, etc. as mentioned by Imbriale in [1] and Akan in [2]. Due to this fact, a satellite communication subsystem for the space segment can require different kinds of antennas. Moreover, these antennas should meet harsh space requirements like atomic oxygen, vibration loads during the launch phase, ionizing radiation, extensive temperature differences as explained by Imbriale and Akan et al. in their studies [1-2].

As it is well known, in a communication subsystem, antennas are initial or final elements for a receiver or transmitter, respectively. Due to the requirement of directing electromagnetic energy into the desired area or receiving a coming electromagnetic wave more directive and effectively in a specific way, these electromagnetic energy transducers are key elements for wireless telecommunication systems. As known, artificial satellites have limited power budget and therefore, required high effective isotropic power (EIRP) for RF transmitters and G/T for receivers should be generally compensated by the antenna on the satellite platform. Furthermore, communication systems should provide a positive link margin to enhance vigorous communication link and link budget.

To compensate for increasing free space loss at the edge coverage (EoC) communication system of the satellite platform, an antenna having isoflux radiation characteristic or steerable antennas are employed. To avoid complexity, additional power consumption, and lower reliability, passive isoflux antennas are usually preferred. Therefore, there are many studies for antennas that have isoflux radiation characteristics in the open literature [3-12]. Huang presented that one can obtain a conical shaped beam using higher-order mode excitation of circular microstrip antenna in [7]. In that study, to obtain a circular polarization two probes with 90^0 phase difference are used. However, Nakano suggested a simple version of this higher-order mode excited circular patch antenna with a circular polarization feature in [8]. In this antenna, there are two perturbation notches to get a

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circularly polarized electromagnetic wave. There are also antennas that have higher circular polarization purity i.e. lower axial ratio compared to microstrip antennas. Two of them are bifilar and quadrifilar helix antennas as presented by Zackrisson, Choi et al. and Colantonio [4-6]. Despite they have wide beamwidth, maximum gain values of them are generally low. Therefore, they are often used for TM/TC communication subsystems of LEO satellites. Moreover, the production stages of these antennas are quite difficult, since their radiation characteristic strictly depends on the physical parameters of the helix structure. Another important point is that some mechanical reinforcement can be required to enhance their strength against to vibration loads of the launch phase. Because in some applications, helix length can be long while its diameter is quite small which can make this antenna vulnerable to the vibration loads. In [11], X-Band choke ring horn antenna was designed and manufactured to use on SWOT mission of NASA as indicated by Chahat et al. The designed antenna has isoflux radiation pattern with circular polarization at X-Band. Another X-Band isoflux antenna design was presented by Fallahzadeh et al. in [12] to obtain a maximum gain at 62.5^0 elevation angle of the antenna.

Polyrod or dielectric rod antennas have been widely used for different applications like wireless communication, since 1939 as stated by Abumunshar and Sertel in [13]. They can also be employed at millimeter-wave integrated circuits to utilize the surface waves [13]. Kobayashi et al. designed a tapered dielectric rod antenna operating at 81.5GHz as indicated in [14]. In another study, a dielectric rod antenna was designed and used for chip to chip communication at W-Band by Ghassemi and Wu in [15]. 3-D printing technique which is a today's technology, can also be applied easily to manufacture polyrod antennas as presented by Huang et al. in their studies [16]. In that paper, the authors designed a wideband circularly polarized dielectric rod antenna that operates between 4.05GHz and 7.55GHz. Then it was manufactured using 3-D printer Zortrax M200 and Flashforge Guider IIs. Polyrod antennas are not only used as single element radiator but also used to form antenna arrays. By Shokouhi and Firouzeh, linear array of dual polarized slot coupled dielectric rod radiators was proposed in their study [17].

Polyrod antennas excited by a circular horn antenna support TE_{11} antenna as mentioned by Milligan [18]. This TE_{11} mode also excites the hybrid mode of HE_{11}. In [19], a rectangular dielectric rod antenna fed by parallel strip line was proposed by Hou et al. The operating frequency band of the antenna was 5.4 to 6.6GHz as mentioned by the authors. Therefore, this study indicates that dielectric rod antennas can be fed by different types of transmission lines. The dielectric rod antennas are also utilized for pulsed power systems as highlighted by Petrella et al. in [20]. In their study, they designed a polyrod antenna that can generate 500 ps pulse with an amplitude of 600 V/cm for a 25 kV input from the pulse transformer to stimulate biological tissues. There are different techniques to enhance bandwidth of a dielectric rod antenna. One of them is presented by Abumunshar and Sertel in [13]. In that study, feed and radiation tapering sections were used in order to get 5:1 impedance and radiation bandwidth that covers 6-30GHz as shown in [13]. So the designed polyrod antenna has an ultra-wide bandwidth. However, there are very limited published study in the literature about polyrod or dielectric rod antennas to use in satellite communication systems as isoflux radiator. The best known study was published by King et al. [21].

To benefit high radiation efficiency, wide bandwidth, and stable radiation pattern characteristic of the polyrod antenna, in this study a modified polyrod antenna design is proposed where a horn antenna structure can be used with a simple geometry of dielectric to maximize the directivity at high elevation angles of the antenna. As it is well known that a horn antenna and conical dielectric part can be easily manufactured today on a computer numerical control (CNC) milling machine. Furthermore, due to its proportional structure, this antenna is quite robust against vibration load. Another advantage of the polyrod antenna is that its maximum gain elevation angle can be modified by altering the geometry of the conical dielectric part. Thus, an isoflux polyrod antenna that has a maximum gain at about $\pm 60^0$ elevation angles has been designed to get an isoflux radiation characteristic to satisfy the link budget requirements of LEO satellite communication systems that operate at X-Band.

First of all, in part two, the importance and the reason of isoflux radiation pattern requirement for LEO satellite communication link are discussed. Afterwards in part three, polyrod antenna has been explained and a basic study and its results are presented. In addition, how the radiation characteristic changes with respect to some varying physical dimensions is studied in this part. Then an optimized polyrod antenna which has maximum gain at higher elevation angle has been proposed and its directivity and axial ratio pattern results are presented. The obtained results are promising to use in space segment for satellite communication, particularly for payload data transfer.

2. Importance of Isoflux Radiation Pattern for Satellite Communication

As mentioned in the previous section, at the EoC more EIRP is needed to reimburse increasing free space loss. For this recompense, increasing output RF power can cost too much, since there would be needed more expensive RF signal amplifying section like Travelling Wave Tube Amplifier (TWTA) or solid-state amplifier component and also it leads to more DC power consumption. Instead of increasing RF output power, there is a passive solution: this is to use an antenna that has isoflux radiation pattern. A simple geometrical calculation can be given to define change of range with respect to the elevation angle of a satellite. As shown in Figure 1, slant range relation between satellite and ground station can be evaluated using earth radius R (equals to about 6378km), satellite altitude h, antenna elevation angle θ, and satellite elevation angle with respect to horizon α.

Then utilizing cosine law on this geometry Slant Range can be approximated for the EoC assuming the ground station is in line of sight of the satellite as below

$$Slant\ Range = [R^2 + (R+h)^2 - 2R(R+h)\cos\gamma]^{1/2} \quad (1)$$

Furthermore, using sine law, the relation between the antenna elevation angle (on satellite) and elevation angle of the satellite can be given as

$$\frac{R}{\sin\theta} = \frac{R+h}{\sin(90+\theta)} \quad (2)$$

Based on these relations, change of the antenna elevation angle (on satellite) versus the elevation angle of the satellite can be demonstrated as given in Figure 2. From Figure 2, it is obvious that the antenna elevation angle equals zero when the ground station is at the nadir point of the satellite i.e. the satellite is exactly on the ground station. Besides, free space loss can be calculated from the Friis transmission equation using slant range relation. It is written as;

$$FSL = \left(\frac{4\pi\ Slant\ Range}{\lambda}\right)^2 \quad (3)$$

In this equation, λ is the wavelength for operating frequency of the communication link between the satellite and the ground station. Using Equation (3) and Equation (2) free space loss has been evaluated with respect to the elevation angle of the satellite as presented in Figure 3.

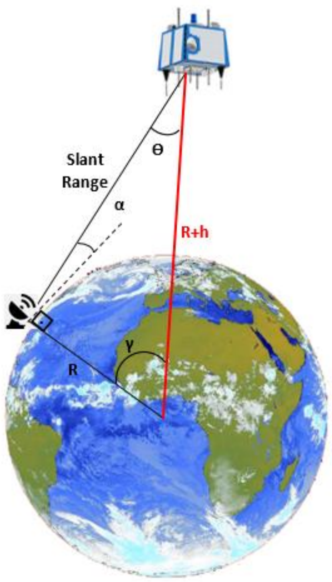

Figure 1. Geometrical illustration of slant range, antenna elevation angle, and satellite elevation angle

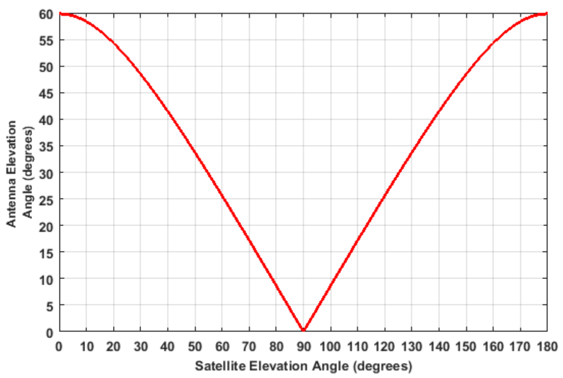

Figure 2. Evaluated antenna elevation angle for the given satellite elevation angle

As expected minimum free space loss occurs at 90^0 value of the satellite elevation angle, since the distance between the satellite and ground station is minimum. However, it is the maximum at 0^0 and 180^0 values of the satellite elevation angle where the distance reaches its maximum value.

3. Polyrod Antenna

In this study, a polyrod antenna has been designed and analyzed to get isoflux coverage for satellite communication systems. Comprehensive experimental studies have been carried out by Mueller and Mallack as given in [22, 23] for the analysis of the polyrod antenna. A polyrod antenna that has cross-sectional dimensions in the order of a wavelength behaves like a dielectric lens. Particularly, assured laws of this behavior have been found by King et al. and Wilkes who are the researchers of the Applied Physics Laboratory of the Johns Hopkins University [21, 24]. Besides, in [22], King obtained a shaped beam radiation pattern to use on satellite platforms by using Silver's analytical beam synthesis approach for circular aperture antenna given in [25]. In [21], the easiness of manufacturing polyrod antenna is especially highlighted. For this antenna, a dielectric rod exceeds the flare of a conical horn antenna and then its diameter is decreased gradually down to the defined value as indicated in Figure 4. The dielectric material is chosen as polystyrene that is a kind of aromatic hydrocarbon polymer for the rod part of this antenna structure.

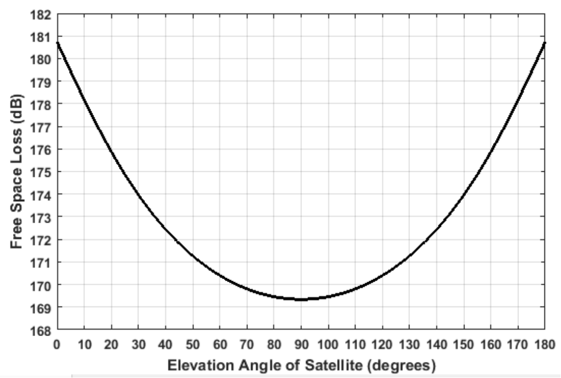

Figure 3 Evaluated free space vs. Elevation angle of the satellite at operating frequency of 7GHz

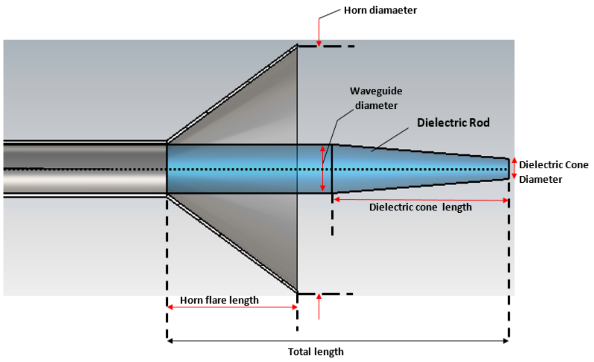

Figure 4. Shaped beam dielectric rod antenna [21]

The dimensional parameters of the antenna are shown in Figure 4.

Related physical dimensions of the polyrod antenna studied by King et al. are given in Table 1 [21]. Polystyrene's dielectric permittivity and loss tangent are 2.5 and 0.00033, respectively.

Using the suggested dimensions given in [21] simulation result for normalized directivity of the antenna at 7.3GHz is given in Figure 5 by utilizing circularly polarized wave excitation. Nonetheless, the same results could not be obtained. The obtained directivity values are about 10.6dBi and 10.1dBi at $\theta = \pm 20^0$ by simulation. Given directivity values are about 12.42dBi, in [21]. It is considered that the reasons for these discrepancies are tolerances of manufacturing and dielectric material permittivity.

For different physical dimensions, simulations have been realized to see the effects of them onto antenna radiation characteristics. Foremost, effect of flare has been studied. For different values of horn radius simulations have been carried out and results are presented in Figure 3. But, as shown in Figure 6, the effect of horn dimension is poor to widen the beamwidth.

Table 1. Polyrod antenna dimensions given in [21]

Dimensions	Inch *(mm)*
Horn Diameter (Flare Diameter)	5.1 *(129.54)*
Waveguide Diameter	1.35 *(34.29)*
Dielectric Cone Diameter	0.564 *(14.33)*
Horn Flare Length	3.72 *(94.49)*
Total Length	9.72 *(246.89)*

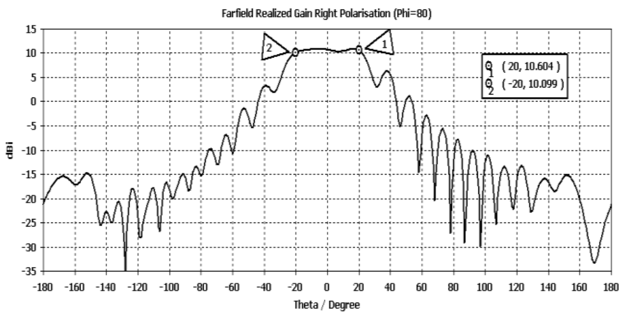

Figure 5. Simulation result for directivity pattern of shaped beam dielectric rod antenna at 7.3GHz using physical dimensions in [21]

Secondly, simulations have been iterated by changing the dielectric rod length, since it is apparent that the dielectric rod is dominant to shape the beam from the study given in [24].

According to these simulations, dielectric rod length is seemingly effective to shape the beam as shown in Figure 7.

4. Design of Polyrod Antenna having Wider Beamwidth

Depending upon orbit height of a satellite elevation angle where the maximum gain is obtained can be a different value. For example, for (Low Earth Orbit) LEO and Middle Earth Orbit (MEO) satellites, this elevation angle will be higher. According to an example of link budget where 800km orbit height, it will be required a maximum directivity at approximately 60^0. Therefore, after many parameter sweeps and optimization process maximum directivity at $\theta = 58^0$ has been accomplished. The cross-sectional view and dimension parameters of the designed polyrod antenna are shown in Figure 8. As dielectric material, another low loss substance PTFE (Teflon) has been selected. Its dielectric permittivity and loss tangent are 2.1 and 0.0002, respectively. In addition, a septum polarizer or dual feed with 90^0 phase difference can be used to form a circularly polarized wave at output of the antenna. Throughout the simulations a septum polarizer has been utilized. Nonetheless, for the sake of brevity its design is not given in this article.

In this structure, the dielectric rod consists of two parts. The first one which is inside the flare follows shape of the cone of horn and then the second part which is outside the horn and its circular area becomes smaller gradually.

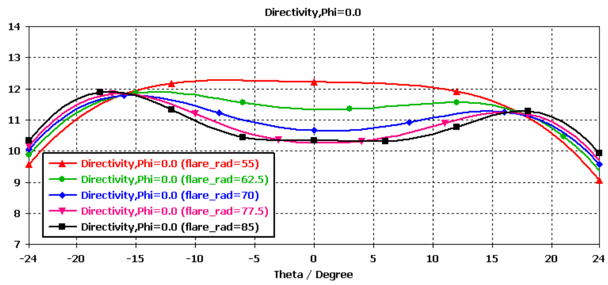

Figure 6. Directivity pattern of polyrod antenna for different flare radius values obtained by simulation at 7GHz

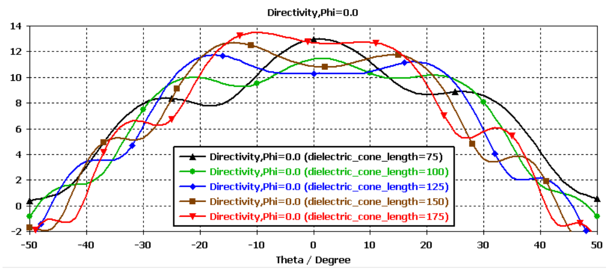

Figure 7. Directivity pattern of polyrod antenna for different dielectric cone lengths at 7GHz

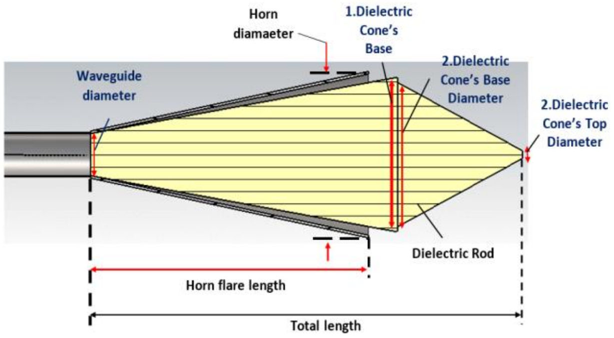

Figure 8. Longitudinal cross-section view and dimensions of the designed polyrod antenna in this study

As stated by Mueller and Wilkes [22, 24], the geometrical transition between first and second dielectric cone is effective to shape the beam of the antenna and it behaves similar to lens antennas. The physical dimensions of the designed antenna are tabulated in Table 2.

The acquired circularly polarized radiation pattern is presented in Figure 9 for the operating frequency of 7GHz. As shown in this figure second maximum (after the boresight) directivity value is 4.96dBic obtained at $\theta = -58^0$ for $\phi=0^0$ cut plane.

However, a tolerable asymmetry is determined again with respect to $\theta = 0^0$. It's tolerable because the directivity at $\theta = 58^0$ is about 4.1dBic. It is evident that once beamwidth widens then the maximum directivity decreases as expected. In Figure 10, the variation of axial ratio with respect to θ at $\phi=0^0$ cut is seen. Particularly, for θ values where maximum directivity is obtained, axial ratio values are lower than 1.5dB. Moreover, between θ angle values where the maximum directivity is obtained, the axial ratio value is almost smaller than 10dB. In that manner, its axial ratio purity is at a reasonable level as a circularly polarized antenna.

Table 2. Dimensions of the designed polyrod antenna in this study

Dimensions	(mm)
Horn Diameter	130
Waveguide Diameter	34.29
1st Dielectric Cone Base Diameter	124.286
2nd Dielectric Cone Base Diameter	116.286
2nd Dielectric Cone Top Diameter	6
Horn Flare Length	240
Total Length	373

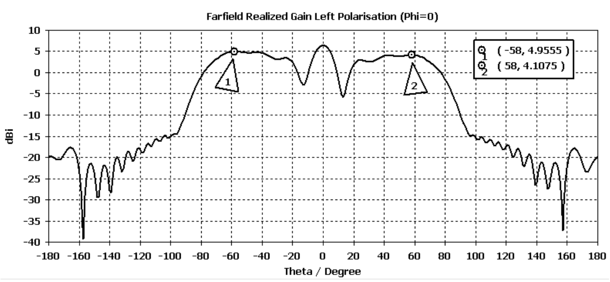

Figure 9. Directivity of the designed antenna at $\phi=0^0$ cut plane.

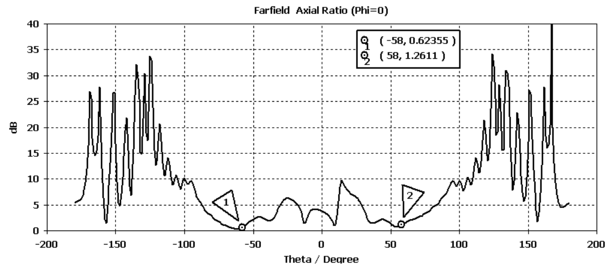

Figure 10. Axial ratio of the designed antenna at $\phi=0^0$ cut plane

Besides, 3-D radiation pattern for directivity is seen in Figure 11. According to this figure conical shaped beam is obvious.

The return loss of the antenna has also been obtained by the simulation and it is given in Figure 12. This result demonstrates 10dB return loss bandwidth of the antenna is at a good value range for the defined frequency band of 7-7.5GHz.

In Table 3, obtained antenna characteristics have been compared to results of some studies available in the literature. As seen from Table 3, in [11, 12] choke ring horn antenna was employed to get isoflux pattern which have a maximum directivity/gain at 60^0 and 62.5^0 elevation angle, respectively.

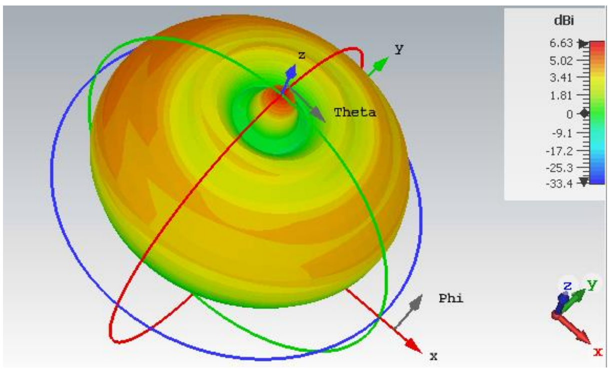

Figure 11. 3-D radiation directivity pattern of the designed antenna

Table 3. Comparison of the proposed polyrod antenna with the studies available in the literature

	This Study	[21]	[11]	[12]
Antenna Type	Polyrod	Polyrod	Choke ring horn	Choke ring horn
Radiation Characteristic	Isoflux	Isoflux	Isoflux	Isoflux
Elevation angle where the max directivity obtained	58^0	20^0	60^0	62.5^0
Operating Frequency Band	X-Band	X-Band	X-Band	X-Band
Maximum Gain	3.8dBic	Not available	4.9dBic	2.5dBic
Polarization	Circular	Circular	Circular	Circular

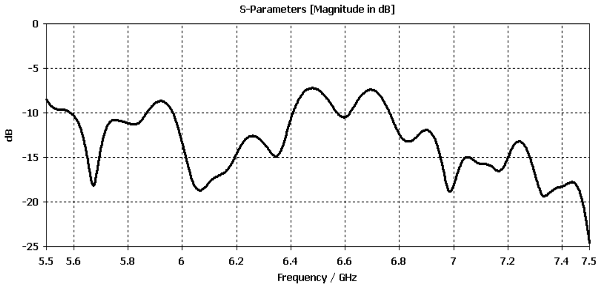

Figure 12. Return loss of the designed antenna.

There is a slightly difference of the elevation angles where the maximum gain is obtained for this study and the antennas given in [11, 12]. Furthermore, the choke ring antenna studied in [11] has maximum gain of 4.9dBic. The proposed polyrod antenna has 3.8dBic maximum gain in this study. This is higher than maximum gain of the antenna presented in [12].

In this paper, a shaped beam polyrod antenna having maximum directivity at about 60^0 has been designed and presented. According to the author's best knowledge there is only one study about isoflux polyrod antenna in the literature. This is the paper published by King et al. [21]. Hence, a direct comparison couldn't be realized for obtained results of the proposed antenna structure in this paper. However, it should be noted that the proposed polyrod antenna's maximum directivity has been obtained at a higher elevation angle value compared to the angle obtained in King's study [21]. Therefore, the proposed antenna is appropriate to utilize it for LEO satellite communication subsystem. Its 10dB return loss bandwidth is about 750MHz (about 11%) and it keeps the radiation pattern stable through this frequency band. Since microstrip patch, bifilar and quadrifilar helix antennas have resonant characteristic, their operating frequency bands are limited approximately 1.5% without an impedance matching. Colantonio et al. [6] designed a stepped coaxial matching circuit to enhance the operating bandwidth of the bifilar antenna. However, in this study there is no need to an additional matching circuit like that.

5. Conclusions

As mentioned in the previous parts of this paper, to widen coverage area of antennas on satellite platforms isoflux radiation characteristic is needed for TM/TC and high throughput payload data transfer communication systems. In this way, link margin of a communication link between satellite and the ground station can be kept above 0dB.

In the open literature, there are many different types of antennas to reach this goal. One of them is polyrod antenna but the given results are only for narrow beamwidth specification i.e. for higher satellite orbits. In this paper, a polyrod antenna that has an isoflux radiation characteristic has been designed and analyzed using CST Microwave Studio™ which is a commercially available 3-D electromagnetic solver, approximately at $\theta = 60^0$. This antenna can radiate circularly polarized electromagnetic wave at 7GHz and it has a conical-shaped pattern. By changing the physical parameters of the dielectric rod and the horn, its theta value where maximum directivity need can be varied. Compared to the designed polyrod antenna by King [21], the proposed antenna has maximum directivity at higher elevation angle (for the antenna) which is subtended to lower elevation angle for the satellite as evaluated in Figure 2. In this way, the coverage area of polyrod antenna has been increased to use on satellites which orbit in lower altitudes. In addition, the proposed polyrod antenna has been compared to choke ring horn antennas available in the literature. Based on these comparisons, the proposed antenna has promising electrical characteristic. It should be also noted that manufacturing process of a choke ring horn antenna is more difficult than the polyrod antenna and this is an important factor which can lead higher manufacturing costs. As future work, manufacturing of prototype, and measurements of the designed antenna will be realized to verify the simulation results. Then, it will be employed for the next satellites to be designed and manufactured at TUBITAK Space Technologies Research Institute.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, has been prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Nomenclature

α	: Elevation angle of satellite
C-Band	: Frequency band between 4 and 8GHz
DC	: Direct Current
EIRP	: Effective Isotropic Radiated Power
EoC	: Edge of Coverage
FSL	: Free Space Loss
G/T	: Receiver gain over noise temperature ratio
γ	: Central angle
h	: Altitude of satellite
λ	: Wavelength of RF signal at the operating frequency
R	: Radius of the Earth
θ	: Elevation angle of the antenna on a satellite
S-Band	: Frequency band between 2 and 4GHz
TM/TC	: Telemetry and Telecommand
W-Band	: Frequency band between 75 and 110GHz
X-Band	: Frequency band between 8 and 12GHz

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