SMALLSAT/CUBESAT GROUND COMMUNICATION METHODS AND LIMITATIONS

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ABSTRACT

This paper explores the viability and suitability of small satellite (SmallSat) constellations for communication missions, with particular focus on data throughput limitations caused by reduced power and aperture size. We explore ad hoc network architecture with multi-antenna techniques to achieve lower life cycle cost and we assert this approach can expand SmallSat mission capabilities.

INTRODUCTION

Historically, earth satellites have served many distinct missions. Prominent among these are scientific observation missions which measure a wide variety of physical characteristics (temperatures, atmospheric chemistry, sea levels, radiation, weather systems) using many forms of instruments (photo imaging, radar, infrared sensors, and spectrometers). Also prominent are communication missions; initially single-satellite, geosynchronous or highly-elliptical orbiting, transponded systems, evolving recently to coordinated, LEO, multiple satellite fleets. A fundamental component of virtually all missions is the ability for ground systems to communicate with the on-orbit satellites, to exchange command and control, and to transport the mission product (science data, end-user communication content).

For many missions, space-ground communication in real-time is not required. An earth-observing satellite in low earth orbit may gather data for one or more complete orbits, subsequently dumping the data set when the satellite is visible to one or more dedicated ground stations. This “store and forward” operation reduces the number of ground terminals required to complete the mission and limits the required geographic range as well, controlling mission costs. Other missions demand low-latency communications, conducted in real-time, eliminating the convenience of storing any data product on-board the satellite. This CONOPS limits the complexity (and therefore cost) of the satellites, at the expense of an increase in ground system costs.

Communication satellites in geosynchronous orbits are, by definition, large and heavy beasts. This derives from their need to provide adequate communication link performance over the significant distance from the GEO altitude and, in most cases, tolerate some level of atmospheric/weather disturbances. Supporting high link margins requires significant power and significant antenna gain. These translate directly to large solar arrays and large antenna apertures. Because these satellites must operate through eclipse conditions, they must also have large capacity batteries. Further, orbits within the GEO arc must be strictly controlled, so these satellites must have means (mechanisms, fuel, and control systems) to perform orbit maneuvers. Because of the high costs to manufacture and launch these GEO satellites, redundancy protects against mission-affecting failures, again increasing weight and costs. All of these factors result in a large, heavy satellite, which is extremely costly to launch and place into orbit. Lastly, GEO satellite communication is always subject to extended end-to-end latency based on propagation delays between earth stations and the GEO altitude.

Communications satellites in lower orbit can be smaller, as the links they support experience much lower free-space loss due to their significantly lower altitude. But unlike a GEO satellite which can see almost an entire earth hemisphere, a LEO system requires more satellites to provide consistent coverage. Further, each satellite in these systems nominally provides services over a small and changing earth section, so that satellite failures do not affect the mission as directly, consistently, or completely as a GEO failure. Replacement of failed satellites is practical because they are smaller and lighter, and boosted to a lower altitude making launch costs are more reasonable. These factors can eliminate the need for redundancies, further reducing costs. Smaller is more cost-effective, but based on the mission need to support viable communication links to small (often hand-held) terminals, there is a practical lower bound for antenna aperture and require power generation.

Recent trends in satellite exploration are in the direction of smaller, simpler, lighter satellites. CubeSats are on the order of 10cm x 10cm x 10cm, and can be assembled for 10's or 100's of thousands of dollars. Owing to their limited size and weight, a single dedicated launch could place many CubeSats into orbit. Alternatively, one or more could "ride along" with the launch of larger systems, further reducing on-orbit costs. The trend towards smaller, simpler, lighter enables many academic and scientific missions which would otherwise be cost-prohibitive. Given the availability of both low-power consumption and, high-performance computing, these satellites can perform sophisticated sensing and analyses. For a communications mission, however, the desire to support reliable, higher-rate communications remains unsatisfied. For many missions, this is less problematic as data latency is not a factor and satellites can choose to downlink data when conditions are optimal. For a communications mission where usage cannot be arbitrarily or inconsistently offered, the limited size of the satellites is prohibitive.

In summary, the performance requirements imposed on a satellite in support of a communications mission are generally orthogonal to the fundamentals of low-cost SmallSat implementations. Still, the affordability of SmallSat implementations, for acquisition, operations, and sustainment, make them a very attractive proposition. Our paper explores the potential for exploiting the cost-effectiveness of SmallSat systems to meet the needs of a communication mission.

Approach

Section 1 of this document describes two conventional communications satellite constellations, one at GEO and one at LEO, and presents their limitations in the context of a global communication system. Section 2 describes an approach utilizing ad hoc, cooperative networking and multi-antenna techniques to provide for viable, cost-effective SmallSat communications systems. Section 3 follows up and describes performance analysis for the proposed architecture.

SECTION 1 - OVERVIEW OF EXISTING SATELLITE COMMUNICATIONS MISSION ARCHITECTURES

A good example of a GEO constellation providing telecommunication services is the Mobile User Objective System (MUOS). MUOS is a multiple user, narrow-band satellite communication system that operates user-access links in the UHF band. It supplements and will eventually replace the US Navy's UHF/UFO system. MUOS operates via 4 bent pipe geo-synchronous satellites linking end-users to 4 globally-placed radio access facilities (RAF). All traffic switching and routing is performed on the ground in dual switching facilities (SF). To ensure reliable service in the event of component (or entire site!) failures, each MUOS satellite simultaneously links with each of two ground stations. Further, each ground station simultaneously links to two MUOS satellites. MUOS offers on-demand, point-to-point, point-to-net, and group services at data rates up to 384 Kbps.

To provide adequate link margin from GEO orbit, the satellite's main antenna is 46 ft in diameter. This large aperture requires a large satellite to support it; the satellite weighs close to 6800 lbs (wet), has a bus width of 14 feet and the solar panels span 92 feet[1] end-to-end. Each RAF requires three 18m antennas to provide adequate capacity, link margin, and availability. MUOS has been developed over the last 10 years and the cost is approaching $7 billion[2]. Because there are only four satellites in the MUOS constellation (plus on on-orbit spare), a single satellite failure immediately and drastically reduces the overall system capacity.

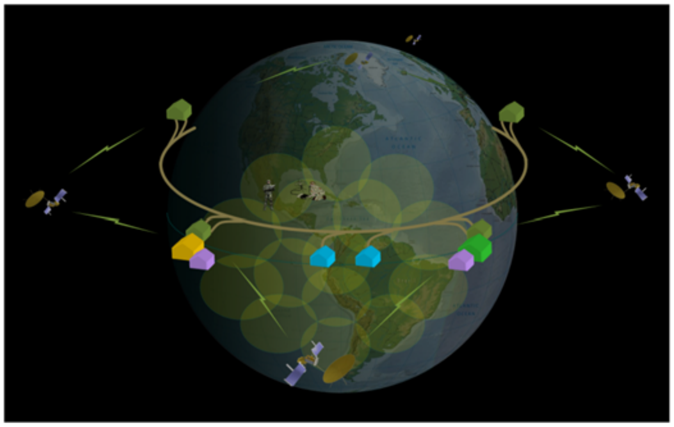


Exhibit 1: MUOS System

LEO satellites provide end-user communication services as well. A good example of this is the Iridium system, which operates 66 satellites in low-earth orbit, symmetrically arranged into 6 nearly-polar planes of 11 satellites each (plus, initially, a spare in each orbital plane). Each satellite maintains up to 4 cross-links with other satellites, creating an on-orbit mesh. The mesh is dynamic, making, breaking, and remaking cross-link connections as the satellites progress in orbit; however, the dynamics of the mesh are completely scripted and controlled from the ground. The satellites are not autonomous and the mesh cannot adapt automatically to missing or failed satellites or to new satellites to improve coverage or capacity. Control and backhaul communication into and out of the orbiting mesh is provided by satellite feeder links managed at system gateways and TT&C facilities. The satellites provide on-demand L-band user links (similar to cell phone service) with data rates to 2400 bps. Higher data rates can be achieved by ganging channels together.

For LEO systems, the impact of a failed satellite results in a temporary outage over a particular coverage area, and while not as drastic as a failure within a GEO system, global coverage is impacted while new LEO satellites are positioned to replace the failed satellite. For the Iridium system, one or two extra satellites (non-service providing) are placed in each orbital plane to serve as a spare for that plane. When a satellite failure occurs in a particular plane, one of the spare satellites for that plane is moved into position to take over service. Extra satellites in the constellation are either repositioned or new satellites are launched to maintain a spare in each orbital plane.

Because the satellites are LEO rather than GEO, required user link margins are achieved with smaller apertures. Still, processing power at the time of development was limited, and the resultant satellite size turned out to be relatively large, weighing close to 1513 lbs. The overall system cost was approximately $5 billion[3]. The Iridium system is almost 20 years old and newer techniques, like ad hoc cooperative networks and multi-antenna strategies, are now available to achieve better performance at lower overall cost.

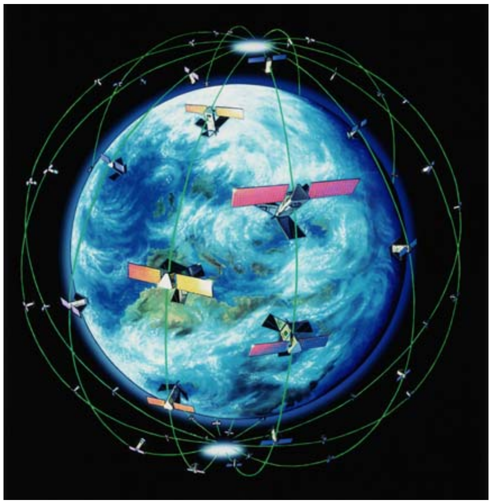


Exhibit 2: Iridium Constellation

SECTION 2 - A SMALL SATELLITE APPROACH

MUOS (and other GEO systems) satellites are very large and heavy, consume significant power, and are acquired and operated at a high cost. However, their stationary position (relative to the earth) enables consistent area coverage simplifying ground systems and operations, and their large footprint permits fewer satellites to complete a system. Iridium (and other LEO systems) satellites are smaller, lighter, consume less power, all of which contribute to a moderate acquisition and operation cost. However, their smaller footprints require more satellites to provide necessary coverage. We would like to extend these size/weight/power/cost benefits toward an end goal of utilizing an emerging class of much smaller satellites, while also improving scalability and resiliency. To achieve performance approximating that of Iridium, using typical, known means and methods, the system satellites cannot be made significantly smaller or lower power. In the following sections we discuss application of emerging methods which promise to break this lower bound, enabling a reduction in constellation throw weight (defined as the total weight of all satellites in the constellation) by a factor of two or three.

Our proposed system comprises three distinct types of network "nodes" (satellite nodes, ground station nodes, and user terminal nodes), interconnected via inter-node links to form an ad hoc mesh network. We propose an on-orbit fleet of SmallSat nodes, employing node intelligence and inter-node cross-links to form a "layered" mesh network (common layered networking protocols and techniques are well know, so we will not discuss them in detail here). Our mesh will be self-formed, and self-healed; each node using radio frequency physical layer (layer-1) search and discovery techniques to locate peer nodes and establish/negotiate inter-node links. The mesh is extended to include ground station and user terminal nodes using similar search and discovery strategies to link satellites to ground stations in view. Cooperation between nodes enables multi-antenna techniques, which can be exploited to improve link performance.

Satellite Nodes

Satellites in this system are assumed to be spherical; half of the surface covered by solar panels uniformly spaced so panels are pointed in all directions. The other half of the sphere is covered by multi-band antenna elements situated so that transmit and receive elements are pointed uniformly in all directions as shown in Exhibit 3. This configuration is not intended to be practical or even achievable; it is only intended to simplify the discussion. Communication links can be formed in any direction, solar pointing is not an issue, and performance analysis is simplified because measures such as satellite weight, power, antenna gain, and link capacity, can be estimated directly from the satellite radius.

Our proposed satellite network nodes autonomously seek and connect (and disconnect) with peer nodes. New operational nodes are automatically assimilated into the fabric without disrupting on-going operations. The response to failing nodes is they are eliminated from the fabric, but remaining nodes and their connections stay viable. The response to a single link on a node failing (or geometrically progressing outside of pointing limits) is that the link is removed from the fabric, but other links on the node remain viable.

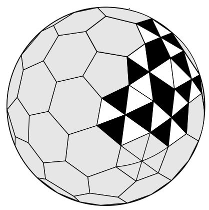


Exhibit 3: Reference Topology for Small Satellite

Each satellite node provides a number of communication links to other nodes (satellite or ground) limited by available transmit power, rather than the number of physical antenna elements on the satellite. If a space-ground link is formed, satellites autonomously limit the number of cross links to increase available power for the ground terminal link. If no ground terminals are visible, satellite nodes maximize the number of cross-links provided.

All satellite communication links combine satellite antenna elements to form beams in the direction of partner nodes. When transmit beams are formed, only the antenna elements on the section of the sphere facing the receive node are excited in a way to form a beam in the direction of the receive node; the other antennas elements are turned off or used for other transmit beams. Similarly, receive beams are formed by combining the signals from antennas elements on the sphere facing the transmit node, other antenna elements on the receive node are turned off or used to form other receive beams. Beam scanning is achieved by selectively turning on or off elements on the sphere and combining them to form a beam in the desired direction[4].

The number of satellites in orbit is selected so that any point on the ground is covered by three or four satellites at all times. This facilitates multi-antenna techniques, improving link performance and system availability. Adding more satellites to the constellation does not significantly improve link performance since multi-antenna gains to individual users do not increase significantly with more than three or four diversity links. Adding more satellites does, however, improve capacity by spreading user demand among the increased numbers of satellites.

With a satellite constellation providing three or four times diversity, failure of any satellite is automatically accommodated by satellites nearby with no disruption of service. Constellation performance is not significantly, or immediately, impacted by failure and maintenance activities. Launching new satellites, can be longer term activities, further reducing costs.

Ground Station Nodes

Ground stations nodes act as routing/switching points in the greater mesh to provide bearer and Command and Control (C2) connectivity. The architecture naturally accommodates multiple ground station nodes with direct space-ground links to the on-orbit mesh. Like the satellite cross-links, the space-ground links are autonomously reformed following orbit progression, using the same independent node behavior to seek and negotiate layer-1 links. At the ground station, electronically scanned beams are employed to search the field of view for satellite nodes. Routing information is propagated through the network, advertising new routes to the network behind the ground node. Like LEO node cross-links, space-ground link bandwidth is negotiated by peer (one satellite, one ground node) endpoints. Adding or removing ground nodes is accommodated automatically, relying on inherent node behavior.

Ground station nodes are assumed to be semispherical phased arrays forming beams in any direction above a minimum elevation angle (Exhibit 4). As with the satellite nodes, this particular design is not intended to be a practical approach, just a way to simplify the discussion and aid in presentation of the overall concept; analysis is simplified as antenna gain and link capacity are estimated directly from the ground station diameter.

One advantage of this approach is the ability to maintain links with multiple satellites from a single ground terminal leading to significant cost savings on the ground. Such a ground approach is scalable, both by adding more ground terminals at strategic locations around the world, or by adding beam processing capability to a particular ground station to create more links. From a commercial perspective, element data from the same ground terminal can be used by any number of satellite operators to independently create links to their satellite (assuming they are operating with compatible frequencies).

Exhibit 4: Semispherical Phased Array

For our system rain and scintillation fades are the dominant fading mechanisms (link is assumed to operate above 10 GHz), and are mitigated with multi-antenna techniques such as large scale site diversity (LSSD). This technique and other similar techniques are most effective when ground stations are placed more than 50km apart (and as much as 1000km apart) where rain attenuation statistics become independent, therefore offering maximum diversity gains[5].

Our system links multiple ground stations through the network mesh and employs multiple antenna techniques to improve space-ground link performance. Ground stations are separated by at least 50km to maximize diversity gains, minimize ground station size and maintain overall space-ground availability (Exhibit 5). Ground stations are added strategically as necessary to provide coverage, capacity and achieve overall availability.

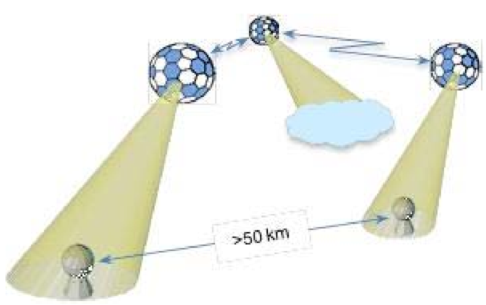


Exhibit 5: Ground Station Node Separation Maximizes Diversity Gains

User Terminal Nodes

Typical, user terminals are small, battery operated, and can be mobile or nomadic. User links transfer data from user terminals to satellites within the field of view. Links are established by user terminals, scanning for satellites and connecting to one or potentially multiple satellites to provide the best link performance. Beacon channels from the satellite provide user terminals with access method information along with frequencies and modulation types to establish links.

User terminal interference at the satellite is reduced through beamforming and frequency reuse patterns. User traffic patterns dictate the modulation types and frequency re-use patterns needed for a particular coverage area. If users are spread over the field of view, satellites allocate bandwidth across all beams uniformly, reusing bandwidth in a uniform manner. Modulation schemes and access methods suited to uniform frequency re-use patterns would be dictated by the satellite. If users are concentrated in a particular geographical area, satellites would allocate more bandwidth to user links in that area, dictating a non-uniform frequency re-use pattern.

Furthermore, user terminals are envisioned to be capable of leveraging other user "team" terminal nodes when necessary and perform cooperative communication. Cooperative communication is a relatively new paradigm where non-collocated terminals employ other available "team" nodes to cooperatively transmit information messages using MIMO and space-time encoding techniques. While details of such techniques are beyond the scope of this paper, such cooperative communication paradigms are especially useful for user terminals achieving both signal diversity and power gains which would otherwise be physically prohibitive.

Network

The advance of wireless terrestrial systems and technologies has led to the development of cooperative, ad hoc, mesh networks. Nodes in these networks act autonomously as cooperative agents to manage the network and efficiently move data from node-to-node through the network. Requiring minimal central control is critical to cost-effectively achieving and maintaining network connectivity. Each node independently and autonomously executes its process, reacting to its surroundings and cooperating with other nodes to enable multi-antenna techniques and exploit diversity. All nodes use autonomous scanning/discovery/ad hoc networking methods to locate peers, negotiate layer-1 links, and update/repair network routing/switching at layer-3 and above. All nodes use Software Defined Radio (SDR) technology to implement the waveforms, enabling updates through the system lifetime. Unlike Iridium, which requires advanced planning and constant control to maintain strict satellite-to-satellite and plane-to-plane spacing necessary to optimize crosslink performance, the subject system would consist of a loosely organized LEO fleet with much less rigid geometry and needing very little active control. The proposed approach envisions launching satellites into nominal orbits which generally provide consistent coverage, allowing them to drift practically uncontrolled through their service lifetimes.

SECTION 3 - SYSTEM PERFORMANCE

Performance Considerations

For any satellite communication system, it is important to maximize throughput and capacity, achieve desired availability, while minimizing system costs. In the discussion below, we provide an upper bound expression for system throughput performance for ad hoc mesh networks and show how size and weight of the satellite system can be improved (thus significantly decreasing launch costs) over the Iridium system by utilizing multi-antenna techniques.

Throughput Performance

One question that arises in communication systems of this type is how does throughput increase as the number of network nodes, *n*, grows? Alternatively, what amount of information can source nodes send to the destination nodes? The seminal work of Piyush Gupta and P.R. Kumar[6] shows that in a network of *n* identical randomly located nodes, each capable of transmitting W bits/sec, the obtainable throughput by each node for a randomly chosen destination is $O\left(W/\sqrt{n\log n}\right)$ bits/sec with a non-interference protocol. Even under ideal circumstances with optimal node placement and optimal traffic assignment, the per-node rate is still on the order of $O\left(W/\sqrt{n}\right)$ bits/sec, suggesting that the $\sqrt{\log n}$ factor is the price to pay for the randomness of the node location. However, by employing network coding[7], shows that $O\left(W/\sqrt{n}\right)$ rate is achievable on a per node basis in networks of randomly located transmit and receive nodes. The constructive strategy achieving the $O\left(W/\sqrt{n}\right)$ rate is based on multi-hop transmission along with pair-wise encoding and decoding at each hop together with a TDMA scheme. Therefore, for a network of *n* identical randomly located nodes, the resulting total network throughput bound is $O\left(W\sqrt{n}\right)$ bits/sec.

Link Performance vs. Satellite Size and Mass

In the paragraphs that follow, we determine size and weight improvements of the proposed satellite system (employing ad hoc mesh networks and multiple antenna techniques) comparable to the Iridium system. Our approach is to develop a relationship between the size and weight of a satellite employing conventional communication methods with the satellite's size and weight. We then apply cooperative network and multiple antenna technologies to the satellite user link to determine achievable size and weight improvements of the satellite within the new system. We then compare satellite size and weight of the new system with that of the Iridium system.

Aperture Size, Aperture Gain, Available Transmit Power and SmallSat Mass

To establish a relationship between satellite communication capabilities and its size and weight, we follow the work described in Jones (2013)[8], which surveyed existing and planned SmallSats/CubeSats and developed relationships between the satellite's size, transmit power, aperture gain and mass. With this foundation, we can calculate available transmit power, aperture gain and satellite mass from the satellite diameter directly.

First we calculate the available power to the transmitter subsystem as:

$$P_{tx} = \frac{\pi\left(\frac{D}{2}\right)^2 \mathrm{C}_S\, t_{sl}\eta_{sp}\eta_d S}{t_{tx}} \qquad [1]$$

where:

P_{TX} is the available transmit power

D is the diameter of the satellite in meters

C_S is the % satellite surface area covered by solar cells (50%)

t_{sl} is the percent time the satellite is in sunlight and is approximated as 60%

η_{sp} is efficiency of the solar panels (35%)

η_d is the power distribution efficiency (80% and includes power supply efficiency)

S is the solar radiation hitting the satellite (1367 watts/meter)

t_{tx} is the percent time the satellite spends transmitting (50%)

Aperture gain is:

$$G_{dB} = 10\log\left(kC_a\left(\frac{\pi D}{\lambda}\right)^2\right) \qquad [2]$$

where:

G_{dB} is the aperture gain in dB

D is the diameter of the satellite in meters

C_a is the % satellite surface area covered by antenna elements (50%)

k is the efficiency factor (52% - 70% antenna efficiency and 74% due to difference in gain between spherical and planar arrays[9])

λ is the operating wavelength (m) of the antenna (f = 1.6 GHz)

Satellite mass is calculated as:

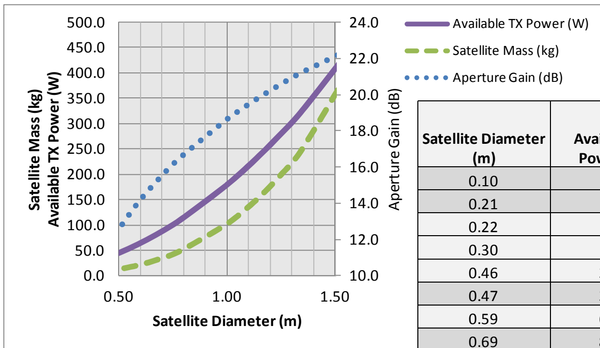
$$m = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \rho \qquad [3]$$

where:

m is the mass of the satellite in kg

ρ is the mass density of the satellite (194.7 kg/m^3)[10]

With these equations, we calculate and plot the relationship between satellite diameter, available power to the TX subsystem, aperture gain and satellite mass – see Exhibit 6.



Satellite Diameter (m)	Available TX Power (W)	Satellite Mass (kg)	Satellite Weight (lb)	Aperture Gain (dB)	Satellite Type
0.10	1.8	0.1	0.2	-1.4	Picosatellite 0.1 to 1.0 kg
0.21	8.2	1.0	2.2	5.2	
0.22	8.6	1.1	2.4	5.5	Nanosatellite 1.0 to 10.0 kg
0.30	16.1	2.8	6.1	8.2	
0.46	38.0	10.0	22.0	11.9	
0.47	39.5	10.6	23.3	12.1	Microsatellite 10.0 to 100.0 kg
0.59	61.5	20.6	45.3	14.0	
0.69	84.2	33.0	72.6	15.4	
0.79	110.5	49.6	109.2	16.5	
0.99	176.4	100.0	220.0	18.6	
1.00	178.7	101.9	224.3	18.6	Minisatellite 100.0 to 500.0 kg
1.10	216.2	135.7	298.5	19.5	
1.25	279.2	199.1	438.0	20.6	
1.40	350.2	279.7	615.4	21.6	
1.70	515.7	500.0	1100.0	23.2	

Exhibit 6: Spherical SmallSat Available TX Power, Aperture Gain and Mass

With these relationships established, we can determine impacts on our satellite mass and system throw weight based on improvements in link performance.

Satellite Size and Mass with Improvements

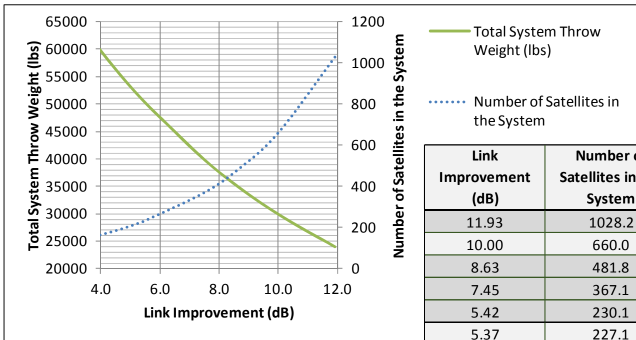
In the discussion that follows, improvements in user link performance from the use of ad hoc cooperative networks and multiple antenna techniques are allocated to decrease satellite aperture size and mass. We assume the satellite is user downlink limited and we start with a spherical satellite with roughly the same performance as an Iridium satellite*. Further, we assume any improvements in link performance are used to make the satellite antenna aperture smaller. With a smaller aperture (i.e. the diameter of the satellite smaller), the power supplied to the transmit subsystem will also be smaller, which means the satellites and the system cannot support the capacity needed. To overcome this hurdle, we increase the number of satellites in our system until our system capacity roughly equals the Iridium system capacity†.

Using the equations above, we calculate total system throw weight, and number of satellites needed to achieve Iridium like capacity vs. link improvement in dB (see Exhibit 7). Our analysis shows that if we assume multi-antenna techniques achieve a 10dB improvement in link performance over the Iridium system, our satellite mass would decrease to roughly 20.6 kg, and the number of satellites required to achieve Iridium like capacity

* In this case we set the user link aperture gain of the spherical satellite to be the same as the user link aperture gain of the Iridium satellite (roughly 24 dB based on the size of the Iridium antenna). Using the equations above, this sets the satellite diameter to be roughly 1.86 m. The power provided to the transmit subsystem for a satellite this size is roughly 615 watts, which roughly compares to the power supplied to the Iridium transmit subsystem[10]. It turns out the weight of the system is nearly equivalent as well – 1431 lbs. for the spherical satellite vs. 1513 for the Iridium satellite.

† Diversity increases the number of links each satellite must service. However, power is split between each diversity link so the total power provided by all links to a particular user remains roughly the same. For example, if we implement a 3x3 MIMO scheme, then the number of users each satellite services goes up by 3. However the total power required by the transmit subsystem remains roughly the same because the power provided by each link drops by 3.

would increase to 660. For our system, the total throw weight reduces to 29,883 lbs. versus the total throw weight for the Iridium system of roughly 99,858 lbs. (1513 lbs. per satellite times 66 satellites in orbit – spare satellites not counted), a significant decrease in launch and system costs.



Link Improvement (dB)	Number of Satellites in the System	Satellite Mass (lbs)	Total System Throw Weight (lbs)	Satellite Type
11.93	1028.2	23.3	23941.9	Microsatellite 10.0 to 100.0 kg
10.00	660.0	45.3	29883.0	
8.63	481.8	72.6	34977.0	
7.45	367.1	109.2	40071.0	
5.42	230.1	220.0	50614.0	
5.37	227.1	224.3	50940.2	Minisatellite 100.0 to 500.0 kg
4.94	206.0	259.6	53487.2	
4.54	187.7	298.5	56034.2	
3.78	157.7	387.6	61128.2	

Exhibit 7: Total System Throw Weight and Number of Satellites in the System vs. Link Improvement (dB)

SUMMARY

System Comparison

The Exhibit 8 table compares the performance of our SmallSat solution, described above, to both the Iridium and MUOS satellite constellations. We show significant improvements in satellite mass and a sizeable decrease in total system throw weight for our system compared to the Iridium system, while achieving essentially the same performance. The decrease in throw weight significantly reduces launch and total system costs.

	Cost	Satellite Mass	Satellites in Constellation	Total Throw
MUOS	$7B	6800 lbs.	4	27,200 lbs. (to GEO)
Iridium	$5B	1513 lbs.	66	99,858 lbs.
SmallSat	Lower	45.3 lbs.	660	29,883 lbs.

Exhibit 8: System Comparison Table

The proposed system also offers the advantage of being more robust than the Iridium system because of the significant increased numbers of satellites. More satellites imply satellite failures gradually degrade the system rather than an abrupt disruption in coverage. Since replacement satellites are easier and cheaper to launch, as well as their replacement is not immediately required, the need for redundancy systems are effectively eliminated on the satellite offering an even further reduction in the satellite's mass. This also has the benefit of reducing satellite complexity and development cost. The ad hoc network makes the system easy to operate and easily scalable; nodes (ground system, user or satellite) can be added without a significant system configuration change.

Since large scale site diversity, or similar technique, is employed on the space-ground links, ground station size is significantly reduced, potentially reducing costs[‡]. Also ground stations can be shared between systems (or missions), significantly reducing system operating costs.

[‡]More work is needed to quantify cost savings. In general, a semispherical phased array will be much more expensive than a parabolic antenna of the same size. However, by employing diversity techniques, a phased array antenna can be made much smaller, lowering costs significantly. A phased array antenna can also service many more satellites and systems than a single parabolic antenna, thus spreading the cost between systems.

Conclusion and Future work

We have presented foundational concepts for a global SmallSat communication system and have shown feasibility of this concept, satisfying our assertion SmallSat mission capabilities can be expanded. Our ad hoc mesh network approach combined with multi-antenna techniques has been shown to provide significant advantages over existing approaches.

More work is needed to validate the approach and to quantify user link improvements and costs savings. Orbital investigations are required to verify coverage estimates and require further work to validate performance assumptions (antenna gains, solar panel efficiencies, etc.). Additional investigation is needed to quantify space-ground link performance improvements for LSSD or other multi-antenna techniques and to determine size and potential cost savings of phased array approach for the ground terminals.

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