Topology Design and Performance Analysis for Networked Earth Observing Small Satellites

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***Abstract*—In order to network small satellite constellations for Earth observation and communication, several limitations must be addressed, including distributed topology management, slow down-link data-rates, and single point-to-point communication. Since distributed satellite constellations exacerbate the severity of these limitations, thorough analysis of a constellation's network performance is required to ensure that task objectives are achievable. In this paper, we designed network topologies using Satellite Toolkit (STK) for two low Earth orbit (LEO) Earth observing small satellite constellations: a sun-synchronous repeating ground track constellation and a flower (an elliptical repeating ground track) constellation. Both constellations include six sink satellites that provide a high speed down-link relay point to a ground station. We compared the constellations' inter-satellite links and down-links with respect to network metrics including access window time, drop-ratio, and throughput. We evaluated these network metrics using the Network Simulator (ns-2). Though previous works have proposed sun-synchronous and flower small satellite constellations for Earth observation, these constellations have not been analyzed for these network metrics. Results show that the sun-synchronous constellation with a repeating ground track outperforms the flower constellation with respect to more access time, lower drop-ratio, and higher throughput. Additionally, our simulations determined the optimum media access control slot time and packet transmission intervals for long distance satellite links. Further, our method of designing satellite constellation topologies in STK and exporting them to ns-2 can be used for future studies on any desired constellation network performance evaluations.**

***Index Terms*—Satellites, Earth Observing Systems, Satellite Communication, Satellite Constellations, Wireless Networks**

I. Introduction

CubeSats are satellites based on a pico-satellite platform developed by Cal-Poly Technical Institute. Even though CubeSats have grown in popularity, these satellites have severe power and communication limitations due to the size constraint of 10x10x10 cm and mass constraint of a kg for a 1U platform [1]. With these limitations, CubeSats have low transmission power due to a limited solar panel capacity of 2 watts and high latency due to the long propagation distance between satellites and ground stations, which can range from 160 km to 2000 km. To mitigate these limitations, researchers design constellations with several CubeSats working together to perform a single task [2].

TABLE I
Applications for Constellation Types

Constellation Type	Typical Tasks
Sun-synchronous Repeating Ground Track (Polar Orbits)	- Earth Observation - Remote Sensing - Communications
Flower (Elliptical Orbits and Circular Sinks)	- Earth Observation - Atmospheric/Weather Monitoring - Experimental Orbits for Global Positioning Systems

A constellation's task dictates constellation's specific design. In some cases, multiple candidate constellation types may be appropriate for the same task. Table I describes two constellation types, the flower constellation [3] and the sun-synchronous repeating ground track (SSRGT) constellation [4], both of which are appropriate for Earth observation.

Traditionally, to minimize deployment cost, the constellation types was selected to minimize the number of satellites given the constellation's coverage requirements. However, when designing constellations of multiple satellites that communicate over inter-satellite links, the constellation's network performance (i.e., the quality of the inter-satellite links) becomes a criterion for constellation selection.

Therefore, in order to compare candidate constellation types for effective satellite mission design, the effect that the constellation's type has on the inter-satellite link network performance must be evaluated. Simulation is a widely used method for evaluating network performance, and satellite packages for are available for OMNeT++, OPNET, QualNet, and the Network Simulator (ns-2) [5]. However, most satellite simulations packages are for large satellites with more powerful transmitters than the transmitters available on CubeSats. Some research focused on evaluating network performance of specific protocols for CubeSat constellations using network simulators [6], [7], however these studies have focused on evaluating protocol performance or optimizing a single CubeSat constellation rather than comparing candidate constellation types using network performance as a criterion.

In this paper, we designed two constellations for low Earth orbit (LEO) CubeSat Earth observing missions, with the SSRGT and flower constellation types with Satellite Toolkit (STK) [13]. We proposed a novel method for evaluating the network performance of arbitrary satellite constellations using the Network Simulator (ns-2), an established network simulator [14].

II. Constellation Topology Design

In order to evaluate constellation type selection, we designed two candidate constellations for a hypothetical Earth observing mission that monitors islands along the Sunda ocean trench for geological events. In order to reduce the complexity of the constellation design process, we designed both candidate constellations to have a small spatial coverage, which is the area of the target a constellation observes [8]. Even with a smaller spatial coverage, however, CubeSats often have limited access to ground stations.

We mitigated the effects of limited CubeSat access to ground stations by employing the data mule methodology proposed by [9]. The data mule methodology consists of using a set of source satellites to collect data, and a set of sink satellites to transport the collected data to a ground station. The sink satellites are larger, more powerful satellites with more access time to ground stations than source satellites, but less access time to target areas than source satellites. In order to maintain relevancy between the two candidate constellations, we designed each candidate constellation to contain six sink satellites and nine source satellites.

A. *Sun-synchronous Repeating Ground Track (SSRGT) Constellation*

SSRGT orbits have desirable features for remote sensing and Earth observation applications, since these orbits have near constant illumination angles and approach targets with identical viewing angles up to twelve times per day [4]. These characteristics are amenable to Earth observation missions in both the visible and infrared spectrum. Satellite systems such as the LANDSAT program [10], and imaging and remote sensing satellites and constellations, such as Spot satellites [11], and RapidEye [12] leverage the SSRGT orbit.

We configured the individual satellites in the SSRGT constellation to maximize the access time to the ground station. To maximize the access time between the source satellites and the target, we distributed the source satellites in our SSRGT constellation equally about a polar orbit at an altitude of 750 km. To maximize the access time between the sink satellites and the ground station, we distributed the sink satellites equally about a circular orbit at a 70° inclination and an altitude of 750 km. Figure 1 shows the SSRGT constellation scenario.

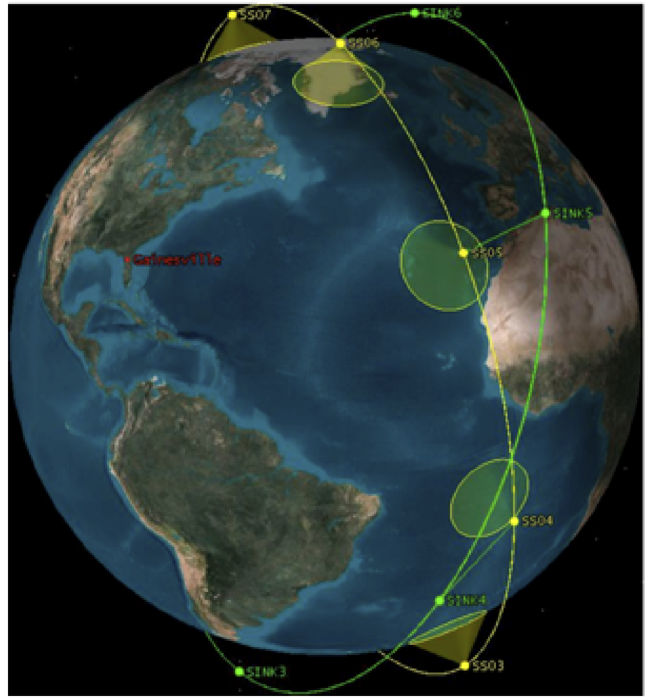

Fig. 1. Diagram of our SSRGT constellation. The right-most lines near the north pole crossing to the left-most near the south pole represent the six sinks' orbiting path. The left-most line near the north pole crossing to the right-most near the south pole represents the nine sensing satellites' orbiting path.

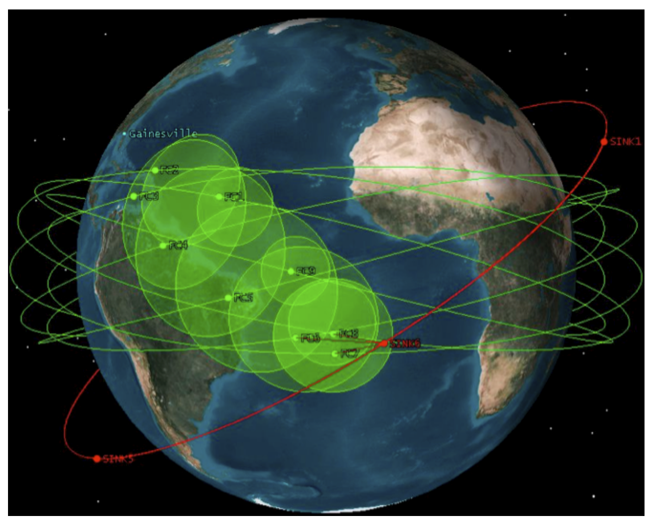

Fig. 2. Diagram of our flower constellation. The bottom-most line on left crossing to the top-most on right is the six sinks orbiting path. The horizontal lines clustered near the equator are the nine sensing satellites orbiting paths.

B. *Flower Constellation*

The flower constellation is a repeating ground track orbit with an axis of symmetry that coincides with the spin axis of the Earth. Flower constellations are well suited for Earth observation because each source satellite in a flower constellation has the same orbit shape and all the satellite node lines are displaced equally along the equatorial plane [3]. Figure 2 shows our flower constellation design.

TABLE II
ORBITAL PARAMETERS

Orbital Properties	SSRGT		Flower	
	Sensing	Sinks	Sensing	Sinks
Apogee Altitude	750 km	750 km	1598 km	1598 km
Perigee Altitude	750 km	750 km	686 km	1598 km
Inclination	97.3°	70°	165°	35°
Right Ascension of the Ascending Node	0°	0°	Satellites 1-9: 0, 40, 80, 120, 160, 200, 240, 280, 320°	0°
True Anomaly	Satellites 1-9: 0, 40, 80, 120, 160, 200, 240, 280, 320°	Satellites 1-6: 0, 60, 120, 180, 240, 300°	Satellites 1-9: 0, 53.54, 98.12, 134.1, 165.2, 194.8, 225.9, 261.88, 306.46°	Satellites 1-6: 0, 60, 120, 180, 240, 300°

Table II shows a comparison of the orbital parameters for our SSRGT and flower constellation designs. In order to maximize access time to the target, all nine flower constellation source satellites are in an elliptical, near-equatorial LEO. In order to accommodate the data mule methodology and maximize sink satellite time to our ground station, we distributed the six flower constellation sink satellites in a traditional circular 1598 km orbit with a 35° inclination.

III. MODELING SMALL SATELLITE CONSTELLATIONS

A. Using Satellite Toolkit to Design Topology

We modeled the topology of the SSRGT and flower constellations using STK and evaluated the network performance using ns-2. In STK, both constellations were simulated over the same three month time period, from January 12th, 2011 16:00 to April 12th, 2011 16:00. The simulation time step was one minute. STKs orbit wizard was used to define specific satellite parameters depending on orbit type. Not only were the same sink satellite orbits used for both simulations, but the same ground station (Gainesville, FL), and the same target area (Jakarta, Indonesia) were used as well to make the constellations as similar as possible. Access time between the sensing satellites and the sink satellites determined the transmission window. The access time is the time, in seconds, for two satellites to communicate with one another, given a range limit in kilometers. The range limit was a maximum of 2000 km, solved from the Friis pathloss equation (1).

TABLE III
PARAMETERS TO CALCULATE TRANSMISSION RANGE

Variable	Value
P_{rx}=Power Received	-116 dBm
P_{tx}=Power Transmitted	30 dBm
G_{tx}=Gain of Tx Antenna	10 dB
G_{rx}=Gain of Rx Antenna	10 dB
λ=Wavelength	.125 meters
d=Transmission Distance	2000 km

$$P_{rx} = P_{tx} + G_{tx} + G_{Rx} - 20 \log \left(\frac{4\pi \times d}{\lambda} \right) \tag{1}$$

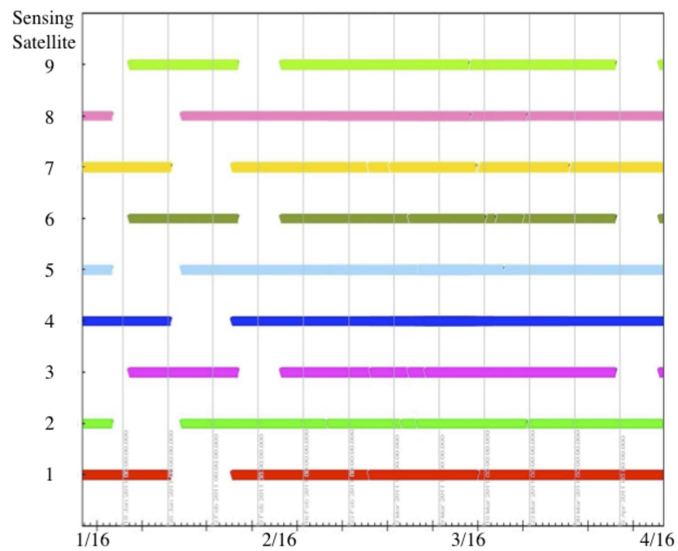

Fig. 3. Chart of an SSRGT constellation if launched January 12th 2011. Bars indicate transmission windows to forward data to the sink satellites. Note that transmission windows are not continuous.

STKs access tool calculated access start time, end time, duration in minutes, the number of accesses, and the maximum and minimum durations. Figure 3 shows accesses between the nine sensing satellites and the six sink satellites for the SSRGT; these access time graphs were initially generated individually and then overlaid to show the overall transmission window that the sensing satellites have with the sink satellites. STKs access tool was used to generate the access time between each sink satellite and a ground station in Gainesville, FL. The access time for the ground station will determine how much time the sink satellites will have to down-link their data.

When establishing an Earth observing constellation mission, the mission's goal can either be to achieve high temporal or spatial coverage. Temporal resolution is the frequency with which an image can be captured. The more often a certain area is imaged then the better the temporal resolution will be. Spatial coverage is the amount of the Earth's surface the constellation covers over a given period of time [8]. Our mission concentrated on temporal resolution over a certain area, Jakarta, Indonesia, which would be beneficial for a disaster monitoring situation such as a tsunami.

B. Using NS-2 to Evaluate Network Performance

The default ns-2 package contains multiple models for simulating satellite constellations and the obvious model choice for our simulations is the ns-2 satellite model, which can simulate well-known constellations such as Iridium [15]. However, since this satellite model only supports circular orbits with un-slotted ALOHA-net as the link layer protocol, we used the ns-2 mobile node model with each satellite represented as an ns-2 node.

The ns-2 mobile node model is robust and supports a wide range of protocols. However, since this model is most appropriate for terrestrial wireless networks, we modified the ns-2 mobile node model to simulate our constellations. Creating a mobile node simulation typically consists of plotting the nodes' movements as tool command language (Tcl) scripts, called scenarios, which are imported into ns-2. However, since ns-2 does not support three-dimensional (3D) positioning, we could not simply write a script to translate the 3D satellite movements into a scenario.

In order to integrate 3D movements into ns-2, we modified ns-2's positioning system. Unlike the other ns-2 simulation models, the ns-2 mobile node model is not easily modifiable and inhibits direct replacement of ns-2's positioning system. To overcome this restriction, we wrote new modules to replace the existing modules interfaced with the positioning system. The new modules used an external database of satellite positions to provide node position information.

To use the STK constellation data in our new ns-2 modules, we used STK to export our SSRGT and flower constellations as comma separated value (CSV) files. The CSV files contained a position for each satellite at every minute. We wrote a Python script to translate the satellites' positions into a structured database and we wrote a C++ library to load, cache, and linearly interpolate the satellites' positions at times between the recorded minute positions. Using our C++ library, we replaced any ns-2 module that used node positions with a version that used STK-exported data.

Figure 4 shows the structure of the ns-2 modules that use the nodes' positions. A node's position has two primary uses in the ns-2 mobile node model. First, the node's position is used to calculate the receive power of the transmissions that a node receives. Each node in ns-2 contains a wireless PHY module that activates when any node in range transmits a packet. The wireless PHY module contains a propagation module that calculates the packet's receive power.

The propagation module uses the transmitting and receiving nodes' positions to calculate the transmission's propagation distance. For simplicity and due to the direct line-of-sight transmissions in LEO, we used the FreeSpace propagation module, which is based on the Friis transmission equation (1). The FreeSpace module uses the distance between the transmitting and receiving nodes to calculate each packet's receive power.

In order to interface with our external satellites' position databases, we added a new module, FreeSpaceSTK. Ns-2 modules can define Tcl commands, which Tcl scripts can

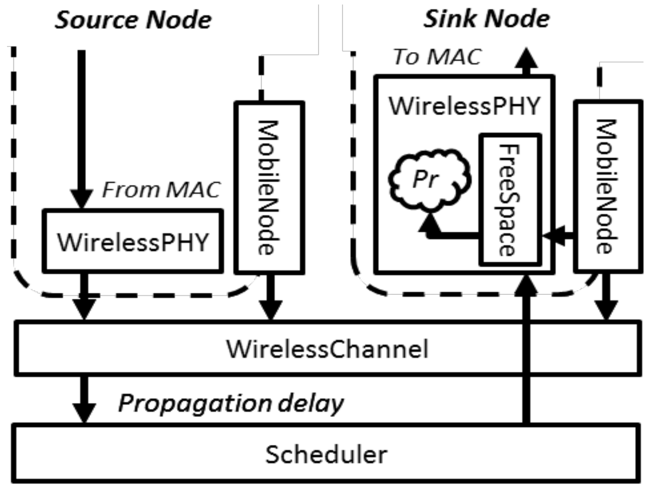

Fig. 4. Diagram of ns-2 wireless transmission simulation

call to perform module-specific actions. We wrote a command handler for the FreeSpaceSTK module for a new command that logically links an ns-2 node to a corresponding satellite position database. The FreeSpaceSTK receive power calculation uses the satellites' position databases instead of the mobile node positions to calculate node distance. FreeSpaceSTK does not, however, calculate the radio propagation delay.

The second primary use for the ns-2 positioning system is to calculate the radio propagation delay. When the ns-2 WirelessChannel module first receives packets from a transmitting node's PHY, the WirelessChannel module calculates the radio propagation delay for each receiving node by dividing the distance between the nodes in meters by the speed of light (3×10^8 meters per second). To transmit the packet with delay, the WirelessChannel module requests the ns-2's scheduler module to schedule a receive event in the receiving PHY.

Since the propagation methods in the WirelessChannel module are not inheritable, we added a new module, WirelessChannelSTK, which duplicated the WirelessChannel module. We modified the WirelessChannelSTK module to use the external satellites' position databases for calculating the distance between the nodes. Using the FreeSpaceSTK module, the WirelessChannelSTK module, and STK-exported constellation information, our modifications allow wireless traffic in ns-2 to resemble traffic between satellites in orbit.

IV. Results

We applied the modifications described in section III to the ns-2 version 2.34 installation running on Ubuntu Linux 10.10. To run our experimental simulations, we created two Tcl scripts: one script defined the nodes using our flower constellation positions and the other script defined the nodes using our SSRGT constellation positions.

The Tcl scripts specified the protocol for each satellite node's network layers. We used the ns-2 module for each node's MAC layer since 802.11b-1999 has acceptable long-range performance and a wide range of available commercial off-the-shelf hardware. For each node's PHY layer, we used the standard ns-2 wireless PHY module with the propagation configured to use our FreeSpaceSTK module.

We configured the FreeSpaceSTK module in one of the Tcl scripts to use the satellite position database for the flower constellation and the other Tcl script to use the satellite position database for the SSRGT constellation. To simulate the communication channel, we used our WirelessChannelSTK module. The nodes defined by the Tcl scripts behaved like satellites in a constellation and could support traffic from most ns-2 agents, ns-2's representation of a protocol.

We wrote a Tcl ns-2 scenario to generate sample traffic for the simulation. In the Tcl ns-2 scenario, each non-sink node generated constant bit rate (CBR) traffic over a User Datagram Protocol (UDP) agent to each of the six sink nodes. To prevent the source nodes that were out of range of any sink satellites from transmitting, we assumed that satellites could detect the presence of sink satellites within 2000 km. Source nodes only transmitted data when they were within 2500 km of a sink node or the ground station in Gainesville, Florida.

A. Drop-Ratio Versus MAC Slot Times

Since the performance of the MAC layer is significantly affected by the large propagation delay between communicating satellites in LEO, we first conducted simulations to find optimal 802.11b-1999 MAC module parameters for our scenarios. The standard 802.11b-1999 slot time, the time allocated for a round-trip packet transmission and acknowledgment is 20 μs, and the short inter-frame spacings (SIFS) is 10 μs [16]. However, for satellites that are 2500 km apart, radio signals take over 8ms to propagate at the speed of light. Our 802.11b-1999 timing parameters were built around the following equation (2).

$$SlotTime = CCATime + TxTxTurnaroundTime + AirPropagtionTime + MacProcessingTime \quad (2)$$

Since the propagation time increases over these distances, we increased the slot time and SIFS to reduce the drop-ratio. The drop-ratio is the reciprocal of the packet-delivery ratio. For our simulation, SIFS were a function of half of the slot time and the distributed coordination function (DCF) inter-frame Spaces (DIFS) were a function of the varying slot time shown in equation (4).

$$SIFS = 1/2 \times SlotTime \quad (3)$$

$$DIFS = 5/2 \times SlotTime \quad (4)$$

Figures 5 and 6 show that for both our flower and SSRGT constellations, the optimal slot time ranges from 500us and 1500us, while the standard 802.11b-1999 slot time causes the MAC to drop nearly all packets. While the round-trip propagation delay between distant nodes may be higher than 1500us, the optimum 802.11b-1999 slot time reflects a trade-off between unnecessary slot time delay for nearby nodes and propagation delay for distant nodes. Since the optimal slot time range is similar for the sink satellite connections to both ground stations and source satellites, sink satellites can use the same PHY for transmitting to sink nodes and the ground station.

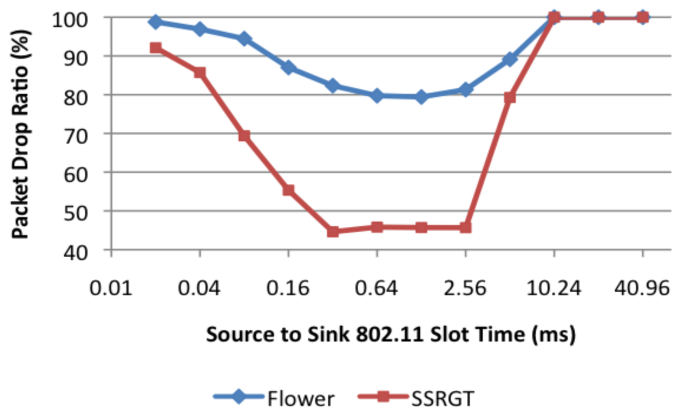

Fig. 5. Packet drop ratio versus MAC slot time.

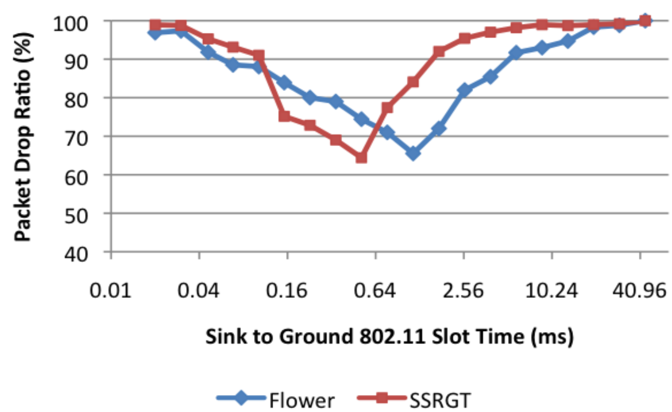

Fig. 6. Ground-sink drop ratio versus MAC slot time.

For the source satellite to sink satellite connections, the SSRGT constellation dropped significantly fewer packets than the flower constellation. With the slot time set at 640us, the SSRGT constellation dropped fewer than 50% of the packets, while the flower constellation dropped more than 75% of the packets. For both the flower and SSRGT constellations, the high drop-ratio in Figures 5 and 6 demonstrate that any network protocol used by the satellites must perform reliably with intermittent connections.

B. Throughput Versus Source Traffic Density

We tested the traffic capacity of the flower and SSRGT constellations' networks by simulating the network throughput while increasing the source traffic density (the rate at which the source nodes send packets). Figure 7 shows the network throughput for both the flower and SSRGT constellations between 10 kBps and 1600 kBps, with the source satellites sending 1 kB packets. Figure 8 shows the packet drop-ratio for the SSRGT and flower constellations as a function of source traffic density.

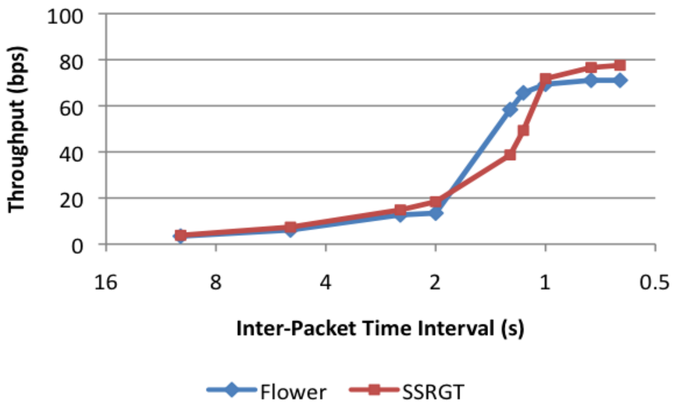

Fig. 7. Throughput versus source traffic density.

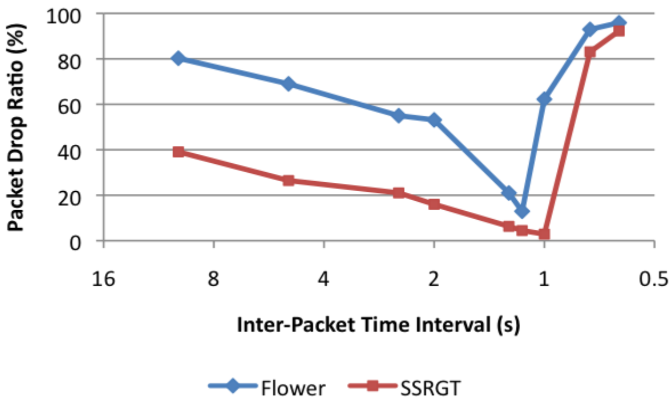

Fig. 8. Packet drop-ratio versus source traffic density.

The flower constellation maintained a similar throughput as the SSRGT constellation even though the SSRGT constellation dropped fewer packets than the flower constellation. The higher packet drop-ratio for the flower constellation as compared to the SSRGT constellation, combined with the constellations' similar throughputs, suggests that the flower constellation has more opportunities than the SSRGT constellation to transmit data from long distances. Both constellations suffered very low throughputs, which is expected due to the weak transmitters and long distances involved in the simulation.

V. Conclusions and Future Work

In this paper, we developed a method for comparing the network performance for any constellation designed in STK based on sink time, drop-ratio, and throughput. Using this method, we designed and compared the network performance of two novel small satellite constellations: a flower constellation and a sun-synchronous repeating ground track (SSRGT) constellation. In order to compare the constellations' network performance, we modified the Network Simulator (ns-2) to use ns-2's mobile node model to simulate complex satellite constellations. Results revealed that as the satellites opportunistically communicated during a week in simulation time, the satellites in the SSRGT constellation dropped fewer packets than the satellites in the flower constellation. During a period of 500 ms to 1 second, the SSRGT satellite showed a higher throughput.

Future work includes improving our constellations' network performance by incorporating feedback from our simulations. In particular, the constellations' throughput is much less than was expected, as compared to previous work using different simulation methods [6], [7]. Future work also includes incorporating multiple ground stations [17] and comparing the network performance and coverage of satellite constellations to satellite cluster formations in which several satellite nodes fly in a single orbit, with one satellite node in the cluster serving as a sink.

VI. Acknowledgment

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