

## The EDSN Intersatellite Communications Architecture

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### ABSTRACT

The Edison Demonstration of Smallsat Networks (EDSN) is a swarm of eight 1.5U Cubesats developed by the NASA Ames Research Center under the Small Spacecraft Technology Program (SSTP) within NASA Space Technology Mission Directorate (STMD). EDSN, scheduled for launch in late 2014, is designed to explore the use of small spacecraft networks to make synchronized, multipoint scientific measurements, and to organize and pass those data to the ground through their network. Networked swarms of these small spacecraft will open new horizons in astronomy, Earth observations and solar physics. Their range of applications include the formation of synthetic aperture radars for Earth sensing systems, large aperture observatories for next generation telescopes and the collection of spatially distributed measurements of time varying systems, probing the Earth's magnetosphere, Earth-Sun interactions and the Earth's geopotential. The EDSN communications network is maintained and operated by a simple set of predefined rules operating independently on all eight spacecraft without direction from ground based systems. One spacecraft serves as a central node, requesting and collecting data from the other seven spacecraft, organizing the data and passing it to a ground station at regular intervals. The central node is rotated among the spacecraft on a regular basis, providing robustness against the failure of a single spacecraft. This paper describes the communication architecture of the EDSN network and its operation with small spacecraft of limited electrical power, computing power and communication range. Furthermore, the problems of collecting and prioritizing data through a system that has data throughput bottlenecks are addressed. Finally, future network enhancements that can be built on top of the current EDSN hardware are discussed.

### INTRODUCTION

The Edison Demonstration of Smallsat Networks (EDSN) is a swarm of eight 1.5U Cubesats developed by the NASA Ames Research Center under the Small Spacecraft Technology Program (SSTP) within the NASA Space Technology Mission Directorate (STMD). EDSN, scheduled for launch in late 2014, is designed to explore the use of small spacecraft networks to make synchronized, multipoint scientific measurements, and to organize and pass those data to the ground through their network. The EDSN swarm will contribute to the understanding of the charged-particle environment in low-earth orbit and set the stage

for missions requiring multiple cooperating, networked spacecraft.

Networked swarms of these small spacecraft will open new horizons in astronomy, Earth observations and solar physics. Their range of applications include the formation of synthetic aperture radars for Earth sensing systems, large aperture observatories for next generation telescopes<sup>2,3,4</sup> and the collection of spatially distributed measurements of time varying systems, probing the Earth's magnetosphere, Earth-Sun interactions and the Earth's geopotential. Similar swarms can be used to explore the properties of other planets, comets and near-earth asteroids.

Not only do swarms of small, relatively low cost spacecraft enable missions that simply cannot be performed with single, large spacecraft, these swarms are inherently robust against random failures. If properly designed, the swarms can be regularly updated with improved technologies and different payloads by simply launching new spacecraft to join an existing swarm, providing continuous improvements to the mission.

To field swarms of tens or hundreds of small spacecraft, new communications concepts will need to be developed to control the movement of data within the swarm and with the ground, pass commands between spacecraft and generally manage the swarm.

### THE EDSN MISSION

The EDSN communications network (Figure 1) is maintained and operated by a simple set of predefined rules operating independently on all eight spacecraft without direction from ground based systems. One spacecraft (the Captain) serves as a central node, requesting and collecting data from the other seven spacecraft (the Lieutenants), organizing the data and passing them to a ground station at regular intervals. The Captaincy is rotated among the spacecraft on a regular basis, providing robustness against the failure of a single spacecraft.

The goal of the EDSN mission is to demonstrate that a swarm of satellites can make spatially distributed, time

correlated science measurements and transfer the data to the ground<sup>4</sup>. This includes the following mission objectives:

1. Flight demonstrate one-way space-to-space data transfer whereby at least 2 satellites transfer data to a third satellite, which then transfers the data to the ground;
2. Flight demonstrate a system to collect multi-point science measurements, transfer science measurements to another satellite and transfer to the ground;
3. Flight demonstrate a reaction wheel based pointing system;
4. Assess the viability of satellites built with Commercial Off The Shelf (COTS) components to operate for 60 days

In addition, EDSN will contribute to the understanding of the charged particle environment in low Earth orbit by making multiple, simultaneous measurements of the charged particle event rate at each spacecraft, distributed tens to one hundred kilometers apart.

The EDSN spacecraft have completed the fabrication assembly phases, and have passed random vibration and thermal vacuum tests as well as mission simulations with all eight flight spacecraft, setting the stage for launch into low-earth orbit in late 2014.

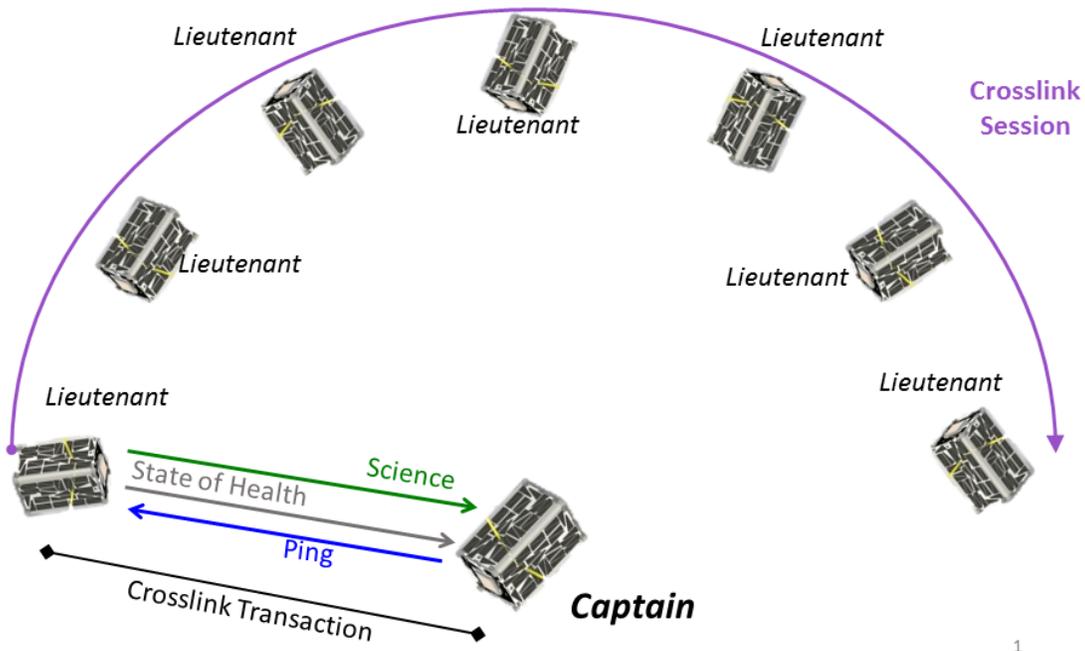


Figure 1: EDSN Communications Concept



**Figure 2: EDSN Spacecraft Ready for Flight (eight flight units, one flight spare)**

### THE EDSN CUBESATS

The EDSN swarm (Figure 2) consists of eight identical 1.5U Cubesat spacecraft measuring 10 x 10 x 17 cm and weighing approximately 1.7 kg. The spacecraft leverages commercial off-the-shelf (COTS) components where possible to keep the recurring bus costs down, providing a basis for future multispacecraft missions. Furthermore, this approach allowed the EDSN team to use some existing test equipment and software, reducing the amount of custom ground support equipment (GSE) that might otherwise have had to be developed for the program. Some key subsystems of the EDSN spacecraft use existing PhoneSat 2.0 hardware and software (e.g. the Nexus S processor board) further reducing cost by using existing, proven hardware and software. Both the EDSN spacecraft and the PhoneSat 2.0 hardware were developed by NASA Ames Research Center (ARC) under the Small Spacecraft Technology Program (SSTP) within the NASA Space Technology Mission Directorate (STMD).

Each EDSN spacecraft (Figure 3) consists of a stack of eight PC boards and a battery pack that plug into a common printed circuit board backplane that runs the length of one 17 cm side of the spacecraft. Four rods with spacers run through the corners of the boards, providing structural support. The stack is enclosed in a

machined aluminum chassis with the solar panels clamped to the exterior.

A Samsung Nexus S smartphone is used as the primary processor to perform such computationally intensive functions as attitude determination and control, orbit propagation (to determine when downlink and science collection windows occur), schedule planning, and data collection and packaging. The Nexus S controls all intersatellite and spacecraft-to-ground communications. Four Arduino (two ATmega2560 and two ATmega328P) microcontrollers manage the GPS receiver, science payload, various sensors and relays and interfaces to the attitude determination and control hardware. The spacecraft data bus is managed through the router board, which is built around the Parallax P8X32A Propeller chip. All commands and data moving between the various EDSN boards go through the router. A data packet system with acknowledgement messages and retransmission for critical packets transmitted between subsystems is implemented in software on the Nexus S, Arduino and router processors.

When the spacecraft is not performing one of its key activities (e.g. taking science data, controlling attitude, performing a crosslink or downlink), the Nexus is turned off and the spacecraft is monitored by the EPS board Arduino, commonly referred to as the

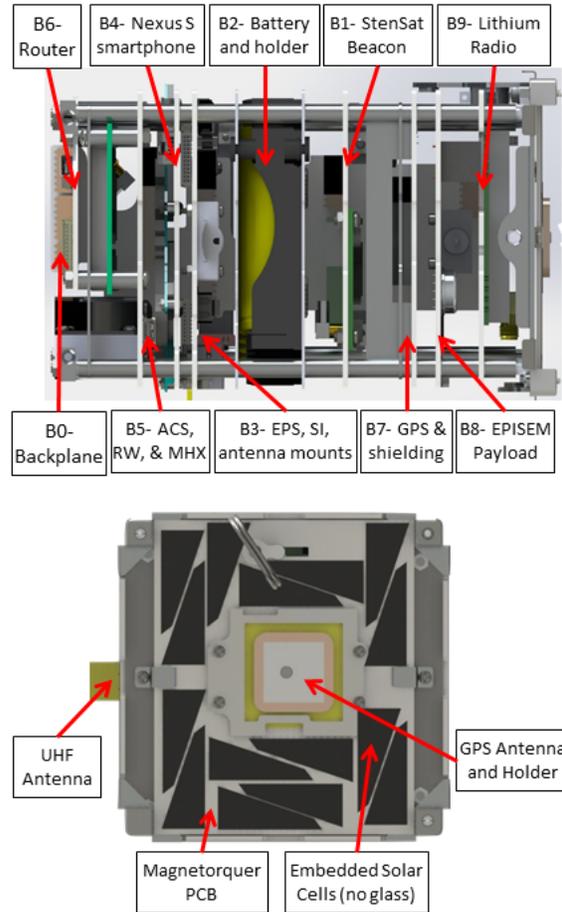
“Watchdog”. The schedule maintained on the Nexus S determines when it should be turned off. At this point a timer is set on the Watchdog that turns the Nexus on again at a specific future time. This low power, or “wait” mode that is provided by the EPS is key to the efficient operation of EDSN as the solar panels provide an orbit average power of just one watt. Solar power is provided by six solar panels that use Spectrolab Triangular Advanced Solar Cells (TASC). 5.2 A-h of electrical energy storage is provided by four lithium-ion 18650 batteries in a COTS holder. The COTS battery holder provides for battery control, battery overcharge protection and bus voltage regulation. A Zener diode is needed to provide over-voltage protection for the bus. The EPS board operates the solid state relays and provides power to onboard systems. When the battery voltage falls below seven volts, all non-essential subsystems are turned off and the spacecraft goes into its low-power “wait” mode. The spacecraft remains in “wait” mode until the battery voltage exceeds eight volts.

The EDSN communications subsystem uses three radios to perform three different tasks. Intersatellite communication (crosslink) is performed with an AstroDev Lithium 1 UHF transceiver attached to a deployable tape-measure monopole antenna. Crosslink occurs at 9600 bps under the AX.25 protocol with one watt transmitted power. The Astrodev receiver is only powered when a crosslink has been scheduled. A MicroHard MHX2420 transceiver is used for S-band downlink to the ground. A single S-band patch antenna is mounted to one end of the spacecraft. A StenSat UHF transmitter attached to a tape measure monopole antenna is used as a beacon, sending packets of data every sixty seconds.

The attitude control system has two distinct modes of operation. Magnetic control is used to detumble the spacecraft and align it with the local magnetic field for GPS acquisition and downlink activities. In this mode, the Nexus S magnetometer is used for attitude determination (i.e. measuring the local magnetic field) and six torque coils embedded in the solar panel printed circuit boards (PCB’s) are used for control. When the spacecraft is performing a sun-pointing demonstration, three orthogonal brushless DC motor reaction wheels control the spacecraft while the Nexus angular rate sensors and solar panel current monitors provide measures of the body rates and sun-vector, respectively. A Novatel OEMV-1 GPS receiver is used to get position, velocity and time fixes approximately once every 25 hours.

The science payload is an Energetic Particle Integrating Space Environment Monitor (EPISEM) that counts charged particle events in low-earth orbit (LEO). This

instrument, developed at Montana State University, is a Geiger-Müller tube that detects penetrating beta/gamma radiation from energetic particles above a certain energy threshold<sup>5</sup>.



**Figure 3: EDSN Spacecraft**

### COMMUNICATIONS CONCEPT

EDSN uses a simple concept for its intersatellite and space-to-ground communications network, designed specifically for the operation of multi-spacecraft swarms when subject to the constraints typical of Cubesat buses and programs. The EDSN swarm is a hub-and-spoke network whereby one spacecraft (the “Captain”) communicates with the other spacecraft (the “Lieutenants”) to collect data packets from them using a single common frequency. The Captain stores these data and sends them to the ground along with its data when a downlink opportunity occurs.

The process of passing information from one Lieutenant (LT) to the Captain (CPT) is called a

“transaction”. A transaction begins when the CPT sends a “ping packet” to the rest of the swarm using the Lithium radio. Since the intersatellite link is omnidirectional and may be received by any LT, the ping packet includes information designating which LT should respond. The CPT will send six pings over a period of 50 seconds to an LT. The CPT will then wait for the LT to respond with its data. While the transmit/receive antennae are omnidirectional monopoles, there are nulls in the antenna patterns. Sending six pings over 50 seconds increases the chances that the LT will “hear” the ping.

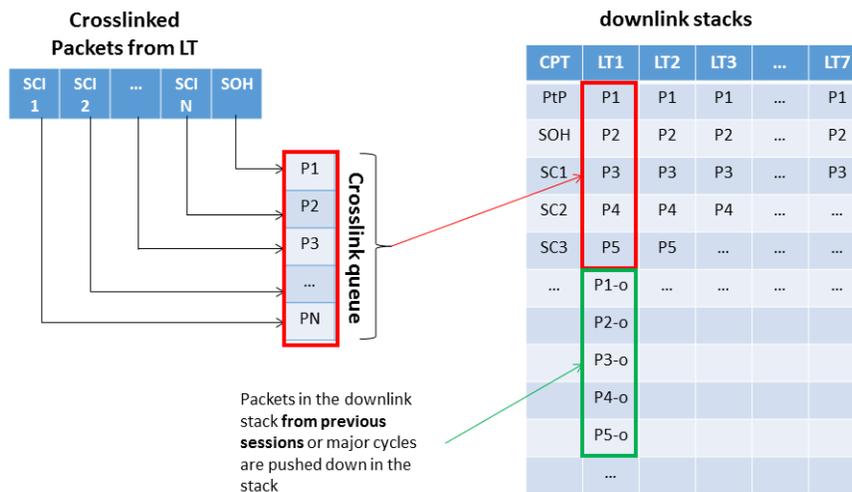
When an LT receives a ping, it first parses the command to make sure it is valid (i.e. that the packet checksum is correct) and that the ping request is for it and not for another LT. By giving each spacecraft a unique identifier (A through H), only one LT is authorized to transmit data at a time. This prevents the LT’s from broadcasting simultaneously and bringing all crosslink communications to a halt. Once the LT confirms that the “ping packet” is for it, it will wait 60 seconds to allow the CPT to stop sending “pings”. It then sends a series of its data packets to the CPT, again using the Lithium radio. First, one state-of-health link (SOH) packet is created and sent over the intersatellite link. This is followed by all of the science packets that are stored in the LT’s science packet queue, as shown in Figure 4. Once the LT has transmitted all of its data, it turns off its Lithium radio, ends its crosslink activity and deletes the state-of-health and science data from its crosslink queue. However, the most recent science packet is kept as part of a beacon packet to be broadcast repeatedly by the Stensat. Note that there are no Acknowledge or Negative Acknowledge messages passed between the CPT and the LT. If a data packet is

not received by the CPT, it is lost. This is acceptable for EDSN since it is a demonstration of the concept of Cubesat based data networks. The system generates many more packets to pass through the network than are required to meet the mission objectives. As will be discussed below, it is anticipated that future enhancements to the architecture will provide greater guarantees of data transmission either through the implementation of an ACK/NACK system, or delay tolerant networks<sup>6</sup>.



**Figure 4: Lieutenant Data Structure**

As the CPT is receiving the data packets from the LT, it places them in a first-in-first-out (FIFO) “transaction queue” in Nexus S memory (Figure 5). This queue is pushed onto a last-in-first-out (LIFO) stack of packets received from that LT. Called the “downlink stack”, the CPT maintains one such stack for each LT, storing the data for downlink to the ground when a downlink opportunity occurs. It also maintains a downlink stack for itself, containing only the Captain’s science packets. This system was implemented to prioritize the most recent SOH data over science data and recent packets over older packets.



**Figure 5: Captain Data Structures**

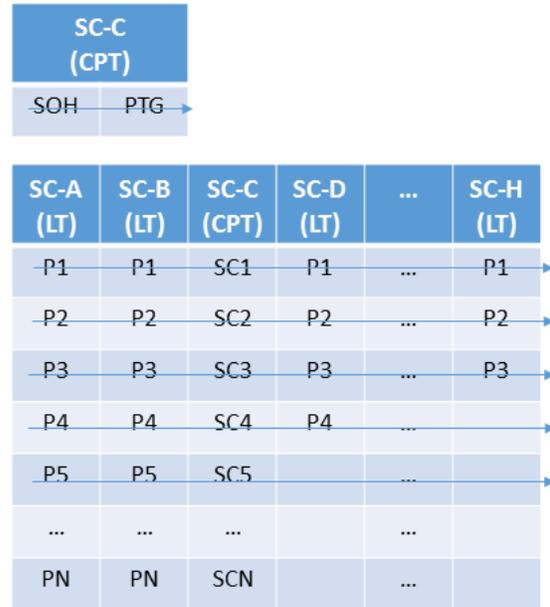
The CPT collects data from an LT for a fixed period of time and ends the transaction once the allocated transaction time has elapsed. If the LT is not in range to get the ping, or is “off” due to a low battery condition, the CPT will listen for the entire transaction duration (approximately four minutes) before moving to the next LT.

The CPT continues to collect data by sending a “ping” to the next LT (e.g. spacecraft B), initiating a new transaction with that LT. This process is repeated until the CPT has attempted to initiate a transaction with each LT in the swarm. The set of seven transactions is referred to as a “session”.

The “Captaincy” of the EDSN swarm is rotated amongst the spacecraft in a present pattern (A-B-C-D-E-F-G-H-A) so that each spacecraft has the opportunity to be CPT. Also, the loss of any single spacecraft does not end the mission, as it would if there were only one spacecraft designated as CPT for the entirety of the mission. The time during which a spacecraft is CPT is called a “minor cycle”. Prior to the start of a minor cycle, each spacecraft gets a GPS fix to determine GPS time, and its position and velocity. GPS time is compared to preloaded table of time windows given in Coordinated Universal Time (UTC) to determine which spacecraft is CPT. If a spacecraft cannot get a valid GPS time, it does not participate in the network activities of the swarm (i.e. it does not attempt to crosslink or downlink). During each minor cycle, between three and four crosslink sessions are scheduled at predetermined UTC times. One downlink activity is scheduled by the CPT per minor cycle when it predicts that it will be passing over a ground station. The LT’s do not attempt to make contact with the ground station.

The downlink session is initiated by the ground station with the Microhard S-band link. The CPT sends data packets to the ground in a predefined order (Figure 6). First, the state-of-health (SOH) packet is sent. This is followed by the “pointing packet”. This contains data related to the sun pointing demonstration that is performed only by the CPT once per minor cycle. The CPT then downlinks the first data packet in each downlink stack, in order of spacecraft, starting with Spacecraft A and proceeding through Spacecraft H. The process of sending packets from the downlink stacks continues with the second packet in each stack and so on until all of the data in the downlink stacks are exhausted, or the link is broken. If the packets in the downlink stacks are exhausted before the link is broken, the CPT will repeat sending all of its downlink data, in the same order until the link is broken or the downlink activity times out.

The system guarantees that the most recent science and SOH data collected by the CPT and sent to the ground first, and that the SOH packets are given priority over the science data packets. Using this system, the ordering of the crosslinked packets is optimized to provide the data needed to meet the mission objectives – monitoring the health of the spacecraft through the SOH packets and collecting multipoint science data.



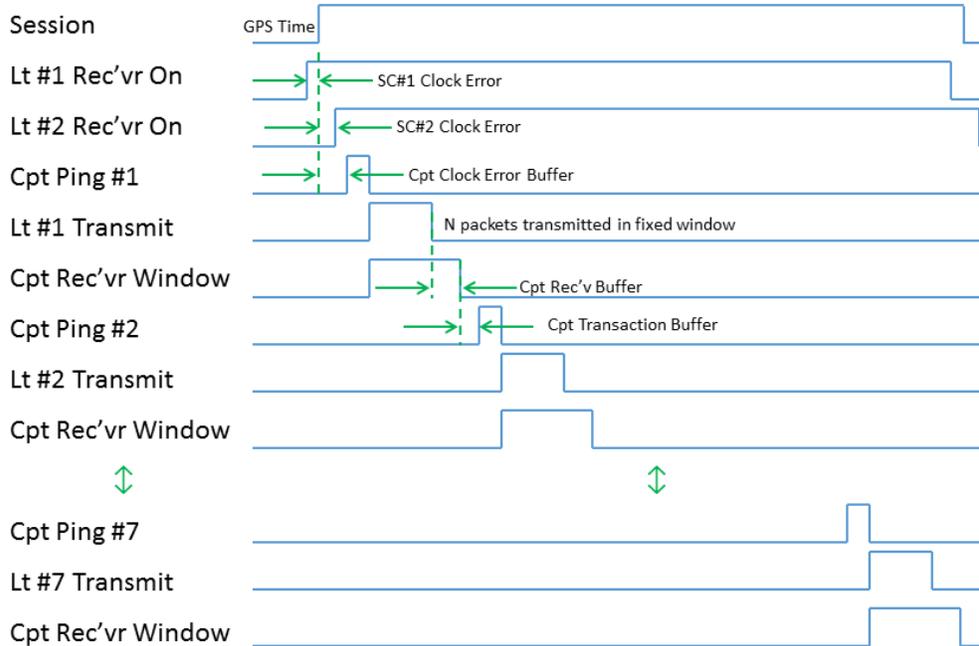
**Figure 6: Downlink Prioritization**

Each minor cycle lasts approximately 25 hours. A set of eight minor cycles where each spacecraft has been CPT once is referred to as a “major cycle”. It is anticipated that two or three major cycles will occur before the spacecraft are too far apart to crosslink, although they will continue to cycle through several more major cycles before the end of the mission.

Implementation of the crosslink communications on Cubesats requires special consideration of their limited power production (approximately one watt orbit average for EDSN). If each LT could leave its crosslink receiver on at all times, the CPT could schedule crosslink sessions based solely on its own priorities. Unfortunately, there is not sufficient power for such an implementation. The EDSN communications architecture avoids this problem by having all EDSN spacecraft schedule crosslink activities at fixed times in UTC. Knowing that the crosslink will only occur at a specific time, the LT’s can use their radios efficiently and only turn the Lithium-1 on when they expect to get a message from the CPT.

Each EDSN spacecraft uses the clock on its Phone as a time reference. This clock is corrected to GPS time once per minor cycle (i.e. every 25 hours) when a GPS fix is established. Drift of this clock due to temperature and aging effects could introduce an error in local time of as much as 12 seconds, causing the LT and CPT clocks to be out of synch. All time based activities include time “buffers” at the beginning and end of the

activity to account for the relative drift of the clocks on different platforms. For example, during a crosslink session, the LT will turn on its receiver 30 seconds prior to the start of the session and leave the receiver on for up to 30 seconds after the end, as defined by its clock. Figure 7 shows the sequence of events that make up a crosslink session, including the overlap of receiver on-times.



**Figure 7: Communications Timing Diagram**

**SOFTWARE IMPLEMENTATION**

The EDSN software was implemented on three processors on the spacecraft. Code on the Arduino microcontrollers perform low-level tasks such as interfacing with hardware and monitoring the battery voltage. Special software on the Propeller chip provides data packet routing services on the spacecraft bus. The most critical software, in terms of the implementation of the EDSN communications architecture, resides on the Nexus S processor – the “Phone”. This software is an autonomous application built on top of the Android operating system. Leveraging the Android software tools and development base helped to simplify the design and decrease development time.

The EDSN spacecraft operate autonomously. No commands are received from the ground, other than a

radio disable command that turns off all transmissions from the spacecraft. This is required by the FCC and is not part of normal operations.

The EDSN application creates a schedule of “activities” with start times and durations. It then executes those activities through the Phonesat Executive, its main thread. The Executive also determines when the phone should be off, passing control of the spacecraft and a time to turn the phone back on to the EPS Watchdog.

There are several key activities that EDSN uses to implement the communication system. These include science data collection, downlink, crosslink, GPS acquisition, and planning.

The downlink and crosslink activities are discussed in detail above. Central to the operation of the downlink and crosslink activities are a set of data structures

(stacks and queues) that store the data packets sent through the network. These were implemented as shown in Figure 8 and are described above in greater detail.

Prior to the start of a minor cycle, a GPS acquisition activity will have been scheduled. After the Executive runs that activity, the GPS state (position, velocity and time) will be fed into an orbit propagator that will predict the position of the spacecraft as a function of time over the next two minor cycles (roughly 50 hours). Using the propagated orbit the satellite is able to schedule a set of activities based on predefined metrics and a priority list. Some activities are scheduled based on time while others are scheduled based on the time at which the spacecraft is predicted to be at a particular

position. The crosslink activity is a time based activity and occurs at a fixed time offset from the beginning of the minor cycle. On the other hand, the downlink and science collection activities are position based activities.

For each activity the satellite generates a table of opportunity windows that state when it is possible for a particular activity to take place. Then based on priority of the activity, the activities are scheduled such that their opportunity windows do not overlap. Once the schedule is generated the executive starts and stops the activities based on the schedule.

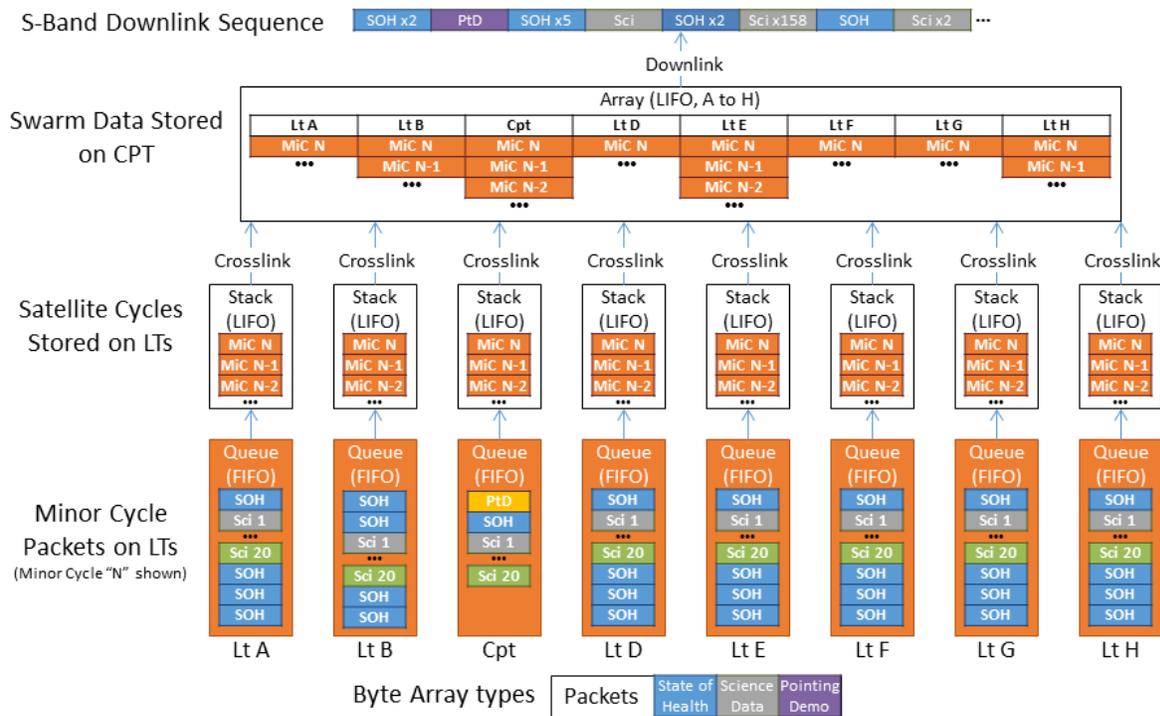


Figure 8: EDSN Communications Data Structures

## TEST RESULTS AND PERFORMANCE

Flight Software (FSW) Release 6.5 was the final version of software loaded onto the eight EDSN spacecraft. This release was validated through a combination of unit tests at the software component level, flight software system tests at the function level and mission simulations that captured the performance of the entire EDSN system, demonstrating that the EDSN communications and FSW systems will meet the mission objectives.

The mission simulation consisted of all eight flight satellites in their flight configurations with spacecraft identifiers, and other flight parameters. This included clearing the spacecraft stored time and memory at the start of the test. The simulation was initiated as if the spacecraft were released from the launch vehicle (i.e. the footswitch interrupt circuit was released) and the simulation was run for about 11 days. This captured the 30 hour initialization of the spacecraft, nine full minor cycles of 25 hours each and a transition to the tenth minor cycle. This demonstrated operation of the

EDSN network over a full major cycle with every spacecraft holding the role of Captain at least once and one spacecraft being Captain twice. A GPS simulator was not available for the mission simulation. So, during the GPS acquisition activities at the starts of minor cycles, ground support equipment (GSE) was used to “spoof” the GPS packet that the processor expected from the GPS receiver. The position and velocity vectors in the GPS packets were generated using STK.

Power to the spacecraft was provided by GSE power supplies and included models of the solar eclipse and expected electrical power levels produced by the solar arrays, with some margin (i.e. power available in the test was less than what is predicted for flight). The spacecraft bus voltages were monitored in real-time using GSE computers with LabView. All RF activities were monitored with GSE as well. A Microhard ground station was used to emulate the ground station at Santa Clara University and collect spacecraft data in a flight-like condition. The Microhard was manually set to initiate contact with the spacecraft five to ten minutes after the expected scheduled contact to allow the team to collect power data during the downlink activity and to simulate the uncertainty that will exist in the timing of the ground station contact. A spare Lithium-I radio was reconfigured to monitor the crosslink activity, but did not interact with the system. An Alinco UHF transceiver was used to monitor the spacecraft beacon messages, emulating ground stations so that the spacecraft could operate in a flight-like configuration. While the beacon is not part of the EDSN network communications system and is not needed to meet the mission objectives, it will be used in flight to provide additional data on the performance of the network. All of these data were recorded by GSE and stored for later processing. The flight-like data were used after the completion of the mission simulation to validate performance per the Mission Simulation Test Procedure and verify requirements.

The EDSN spacecraft passed all tests, clearing flight software as ready for flight in November, 2014. Specifically, the spacecraft met all mission objectives, transmitting science and state-of-health data to the ground stations over both the crosslink-downlink channel and the beacon channel. Packets were collected from all eight spacecraft, even though some beacon packets were lost due to poor orientation in the laboratory relative to the ground station, or to simultaneous transmission by two or more spacecraft. Furthermore, the network behaved as expected even in the face of a missed Captain (due to a GSE failure in the GPS packet loading) and missed crosslink opportunities (due to the Captain scheduling a higher priority operation when the Lieutenants expected a

crosslink to occur). In a few instances, the downlink in a minor cycle was scheduled before the Captain collected all of its science data. These data were stored until the next minor cycle and passed to the next Captain, as expected.

Other issues, not related to the operation of the EDSN network were observed, dealing primarily with the behavior of the Stensat beacon, as implemented by EDSN. It was noted that the beacon packets from some spacecraft overlapped each other, despite the system being designed with differing transmission offsets between spacecraft to prevent this from occurring. In some instances, the periodicity of the beacon packets would change when transitioning from Phone operation to the Watchdog low power mode. Finally, on a few occasions, the GPS receiver on a spacecraft detected a GPS signal from the in-lab repeater before the “spoof” message could be uploaded from the GSE. Since the position, velocity and time did not match those of an orbital trajectory, the spacecraft flagged the GPS data as invalid and then attempted to get another GPS fix, as it was designed to do.

#### **FUTURE ARCHITECTURE ENHANCEMENTS**

The coordinated operation of many spatially distributed spacecraft will open new markets and enable new scientific breakthroughs that can only be achieved with swarms of capable, low cost spacecraft making measurements simultaneously at different locations. This will finally put smallsats on the same stage as their much larger brethren by showing that multiple small spacecraft can perform missions that simply cannot be done with a single, traditional spacecraft, no matter how large it is.

EDSN is an important demonstration of key communications capabilities that are necessary to realize the goal of swarms of Cubesats operating in unison to create a system of systems that is truly greater than the sum of its parts. Using its simple hub-and-spoke polling system, the 1.5U EDSN spacecraft will demonstrate:

- Time synchronized measurements on spatially distributed platforms
- Collection of data from all spacecraft in the swarm with a single central spacecraft
- One-way operation of the swarm (data collection) through a single spacecraft that is in periodic contact with the ground
- Autonomous operation of the swarm (i.e. without intervention from ground control)
- Redundancy in swarm operations through the simple, pre-scripted periodic hopping of the Captain

Future missions can use the EDSN communications architecture as a basis for networking a small number of spacecraft together, provided the spacecraft do not drift beyond their crosslink communications range during the mission. Obviously, this architecture can be used for additional investigations in the Earth environment and Earth-sun interactions by flying similar spacecraft in other orbits, sampling other orbit altitudes and the Van Allen belts. An enhanced spacecraft bus would allow investigations of the Earth's Magnetopause, Magnetosheath and Magnetic Tail. These spacecraft could use the EPISSEM as a payload, or fly sensitive magnetometers, Langmuir probes or electrometers.

The EDSN architecture can be enhanced to provide additional capabilities to Cubesat swarms, further expanding their utility. These include:

- Controlling the spacecraft in the swarm by routing commands from the ground through the network to individual spacecraft;
  - Autonomous configuration of the network by selection of the Captain (or Captains) based on data available to the spacecraft in the swarm. For example, multiple spacecraft could "negotiate" who should be Captain at any given time based on the amount of data needed for downlink, the power state of the spacecraft or the quality of the ground station pass. This can be compared to the EDSN approach to Captain selection, which is predetermined before the mission even flies and programmed into every spacecraft;
  - Precise time synchronized measurements by radio command from the Captain, whereby every LT in a swarm would take data upon receiving a command from the CPT;
  - Improved synchronization of time across the swarm either by using the crosslinks to lock all clocks in the swarm to the CPT, or by providing each spacecraft with a high quality local clock (e.g. chip-scale atomic clock) to improve time knowledge between GPS updates;
  - Collection of GPS pseudo-range and carrier phase data for precision position and swarm geometry knowledge via differential GPS;
  - Mapping of network topology to determine which spacecraft can communicate with which spacecraft;
  - Routing of packets through the network by multiple hops based on the network topology map so that spacecraft not in direct contact with the CPT can still pass their data to the ground;
- Allowing multiple Captains to take advantage of more ground pass opportunities to get more data from the swarm to the ground;
  - Passing of large data files between spacecraft (e.g. image files);
  - Prioritization of data messages by the Captain or Lieutenant for downlink;
  - Addition of ACKnowledge/NACKnowledge protocol during crosslink and downlink transactions to increase the probability that data packets pass through the network and are not dropped;
  - Scheduling of downlinks to multiple ground stations to increase data throughput;
  - Addition of a standard network layer to the system to take advantage of COTS software and protocols;
  - Interlinking of multiple Captains to create a "cluster of clusters".

The extension of the EDSN communications architecture through a series of small satellite demonstrations will enhance the capabilities of swarms of Cubesats to perform vital, cutting edge research and to open new commercial markets

## CONCLUSIONS

The EDSN communications architecture provides a robust, low cost and simple system that can be implemented on Cubesat-class spacecraft, with their need for low-power, COTS solutions. As such, this architecture can be the basis of swarm missions in the immediate future and for missions requiring incremental improvements as described above.

The EDSN spacecraft have passed all of their environmental and functional tests. Mission simulations of the eight flight spacecraft have established that the flight software and communications architecture are ready for flight and will meet the mission requirements.

When it flies in late 2014, EDSN will open new opportunities for small spacecraft to contribute to scientific and commercial endeavors in space.

## ACKNOWLEDGMENTS

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