From Foe to Friend: The Surprising Turn of MegaConstellations in Radio Astronomy

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Abstract

Cheap spaceflight has ushered in an explosive growth era for Low Earth Orbit (LEO) satellites. While this has brought us LEO satellite megaconstellations for ubiquitious high-speed data, it has also enabled a proliferation of nanosatellites (e.g. CubeSats) launched by diverse organizations. An unfortunate side-effect is harmful interference to sensitive receivers like those of radio astronomy — no place on Earth is safe. *How can we enjoy the fruits of the satellite revolution without blinding ourselves to the secrets of the universe?*

Networking is the key. This paper proposes InOrbitNet, which aggregates and backhauls traffic from low-capability nanosatellites using highly-capable LEO megaconstellations. By simulating LEO and nanosatellite orbit transitions, we show that orders-of-magnitude reductions in latency and significant increases in capacity are possible as compared to the current non-networked direct-to-ground approach. But more importantly, because LEO megaconstellations are highly capable and tightly managed, this consolidation of RF footprints also allows radio astronomy to be protected from interference.

CCS Concepts

• **Networks → Physical links**; **Network performance modeling**; **Network performance evaluation**; **Network mobility**.

Keywords

Satellite networking, megaconstellation backhauling, scientific coexistence, Nanosatellites, Low-earth orbit satellites

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1 Introduction

In recent years, the number of Low-Earth Orbit (LEO) satellites has surged dramatically. These satellites have a wide range of applications, including Earth observation, communication services, scientific research, technology demonstration, and education. The primary driver behind this trend is the significant reduction in launch costs, thanks to services like SpaceX's rideshare program. Today, the cost of launching 1 kg into low-Earth orbit is $2,720, a staggering 95% decrease from just a decade ago [15].

LEO satellites employ various wireless technologies to transmit collected data back to Earth via downlink and receive instructions and updates via uplink. However, these tend to be point-to-point links, not networks with shared infrastructure. This connectivity approach has two major issues:
1) Satellite connectivity challenges: Most smaller satellites with limited resources use the license-free UHF band that can achieve only very low bandwidths, on the order of kbps. They can optionally utilize higher frequency bands to achieve a bandwidth of a few Mbps, although this comes with additional licensing procedures and fees. The limited communication window with a single ground station (up to one hour per day) further reduces the already low bandwidth, making it impractical for many applications. Increasing the number of ground stations at different locations on Earth to increase coverage becomes an expensive and non-scalable solution that defeats the purpose of these low-cost satellites.
2) Interference for radio astronomy: These satellite-to-Earth links emit unwanted energy in nearby frequency bands used by sensitive radio telescopes, degrading their measurements. Radio astronomy plays a vital role in our understanding of the universe, recently exemplified by groundbreaking images of accretion disks around black holes captured by radio telescopes [20]. However, the increasing number of LEO satellites has created a significant threat to the future of radio astronomy. Radio astronomy observations are constrained by physics, and thus have little to no flexibility about their observing frequencies. The observed celestial phenomena usually emit extremely faint signals — on the order of 0.001Jy, or $-230\text{dBm/m}^2/\text{Hz}$, which is at least 120dB below any meaningful broadband communications signal. As a result, a small sideband emission into radio astronomy bands can render measurements unusable.

Satellite internet megaconstellations like Starlink have the potential to revolutionize LEO satellite connectivity. We will refer to these systems as megaconstellations for brevity. With internet infrastructure now in space, we believe it is an opportune time for the networking community to rethink wireless connectivity for LEO satellites. This is particularly beneficial for nanosatellites in low-Earth orbit, which have limited resources but can leverage the proximity to megaconstellations.

We propose a vision where LEO satellites transition away from direct-to-Earth wireless links and instead leverage megaconstellations like Starlink as a network backhaul to connect to the internet. Our approach, dubbed InOrbitNet, offers solutions to both mentioned challenges: Firstly, it has the potential to provide higher bandwidth and lower latency links for LEO satellites because they are typically closer to a megaconstellation satellite than a ground station. Secondly, this approach significantly reduces interference for radio astronomy.

Notably, while megaconstellations themselves can cause radio interference for astronomy, our proposed vision has two key advantages:

1) Lower overall interference: by utilizing existing frequency bands allocated to mega constellations, LEO satellites can dramatically reduce their spectral footprint, effectively eliminating transmissions in many bands adjacent to dedicated radio astronomy bands.

2) Effective coordination: InOrbitNet enables radio astronomy to coordinate with a limited number of entities for interference mitigation, simplifying the process and eliminating the complexity of coordinating with thousands of satellite operators worldwide or demanding international regulations. In fact, Starlink is already collaborating with the astronomy community to mitigate the impact of its satellites on astronomical observations [4, 8].

We simulate wireless links between various nanosatellites and existing Starlink satellites. Our results reveal that existing Starlink satellites can maintain near continuous connectivity with nanosatellites orbiting at altitudes below 600 km. Moreover, our results show a median bitrate of 15.9 Mbps for these wireless links, a 15x improvement compared to bitrates achieved by a single ground station. As companies deploy denser constellations, we anticipate a significant increase in bitrates. This paper makes the following contributions:

- We propose a paradigm shift, called InOrbitNet, in LEO satellite connectivity that can significantly reduce RF interference for radio astronomy.
- InOrbitNet provides more robust connectivity for LEO satellites, offering higher bitrates and lower latencies than existing satellite-to-Earth communication systems.
- Through extensive simulation, we demonstrate the feasibility of InOrbitNet, highlighting a 14× improvement in link throughput and a 240× reduction in latency.

2 InOrbitNet

Since megaconstellations are now providing internet services from space, in this paper we ask: *can they provide internet connectivity to other satellites in orbit, thereby addressing connectivity and interference challenges?* To answer this question, we propose a system called InOrbitNet in which LEO satellites utilize existing megaconstellation satellites to relay their traffic rather than communicating directly to Earth. We now explain how InOrbitNet address these challenges.

2.1 In orbit backhauling for LEO satellites

Can InOrbitNet solve the bandwidth limitation of LEO satellites? From a theoretical perspective, this is plausible because LEO satellites are typically closer to one of the many megaconstellation satellites than a ground station, potentially allowing a larger link budget. Figure 1 shows the distribution of orbital altitude of LEO satellites alongside the orbit altitude of a few major internet service megaconstellations.

The figure reveals that most LEO satellites fly at an altitude similar to that of Starlink satellites. For those orbiting at higher altitudes, they may be closer to other megaconstellations. Since Starlink has the largest number of operational satellites, we use it as a case study in our analysis of the feasibility of the ideas presented in this paper. In Section 3.3, we provide an in-depth analysis of bitrates achievable by LEO satellites if they route their traffic through nearby megaconstellation satellites.

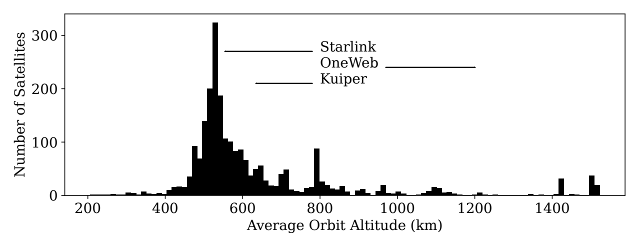
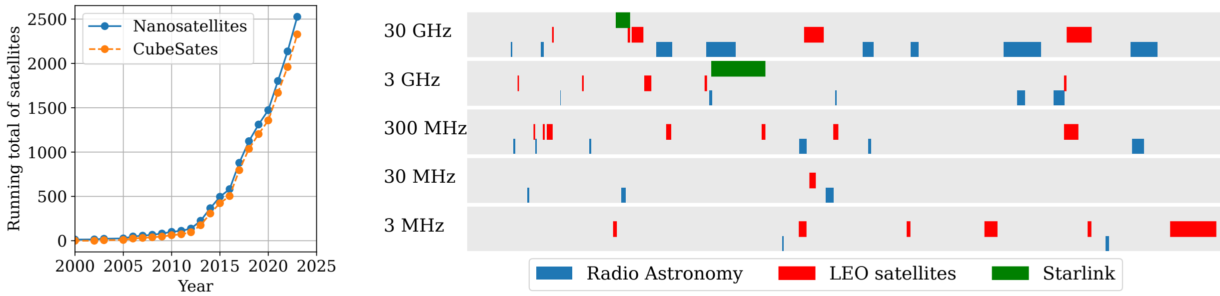


Figure 1: Altitude of LEO satellites vs. megaconstellations

2.2 Protection for radio astronomy

Figure 2a illustrates the exponential growth in nanosatellite (mostly CubeSats) launches over the last 15 years. With launch costs continuing to plummet, it is projected that numerous nanosatellites will be launched in the future, further exacerbating the radio interference issue facing radio astronomy. The problem of interference for radio telescopes from satellites stems from two major issues: 1) Satellites use a variety of frequency bands for communications. The non-comprehensive list of bands presented in Figure 2b shows that almost every radio astronomy band has a neighboring band for satellite communication. This proximity poses the



(a) Nanosatelltites launched

(b) Comparison of bands used by radio astronomy and satellites

Figure 2: Nanosatellites are being launched at an unprecedented rate. The proximity of the frequency bands they use to those of radio telescopes creates a significant threat to the future of radio astronomy. Data source: [17, 28]

danger of leaking energy from satellite bands to radio astronomy bands. Due to the extreme sensitivity of radio telescopes' receivers, even the smallest amount of energy can render a radio telescope's measurements useless. 2) LEO satellites are operated by numerous international entities, making it impractical for radio astronomers to collaborate with all of them to reduce interference. As we will demonstrate in Section 3.1, the interference created by just a few satellites can be enough to disrupt radio astronomy.

InOrbitNet solves these issues by aggregating LEO satellite traffic in the existing bands allocated to megaconstellations. Therefore, it can free up many of the existing frequency bands, significantly reducing unwanted emission in radio astronomy bands. Megaconstellation systems still use a few bands close to radio astronomy bands, but this issue can also be addressed. Since communication is now more centrally managed by a few large megaconstellation operators rather than thousands of international entities, it becomes much easier for radio astronomers to coordinate with them to protect their measurements from unwanted emissions from the megaconstellation system. In fact, Starlink is already collaborating with radio astronomers to build a system to protect radio astronomy measurements from megaconstellation systems.

3 Evaluation

3.1 Interference for radio astronomy

In this section, we investigate the impact of radio interference from LEO satellites on radio astronomy, particularly in the context of increasing satellite density in the future. We model how radio astronomy will be impacted if interference avoidance techniques, such as InOrbitNet, are not employed in the future. Calculating the interference received at a radio telescope's antenna requires precise modeling of numerous aspects of these systems, including the satellites' orbits, transmission power in the radio telescope's frequency band, and the radio telescope's antenna pattern.

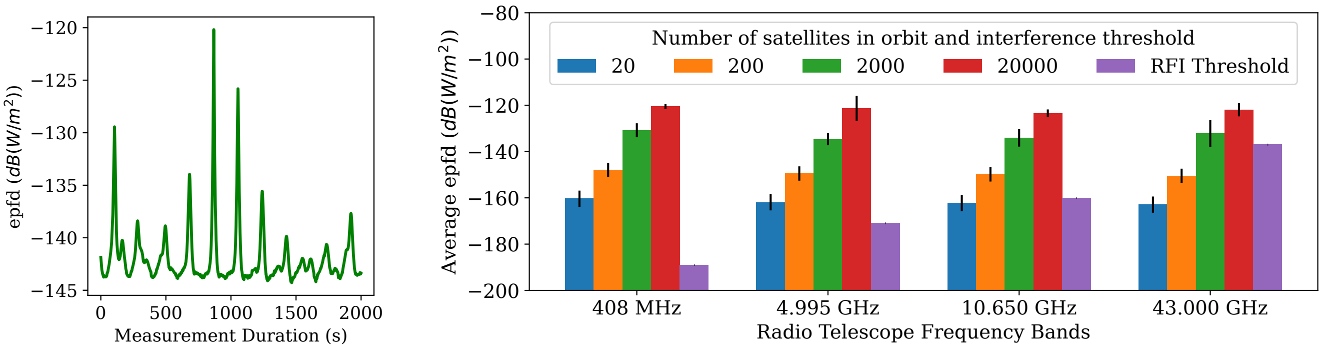
Modeling LEO satellites
To estimate the interference caused by LEO satellites in the future, where a larger number of satellites will be in orbit, we have developed a simulation that emulates any number of satellites in orbit, with user-defined orbital parameters such as inclination, longitude of the ascending node, and true anomaly. The simulation generates Two-Line Elements (TLEs) for these satellites and utilizes a SGP4 model (based on the Python pypredict library [6]) to calculate the movements of these satellites, enabling the precise calculation of each satellite's location at any given time.

Modeling radio telescopes
The antenna of a radio telescope is extremely directional, and as a result, the power of the received interfering signals will depend on the direction of the arriving signal. We have implemented the antenna pattern, based on ITU-R S.1428-1 [14], to calculate interference for radio telescopes. Although our simulator can support any radio telescope, for simplicity, we consider the Green Bank Telescope (GBT) [1] as our reference telescope for all measurements in this paper. The GBT is the largest steerable radio telescope in the world, and protecting it from radio interference is a critical issue.

Modeling interference at the radio telescope
The ITU defines the instantaneous equivalent power flux-density (epfd) in the reference bandwidth at the radio telescope from a LEO satellite in ITU-R M.1583* [12] as follows:

$$\text{epfd} = 10 \log_{10} \sum_{i=1}^{N} 10^{\frac{P_i}{10}} \cdot \frac{G_{t,i}}{4\pi d_i^{\,2}} \cdot \frac{G_{r,i}}{G_{r,\max}} \quad (1)$$

where P_i is the linear scale power of i'th satellite in the radio telescope band. We use the emission mask defined by NTIA [29] to calculate P_i for given operating bands of satellites and the radio telescope. $G_{t,i}$ is the transmit antenna gain of the satellite in the direction of the radio telescope. $G_{r,i}$ is the receive antenna gain of the radio telescope, in the direction of the transmitting satellite, while $G_{r,\max}$ is the maximum



(a) Example instantaneous epfd

(b) Average epfd across different radio astronomy bands.

Figure 3: Equivalent power flux density (epfd) is a measure of the total power emitted by a group of satellites per unit area, normalized to a reference frequency and bandwidth, expressing the combined effect of their transmissions on radio astronomy observations. (a) epfd during a 2000-second measurement for 2000 satellites. (b) Average epfd for different number of satellites and frequency bands. The error bars show the standard deviation of 24 runs of the simulator.

antenna gain of the telescope. d_i is the distance between the satellite and radio telescope.

Simulation methodology

Our simulator computes the location of all LEO satellites in every step of the simulation. Then, these locations are used to find the distance of each satellite to the Green Bank radio telescope. The location information is also used to determine the angle between the telescope's look angle and the satellite, in order to calculate directional gains $G_{r,i}$ and $G_{t,i}$. Equation (1) is used to calculate the epfd at the radio telescope. Then, the simulator increments the time (by, e.g., 1 second) and repeats the process for the duration of the measurement. Since radio telescopes try to receive very weak signals from deep space, their measurements typically last for at least several minutes. We use 2000 seconds for the duration of measurement as recommended by the ITU [7].

Figure 3a shows how epfd from 2000 LEO satellites at the Green Bank Telescope changes over 2000 seconds. The peaks in the plot occur when a satellite approaches the look angle of the telescope, and as a result, the antenna gain of the telescope amplifies the unwanted signal. Since LEO satellites fly very fast, they remain within the telescope's narrow beam for a very short time, creating narrow peaks.

In order to determine if the interference from LEO satellites can negatively impact the radio telescope's measurement, we need to calculate the average epfd over the measurement duration. Finally, we compare the average epfd with the maximum interference thresholds published in ITU-R RA.769-2 [13] for different radio astronomy frequency bands.

Simulation results

Figure 3b shows the average epfd under different scenarios. Each bar shows the average of 24 runs of 2000-second measurements for different start times along with the standard deviation. We tested the impact of interference in 4 different radio astronomy frequency bands: 408 MHz, 4.995, 10.650, and 43 GHz. We model several densities of satellites and their interference on the radio telescope. The figure also shows the interference threshold for each of these bands. The frequency bands of the interfering LEO satellites are 437.5 MHz, 5.84, 10.475, and 47.1 GHz. Unfortunately, in the three lower frequency bands even 20 satellites can create an average epfd that is above the acceptable threshold. To make the situation worse, as we increase the number of satellites the average epfd increases significantly. For example, even in the 43 GHz band that has the highest RFI threshold, 2000 satellites can push the interference level beyond acceptable levels.

These results clearly demonstrate the need for interference avoidance techniques, such InOrbitNet, to prevent a future in which radio astronomy from Earth is no longer possible. If this system is developed and all future LEO satellites utilize megaconstellations instead of their own satellite-to-Earth links, the interference in all of these bands (except those used by megaconstellations) would be eliminated. If megaconstellations cooperate with radio astronomers, as seen in the case of Starlink, interference can be avoided in the radio astronomy bands that are close to bands used by megaconstellations.

3.2 Feasibility of in-orbit backhauling

We simulated the orbits of 500 LEO satellites, chosen randomly among satellites listed as active on CelesTrak [16] whose orbits have apogees below the Starlink constellation, along with the Starlink constellation over a 24 hour period at 10 second granularity using SkyField [24]. Using the orbital data, we found the nearest Starlink satellite at each point in time. For comparison we also find the distance to the nearest

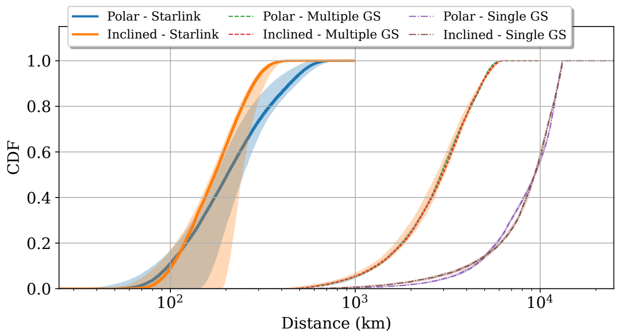


Figure 4: CDF of the distance from 500 LEO satellites to the nearest Starlink satellite or ground station(s). The center line is median CDF value, and shaded areas cover the 10% to 90% values.

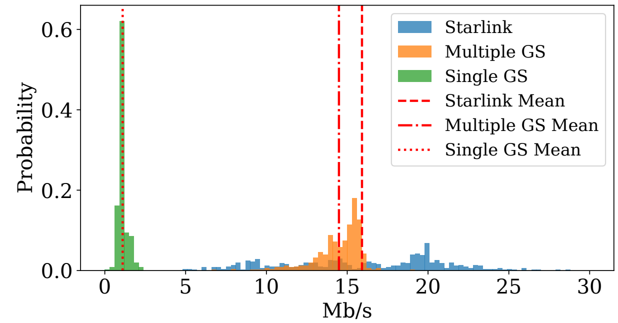


Figure 5: Average upload throughput over 24 hours under different connectivity models, simulated for 500 LEO satellite orbits. The mean throughputs are 15.9, 14.5 and 1.1 Mbps for Starlink, multiple and single ground stations.

AWS ground station[1] and to a single ground station a typical nanosatellite operator may have access to. Figure 4 plots the CDF of the distance from each LEO satellite to Starlink, to an AWS ground station, and to the single ground station. In other words, the fraction of the time that each satellite spends within a certain distance of the components of a candidate communication network. The CDFs are also broken out by whether a satellite's orbit is polar or inclined, since most of the Starlink constellation exists in inclined orbits.

The median LEO satellite spends 50% of the time within 200 km of a Starlink satellite, versus ~3000 km for the AWS network and ~8000 km for a single ground station. Based on the much higher time spent in proximity to a Starlink satellite compared to even a network of ground stations, we anticipate notable improvement to upload capabilities.

3.3 Throughput of in-orbit backhauling

Based on the orbital simulations from Sec. 3.2, along with publicly available data on upload frequency bands and antenna parameters, we perform a basic simulation of the link SNR from a LEO satellite to the nearest Starlink satellite or ground station. We assume an isotropic 1W antenna for the transmitter. We require that connections occur at an angle $\geq 25°$ below the horizon for Starlink, matching ground antenna behavior, and at $\geq 5°$ above the horizon for ground stations. This causes gaps in coverage, since a satellite may not fall within the allowable cone from a Starlink satellite even when physically close, depending on its orbit altitude. Finally, we use the SNR value to calculate the Shannon capacity of a 10 MHz channel, resulting in a concrete upload capacity measured in bits per second. This allows comparison based primarily on physical parameters rather than specific protocols used by each network operator. We use 8 GHz for ground stations and 14 GHz for Starlink connections. A future system may use lower frequencies, reducing directionality and connection dropouts, but we chose to investigate the harder scenario. Figure 5 plots the average upload throughput over the 24 hour period for each candidate backhaul network. Starlink and the AWS ground station network have similar mean throughputs, but Starlink is much more dependent on the exact orbit of a satellite, resulting in a larger variance. A single ground station can only support about $^{1}/_{15}$ the throughput of the others.

3.4 Latency of in-orbit backhauling

Building on the simulated link capacities, we simulate the upload latency, defined as time from when a unit of data is generated on the satellite to when it has completed transmission to earth, for constant 1 and 5 Mbps traffic demands for each network. Starlink has the shortest dropouts in coverage, resulting in a median latency of 54 s for 1 Mbps and 76 s for 5 Mbps. The AWS ground network has 15 and 17 *minute* latencies due to gaps in coverage, and the single ground station has a median latency of $4^{1}/_{2}$ *hours* for 1 Mbps traffic. The latency is driven almost entirely by queuing while no connection exists (we use Starlink's claimed maximum 100 ms ping). Small latency increases at 5 Mbps are caused by time taken to flush longer queues. Note that a single ground station cannot sustain a 5 Mbps link, and therefore has not been included. Figure 6 plots the latency distributions. Here we see where the globally distributed coverage of a megaconstellation provides a significant advantage for latency-sensitive applications, or for cases when a radio astronomy experiment forces communication to reduce or cease in a specific location. The gap in coverage from a temporary quiet zone could be much larger for a fixed ground station.

[1] Amazon Web Services offers a ground station-as-a-service product, providing access to a network of 12 globally distributed ground stations.

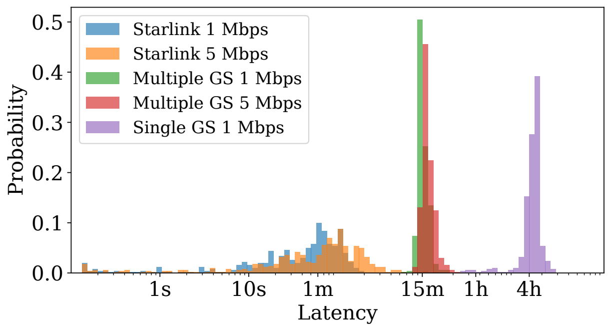


Figure 6: Satellite upload latency under different connectivity models, simulated for 500 LEO satellite orbits and 1 and 5 Mbps constant traffic demand.

4 Related Work

Radio Frequency Interference (RFI) from satellite-borne emitters has been of concern to passive and scientific radio observers for decades, affecting both radio astronomy, and passive radiometry for Earth sensing and weather prediction [9, 11, 21, 23]. There are a multitude of ways a satellite-borne transmitter might affect a passive observer. First, if an emitter's frequency and orientation match that of the passive observer, this can saturate the sensitive instrument [3] and lead to irreversible hardware damage. Even if a transmitter does not operate at the same, but a neighboring frequency, insufficient suppression of sideband emissions may lead to interference, especially in cases where the satellite-borne transmission intersects the passive observer's boresight perimeter [23]. These issues are going to be further exacerbated by the increase in CubeSat satellites. Efficient backhauling and orbit-to-ground traffic aggregation will ensure RFI is kept to acceptable and manageable levels.

Radio Quiet Zones (RQZ): Radio astronomy and defense research facilities are often deployed in remote and sparsely populated areas, which are inherently radio-quiet. Some radio quiet zones are further enforced by national policies [2, 5], which prohibit any emissions in a wide frequency range and grant the zone manager permission to authorize spectrum access by other parties. Unfortunately, existing NRQZ regulations do not protect incumbents from satellite transmissions. The National Science Foundation and SpaceX recently announced a spectrum coordination agreement to benefit radio astronomy [4]. Efforts from this collaboration will result in operational data sharing frameworks [8] and models for protective coexistence between passive and active instruments.

Radio Dynamic Zones (RDZ). Spectrum sharing conflicts and attempts for harmonious coexistence, are only going to increase, as all stakeholders evolve in their capabilities and respective spectrum needs [31]. Accordingly, the only way forward for interference-free or interference-controlled operation of spectrum stakeholders is dynamic sharing of the same radio resources. RDZs are being conceptualized [31] as regional-scale testbeds to facilitate the development and in-situ testing of spectrum sharing technologies.

Nanosatellite to satellite communication: Experimental missions have demonstrated low data rate communication from nanosatellites to legacy L-band constellations [19, 25, 30] and accurate pointing with Ka band beams [18], validating the feasibility of our approach. These missions supported data rates of 9.6 kbps or less, or were designed to communicate with a single ground station. Other work has investigated LEO mega-constellation backhaul for aircraft [22] and as an alternative to terrestrial cellular networks [26, 27].

5 Discussion and Conclusion

This work pioneers the use of megaconstellations for in-orbit backhauling, enabling LEO satellites to access the Internet. Our simulation results validate the potential of this approach to transform satellite connectivity. By leveraging megaconstellations, this approach not only enhances the capabilities of LEO satellites but also significantly mitigates Radio Frequency Interference for radio astronomy. We believe this approach creates a compelling opportunity for the networking community to reevaluate LEO satellite connectivity and fully harness the architectural potential of megaconstellations. Some important topics for further exploration remain:

Networking with predictable future. Traditional wireless networking and link scheduling were designed for unpredictable and rapidly changing channel conditions. In contrast, space-based wireless communication offers a simpler environment, with no obstacles or reflectors, and the location of megaconstellations is highly predictable. This allows wireless channel conditions to be estimated well in advance. New link scheduling algorithms are needed to determine which satellite should service a nanosatellite to 1) achieve the desired throughput, 2) minimize satellite switching to reduce interruptions, and 3) lower power consumption on nanosatellites.

What if a Starlink satellite is not within ground station range? Modern megaconstellations use satellite-to-satellite laser links in areas where ground stations are not available, making services available around the globe at the cost of variable latency. We do not currently consider the amount of time added to ferry nanosatellite traffic from the LEO backhaul to the ground, but this can be assumed to be at the sub-second level. Under current megaconstellation densities, this is not the dominant source of delay but as megaconstellations scale up by an order of magnitude as expected, it will be important to analyze this more carefully.

Security of nanosatellites. A crucial question arises when nanosatellites use megaconstellations to connect to the Internet: how to protect the security of a connected satellite? Can a malicious actor take control of the satellite and repurpose it for their own uses? This is not a new concern, as some satellites, including military ones, have been hijacked by criminals to extend the range of wireless communication. Specifically, they have used satellites to relay voice communications in the VHF band to someone outside the normal communication range [10]. Because these hijackers transmit signals actively, it is easier to detect such activities than a hacker who might be hiding and only uses the Internet to gain access to a satellite.

The impact of attitude control. Many satellites do not have a proper attitude control, therefore, they have very limited aiming capability. This creates an interesting challenge for using directional antennas in higher frequency bands.

Acknowledgments

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References

[1] [n. d.]. Green Bank Observatory. https://greenbankobservatory.org/

[2] [n. d.]. National Radio Quiet Zone. https://greenbankobservatory.org/about/national-radio-quiet-zone/

[3] [n. d.]. NRAO – Radio Frequency Interference. https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/rfi

[4] [n. d.]. NSF and SpaceX Finalize Radio Spectrum Coordination Agreement. https://public.nrao.edu/news/nsf-spacex-finalize-radio-spectrum-coordination-agreement/

[5] [n. d.]. Welcome to the Table Mountain Field Site and Radio Quiet Zone. https://its.ntia.gov/research/table-mountain/tm-home

[6] 2024. PyPredict. https://pypi.org/project/pypredict/.

[7] Yucheng Dai, Dong Han, and Hlaing Minn. 2019. Impacts of Large-Scale NGSO Satellites: RFI and A New Paradigm for Satellite Communications and Radio Astronomy Systems. *IEEE Transactions on Communications* 67, 11 (2019), 7840–7855.

[8] Christopher De Pree, William Armentrout, Anthony Beasley, Bang Nhan, Sheldon Wasik, Daniel Dueri, and Matt Iverson. 2024. Toward Spectrum Coexistence: An Update on NRAO Coordinated Testing with the Starlink Satellite Constellation. In *American Astronomical Society Meeting Abstracts*, Vol. 56. 174–03.

[9] F Di Vruno, B Winkel, CG Bassa, GIG Józsa, MA Brentjens, A Jessner, and S Garrington. 2023. Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz. *Astronomy & Astrophysics* 676 (2023), A75.

[10] Jason Fritz. 2013. Satellite hacking: A guide for the perplexed. *Culture Mandala* 10, 1 (2013), 5906.

[11] Dylan Grigg, SJ Tingay, Marcin Sokolowski, RB Wayth, Balthasar Indermuehle, and Steve Prabu. 2023. Detection of intended and unintended emissions from Starlink satellites in the SKA-Low frequency range, at the SKA-Low site, with an SKA-Low station analogue. *Astronomy & Astrophysics* 678 (2023), L6.

[12] International Telecommunication Union (ITU). [n. d.]. M.1583: Interference calculations between non-geostationary mobile-satellite service or radionavigation-satellite service systems and radio astronomy telescope sites. ([n. d.]).

[13] International Telecommunication Union (ITU). [n. d.]. RA.769: Protection criteria used for radio astronomical measurements. ([n. d.]).

[14] International Telecommunication Union (ITU). [n. d.]. S.1428: Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz. ([n. d.]).

[15] Harry Jones. 2018. The recent large reduction in space launch cost. 48th International Conference on Environmental Systems.

[16] T.S. Kelso. [n. d.]. CelesTrak. https://celestrak.org/.

[17] Erik Kulu. 2024. Nanosats Database. https://www.nanosats.eu/.

[18] Dorothy Lewis, Andres Martinez, and Andrew Petro. 2015. *Integrated Solar Array and Reflectarray Antenna for High Bandwidth Cubesats*. Technical Report. NASA Ames Research Center.

[19] Miguel Limón-González, Enrique Rafael García-Sánchez, Héctor Simón Vargas-Martínez, Nicolás Quiroz-Hernández, and Selene Edith Maya-Rueda. 2023. Performance Analysis of Inter-Satellite and Satellite-Ground Communication: A Report on Flight Data for a Low Earth Orbit CubeSat. *Aerospace* 10, 11 (2023). https://doi.org/10.3390/aerospace10110973

[20] Ru-Sen Lu, Keiichi Asada, Thomas P Krichbaum, Jongho Park, Fumie Tazaki, Hung-Yi Pu, Masanori Nakamura, Andrei Lobanov, Kazuhiro Hada, Kazunori Akiyama, et al. 2023. A ring-like accretion structure in M87 connecting its black hole and jet. *Nature* 616, 7958 (2023), 686–690.

[21] Priscilla N Mohammed, Mustafa Aksoy, Jeffrey R Piepmeier, Joel T Johnson, and Alexandra Bringer. 2016. SMAP L-band microwave radiometer: RFI mitigation prelaunch analysis and first year on-orbit observations. *IEEE Transactions on Geoscience and Remote Sensing* 54, 10 (2016), 6035–6047.

[22] Niloofar Okati and Taneli Riihonen. 2022. Downlink and uplink low earth orbit satellite backhaul for airborne networks. In *2022 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 550–555.

[23] J.E.B. Ponsonby. 1994. Impact of the direct sequence spread spectrum signals from the global satellite navigation system GLONASS on radio astronomy: problem and proposed solution. In *Proceedings of IEEE 3rd International Symposium on Spread Spectrum Techniques and Applications (ISSSTA'94)*. 386–390 vol.2.

[24] Brandon Rhodes. 2020. Skyfield: Generate high precision research-grade positions for stars, planets, moons, and Earth satellites. https://ascl.net/1907.024.

[25] Christian Rodriguez, Henric Boiardt, and Sasan Bolooki. 2016. CubeSat to commercial intersatellite communications: Past, present and future. In *2016 IEEE Aerospace Conference*. 1–15. https://doi.org/10.1109/AERO.2016.7500525

[26] Beatriz Soret, Israel Leyva-Mayorga, Stefano Cioni, and Petar Popovski. 2021. 5G satellite networks for Internet of Things: Offloading and backhauling. *International Journal of Satellite Communications and Networking* 39, 4 (2021), 431–444.

[27] Yekta Turk and Engin Zeydan. 2019. Satellite backhauling for next generation cellular networks: Challenges and opportunities. *IEEE Communications Magazine* 57, 12 (2019), 52–57.

[28] National Telecommunications U.S. Department of Commerce and Information Administration. 2003. *U.S. Frequency Allocation Chart*.

[29] National Telecommunications U.S. Department of Commerce and Information Administration. 2017. *Manual of Regulations and Procedures for Federal Radio Frequency Management*.

[30] Henry D. Voss, Jeff Dailey, Joseph W. Crowley, Bob Bennett, and Art F. White. 2014. TSAT Globalstar ELaNa-5 Extremely Low-Earth Orbit (ELEO) Satellite. https://api.semanticscholar.org/CorpusID:115560601

[31] Mariya Zheleva, Christopher R Anderson, Mustafa Aksoy, Joel T Johnson, Habib Affinnih, and Christopher G DePree. 2023. Radio Dynamic Zones: Motivations, challenges, and opportunities to catalyze spectrum coexistence. *IEEE Communications Magazine* (2023).