A Survey of Communication Sub-systems for IntersatelliteLinked Systems and CubeSat Missions

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Abstract—Intersatellite links or crosslinks provide direct connectivity between two or more satellites, thus eliminating the need for intermediate ground stations when sending data. Intersatellite links have been considered for satellite constellation missions involving earth observation and communications. Historically, a large satellite system has needed an extremely high financial budget. However, the advent of the successful CubeSat platform allows for small satellites of less than one kilogram. This low-mass pico-satellite class platform could provide financially feasible support for large platform satellite constellations. This article surveys past and planned large intersatellite linking systems. Then, the article chronicles CubeSat communication subsystems used historically and in the near future. Finally, we examine the history of inter-networking protocols in space and open research issues with the goal of moving towards the next generation intersatellite-linking constellation supported by CubeSat platform satellites.

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

I. INTRODUCTION

In 1954, the United States Navy started relaying signals off the moon. This simple reflection experiment led to the world’s first space communications satellite system: Communication Moon Relay (CMR). CMR allowed Hawaii to communicate with Washington, DC [1]. For many years after, satellite systems were simple relays consisting of a ground station to satellite uplink channel, and a satellite to ground station downlink channel. Following simple relay systems, a constellation of satellites that communicated directly with one another was designed. Instead of simple uplinks and downlinks between a satellite and its ground station, these systems would use satellite-to-satellite relays known as crosslinks. Crosslinks allowed for less ground stations. Also, frequencies that are quickly attenuated in the atmosphere could be used, making the link undetectable and unjammable from the ground. In section II, this paper surveys the frequency, protocol, application, and orbit of satellite systems launched that featured a crosslink. With CubeSats seen as a viable platform for intersatellite communications, the report details frequency allocation, protocol, application, orbit, and communication subsystems used for all CubeSats in section III. In section IV, open research issues such as internet protocol layering, delay tolerant networking layering, radio frequency allocation, optical communications, applications, and orbital properties are analyzed.

II. INTERSATELLITE LINKING COMMUNICATION SUB-SYSTEMS

Intersatellite links have appeared in certain large platform satellite constellations for over 30 years. Examples of these large communication relay constellations include TDRSS and Iridium. More recently, CubeSats have changed the communication philosophy from long-range point-to-point propagations to a multi-hop network of small orbiting nodes [2]. Separating system tasks into many dispersed sensor nodes can increase overall constellation coverage, system survivability, and versatility [3]. However, to understand the challenges involved in satellite networking, large-platform intersatellite linking systems were chronicled and listed in table I. Details of the frequency, protocol, application, and orbit of all the intersatellite linked satellite systems are presented in this section.

<table>
<thead>
<tr>
<th>Launch Year(s)</th>
<th>Satellite(s)</th>
<th>ISL Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972-1978</td>
<td>OSCARs 6, 7, 8</td>
<td>146 MHz</td>
</tr>
<tr>
<td>1976</td>
<td>LES-8 and 9</td>
<td>36, 38 Ghz</td>
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<tr>
<td>1983-2013</td>
<td>TDRSS</td>
<td>C, Ku, Ka</td>
</tr>
<tr>
<td>1985-1995</td>
<td>Luch</td>
<td>UHF, Ka</td>
</tr>
<tr>
<td>1994</td>
<td>ETS-6</td>
<td>2, 23, 32 GHz, Optical</td>
</tr>
<tr>
<td>1997</td>
<td>Navstar Block IIR</td>
<td>UHF</td>
</tr>
<tr>
<td>1997</td>
<td>Iridium</td>
<td>23 GHz</td>
</tr>
<tr>
<td>1998</td>
<td>Comets (ETS-7)</td>
<td>2 GHz</td>
</tr>
<tr>
<td>1994-2003</td>
<td>MuSTaR II/III</td>
<td>60 GHz</td>
</tr>
<tr>
<td>1998</td>
<td>Spot-4</td>
<td>Optical</td>
</tr>
<tr>
<td>2001</td>
<td>Artemis</td>
<td>S, Ka Optical</td>
</tr>
<tr>
<td>2002</td>
<td>Envisat</td>
<td>S-band</td>
</tr>
<tr>
<td>2002</td>
<td>ADEOS-II</td>
<td>2 GHz, 26 GHz</td>
</tr>
<tr>
<td>2005</td>
<td>OICETS</td>
<td>Optical</td>
</tr>
<tr>
<td>2010</td>
<td>AEHF SV-1</td>
<td>60 GHz</td>
</tr>
<tr>
<td>2015</td>
<td>Iridium Next</td>
<td>23 GHz</td>
</tr>
</tbody>
</table>
A. 1972, 74, 78 OSCARS 6, 7, 8

The Radio Amateur Satellite Corporation’s (AMSAT’s) first generation of Orbiting Satellites Carrying Amateur Radio (OSCARs) were launched in the early 1960s. Soon after, AMSAT began work on a second-generation known as OSCARS 6, 7, and 8. These amateur satellites were characterized by an intersatellite repeater capability [4]. OSCAR 6 received at VHF frequency of 146 MHz and transmitted at 29.5 MHz with a repeater bandwidth of 100 kHz. OSCAR 7 had two repeaters. The first repeater was similar to OSCAR 6 except for a slight frequency change and increased output transmission power. OSCAR 7’s other repeater received at UHF 432 MHz and transmitted at VHF, 146 MHz. An on-board timer on OSCAR 7 automatically switched from one repeater to the other daily. Also, satellite communication control circuitry automatically switched one repeater on in a low-power mode when the battery was discharged to a certain point. On several occasions, OSCAR 6 and 7 were used together with a 432 MHz uplink to OSCAR 7, a 146 MHz intersatellite link, and a 29 MHz downlink from OSCAR 6. OSCAR 8 also had two repeaters. OSCAR 8’s first repeater was the same as OSCAR 7, operating at a 146 MHz crosslink and 29 MHz downlink. OSCAR 8’s second repeater received at 146 MHz and transmitted at 435 MHz. Only one repeater was on at a time. So, OSCARs 7 and 8 could relay to OSCAR 6 or themselves. As a result, AMSAT demonstrated the first simple omni-directional intersatellite repeating system. AMSAT’s OSCAR 7 still remains semi-operational.

B. 1976, LES-8 and 9

The Lincoln Laboratory experimental satellites 8 and 9, known as LES-8 and LES-9, demonstrated long-range digital transmissions in many bands between themselves and ground terminals. Once launched, LES-8 and LES-9 thrust 90° apart to a coplanar, inclined, circular, geosynchronous orbit [5].

Engineers at Lincoln desired crosslinks at a 60 GHz frequency band because of how oxygen molecules in the atmosphere absorb 60 GHz. This is much like how water absorbs the microwave band. However, with the technology in 1971, little test equipment was available beyond 40 GHz. As a result, LES-8 and LES-9 demonstrated crosslinks at the Ka-band (36 GHz and 38 GHz) [6]. 60 GHz crosslinks came later in MilSTAR constellation described in section II-J. Intersatellite antennas were either a 24 db gain horn with 10° beamwidth or a more directional 42.6 db gain dish with 1.15° beamwidth. The satellites were steerable +/-10° by a gimbaled flat plate [7].

As for a power budget, LES-8 and LES-9 had no solar cells or batteries. Instead, radioisotope thermoelectric generators (RTGs) powered the satellites. RTGs are the same sources that power the 1977 Voyager 1 and 2 spacecraft that have explored beyond our solar system.

An advantage of the Lincoln Lab’s space communications program was that each LES was developed in the same facility. Lincoln Labs was able to experiment extensively for end-to-end communication testing including the ground terminals that Lincoln developed for the Air Force and Navy. The smooth testing following the launching of the satellites could be attributed to this.

Optical crosslink communication for LES-8 and LES-9 was also considered. However, the idea was later dismissed in 1971 because it was considered infeasible with the current technology and beyond the resources of the project [5]. Optical crosslinks were accomplished with the Artemis satellite described in section II-K. So, one can conclude that LES-8 and LES-9 set the groundwork for many future satellite communication systems.

C. 1983-2013, TDRSS

Starting in 1983, NASA launched a series of geostationary satellites to relay low earth orbit (LEO), 300 km to 1,000 km, spacecraft communications. This Tracking and Data Relay Satellite System (TDRSS) satellite communication system increases the time window that spacecraft are in communication with ground terminals from ten minute intervals to virtually round the clock.

Another advantage of TDRSS is during atmospheric re-entry of manned missions. During re-entry of spacecraft during Mercury, Gemini, and Apollo missions, communication was lost due to the tremendous heating experienced by the craft and is termed “re-entry blackout”. However during the space shuttle missions, communication was not lost because TDRSS relayed transmission from the cooler conditioned antennas on top of the shuttle.

Previously launched from space shuttle missions, the most recent generation of TDRSS are launched from rockets. This generation of TDRS provides downlinking datarates of 300 Mbps and 800 Mbps in Ku/Ka and S-bands respectively with five meter diameter dishes [8]. Also, a C-band phased array antenna can receive from five different spacecraft while transmitting to another location simultaneously [9].

TDRSS supports some of NASA’s most famous missions. LEO spacecraft such as the space shuttle, Hubble telescope, LANDSAT, ISS all have their signals relayed
from TDRSS to NASA ground terminals [10]. TDRSS has three main command and control ground terminal locations at White Sands (WSGT) in New Mexico, Goddard (GRGT) in Greenbelt, Maryland, and Guam (STGT) as shown in figure 2.

Figure 2. NASA’s TDRSS. The three ground terminals are Goddard (GRGT), White Sands (WSGT) and Guam (STGT).

D. 1985-1995, Luch

The Luch Satellite Data Relay Network, also referred to as Altair and Gelios, is considered Russia’s answer to NASA’s TDRSS. Until this series of geosynchronous Russian satellite relay stations, cosmonauts were in contact with ground stations only when flying over the Soviet Union or through communication ships at sea. To mitigate the five million dollars a week cost of keeping communication ships at sea, the geosynchronous satellites could relay communications to ground control at all times [4]. A series of five Luch satellites were launched from 1985 to 1995. The platform bus was called: Cosmos 1700, 1897, 1987, 2054 from 1985 until 1989 then Luch 16, and Luch 1 from 1994 and 1995.

Frequencies reported for use by the Luch satellites are: 15.05 GHz and 13.52 GHz to and from low-orbit satellites, 700 MHz and 900 MHz to and from low-orbit satellites, 14.62 GHz for uplinks from control stations; and 10.82 GHz, 11.32 GHz, and 13.7 GHz for downlinks to control stations. These frequencies have been used for communications, including voice and television signals, with the Mir space station, and the Buran reusable launch vehicle. The Luch satellites also have other uses such as teleconferencing. Antenna beamwidths are 0.5° for 13 and 15 GHz links, 5° for 700 MHz to 900 MHz links, and 1° for 11 GHz and 14 GHz links [11].

A further three satellites, Luch-5A (2011), Luch-5B (2012) and Luch-4 (2013), are planned for launch to rebuild the system and provide the Russian Orbital Section of the International Space Station with relay coverage.

E. 1994, ETS-6

The Experimental Test Satellite (ETS-6) was developed and launched by NASDA, Japan’s National Space Development Agency, renamed to JAXA, Japan Aerospace Exploration Agency after 2003. The satellite had an S-band, Ka-band, and optical intersatellite link. ETS-6 included an S-band of similar specifications to that of NASA’s TDRSS to have compatibility.

ETS-6’s S-band antenna was built as a phased array with 19 elements to receive from two spacecraft and transmit to one simultaneously with a 1000 km range. Downlink and uplink channels used 20 GHz and 30 GHz carriers respectively. All transmissions used phase shift keying (PSK) with code division multiple access (CDMA). Typical rates were 300 kbps with a maximum datarate of 1.5 Mbps [12].

ETS-6 also had a crosslink channel transmitting at 23 GHz and receiving at 26 GHz. This carrier had a maximum datarate of 10 Mbps [12], and was designed for compatibility with NASA TDRSS advanced now in orbit on TDRS 8 to 10 and ESA’s relay satellite system discussed in section II-K.

ETS-6 had another communication payload that transmitted at 38 GHz and received at 43 GHz. The payload demonstrated ground communication with low power 500 mW small antenna 30 cm diameter dish earth terminals with datarates of 64 kbps to 512 kbps. Intersatellite communication experimented with this payload was also emulated from earth terminals with a maximum datarate of 10 Mbps [4]. This transceiver used a 40 cm dish antenna.

The last experimental payload for ETS-6 was an optical transmitter to demonstrate laser intersatellite linking communication with a maximum datarate of 1 Mbps. The ground station used an argon laser to uplink, then ETS-6 downlinked with a GaAlAs diode laser. A fine pointing mechanism pointed ETS-6’s transceiver to an accuracy of 0.0001° [13].

F. 1997, Navstar Block IIR and IIF GNSS

To the authors’ knowledge, ISLs in GNSSs have only been launched starting with the US GPS Navstar blocks IIR and IIF. These satellites use the UHF band for crosslink transmissions. There have been plans for ISLs to appear in many other navigational satellite systems from many space agencies including Glonass from Russia, Galileo from ESA, Compass from China, Japan’s QZSS, and India’s Indian Regional Navigational Satellite System or IRNSS.

GPS Navstar Block IIR and IIF satellites use the UHF ISLs for gathering neighboring satellite distances and constellation status. Navstar satellites broadcast the constellation’s ephemeris, a table of the GPS constellation satellites positions at the given time. Satellites not equipped with the links only receive this information by the ground terminal with an average contact frequency of 12 hours. Frequent ephemeris updates through ISLs can allow the Navstar system to have automated navigation.
G. 1997, Iridium

In 1997, Motorola Inc. built a constellation of LEO satellites called Iridium to provide global satellite phone coverage. The Iridium constellation is operated with satellites that can intersatellite link, providing satellite calls and digital data to traverse through Iridium satellites instead of a cellular phone’s network of base stations.

The constellation includes 66 Iridium satellites and six spares orbiting in low earth orbit [14]. 7.5 km/second is the approximate orbital velocity for Iridium satellites, and LEO satellites in general.

Figure 3. Iridium constellation generated by the satellite constellation visualization "SAVI" (credit: SAVI)

Each Iridium satellite can have up to four simultaneous crosslinks with a carrier frequency ranging from 13.18 GHz to 13.38 GHz, and a datarate of 10 Mbit/s [14]. Six satellites are contained in eleven orbital planes. Satellites in the same plane can link north and south or east and west with neighboring orbital planes. The polar orbits create two cross-seams. A cross-seam is where one plane orbits north to south and the neighboring plane orbits north to south. As a result, the satellites only link with neighbor planes orbiting in the same direction due to a high Doppler shift. Iridium satellites orbit from pole to pole in approximate 100 minutes [15]. The Iridium satellite density at the North and South poles gives excellent coverage for research facilities.

For processing, each Iridium satellite is equipped with seven Motorola/Freescale PowerPC 200 MHz 603E processors [16]. The four crosslink antennas each have a dedicated processor. Each Iridium satellite is controlled with two processors, with one being a spare. An extra processor was installed late in the design phase for processing phone calls and resource management. A custom backplane network connects the seven processors together.

Satellite phone hand-offs are done from neighboring orbital planes when a satellite moves over the horizon. At the equator where the orbital planes are spread farthest, the user may notice a quarter-second gap where the handoff occurs about every seven minutes. Different channels and timeslots can be transferred within the same call from a satellite in the same spot beam.

The Iridium system has control segments at ground stations that can access the public telephone system through telephony gateways in Arizona and Hawaii [16]. Iridium satellites can receive updated frames and routing tables when in line of sight of these gateways. The new tables can then be sent on to the neighboring Iridium satellites so the whole constellation is rapidly updated.

Satellite phones with a line of sight can uplink directly to Iridium satellites to make a call. The phone’s signal is received by a 48 spot beam antenna with 16 beams divided in three sectors that handles 1100 simultaneous phone calls [16]. The developers of Iridium previously conducted government studies in the late 1980s concluding that high datarate optical crosslinks were more complicated and higher risk than microwave. In the end, microwave crosslinks were chosen because at the time they have more than enough bandwidth for the system and support the mass and power budget allocated for each 680 kg Iridium satellite.

H. 1998, The proposed Teledesic System

In 1995, an ambitious intersatellite linking communication system known as Teledesic was proposed. The original proposal called for 840 active satellites in LEO [17]. Due to funding issues, the proposal was changed to 288 active satellites at MEO. The constellation was to have 24 satellites in 12 orbital planes. Teledesic allocated the Ka-band spectrum for use with non-geostationary satellites. Each satellite had 3-axis stabilization with an antenna on the bottom and solar panels on top. This system was one of the first to design satellites as compatible buses with over 20 different launch systems. Such flexibility is needed when launching hundreds of satellites. The Teledesic terminals also were flexible by allowing a variety of communication protocols including IP, ISDN, and ATM.

In February 1998, a test satellite named Teledesic T1 was launched. Teledesic T1 weighed 120 kg and used downlink frequencies of 18.8 GHz to 19.3 GHz and uplink frequencies of 28.6 GHz to 29.1 GHz [17]. Each Teledesic cell had a max rate of 64 MBps. However, after the commercial failing of the Globalstar system (46 operational satellites), work was suspend on Teledesic in 2002.

I. 1998, COMETS (ETS-7)

Conducted by the Japanese National Space Development Agency (JAXA after 2003), the Communications and Broadcasting Engineering Test Satellite (COMETS) built upon technology from ETS-6 satellite from section II-E [18]. Both the ETS-6 satellite and the COMETS satellite had roughly the same mass.
The crosslinks on COMETS were to demonstrate data communication between LEO earth observation and COMETS geosynchronous spacecraft, and to determine spacecraft positions from the crosslink data. NASA designed COMETS intersatellite frequencies to be compatible with NASA TDRSS, and ESA's future data relay systems. The payload experiments led to the design of Japan’s data relay system for which the first satellite was launched in 2002, detailed in section II-L.

COMETS used S- and Ka-bands for the crosslinks and K-band for uplinks and downlinks. Both intersatellite linking frequency bands allowed for a single transmit (COMETS to LEO) and receive (LEO to COMETS) channels. For S-band COMETS transmitted at a datarate of 100 bps to 300 kbps and receive at 100 bps to 6 Mbps. For Ka-band, COMETS transmitted at 100 bps to 300 kbps and received at 1 to 120 Mbps. BPSK and QPSK were supported modulation rates [19]. The COMETS mission was to prove that a geosynchronous 3.6 meter diameter antenna satellite antenna could track an LEO spacecraft with a gain loss of less than 0.5 dB at Ka-band [20]. COMETS had two other dish antennas for mobile communication and feeder links and for a broadcast payload. However, COMETS launch failed to put the satellite into the mission’s correct orbit for a successful mission.

J. 1994-2003, MILSTAR

The Military Strategic and Tactical Relay (MILSTAR) satellite constellation provides global survivable communications for US forces. Two Milstar-1 satellites have a low-data-rate (LDR) crosslink communications payload and the four Milstar-2 satellites have a medium-data-rate (MDR) payload and a Milstar-1 compatible LDR crosslink [21]. All Milstar satellites uplink at 44 GHz and 300 MHz, downlink at 20 GHz and 250 MHz and crosslink at 60 GHz [22]. The LDR relays provide 200 channels for 75 to 2400 bits/sec coded Teletype and voice data. MDR provides datarates of 4800 bits/sec to 1.544 Mbit/sec [21]. The total crosslink capacity for Milstar-2 satellites are 10 Mbit/sec. Each spacecraft has an approximate mass of 4,500 kg. All Milstar satellites are operational except for a Milstar-2 that was lost due to a launch failure [23].

K. 2001, ESA’s Artemis links Spot-4, Envisat, Adeos-II, and OICETS

The ESA's goal for Artemis was to demonstrate technologies needed for data relay and for mobile communications [24]. The Artemis satellite was to demonstrate data relay satellite services using Ka-band, S-band, and optical frequencies (800 nm wavelength) for the ESA data relay system. For the optical communications links, the Silex (Semiconductor Intersatellite Link Experiment) equipment was developed for both Artemis and France’s low-orbit, earth resources satellite, Spot 4.

In 2001, Artemis demonstrated of its SILEX payload, which relayed a remarkable quality image from Spot 4, seen in figure 4. Spot 4 transmitted data at 50 Mbps to Artemis but is only equipped to receive a beacon without data. Artemis has also supported relaying more than two-thirds data from ESA’s Envisat since April 2003 by 26 GHz Ka-band for payload data and telemetry links in the S-band.

The Japanese satellite Adeos-II launched in 2002 also links to Artemis in the same fashion. In 2005, the Artemis optical data relay payload completed in-orbit testing with the Japanese OICETS where 50 Mbps to Artemis and 2 Mbps from Artemis, was demonstrated [25].

Figure 4. Relayed Spot-4 image from Artemis in 2001 (credit: ESA [25])

The optical communication payload on Artemis is called the Optical Payload for Inter Satellite Link Experiment (OPALE). It is split into two units. One includes equipment that must be close to the optics; this unit has fine pointing optics and is mounted on two-axis gimbals that do coarse pointing. The other unit is in the satellite body and includes all equipment that does not need to be on gimbals. The payload can both transmit and receive data [25].

L. 2002, JAXA’s Kodama links DAICHI, SDS-1, Adeos-II, OICETS, and ISS Kibo

JAXA’s data relay test satellite (DRTS) named Kodama was launched in September of 2002 in a geostationary orbit. The satellite relays data in optical and s-bands among LEO spacecraft, enhancing live communications from 2% to 60% [26].

Kodama successfully intersatellite linked optically with DAICHI, a land observing satellite at a data rate of 278 Mbit/second. KODAMA can also link with OICETS (Optical Interorbit Communications Engineering Test Satellite), Small Demonstration Satellite-1 (SDS-1), Adeos-II, and ESA's Envisat [27] detailed in section II-K. Kodama also relays data from the International Space Station’s Japanese Experiment Module, Kibo, to broadcast the activities of astronauts [26].
M. 2010, AEHF

To replace an aging Milstar system detailed in section II-J, the Advanced Extremely High Frequency (AEHF) is being launched as communication satellites geostationary orbits. Currently only one satellite, AEHF SV-1, is launched [28]. The AEHF system operates at 44 GHz uplink (EHF band) 20 GHz downlink [28], and 60 GHz crosslink compatible with Milstar-2’s 10 Mbps total crosslink capacity detailed in section II-J and 60 Mbps capacity with other AEHF satellites.

Also similar to the Milstar satellites, AEHF satellites are equipped with security features including resistant jamming, encryption, and frequency-hopping. The AEHF system can detect a jamming source and then apply adaptive antennas to transmit nulls toward sources. AEHF is compatible Milstar’s low and medium data rates and also high a higher signaling method with a data rate of up to 8.192 Mbit/sec [28].

N. 2015, Iridium Next

As an update to the Iridium system, detailed in section II-G, the Iridium Next satellite constellation was announced in 2007. The constellation is the same as Iridium with 66 operating LEO satellites. This second-generation Iridium design will emphasize data transmission [29]. Since the satellite can be controlled from a single ground point, other companies have partnered with Iridium to incorporate on-board camera and sensor payloads. The estimated launch data for the constellation start in 2015 [29].

Gateway ground stations for Iridium NEXT in Tempe, Arizona and Wahiawa, Hawaii [16] will control the constellation with uplinking from the Ka-band 19.4 GHz-19.6 GHz and downlinking 29.1 GHz-29.3 GHz. ISLs will use the Ka-band ranging from 23.18 GHz to 23.38 GHz [29]. Mobile satellite phones from the ground users or hot-spot stations will use the L-band ranging from 1616 MHz to 1626.5 MHz to uplink to the satellite constellation. The frequency license rules for the user’s location will determine the exact L-band frequency [29]. Normal satellite phone datarates for Iridium NEXT are reported at 1.5 Mbit/sec. Users can also purchase larger equipment to use the premium high-speed Ka-band service of 8 Mbit/sec [29]. Iridium NEXT will also be compatible with the original Iridium constellation.

III. CUBESAT COMMUNICATION SUB-SYSTEMS

Starting in 1999, the CubeSat was an idea to standardize a platform for low-cost pico-satellite missions and experiments, particularly at the university level. The CubeSat name is given from the pico-satellite’s cube-like structure of 1 kg mass and 10 cm a side. A standardized structure allows CubeSats to share in launches with standard tubes shown in figure 5, and called Poly Picosatellite Orbital Deployers also known as P-PODs. The CubeSat platform is seen as the most feasible direction to take intersatellite links in the future. Thus, this section III surveys all CubeSat communication subsystems.

Over the past eight years, the CubeSat platform has flown successfully for many educational and scientific low earth orbiting satellite missions. To further CubeSat mission applications, a focus needs placed on inter-satellite networking that could improve the overall datarate and downlink time window of a CubeSat to ground terminal. Universities are developing a new robust, ad-hoc, long distance, high data rate protocol for CubeSats. However, in order to create this CubeSat protocol, a study of every inter-satellite linking mission and CubeSat mission communication system is presented in this report. Special focus is put on the data downlinking transceiver and communication protocol used.

A. 2003, Eurockot LV, Pletsak, Russia

Coordinated by University of Toronto’s Space Flight Group in 2003, the Nanosatellite Launch System (NLS) provides a low-cost launch service for nanosatellites [31]. The first batch of six CubeSats were launched into a polar sun-synchronous orbit at 810 km [30]. The CubeSats launched from Plesetsk, Russia [30]. The launch integration effort for three 1U satellites was known as Nanosatellite Launch service 1 (NLS1). NSL1 CubeSats included AAUSat from Aalborg, DTUSat from Denmark, and CanX-1 from University of Toronto. The three satellites were launched from the first P-POD. NLS2 launched QuakeSat, a 3U CubeSat from Stanford University, which took up an entire second P-POD. Also on the Eurockot, two Tokyo Pico-satellite Orbital Deployers or T-PODs, deployed CUTE-I from Tokyo Tech. and XI from Tokyo University.

The two communication system characteristics that were common among the six CubeSats were the use of the AX.25 Link Layer Protocol specification and the frequency range from 432-438 MHz for their beacons and downlink. The only deviation from the AX.25 protocol was the CanX-1 satellite due to a proprietary nature of the information it was collecting and the addition of the PacSat layer to QuakeSat-1. However, CanX-1 Radio contact was never established. The choice of the AX.25 protocol allows amateur radio operators worldwide to collect information from the satellites and enhance the ground station effort. By utilizing the amateur radio community, the satellites could potentially transmit more...
TABLE II. HISTORY OF CUBESAT DATA TRANSMITTERS BY LAUNCH DATE 2003-2005 [30]

<table>
<thead>
<tr>
<th>Launch Date/Location</th>
<th>Satellite(s)</th>
<th>Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Protocol</th>
<th>Band Rate/Modulation</th>
</tr>
</thead>
<tbody>
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<td>June 30, 2003</td>
<td>AAU1 CubeSat</td>
<td>1U</td>
<td>437.475 MHz</td>
<td>500 mW</td>
<td>AX.25, Mobitex</td>
<td>9600 baud GMSK</td>
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<tr>
<td></td>
<td>Eurockot</td>
<td>1U</td>
<td>437.475 MHz</td>
<td>400 mW</td>
<td>AX.25</td>
<td>2400 baud FSK</td>
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<tr>
<td>Plesetsk Cosmodrome</td>
<td>CanX-1</td>
<td>1U</td>
<td>437.880 MHz</td>
<td>500 mW</td>
<td>Custom</td>
<td>1200 baud MSK</td>
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<td>Russia</td>
<td>Cute-1 (CO-55)</td>
<td>1U</td>
<td>437.470 MHz</td>
<td>350 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
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<tr>
<td></td>
<td>QuakeSat-1</td>
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<td>436.675 MHz</td>
<td>2 W</td>
<td>AX.25 w/Pacsat</td>
<td>9600 baud FSK</td>
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<tr>
<td></td>
<td>XI-IV (CO-57)</td>
<td>1U</td>
<td>437.490 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
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<tr>
<td>October 27, 2005</td>
<td>XI-V (CO-58)</td>
<td>1U</td>
<td>437.345 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
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<tr>
<td>SSETI Express</td>
<td>NCube-2</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
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<tr>
<td>Plesetsk Cosmodrome</td>
<td>UWE-1</td>
<td>1U</td>
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<td>1 W</td>
<td>AX.25</td>
<td>1200/9600 baud AFSK</td>
</tr>
</tbody>
</table>

data, thus provide more utility, if the data could be effectively re-assembled by the ground station [32].

QuakeSat-1 used PacSat Protocol Suite, part of the UoSAT and Microsat File transfer protocols. The suite defines file transfer protocols for use by LEO Packet Radio Satellites (PACSATS). Published in 1990, was the first digital store and forward packeting protocol used for CubeSats [33].

Generally, CubeSats use Commercial Off-the-Shelf (COTS) radios, and modify them for use in space. The only published exception from the use of COTS equipment on this mission was the Japanese CubeSat XI-IV, which used a transceiver and beacon that was developed within the University. However, the first three development versions of the satellite integrated a COTS transceiver until the flight model was ready [34].

The results from the first batch of CubeSats have been mixed. The two Japanese satellites, Cute-1 and XI-IV, were successful, as they sent telemetry data until December 2008 and March 2009 respectively. The 3U QuakeSat-1 with PacSat can also be considered a success because it worked for more than seven times the design life of six months, and provided significant usable data. QuakeSat-1 also demonstrated the use of solar panels for a higher maximum transmitting power. CanX-1 and DTUsat-1, however, never functioned on orbit and AAU1 had a significantly decreased lifetime, due to battery packaging problems, and a degraded communications system that led to only beacon packets being transmitted for the life of the satellite [35]. The most notable characteristic for the launch is the use of dedicated beacon transmitters by the two Japanese satellites Cute-1 and XI-IV. These satellites also utilized dedicated antenna designs for the transceiver and the beacon, monopoles for Cute-1, and dipoles for XI-IV [34].

B. 2005, SSETI Express, Plesetsk, Russia

Upon the success of the first CubeSat launch more educational CubeSat projects were started. Sponsored by the European Space Agency Education office, a micro-satellite called SSETI Express was launched in 2005 in a sun-synchronous polar low earth orbit [30]. Although the SSETI Express microsatellite failed almost immediately after launch, three CubeSats including XI-V (University of Tokyo), NCube-2 (University of Oslo and others), and UWE-1 (University of Würzburg) were successfully launched [30]. These CubeSats, known as NLS3, brought together many universities across Europe, and educated hundreds of students [31].

The CubeSats all operated in the Amateur Band and used the amateur AX.25 protocol to simplify the ground station operation and increase the number of worldwide downlink points. Though the types of transceivers are unknown, it is known that NCube-2 and UWE-1 utilized commercial transceivers and the XI-V satellite family (identical to XI-IV in every aspect) continued to use the transceivers and beacons developed within the University of Tokyo.

NCube-2, with a UHF and experimental S-band transmitter, never transmitted to its ground station, and was declared dead on orbit. XI-V and UWE-1 both functioned as intended and utilized monopole antennas for their communications subsystem. Again, the Japanese Satellite XI-V used a separate beacon to provide redundancy [30].

UWE-1 was designed to test TCP/IP protocols in space and the effects of low bandwidth, long path delays, and dropped packets [34]. The main processor performed all the TNC functions, packeting all the data into the AX.25 frame [36]. It then sent these frames using a 6-pack protocol (similar to KISS) to the TNC. This allowed the main processor to control the Data Link Layer settings of the radio, improving system performance. Numerous other ground stations around the world received these beacons and forwarded the data to the university [34], but the CubeSat stopped functioning in November 2005, about three weeks after launch [30].

C. 2006, M-V-8, Uchinoura, Japan

Single CubeSat launches have been rare. However, Cute 1.7 + APD was a 2U CubeSat that was individually launched by Tokyo Tech from Japan and tested an upgrade to the Tokyo Pico-satellite Orbital Deployer (T-POD) that could accommodate 2U CubeSats. CUTE 1.7 + APD had a highly elliptical orbit from 250-280 km in perigee height and 750 km in apogee height. This resulted in a short lifetime of over two months [30]. The CubeSat demonstrated
TABLE III. HISTORY OF CUBESAT DATA TRANSMITTERS BY LAUNCH DATE 2006-2008

<table>
<thead>
<tr>
<th>Launch Date/Location</th>
<th>Satellite(s)</th>
<th>Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Protocol</th>
<th>Band Rate/Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 21, 2006 MV8</td>
<td>Cute-1.7 APD</td>
<td>2U</td>
<td>437.505 MHz</td>
<td>300 mW AX.25</td>
<td>SRL1 1200 AFSDK GMSK</td>
<td></td>
</tr>
<tr>
<td>July 26, 2006</td>
<td>Ion</td>
<td>2U</td>
<td>437.505 MHz</td>
<td>2 W   AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td>DNEPR-1 Failed</td>
<td>Sacred</td>
<td>1U</td>
<td>467.870 MHz</td>
<td>400 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td>Baikonur, Cosmodrome</td>
<td>KuteSat Pathfinder</td>
<td>1U</td>
<td>437.385 MHz</td>
<td>500 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td>Kazakstan</td>
<td>Ice Cube-1</td>
<td>1U</td>
<td>437.305 MHz</td>
<td>600 mW AX.25</td>
<td>9600 baud FSK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ice Cube-2</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>600 mW AX.25</td>
<td>9600 baud FSK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rincon-1</td>
<td>1U</td>
<td>436.870 MHz</td>
<td>400 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEEDS</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>450 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HaiSat1</td>
<td>1U</td>
<td>437.465 MHz</td>
<td>500 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NCube1</td>
<td>1U</td>
<td>437.305 MHz</td>
<td>1 W   AX.25</td>
<td>9600 baud GMSK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Merope</td>
<td>1U</td>
<td>145.908 MHz</td>
<td>500 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IceCube-1</td>
<td>1U</td>
<td>902.928 MHz</td>
<td>2 W   AX.25</td>
<td>9600 baud GFSK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CP1</td>
<td>1U</td>
<td>436.845 MHz</td>
<td>500 mW AX.25</td>
<td>15 baud DTMF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CP2</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>1 W   AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mea Huaka (Voyager)</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>500 mW AX.25</td>
<td>1200 AFSDK</td>
<td></td>
</tr>
<tr>
<td>December 16, 2006 Wallops, US</td>
<td>GeneSat-1</td>
<td>3U+</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>April 17, 2007</td>
<td>CSTB1</td>
<td>1U</td>
<td>400.0375 MHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>1200 baud AFSDK</td>
</tr>
<tr>
<td></td>
<td>AeroCube-2</td>
<td>1U</td>
<td>902.920 MHz</td>
<td>2 W</td>
<td>Proprietary</td>
<td>38.4 kbps</td>
</tr>
<tr>
<td></td>
<td>CP4</td>
<td>1U</td>
<td>437.325 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSDK</td>
</tr>
<tr>
<td></td>
<td>Libertat-1</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>400 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAPE1</td>
<td>1U</td>
<td>436.245 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td></td>
<td>CP3</td>
<td>1U</td>
<td>437.845 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSDK</td>
</tr>
<tr>
<td></td>
<td>MAST</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>April 28, 2008</td>
<td>Delfi-C3 (DO-64)</td>
<td>3U</td>
<td>435.55 MHz</td>
<td>200 mW</td>
<td>Linear</td>
<td>40 KHz wideband</td>
</tr>
<tr>
<td>Satish Dhawan, India</td>
<td>Seeds-2 (CO-66)</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>450 mW AX.25</td>
<td>1200 baud AFSDK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CanX-2</td>
<td>3U</td>
<td>2.2 GHz</td>
<td>500 mW</td>
<td>NSP</td>
<td>16-256 kbps BPSK</td>
</tr>
<tr>
<td></td>
<td>AUSAT-II</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>300 mW AX.25</td>
<td>SRL1 1200 AFSDK GMSK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cute 1.7 APD-2</td>
<td>3U+</td>
<td>437.475 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td></td>
<td>Compass-1</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>300 mW AX.25</td>
<td>1200 baud AFSDK/MSK</td>
<td></td>
</tr>
<tr>
<td>August 3, 2008 Falcon 1 Failed</td>
<td>PRExsat</td>
<td>3U</td>
<td>437.845 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSDK</td>
</tr>
<tr>
<td>Omelek, Marshall Islands</td>
<td>NanoSail-D</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
</tbody>
</table>

use of a tether, an avalanche photodiode, a magnetic torque attitude control system (ACS), and a computer from a personal digital assistant. During the flight time CUTE 1.7 successfully transmitted about one megabyte of mission information to the ground station [30].

CUTE-1.7+APD downlinked at 430 MHz and received uplink at 1200 MHz. The L-band uplink was used as a public personal message box for space. The message box performed at store and forward experiment by transmitting stored messages for a duration of time to amateur radio ground stations. CUTE-1.7+APD was also known as OSCAR-56 because it was an operational digital repeater [30].

D. 2006, DNEPR-1 Failure, Baikonur, Kazakhstan

This large sun-synchronous orbit launch was aboard a Dnepr rocket and contained five P-PODs housing 14 CubeSats. Unfortunately, about two minutes into the launch the Dnepr failed and all the CubeSats were lost.

Common characteristics among the CubeSats was the use of the AX.25 protocol within the 432-438 MHz band. The only deviations from the standard within the launch were the MEROPE by Montana State University which utilized the AX.25 protocol at a significantly lower frequency (144-146 MHz range) [37] and the AeroCube-1 that operated in the amateur band between 902-928 MHz [30]. Most of the satellites utilized monopole or dipole antennas. Notable exceptions were the use of a patch antenna by ICE Cubes 1 and 2 from Cornell University and the incorporation of an active antenna array on Mea Huaka from the University of Hawaii as part of the experimental payload [38]. This batch of satellites also began to incorporate the use of an attitude control system. At least eight of the satellites included magnetorquers, hysteresis rods, or electronic propulsion systems in the satellite [30]. The use of stabilizing devices in CubeSats could significantly improve the capabilities of the communications subsystem and allow a link to be closed with a reduction in power using a higher data rate [39]. Attitude control could also contribute to directionally pointing CubeSat links allowing for higher gain antennas.
E. 2006, Minotaur-1, NASA Wallops, VA, USA

GeneSat-1 was a joint project between NASA and academia that sought to evaluate biological payload experiments in a CubeSat [40]. GeneSat-1 was launched by a Minotaur rocket to an altitude of 415 km circular orbit [30].

The primary telemetry, tracking, and command link for GeneSat was a Microhard MHX-2400 frequency hopping spread spectrum Radio operating at 2.44 GHz and transmitted through a patch antenna. GeneSat also used a beacon operating in the Amateur Band from 432-438 MHz to serve as a risk reduction for the Microhard Radio, and to provide amateur radio operators the opportunity to collect satellite information [40]. GeneSat-1 was successful and downloaded the 500 kb required for its primary mission and continues to transmit beacon information [34]. NASAs GeneSat-1 3U platform bus, seen in figure 6, has been used in NASAs later PharmaSat, PREsat, O/OREOS, and NanoSail-D CubeSats.

Figure 6. The GeneSat-1 bus has been replicated for future NASA CubeSats such as PharmaSat, PREsat, and NanoSail-D1/-D2. (credit: NASA/ARC)

F. 2007, DNEPR-2, Baikonur, Kazakhstan

Unlike the first Dnepr launch, this DNEPR LV launch successfully deployed three P-PODs in space, dropping the satellites in a polar sun-synchronous. The fourth major CubeSat launch contained several unique elements as Boeing entered the fray of the CubeSat community with their entry of CTSB-1 and Tethers Unlimited launched three tethered CubeSats known as MAST. Aerospace Corporation also launched their second CubeSat and California Polytechnic Institute launched CP3 and CP4, their third and fourth CubeSat [41].

Satellites CTSB-1, AeroCube-2, and MAST utilized proprietary packet protocols for their missions. These missions were also unique in their use of the frequency spectrum and the licensing requirements associated. CTSB-1 used an experimental license that operated at 400 MHz, AeroCube-2 used ISM license between 902-928 MHz [41], and MAST used the same transceiver as GeneSat-1, a Microhard MHX2400 transceiver operating at 2.4 GHz.

The remaining satellites in the flight continued to use the AX.25 protocol along with frequencies within the UHF band. These satellites have had a mixed rate of success. Essentially all of the satellites have established communications with the ground. The exceptions were CAPE, which was integrated with a non-functioning receiver due to time constraints and Libertad-1, which had a non-functioning ground station when it was launched and the university personnel were not able to complete repairs in time to communicate with the satellite [34]. The remainder had down linked telemetry from several hundred kilobytes to several megabytes over the course of a year [34].

G. 2008, PSLV-C9 Satish Dhawan Space Centre, India

The first launch of multiple CubeSat outside of the former Soviet Union was supported as Nanosatellite Launch Systems 4 and 5 (NLS4 and NLS5) [31]. The launch consisted of satellites from Canada, Europe, and Japan. The satellites were launched using an eXperimental Push Out Deployer (X-POD), a launch system built for custom dimensions from pico-satellite to large nanosatellite classes.

Notably, Delfi-C3 from Delft University of Technology in Holland was deployed to test wireless link data transfer within the satellite and new thin film solar cells. Nihon University deployed SEEDS, a satellite similar to one destroyed in the DNEPR Launch Vehicle failure discussed in section III-D.

Every satellite within the fifth batch used the 432-438 MHz portion of the AM band for part of its communications subsystem. CanX-2 also used the 2.390-2.450 GHz portion of the Amateur band for an additional downlink using a modified AX.25 protocol that the design team named the Nanosatellite Protocol (NSP) [42]. CanX-2 used two patch antennas for the S-Band transceiver and a quad-canted turnstile antenna for the downlink in the 70 cm band [30]. CUTE 1.7 + APD II used the Amateur frequencies available from 1240-1300 MHz for its uplink and maintained the AX.25 protocol for its transmissions [42]. According to AMSAT, all the satellites launched in the fifth batch are still in operation and transmitting to the ground station, except Compass-1, which is semi-operational as of September 2011.

H. 2008, Falcon-1 Failure, Omelek Island

In August of 2008, SpaceX’s Falcon 1 rocket was used to launch the US Air Forces Trailblazer satellite along with two 3U CubeSats from NASA called NanoSail-D and PREsat. However, two minutes and forty seconds into the launch the Falcon’s 1st stage hit the 2nd stage. As a result, the entire rocket and payload flew off course into the Pacific Ocean.

NASA’s Ames Research Center built the NanoSail-D CubeSat to study the use of a solar sail for deorbiting. The satellite was designed to have an elliptical orbit with an apogee of 685 kilometers and perigee of 330 kilometers.
Once in orbit, the satellite was to deploy a ten meter solar sail to create drag to deorbit. After the first seven days of orbit the satellite would run out of power [30]. More details are in section III-N that discusses NanoSail-D2. Built in six months from NASA Ames, the PharmaSat Risk Evaluation (PRESat) CubeSat’s payload had an optical system and other sensors to monitor health, growth, and density yeast cells in low earth orbit.

I. 2009, Minotaur-1, Wallops, MD

In 2009, the US launched a batch of CubeSats which included NASAs second CubeSat, Pharmasat-1, along with Aerocube-3, Hawksat-1, and CP6 from California Polytechnic State University aboard a Minotaur-1 rocket [34]. Pharmasats subsystems were mostly the same as Genesat. NASA developed the Microsatellite Free Flyer program that will leverage a standard subsystem baseline in 1U of the cube and allow various payload configurations in the remaining 2U of the satellite. Aerocube-3 and Hawksat-1 did not publish information regarding their projects. CP6 has also limited information on the subsystems available to the public. However, based on the published frequencies and available computer assisted drawings of CP6 and Hawksat-1, it can be assumed that the communications systems use a half-wave dipole.

J. 2009, STS-127 Space Shuttle Endeavor

Space Shuttle Endeavor’s STS-127 mission segment known as LONESTAR-1 launched the ”DRAGONSAT payload” a satellite (12.7 cm) known as BEVO-1 and a CubeSat called AggieSat-2 on July 20th 2009. BEVO-1, however was never operational upon launch [34]. However, AggieSat2 experimented with a unique dual-GPS system known as DRAGON by Johnson Space Center. To send commands to the CubeSat and poll responses, Aggiesat-2 utilized software called client [34]. The Client application allowed AggieSat 2 lab member to conduct mission operations such as downlinking temperature, battery, and DRAGON GPS data during the CubeSat overpass. Ninety-nine contacts were made by Texas A&M students and another thirty contacts were sent in by amateur radio operators around the world during AggieSat-2’s 230 days of orbit.

K. 2009, ISI Launch 01, Satish Dawan Space Center, India

The Innovative Solutions In Launch 01 (ISI Launch 01) was the second launch from India. All CubeSats were of a 1U platform.

SwissCube-1 used a small experimental sensor to detect nightglow, earth’s atmospheric emission of light that allows earth sky to never be completely dark, even after the reflected light from stars is removed. When SwissCube was first launched in September of 2009, satellite rotated too fast to take pictures. This was likely a consequence from the deployment of its antennas. Researchers and students had no stable picture until the CubeSat stabilized on its own, which could take up to a year. There would be no guarantee that SwissCube could resist solar radiation and extreme temperature changes for longer than four months. However, in November 2010, after more than one year of waiting, the rotation of Swisscube eased, but SwissCubes’s functions had deteriorated. Hoping to restore the defaults, a system restart was planned. To restart, the team purposely drained the batteries by communicating with the CubeSat as long as possible upon an overpass. To the relief of the team, the system rebooted as expected and all functions were restored. In early 2011, using three electro-magnets, the team aligned SwissCube with the magnetic field and stabilized the CubeSat. SwissCube-1 took its first visible light picture during February 2011 and its first airglow picture during March 2011 shown in figure 7 [43].

ITUpSAT1 (Istanbul Technical University PicoSatellite-1) mission goals were to demonstrate a passive CubeSat stabilization system and to downlink an image from a CMOS camera payload of 640x480 pixel resolution. A MicroHard MHX-425 transceiver was used for ITUpSAT1’s communications sub-system. The MHX-425 has 1 W transmit power, configurable frequency hopping patterns, and a high sensitivity of -115 dBm for receiving uplinks. ITUpSAT1 downlinked 19200 baud from the MHX-425 transceiver.

BeeSat-1 or Berlin Experimental and Educational Satellite 1, was built to demonstrate small reaction wheels for attitude control and had a 640x480 pixel resolution camera. BeeSat was also equipped with a sprightly 60 MHz ARM-7 CPU, 2 Gb of SRAM, 4 Mb of store and forward telemetry memory queue and 16 Mb of flash memory [44].

The University of Wurzburg’s Experimental satellite 2 (UWE-2) experimented with optimization for inter-networking specifications to work in long propagation environments.

All CubeSats were launched in to a sun synchronous, slightly elliptical orbit. The orbit has a 98 minute period of revolution. As of January 2011, SwissCube, BeeSat are still operational [34].
TABLE IV.
HISTORY OF CUBESAT DATA TRANSMITTERS BY LAUNCH DATE 2009-2011 [34]

<table>
<thead>
<tr>
<th>Launch Date/Location</th>
<th>Satellite(s)</th>
<th>Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Protocol</th>
<th>Baud Rate/Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 19, 2009</td>
<td>PharmaSat</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>Minotaur-1</td>
<td>CP6</td>
<td>1U</td>
<td>437 MHz</td>
<td>1 W</td>
<td>CC1000 AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Wallops, US</td>
<td>HawkSat-I</td>
<td>3U</td>
<td>425 GHz</td>
<td>1 W</td>
<td>MHX-425 NSP</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td></td>
<td>AeroCube-3</td>
<td>1U</td>
<td>900 MHz</td>
<td>2 W</td>
<td>FreeWave FHSS</td>
<td>Proprietary</td>
</tr>
<tr>
<td>July 30, 2009 STS-127</td>
<td>Aggiesat-2</td>
<td>1U</td>
<td>436.25 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
</tbody>
</table>

| September 23, 2009   | SwissCube    | 1U   | 437.505 MHz| 1 W  | AX.25 | FSK 1200 baud |
| ISILaunch 01         | ITUpSat-1    | 1U   | 437.325 MHz| 1 W  | Custom | GFSK 19.2 kbps |
| India                | UWE-2        | 1U   | 437.385 MHz| 500 mW| AX.25 | 9600 BPS |
|                      | BeeSat       | 1U   | 436 MHz   | 500 mW| AX.25 | 4800 and 9600 GMSK |
| May 20, 2010         | Hayato (K-Sat)| 1U | 13.275 GHz| Custom| 10kbps/1 Mbps |
| Japanese H-IIA       | Waseda-Sat-1 | 1U   | 437.485 MHz| 1 W | AX.25 | 9600 baud FSK |
| Japan                | Negai        | 1U   | 427.305 MHz| 1 W | AX.25 | 1200 FSK |
| July 12, 2010        | TSat-1       | 1U   | 437.305 MHz| 400 mW| Custom | CW 110 WPM |
| PSLV-C15 India       | StudSat      | 1U   | 437.505 MHz| 450 mW| AX.25 | 9600 baud FSK |
| November 20, 2010    | O/OREOS      | 3U   | 437.305 MHz| 1 W | AX.25 | 1200 FSK |
| STP-S26              | RAX1         | 3U   | 437.505 MHz| 2 W | AX.25 | 9600 baud FSK |
| Kodiak, Alaska       |              |      | 2.4 GHz   | 2 W  |        |            |
|                      | NanoSail-D2  | 3U   | 437.275 MHz| 1 W | AX.25 | 1200 baud FSK |
| August 12, 2010      | Perseus (4)  | 1.5U | PI | PI | PI | PI |
| Falcon 9-002         | QBX (2)      | 3U   | PI | PI | PI | PI |
| Capa Canaveral       | SMDC-ONE     | 3U   | UHF | PI | PI | PI |
|                      | Mayflower    | 3U   | 437.600 MHz| 900 mW| AX.25 | 1200 AFSK |
| March 4, 2011        | E1P          | 1U   | 437.505 MHz| 1 W | KISS/Custom | 1200 FSK |
| Taurus XL Failure    | Hermes       | 1U   | 2.4 GHz   | 1 W | MHX-2420 | 56.2 kbps |
| Vanderberg, CA       | KySat        | 3U   | 436.790 MHz| 1 W | AX.25 | 1200 FSK |
| Oct 12, 2011 India   | JUGNU        | 3U   | 437.275 MHz| 500 mW| CW | 20 WPM |
| Oct 28, 2011         | DICE-1/2     | 1.5U | 460/465 MHz| 2 W | PI | 1.5 Mbps |
| Elana 3              | M-Cubed      | 1U   | 437.485 MHz| 1 W | AX.25 | 9600 GMSK |
| Vanderburg, CA       | RAX-2        | 3U   | 437.345 MHz| 2 W | AX.25 | 9600 FSK |
|                      |              |      | 2.4 GHz   | 2 W  |        |            |
|                      | E1P-2        | 1U   | 437.505 MHz| 850 mW| AX.25 | 1200 FSK |
|                      | AubieSat-1   | 1U   | 437.475 MHz| 708 mW| CW | 20 WPM |

L. 2010, Japanese H-IIA F17, Tanegashima Space Centre

Three 1U CubeSats Hayato, Waseda-SAT2, and Negai were launched from the Yoshinobu Launch Complex at the Tanegashima Space Centre [34]. Two JAXA Picosatellite Deployers or J-PODs released the CubeSats. Hayato and Negai shared a J-POD while Waseda-SAT was stored in a second J-POD. These satellites were launched in extremely low earth orbits of 300 km. Hayato contained a dielectric patch antenna for X-band communication and a pantograph space boom of 60 cm for space weather study of water vapor in the earth’s atmosphere. Waseda-SAT2 was launched for earth observation and to test the use of extending paddles to provide attitude control. Negai was launched to perform an orbital FPGA experiment. Negai also returned images of the Earth.

M. 2010, PSLV-C15, Satish Dhawan Space Centre

Supported as NLS6 [31], TISat and the Indian StudSat were launched into a 700 km sun-synchronous orbit [34]. The Studsat took images of earth’s surface with a resolution of 90 meters. TISat-1 is experimented with the durability of exposed thin bonding wires and printed circuit board tracks. TISat-1 also developed in-house all baseband modulation schemes in firmware. Both TIsat-1 and StudSat are currently operating with amateur radio stations around the world.

N. 2010, STP-S26, Kodiak, Alaska

Launched from Kodiak Island Launch Complex, Alaska, RAX-1, O/OREOS and NanoSail-D2 piggy-backed on the Formation Autonomy Spacecraft with Thrust, Relay, Attitude, and Cross-link (FASTRAC). The goal of the RAX-1 mission to study plasma instabilities in the lower polar thermosphere that can amount magnetic field-aligned irregularities. magnetic field-aligned irregularities in between 80 to 400 km can jam wireless communication signals of spacecraft downlinking to ground stations. RAX1 used a standard 2 watt UHF AX.25 communication sub-system
to downlink data back to a ground terminal in Michigan. Due to an aberration in RAX-1’s solar panels, the CubeSat was unable to generate power after several months. However, during operation RAX-1 was able to downlink bistatic radar measurements never attempted at this altitude. RAX-2 is being rebuilt for a NASA’s Elana 3 launch, detailed in section III-R.

NASA’s O/OREOS or Organism Organic Exposure to Orbital Stresses is a 3U CubeSat built to study microorganisms’ health in space. Microorganisms health data is downlinked using UHF AX.25, so amateur radio stations around the world can receive and forward the packets to NASA website for study [45]. O/OREOS also send data through s-band transmission to NASA over a microhard MHX-2420 transceiver [45]. O/OREOS was built with a mechanism of two aluminum plates that separated with a spring. This mechanism increases the device’s volume by 60%, creating drag, to slowly deorbit the CubeSat. This is shown in figure 8.

Figure 8. NASA’s expanded CubeSat O/OREOS. Key: 1. UHF transmitter, 2. Microhard MHX-2420, 3. ACS, 4. Expanded deorbit device, 5. Solar Cells, 6) Lithium Ion Batteries (credit: NASA [45]).

Last, NASA’s NanoSail-D2 30-square-meter sail has was unfurled and the satellite has lowered its altitude. In fact, NanoSail-D2’s can be seen at observatories. Orbital attitude, sail direction of pointing, and solar activity all affects NanoSail-D2’s ascent rate [46].

O. 2010, Falcon 9-002, Cape Canaveral, FL

The last CubeSat launch for 2010 was done from a Falcon-9 rocket. Eight CubeSats piggybacked on an evaluation mission for SpaceX’s Dragon C1 capsule to provide supplies to the ISS in the future.

Two P-PODs contained four 1.5U satellites from Los Alamos National Laboratory called Perseus. The only known communication includes successful testing of two-way communication, three-way communication (two ground stations and a satellite), and collection of telemetry [34].

Another two P-PODs contained two 3U QbX satellite from the NRO’s Colony-1 program [34]. No information has been further published.

One P-POD housed an experimental US Army communications 3U CubeSat known as SMDC-ONE. SMDC-ONE uses a UHF transceiver to poll sensors to collect data and relay the data to ground terminals [34].

The last P-POD housed 3U CubeSat known as Mayflower-Caerus. The CubeSat was built as a joint mission. One unit of the 3U of the CubeSat was Caerus from the University of Southern California. The other two units made up Mayflower from Novaworks of Northrop Grumman. The CubeSat has experimental propulsion systems and eight extra solar panels that deploy as two arrays, the CubeSat downlinks using the UHF band to amateur radio stations [34]. The CubeSat re-entered the atmosphere during December of 2010.

P. 2011, Tarus XL Failure, Vanderburg AFB, CA

NASA’s ELaNA is an Educational Launch of Nanosatellites program where CubeSat launch are coordinated by piggybacking along with larger satellites. On March 4, 2011, NASA’s Glory satellite, Kentucky Space’s KySat-1, Hermes, and Explorer-1 prime were launched from a Tarus rocket. Unfortunately during separation from the rocket, all the satellites were lost including NASAs Glory satellite set to monitor climate change [34].

KySat-1 carried a secondary technology demonstration payload; investigating the use of S-band communication at high bandwidths [34].

Hermes had an experimental high-speed payload using an MHX-2420 transceiver that would have allowed the CubeSat to downlink with a datarate of 115.2 kbits/sec without FEC under ideal conditions. With FEC, the baudrate drop to 57.6 kbit/sec, still much fast than the UHF 1200 baud system. The CubeSats was to have downlinked data of near magnetic fields and temperatures.

Explorer-1 [Prime], also known as E1P and Electra, was a re-flight mission of Explorer 1, the first American satellite, using modern technology. A second Explorer-1’ F2 is built for launch on NASA’s Educational Launch of Nanosatellites (Elana) 3 detailed in section III-R.

Q. 2011, Jugnu, Satish Dawan Space Center, India

Built by the Indian Institute of Technology Kanpur, Jugnu is a 3U CubeSat to demonstrate Micro Imaging System, a near infrared camera to monitor crop irrigation. For tracking the Jugnu uses a GPS receiver and inertial measurement unit (IMU). The CubeSat uses UHF CW signals and radio amateurs have been reporting receiving signals since late 2011.

R. 2011, Elana, Vandenberg AFB, CA

On October 28th, 2011 three P-PODs carrying six piggybacked CubeSats on a Delta II launched successfully from Vandenberg Air force Base. All three P-PODs deployed successfully and ground operators around the world are tracking the CubeSats. As of the evening of October 28th, signals from Aubiesat-1, E1P-2 and RAX-2 had been received.
The Dynamic Ionosphere CubeSat Experiment (DICE) is a CubeSat mission with the goal to map the geomagnetic SED (Storm Enhanced Density) plasma bulge and plume formations in earth’s ionosphere. DICE-1 and DICE-2 are two identical 1.5U spin-stabilized spacecraft that downlink to a USRL ground station. DICEs’ L-3 Cadet transceiver can downlink at a maximum datarate of 1.5 Mbps [47].

Michigan Multipurpose Minisat’s (M-Cubed) objective is to obtain a mid resolution sole from a single CubeSat [48]. Data and commands are transmitted using the AstroDev Lithium 1 radio. A dedicated receiver will operate at all times, while the dedicated transmitter will be operated only to send a beacon signal or transmit picture data. Both receiver and transmitter are the same component, AstroDev Lithium 1s, hard-wired to their independent tasks [48].

Radio Aurora Explorer 2 (or RAX2) is a redesigned version of RAX1 to overcome to power problems that occurred in the first launch. Significant changes from RAX1 to RAX2 include seven solar cells per panel instead of eight allowing increased photo-diodes as sun-sensors. The communication sub-system is identical to RAX1 in section III-N.

Explorer 1 [PRIME] 2’s (E1P2) Geiger-Mueller Counter will send telemetry using a custom KISS protocol. Any TNC capable of operating in KISS mode can decode the beacon. The connection of a KISS TNC to the E1P Telemetry Decoder is accomplished via a serial connection. The transmitter used onboard the spacecraft has a crystal oscillator that suffers from extreme temperature fluctuations. This means that general purpose Doppler correction software used by many amateurs is unsuitable for tuning the E1P downlink. The unstable oscillator causes the downlink frequency to shift from the center frequency up to +/-12 kHz. To allow the receiving station to decode a packet, a tracking tone at 2200 Hz is downlinked. The E1P staff then wrote software for ICOM’s CI-V connection.

AubieSat-1 is a 1U CubeSat built by students of the Auburn University to demonstrate gamma ray monitoring instruments during thunderstorms at high altitudes. AubieSat-1 uses CW to downlink all data [34].

Table V lists all the upcoming CubeSats and launch statuses. Many CubeSats are demonstrating ground-breaking technologies in LEO. For example, OUFTI-1 is testing an amateur radio digital communication protocol known as D-STAR. D-STAR stand for Digital Smart Technologies for Amateur Radio.

D-STAR is a VHF/UHF/1.2 GHz digital voice and data protocol that can use an Ethernet connection at 128 kbps and a digital data and digital voice at 4.8 kbps in GMSK transmission. To improve these protocols further, a study done by Ronan concluded that adding delay tolerant networking over an AX.25 or D-star protocol [49].

Also notably for future launches, Surrey Satellite Technology Ltd has developed the Surrey Training Research and NanoSatellite Development (STRaND-1) satellite, a 3U CubeSat containing an android Nexus-1 cellphone payload to demonstrate 802.11 communications in LEO. The expected launch is in early 2012. Besides a smartphone payload, STRaND-1 will also demonstrate miniature reaction wheels for attitude control and pulse plasma thrusters [50].

Also of note, FITSAT-1 (aka NIW AKA) will be launched from the ISS Kibo module September 2012 as shown in figure 9. When launched FITSAT-1 will be the first using a 5.8 GHz band to transmit high-speed digital data at a rate of 115.2 kbps. A UHF AX.25 transceiver will be used for telemetry and telecommand purposes and a UHF CW beacon will also be provided. FITSAT-1 will be deployed along with the satellites RAIKO and WEWISH into a very low earth orbit of 350 km. The following downlink frequencies have been coordinated by the IARU Satellite Frequency Coordination Panel: CW 437.250 MHz, FM 437.445 MHz, high-speed data 5.84 GHz.

NASA Ames’ PhoneSat-V1 (version 1) is a technology demonstration mission intended to prove that a smartphone can be used to perform functions required of a
spacecraft bus. The satellite is built around the Nexus One smartphone that will be running the Android operating system and enclosed in a standard 1U CubeSat structure. The main function of the phone is to act as the onboard Computer, but the mission will also utilize the phone’s memory card for data storage, five mega-pixel camera for earth observation, and 3-axis accelerometer and 3-axis magnetometer for attitude determination. The satellite will operate on battery power only with a mission lifetime of approximately one week with a Stensat UHF (440 Mhz) downlink only using AFSK AX.25 packet. A very low earth orbit of 390 km with a launch on a Taurus II from Wallops Flight Facility is planned for early 2012. A frequency of 437.425 MHz has been coordinated.

For a commercial testing, PhoneSat V1 has been validated in a thermal-vacuum from -35°C to 40°C and on sub-orbital rocket launches up to 10 km in the summer of 2010. The source code for Autonomous Vehicle Control System (AVCS) software is licensed under the Apache 2.0 license and is made available via GitHub instead of NASA Open Source Agreement (NOSA). The hope is to stimulate an open source toolkit for CubeSat to get the hacker community involved in space.

Many future CubeSat sub-systems such as University of Florida’s SwampSat and NASA Ames’ PhoneSat V1 have been tested through high-altitude balloon (HAB) launches up to 30 km. HAB launches are a cost effective method to show semi-flight heritage without losing the entire satellite system. Balloon launches provide testing analogous to space. The balloon launches are useful long distance radio tests and simulate tumbling with a clean RF line of sight signal. The environment is operationally similar to orbital flight. Figure 10 shows a test for SwampSat communication sub-system.

IV. INTER-NETWORKING ISSUES IN SPACE

The majority of intersatellite missions discussed in section II are closer to a tape-recorded bit stream, than a packeting format for communications. However, there have been recent missions with packet communication protocol in space. In 1996, NASA JPL gave the United Kingdom’s Defense Evaluation and Research Agency’s (DERA) STRV-1b satellite an IP address, simple ping capability, and used FTP with CCSDS [51].

In 2000, NASA Goddard flew an IP stack on SSTL UoSAT12. SSTL’s UoSAT12 flew on-board 10 Mbps Ethernet and developed a High-Level Data Link Control (HDLC) for AX.25 IP stack that uploaded to the satellite later to experiment with internet communications in space. UoSAT12 had a web server in space that integrated with the Internet. Through the experiment, it was learned that the Ethernet processors drew high amounts of power so they haven’t flown since. Since UoSAT12 used standard Open Systems Interconnection (OSI) protocols, SSTL’s disaster monitoring constellation (DMC) was able to use a terrestrial Internet router with small modifications for space. Cisco systems put a Cisco router in LEO on the DMC alongside imaging payloads in 2003.

Human Internet access will require an Internet protocol because people are an unpredictable traffic generator and the Internet protocol is built to cope with unpredictable traffic. So, a Cabletron router flew on the ISS Russian module. The Russian agency experimented with a commercial product by simply making the cables more robust. The orbiting communications adapter tunnels across NASA’s TDRSS satellites. In 2001, NASA experimented with VoIP and a Cisco soft phone from Atlantis. In 2003, the Communications and Navigation Demonstration On Shuttle (CANDOS) was tested on-board Columbia. In January 2003, NASA and Space Dev launched the LEO
CHIPSat using FTP and TCP/IP. In 2007, MidSTAR-1 and CFESat launched using experiment Configurable Fault Tolerant Processors (CFTPs) and FPGAs for communications. In 2009, the Cisco Internet Routing in Space (IRIS) was launched in geostationary orbit on Intelsat-14. Still, CubeSats in the last eight years and that are planned to launch in the next two years utilize transceivers that continue to operate with the AX.25 protocol.

A. Internet Protocol Layering

The Interplanetary Internet was an effort announced in 1998 by Vint Cerf of TCP/IP fame. Vint Cerf worked with Adrian Hooke of NASA Jet Propulsion Lab (JPL) and set up CCSDS (Consultative Committee for Space Data Systems) in 1982. CCSDS is an OSI standards subgroup that sets communication standards for space environments. One challenge for the CCSDS is that satellite and spacecraft communication design predates modern computer networking. One common thread of the ISL systems in section II use a tape-recorded bit stream and not a packeting format. As a result, it is very difficult to handle and move data around a space Internet. Hook is interested in moving toward packets and networking. Given that deep has very long probation delays, a lot of terrestrial protocols such as TCP itself don’t work because they time out. Cerf and Hook collaborated and have had a public forum on how NASA should design space inter-networking.

Inside NASA JPL, the development of space protocols has been done by Scott Burleigh [52]. Burleigh developed CCSDS CFDP, the Bundle Protocol for Delay Tolerant Networking, and the Licklider transport protocols that transports the bundle. NASA carefully adopts these protocols and keeps the legacy CCSDS base because of the risk involved in space communications. CCSDS File Delivery Protocol (CFTP) is like the Bundle protocols because it layers over everything such as TCP and UDP. CFTP lite is in use by the Messenger Mercury probe and the Deep Impact comet mission (DINET) EPOXI-I [52]. There’s now a heritage of LTP with a bundle layer running over it. Licklider LTP is known as a lite version CFDP. As a result the JPL approach takes CCSDS protocols and develops over them for very long communication mission to Mars and asteroids for deep space networking. NASA has proven this approach by networking NASA rovers to relay through ESA orbiters to downlink data from Mars to earth.

Keith Hogie at NASA Goddard has an alternative engineering approach to space inter-networking. In networking, we often use OSI layers for modularity, allowing quicker development. Hogie has developed for CCSDS a number of times, and noticed that with CCSDS communication every layer must be optimized to get the most out of deep space links. CCSDS is not truly layered or modular. For example, if introducing turbo coding or LDPC in the lower physical layer in the CCSDS stack, the framing changes. So, framing and everything all the way up the stack would need reimplemented. So, an alternative approach is to use commercial standards particularly IP over standard frame relay over ISO standard HDLC (serial/HDLC/FR/IP). AX.25 runs over HDLC as well. Hogie demonstrated this first in Uosat-12 and then CANDOS Columbia mission in the payload bay. Also, HDLC can be layered over the CCSDS, where CCSDS is treated as the channel. As a result, CCSDS and a layer stack can be complimentary [53].

The modular approach is not as optimized but could work when engineering development resources are not available, particularly at the university level. For a university CubeSat project, using network IP layers makes sense because a CubeSat is looked at as educational open source tool. Universities would naturally like to redevelop small areas of stack layers for every subsequent launch. Second, most of the stacks would already be simulated and developed, so layers could be implemented faster and cheaper. Third, CubeSats would not be launched for deep space, CubeSats would be in LEO where the IP layering approach has been successfully experimented with on CANDOS, DMC, and ISS. Perhaps a CubeSat stack could be layered as S-band RF / modem / HDLC / Frame Relay / IP / UDP / DTN lite protocol for CubeSat.

B. Delay Tolerant Networking Layering

The bundle DTN protocol can compliment the CCSDS deep space protocol and near-earth orbit commercial protocol stack layers as a layer that runs over both. The DTN layer may do what the Internet did in the 1970s by layering over all networks by ignoring the properties of the lower layer and sitting on top. IP is very useful in operational use in space networks because its understood, implemented, and reusable. The DMC used IP on the ground stations and in orbit. However, due to asymmetric links and different transport layer like UDP should replace TCP. As a NASA DTN/IP debate progressed, it was decided that there room for both IP and DTN, so it is a matter of finding the best solution for the application [53]. Some problems with DTN bundling have been learned from experiments in space. First, if the communication system does not implement the optional bundle protocol security suite, there is no error detection at all. If you do, everything is considered an attack. This is a reliability issue because there is no error detection, and reusing security to give reliability is not ideal.

Also, it was decided that every spacecraft should have a clock and that clock should resynchronize with the ground. However, bundles are set with expiring times meaning when the bundle arrives with a missed set clock the bundle agent would drop the entire bundle. If the spacecraft has an incorrect time, the protocol cannot make a time correction because the spacecraft’s clock is in the past. In addition, every bundle agent is expected to know current UTC. This has limits in space because the spacecraft clocks drift with temperature. Synchronization is a problem. Bundles can be dropped when expiring.
C. Radio Frequency Allocation

The majority of CubeSat projects in last eight years and that are planned to launch in the next two years still utilize transceivers and beacons that continue to downlink on the UHF band and utilize the AX.25 protocol with no inter-satellite links. A smaller fraction do plan to operate at frequencies up to 5.8 GHz and as low as 145 MHz.

In the near future, CubeSat programs could use higher frequencies in either the C-Band or X-Band and further reduce the size and mass of the transceiver and the antenna and gain additional bandwidth to support payloads that have a significant data downlink requirement. The designers would have to consider the utility of additional bandwidth and decreased size and weight against increased power requirements to close the link with the ground station as the energy-per-bit is decreased for the same power consumption. As CubeSat power generation systems become more effective and the satellites achieve three-axis stability, higher operating frequencies become increasingly feasible while permitting smaller components and increased antenna gain. However, designers must account for the increased gain trade off with beamwidth. In which case, a highly precise pointing mechanism in the attitude determination control systems would be required [54]. With this new technology an update to the AX.25 protocol is needed to further CubeSat mission capability such as mission needing clusters or constellations.

D. Optical Communications

Larger optical communication payloads have been tested and proved in Artemis, Spot-4, Envisat, Adeos-II, OICETS, Kodama, DAICHI, and SDS-1 at extremely high wireless data rates. However, the technology has not fit in the CubeSat form [55]. However, NASA has recently invested in demonstration of a small optical modem technology for small satellites. Since optical links can be easily blocked by cloud coverage that makes ISLs in the optical spectrum even more important. Thus, combining an optical intersatellite links between small LEO spacecraft with larger geosynchronous relays even more advantageous. The first step would be to produce a prototype to demonstrate that this technology could be packaged for the CubeSat platform. A first step is planned for NASA’s Laser Communication Relay demonstration. The mission is to determine if a reliable, cost-effective optical transceiver can be built with a similar mass and power as an RF system.

High-rate communications could revolutionize space science and exploration. Space laser communications could enable applications that need high bandwidth such as imaging. The data throughput goal for the optical downlink is 100 Mbps. To compare, data from the Mars orbiter is sent back at a rate of 6 Mbps.

E. Application and Orbital Properties

Many conclusions can be drawn from analyzing large ISL systems application and orbital properties. First, a satellite application dictates a constellation’s specific topology design. Geosynchronous systems such as TDRSS, Lach, DRTS, and ESA’s relay have made used of linking LEO spacecraft such as Hubble, Space Shuttle and ISS. CubeSats have always been launched for LEOs. As an LEO spacecraft, a CubeSat may pass over a ground station ten minutes at a time, three times in 24 hours at best. Linking to a geosynchronous point could provide nearly round-the-clock communication coverage.

Figure 11. Diagram of the 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. [56]

In some cases, multiple candidate constellation types may be appropriate for the same task. Traditionally, to minimize deployment cost, the constellation types were 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) should become a criterion for constellation selection. For example, a net topology study was done simulating two LEO constellation types, the flower constellation and the sun-synchronous repeating ground track (SSRGT) constellation shown in figure 11, both of which are appropriate for earth observation [56].

V. Conclusion and Future Work

This article surveyed every intersatellite linking system launched analyzing the frequency, protocol, application and orbit in section II. One common thread was that every ISL system transmitted bit streams forwarded by dummy relays satellites instead of packets routed by cognitive nodal satellites. Another commonality was that these large satellite systems have historical needed an extremely high financial budget for a limited amount of relay points. However, the advent of the CubeSat platform could provide a financially feasible network of many LEO nodes to support future satellite constellations. So,
section III describes the frequency, protocol, application, orbit and communication subsystems used for all past and near future CubeSat launches. The section concludes that most CubeSat systems use the amateur band UHF/VHF frequencies with AX.25 or CW protocols. However, many CubeSats are experimenting with higher data-rates and proprietary protocols in the s-band. So, section IV examined the history of space inter-networking protocols and open research issues such as internet protocol layering, delay tolerant networking layering, radio frequency allocation, optical communications, applications, and orbital properties.

For future work, NASA and CCSDS will continue to develop the Internet protocol layer for space. The Wireless and Mobile Systems (WAMS) lab at the University of Florida is supporting NASA’s efforts for delay tolerant network layering of small satellites. Also a Center for High-performance and Reconfigurable Computing (CHREC) is designing a fault-tolerant FPGA ability for reconfigurable cognitive small-satellite nodes. Last, the Space Systems Group (SSG) is building a prototype control moment gyroscope system to precisely point a CubeSat in a particular direction with an accuracy of 1°. Addressing these issues allows us to reach the goal of a next generation intersatellite-linking constellation supported by CubeSat platform satellites.

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