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Design and Link Budget Calculations of a 2x2 Ka-Band Phased Array Receive Antenna for Communication with Geostationary Satellites on Ankara-Paris Flights

Batuhan KOYUNCU[1*] Özgür DÜNDAR[2] Berkin FENLİ[3] Esra Benli ÖZTÜRK[4]

[1,3,4] Turkish Aerospace Industries, Inc., Ankara, Türkiye

[2] Necmettin Erbakan University, Faculty of Engineering, Department of Aeronautical and Aerospace Engineering, Konya, Türkiye

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ABSTRACT

This study focuses on the design and performance analysis of a 2x2 Ka-Band phased array patch antenna developed to address the increasing demand for internet connectivity in aviation. Taking advantage of the low profile, lightweight, and aerodynamic benefits of microstrip antennas, the system was designed and simulated using HFSS software. Impressive results were achieved at a center frequency of 19.49 GHz, with a bandwidth of 2.36 GHz and a return loss (S11) of -32.47 dB. The antenna provides a gain of 14.90 dBi, indicating a sufficient performance level for Ka-band communication. Additionally, the use of Rogers RT/Duroid 5880 substrate and the edge-fed structure ensures stability in high-frequency operations. One of the notable contributions of the paper is the link budget analysis conducted via the Systems Tool Kit (STK) software. Based on a flight scenario between Ankara and Paris, the simulations demonstrated that the system can maintain uninterrupted communication with a geostationary satellite, achieving an Eb/N0 value of 13.60 dB and a margin of 0.55 dB. Variations in signal strength along the flight path were evaluated, and the system's response to different altitudes and elevation angles was examined. Overall, the study presents a low-profile and efficient antenna solution for satellite-based internet services in civil aviation, laying a robust foundation for future enhancements such as larger arrays (e.g., 4x4) and adaptive beamforming algorithms.

Ankara – Paris Arası Uçuşlarda Jeosenkron Uydularla Haberleşebilen 2x2 Ka-Bant Faz Dizinli Alma Hattı Anteni Tasarımı ve Hat Bütçesi Hesaplamaları

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ÖZET

Bu çalışma, havacılıkta artan internet bağlantısı ihtiyacına yönelik olarak geliştirilen 2x2 Ka-Bant faz dizinli alma hattı anteninin tasarımı ve performans analizine odaklanmaktadır. Mikroşerit antenlerin düşük profil, hafiflik ve aerodinamik avantajlarından faydalanılarak tasarlanan sistem, HFSS yazılımı ile simüle edilmiş ve 19.49 GHz merkez frekansta, 2.36 GHz bant genişliği ve -32.47 dB'lik geri dönüş kaybı (S11) ile etkileyici sonuçlar elde etmiştir. Antenin 14.90 dBi kazanç sağlaması, Ka-band haberleşmesi için yeterli bir performans düzeyine işaret etmektedir. Ayrıca kullanılan malzeme (Rogers RT/Duroid 5880) ve kenar beslemeli yapı sayesinde yüksek frekanslı çalışmalarda kararlılık sağlanmıştır. Makalenin öne çıkan katkılarından biri de, Systems Tool Kit (STK) yazılımı aracılığıyla yapılan bağlantı bütçesi analizidir. Ankara-Paris arası uçuş senaryosuna dayalı olarak yapılan simülasyonlar, 13.60 dB'lik Eb/N0 değeri ve 0.55 dB marjin ile sistemin jeosenkron bir uydu ile kesintisiz haberleşmeyi sürdürebileceğini göstermiştir. Uçuş rotası boyunca sinyal gücündeki değişkenlikler değerlendirilerek, sistemin farklı irtifa ve eğim açılarına karşı tepkisi incelenmiştir. Genel olarak çalışma, sivil havacılıkta uydu tabanlı internet hizmetleri için düşük profilli ve etkili bir anten çözümü sunmakta; ileride daha büyük diziler (örneğin 4x4) ve uyarlanabilir yönlendirme algoritmalarıyla geliştirilmeye açık sağlam bir temel oluşturmaktadır

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***Corresponding Author:** Batuhan Koyuncu, *batuhankoyuncu1@gmail.com*

INTRODUCTION

The aviation industry has undergone significant technological advancements in response to growing passenger demands for enhanced in-flight services. Among these advancements, satellite-based internet services have become essential for providing seamless connectivity over vast geographic areas [1,2]. The Ka-band (receive: 17.7-21.2 GHz, transmit: 26-31 GHz) is widely preferred for satellite communication because it supports high data rates with reduced latency compared to lower frequency bands. However, achieving optimal performance in Ka-band communication requires advanced antenna technologies and robust satellite communication systems [3,4].

Phased array antennas have emerged as a preferred choice for civil aviation applications due to their low-profile design and aerodynamic advantages over conventional parabolic reflector antennas [5]. Table 1 compares the advantages and disadvantages of different antenna types used in aviation satellite communications.

Table 1
Antenna Types Used in Aviation Satellite Communication

Antenna Type	Antenna Type	Antenna Type
Parabolic (Reflector) Antenna	• High gain • stable long-distance communication	• Requires mechanical steering • aerodynamic limitations
Phased Array Antenna	• Electronic beam steering • Low profile and aerodynamic design	• higher power consumption • Lower gain compared to parabolic antennas

An analysis of the table indicates that phased array microstrip antennas stand out as the preferred choice for Ka-band satellite-based internet communication in civil aviation. This preference is primarily attributed to their ease of satellite tracking and aerodynamic advantages compared to other antenna types.

Microstrip antennas consist of a conductive patch and a ground plane positioned on a dielectric substrate. The patch, typically made of conductive materials such as copper or gold, can be designed in various geometric shapes, including rectangular, circular, or triangular configurations. Due to their lightweight structure, low profile, and ease of fabrication, microstrip antennas are widely employed in applications such as aircraft, spacecraft, and mobile radio communication systems [6]. However, they exhibit inherent limitations, including narrow bandwidth and low gain. To mitigate these disadvantages while enhancing their performance, array antenna configurations have been developed [7].

Microstrip array antennas, which integrate multiple antenna elements, offer improved gain and narrower beamwidth. By incorporating phase shifters, the direction of the signal can be electronically controlled, which is critical for satellite tracking in mobile platforms such as aircraft [8].

Recent advancements in microstrip array antenna technology have significantly expanded their applicability across various fields, including satellite communications. Their adoption in civil aviation, particularly within the Ka and Ku frequency bands, has been increasing rapidly [4, 9, 10].

This study focuses on the design of a 2×2 microstrip array antenna operating in the Ka-band receive frequency range of 18–21 GHz for satellite-based internet communication on passenger aircraft. Additionally, the communication performance of the designed array antenna with a geostationary (GEO) satellite is evaluated through link budget analysis.

The phased array antenna design and its optimizations were conducted using the High Frequency

Structural Simulator (HFSS) software. HFSS serves as an effective tool for simulating electromagnetic fields and conducting detailed antenna performance analyses [11]. Through this software, critical antenna parameters such as gain, return loss (S11), and bandwidth were analyzed. Further enhancements were implemented to optimize frequency and gain performance.

Once the 2×2 phased array antenna design was finalized, its integration into a potential passenger aircraft and link budget analyses with a GEO satellite were carried out using the Systems Tool Kit (STK) software. STK is a comprehensive simulation tool for modeling communication links between satellites and mobile platforms such as aircraft [12]. The simulations and analyses provided insights into key performance metrics, including signal strength, data transmission rates from the satellite, and variations in link budget margins over the flight duration.

Link budget analysis plays a critical role in evaluating the performance of satellite communication systems. This analysis accounts for signal power levels, atmospheric effects, and various losses to determine overall system efficiency [13]. In this study, a detailed link budget analysis of the communication between the 2×2 microstrip phased array antenna and a GEO satellite was conducted. These calculations provide an assessment of the antenna's effectiveness and its potential performance under real-world conditions.

The results of this study demonstrate the feasibility of utilizing the designed 2×2 microstrip phased array antenna for satellite-based internet communication on passenger aircraft operating within the Ka-band receive frequency range (18–21 GHz). The simulation results and performance evaluations confirm that the antenna is capable of establishing a reliable communication link between the aircraft and the satellite. The development of such antenna designs contributes to the improvement of in-flight internet service quality, fostering innovative solutions within the aviation sector. Furthermore, this study aims to serve as a foundation for future research and development efforts in antenna design for satellite communication applications.

METHODOLOGY

Microstrip Antenna Design

Before initiating the design of a 2×2 microstrip array antenna operating within the Ka-band frequency range (18–21 GHz), a single patch antenna was initially designed to operate at the same frequency. After evaluating the simulation results of the single patch antenna, a multi-element array structure was developed and analyzed.

In the design of the single microstrip patch antenna, the first step involves calculating the antenna width (W). The calculation of W requires the dielectric constant (ϵ_r) of the selected antenna substrate material and the operating center frequency (f_r) [9]. In this study, Rogers RT/Duroid 5880, a widely used substrate material in the aerospace and communication industries, was chosen. This material has a dielectric constant of 2.2 and a thickness of 1.575 mm.

For the computation of the antenna width (W), additional parameters such as the dielectric constant of free space (ϵ_0) and the magnetic permeability of free space (μ_0) must also be considered. The antenna width is calculated using Equation (1), where the speed of light is assumed to be $c_0 = 3x10^8\ m/s$.

$$W = \frac{1}{\left(2f_r\sqrt{\mu_0\varepsilon_0}\right)}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{c_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

After calculating the W length, it is verified whether the condition W/h ≥ 1 is satisfied.

Subsequently, the effective dielectric constant (ϵ_{reff}) is computed using Equation (2) [9].

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

Next, the effective electrical length (L_{eff}) is determined using Equation (3).

$$L_{eff} = \frac{c_0}{2f_c\sqrt{\epsilon_{reff}}} \tag{3}$$

After calculating the values of W, ϵ_{reff} and L_{eff}, the final length of the microstrip patch antenna (L) is determined using Equations (4) and (5).

$$\Delta L = 0{,}412\, x \frac{(\epsilon_{reff} + 0{,}3)\left(\frac{W}{h} + 0{,}264\right)h}{(\epsilon_{reff} - 0{,}258)\left(\frac{W}{h} + 0{,}8\right)} \tag{4}$$

$$L = \frac{c_0}{2f_c\sqrt{\epsilon_{reff}}} - 2\Delta L \tag{5}$$

Link Budget Design Parameters

Link budget calculations are among the most critical analyses in wireless communication systems. Particularly in long-distance communication scenarios, such as ground-to-satellite communication, a comprehensive evaluation of all parameters affecting RF transmission and reception is required to ensure successful data exchange. The link budget represents a systematic approach to analyzing these parameters and determining the overall feasibility of a communication system.

In this study, a link budget analysis was conducted for a 2×2 phased array Ka-band receive antenna. The analysis focuses on evaluating the communication link between a receive antenna mounted on a passenger aircraft and a potential GEO satellite.

For the theoretical analysis of the link budget, the first step is to calculate the Effective Isotropic Radiated Power (EIRP) of the RF transmission source. EIRP quantifies the radiated power of an antenna in a specific direction. In this scenario, the RF transmission source is the satellite, meaning the EIRP of the satellite must be considered as the primary reference [14]. This value can be calculated theoretically or obtained directly from the satellite operator's specifications. The satellite EIRP is determined using Equation (6).

$$EIRP = P_t + G_t - L_t\ (dB) \tag{6}$$

During the transmission of the RF signal from the satellite to the aircraft, several losses occur, primarily due to distance and propagation effects. One of the most significant losses in satellite communication is Free Space Path Loss (FSPL), which quantifies the attenuation of the signal as it propagates through free space. FSPL is calculated using Equation (7).

$$L_{FS}(dB) = 20\,log(f\,) + 20\,log(r) + 32.44 \tag{7}$$

To ensure the accuracy of the link budget calculation, all potential losses in the system must be precisely analyzed and incorporated into the overall assessment. In addition to Free Space Path Loss (FSPL), other factors contributing to signal degradation must be considered, including:

- Implementation losses (e.g., hardware imperfections and inefficiencies),
- Antenna misalignment losses (caused by deviations in beam pointing accuracy),
- Atmospheric losses, which are determined based on the ITU-R P.618 standard, accounting for attenuation due to rain, clouds, and atmospheric gases.

Once all individual losses are identified, the total transmission loss is computed using Equation (8).

$$L_{Total} = FSPL + L_{atm} + L_{pointing} + L_{imp}\ \text{dB} \tag{8}$$

On the receiver antenna side, the G/T value is used as an input for the link budget analysis. This term represents the ratio of an antenna's gain (G) to the system's total noise temperature (T) and serves as a key parameter in assessing the receiver performance in satellite communication. The G/T value of the aircraft-mounted antenna is calculated using Equation (9).

$$\frac{G}{T} = Gr - 10\,log10(T_{sys})\ dB \tag{9}$$

Another crucial aspect of link budget calculations involves the carrier parameters of the RF connection, which define the characteristics of the transmitted and received signal. The first carrier parameter to be calculated is the symbol rate (SR), which represents the number of symbols transmitted per second.

The symbol rate (SR) is determined based on the net data rate (DR), the forward error correction (FEC) rate, and the modulation order (M). For Quadrature Phase Shift Keying (QPSK) modulation, the modulation factor is M = 2. The symbol rate (SR) is calculated using Equation (10).

$$SR\ (Msps) = \frac{DR}{M * FEC} \tag{10}$$

In determining the carrier bandwidth for the aircraft-satellite communication link, the roll-off factor (RO) is taken into account. The carrier bandwidth (BW) is computed using Equation (11).

$$BW\ (MHz) = SR * (1 + RO) \tag{11}$$

In the final stage of link budget calculations, performance parameters are incorporated into the analysis. One of the key parameters is the Carrier-to-Noise Ratio (C/N), which quantifies the ratio of the received carrier signal power to the noise power in the communication channel. The C/N value is calculated using Equation (12) [9].

$$\left(\frac{C}{N}\right) = EIRP + \left(\frac{G}{T}\right) - \left(L_{fspl} + L_{other\ losses}\right) - (-228{,}6) - B_N \tag{12}$$

Another key performance parameter in link budget calculations is the Energy per Bit to Noise Power Spectral Density Ratio (Eb/N0). This metric quantifies the electrical signal power per bit relative to the noise spectral density, providing a critical measure of communication link efficiency. The Eb/N0 value is determined using Equation (13).

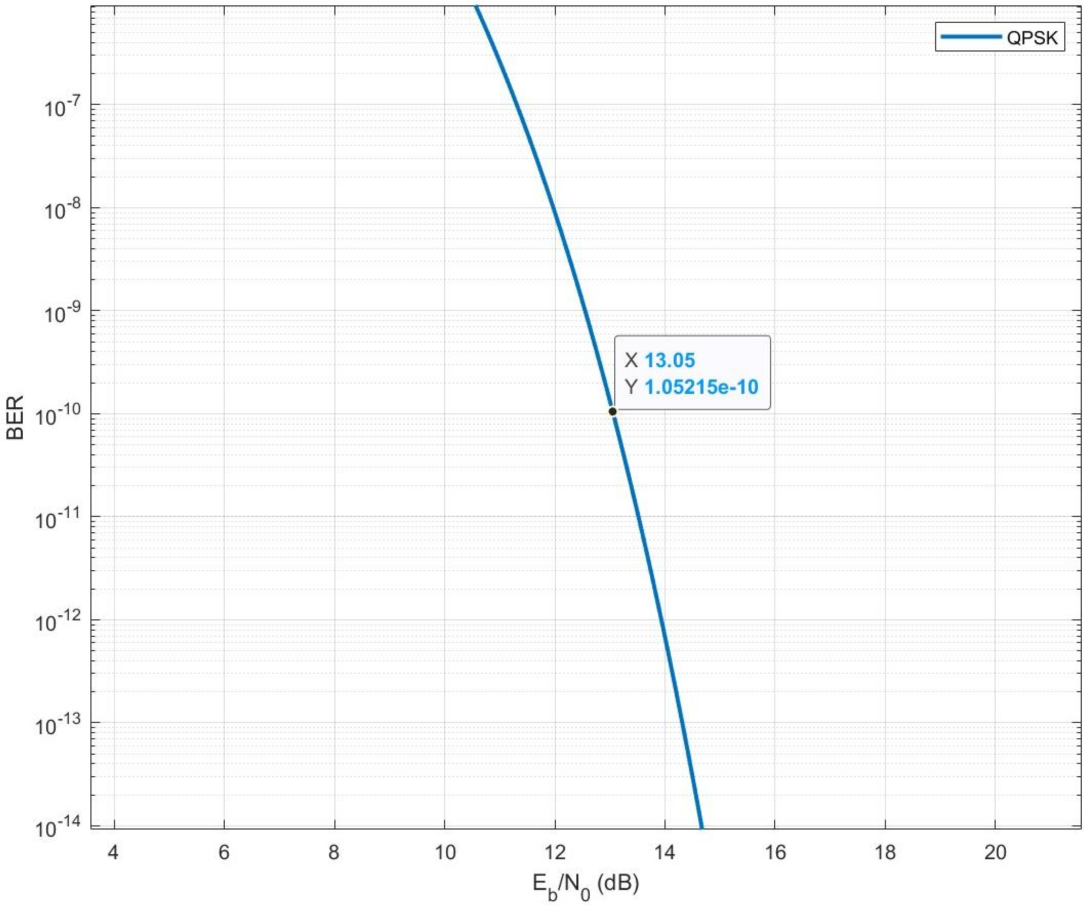
$$\left(\frac{E_b}{N_0}\right) = \frac{BW}{DR} * \left(\frac{C}{N}\right) \tag{13}$$

To evaluate system performance, it is crucial to determine the minimum required Eb/N0 value for the communication system. A comparative analysis between the theoretical Eb/N0 value and the actual Eb/N0 obtained from the system provides an accurate assessment of link reliability and signal quality.

In this study, the target Bit Error Rate (BER) is set to 10^{-10}, which ensures highly reliable data transmission. For Quadrature Phase Shift Keying (QPSK) modulation, the minimum required Eb/N0 values are illustrated in Figure 1.

This comparison is critical in verifying whether the communication system meets the required performance criteria, ensuring that the satellite-aircraft link operates effectively under real-world conditions.

Figure 1
Theorical Eb/N0 Values



As part of the link budget performance evaluation, the measured Eb/N0 value obtained from system simulations is compared with the theoretically calculated minimum required Eb/N0. This comparison ensures that the communication system meets the required performance thresholds for reliable data transmission.

The link margin is calculated using Equation (14).

$$\left(\frac{E_b}{N_0}\right)_{margin} = \left(\frac{E_b}{N_0}\right)_{received} - \left(\frac{E_b}{N_0}\right)_{theorical} \tag{14}$$

FINDINGS

Microstrip Antenna Designs and Simulations

The microstrip antenna designs were implemented in HFSS (High Frequency Structural Simulator) following the theoretical design methodology and steps outlined in the Methodology section. The designed antennas operate within the Ka-band receive frequency range (18–21 GHz), specifically optimized for satellite-to-aircraft communication.

As the initial step, a single patch antenna was designed and simulated. Following the performance evaluation of the single patch antenna, a 2×2 phased array configuration was developed. The design parameters used for the antennas are provided in Table 2.

Table 1

Microstrip Antenna Design Parameters

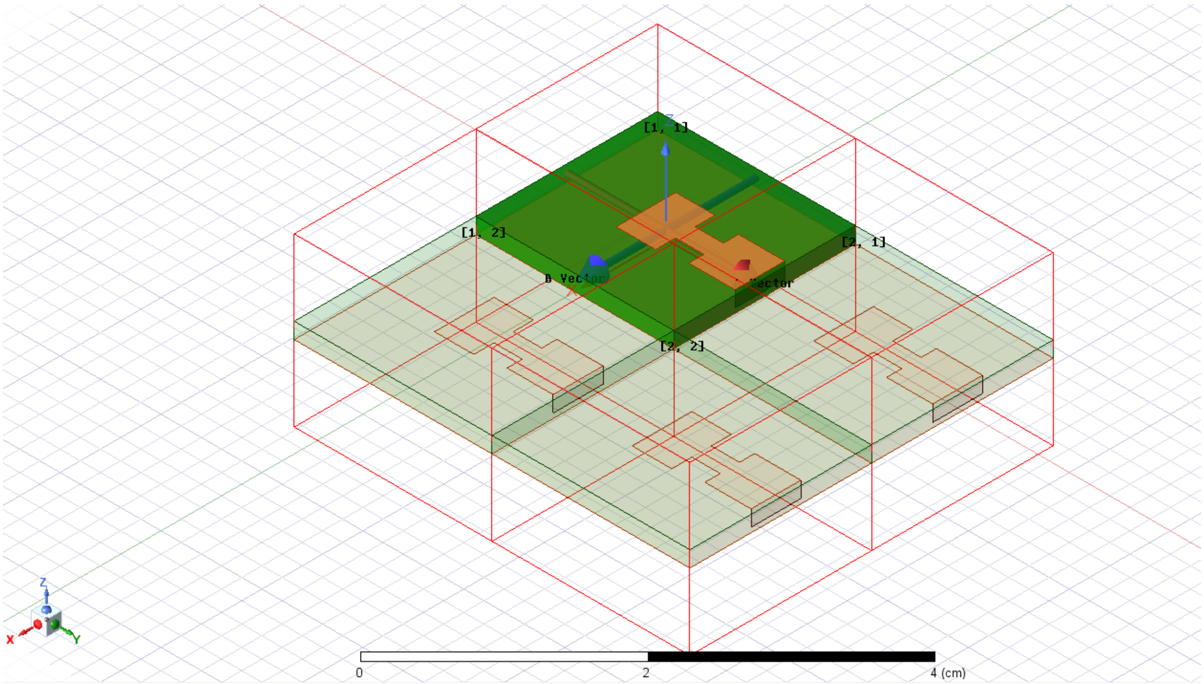
Parameter	One Patch Antenna	2x2 Array Antenna
Dielectric Material	Rogers RT/Duroid 5880	Rogers RT/Duroid 5880
W	0.59 mm	0.59 mm
L	0.39 mm	0.39 mm
ϵ_r	2.2	2.2
h	1.575 mm	1.575 mm
f_c	19.69 GHz	19.49 GHz
Substrate X	18 mm	36 mm
Substrate Y	19.6 mm	39.2 mm

The Ka-band 2×2 microstrip array antenna simulations were conducted using the HFSS software, based on the antenna design parameters provided in Table 2. In these designs, a microstrip feed was employed, and impedance matching was achieved using the edge-feed method.

Through the simulation process, the return loss (S11) was optimized, and adjustments were made to the center frequency and bandwidth to enhance performance. The final 2×2 array antenna design is illustrated in Figure 2.

Figure 2

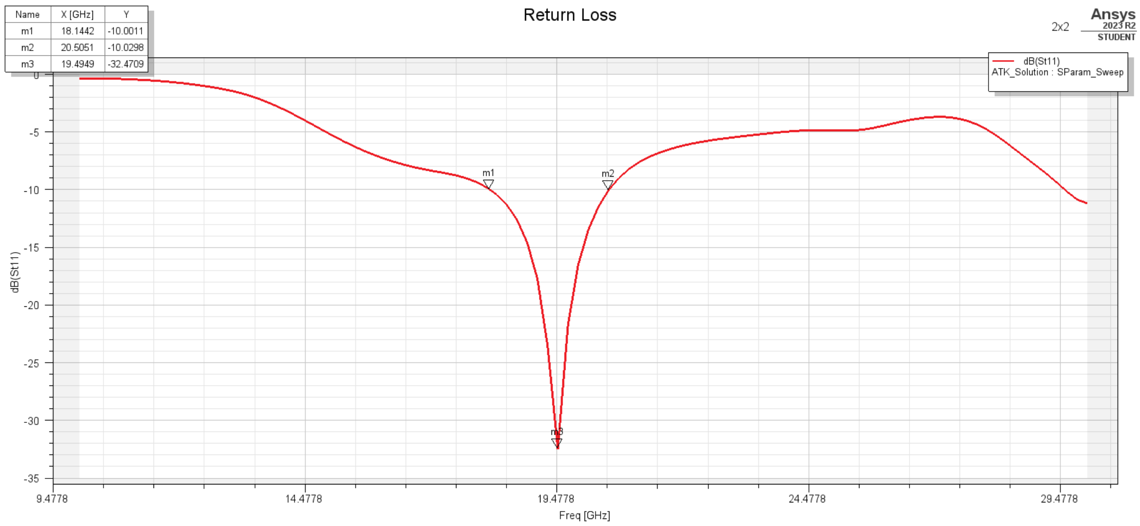
2x2 Microstrip Array Antenna View



The simulation results of the designed 2×2 microstrip array antenna indicate a return loss (S11) of -32.47 dB, with a center frequency of 19.49 GHz. Additionally, when considering the region where the return loss graph remains below -10 dB, the antenna bandwidth is determined to be 2.36 GHz. The

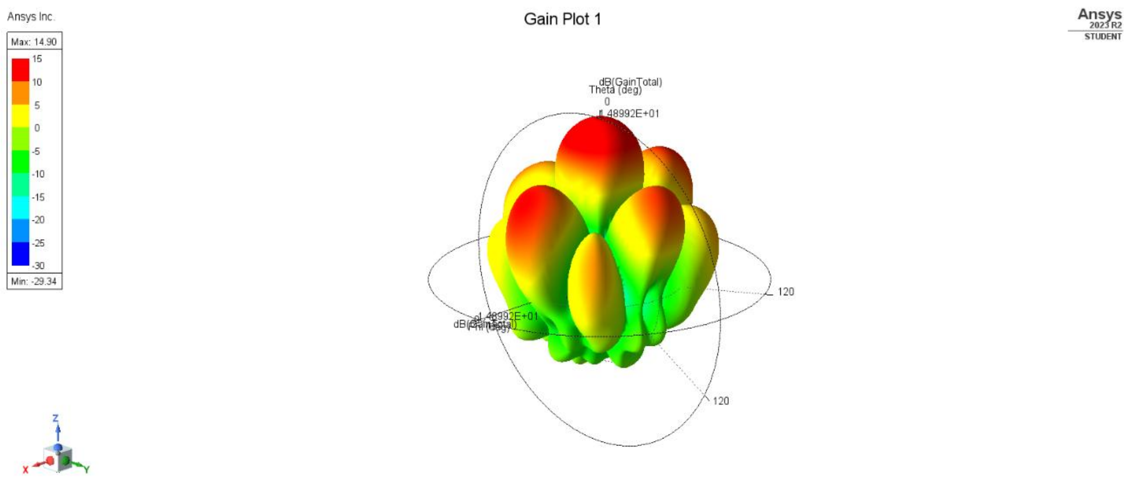
S11 return loss graph is illustrated in Figure 3.

Figure 3
2x2 Microstrip Array Antenna Return Loss Graph



The simulation results for the 2×2 microstrip array antenna indicate a gain of 14.90 dBi. The 3D gain pattern of the designed antenna is presented in Figure 4.

Figure 4
2x2 Microstrip Array Antenna 3D Gain Graph



Link Budget Simulations

As part of the link budget simulations, the theoretical calculations were first conducted using the formulas provided in the Methodology section. Following these theoretical calculations, a satellite-to-aircraft communication scenario was modeled using the simulation software, and link budget simulations were performed.

The communication parameters used as inputs for the link budget simulations are presented in Table 3. The table indicates that the theoretical Eb/N0 margin was calculated to be 0.55 dB.

Table 2

Link Budget Parameters

Parameter	Symbol	Value
Frequency	f_c	19.49 GHz
Satellite Range	r	35786 km
Satellite Orbit	Sat-Lon	41° East
Effective Isotropic Radiated Power	**EIRP**	**57 dBW**
Free Space Path Loss	L_{FS}	209.31 dB
Athmospheric Loss	L_{atm}	1.5 dB
Pointing Loss	$L_{pointing}$	0.21 dB
Implementation Loss	L_{imp}	0.18 dB
Total Propagation Loss	$\boldsymbol{L_{Total}}$	**211.20 dB**
Gain / Temperature	**G/T**	**16.60 dB**
Bandwith	**BW**	**23.625 MHz**
Theorical Eb/N0 (QPSK)	$\left(\frac{E_b}{N_0}\right)_{theorical}$	13.05 dB
Received Eb/N0	$\boldsymbol{\left(\frac{E_b}{N_0}\right)_{received}}$	**13.60 dB**
Margin	$\boldsymbol{\left(\frac{E_b}{N_0}\right)_{margin}}$	**0.55 dB**

The link budget analysis was conducted using the simulation software, incorporating the input parameters from the link budget calculations. The analysis scenario involved a Ka-band 2×2 microstrip array antenna mounted on a passenger aircraft traveling from Ankara to Paris, communicating with a potential GEO satellite positioned at 41° East longitude.

The performance of the communication link was evaluated based on this scenario. The visual representations of the simulation environment are provided in Figure 5 and Figure 6.

Figure 5
2D-3D Simulation Output

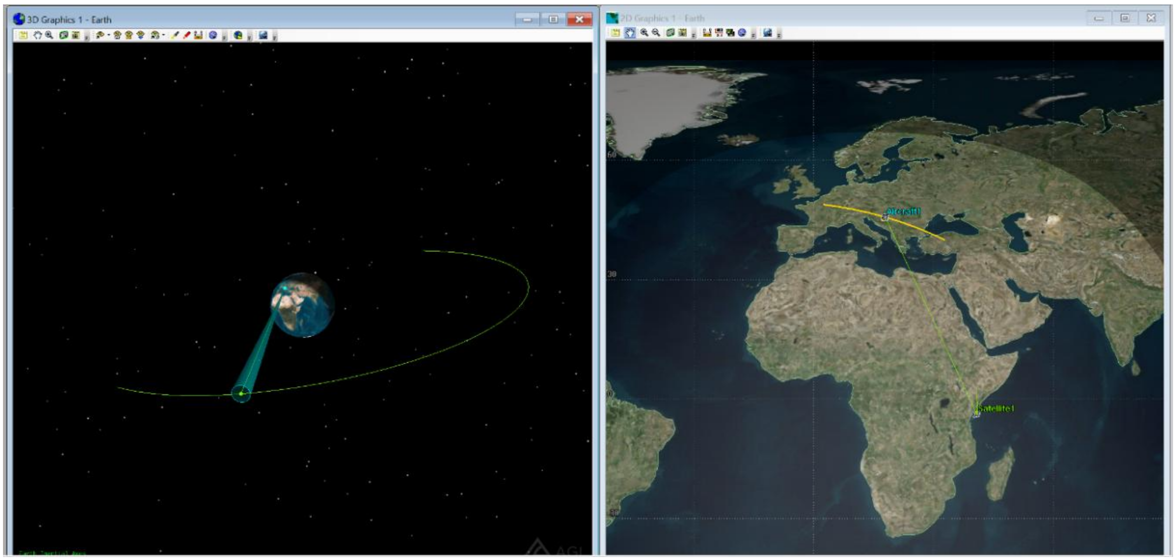
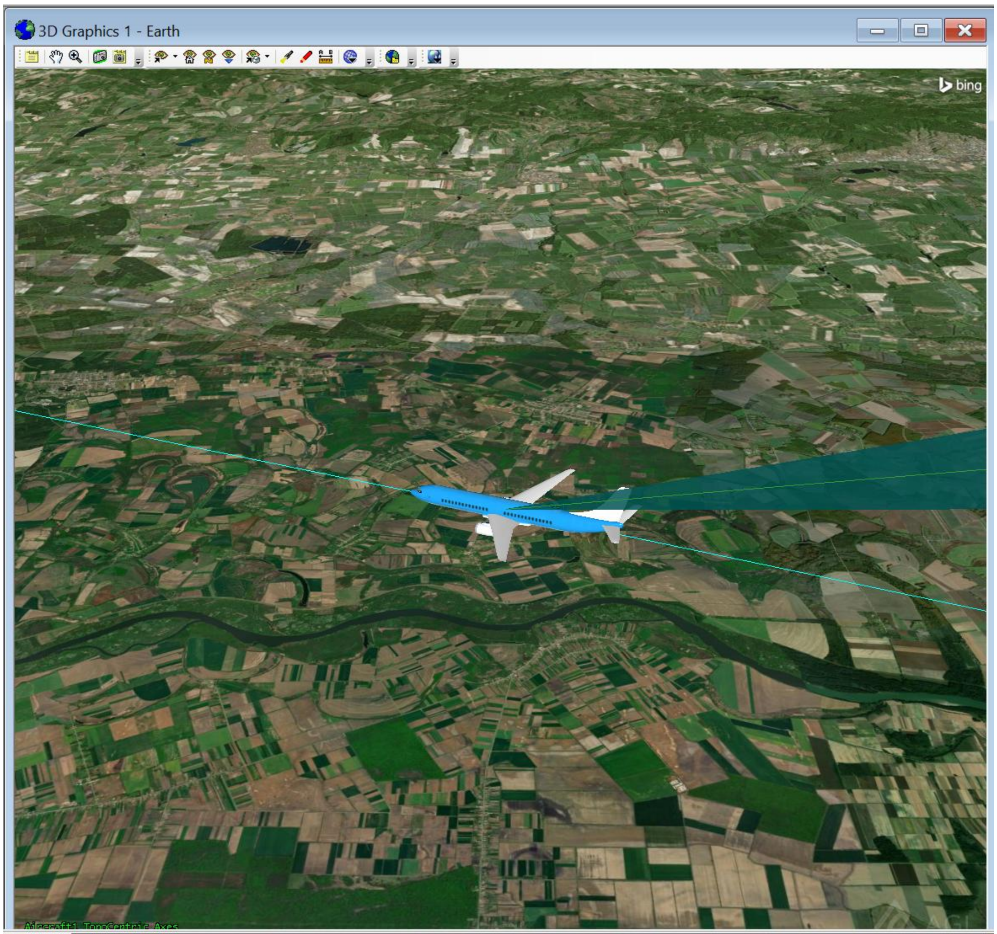


Figure 6
The Satellite Tracking Visualization of the 2×2 Array Antenna Mounted on the Aircraft.



In this study, the objective was to ensure the continuous tracking and communication of a 2×2 microstrip array antenna mounted on a passenger aircraft with a GEO satellite during a flight from Ankara to Paris. To achieve this, a phased array antenna structure was designed (as shown in Figure X), incorporating an electronically steerable beam system. This system automatically adjusts the antenna's phase angles based on the satellite beacon signal strength, enabling uninterrupted satellite tracking throughout the flight [7].

Following the definition of the satellite and aircraft communication scenario in the simulation program, the link budget simulation was conducted for the entire flight duration. The variations in link budget values over time, from Ankara to Paris, are illustrated in Figure 7 and Figure 8.

Figure 7

Link Budget Simulation Outputs-1

Time (UTCG)	EIRP (dBW)	Rcvd. Frequency (GHz)	Rcvd. Iso. Power (dBW)	Flux Density (dBW/m^2)
1 Jan 2025 09:00:00.000	57.000	19.489993	-152.782	-105.530450
1 Jan 2025 09:10:00.000	57.000	19.489992	-152.798	-105.546371
1 Jan 2025 09:20:00.000	57.000	19.489992	-152.814	-105.562522
1 Jan 2025 09:30:00.000	57.000	19.489992	-152.831	-105.578886
1 Jan 2025 09:40:00.000	57.000	19.489992	-152.847	-105.595448
1 Jan 2025 09:50:00.000	57.000	19.489992	-152.864	-105.612192
1 Jan 2025 10:00:00.000	57.000	19.489992	-152.881	-105.629101
1 Jan 2025 10:10:00.000	57.000	19.489992	-152.898	-105.646161
1 Jan 2025 10:20:00.000	57.000	19.489992	-152.915	-105.663357
1 Jan 2025 10:30:00.000	57.000	19.489992	-152.933	-105.680675
1 Jan 2025 10:40:00.000	57.000	19.489992	-152.950	-105.698100
1 Jan 2025 10:50:00.000	57.000	19.489992	-152.968	-105.715621
1 Jan 2025 11:00:00.000	57.000	19.489991	-152.985	-105.733223
1 Jan 2025 11:10:00.000	57.000	19.489991	-153.003	-105.750895
1 Jan 2025 11:20:00.000	57.000	19.489991	-153.021	-105.768625
1 Jan 2025 11:30:00.000	57.000	19.489991	-153.038	-105.786402
1 Jan 2025 11:40:00.000	57.000	19.489991	-153.056	-105.804217
1 Jan 2025 11:50:00.000	57.000	19.489991	-153.074	-105.822058
1 Jan 2025 12:00:00.000	57.000	19.489991	-153.092	-105.839918
1 Jan 2025 12:10:00.000	57.000	19.489991	-153.110	-105.857786
1 Jan 2025 12:20:00.000	57.000	19.489991	-153.128	-105.875657
1 Jan 2025 12:30:00.000	57.000	19.489991	-153.145	-105.893521
1 Jan 2025 12:40:00.000	57.000	19.489991	-153.163	-105.911374
1 Jan 2025 12:50:00.000	57.000	19.489991	-153.181	-105.929207
1 Jan 2025 13:00:00.000	57.000	19.489991	-153.199	-105.947017
1 Jan 2025 13:01:25.939	57.000	19.489991	-153.201	-105.949565

Figure 8

Link Budget Simulation Outputs -2

g/T (dB/K)	C/No (dB*Hz)	Bandwidth (kHz)	C/N (dB)	Eb/No (dB)	BER
16.600000	91.416767	23625.000	17.6830	13.1456	6.645231e-11
16.600000	91.400847	23625.000	17.6671	13.1296	7.178927e-11
16.600000	91.384696	23625.000	17.6510	13.1135	7.761965e-11
16.600000	91.368331	23625.000	17.6346	13.0971	8.398603e-11
16.600000	91.351769	23625.000	17.6181	13.0806	9.093421e-11
16.600000	91.335026	23625.000	17.6013	13.0638	9.851336e-11
16.600000	91.318116	23625.000	17.5844	13.0469	1.067762e-10
16.600000	91.301056	23625.000	17.5673	13.0298	1.157793e-10
16.600000	91.283860	23625.000	17.5501	13.0126	1.255831e-10
16.600000	91.266543	23625.000	17.5328	12.9953	1.362522e-10
16.600000	91.249117	23625.000	17.5154	12.9779	1.478554e-10
16.600000	91.231597	23625.000	17.4979	12.9604	1.604662e-10
16.600000	91.213995	23625.000	17.4803	12.9428	1.741628e-10
16.600000	91.196323	23625.000	17.4626	12.9251	1.890283e-10
16.600000	91.178593	23625.000	17.4449	12.9074	2.051510e-10
16.600000	91.160815	23625.000	17.4271	12.8896	2.226246e-10
16.600000	91.143001	23625.000	17.4093	12.8718	2.415484e-10
16.600000	91.125159	23625.000	17.3914	12.8539	2.620276e-10
16.600000	91.107300	23625.000	17.3736	12.8361	2.841736e-10
16.600000	91.089431	23625.000	17.3557	12.8182	3.081043e-10
16.600000	91.071561	23625.000	17.3378	12.8003	3.339441e-10
16.600000	91.053696	23625.000	17.3200	12.7825	3.618249e-10
16.600000	91.035844	23625.000	17.3021	12.7646	3.918855e-10
16.600000	91.018010	23625.000	17.2843	12.7468	4.242729e-10
16.600000	91.000201	23625.000	17.2665	12.7290	4.591421e-10
16.600000	90.997652	23625.000	17.2639	12.7264	4.643491e-10

DISCUSSION AND CONCLUSIONS

This study focuses on the design and simulation of a 2×2 microstrip array antenna mounted on a passenger aircraft to enable seamless in-flight internet connectivity via a GEO satellite. The designed antenna operates within the Ka-band receive frequency range (18–21 GHz) and features Rogers RT/Duroid 5880 as the dielectric material, with an edge-feed microstrip feeding structure.

The simulation results of the 2×2 microstrip antenna indicate a center frequency of 19.49 GHz and a bandwidth of 2.36 GHz. The return loss (S11) is -32.47 dB, and the antenna gain is 14.90 dBi.

The performance analysis of the 2×2 phased array antenna was initially conducted through theoretical calculations, followed by simulations using a dedicated software environment. The simulation scenario included a passenger aircraft and a potential GEO satellite located at 41º East longitude, at an altitude of 35,786 km. The assumed flight route was from Ankara to Paris. The satellite EIRP was set at 57 dBW, and the G/T value of the aircraft-mounted 2×2 array antenna was 16.60 dB. The carrier signal transmitted from the satellite utilized QPSK modulation with a bandwidth of 23.625 MHz, supporting a theoretical data transmission rate of 30 Mbps.

The system was designed to achieve a Bit Error Rate (BER) of 10^{-10}. For QPSK modulation, achieving this BER level requires a minimum Eb/N0 value of 13.05 dB. The BER vs. Eb/N0 graph is presented in Figure 1. The simulation results yielded an Eb/N0 value of 13.60 dB, indicating that the system achieves satellite communication with an approximate 0.55 dB link margin.

To further validate the antenna’s performance, link budget simulations were conducted for the entire Ankara–Paris flight route. The analysis showed that performance metrics were higher at the Ankara location and gradually decreased as the aircraft approached Paris. This reduction in signal quality is primarily attributed to the decreasing elevation angle between the aircraft and the satellite, as well as the increasing distance, which results in higher transmission losses over time.

The overall simulation results indicate that the Eb/N0 value remained around 13 dB throughout the flight, while the BER never exceeded 10^{-10}. The link budget simulation results are illustrated in Figure 7 and Figure 8. These findings confirm that the theoretical and simulation results are highly consistent, demonstrating the feasibility of using the designed 2×2 microstrip array antenna for satellite communication on passenger aircraft.

The study concludes that, under suitable operational conditions, the proposed 2×2 phased array antenna can provide continuous and high-quality communication with a GEO satellite throughout the flight duration.

Author Contributions

Research Design (CRediT 1): Author 1 (50%) – Author 2 (50%)

Data Collection (CRediT 2): Author 1 (50%) – Author 2 (30%) – Author 3 (10%) – Author 4 (10%)

Research, Data Analysis, and Validation (CRediT 3-4-6-11): Author 1 (50%) – Author 2 (50%)

Manuscript Writing (CRediT 12-13): Author 1 (50%) – Author 2 (30%) – Author 3 (10%) – Author 4 (10%)

Manuscript Review and Editing (CRediT 14): Author 1 (50%) – Author 2 (50%)

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Conflict of Interest

None

Sustainable Development Goals (SDG)

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