Fused Low-Earth-Orbit GNSS

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The traditional global navigation satellite system (GNSS) immunity to interference may be approaching a practical performance ceiling. Greater gains are possible outside traditional GNSS orbits and spectrum. GNSS from low Earth orbit (LEO) has long been viewed as promising but expensive, requiring large constellations for rapid navigation solutions. The recent emergence of commercial broadband LEO megaconstellations invites study on dual-purposing these for both communications—their primary mission—and a secondary positioning, navigation, and timing (PNT) service. Operating at shorter wavelengths than traditional GNSS, these constellations would permit highly directive, relatively compact receiver antennas. PNT-specific on-orbit resources would not be required: the transmitters, antennas, clocks, and spectrum of the hosting broadband network would suffice for PNT. The noncooperative use of LEO signals for PNT is an option, but cooperation with the constellation operator (“fusion” with its communications mission) eases the burden of tracking a dense low-altitude constellation from the ground and enables a receiver to produce single-epoch stand-alone PNT solutions. This article proposes such a cooperative concept, termed fused LEO GNSS. Viability hinges on opportunity cost, or the burden a secondary PNT mission imposes on the communications constellation operator. This is assessed in terms of time-space-bandwidth product and energy budget. It is shown that a near-instantaneous-fix PNT service over ±60° latitude (covering 99.8% of the world’s population) with positioning performance superior to traditional GNSS pseudorangeing would cost less than 1.6% of downlink capacity for the largest of the new constellations, SpaceX’s Starlink. This allocation is comparable to adding one user consuming 5.7 Mb/s of broadband service to each cell.

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I. INTRODUCTION

Use of low-Earth orbit (LEO) constellations for positioning, navigation, and timing (PNT) dates back to the earliest operational satellite navigation constellation, TRANSIT [2]. Based on Doppler measurements extracted from narrowband UHF signals received from a single satellite at a time, TRANSIT required several minutes for convergence to a sub-100-m solution.

The trade studies from which the global positioning system (GPS) was later conceived revealed that a medium Earth orbit (MEO) system with wideband signals would be more resistant to jamming than TRANSIT and would be capable of satellite-redundant instantaneous positioning with only a few dozen space vehicles (SVs) [2, Ch. 1]. L band was chosen because its wavelengths are short enough for ionospheric transparency yet long enough to avoid significant attenuation due to rainfall and water vapor [3]–[5]. By now, all traditional global navigation satellite systems (GNSS) have settled into a system architecture similar to that of GPS to great success: billions of users across the globe benefit from low-cost, high-accuracy, near-instantaneous positioning and timing.

Nevertheless, the traditional GNSS architecture suffers from some deficiencies. Non-GNSS uses of the congested space-to-Earth spectrum in the L band have prevented the allocation of much greater bandwidth for GNSS in that band. Constellation survivability is limited by the small number of SVs, which make attractive targets for antisatellite warfare [6], [7]. Jamming immunity is limited by the weakness of the signals, which, being diffused over an entire hemisphere, are easily overwhelmed [8], [9]. And positioning precision is limited by both signal weakness and bandwidth, which place information-theoretic lower bounds on ranging uncertainties [3].

In response to a pressing need for greater robustness and accuracy, GNSS has evolved over the past two decades. Several new constellations have been launched, and new signals have been introduced at separate frequencies—most with binary offset carrier waveforms that more efficiently allocate signal power [2], [5]. Nonetheless, GNSS remains principally MEO, L-band, and confined to a bandwidth occupying less than 125 MHz. Given tight budgets and enormous design inertia owing to the need for backward compatibility, radical changes in traditional GNSS over the next 30 years are unlikely. Spot beams, a promising feature of the GPS III program for improved jamming immunity [10], have been abandoned. Calls to introduce new GNSS signals in the C band (e.g., [11]) have not gained traction. Upgraded SVs and more sophisticated receiver antennas will continue to extract gains in interference immunity, but likely not tens of decibels.

In short, traditional GNSS have been brilliantly successful, yet for some applications, they remain inadequate with regard to accuracy, constellation survivability, or robustness to interference—for both civil and military users. To address these limitations, this article introduces a concept for LEO
TABLE I
Contrasting Traditional GNSS, Previous Hosted-Payload Proposals, and Fused LEO GNSS

| Characteristic          | Traditional GNSS | Hosted [25] | Fused (hemi RX) | Fused (array RX) |
|-------------------------|------------------|-------------|-----------------|------------------|
| Single-epoch PNT        | ☑                | ☑           | ☑               | ☑               |
| Unlimited users         | ☑                | ☑           | ☑               | ☑               |
| Low Earth Orbit         | ☑                | ☑           | ☑               | ☑               |
| Mega-constellation      | ☑                | ☑           | ☑               | ☑               |
| On-orbit POD            | ☑                | ☑           | ☑               | ☑               |
| Non-atomic clocks       | ☑                | ☑           | ☑               | ☑               |
| Time multiplexed        | ☑                | ☑           | ☑               | ☑               |
| Excess bandwidth        | ☑                | ☑           | ☑               | ☑               |
| Zero age-of-ephemeris   | ❤                | ❤           | ☑               | ☑               |
| Highly directional      | ❤                | ❤           | ☑               | ☑               |

PNT that exploits current and upcoming broadband LEO megaconstellations via a novel “fused” communications- and PNT service. The practical costs and challenges facing past LEO GNSS proposals, including hosted-payload LEO GNSS and signal-of-opportunity (SoP) LEO GNSS, motivate the article’s proposed architecture.

This article makes three primary contributions. First, it summarizes the features of modern broadband LEO system design and operation relevant to dual-purposing such systems for PNT. Second, it presents a detailed concept of operations for fused LEO GNSS, to be defined in the next section. Third, it provides an analysis of the opportunity cost to constellation providers for reallocating resources to provide a fused PNT service. This article is organized around these primary contributions.

The earlier paper published in [12] is complementary to this article, which provides a complete description of the fused LEO GNSS concept and a detailed opportunity cost analysis. The reader is referred to [12] for analyses of achievable fused LEO GNSS positioning precision and antijam advantage compared to traditional GNSS. Summary values from these analyses are provided in Table I for reference.

II. LEO GNSS

Expansion of GNSS back to the LEO ambit of TRANSIT beckons as a promising way to address the limitations of traditional GNSS. Megaconstellations of commercial satellites in LEO are being launched (SpaceX’s Starlink and OneWeb’s constellations) or planned (Amazon’s Kuiper constellation) to provide broadband connectivity across the globe. Such services’ global reach, low latency, and wide bandwidth situate them to revolutionize broadband communications.

This article seeks to establish a less-obvious assertion: These constellations could also revolutionize satellite-based PNT. Their SVs are far nearer and more numerous than those of traditional GNSS in MEO or geostationary orbit, and their communications transponders have both exceedingly high gain and access to a vast allocation of spectrum. Potential commercial LEO PNT signals are thus more precise, powerful, and jam-resistant than those of traditional GNSS.

Dual-purposing LEO communications constellations for PNT is not a new concept. The emergence of the Globalstar and Iridium constellations in the late 1990s offered the prospect of LEO-provided navigation based on both Doppler and ranging. These constellations employ communications waveforms whose frequency and group delay can be measured opportunistically (i.e., without special cooperation by the constellation operator) and converted to typical GNSS observables: Doppler, phase, and pseudorange measurements [13]–[19] (see [2, Ch. 2] for definitions of these observables). But as with TRANSIT, only one or two Globalstar or Iridium SVs are simultaneously visible to a typical terrestrial user, preventing accurate instantaneous positioning. Instead, both theoretical [20] and experimental [15], [19], [21], [22] research has shown that several minutes of single-satellite passage across the sky are necessary for positioning to an accuracy below 100 m. This remains true for IridiumNEXT, whose constellation is patterned after the original Iridium constellation [23].

The emergence of megaconstellations of LEO satellites whose signals can be exploited for many-in-view navigation, whether opportunistically or with the cooperation of the constellation operator, is an entirely new phenomenon. The literature exploring the use of such constellations for PNT begins with [24], [25]. This article belongs to this category.

Although not originally intended for PNT, broadband megaconstellations are designed for rapid technological refresh via software or hardware and so may be adaptable for PNT. But unlike traditional GNSS, in which costs are borne by nation-states and service is free-of-charge, commercial GNSS providers will seek to recoup costs from users. For such a scheme to be viable, it must be economical, that is, it must offer fundamental advantages over traditional (free) GNSS commensurate with the price tag, otherwise there will be no demand; and must be sufficiently inexpensive to provide, otherwise there will be no supply. This article explores both facets of this problem.

A. Hosted Payload LEO GNSS

In their groundbreaking work, Reid et al. [24]–[27] analyzed the performance of potential LEO GNSS implemented using hosted payloads: dedicated PNT hardware onboard each satellite. There are good reasons to explore a hosted payload solution: Such payloads are modular, independent of the satellite’s primary communications mission, and may be iterated and upgraded for future launches. As laid out by Reid et al., hosted PNT signals provide continuous global coverage and may be incorporated into user pseudorange navigation equipment nearly as readily as traditional GNSS signals. Reid et al. estimate that the...
system would enjoy a 30 dB improvement in signal-to-noise ratio (SNR), and thus resistance to jamming, over traditional GNSS.

A hosted payload approach along those lines is not radically dissimilar to traditional GNSS. No theoretical obstacle bars the way. However, space hardware development is costly and challenging as a practical matter. And a hosted payload would be costly: besides the cost of each payload, there are costs associated with renting space and hookups on the host satellite, costs for running necessary radiofrequency interference and compatibility testing, and both costs and risks of delay in securing the necessary frequency allocations.

B. Signal-of-Opportunity LEO GNSS

A growing area of PNT practice draws measurements from the so-called signals of opportunity (SoPs), typically wireless communications signals [28]–[30]. SoP techniques seek to eliminate the need for cooperation with the wireless system operator. Satellite downlink signals from the new LEO megaconstellations could be processed as SoPs, as has been done previously with the smaller Iridium and Globalstar constellations [15]–[19], [21]–[23]. Such SoP-based LEO GNSS has several benefits. First, there is no need for cooperation with the constellation owner, which eliminates a potential coordination barrier to offering a PNT service. Second, users may exploit LEO SoPs without compensating the constellation owner, as has been the case with terrestrial cellular SoPs [30]. Third, since SoP-based PNT is necessarily passive, it preserves users’ anonymity. Taken together, these three advantages are unique to SoP-based PNT and cannot be directly matched by nonopportunistic techniques.

Despite these advantages, SoP-based LEO GNSS suffers a key limitation, which might be termed the “few-in-view” problem. With fewer than four (or, in the case of Doppler-based PNT, eight) satellites in view, near-instantaneous cold-start PNT with inexpensive clocks is not possible: the time to achieve a PNT fix stretches from seconds, as with traditional GNSS, to several minutes, as with TRANSIT, Iridium, and Globalstar [21], [31]–[33].

One might expect LEO megaconstellations to provide greater SV coverage for SoP-based PNT than do the relatively small Iridium and Globalstar constellations. However, a large fraction of megaconstellation SVs will orbit at altitudes lower than Iridium and far lower than Globalstar, offering smaller terrestrial service areas per vehicle [34], [35]. Moreover, not all overhead satellites may direct energy to a given user’s location. Although early SpaceX regulatory filings indicated its Starlink megaconstellation SVs would broadcast a quasi-omnidirectional beacon signal to aid network entry, it is not clear whether such a beacon will always be present in the system as launched. Recent work by Neinavaie et al. detected Doppler-trackable beacons [36], but in a contemporaneous Starlink signal analysis, this article’s authors found that such narrowband emissions appeared to be absent when the downlink was busy. Thus, beacon signals may only be sent when the downlink is idle, rendering them intermittent or totally unavailable once the system is more fully burdened.

Consequently, the only SoPs available from Starlink may be the broadband signals carried in narrow spot beams from each SV toward a small number of assigned compact service regions [37]. Significantly, the present authors’ Starlink signal analysis has revealed that each service region is illuminated by broadband signals from at most two SVs. Thus, areas with no active subscribers may receive no broadband signals at all. Other broadband megaconstellation operators will likely adopt designs similar to Starlink’s. The net effect, at any given instant, will be a reduction in the number of satellites actively illuminating the SoP user’s location. (Supplementary Material D analyzes a scenario in which the global average number of SoPs from a LEO megaconstellation is less than that of Iridium by a factor of 6.3×.) This takes single-mega-constellation-based SoP LEO GNSS from one-in-view to less-than-one-in-view, with a time to fix that will be unacceptably long for many applications.

C. Fused LEO GNSS

Cooperation with megaconstellation operators could solve the few-in-view problem, enabling nearly-instantaneous-time-to-fix global PNT via traditional-GNSS-like multilateration. In this paradigm, PNT becomes a secondary service that augments the LEO megaconstellations’ primary communications mission. Befitting its ancillary status, the PNT service ought not to require significant changes to the SVs or to the constellation’s allocation of on-orbit resources. This article, therefore, focuses on solutions that “fuse” the requirements of PNT into the existing capabilities of the megaconstellation. In fused LEO GNSS, the hardware already designed and the spectrum already allocated for the satellites’ primary broadband mission is dual-purposed for PNT. While this is also true of SoP LEO GNSS, fused LEO GNSS goes further to fully exploit the broadband signal’s capabilities.

To support a fused LEO GNSS service, the constellation operator arranges for intermittent spot-beam coverage of areas where PNT users are present, providing signals from enough satellites for receivers to produce single-epoch stand-alone PNT solutions. Such cooperation also has the benefit of eliminating the duplication of effort associated with third-party tracking of orbits and clocks for a dense constellation.

Compared to hosted-payload LEO GNSS, fused LEO GNSS sacrifices nothing in performance while eliminating the costs of special-purpose on-orbit hardware. In fact, where previous proposals targeted positioning precision on par with traditional GNSS pseudoranging (on the order of 3 m), fused LEO GNSS can improve on this by more than an order of magnitude [12]. Moreover, it offers a significant antijam advantage over L-band hosted-payload solutions in terms of tolerable signal-to-interference ratio, thus making it attractive as a means for delivering assured
PNT (A-PNT). This advantage comes at the cost of larger and potentially more expensive user equipment as compared to a hosted payload solution: for maximal antijam performance, a fused LEO receiver will require a phased-array antenna. But for many applications, the user equipment, such as the satellite hardware, will be dual-purposed for both communications and PNT: the same mass-market antenna and radio connecting a vehicle to a LEO communications network will be used for positioning at little additional cost.

These strengths emerge from two features of fused LEO GNSS. First, the plentiful data bandwidth present in each broadband satellite transmission burst permits supplying users with up-to-the-instant (and therefore highly accurate) orbit and clock products. Such orbit and clock products need not depend on atomic clocks onboard the SVs nor an extensive SV-observing network on the ground. Instead, the PNT service can employ a multitier GNSS architecture in which each SV’s orbit and clock models are obtained via on-orbit precision orbit determination (POD) based on an onboard traditional GNSS receiver driven by a modest-quality clock [24]. Second, unlike traditional L-band services, commercial broadband signals in K-band and V-band have both high SNR and large bandwidth. This greatly reduces receiver noise and multipath as a source of user-ranging error even when the ranging signal used over the communications link adopts the same structure and spectral profile as the usual communications signals. Furthermore, because these signals have a much shorter wavelength than traditional GNSS, it is possible to build a highly directional receiver phased array for an additional 30 dB of antijam performance that is compact relative to its L-band equivalent.

PNT precision, antijam performance, and other constellation characteristics are compared in Table I for traditional GNSS, hosted-payload LEO GNSS, and fused LEO GNSS. SoP LEO GNSS is not included due to its few-in-view problem.

For use cases in which a hemispherical antenna is preferred, such as handheld devices, the fused SNR is not high enough to permit ephemeris and clock model updates via the standard broadband data link. Thus, a backup communications link, such as a cellular data service, would be required. Note that certain design elements that give fused LEO GNSS its performance advantage could be incorporated into future hosted payload proposals. However, this article only makes comparisons against published proposals.

To be viable, a fused LEO GNSS service must be cost-effective for providers. As one of its key contributions, this article shows that providing PNT service to every user in one service cell (e.g., for the Starlink constellation, a hexagon of up to 1090 km² [39]) is roughly and costly; in terms of constellation resources spent providing PNT signals, as a single 5.7 Mb/s downlink stream. Also, since broadband service expends constellation resources in proportion to the number and activity level of subscribers, GNSS service consumes resources in proportion to coverage area. For this reason, in dense urban centers where only a small fraction of potential broadband subscribers can be accommodated and alternatives for broadband connectivity abound, a fused LEO GNSS service could be a profitable complement to a megaconstellation’s primary broadband mission.

Indeed, it has been observed [40] that effective subscriber density constraints in first-generation K, broadband LEO systems could be severe. For this reason, population distribution statistics are invoked only indirectly in what follows, insofar as they are needed to predict the global distribution of downlink power expenditure onboard the SVs.

III. BROADBAND LEO CONCEPT OF OPERATIONS

This section presents a summary discussion, not of fused LEO GNSS, but of the type of modern broadband LEO system upon which fused LEO GNSS may be built. This digression is necessary for two reasons. First, fused LEO GNSS is an exercise in reuse. To rearrange the building blocks of a broadband LEO system into a GNSS, one must first identify these building blocks and understand their operation. Second, a provider contemplating fused LEO GNSS faces costs arising from lost opportunities for profitable broadband service. Quantifying such opportunity costs, as will be attempted in a later section, requires an understanding of the resource constraints that will dominate the cost analysis. This section summarizes relevant portions of what is known and lays out reasoned speculation about what is unknown, regarding the concept of operations of broadband LEO systems.

Plans for each of the leading broadband LEO projects, including SpaceX’s Starlink, Amazon’s Kuiper, and OneWeb, envision thousands to tens of thousands of SVs in orbits ranging from 335 to 1325 km altitude. These systems are proposed to provide broadband worldwide connectivity to consumers via the K and Ku microwave bands between 10–30 GHz. Compared with existing infrastructural wireless systems, such as LTE and Wi-Fi, broadband LEO systems offer greater availability in remote locations at a lesser infrastructural investment. In densely populated regions, the systems are not expected to compete with cable, fiber, and 5 G to serve a large fraction of users but would still offer competitive bandwidth and latency to a limited user subset.

To the extent possible, this article will remain agnostic to the details of any particular broadband LEO system. However, it will be helpful to refer to concrete examples at some points in the discussion. At such points, this article will refer to information gleaned from public statements and filings with the U.S. Federal Communications Commission regarding SpaceX’s Starlink constellation, currently the most mature and ambitious broadband LEO contender, with plans for up to 42 000 LEO spacecraft.

A. Architecture

A broadband LEO SV functions as a cross between a wireless router and a cellular base station. It operates according to a dynamic schedule that allocates resources of
time, space, and frequency to route packets of data among gateways and users. Users are paying subscribers equipped with directional transceivers (“modems”), mounted either on static or vehicular platforms. Gateways are special ground sites with (potentially) superior antennas, unobstructed skylines, and high-bandwidth low-latency connections to the Internet.

B. Initialization

After power-on, a user’s modem attempts to enter the network by searching for information that will allow it to connect to an SV: orbital parameters, positioning, timing, and antenna orientation. Any parameters that it cannot obtain or recall, it must determine by a guess-and-check strategy. The user modem tunes its phased-array antenna to point in certain directions where an SV might be found and then either listen for a signal on a particular downlink frequency or transmits a connection request on a particular uplink frequency. Until it receives a signal or a response, it keeps trying with other directions and frequencies. Once a connection is established, the user modem and network exchange authentication tokens.

C. Steady-State Operation

After initialization, operation likely proceeds as in Wi-Fi or cellular communications with central scheduling: the user modem may notify the SV, within certain windows of time and frequency, that it wishes to uplink a packet of, e.g., dynamic host configuration protocol or Internet protocol (IP) data. At its discretion, the SV grants the user modem an uplink time-slot. The modem listens for such a scheduling directive, waits for the appropriate moment, and then encodes and transmits the packet. Conversely, when a packet addressed to a user arrives at the SV from a gateway, the SV queues the packet for downlink transmission. The user modem monitors the downlink channel for messages. As with Wi-Fi or any other wireless Internet medium, the broadband LEO architecture need not make any special affordance for higher level abstractions, such as data fragmentation and reassembly, reliable and in-order delivery, Internet sockets, or applications such as the Web: these features are provided by IP and communication layers built atop it, such as the transmission control protocol (TCP) and the hypertext transport protocol, in accordance with the so-called end-to-end principle.

D. Error Correction and Retransmission

Each transmitted packet is encoded using error detection (e.g., cyclic redundancy check) and error correction (e.g., Turbo codes) mechanisms. If a packet is decoded successfully, the receiver (user modem or SV) sends back an acknowledgment (ACK). If a packet fails to decode, the receiver sends back a negative acknowledgment (NAK). A packet that has been NAK’d may be scheduled for another transmission attempt using automated repeat request (ARQ) or hybrid ARQ (H-ARQ).

E. Multiplexing

General wireless principles offer a number of options for partitioning a shared downlink channel among multiple users, or among distinct data streams, including code-, time-, frequency-, and space-division multiplexing (C/T/F/SDM). Typically, several techniques are employed to achieve high spectral efficiency at a modest computational cost. K-band broadband LEO systems operate on a dynamic, wideband, dispersive channel [41]. These are the same parameters that characterize the radio-layer design of existing mobile wireless networks such as LTE and Wi-Fi, and hence one may expect similar solutions to apply.

LTE and Wi-Fi use orthogonal frequency-division multiplexing (OFDM) to eliminate dispersive intersymbol interference due to, e.g., multipath scattering, and SDM in the form of beamforming to boost signal strength. This article presumes that broadband LEO systems will also apply OFDM, acknowledging its preeminence in modern wireless technologies. OFDM’s spectrally-flat signals are not theoretically ideal for ranging, but when wide enough offer excellent precision [12]. Beamforming, discussed further in Section III-F, is critical to close link budgets and to avoid causing interference. Apropos of fused LEO GNSS, beamforming implies that SoPs from broadband LEO SVs cannot be expected to be strong enough for navigation unless a “spot” beam is directed toward the listener’s geographical vicinity.

The third form of multiplexing likely to be in use—and relevant for fused LEO GNSS—is time division. In FDD LTE, the channel is licensed to the mobile network operator, and is provisioned for a single transmitter in a given spatial region. Time division is used for sharing resources between users, with time being divided into frames, subframes, and
This operation is a complex matrix multiply for each frequency, but such a cavalier description belies significant implementation challenges.

For this article, what is relevant is the procedure for “steering” the array. The phasing elements require multibit coefficients for configuration. During steering, the SV’s central processing unit (CPU) must compute (or retrieve from a look-up table) a new set of coefficients for the desired beam pattern. These coefficients must then be transferred to the phasing network. To free up the CPU’s I/O resources for other tasks, direct control over the phasing elements would typically be delegated to an external multiplexer, shown in Fig. 1 as a serial-to-parallel converter. (This example architecture is not the only way to design such a circuit; it serves only to facilitate the parameter definitions needed for this article.) Over some interval $T_{\text{set-up}}$, the CPU loads coefficients into this multiplexer. Then, on a signal from the CPU, the updated coefficients are simultaneously imposed on the phasing network. Such an arrangement is favorable because it minimizes the “downtime” during steering in which the phasing network is in an indeterminate state and so cannot be relied upon to produce a valid beam pattern. The downtime could be made as short as a few times the light-crossing time of the phased array: some few nanoseconds. The downtime will be denoted by $T_{\text{switch}}$ in what follows.

Note that $1/T_{\text{set-up}}$ is an upper limit on the rate at which the array may be restereed. $T_{\text{switch}}$ may be expected to be shorter than $T_{\text{set-up}}$, so while it also imposes an upper limit, it is a less stringent one. Also, for reasons of cost, it is reasonable to assume that user modems will only be capable of transmitting or receiving a single beam at a time.

G. Channels

The number of disjoint frequency channels available is a function of spectrum licensing and desired system bandwidth to a single user. Public filings for Starlink indicate that the K-band spectrum in the ranges $10.7–12.7$ GHz, $17.8–18.6$ GHz, $18.8–19.3$ GHz, and $19.7–20.2$ GHz will be broken into $76 \times 50$ MHz downlink channels. This article does not assume that all channels are available on all beams, nor that all available channels may be transmitted simultaneously by any one beam. Instead, it assumes that there is some number $N_{\text{bc}}$ of “beam-channels” that represents the greatest number of simultaneous transmissions from the SV. For Starlink, this number is at most $264$, although it may be less. When concrete values are required in what follows, this article will assume $N_{\text{beams}} = 15$, $N_{\text{channels}} = 76$, and $N_{\text{bc}} = 264$.

H. Flux

One consideration particular to first-generation broadband LEO proposals has been driven by the opening of spectrum in the K band. Operators can access this spectrum only by adhering to certain limits on the flux of RF energy at the surface of the Earth intended to prevent interference with terrestrial K-band services. For instance, Starlink...
has declared that the system will generate no more than $-122.0 \text{ dB}(50 \text{ MHz/m}^2/\text{MHz})$ in the 10.7–12.7 GHz band as observed at ground level at elevation angles above 25°.

It has been revealed in public filings for Starlink that a single beam from a single broadband LEO SV is powerful enough and directional enough to saturate this flux limit. While a shrewd operator might wish to increase system capacity in densely populated urban regions by focusing several beams from several SVs onto one location, taking advantage of user antenna directionality to boost spatial reuse, this would not avail: each beam would have to operate with either reduced power or reduced duty cycle to avoid exceeding the flux limit.

Note, however, that the flux limits are per megahertz, so an operator might be permitted to focus multiple beams on the same location, provided these are on disjoint channels. This solution might cause other problems if it resulted in all available channels being occupied serving a dense region, leaving none available to serve a nearby sparse region due to the possibility of same-channel interference.

J. Cellular Scheduling

For reasons of latency and efficiency, it makes sense to delegate, insofar as possible, the global network coordination and packet scheduling problem to the SVs. Setting aside for the moment the question of how SVs know which cells to serve on which beams and frequencies, each SV may independently make millisecond-level decisions about the scheduling of uplink and downlink packets; these decisions have no impact on other cells. The alternative would be for SVs to consult with their gateways, or even with a central server, before a user’s request for data could be satisfied, which would needlessly incur several milliseconds of additional latency and tie up gateway bandwidth.

On the other hand, it is not easy to fully decentralize the global network coordination problem. One could imagine designing a fixed prearranged schedule of assignments of SVs to service cells, but this scheme fails on several counts. 1) As megaconstellations are gradually deployed, the schedule must be constantly adjusted to account for unfilled orbits. 2) Dense deployments, such as Starlink, are expected to be spread over a number of “shells” at different orbital altitudes, making their global configuration aperiodic. Even if orbital periods are commensurate, a megaconstellation will necessarily be in constant flux as SVs are added or replaced. 3) A prearranged schedule fails to accommodate dynamic variations in the health, level of battery charge, and access to gateway bandwidth of individual SVs.

It would be straightforward to periodically recompute, at a central location, the assignment of SV beams to cells and gateways to SVs, and for commands affecting this schedule to be uplinked to the SVs via the gateways. Whether operating at initial operational capability or full capability, tasking each SV beam to serve many cells or just one, such central coordination would give the operator much-needed flexibility.

How often must this computation take place? The orbital motion of LEO SVs across the user’s sky plays out over a period of several minutes so that during the interval from when an SV becomes the “most suitable” to serve a given cell to the time that it is no longer the most suitable,
hundreds of thousands of packets may be sent. Assignments of gateways to SVs will evolve over similar time-scales.

Downlink scheduling plays a critical role in costing out the fused LEO concept, which involves additional steering costs and additional transmissions. For systems, such as Starlink, that use frequency-division duplexing, with uplink channels disjoint from downlink channels, the uplink schedule is expected to be largely unaffected by fused LEO GNSS.

Will broadband LEO SVs be able to steer their (possibly paired) transmit and receive beams separately and use them simultaneously? Public filings do not make this clear. However, if the differences in wavelength between the uplink and downlink channels are significant, as is the case for Starlink, it seems reasonable to assume that a separate set of phasing coefficients would be required for each, if not completely separate antenna hardware, implying independently-steerable uplink and downlink antennas at the SV.

K. Power Management

Broadband LEO constellations can be expected to operate with highly efficient power management strategies. Their SVs’ solar arrays will be sized just large enough to meet some low multiples of the expected average energy demand per orbit at the end of life, and their batteries will be sized just large enough to meet some fraction of peak regional demand, and to sustain operations during eclipse [42]. Regional or global scheduling algorithms will optimize energy usage across the constellation by tasking each active SV to nearly exhaust its collected energy per orbit.

This is not to say that SVs will operate continuously at or near their maximum load power. Rather, they will be commanded to enter a “deep sleep” minimum-power state during a portion of their orbit while nearby SVs carry the burden of providing uninterrupted service. Such duty cycling is rational because, just as for smartphones [43], an SV’s useful work is a nonlinear function of its expended energy. Greater efficiency obtains when a subset of SVs operates near maximum power and the complement operates at minimal power than when each SV is active but not fully tasked. One may expect that over oceans a majority of SVs will be idled, whereas over some populated areas all will be fully tasked.

The constellation enters a scarce energy regime when the constellation-wide energy collected per orbit is inadequate to support the demanded communications operations. One might expect the constellation to be designed never to enter this regime, given that opportunities for the profitable exchange of data are lost. But as with electricity provision [44] and terrestrial broadband provision [45], it is wasteful to design a network for peak demand if the peak-to-average demand ratio is high. LEO broadband providers are likely to accommodate congestion just as their terrestrial counterparts do, namely, by throttling data speeds or by implementing time-dependent pricing [45].

L. Visibility

For K-band operation, in particular, the ITU Radio Regulations require broadband LEO operators to avoid SV-to-user lines-of-sight that pass too close either to geostationary orbit or to the horizon. SV beams cannot be assigned to serve cells for which the line-of-sight falls into one of these “exclusion masks.” The two types of masks reduce the number of available SV beams at low and high latitudes, respectively.

IV. FUSED LEO GNSS CONCEPT OF OPERATIONS

To achieve latency and performance competitive with traditional GNSS, fused LEO GNSS will need to employ single-epoch code-phase pseudoranging using bursts transmitted from four or more SVs. This will require changes to broadband LEO operators’ coordination and scheduling algorithms: multiple SVs must provide time-multiplexed ranging signals to each cell to support pseudorange-based PNT. These broadcast-ranging signals are an addition to the broadband LEO system, but they share the same modulation and encoding as the data service.

A. Obstacles

A comprehensive proposal for fused LEO GNSS must address certain key obstacles: Broadband service in a given cell is expected to be provided by a single SV for minutes at a time. Multi-SV-to-cell pseudoranging will require changes to both the central scheduler that matches SV beams with cells, and to the onboard schedulers that must avoid collisions with cross-cell ranging signals, i.e., those from other SVs (see Section IV-D). The downlink transmitters are not designed to produce traditional ranging waveforms (see Section IV-C). The broadband LEO SVs’ positions and clock offsets may not be known to have high enough accuracy either to the broadband system or to user modems, so a precision orbit and clock determination capability are needed (see Section IV-E). The onboard clocks are likely not stable enough for nanosecond-accurate forecasting beyond a minute, so a “zero age-of-ephemeris” solution is required (see Section IV-C). Finally, the SVs have limited power and limited resources for downlink scheduling, array steering, and command-and-control signaling. Any resources diverted from the constellation’s primary communications mission must be paid for by PNT customers (see Section V).

B. System Overview

The underlying broadband LEO system may be depicted as in Fig. 3 in terms of the relationships between SVs, beams, cells, and users. The fused LEO GNSS concept in Fig. 4 mirrors this structure with two alterations. First, SV beams may receive additional “secondary” cell assignments. Each beam will broadcast periodic ranging signals to all of its assigned cells, primary and secondary, but it will only provide broadband service to the cells for which it is primary. Second, whereas broadband connectivity is tied back to a gateway, PNT is tied back to traditional GNSS signals, as observed via GNSS receivers on the
In this way, LEO provides a second “tier” of PNT service, with traditional GNSS serving as the first tier (see Section IV-E). Note that although dependent on traditional GNSS, such multiterriered fused LEO GNSS is well-protected from terrestrial GNSS interference sources: L-band signal spreading loss to LEO is more than 145 dB [46].

The total number of assignments (primary or secondary) for each served cell is equivalent to the number of signals provided for pseudoranging, denoted \( n \). To fully constrain the three-plus-one dimensional PNT solution, \( n \geq 4 \). When a concrete baseline value is required, \( n = 5 \) will be assumed in what follows. For a customer willing to pay a high price for ultimate performance, \( n \) may be as large as the full number of SVs in view, circa 40 [12].

Two SVs in a ranging scenario are depicted in Fig. 5. Users in the service cell require a diversity of directions-of-arrival to obtain a robust positioning and timing solution. To maximize geometric diversity with \( n = 5 \), the operator could assign to a cell those SVs near the vertices of a square pyramid; e.g., the northernmost, easternmost, southernmost, westernmost, and zenith-most SVs in view among those that are not in an exclusion mask [47]. (The pyramid need not align with the cardinal directions.)

C. Pseudoranging Service

Ideally, one uses a ranging signal for ranging and a communications signal for communications. For fused LEO GNSS, however, it is greatly disfavored to change the function of the SV transmitter, both because modulations tend to be fixed in hardware, and because a high-bandwidth side-channel for orbit and clock data embedded in the ranging burst is highly valuable. Accordingly, fused LEO GNSS adopts the unmodified communications waveform for both data and ranging. There is a small degradation in possible ranging precision arising from this compromise, but it is dominated by other sources of error.

Service consists of a series of ranging bursts, each modulated just like ordinary broadband data, with three exceptions. First, the user modem must be able to regenerate the transmitted waveform and perform cross correlation, so the data bits encoded and modulated to form the ranging burst must be largely known in advance to the modem. This cross correlation results in a code-phase time-of-arrival measurement, which may then be compared with the nominal time-of-departure of the burst to form a pseudorange measurement. Second, the burst is very short. A duration of \( T_{\text{burst}} = 500 \mu s \) is more than adequate: the contribution to ranging error due to finite burst duration is far less than other sources of error [12]. For this reason, it is also not a problem to set aside a portion of the ranging burst to contain data not known in advance to the receiver, such as up-to-date clock and orbit ephemerides. This portion of the burst is ignored during correlation. Because the entire clock and orbit ephemeris fits into a small fraction of a single ranging burst—which might easily accommodate tens of kilobits of data—user pseudoranges need never be based on stale or forecast data. This “zero age-of-ephemeris” eliminates the need for atomic clocks on the LEO SVs. Third, the burst is not acknowledged by one ground receiver (i.e., unicast) but instead is broadcast to all receivers in the cell.
One significant challenge here is that, as noted in [41], the K-band channel is dispersive, with a worst-case coherence bandwidth of only 3 MHz. A naïve cross correlation on a 50 MHz-wide signal would not produce a peak with a width approaching $1/(50\,\text{MHz})$; instead, in a worst case, a broad, incoherent peak would be expected with width on the order of $1/(3\,\text{MHz})$. The dispersion on the channel may be decomposed into the following factors:

1) the frequency response of the transmit filters, amplifiers, and phased array;
2) the frequency response of the atmospheric channel;
3) the aggregate effect of multipath scattering;
4) the frequency response of the receive array, filters, and amplifiers.

Each of these can be managed in fused LEO GNSS: atmospheric dispersion at K-band is negligible for the bandwidths envisioned (Hobiger et al. [48] report submillimeter delay sensitivity to dry air pressure, water vapor, and surface air temperature for a 200 MHz-wide Ku-band signal), non-line-of-sight multipath effects will be suppressed by the directionality of the receive phased array, and the transmit and receive frequency responses may be estimated using the training preamble that is in any event required for OFDM.

D. Global Scheduling

This article draws a distinction between two objects that might be termed “schedules.” Global schedules are computed centrally and in advance by the broadband LEO provider and consist of assignments of SV beams to provide service to certain cells at certain times. Local schedules are computed on-the-fly on each SV as packets arrive and are dispatched. Global schedules may be valid for multiple minutes and can be forecast due to orbital predictability. Local schedules cannot be forecast due to the unpredictable timing of packets.

The global scheduler’s role in broadband LEO is to compute a conflict-free assignment of SV beams to cells: the “primary” assignments in the parlance of fused LEO GNSS. These assignments respect power, visibility, and exclusion mask constraints. In fused LEO GNSS, the global scheduler must additionally solve a system of constraints on the interdeparture and interarrival times of ranging bursts, particularly those “secondary” ranging bursts directed to a cell from a nonprimary SV. Care is required in scheduling these cross-cell ranging bursts so as to avoid collisions on the ground. In Fig. 6, bursts TX1 and TX2 from two different SVs arrive in the same cell. The wavefronts of each burst sweep across the cell in different directions, consistent with the geometry of Fig. 5. If a user at the eastern edge of the cell is to decode both bursts (for instance, if the first burst is data addressed to this user and the second burst is a ranging broadcast), then an interval $T_{\text{switch}}$ must be allowed between the end of the first burst and the arrival of the second for the user’s modem to retune its antenna.

1) Feasibility: A global schedule is feasible if and only if it satisfies all feasibility constraints at each transmitter and all feasibility constraints at each receiver. (Recall that only the downlink is changed in fused LEO GNSS, so the transmitter here is one SV beam, and the receiver is one user modem.) Let GNSS scheduler refer to the subroutine of the global scheduler concerned with fused LEO GNSS operations, and let the GNSS schedule be its product. GNSS schedules are periodic. One may visualize their period $T_{\text{period}}$ as one revolution of the hand of a clock (see Figs. 7 and 8) with the schedule of ranging bursts repeating after this interval. The relative timing of events differs between transmit and receive clocks due to time-of-flight effects. Transmit and receive constraints under which the GNSS...
A GNSS schedule consists of the following data:

1) $T_{\text{period}}$;
2) for each cell $k$, and for each ranging signal $s = 1 \ldots n$, a tuple (SV, channel, time modulo $T_{\text{period}}$, $T_{\text{flight}}$, $T_{\text{sweep}}$) indicating that a ranging burst will be sent by this SV on this channel toward this cell at such times.

Timing information may be quantized to a resolution of 1 μs without any significant loss of scheduling flexibility. Each SV must be provided with all assignment tuples involving either itself or any of its primary cells. The time-of-flight data in secondary (cross-cell) assignment tuples allow each SV to determine when it is safe to schedule data bursts. Optionally, the timing and time-of-flight parameters for primary ranging bursts may be left out of the GNSS schedule to be determined by local scheduling on each individual SV.

2) Optimization: The GNSS scheduler must be an efficient algorithm for finding feasible global schedules. Among feasible schedules, it will also optimize: the GNSS scheduler will prefer assignments that minimize the impact on local data scheduling, maximize the geometric diversity of ranging signals in each cell, and minimize system power consumption. The relative importance of these objectives could depend on the prices paid by customers for broadband and PNT services, and on the number of customers of each type in each cell. Given the complexity and nonconvexity of this problem, approximations or heuristics will likely be required.

3) Complexity: How complex is the global scheduling problem, and how over- or underconstrained is the feasibility problem? One way to grapple with this question is to consider a simple greedy baseline GNSS scheduler that runs after the global broadband scheduler has made its assignment of primary SV beams to cells over the next planning window. The GNSS scheduler allocates a “transmit cube” array to represent the ranging-specific status of SV $i$, beam-channel $bc$ at time $t$ mod $T_{\text{period}}$ (see Fig. 9). Recalling that data service is scheduled locally, and hence does not appear in the global schedule, the enumerated status values stored in the TX cube are Idle, Burst, and Switch. The GNSS scheduler also allocates a “receive cube” array to represent the ranging-specific status of cell $k$, channel $j$ at time $t$ mod $T_{\text{period}}$ (see Fig. 10). The enumerated status values stored in the RX cube are Idle, Burst, Switch, and Exclude. During construction of the TX and RX cubes, the GNSS scheduler consults an “availability” array, which indicates whether SV $i$ is available to provide signals to cell $k$, or is excluded from doing so for any reason.

The greedy baseline GNSS scheduler iterates over cells $k$. For each cell, it iterates over ranging signals $s = 1 \ldots n$. For each signal, it iterates over available SVs $i$. To maximize geometric diversity for $n = 5$, a “goal direction” is defined for each $s$, and available SVs are iterated in descending order of alignment of their line-of-sight vectors with the goal direction. The goal directions form a square pyramid of points in the sky [47]: for $s = 1$, the zenith; for $s = 2$, local north;
Fig. 9. TX cube. The GNSS scheduler uses such a representation to track when each (beam, channel) pair of each SV has been reserved for ranging. Burst durations and cube occupancy are greatly exaggerated for clarity of visualization. Beam channels belonging to a single beam are shown separated by thicker lines.

Fig. 10. RX cube. The GNSS scheduler uses such a representation to track when each channel in each cell has been reserved for ranging. The true RX cube has a more complicated adjacency relationship than shown here because service cells form a 2-D hexagonal grid rather than a 1-D line. Burst durations and cube occupancy are greatly exaggerated for clarity of visualization.

for $s = 3, 4, 5$, local east, south, and west, respectively. The greedy scheduler proceeds from SV to SV in this order, attempting to find idle space in the corresponding planes of the TX and RX cubes to make an assignment. When it finds a suitable space, it adds the assignment tuple to the output GNSS schedule, updates the TX and RX cubes, and proceeds to the next signal $s + 1$. If all available SVs are exhausted and $n$ signals have not been assigned for cell $k$, then the greedy scheduler fails. If all cells have been assigned $n$ signals each, then the greedy scheduler succeeds. Is this procedure likely to succeed? Does the answer depend upon whether cells are iterated in geographic order, or...
where the inequality allows for possible overcounting of switching times, and nonuniform beam bandwidth is ignored.

Similarly, each primary or secondary assignment reserves one downlink channel in a cell for an interval of up to $T_{burst} + T_{sweep}$, and each secondary assignment additionally reserves the channel for $2T_{switch}$. Finally, constraint 8) requires that each cell’s $N_{adj}$ adjacent cells be reserved for time $T_{burst} + T_{sweep}$ for each assignment. Summing over assignments and dividing by the RX cube volume $V_{RX} = N_{cells}N_{channels}T_{period}$, one obtains

$$R_{RX} \leq \frac{n(N_{adj} + 1)(T_{burst} + T_{sweep}) + 2(n - 1)T_{switch}}{N_{channels}T_{period}}$$

(2)

$$T_{sweep} \leq \frac{D}{c} \cos(\phi_0)$$

(3)

where the first inequality allows for possible overcounting of switching times and adjacent-cell exclusions, $\phi_0$ is the minimum elevation mask angle, $D$ is the cell diameter, and $c$ is the speed of light.

To obtain estimates for these reservations in practice, let $N_{cells} = 850,000$, $N_{adj} = 6$, $N_{sats} = 10,000$, $n = 5$, $N_{channels} = 76$, $N_{beams} = 15$, $T_{burst} = 500 \mu s$, $T_{switch} = 100 \mu s$, and $T_{period} = 1 \text{s}$. For $T_{sweep}$, assume a minimum elevation angle $\phi_0 = 40^\circ$ and a cell diameter $D = 29 \text{ km}$. (Other parameter values may be explored using the code in Supplementary Material A.) Then

$$R_{TX} \leq 1.60\% \quad R_{RX} \leq 0.03\%$$

That the TX and RX cubes are overwhelmingly Idle is significant because the scheduling problem within each cube is equivalent to the graph coloring problem [49] for which upper bounds exist on the number of required colors (analogous to the number of time slices of the cube) for various algorithms [50]. So, as long as the cube reservations are sparse, feasible schedules can be found with even very simple algorithms [49]. One may, thus, presume that the feasibility problem is greatly under-constrained, and the optimization problem will be of greater interest than the feasibility problem in future work.

The global TX and RX reservations also equal the mean reservations for any given SV beam-channel or cell, respectively. Thus, the impact on the local scheduling problem should be small as well. This article accordingly does not elaborate on local scheduling.

One might question whether all or only a subset of SVs in a broadband LEO system ought to be involved in fused LEO GNSS. Indeed, the low reservation numbers indicate that such subsetting would be possible. However, due to switching times, it is less costly for an SV to provide ranging bursts to its primary cells than otherwise. It is preferable, then, to task every SV having one or more primary cells to provide ranging service to those cells. Load shifting over regions with few subscribers could mean that some SVs are placed into power-saving mode, while the remainder is tasked close to 100% capacity. In this case, GNSS duties

randomly? Or upon whether iteration is instead first over
signals and then over cells? A key clue is that the TX and
RX cubes remain overwhelmingly Idle in any event, as will
be shown.

4) Schedule Sparsity: If one presupposes that a feasible
schedule exists, it consists of $N_{cells} \cdot n$ assignment tuples,
of which a fraction $(n - 1)/n$ are secondary, and the rest
are primary. The fraction of the TX cube that is nonIdle is
then equal to the sum duration of these assignments,
divided by the dimensions of the cube. This fraction, which
counts transmitter resources devoted to the megacon-
stellation’s secondary PNT mission and thus rendered un-
available for its primary communications mission, will be
called the transmit reservation $R_{TX}$. Similarly, the fraction
of the RX cube that is nonIdle will be called the receive
reservation $R_{RX}$.

Each primary assignment reserves a single downlink
SV beam-channel for an interval $T_{burst}$. Each secondary
assignment reserves the entire SV beam for $T_{burst} + 2T_{switch}$. Summing up all the primary and secondary assignments and dividing by the TX cube volume $V_{TX} = N_{bc}N_{sats}T_{period}$, one obtains TX reservation

$$R_{TX} \leq \frac{N_{cells}T_{burst} + (n - 1)(T_{burst} + 2T_{switch})N_{bc}}{N_{bc}N_{sats}T_{period}}$$

(1)
would also be concentrated as much as possible to minimize the number of active SVs.

E. Orbit and Clock Determination

Both hosted payload and fused approaches to LEO GNSS require continual highly accurate estimates of the SV orbital ephemerides and of the time offsets of the spaceborne clocks. Such estimation should ideally take advantage of constellation-to-ground ranging, intraconstellation ranging, and onboard GNSS receivers. In the near term, however, broadband LEO providers should not be expected to build out an observational network of ground stations extensive enough (e.g., covering ocean regions), or intraconstellation ranging accurate enough, to significantly improve on-orbit and clock determination based on onboard GNSS receivers, which can be expected to constrain forecasting uncertainties for clocks and orbits to 14 cm RMS after one second, as estimated in [12] based on Montenbruk et al. [51]. Even better results are likely possible using the more recent results of Montenbruk et al. [52], [53].

Thus, in the near term, LEO GNSS will operate in what Reid et al. [24] refer to as a multitier GNSS architecture, with each SV carrying, and dependent on, a GNSS receiver. This architecture is intermediate in assurance between traditional GNSS and fully autonomous LEO A-PNT: it is reliant on GNSS being available in orbit but provides highly jam-resistant signals to users on the ground.

V. Cost Model

The opportunity cost of PNT provisioning for fused LEO GNSS is the value of the best alternative use of the same resources. In the context of this article, the opportunity cost of fused LEO GNSS is the value of foregone broadband service. To determine what quantity and value of broadband service is foregone, one would need to know both the load on the system—since idle resources cannot be wasted by putting them to profitable use—and the billing structure for broadband data. Neither is publicly known. To address the first issue, this article will focus on worst case opportunity cost: lost opportunities for profitable broadband service assuming the broadband LEO system is loaded at 100% at all times, i.e., that there is at least one constellation resource that is 100% utilized, the so-called bottleneck resource. To address the second issue, rather than giving costs in monetary units, this article will express costs as reservations: percentages of potential bottleneck resources.

Lost opportunities for broadband data transmission may be interpreted differently depending on the subscription model. For a given number of users with fixed load patterns, opportunity costs manifest as small penalties to latency and throughput. If the number of subscriptions is variable but subscriber bandwidth and latency are held constant, opportunity costs manifest as a reduction in the number of subscriptions that may be sold. The former model is more likely to apply for broadband LEO: guarantees in consumer Internet service tend to be aspirational because the quality of service can be more nimbly modulated than the number of subscribers.

This section will consider potentially constraining resources one at a time, supposing that each, in turn, is the bottleneck resource. One presumes that a prescient broadband LEO system operator would provision the constellation such that each constraint is nearly binding in practice; otherwise, costs could have been cut in some subsystem(s). Discussion and interpretation of the results follows in Section V-H.

A. Scope

The opportunity cost of a fused LEO GNSS service could be assessed for both downlink and uplink, and for the SV modem, the user terminal (UT), and the gateway terminal. But not all link-endpoint combinations are independently affected. For example, LEO GNSS never prevents an SV from receiving uplinked broadband data from UTs: SVs are assumed to be full duplex and they receive no LEO-GNSS-specific signals from the UTs. The only effect LEO GNSS has on uplink reception involves command-and-control traffic from the gateway terminals, which (see Section V-F) is shown to be slight.

From the perspective of a (presumably typical) half-duplex UT, time is the limiting resource. When the UT tunes to one channel, it cannot hear the others; when it points toward one transmitter, it cannot decode another. With the introduction of a fused LEO GNSS service, non-participating UTs will notice a slight reduction in available opportunities to receive downlink packets (see Section V-B). Participating UTs will additionally spend time directing their array and/or tuning their receiver to capture scheduled ranging bursts (see Section V-G). However, if the UTs are not already 100% busy, fused LEO GNSS will have no effect on uplink transmission.

Thus, in what follows, SV downlink transmission resources will receive more attention than SV uplink reception resources, and UT resources will only be considered in terms of a lumped duty cycle.

B. Downlink Capacity

If an SV’s local scheduling problem becomes overconstrained—that is, if no more downlink data packets can be scheduled, but packets are available from the gateway—then downlink capacity becomes a bottleneck resource. In this case, either data or ranging service is delayed, depending on what promises of latency, throughput, or reliability are in effect. (One presumes that to avoid excessive buffering some form of active queue management is needed at the gateway [54].)

At most, every channel of every beam of every satellite can be active, and at most, every channel of every cell can be active. The maximum downlink throughput of the LEO broadband system is subject to both limits.
A broadband LEO downlink without fused LEO GNSS can, thus, deliver no more than 

\[ C_{DL_{before}} = \frac{\min[V_{TX}, V_{RX}]}{T_{period}} \]  

(4)

channels’ worth of data at once. A “channel’s worth” is one spatial degree of freedom—one beam of a satellite or one cell—times one unit of bandwidth allocation. (A subtler calculation would involve multicoloring of the hexagon graph; (4) is merely an upper bound.)

Converting (4) into bits per second requires a model of the link budget, SNR, and forward error correction scheme. (Supplementary Material A develops a concrete estimate for this conversion factor assuming the use of Turbo codes [55]). Under the modeling assumptions further detailed in the Supplementary Material, each channel’s worth of bandwidth (modeled as 50 MHz) supports 114.5 Mb/s of data.

Introducing fused LEO GNSS decreases each argument of the min function in (4) in proportion to the corresponding reservation. The remaining downlink capacity is 

\[ C_{DL_{after}} = \frac{\min[V_{TX}(1 - R_{TX}), V_{RX}(1 - R_{RX})]}{T_{period}} \]  

(5)

for a relative change of

\[ R_{DL} = \frac{C_{DL_{before}} - C_{DL_{after}}}{C_{DL_{before}}} = 1.60\% \]  

(6)

or an absolute change of 5.7 Mb/s per cell.

C. Scheduling Complexity

To obtain a concrete bound on the computational complexity of global scheduling, consider a greedy randomized scheduler. The expected number of attempts needed to pick an available tuple (SV, beam, channel, time) by rejection sampling scales as \(1/p\) with the probability \(p\) of success, or the probability that a randomly chosen tuple of parameters points to unallocated space within both the TX and RX cubes. As more allocations are added to the schedule, the empty space in the cubes decreases, and the chance that the next randomly-sampled tuple of parameters will be feasible falls. Let \(p_{min}\) be the probability of success for the last tuple to be scheduled. Then the expected complexity of building a schedule with \(n N_{cells}\) total allocations is no greater than \(n N_{cells}/p_{min}\). By the union bound

\[ p_{min} \geq 1 - P[TX \text{ cube collision}] - P[RX \text{ cube collision}]. \]  

(7)

These two quantities differ from the transmit and receive reservations by a factor less than 2 due to the need to avoid overlap between allocations of finite extent. One may, therefore, bound the expected time complexity of finding a feasible schedule by

\[ \frac{n N_{cells}}{1 - 2R_{TX} - 2R_{RX}} = 4.4 \times 10^{106} \text{ steps}. \]  

(8)

Each step requires sampling a random tuple, testing for collisions in each cube, and potentially writing a new allocation into each cube. These millions of steps can be completed in less than a second on a modern processor.

D. Phased Array Setup

Another constellation resource consumed by fused LEO GNSS is serial bandwidth for phased-array setup (see Section III-F). This section first estimates a baseline for the SV’s capacity to steer a beam, expressed through the parameter \(T_{steer}\), from considerations of link budget and end-to-end latency. It then compares this quantity to the fused LEO GNSS schedule to compute the consumed portion \(R_{SU}\) of constellation steering resources.

1) \(T_{steer}\): Broadband LEO SVs steer their arrays both to compensate for the continuous orbital motion and to switch between service cells. Orbital motion changes the SV-UT line-of-sight by up to \(\omega = 0.73^\circ/s\). With a phased array, steering occurs in discrete steps. Suppose these occur at intervals \(T_{steer}\). If steering events are infrequent, the steering error cannot be kept small, and antenna gain along the line-of-sight fluctuates downward. Thus, the communications link budget imposes an upper bound on \(T_{steer}\).

Consider a 2.0°-wide beam (see Supplementary Material D, Table I), measured in terms of full-width at half maximum (FWHM). The decrease in antenna gain (pointing loss) at an angle \(\Delta \theta\) off-axis is \(L_{\text{pointing}} = 12 \text{ dB}(\Delta \theta/\text{FWHM})^2\) under the Gaussian approximation. Given a loss budget \(L_{max}^\text{pointing}\) the interval between steering events must not exceed

\[ T_{steer}^\text{max} \leq \frac{2\Delta \theta}{\omega} = \frac{\text{FWHM}}{\omega} \sqrt{\frac{L_{max}^\text{pointing}}{3 \text{ dB}}}. \]  

(9)

If \(L_{\text{pointing}}\) is given rather than \(L_{max}^\text{pointing}\), the 3 in the denominator is replaced by 1. An exact relationship between \(\Delta \theta\) and \(L_{\text{pointing}}\) is discussed in Supplementary Material C, following [56]. \(T_{steer}\) can further be cast in terms of lost throughput: for instance, to limit throughput losses due to misalignment to 0.10%, \(T_{steer}\) must be less than 260 ms.

The second cause of steering events is switching service cells. If an SV serves broadband to one cell per beam, there may be minutes between these switching events. However, an SV beam serving multiple cells must steer more frequently. To reach a target latency—for Starlink, 20 ms [57]—a user can never be neglected for a period approaching the end-to-end latency. The downlink array must be steered more than once per 20 ms for each cell it serves with broadband. This is expected to be the case early in the deployment of any mega-LEO constellation when few SVs are available. Suppose, then, that downlink arrays are designed for a small multiple of 50 steering events per second. This is vastly more than \(1/T_{steer}^\text{max}\) but only sufficient for a small number of service cells per beam. To pick a concrete number, suppose each array can accept a new set of coefficients each \(T_{set-up} = 5\) ms.

2) \(R_{SU}\): Fused LEO PNT requires each array to be steered frequently to provide secondary ranging bursts. If the GNSS schedule is designed jointly with the broadband schedule so that a beam’s broadband service assignments

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coincide with its ranging service assignments, then the need for additional steering events may be reduced. Otherwise, this limits the opportunities for assigning many cells’ broadband service to the same SV.

Recall (see Section IV-D1) the assumption that “switching back” has no setup cost: during switching, the banks of memory holding old and new coefficients are swapped without erasing so that switching back does not require reloading coefficients. Otherwise, the steering bandwidth utilization must be doubled.

Steering bandwidth is the least abundant resource considered so far. The GNSS schedule includes a total of \((n - 1) N_{\text{cells}}\) secondary assignments, each requiring one SV beam’s phasing array to be busy loading coefficients for an interval \(T_{\text{set-up}}\) once per \(T_{\text{period}}\). Considered as a fraction of total steering setup capacity in the same way as the TX reservation, the mean setup reservation \(R_{\text{SU}}\) is given by

\[
R_{\text{SU}} = \frac{(n - 1) N_{\text{cells}} T_{\text{set-up}}}{N_{\text{beams}} N_{\text{sats}} T_{\text{period}}} = 11.3\%.
\]

E. Power

Available electrical power becomes a bottleneck resource when the constellation operates in a scarce energy regime (see Section III-K). The opportunity cost of fused LEO GNSS attains a maximum in this regime: a Joule expended on a ranging burst is a Joule that could have been spent on broadband service. Moreover, if the SV’s battery is sized so that peak power loads are amortized across the orbit, then the cumulative energy expended per orbit drives the calculation of opportunity cost, in which case it makes no difference at what point in the orbit the ranging burst is transmitted, whether over a sparsely- or densely-populated area: the opportunity cost per burst remains the same (maximum) value for every burst.

As discussed in Section III-K, SVs will be commanded to enter a “deep sleep” state during some portion of their orbit and otherwise may be expected to operate near capacity. The burden of fused LEO GNSS in any given region is distributed among the active SVs. Let \(E_{\text{burst}}\) be the average energy expended by an SV to transmit a data or ranging burst via a single channel of a single beam, let \(E_{\text{orbit}}\) be the average energy expended by an SV’s transmitters per orbit, and let \(T_{\text{orbit}}\) be the average orbital period. The number of ranging bursts per orbit per satellite is \(n N_{\text{cells}} T_{\text{orbit}} / T_{\text{period}} / N_{\text{sats}}\). Then the mean energy reservation \(R_{\text{E}}\), or the mean energy allocated per orbit for fused LEO GNSS as a fraction of total-constellation mean energy expended for downlink, can be approximated as

\[
R_{\text{E}} = \frac{n N_{\text{cells}} T_{\text{orbit}} E_{\text{burst}}}{T_{\text{period}} N_{\text{sats}} E_{\text{orbit}}}. \tag{11}
\]

Without detailed knowledge of the broadband LEO system is not possible to estimate \(E_{\text{burst}} / E_{\text{orbit}}\), the ratio of the modem’s energy consumption to transmit a single burst on a single channel of a single beam to the total energy expended on downlink over an orbit. A more accessible parameter is the transmitter peak-to-average power ratio (PAR) for an SV: the ratio of the power consumed when the downlink is operating at full capacity to the power consumed by the downlink on average. At maximum output, the transmitters use \(P_{\text{TX}}^{\text{max}} = \frac{N_{\text{bc}} E_{\text{burst}}}{T_{\text{orbit}}}\), whereas, on average, they use \(P_{\text{TX}}^{\text{mean}} = \frac{E_{\text{burst}}}{T_{\text{orbit}}}\). This implies

\[
\text{PAR} = \frac{P_{\text{TX}}^{\text{max}}}{P_{\text{TX}}^{\text{mean}}} = \frac{N_{\text{bc}}}{T_{\text{burst}} / T_{\text{orbit}}} E_{\text{burst}} = \frac{E_{\text{burst}}}{T_{\text{orbit}}}. \tag{12}
\]

\[
R_{\text{E}} = \frac{n N_{\text{cells}} T_{\text{burst}} \text{PAR}}{T_{\text{period}} N_{\text{sats}} N_{\text{bc}}}. \tag{13}
\]

Suppose SVs spend equal power on each visited subscriber so that, to a first approximation, power is consumed in proportion to the number of subscribers-in-view. Then PAR can be predicted from the geographic distribution of LEO broadband subscribers. (This assumes that the average power allocated to fused LEO GNSS is a small fraction of each SV’s total average power load.) The distribution of broadband subscribers is, thus, a key input in estimating the power opportunity cost of fused LEO GNSS.

1) Estimating the Geographic Subscriber Distribution: In urban centers, terrestrial broadband Internet service enjoys better scaling than broadband LEO service: terrestrial capacity can be expanded locally, whereas LEO capacity can only be expanded globally. For this reason, the population distribution of the world is not a good estimate of the distribution of potential subscribers. Suppose the set of potential customers is primarily rural and lacks access to terrestrial broadband alternatives. How might the distribution of such be estimated?

Let \(\rho_{\text{max}}\) be the maximum population density that can be competitively served by broadband LEO. For instance, suppose that in regions exceeding this density, terrestrial broadband is available and inexpensive, and satellite downlink capacity is saturated due to regulatory flux limits (see Section III-H). Let \(\rho_{\text{max}}\) be estimated by \(\hat{\rho}_{\text{max}} = \gamma \cdot \hat{\rho}_{\text{USA}}\), where \(\hat{\rho}_{\text{USA}}\) is the density threshold in the United States, and \(\gamma\) accounts for international differences in broadband usage per (potential) customer.

In Supplementary Material B, \(\hat{\rho}_{\text{USA}}\) is determined from the estimated number of U.S. citizens without options for purchasing terrestrial broadband Internet (42 million circa 2020) [58]. The Supplementary Material supposes these individuals to be precisely those residing in the lowest density regions. From the Gridded Population of the World, Version 4 (GPWv4) [59], Supplementary Material B extracts, for each cell within the land area of the United States, both the population density and the integrated population count. It finds the cumulative distribution of individuals by the density of their regions, accumulating population counts in order from least dense to most dense. This cumulative distribution first exceeds the target threshold of 42 million people at a density of 63.2 people/km².

Supplementary Material B estimates \(\gamma\) as the ratio of active mobile broadband subscriptions per 100 inhabitants in the developed world to that in the entire world. That is, holding all else equal, if mobile broadband subscriptions are more numerous on a per-inhabitant basis in some region,
then the broadband LEO system will tend to saturate (that is, reach its maximum sustainable subscribers/km²) at fewer inhabitants per square kilometer there. This ratio is approximately 122/83 (circa 2019) [60], giving a global average value of ²ρmax = 92.7 people/km². This holds under the simplistic assumption that mobile broadband penetration can be taken as a proxy for LEO broadband demand. The reality is more complicated since high-rate mobile broadband may be a substitute for broadband LEO; but a more precise value would be unlikely to significantly change the result.

To account for limited system capacity in populous regions—which may nevertheless contain a substantial number of subscribers—Supplementary Material B limits all regions to a maximum density of ²ρmax. A grid ²p′ij of potential-subscriber counts is computed from the GPWv4 population density grid, and then summed over the circular neighborhood (correcting for spherical geometry) of every potential satellite location. This yields a visible-subscriber count. Finally, this count array is sampled over various orbital parameters to obtain a distribution, from which peak and average values may be computed. For a LEO constellation at an altitude of 550 km and an orbital inclination of 53 ° (Starlink’s proposed B subconstellation [39]), the peak-to-average population density ratio resulting from such calculations is 9.6 (see Supplementary Material B), which may be taken as a proxy for PAR. Filling in the other quantities involved in ²R_E with the values given in Section IV-D4, one finds that the mean energy reservation is ²R_E = 0.77%.

F. Command-and-Control Bandwidth

Fused LEO GNSS will require only a negligible amount of command-and-control bandwidth. This article assumes that each SV independently performs precision orbit determination using an on-board GNSS receiver. This requires streaming traditional GNSS satellites’ precise orbit and clock models from the gateway. Such a stream could be derived from, for instance, the IGS Real Time Service [62], which consumes little bandwidth: 400 to 800 bit/s for precise orbit and clock corrections including every constellation, 3.4 bit/s for global ionospheric model coefficients, and optionally 17 kbit/s of broadcast ephemeris data for navigation bit wipe-off.

The LEO GNSS schedule must also be distributed, sending each SV its assignments and those secondary assignments that affect its primary cells (see Section IV-D1). Overall, each primary assignment in the GNSS schedule will be sent to exactly one SV, and each secondary assignment will be sent to exactly two: the transmitter and the SV that is primary for the target cell. The total bandwidth used distributing assignments is, therefore, (2n − 1)N_cells times the size in bits of one assignment. Examining the range and quantization of each parameter in an assignment tuple, one finds that the tuple may be encoded in 59 bits (see Supplementary Material A). The uplink bandwidth used by fused LEO GNSS is dominated by the cost of uplinking assignments. Summed over the entire constellation, this assignment uplink cost may be computed as

$$C_{AU} = (2n - 1)N_{cells} \cdot 59 \text{ b} < 54 \text{ MiB}. \quad (14)$$

The data portion of each primary ranging burst will include a copy of the secondary assignments. Users also need the line-of-sight direction to each secondary SV for steering. It is sufficient to provide orbits accurate to ~10 km (see Supplementary Material C) for this purpose: once a secondary burst is decoded, the user will have high-accuracy ephemeris for that SV.

These assignments and ephemerides need to be updated on the SV no more than a few times per minute. On a per-SV basis, the total uplink cost is approximately 3.5 kb/s (see Supplementary Material A).

G. UT Duty Cycle

For reasons of cost, full-duplex UTs seem a remote possibility. Consider, then, a half-duplex UT that divides its time between uplink, downlink, switching between the two, and sitting idle. Let the duty cycles of these activities be expressed as

$$d_{UL}^{UT} + d_{DL}^{UT} + d_{switch}^{UT} + d_{idle}^{UT} = 100\% \quad (15)$$

From the perspective of an individual UT, there are three cases to consider with regards to fused LEO GNSS service: service may be absent, unneeded, or in use. If service is absent, the UT may spend up to 100% of its time in either of the uplink or downlink states, achieving maximum data throughput.

If service is present, then whether or not it is needed by this UT, the downlink channel is partly occupied, and hence unavailable for other purposes. The downlink duty cycle for an individual UT, d_UL^{DL}, is then bounded above by 1 − R_{RX} = 99.97%, and the average downlink duty cycle for all UTs, d_UL^{DL}, is bounded above by 1 − R_{DL} = 98.4%. Uplink, switching, and idle duty cycles are not directly impacted unless the UT is listening for fused LEO GNSS.

If an individual UT is using fused LEO GNSS, then a cost d_{PNT} is subtracted from the right-hand side of (15), with

$$d_{PNT} \leq nT_{burst} + 2(n - 1)T_{switch} = 0.33\% \quad (16)$$

This is a less stringent limitation than the former bounds on downlink duty cycle, but it directly bounds d_{UL}^{UT} ≤ 99.67%.

H. Discussion

Regarding the mean downlink reservation ²R_{DL}: If the broadband data load on an SV keeps its transmitters busy less than 98.4% of the time, then ²R_{DL} represents essentially zero opportunity cost. Recall that ranging bursts do not involve gateway or intersatellite link traffic. It may be that gateway retransmissions or temporary link interruptions cause the SV’s packet buffers to be empty more than 1.6% of the time even under heavy offered broadband load. If buffers are kept deliberately small for low latency [54], [57], link utilization might be bounded away from 100%
due to the behavior of TCP. Like water poured into the interstitial spaces in a jar of sand, the channel reservation for fused LEO GNSS ranging bursts may not displace any data traffic at all. In any event, a global schedule providing \( n = 5 \) ranging signals per second to every cell between \( \pm 60^\circ \) latitude would tie up no more than 1.6% of system downlink capacity. This allocation is comparable to adding one user consuming 5.7 Mb/s of broadband service to each cell (see Supplementary Material A).

The mean energy reservation \( \bar{R}_E \) at 0.77% assumes that the SV is capable of transmitting on all \( N_S = 264 \) beam-channels at once. If this is not true, it would imply a larger value of \( E_{burst}/E_{orbit} \) and hence \( \bar{R}_E \). The code in Supplementary Material A permits the exploration of alternative scenarios.

The mean setup reservation \( \bar{R}_{SU} = 11.3\% \) appears large but its impact is subtle. Broadband LEO service does not fail catastrophically when beam steering is overtaxed. Instead, the link budget gradually degrades as beams spend more time out of perfect alignment. Spill-over into adjacent cells also increases. These potential problems are reduced if cross-cell ranging bursts are timed to coincide with steering updates, although this is not a complete solution. There is not enough time to load fresh coefficients for cell A while ranging is served to cell B if \( T_{set-up} > T_{burst} + 2T_{switch} \). As discussed previously, if the array hardware permits recalling one or more sets of coefficients rather than reloading them from the CPU, switching costs can be substantially mitigated. In this case, the strategy would be to begin loading coefficients further in advance of the cross-cell burst.

In any event, as indicated in Section V-D, the bulk of switching events for broadband service is for time multiplexing and not for maintaining the link budget. Foregone opportunities to load new coefficients due to fused LEO resource utilization lead to minuscule pointing-related throughput losses of 0.5 ppm. The true impact of \( \bar{R}_{SU} \) is that an SV tasked with fused LEO GNSS cannot afford to time-multiplex between so many cells as an SV free of fused LEO assignments. Fortunately, the size of this effect will diminish as mega-LEO constellations approach full utilization since time multiplexing between cells is not helpful if a single cell consumes 100% of a beam’s throughput.

The foregoing mean reservations have all been calculated assuming a global (\( \pm 60^\circ \) latitude) fused LEO GNSS service without regard to the distribution of users. An alternative model would provide service only to areas where subscribers are located. For even greater flexibility in matching supply with demand, such targeted service could be paired with time-varying subscription rates. Under this model, flexible customers demanding continuous high-accuracy LEO GNSS could obtain it but at a significant cost during periods and within regions of peak broadband demand. Conversely, subscribers willing to accept opportunistic LEO GNSS service could obtain it cheaply when and where its provision presents a near-zero marginal cost to the broadband LEO system.

VI. CONCLUSION

This article presented a concept of operations for fused LEO GNSS, enabling the exploitation of powerful new broadband LEO constellations for global PNT. It laid out a summary and analysis of what is publicly known and what may reasonably be inferred about broadband LEO systems, insofar as this information is needed to explore dual-purposing these systems for PNT. Finally, it analyzed the opportunity cost to constellation providers for reallocating resources to provide a fused LEO GNSS service. For a constellation, such as SpaceX’s Starlink, to provide continuous service to 99.8% of the world’s population would require reserving at most 1.6% of system downlink capacity, 0.77% of system energy capacity, and 3.5 kb/s per SV of command-and-control bandwidth. This provisioning scenario reserves 11.3% of the constellation’s capacity for beam-steering, limiting the number of cells served by each SV beam.

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