… CubeSat Networks …

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Abbreviations

LEO	Low Earth Orbit
SMB	Small to Medium Business
COTS	Commercial Off-The-Shelf
ADCS	Attitude Determination and Control Sub-systems
C&DH	Command And Data Handling
ISS	International Space Station
CSN	CubeSat Network
NASA	National Aeronautics and Space Administration
EDSN	Edison Demonstration of Smallsat Networks
CNSA	China National Space Administration
S2G	Space To Ground
WSN	Wireless Sensor Network
MANET	Mobile Ad-hoc Network
ISC	Inter-Satellite Communication

Chapter 1: Introduction

In this chapter the details of the general background and motivation for this project are provided. The content herein is intended to provide a brief overview of the CubeSats and inter-CubeSat communications. The core objectives of this work and the general structure of this document are also covered.

1.1 Background

Due to prohibitive costs and technical requirements access to low Earth orbit (160 – 2,000km) (LEO) has typically been restricted to military, government and large corporate institutions [1]. Over the past decade, two factors have disrupted the status quo and opened access to LEO for academic intuitions and SMBs alike. The first factor is the private space race. Renewed competition has caused a dramatic drop in the "unit cost to LEO", which refers to the cost of launching one kilogram to LEO. In 2001 the NASA's Space Transport System's space shuttle unit cost to LEO was approximately $60,000, with a fully loaded cargo bay. Today, thanks in large part to the competitive prices of SpaceX, the minimum unit cost to LEO is in the region of $4,000 [2].

The second, and perhaps most influential factor, is the induction of new small satellites classifications such as the 'Micro', 'Nano', 'Pico' and 'Femto' classes. This work focuses on the capabilities and applications of CubeSats which, almost always, fall into the Nanosatellite (NanoSat) class. NanoSats have a wet mass of between 1kg and 10kg. The wet mass refers to the mass of the satellite along with the mass of the propellant required to 'lift' the satellite to its desired orbit. Like almost all satellites, the form factor of NanoSats is tailored to match the utilized launch vehicle. However, unlike many other classes, an open 'CubeSat' standard for NanoSats has been developing and gaining popularity over the past decade [3]. There is considerable open-sourcing of the design and implementation of CubeSat components. Such open-sourcing is historically rare in the satellite industry.

CubeSats, as the name suggests, adopt a cube form factor. Each Cube, often referred to as a 'unit', is 10cm to a side. Multiple units are often combined in order to form larger CubeSat. Six unit configurations are typically the largest form factor used [4, 5]. CubeSats are generally constructed solely of commercial off-the-shelf components (COTS) components instead of those designed specifically for the extremes of space environments. Single unit CubeSats have been shown capable of containing many of the standard sub-systems that one may find on larger class satellites such as: orbital control [6], attitude determination and control (ADCS) [7], communications [8-10], command and data handling (C&DH) [11, 12], power management and so on. Along with several sub-systems, a CubeSat may carry a small 'payload' which is often a scientific instrument or some previously 'unflown' implementation of a sub-system such as an experimental antenna [13]. CubeSats have become increasingly popular with the space industry both for testing new technologies and for commercial applications. However, the primary applications for CubeSats remain within the educational and academic domain [14].

What gives CubeSats, and other small satellites, an advantage over other larger satellites is their ability to ‘hitch’ a ride alongside larger launch payloads. Effectively all modern launch payloads are designed to match the capabilities of the launch vehicle. Frequently, launch vehicles will have some spare volume and lift capacity. Multiple CubeSat launchers have been developed which make use of this spare volume and lift capacity [15, 16]. In cases where cargo and/or personnel are being delivered to the ISS for instance, CubeSats often hitch a ride. These CubeSats are then launched from the ISS’s dedicated CubeSat launcher.

As a result of the lowering unit costs to LEO and the increasing affordability, availability and capabilities of CubeSat components, CubeSat mission have become increasing ambitious [17-19]. This project focuses on a particular subset of emerging CubeSat missions which involve networked swarms of CubeSats; these will simply be referred to as CubeSat networks (CSNs). The multi-CubeSat missions offer greater redundancy which addresses the platform’s limited power and durability. Missions which involve CSNs seek to advance the platform by introducing varying degrees of autonomous cooperation and coordination between CubeSats. It is this cooperation and coordination that presents various new CubeSat mission applications. CSNs stand to enable the collection of greater volumes of scientific data, novel interferometry [20], high fidelity sensory data, inexpensive low-data rate terrestrial communications and improved air traffic monitoring [21]. The space industry has taken the first crucial steps into designing and testing CSNs with missions such as NASA’s EDSN (Edison Demonstration of

Smallsat Networks) [22] and Nodes (Network & Operation Demonstration Satellites) [12] and the CNSA's Tianwang-1 [23].

This work seeks to build upon data from the aforementioned missions. The overall aim being the exploration of certain fundamental aspects of the communication approaches employed in CSNs. In particular, this work attempts to identify how CSN based missions may approach communication in order to optimize space to ground (S2G) data throughput while remaining sensitive to CubeSat power consumption.

1.2 Objectives

CSNs share many similarities with terrestrial concepts such as wireless sensor networks (WSNs) and mobile ad-hoc networks (MANETs). The state of the art in CSNs has its basis in work in these fields. However, much of the existing work relating to CSNs was published prior the design and launch of the first CSN. As a result, authors were often forced to make several assumptions as to the capabilities and constraints of CSNs.

The general motivation of this work is to assess CSN network and MAC layer protocol design. This assessment requires the analysis of existing work relating to WSNs, MANETs, CSNs, and the design and implementation of CubeSat missions. As mentioned, there are numerous varied applications of CSNs. As such, this work narrows the scope of interest to a generic and common scientific mission. This chosen mission employs a number of CubeSats each of which carries an identical scientific instrument. This scientific instrument produces some data which must be communicated to ground. It is then objective of the CSN to coordinate in order to efficiently route this data to ground. For the scientist on the ground the core concern is the quality and the quantity of the data received. It is assumed that issues relating to data quality are fully addressed. This leaves the quantity of data received as the metric for success for this hypothetical mission. With this the core objective of this work becomes the exploration CSN protocol design in order to maximize S2G data throughput.

In terms of power, satellite-to-satellite S2S is generally considerably less expensive than S2G communication. S2S data rates are more likely to lie within the region of Mbps whereas S2G data rates are frequently as low as 12kbps. These imbalances present an optimization problem. Increasing the amount of S2G communication will increase S2G throughput but, it will also consume more battery overall and reduce the mission's lifetime. S2S may be used to communicate data to a CubeSat which has more battery power and/or a better window of opportunity for S2G communications. Of course, too much S2S communication may prove wasteful when all CubeSats have enough battery and suitable S2G communication windows. Any solutions proposed by this work intend to address the challenges arising from balancing power consumption with S2G throughput.

This work presents simulations, carried out using OMNeT++ [24], of modified communications protocols. These protocols were chosen and implemented with consideration to the aforementioned power v. throughput challenge. As far as possible, CubeSat S2G and S2S communication as well as power consumption characteristics are modelled on the current state of the art.

1.3 Thesis Structure

This document is divided into six chapters. The Introduction chapter offers a basic overview of the background of the project and the motivations and objectives thereof. This chapter aims to provide suitable material for lay-readers to understand the context and general scope of the project.

The State of the Art chapter …

The Proposed Protocols chapter …

The Simulations chapter …

The Results chapter …

Finally the Conclusions chapter …

Chapter 2: State of the Art

The major literature informing this work can be roughly divided into three broad categories: terrestrial communications, CubeSat communications and CSN missions. Along with these categories this chapter provides an in-depth exploration into the CubeSat platform. This exploration is followed by a section detailing relevant terrestrial communication technologies, which focuses on Wireless Sensor Networks (WSNs) and Mobile Ad-Hoc Networks (MANETs). Such terrestrial technology is important context for the following section on CubeSat communications. This section seeks to examine CubeSat communications within the context of the previous sections.

This chapter concludes by examining several relevant missions. In many cases these missions provide a sanity check for preceding sections. In particular, the challenges of launching and operating space craft in LEO provide crucial context to prior art detailing CubeSat communications. Finally several notable secondary areas of research are highlighted. These areas fall outside of the scope of this work but are nonetheless influential in the greater context of space-bound communications.

2.1 CubeSats

CubeSats typically fall within the satellite weight classification of 'Nano' satellites (1-10kg). CubeSats are further classified by the number of 'units' which they contain, where a unit is a 10cm cube. A one unit CubeSat is referred to as a '1U'. Configurations of 2U, 2.5U, 3U and 6U are all common.

CubeSats were first proposed by Bob Twiggs of Stanford University and Jordi Puig-Suari of California Polytechnic State University in 1999 [25]. In 2000 the first published work detailing a new CubeSat standard was published [25]. The platform was intended as an answer to the prohibitive costs and challenges involved in low-resource academic satellite development. At the time, there were effectively no standard approaches or components for the design and implementation of small satellites. Researchers relied almost entirely on acquiring a place for instruments on larger satellites or pursuing the development of research satellites as lengthy collaborations across multiple research institutions. Frequently, research only required satellites with basic capabilities.

2003 saw the first launch of a CubeSat on-board a Russian Eurorockot [24]. At the time of writing there have been 487 CubeSats launched [26] since 2003. Spread across 14 years this number may seem unimpressive however, approximately 75% of all these launches have taken place during the previous 5 years. This is due almost entirely to the recent boom in the private space industry which has greatly lowered the cost of access to LEO [1].

Thanks in large part to a San Francisco based company named Planet Labs [27], roughly 40% of all launched CubeSats were developed by commercial entities. Comparatively, academic/research institutions have developed approx. 40% and the remaining 20% is divided between civilian and military institutions. In terms of use cases, roughly 60% of all missions are dedicated to Earth imaging, 20% to technology demonstration, 10% to education, and the remaining 10% is divided between various commercial, military and science applications [26].

Unsurprisingly, the core motivation behind the recent popularity of CubeSats is their cost. Costs are driven down by three factors, the use of COTS components, open sourcing, and reduced launch costs. Effectively every component of a modern CubeSat is available in COTS form. Retailers such as Clyde Space offer a wide range of products from power to attitude determination and control systems [28]. COTS components reduce costs significantly by removing the need to develop or source custom components from third parties.

Combined with COTS components open sourcing lowers costs further by reducing development time and the need for expertize. Open and often proven approaches for both soft and hard CubeSat systems are becoming widespread as the platform develops [3]. Although this may seem intuitive, such sharing and open-sourcing of work in the satellite industry has been historically rare. To date, there is no accepted standards body for the domain. Researchers such as Puig-Suari at the California Polytechnic State University (CalPoly) have driven the domain forward since its inception, creating a number of pseudo-standards. Crucially, CalPoly lead the development and design of standard CubeSat deployers [29]. Such deployers became common place have come to defined the de-facto standards for the domain. A similar pattern can be seen elsewhere in the domain such as with the development of a pseudo-standard satellite bus design [30]. Recently, "OpenOrbiter" by Straub et. al from the University of North Dakota is a prime example of open pseudo-standard framework for CubeSat development [31].

Depending on the complexity of the CubeSat, development costs may range anywhere from $50,000 to $250,000 [32]. This can be compared to a development cost in the order of millions of dollars for larger satellites weighing over 100kg. A similar gap has emerged in terms of launch costs. Satellites over 100kg may see launch costs in the order of hundreds of thousands if not millions of dollars, depending on the launch vehicle and orbital requirements. CubeSats avoid these costs by 'hitching' a ride alongside larger payloads using volume and lift capacity not required by primary or secondary payloads. Providers such as SpaceX have disruptive the satellite industry further by offering greatly reduced cost access to LEO [33]. These factors have led to CubeSat launch costs as low as $10,000 [32]. With recent development towards multi-CubeSat and CSN mission, multiple CubeSats may take the place of their larger counterparts at a fraction of the cost. CubeSats are also making the move beyond LEO with new developments towards deep space and lunar applications [16, 18].

2.1.1 Capabilities

This section provides an overview of the state of the art technical capabilities of CubeSats. In line with this work's objectives, a focus is placed on technologies relating to communication and power. This section aims to provide context to the upcoming sections on terrestrial and CubeSat communications. In many cases, there is a need to reality check potential communications strategies with the current and emerging capabilities of the CubeSat platform.

2.1.1.1 Space-to-Ground Communication Systems

There is considerable variance in the implementation of S2G CubeSat communication sub-systems. The choice of and design of a system is application dependent however there are some broad patterns worth noting. For instance, the most common protocol for S2G communications is AX.25 [34]. Implementations using AX.25 at the link layer generally utilize a flavour of UDP/IP at higher protocol layers. CubeSat S2G communications sub-systems typically consume between 1W to 3W of power during transmission and can achieve data rates between 9.6kbps and 12kbps when using AX.25 [35].

There are some notable outliers to the trends in CubeSat S2G commutations which have considerably advanced domain. In particular, NASA's Dynamic Ionosphere CubeSat Experiment (DICE) mission achieved a remarkable S2G maximum data rate of 3Mbps [36]. Such rates were achieved using a custom SDR based sub-system consuming roughly 9W and operating within the UHF band. The DICE mission holds the record for the highest S2G data rate achieved by a CubeSat. At present there are few missions that attempt a downlink rates in the order of Mbps, with the notable exception of JPL's ISARA mission [37]. The majority of upcoming missions aim to achieve communication rates in the order of hundreds of kbps.

In order to approach protocol design for the throughput v. power consumption problem, 'baseline' state of the art S2G characteristics were chosen. One of the primary inspirations for the work was the CNSA's Tianwang-1 (TW-1) mission [38]. This mission is an ideal candidate to use as a baseline for S2G communication modelling as the mission was designed specifically to test CubeSat intercommunications. As such, it is representative of the capabilities future CSN missions may achieve. TW-1 achieved S2G data rates of 125kbps. Details regarding the power consumption of the TW-1 S2G sub-systems are unavailable. However, by examining previous and upcoming missions as well as work on energy budget analysis [39] one may safely assume a peak transmission power consumption of 3W.

2.1.1.2 Satellite-to-Satellite Communication Systems

S2S communications is by no means a new concept. CubeSat based S2S communication began to gain popularity following a paper published in 2008 on the “Development of a Satellite Sensor Network for Future Space Missions” by Vladimirova et. al. CubeSat S2S communication remained purely conceptual until 2016 that the NASA Nodes mission made it a reality [12].

Unlike the case of S2G communications there is little prior art regarding the S2S capabilities of CubeSats. This is unsurprising considering the age of the domain. There are effectively two cases which inform the state of the art S2S capabilities of CubeSats: The NASA’s Nodes mission and Gamalink [40]. Comparatively, Gamalink is considerably more advanced than the systems employed on the Nodes mission. Nodes utilized a UHF transceiver and the AX.25 protocol to achieve S2S data rates of 1.2kps. As Nodes was a first in many regards it is unsurprising that the mission designers opted for a well-known and basic approaches to CubeSat communications.

Gamalink is a proprietary SDR based technology developed by a Portuguese Aerospace and Defence company by the name of Tekever. Gamalink is unquestionably the current state of the art in CubeSat S2S communications. Gamalink has been successfully tested on the TW-1 mission [23] it is also marked for use by several other missions such as i-INSPIRE II [41], DelFFi [42] and ESA's Proba 3 [43].

Due to the Gamalink's proprietary nature and its potential military applications details regarding Gamalink are exceptionally sparse. During research no information regarding protocol use or design was available. Tekever make several allusions to MANETs even stating that Gamalink implements an "SDR-based Ad hoc Space Network" (SASNET). This is a clear indication that the state of the art in MANET technology is integral to the design and development of Gamalink.

Despite the lack of protocol stack information, several key data points regarding Gamalink are available. According to promotional material presented to ESA Gamalink is capable of achieving data rates up to 2Mbps however, i-INSPIRE mission designers state that the maximum data rate as 1Mbps [41]. Gamalink operates in the S-Band (2.40-2.45 GHz) with a bandwidth of 40Mhz, making the Mbps scale data rates believable. While transmitting Gamalink consumes up to 1.5W and while receiving up to 200mW [42]. Using these details and assuming a maximum data rate of 2Mbps, a state of the art baseline can be established for CubeSat S2S communications to be used alongside the S2G baseline.

2.1.1.3 Other Capabilities

Although the primary relevant CubeSat capabilities have been covered in the preceding sections, there are certain other capabilities worth discussing in brief. In general, the capabilities of CubeSats have progressed closer and closer to those of larger satellites. Despite strict power, weight and size constraints effectively all major large satellite sub-systems have a corresponding, scaled down, CubeSat equivalent.

Attitude determination and control sub-systems (ADCS) are implemented to ensure correct spacecraft orientation. ADCS are critical to insuring correctly positioned solar panel, antennae and or payload instruments. In almost all cases craft will also be required to 'de-tumble' prior to launch. There are numerous tested examples of ADCS technologies for CubeSats [7, 44, 45] including several which are available COTS. Along with ADCS some basic orbital control and manoeuvrability systems have also been tested at the CubeSat scale [6]. Such systems provide CubeSats with the basic capabilities to maintain regular orbits and formations.

Determining accurate time and position are two classic challenges for spacecraft that have been long solved in the domain of CubeSats. By communicating with larger satellites within the Global Navigation Satellite System (GNSS) CubeSat may acquire precise GPS time and position. CubeSat missions often regularly update such information in order to coordinate in-orbit operations and S2G communications. One work by Glennon et al. entitled "Synchronization and syntonization of formation flying CubeSats using the namuru V3. 2 spaceborne

GPS receiver" provides a clear overview of necessary CubeSat capabilities within multi-CubeSat missions [46].

Finally, it is worth noting that the aforementioned Gamalink technology provides functionality beyond that of S2S communications. Gamalink also provides the secondary functions of GNSS receiving, attitude determination, ranging (5m resolution) and distributed clock synchronization.

2.1.2 Applications

This section examines a number of CubeSat missions. References to CubeSat 'applications' should be considered synonymous with CubeSat's mission objectives. Two categories of application are considered, sensing missions and CubeSat network missions. This is not intended to assert that sensing missions and CSN missions are disjoint. CSN missions are highly suited to collaborative sensing applications and may, within the context of this work, be consider to be a class of specialized sensing application.

2.1.2.1 Sensing Missions

When approaching the challenges relating to balancing S2G throughput with energy consumption, it is beneficial to establish a broad application case. As discussed, Earth observation is the most popular application of CubeSats to date. More generally, the majority of CubeSat missions have involved, to varying extents, some form of sensing. The application case chosen by this work is a simplified CubeSat mission involving a number of CubeSats. Each CubeSat is assumed to carry some sensing instrument. This instrument is considered to be a black box which performs some sensing and produces some data. The goal of each CubeSat then becomes communicating as much of its data to ground as possible. This scenario is detailed further in the Simulation chapter.

Two recent sensing missions are worth detailing: 3Cat-2 [47] and RAVAN (Radiometer Assessment using Vertically Aligned Nanotubes) [48]. 3Cat-2 is 6U CubeSat developed at the Universidad Politécnica de Cataluña. It was launched in August of 2016 aboard a CZ-2D (Chang Zheng-2D) operated by the CNSA. 3Cat-2 represents a significant mission in the state of the art for Earth Observation missions. It's extensive use of GNSS based systems make it an interesting case for the application of CSNs. Also, 3Cat-2's S2G downlink operates at a maximum of 115kps. Recall that this is a similar rate as achieved by the Tianwang-1 mission which forms the basis for this work's chosen model for S2G communications.

3Cat-2's particular application case is ocean altimetry by means of GNSS-Reflectometry. 3Cat-2 performs altitude observations by examining the scattering and reflection of signals off of bodies of water. These are an 'active' form of measurement which depend on incident signals; RADAR is another example of an active sensing.

Mission developers of 3Cat-2 have not stated a direct desire to pursue a multi-CubeSat mission. However, 3Cat-2's active sensing is uniquely suited to a CSN adaptation. Coordinated and synchronized measurement of signals by multiple craft in orbit could greatly improve observation fidelity and provide unique multi-dimensional data. Comparatively, 'passive' EO such as direct imaging benefits less from adaptation with CSNs.

RAVAN is a 3U CubeSat developed at the Johns Hopkins Applied Physics Laboratory. RAVAN was launched November of 2016 aboard an Atlas-5 as part of NASA's ELaNa (Educational Launch of Nanosatellites) program. RAVAN is highly relevant to this work as the mission designers clearly specify future intentions to develop a constellation of RAVAN craft. In satellite nomenclature a constellation is considered a formation of satellites evenly distributed over the surface of the Earth. In this work we treat the physical formation of craft as unimportant.

RAVAN carries an experimental carbon nanotube based radiometer. RAVAN's instrument performs multi-spectral measurements of outgoing radiation from Earth's surface. These measurements reveal trends regarding Earth's Radiation Budget (ERI) which are valuable to climate scientists. As mentioned, RAVAN is intended as a first test in a larger plan to develop a constellation of craft [49]. The spacing of the forty proposed RAVAN craft which would make S2S communication infeasible using current technologies. Nonetheless, RAVAN is strong example of the growing interest in multi-CubeSat missions.

It should be noted that CubeSat sensing is a deep and broad field. The examples of RAVAN and 3Cat-2 are in no way intended to illustrate a comprehensive study of the field. Notable upcoming missions such as CeREs (a Compact Radiation belt Explorer) [50], LAICE (Lower Atmosphere/Ionosphere Coupling Experiment) [51], and SOCON (Sustained Ocean Observation from Nanosatellites) [52] seek to advance the diverse applications of CubeSat mission. In several regards, it is these advanced applications that drive interest in CSN style missions. As applications develop so too does interest in advancements such as multi-point measurements, in-orbit interferometry [53] and synchronized observation. These advances call for the introduction of CSNs. CSNs are, in many regards, an obvious next step in the development of CubeSat sensing missions.

2.1.2.2 CubeSat Network Missions

There are three major missions to consider in the area of CSNs: NASA's EDSN and Nodes, and CNSA's Tianwang-1 (TW-1). Of these missions, both Nodes and TW-1 have successfully flown. The eight CubeSat "Edison Demonstration of Smallsat Networks" (EDSN) mission was lost due to a failure during launch. The mission is still worth examining however as two of the remaining EDSN craft we used during the successful Nodes missions.

Two articles detailing the EDSN mission were published in 2014 prior to the loss of the mission in November 2015. The first work examines the inter-satellite communications architecture of the mission [54]. While the second work details lessons learned during development [55]. The primary objective of the EDSN mission was to implement autonomous communication and coordination of CubeSat's in orbit. Each ESDN craft is a 1.5U CubeSat weighing ~1.73kg. A Samsung smartphone provides each craft's activity scheduling and execution. Several secondary COTS micro-controllers handle various activities involving GNSS, data handling, scientific measurments, ADCS and additional sensor inputs. The scientific payload is an instrument designed to characterize radiation in LEO called the "Energetic Particle Integrating Space Environment Monitor" (EPISEM). Although the scientific objectives of the mission were secondary to the implementation of an in-orbit CubeSat network, it is clear that EDSN falls within the category of sensing applications and is not entirely dissimilar to the RAVAN mission.

In terms of communications and power, the works published on EDSN provide a wealth of information. These works go as far as to state exactly which COTS components were used in the construction of EDSN craft. Each craft houses three primary radios: A MicroHard MHX2420 transceiver for S-Band S2G communication, an AstroDev Lithium 1 UHF transceiver for S2S communication and a StenSat UHF transmitter for beaconing. Satellite beaconing is required by the North American Aerospace Defense Command (NORAD). The AstroDev transceiver enables a 9.6kbps S2S communications using AX.25 as the link layer protocol. The Nodes mission scaled this data rate back to 1.2kbps, potentially to increase the maximum S2S communication range. Details regarding the MHX2420's S2G data rate are not provided.

Each EDSN craft carries four lithium ion batteries which combine to provide a maximum energy storage of 5.2 amp hours. The craft's bus operates at around 8 volts. This implies a total energy provision of approx. 41.6 watt hours. Six solar panels provide an average recharge of 1 watt during operation. These figures provide important context to the power consumption simulation results discussed in later chapters.

As mentioned EDSN employs AX.25 at the link layer for S2S communication. The link layer, as detailed by the OSI reference model [56], is concerned primarily with medium access control (MAC). For the majority of CubeSat missions, AX.25 along with a basic application layer which communicates directly with the link layer is sufficient for S2G communication [35]. However, S2S communication introduces new challenges which warrant more complex approaches. In the case of EDSN a custom “Captain – Lieutenant” (Cpt/Lt) protocol was designed on top of AX.25. T

he network formed by the EDSN craft is referred to as a “hub-and-spoke” (or star) network. Once craft is designated as the “Captain” (Cpt) and all others are designated as “Lieutenants” (Lts). In general terms the Cpt acts as a central router to ground. All Lts send their data exclusively to the Cpt. The Cpt then communicates as much of this data to ground as possible. Lt communication in EDSN purely is reactive. The Cpt sends six pings over 50s seconds. Each set of pings specifies only one Lt from which the Cpt is requesting data. Only after receiving a valid ping does an Lt forward its data to the Cpt. This scheme of Cpt request followed by Lt response suggests no overlapping Lt on the shared S2S frequency thus greatly reducing the possibility of collisions.

There is no acknowledgment scheme employed in EDSN’s Cpt/Lt protocol. Lts send one “state-of-health” (SOH) packet followed by all queued science packets. The Cpt prioritizes the communication of these SOH packets to ground and treats science packets generated by Lts or by its own instrument in a LIFO manner. After ending a communication with an Lt, the Cpt will then proceed to ping each remaining Lt in a fixed order. The Cpt will wait up to four minutes for a response from a pinged Lt before moving onto pinging the next Lt.

The Cpt role is “rotated” amongst the EDSN craft in a pre-defined fixed pattern. There is no real-time logic or election employed. Each craft periodically receives GPS time in order to determine whose turn it is to assume the role of Cpt. If a craft cannot get GPS time it does not participate in either S2S or S2G communications. The duration a craft holds the Cpt role is referred to as a “minor cycle”. Each minor cycle lasts roughly 25 hours and includes 3-4 S2S sessions. Each session being an attempt by the Cpt to communicate with each Lt in the network. The Cpt self-determines one, and only one, S2G session during its minor cycle. This session is scheduling by predicting the next ground station fly-over period (window) based on the craft’s GPS location and velocity data. As S2G communication occurs using a separate radio at a separate frequency to S2S communication, S2G sessions can take place in parallel with an S2S session. Eight minor cycles, one for each craft, come together to form a major cycle. A major cycle lasts for roughly eight days. EDSN mission planners predicted that after three major cycles (three and one half weeks) the craft would have drifted too far apart (>120km) for S2S communication to be feasible.

During a minor cycle it is not feasible for all Lts to keep they S2S transceivers continually on and in receiver mode. As such, along with the Cpt pinging scheme, all S2S sessions are scheduled. An Lt will only turn start listening for Cpt pings at a predetermined time during each minor cycle. During a minor cycle each craft updates it’s GPS time, position and velocity only once. Mission designers predict the maximum relative clock drift between an Lt and the Cpt to be 12 seconds. As such, an Lt will begin listening for Cpt pings 30 seconds before the scheduled time and will continues listening 30 seconds after the expected final, sixth, ping. Each session start time is determined by a table of offsets. This offsets are relative to the start times of each minor cycle. Each craft is pre-programmed with the same minor-cycle start times and offset tables.

Following directly from the work on EDSN, the Nodes mission was successfully deployed from the ISS in May of 2016. Nodes included two leftover CubeSat's from the EDSN mission which were used during the testing and development of EDSN. Effectively all aforementioned salient aspects of the EDSN mission remain. Despite only involving two craft, Nodes was able to achieve many of the objectives of EDSN. Nodes makes small changes to mission objectives and some notable changes to the custom Cpt/Lt communication protocol. These changes are detailed in a work published in 2016 following the mission's successful launch, deployment and conclusion [12].

Where EDSN was focus purely on S2G communication, Nodes advances one step further by introducing a demonstration of G2S remote commands. In Nodes, the objective was set to communicate a command to the elected Cpt. The Cpt would could then forward this command to the Lt for execution. Unlike with science and state-of-health packets, command packets are implement specialized command acknowledgements and responses. Although this work focuses purely on S2G communications, it is worth noting that Nodes was the first demonstration of indirect command and control using only CubeSats.

There are several notable changes made in Nodes to the Cpt/Lt protocol. Firstly, 12 pings over 110 seconds are used rather than 6 pings over 50 seconds. Rather than a fixed order of minor-cycles, the captaincy is negotiated between the Nodes craft. A default Cpt craft compares metrics relating to battery voltage, amount of science data collected and the predicated duration of the next pass over the ground station. At the start of each minor cycle a default Cpt is selected which manages the negotiation. Once the default Cpt has compared its own metrics with that of the Lt it will either continue as Cpt or send a "promote" command to the Lt. The default Cpt will demote itself to the Lt role once the promote command has been acknowledged. As before, the Cpt will continue operations regardless of the presence of any communication with the Lt. All other aspects of the Cpt/Lt protocol are unchanged.

Over the course of its three week mission, Nodes completed and/or exceeded all five of its mission objectives: The collection and receipt of five 'sets' of science data, five successfully S2G sessions, one successfully executed indirect command, two successful captaincy negotiations and the collection and receipt of 20 days of spacecraft state-of-health. Of a total 470 science packets generated (science undisclosed) a total of 356 were successfully received at ground, ~25% packet loss. Five successful negotiations were carried out and 165 commands were executed by Nodes craft. Following the success of Nodes, mission designer clearly lay out numerous desirable enhancements: improved clock synchronization, inter-sat ranging, multi-hop routing, further acknowledge systems and/or delay tolerant networking principles, multiple ground stations and the interlinking of multiple Cpts to form clusters of clusters. Several of these suggested areas of future work are addressed in the protocols proposed and simulated in this work.

The CNSA's Tianwang-1 (TW1) mission, also referred to as STU-2, was a three CubeSat CSN mission involving numerous commercial and academic entities lead by the Shanghai Engineering Centre for Microsatellites (SECM). The majority of the published work relating to TW1 details its ADCS and novel propulsion systems [44, 57]. A presentation by Wu et al. during the 30th Annual AIAA/USU Conference on Small Satellite in 2016 offered a brief overview of the mission's

Gamalink communication system [38]. However, as discussed, the details of the proprietary Gamalink technology are closely guarded. For known details on Gamalink see the preceding "Satellite-to-Satellite Communication Systems" sub-section. In comparison to EDSN and Nodes there is little information available regarding TW-1.

TW-1 was launched in late September of 2016 three months after the deployment from the ISS of the Nodes mission. TW-1 was, like Nodes, was primary a technology demonstration mission. TW-1's objectives were to flight test Gamalink, an ADCS and a propulsion (orbital control) system. TW-1 consisted of one 3U Cubesat (TW-1A) and two 2U satellites (TW-1B/C). TW-1A housed the experimental propulsion systems. This propulsion system allowed TW-1A to remain within range of TW-1B for a time far longer than would have been possible with an uncontrolled orbit. TW-1 collected data on aircraft flight patterns using an on-board Automatic Dependent Surveillance (ADS) receiver. TW-1 also performed earth observation by using visual spectrum cameras to image polar regions. In line with its objective, TW-1 performed a number of in-orbit tests on its experimentation sub-systems. S2G communication of the mission's various results was demonstrated at a rate of 125kbps, far beyond the rates achieved by Nodes. Apart from this figure, there is effectively no further relevant published information regarding TW-1's energy or communication capabilities.

There are several other missions, besides EDSN, Nodes, and TW-1, that can provide insight into the state of the art of CSNs: ESA's AIM COPINS [58], GomX-4 [59, 60] and Proba-3 [43], NASA's CPOD [61] and TROPICS [62], QB50 [63] and

OLFAR [53]. With the exception of COPINS which was defunded, these missions are, at the time of writing, in development or awaiting launch.

2.2 Terrestrial Communications

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At the highest level these sub-domains are Wireless Sensor Networks (WSNs) and Mobile Ad-Hoc Networks (MANETs). Within the sub-domain of WSNs works relating to data collection, energy aware networking protocols and to a lesser extent data dissemination are of interest. MANET related works are relevant in their treatment of the mobility of network members. As such particular attention is paid to Vehicle Area Networks (VANETs) which share many of the same properties as CSNs. Like CSNs, VANETs have intermittent, potentially unpredictable access to a greater and more 'static' network . Also, the position, state and intent of network members is often be unknown prior to communication.

2.2.1 Wireless Sensor Networks

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WSN data collection is examined by Francesco et al. in their extensive survey paper of 2011 [64]. The work is particularly useful as it focuses on WSNs with mobile elements (WSN-MEs). It places a strong focus on mobility while maintaining and referencing the existing relevant state of the art in WSN routing, data collection, power management and so on. In many respects, this work by Francesco et al. represents an ideal overview of WSNs topics which are relevant to

CSNs. Complementing this work is another survey by Rault et al. published in 2014 which examines energy efficiency in WSNs [65]. The work approaches WSNs in more general terms. It's value, in a similar manner to the aforementioned survey, comes from the exploration of the many dimensions of its focus covering relevant elements across several WSN topics such as routing, duty cycling, mobility and so on.

2.2.2 Mobile Ad-Hoc Networks

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There is, as suggested by the existence of WSN-MEs, often considerable overlap between paradigms within the fields of MANETs and WSNs. This overlap is quite obvious when comparing the work of Aung et al in their review of "group mobility models for mobile ad hoc networks" [66] and the aforementioned work of Francesco et al. In general, the most discussed and active topic within MANETs is that of routing. In this regard the work of Mohseni et al. in their survey of routing protocols in MANETs [67] provides a more detailed view of many of the aspects mentioned in brief by Francesco et al.

Finally, the area of VANETs, contains many parallels to CSNs. In fact, there is a further concentration of VANETs dubbed FANETs (Flying Ad-Hoc Networks) [68]. A survey by Bekmezci et al. introduces MANETs and VANETs and in the context of both fields FANETs. The authors deal primarily with unmanned aerial vehicles (UAVs). As expected, FANETs, as described, are a sub-class of VANETs which include many of the same challenges, restriction and properties of CSNs.

2.3 CubeSat Communications

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Even before missions implementing CSNs had begun development the academic community produced several works examining the inter-communication of CubeSats. Most notably Challa and McNair of University of Florida provide extensive explorations of distributed applications implemented on CSNs [35, 69-72]. These works are somewhat out of the scope of this project as they deal more with applications running upon CSNs rather than the operation of the CSN itself. Despite this, these works provide an insight into potential future applications of CSNs .

The most relevant work in this area is the extensive survey of "Inter-Satellite Communication for Small Satellite Systems" by Radhakrishnan et al. [9]. The survey provides an overview of the state of the art as well as a roadmap for exploring numerous areas within the field. The survey focuses on the physical, data link and network layers of the OSI networking reference model [73]. The authors detail relevant prior art in these areas and provide analyses of the relevant efficacies of the various approaches. Another work involving authors of the aforementioned survey paper provides the starting point for simulations. The work examines potential optimal MAC protocol implementations for small satellite systems [74].

Although the work by Radhakrishnan et al. is by far the most relevant there are other works worth mentioning which inform the current state of the art. Wong et al., operating mainly out of NASA's Goddard Flight Center, examine a potential future for CSNs where space to ground communications are performed through relay with existing space bound communication networks [10]. This concept is explored for deep space missions in much of the preliminary development of the COPINS mission [58]. Another survey style paper on inter-satellite link for CubeSats by Budianu et al. [8] published in 2013 provides a broader overview of the field with more attention to antenna design and link budget analysis. The authors only touch briefly on networking protocols making the work less relevant in this case.

Lastly, the SDR based "Gamalink" [40] technology of Tekever is prevalent in the design of many recent missions involving CSNs and, in fact, small satellite crosslink communications in general. The technology is employed in the design of the aforementioned Tianwang-1, Proba 3, QB50 missions as well as several others. Gamalink is mentioned in several works with varying degree of relevancy to this project [42, 75-78]. The technology is unquestionably the current state of the art in "turnkey" inter-satellite communications for small satellite form factors. Unfortunately, the implementation details of Gamalink are carefully restricted, perhaps to protect IP but also perhaps the technology may also see use for military applications. Considerable effort was dedicated to attempting learn the implementation details of Gamalink. Despite contacting various persons involved in the development of the technology and examining all relevant literature no concrete details as to the MAC and network protocols used by Gamalink were obtained.

2.4 Other Areas of Note

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2.5 Summary

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Chapter 3: Proposed Protocols

3.1 Introduction

… Objectives, Requirements, Restrictions

3.2 Objectives

…

3.3 Assumptions

… Large sections covering basis, defense and compromise of all relevant assumptions

3.4 Restrictions

…

3.5 Summary

…

Chapter 4: Simulation

4.1 Introduction

… Include formations/scenarios examined

4.2 OMNeT++

…

4.3 Protocol Implementation

…

4.4 Simulation Design

… Assumptions, simplications etc.

4.5 Simulation Analysis

…

4.6 Discussion

…

Chapter 5: Results

5.1 Introduction

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5.2 Key Metrics

…

5.3 Simulation Results

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5.3.1 Scenario 1

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5.3.2 Scenario 2

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5.3.3 Scenario 3

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Chapter 6: Conclusions

6.1 Discussion

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6.2 Future Work

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Will format references section last

References

[1] L. Brennan and A. Vecchi, *The business of space: The next frontier of international competition*: Palgrave Macmillan, 2011.

[2] G. Johnson. (2012, January, 15). *Revised, Expanded Launch Cost Data*. Available: http://exrocketman.blogspot.ie/2012/05/revised-expanded-launch-cost-data.html

[3] A. Scholz and J.-N. Juang, "Toward open source CubeSat design," *Acta Astronautica*, vol. 115, pp. 384-392, 2015.

[4] S. Padmanabhan, S. Brown, B. Lim, P. Kangaslahti, D. Russell, and R. Stachnik, "Airborne Deployment and Calibration of Microwave Atmospheric Sounder on 6U CubeSat," in *AGU Fall Meeting Abstracts*, 2015.

[5] V. Hernandez, P. Gankidi, A. Chandra, A. Miller, P. Scowen, H. Barnaby*, et al.*, "SWIMSat: Space Weather and Meteor Impact Monitoring using a Low-Cost 6U CubeSat," 2016.

[6] U. Kvell, M. Puusepp, F. Kaminski, J.-E. Past, K. Palmer, T.-A. Grönland*, et al.*, "Nanosatellite orbit control using MEMS cold gas thrusters," *Proceedings of the Estonian Academy of Sciences,* vol. 63, p. 279, 2014.

[7] X. Sun and X. Wu, "A cubesat attitude control system with linear piezoelectric actuator," in *Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA), 2014 Symposium on*, 2014, pp. 72-75.

[8] A. Budianu, T. J. W. Castro, A. Meijerink, and M. J. Bentum, "Inter-satellite links for cubesats," in *Aerospace Conference, 2013 IEEE*, 2013, pp. 1-10.

[9] R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto, and S. C. Burleigh, "Survey of Inter-satellite Communication for Small Satellite Systems: Physical Layer to Network Layer View," *IEEE Communications Surveys & Tutorials,* vol. 18, pp. 2442-2473, 2016.

[10] Y. F. Wong, O. Kegege, S. H. Schaire, G. Bussey, S. Altunc, Y. Zhang*, et al.*, "An Optimum Space-to-Ground Communication Concept for CubeSat Platform Utilizing NASA Space Network and Near Earth Network," 2016.

[11] W. Harrington and J. Heath, "Development of a Low-Cost, Open Software/Hardware Command, Control and Communications Module for CubeSats," in *AIAA SPACE 2016*, ed, 2016, p. 5616.

[12] J. Hanson, A. G. Luna, R. DeRosee, K. Oyadomari, J. Wolfe, W. Attai, *et al.*, "Nodes: A Flight Demonstration of Networked Spacecraft Command and Control," 2016.

[13] A. Tatomirescu, G. F. Pedersen, J. Christiansen, and D. Gerhardt, "Antenna system for nano-satelite mission GOMX-3," in *Antennas and Propagation in Wireless Communications (APWC), 2016 IEEE-APS Topical Conference on*, 2016, pp. 282-285.

[14] M. Swartwout, "The first one hundred CubeSats: A statistical look," *Journal of Small Satellites,* vol. 2, pp. 213-233, 2013.

[15] K. Kelley, "Launch systems to support the booming nanosatellite industry," in *Aerospace Conference, 2015 IEEE*, 2015, pp. 1-6.

[16] D. Hitt, K. F. Robinson, and S. D. Creech, "NASA's Space Launch System: A New Opportunity for CubeSats," 2016.

[17] D. Masutti, T. Banyai, J. Thoemel, T. Magin, B. Taylor, and D. Kataria, "Investigating the Middle and Lower Thermosphere using a Cubesat Constellation: the QB50 Mission and its Particular Challenges," in *EGU General Assembly Conference Abstracts*, 2015, p. 9016.

[18] M. Tsay, J. Frongillo, K. Hohman, and B. K. Malphrus, "LunarCube: A Deep Space 6U CubeSat with Mission Enabling Ion Propulsion Technology," 2015.

[19] R. W. Ridenoure, D. A. Spencer, D. A. Stetson, B. Betts, R. Munakata, S. D. Wong, *et al.*, "Status of the Dual CubeSat LightSail Program," in *AIAA SPACE 2015 Conference and Exposition*, 2015, p. 4424.

[20] R. Glumb, C. Lietzke, S. Luce, and P. Wloszek, "Cubesat Fourier Transform Spectrometer (CubeSat-FTS) for Three-Dimensional Global Wind Measurements," in *American Meteorological Society Annual Meeting,(January 2015)*, 2015.

[21] S. Nag, J. L. Rios, D. Gerhardt, and C. Pham, "CubeSat constellation design for air traffic monitoring," *Acta Astronautica,* vol. 128, pp. 180-193, 2016.

[22] D. Westley, A. Martinez, and A. Petro, "Edison Demonstration of Smallsat Networks," 2015.

[23] R. Barbosa. (2015, September, 24). *China debuts Long March 11 lofting Tianwang-1 trio*. Available: NASASpaceFlight.com

[24] A. Varga, "OMNeT++," *Modeling and tools for network simulation,* pp. 35-59, 2010.

[25] H. Helvajian and S. W. Janson, *Small satellites: past, present, and future*: Aerospace Press, 2008.

[26] M. Swartwout, "Cubesat database," *St. Louis University.[Online].[Accessed 7 February 2015]*, 2015.

[27] C. Boshuizen, J. Mason, P. Klupar, and S. Spanhake, "Results from the planet labs flock constellation," 2014.

[28] R. A. Deepak and R. J. Twiggs, "Thinking out of the box: Space science beyond the CubeSat," *Journal of Small Satellites,* vol. 1, pp. 3-7, 2012.

[29] J. Puig-Suari, J. Schoos, C. Turner, T. Wagner, R. Connolly, and R. Block, "CubeSat developments at Cal Poly: the standard deployer and PolySat," in *Proceedings of SPIE-The International Society for Optical Engineering*, 2000, pp. 72-78.

[30] J. Farkas, "CPX: Design of a standard cubesat software bus," *California State University, California, USA*, 2005.

[31] J. Straub, C. Korvald, A. Nervold, A. Mohammad, N. Root, N. Long, *et al.*, "OpenOrbiter: A low-cost, educational prototype CubeSat mission architecture," *Machines,* vol. 1, p. 1, 2013.

[32] A. K. Nervold, J. Berk, J. Straub, and D. Whalen, "A Pathway to Small Satellite Market Growth," *Advances in Aerospace Science and Technology,* vol. 1, p. 14, 2016.

[33] K. Hayward, "The Economics of Launch Vehicles: Towards a New Business Model," in *Yearbook on Space Policy 2015*, ed: Springer, 2017, pp. 247-256.

[34] W. A. Beech, D. E. Nielsen, J. T. Noo, and L. K. Ncuu, "AX. 25 Link Access Protocol for Amateur Packet Radio, Version: 2.2 Rev," in *Tucson Amateur Packet Radio Corp*, 1997.

[35] P. Muri and J. McNair, "A survey of communication sub-systems for intersatellite linked systems and CubeSat missions," *JCM,* vol. 7, pp. 290-308, 2012.

[36] C. Fish, C. Swenson, T. Neilsen, B. Bingham, J. Gunther, E. Stromberg, *et al.*, "Dice mission design, development, and implementation: Success and challenges," 2012.

[37] R. Hodges, B. Shah, D. Muthulingham, and T. Freeman, "ISARA–Integrated Solar Array and Reflectarray Mission Overview," 2013.

[38] S. Wu, W. Chen, and C. Chao, "The STU-2 CubeSat Mission and In-Orbit Test Results," 2016.

[39] S. S. Arnold, R. Nuzzaci, and A. Gordon-Ross, "Energy budgeting for CubeSats with an integrated FPGA," in *Aerospace Conference, 2012 IEEE*, 2012, pp. 1-14.

[40] A. Oliveira. (2015, 02-02). *Final Report Summary - GAMALINK (Generic SDR-bAsed Multifunctional spAce LINK)*. Available: http://cordis.europa.eu/result/rcn/172006_en.html

[41] (2016, April 14th). *CubeSat Design Overview Report*. Available: http://sydney.edu.au/engineering/aeromech/AERO3760/private/CDR/1%20%20Critical%20Design%20Overview%20i-INSPIRE%EF%BC%92.pdf

[42] J. Guo, J. Bouwmeester, and E. Gill, "From Single to Formation Flying CubeSats: An Update from the Delft Programme," 2013.

[43] M. Focardi, V. Noce, S. Buckley, K. O'Neill, A. Bemporad, S. Fineschi, *et al.*, "The shadow position sensors (SPS) formation flying metrology subsystem for the ESA PROBA-3 mission: present status and future developments," in *SPIE Astronomical Telescopes+ Instrumentation*, 2016, pp. 99044Z-99044Z-17.

[44] G. Sun, X. Xia, S. Wu, Z. Wu, and W. Chen, "Attitude Determination and Control System Design for STU-2A CubeSat and In-Orbit Results," 2016.

[45] J. Li, M. Post, T. Wright, and R. Lee, "Design of attitude control systems for cubesat-class nanosatellite," *Journal of Control Science and Engineering,* vol. 2013, p. 4, 2013.

[46] E. Glennon, J. Gauthier, M. Choudhury, A. Dempster, and K. Parkinson, "Synchronization and syntonization of formation flying cubesats using the namuru V3. 2 spaceborne GPS receiver," in *Proceedings of the the ION 2013 Pacific PNT Meeting, Honolulu, HI, USA*, 2013, pp. 23-25.

[47] A. Cortiella, D. Vidal, J. Jané, E. Juan, R. Olivé, A. Amézaga*, et al.*, "3CAT-2: Attitude Determination and Control System for a GNSS-R Earth Observation 6U CubeSat Mission," *European Journal of Remote Sensing,* vol. 49, pp. 759-776, 2016.

[48] W. H. Swartz, S. R. Lorentz, P. M. Huang, A. W. Smith, D. M. Deglau, S. X. Liang*, et al.*, "The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat Mission: A Pathfinder for a New Measurement of Earth's Radiation Budget," 2016.

[49] W. H. Swartz, L. P. Dyrud, S. R. Lorentz, D. L. Wu, W. J. Wiscombe, S. J. Papadakis*, et al.*, "The RAVAN CubeSat mission: advancing technologies for climate observation," in *Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International*, 2015, pp. 5300-5303.

[50] S. Kanekal, P. O'Brien, D. N. Baker, K. Ogasawara, J. Fennell, E. Christian*, et al.*, "Radition belt dynamics: Recent results from van Allen Probes and future observations from CeREs," in *41st COSPAR Scientific Assembly, abstracts from the meeting that was to be held 30 July-7 August at the Istanbul Congress Center (ICC),*

Turkey, but was cancelled. See http://cospar2016*. tubitak. gov. tr/en/, Abstract PRBEM. 2-1-16.*, 2016.

[51] J. Westerhoff, G. Earle, R. Bishop, G. R. Swenson, S. Vadas, J. Clemmons*, et al.*, "LAICE CubeSat mission for gravity wave studies," *Advances in Space Research,* vol. 56, pp. 1413-1427, 2015.

[52] J. M. Morrison, H. Jeffrey, H. Gorter, P. Anderson, C. Clark, A. Holmes*, et al.*, "SeaHawk: an advanced CubeSat mission for sustained ocean colour monitoring," in *SPIE Remote Sensing*, 2016, pp. 100001C-100001C-11.

[53] M. Bentum, A. Meijerink, A.-J. Boonstra, C. Verhoeven, and A.-J. v. d. Veen, "OLFAR: the orbiting low frequency array, how a cube sat swarm becomes a novel radio astronomy instrument in space," *De Vonk,* vol. 25, pp. 1-5, 2010.

[54] J. Hanson, J. Chartres, H. Sanchez, and K. Oyadomari, "The EDSN intersatellite communications architecture," 2014.

[55] J. Chartres, H. Sanchez, and J. Hanson, "EDSN development lessons learned," 2014.

[56] J. D. Day and H. Zimmermann, "The OSI reference model," *Proceedings of the IEEE,* vol. 71, pp. 1334-1340, 1983.

[57] K. I. Parker, "State-of-the-Art for Small Satellite Propulsion Systems," 2016.

[58] O. Barnouin, J. Biele, I. Carnelli, V. Ciarletti, A. Cheng, A. Galvez*, et al.*, "The Asteroid Impact and Deflection Assessment (AIDA) mission: Science Proximity Operations," in *LPSC 2016 47th Lunar and Planetary Science Conference*, 2016, p. 1427.

[59] M. Bisgaard, D. Gerhardt, H. Hermanns, J. Krčál, G. Nies, and M. Stenger, "Battery-Aware Scheduling in Low Orbit: The GomX–3 Case," in *FM 2016: Formal Methods: 21st International Symposium, Limassol, Cyprus, November 9-11, 2016, Proceedings 21*, 2016, pp. 559-576.

[60] B. Niels, "ESA and GomSpace Sign Contract to Launch Advanced Nanosatellite," ed. Web: GOMspace, 2016.

[61] M. Villa, A. Martinez, and A. Petro, "Cubesat Proximity Operations Demonstration (CPOD)," 2015.

[62] D. Cecil, "Potential Future NASA Satellite Data and Applications for Tropical Cyclones," 2016.

[63] E. Gill, P. Sundaramoorthy, J. Bouwmeester, B. Zandbergen, and R. Reinhard, "Formation flying within a constellation of nano-satellites: The QB50 mission," *Acta Astronautica,* vol. 82, pp. 110-117, 2013.

[64] M. Di Francesco, S. K. Das, and G. Anastasi, "Data collection in wireless sensor networks with mobile elements: A survey," *ACM Transactions on Sensor Networks (TOSN),* vol. 8, p. 7, 2011.

[65] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," *Computer Networks,* vol. 67, pp. 104-122, 2014.

[66] C. Y. Aung, B. C. Seet, M. Zhang, L. F. Xie, and P. H. J. Chong, "A review of group mobility models for mobile ad hoc networks," *Wireless Personal Communications,* vol. 85, pp. 1317-1331, 2015.

[67] S. Mohseni, R. Hassan, A. Patel, and R. Razali, "Comparative review study of reactive and proactive routing protocols in MANETs," in *Digital ecosystems and technologies (DEST), 2010 4th IEEE international conference on*, 2010, pp. 304-309.

[68] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, "Flying ad-hoc networks (FANETs): A survey," *Ad Hoc Networks,* vol. 11, pp. 1254-1270, 2013.

[69] O. N. Challa, "CubeSat Cloud: A framework for distributed storage, processing and communication of remote sensing data on cubesat clusters," 2013.

[70] O. N. Challa and J. McNair, "Cubesat torrent: Torrent like distributed communications for cubesat satellite clusters," in *MILCOM 2012-2012 IEEE Military Communications Conference*, 2012, pp. 1-6.

[71] O. Challa and J. McNair, "Distributed Computing on CubeSat Clusters using MapReduce," in *Proceedings of the 1st Interplanetary CubeSat Workshop, Cambridge, MA*, 2012.

[72] O. N. Challa and J. McNair, "Distributed Data Storage on CubeSat Clusters," *Advances in Computing,* vol. 3, pp. 36-49, 2013.

[73] G. Bora, S. Bora, S. Singh, and S. M. Arsalan, "OSI reference model: An overview," *International Journal of Computer Trends and Technology (IJCTT,* vol. 7, 2014.

[74] R. Radhakrishnan, W. W. Edmonson, F. Afghah, J. Chenou, R. M. Rodriguez-Osorio, and Q.-A. Zeng, "Optimal multiple access protocol for inter-satellite communication in small

satellite systems," in *4S Small Satellite Systems and Services Symposium*, 2014.

[75] M. Alawieh, N. Hadaschik, N. Franke, and C. Mutschler, "Inter-satellite ranging in the Low Earth Orbit," in *Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2016 10th International Symposium on*, 2016, pp. 1-6.

[76] E. Baceski, S. Gökçebağ, A. Erdem, C. G. Erbay, M. Akyol, K. Arslankoz, *et al.*, "HAVELSAT: A software defined radio experimentation CubeSat," in *Recent Advances in Space Technologies (RAST), 2015 7th International Conference on*, 2015, pp. 831-834.

[77] S. Wu, W. Chen, Y. Zhang, W. Baan, and T. An, "SULFRO: A Swarm of Nano-/Micro-Satellite at SE L2 for Space Ultra-Low Frequency Radio Observatory," 2014.

[78] R. Schoemaker, "Robust and Flexible Command & Data handling on Board the Delffi Formation Flying Mission," 2014.