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ENHANCING DATA DOWNLINK PERFORMANCE WITH BEAM STEERABLE REFLECTARRAY ANTENNAS

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ABSTRACT

The increasing importance of satellite data downlink in remote sensing missions has underscored the role of antenna performance in determining data transfer speed and volume. The authors propose a novel approach to enhance data downlink performance in remote sensing applications for Low-Earth Orbit (LEO) satellites. The proposed method reduces the complexity of the telecommunications system by employing an X-Band digital beam steerable reflectarray for Earth Observation (EO) Synthetic Aperture Radar (SAR) and ground communications, thereby streamlining satellite operations. This method was evaluated over a simulated two-day period in a 550 km sun-synchronous orbit to estimate access time and data transfer efficiency. Our results demonstrate that beam steerable reflectarray antennas offer considerable advantages over traditional antenna solutions, with improved access time and increased data transfer efficiency. These findings hold significant implications for the design and deployment of satellite constellation systems, potentially enhancing the performance of data downlinks in remote sensing missions.

***Index Terms*—** Satellite data downlink, reflectarray antennas, remote sensing, communication, latency

1. INTRODUCTION AND MOTIVATION

Satellite data downlink is a critical aspect of remote sensing missions as it enables the transmission of large amounts of data from the satellite to the ground [1] and is considered one of the current bottlenecks in current small SAR satellites [2]. The antenna performance for this purpose plays a significant role in determining the speed and volume of data transfer, even more so when trying to miniaturize the satellite size. With higher downlink capabilities, more data will be available in the same timeframe compared to a link with a lower gain antenna on the satellite side, which is a significant asset in future constellations addressing latency reduction [3]. This work is part of an ongoing PhD study on smart reflectarray antennas (SATORI), which also studies the re-use of the same antenna for both SAR and communications. This paper covers one of the use cases to show how satellites can benefit from reconfigurability, enhancing aspects of remote sensing, communications and other research fields. The authors analyze how to improve data downlink performance in remote sensing applications for Low-Earth Orbit (LEO) satellites while reducing the telecommunications system complexity by sharing an X-Band digital beam steerable reflectarray for Earth Observation (EO) Synthetic Aperture Radar (SAR) and ground communications, as proposed in [4].

The study includes a detailed analysis of different antenna solutions, including patch, parabolic, and a novel digital beam steerable reflectarray antenna. The study considers various factors that affect the performance of downlink communication, such as the frequency band, the modulation scheme, and the noise level at the receiver. The study also considers the impact of different ground station configurations and assumes an adaptive transceiver to allow communications at varying data rates based on the signal-to-noise ratio. The study results show that smart reflectarray antennas offer significant advantages over other antenna solutions for data downlinks in remote sensing applications by providing the best data transfer performance while keeping the same order of magnitude of higher complexity systems. The findings of this paper have important implications for the design and deployment of satellite constellation systems. The results highlight the potential of smart reflectarray antennas to enhance the performance of data downlinks in remote sensing missions, where data availability is crucial for mission success. Overall, this study contributes to the ongoing efforts to improve the performance of remote sensing missions and advance the field of space communication.

The paper is organized as follows: the next section addresses the system model and problem formulation; section III focuses on the obtained results analysis; section IV

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presents the conclusions of this work.

2. SYSTEM MODEL AND PROBLEM FORMULATION

This section details the proposed method to study the downlink connection between a satellite and a ground station, focusing on how different antennas can help increase performance.

Initially, the authors propagated an arbitrary 550 km altitude sun-synchronous orbit for two days to estimate the access time between the satellite and the ground station, containing the azimuth, elevation, and range information. Then, by having these parameters available, it was possible to compute the link Signal-to-Noise Ratio (SNR) and, therefore, the Shannon channel capacity to estimate the maximum link data rate over a 20 MHz bandwidth channel. The SNR measures a signal strength relative to background noise, and Shannon channel capacity represents the maximum rate at which information can be transmitted over a communication channel without error.

The transceivers in both ends are assumed to be adaptive, allowing communications from high data rates at large SNR to lower data rates at low SNR values. A typical channel capacity for a satellite to ground downlink communication depends on various factors, including the frequency band, the modulation scheme, and the noise level at the receiver. As for the typically used Shannon capacity fraction when projecting downlink communication, it is common to aim for $50 - 80\%$ of the limit due to performance efficiency [5, 6]. This value allows having some margin for channel conditions variations, such as fading and interference, which can affect the achieved capacity. Nevertheless, this study covers an even more pessimistic case by considering a 30% fraction of the channel capacity in all antenna approaches to analyze a worst-case scenario. On the ground side, the authors used a simple ground station at mid-latitudes as a reference, with the following specifications:

- a minimum elevation angle of 5 degrees;
- a 50% of efficiency 3-meter dish;
- a pessimistic consideration of 5 dB extra losses on the RX circuit.

Regarding the antennas, there were five antenna solutions studied:

- a fixed patch antenna with 6 dBi gain and $60°$ beamwidth;
- a patch antenna with 6 dBi gain on a mechanically steerable satellite between $-45°$ and $45°$;
- a fixed parabolic reflector with 33 dBi gain;
- a parabolic reflector with 33 dBi gain on a mechanically steerable satellite between $-45°$ and $45°$;
- an electronic beam steerable reflectarray with 30 dBi gain capable to steer its beam between $-45°$ and $45°$.

This study considered TX output power of 36 dBm on the satellite side. Algorithm 1 details the approach to studying the total possible amount of data to be transferred from the satellite to the ground. The algorithm ran independently for each antenna, and the only difference was in the computation of the link SNR due to each antenna gain difference concerning gain and radiation pattern.

Algorithm 1 Satellite Scenario and Link Budget

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Require: simulation duration, satellite, ground station and link parameters
Ensure: SNR, channel capacity, transmitted data
  Define the Satellite (SAT) parameters
  Define the Ground Station (GS) parameters
  Define an Access Analysis
  Compute the distance between the SAT and GS
  for each minute in scenario duration do
      if satellite has access to the ground station then
          Compute azimuth, elevation, and range between them
      end if
  end for
  Compute link losses for each range vector position
  Compute SNR for the link
  for each time step in the satellite scenario do
      Compute channel capacity as a fraction of the Shannon limit
  end for
  Compute the amount of data transferred for each interval
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3. ANALYSIS

Table 1 compares the transferred data volume between a satellite and a ground station using different antenna approaches for data downlink on the satellite end. Also, it shows how many contacts between the satellite and the ground station are required for the satellite to be able to download 10 MB of data, corresponding to a typical geo-referenced SAR image. On a qualitative level, the table presents the antennas electrical, mechanical and integration complexity properties, being the " + " considered as an advantage, "0" as neutral, and " − " as a disadvantage. As mentioned previously, this paper studies five antenna solutions: patch and parabolic antenna (static pointing to nadir and with mechanical steering) and an innovative digital beam steerable reflectarray. The results show that, although having the highest gain, the static parabolic antenna has the worst downlink capacity since it

	Patch antenna	Patch antenna with mechanical steering	Parabolic reflector	Parabolic reflector with mechanical steering	Beam steerable reflectarray
Total transferred data (MB)	22.16	31.76	8.28	210.78	164.27
Time to download 10 MB (seconds)	3419	2846	-	293	414
Number of contacts to download 10 MB	4	3	-	1	1
Total access time (seconds)	3900				
Bandwidth	-	-	+	+	-
Volume	+	0	-	-	(Stowed Volume) 0
Power consumption	+	-	+	-	+
Mass	+	0	-	-	+
Assembly complexity	+	+	-	-	+

Table 1. Results comparison for the different downlink antennas approach.

has a too narrow beamwidth to allow for significant communication link establishment opportunities. Both patch antenna solutions present a better performance, but the steering capability allows the satellite to download almost 1.5 times more data when compared to the static patch antenna. Although satellite mechanical steering helps increase the transmitted data, it requires a more actuating Attitude Determination and Control System (ADCS) to allow the satellite to precisely and rapidly point to the ground station. Also, this manoeuvre requires higher power consumption. The digital beam steerable reflectarray presents the second-best data transfer performance, next to the parabolic antenna with mechanical steering. Although not so efficient, the reflectarray has a simpler planar structure compared to reflectors. The steerable reflector topology allows for 30% more data to be downloaded but only allows for feed or satellite mechanical steering, which is slower, bulkier, and power costly compared to the reflectarray [7]. Furthermore, since the parabolic reflector presents a very small beamwidth, it requires an ADCS with even more precise pointing accuracy when compared to the patch antenna one. Considering table 1, it is possible to conclude that the reflectarray is the most versatile approach since it allows for a high data transfer compared to both patch antennas while keeping the same order of magnitude of higher complexity systems. Table 1 also shows the number of contacts required for the satellite to download 10 MB towards the ground.

It is significant to highlight that this analysis only covers a single ground station, so the total data transfer would increase proportionally. By scaling the number of ground stations, the time to download data would drastically increase, and this would be even more noticeable on beam steering (mechanical/electronics) systems. This study shows that beam steerable reflectarray antennas offer significant advantages for data downlink in remote sensing applications, with improved access time and increased data transfer efficiency compared to other antenna solutions. These results have important implications for the design and deployment of satellite constellation systems and highlight the potential of beam steerable reflectarray antennas to enhance the performance of data downlink in remote sensing missions, where data availability is the critical aspect when designing such a system. In addition, to improve the satellite downlink capacity, sharing the same antenna for EO applications and communications allows for satellite complexity reduction. Such findings show that simpler ground stations distributed around the globe are enough to use in future satellite constellations instead of specific and costly ground station facilities, reducing the overall constellation maintenance cost.

On the other hand, sharing a single antenna for communication and EO purposes introduces several technical and operational challenges that this paper also covers, presenting some possible solutions to tackle them:

- **Frequency and Bandwidth Constraints**: EO sensors and communication systems often operate at different frequencies. Sharing a single antenna might limit the ability to optimize the antenna design for each specific frequency, resulting in decreased performance for both functions. The solution is to tune the antenna for the satellite principal function, like SAR. Although the communication link would have lower radiation efficiency, the high antenna area can compensate for this effect and still outperform when compared to the remaining solutions.

- **Time Division**: EO and communication tasks may need to be performed at different times to avoid interference and ensure efficient antenna usage. This could result in a complicated scheduling problem, potentially limiting the operational flexibility of the satellite if it is required to perform SAR in the same zone as the ground station. Using more than one ground station mitigates this problem.

- **Beam Steering and Pointing Precision**: EO and communication applications may require the antenna beam to be pointed in different directions in a very close geographic zone. Mechanisms for mechanical beam steering may be complex and energy-consuming, and might not offer the required precision for both tasks. Having an electronic beam steerable contributes to the overall beam steering mechanism.
- **Redundancy and Reliability**: If there is only a single antenna for both EO and communications, a failure in the antenna could lead to a total loss of both capabilities. The satellite shall have a separate and redundant antenna for downlink purposes to overcome this problem.
- **Power Constraints**: EO applications often require high-power transmissions, which may not be compatible with the power requirements of the communication system. Balancing the power needs of both functions can solve this issue.

4. CONCLUSIONS

This study highlights the significant advantages of using beam steerable reflectarray antennas for dual applications, such as remote sensing and data downlink operations. These antenna solutions show improvements in access time and data transfer efficiency compared to the standard approach of having a separate antenna for downlink-only purposes. The implications of these findings are broad, extending to the design and deployment of satellite constellation systems. This emphasizes the potential of beam steerable reflectarray antennas to enhance data downlink performance in remote sensing missions, where data availability is a primary consideration in system design. By improving the satellite downlink capacity and reducing the overall complexity of the satellite, this approach has significant potential. However, this paper also outlines the operational and technical challenges associated with using a single antenna for both communication and EO purposes, offering potential solutions to these issues. In addition, these findings suggest that future satellite constellations can have simpler globally distributed ground stations. This could negate the need for specialized, costly ground station facilities and lead to significant reductions in the overall maintenance cost of the satellite constellation. In summary, this study provides valuable insights and data-driven evidence supporting the use of beam steerable reflectarray antennas in remote sensing applications. Future work should focus on exploring the application of these findings in different types of satellites or systems.

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