

... CubeSat Networks ...



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--/--/2017

Acknowledgements

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Abstract

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Abbreviations

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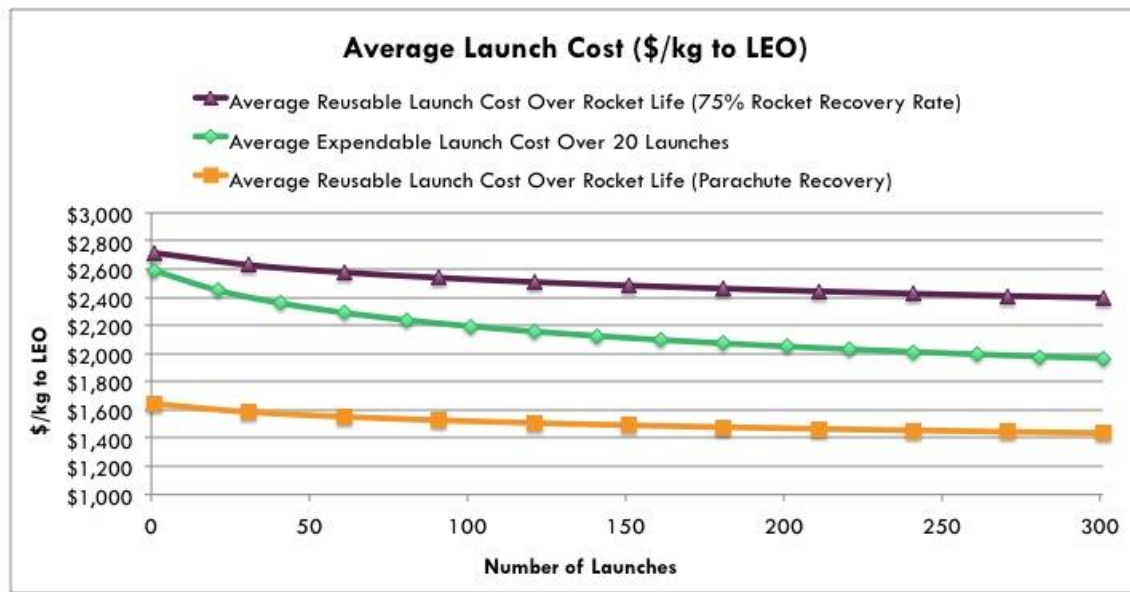
LEO	Low Earth Orbit
SMB	Small to Medium Business
COTS	Commercial Off-The-Shelf
ADCS	Attitude Determination and Control Sub-systems
C&DH	Command And Data Handling
ISS	International Space Station
CSN	CubeSat Network
NASA	National Aeronautics and Space Administration
EDSN	Edison Demonstration of Smallsat 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. Thanks in large part to the competitive prices of SpaceX, the minimum unit cost to LEO is in the region of \$4,000 [2]. Analysis of launch vehicles currently under development has led to predictions of further drops in this cost as a result of increased reusability (Figure 1).



Source: United Launch Alliance, NASA, SpaceX, ARK Investment Management LLC

Figure 1 A projection of unit costs to LEO as the number of launches of a particular vehicle type increases. Image Credit: ARK Investment Management LLC.

The second, and perhaps most influential factor influencing affordable access to LEO, is the induction of new small satellites classifications. 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 or deployment mechanism. However, unlike many larger classes, there is considerable open-sourcing of the design and implementation of CubeSat components [3]. Such open-sourcing is historically rare in the satellite industry.

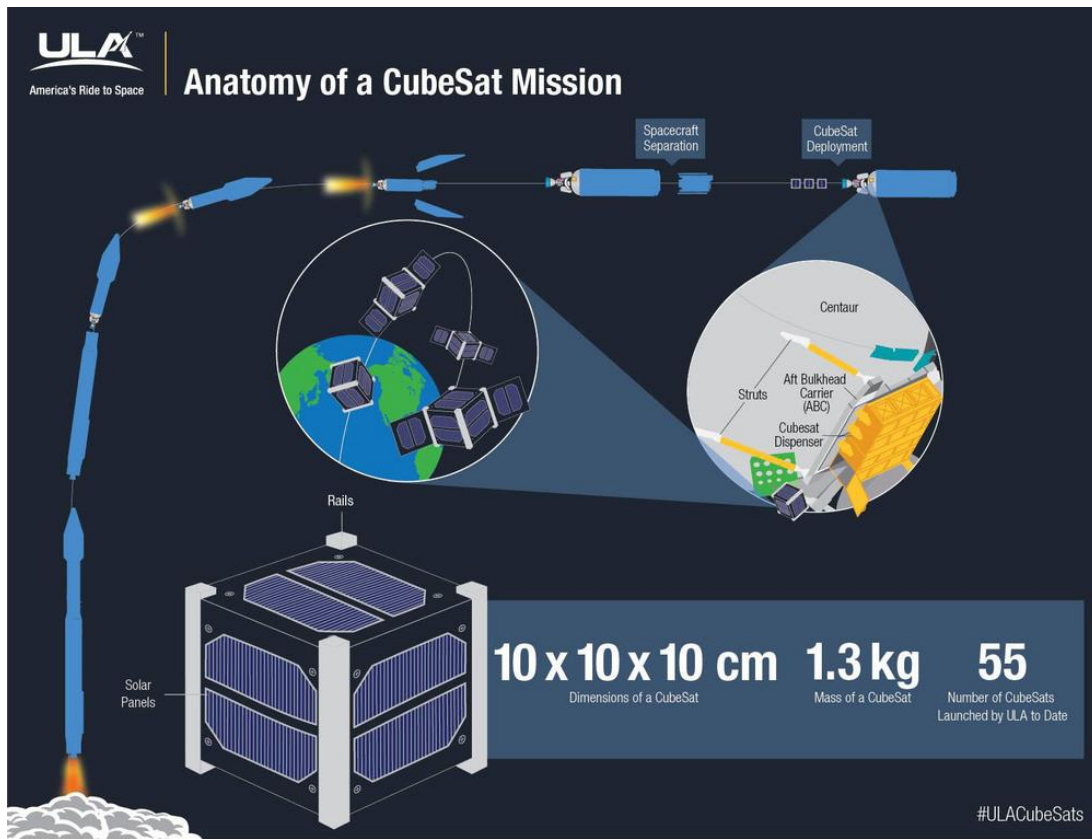


Figure 2 An illustration of the CubeSat form factor and a deployment approach. Here CubeSats are deployed prior to delivery of the primary payload using a dispenser attached to the final stage of the launch vehicle. Image Credit: United Launch Alliance

CubeSats, as the name suggests, adopt a cube form factor. Each Cube, often referred to as a 'unit', is 10cm to a side (Figure 2). 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 increasingly 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] (Figure 3) and Nodes (Network & Operation Demonstration Satellites) [12] and the CNSA's Tianwang-1 [23].

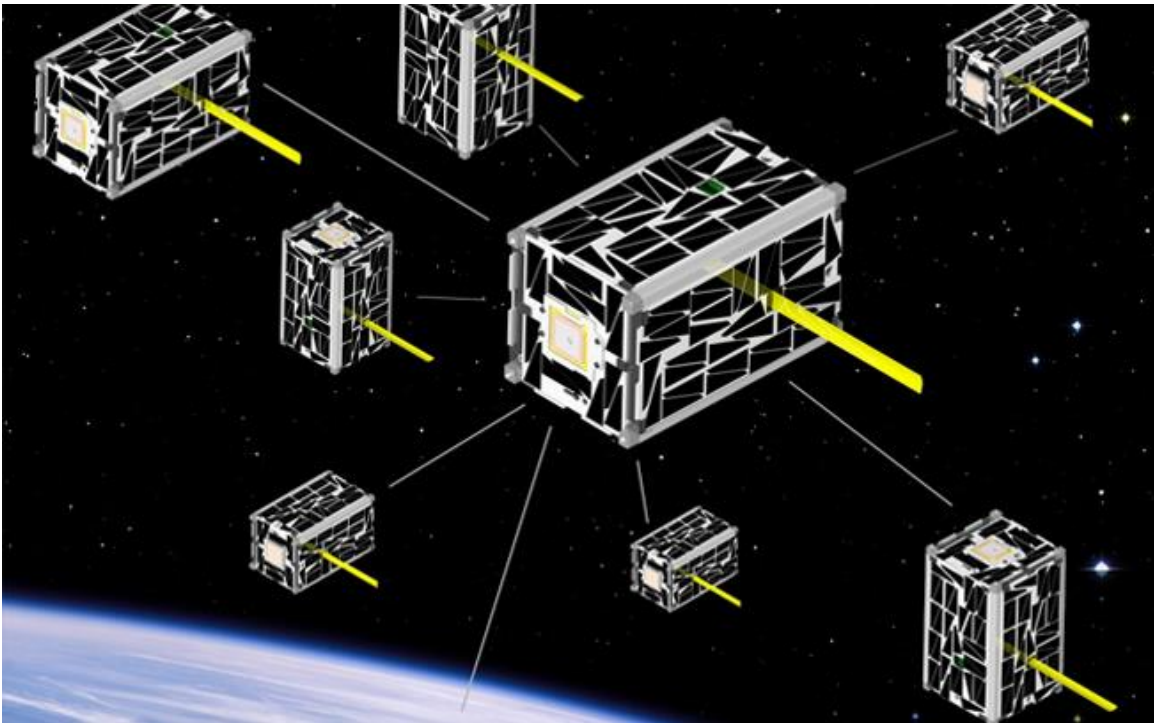


Figure 3 An illustration of EDSN CubeSats in orbit forming a star topology style network. Image credit: NASA Ames Research Centre.

This work seeks to build upon data from the aforementioned missions. The overall aim being the exploration of 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 and varied applications of CSNs. 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.

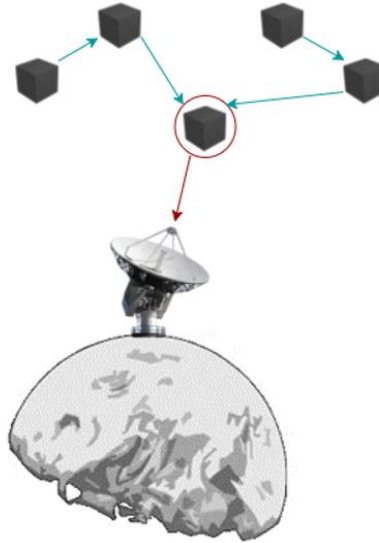


Figure 4 A basic illustration of a multi-hop CSN in orbit. S2S links are shown in blue while the S2G link is shown in red.

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 power 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 such

fundamental challenges which arise when attempting to balance 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 (PvTP) challenge. As far as possible, simulations of CubeSat S2G and S2S communication as well as power consumption 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, aims and general scope of the project.

The State of the Art chapter seeks to examine the relevant prior art relating to CubeSat and terrestrial communications as well as detailing the current capabilities and applications of CubeSats. This chapter presents varying levels of depth on differing sections. Works relating CubeSat communications and applications are explored with the greatest depth. Prior art relating to terrestrial communications, much of which provides the basis for CubeSat communications, is addressed in less depth. This chapter serves as an extension to the background of PvT challenge and as the rationale behind many of the choices made during protocol and simulation design.

The Proposed Protocols chapter following directly from the State of the Art chapter, this chapter identifies key points within the state of the art. These points serve as the basis to the final protocol design intended to address the PvTP challenge. In some cases, references are made to restrictions placed open protocol design which are discussed further in the Simulation chapter. In parallel to the justification of design choices, this chapter presents in-depth explanations and illustrations of the final protocols. This chapter serves as a bridge between the State of the Art and Simulation chapters. It draws from both in order to describe and justify, as clearly as possible, this work's approach to the PvTP challenge.

The Simulation chapter deals primarily with the experimental setup, implementation and analysis of the proposed protocols using OMNeT++. Detailing the experimental setup involves examining the assumptions made regarding CubeSats and space-bound wireless communications. These assumption are important in establishing the fidelity of the final simulation. This chapter also places a focus on the challenges relating to the implementation and analysis of the proposed protocols. As such, this chapter serves, not only to provide experimental context to the Results chapter but also, as a general guide to the production of similar OMNeT++ based work.

The Results chapter introduces the key metrics chosen for the analysis of performance of the implemented protocols. These key metrics are then presented graphically in a number of figures across several simulations scenarios. Scenarios are divided into chapter sub-headings. Each scenario represents a particular parameterization or configuration of the base simulation described in the

Simulation chapter. Discussion is provided for each scenario and a final short summary of the results collection concludes the chapter.

Finally the Conclusions chapter presents several areas of discussion and closing thoughts relating to the work reviewed and carried out. The core intention of the chapter is present the findings of this work in the larger contexts of CubeSats, satellites and the space industry. The chapter concludes by detailing potential future work in the development of the proposed protocols and in simulating CubeSat communications.

Chapter 2: State of the Art

The major literature informing this work can be roughly divided into three broad sections: CubeSats, terrestrial communications, and CubeSat communications. The first of these sections provides an in-depth exploration into the CubeSat platform along with the relevant capabilities and applications thereof. This section is followed by an examination of relevant terrestrial communication technologies which focuses on Wireless Sensor Networks (WSNs) and Mobile Ad-Hoc Networks (MANETs). Detailing relevant terrestrial technology provides important context for the following section on CubeSat communications. This final primary section seeks to explore, in depth, examples of the latest proposed approaches to CubeSat communications. Finally several notable secondary areas of research are discussed in brief. These areas fall outside of the scope of this work but are nonetheless influential in the greater context of space-bound communications.

This chapter covers several areas which provide a fundamental background to CSNs, the PvTP challenge, and this work's proposed solutions. This chapter is not intended as an exhaustive review of all potentially relevant materials. Rather, this chapter is concerned with works which may clarify the chosen problem, detail potential approaches thereto and justify or challenge this work's design decisions.

2.1 CubeSats

CubeSats typically fall within the ‘Nano’ satellite weight class (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 1U, 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 [26]. The platform was intended as an answer to the prohibitive costs and challenges involved in low-resource satellite development for academic purposes. At the time, there were effectively no standard approaches or components for the design and implementation of small satellites. Researchers relied almost entirely on placing instruments alongside primary payloads on larger satellites or pursuing the development of research satellites as lengthy collaborations across multiple research institutions. This was despite the fact that, frequently, research only required satellites with basic capabilities.

2003 saw the first launch of a CubeSat on-board a Russian Eurorocket [25]. At the time of writing there have been 487 CubeSats successfully launched or deployed into orbit [27] 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 largely 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 [28], roughly 40% of all CubeSats were developed by commercial entities. Academic/research institutions have developed approx. 40% and the remaining 20% is divided between civilian and military institutions. In terms of CubeSat applications, 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 scientific applications [27].

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 low 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 batteries to attitude determination and control systems [29]. 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 external expertise. Open and often proven approaches for CubeSat systems are becoming increasingly 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 by creating a number of pseudo-standards. Crucially, CalPoly lead the development and design of standard CubeSat deployers [30] (Figure 5). Such deployers have come to define the de-facto

standards for the domain. A similar pattern can be seen elsewhere in the domain such as with the development of a proposed standard satellite bus design [31]. Recently, “OpenOrbiter” by Straub et al. from the University of North Dakota is a prime example of open pseudo-standard framework for CubeSat development [32].



Figure 5 Three 1U CubeSats beside a 3U (Poly Picosatellite Orbital Deployer) P-POD developed at CalPoly. The spring mechanism used by P-PODs to deploy CubeSats can be seen within the main housing. Image Credit: Montana State University

Depending on the complexity of the CubeSat, development costs may range anywhere from \$50,000 to \$250,000 [33]. 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. This of course depends heavily on the launch vehicle used and the orbital requirements

(Low, High, Medium, Solar etc.). CubeSats avoid these costs by ‘hitching’ a ride as secondary payloads by using volume and lift capacity not required by the primary payload. Providers such as SpaceX have disrupted the satellite industry by offering greatly reduced cost access to LEO [34]. These factors have led to CubeSat launch costs as low as \$10,000 [33]. With recent development towards multi-CubeSat and CSN missions, 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] (Figure 6).

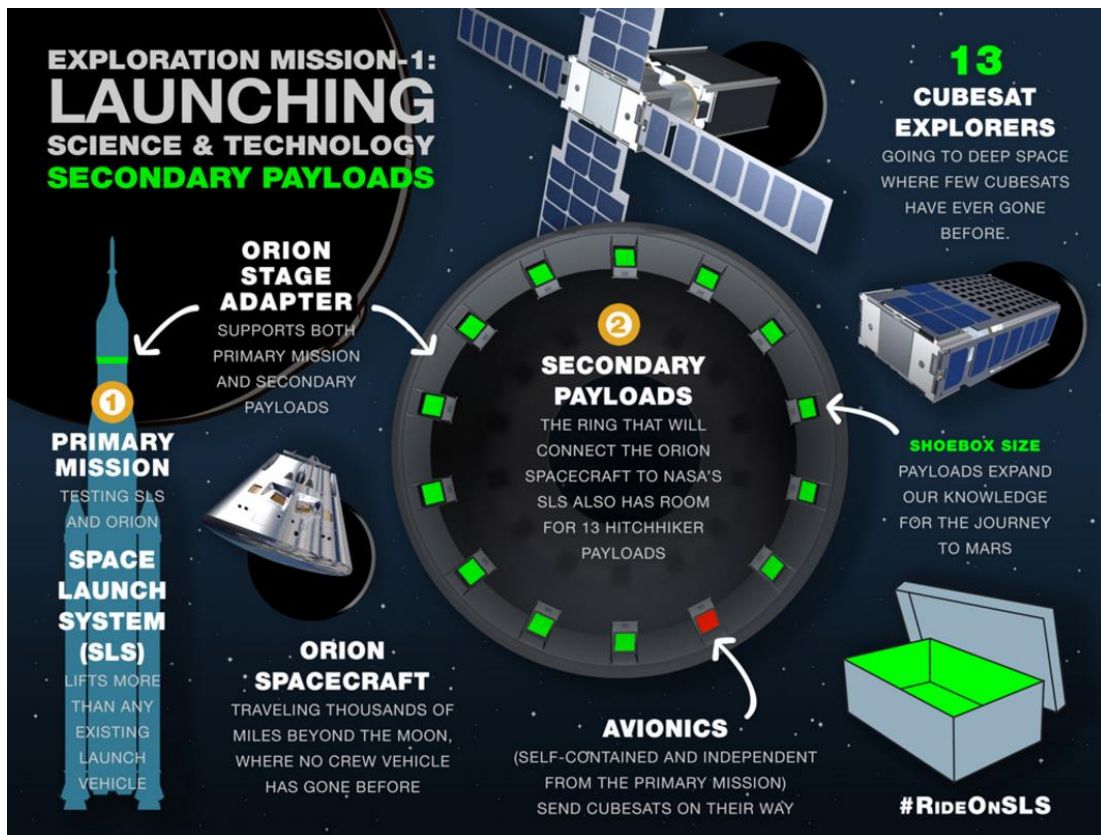


Figure 6 An illustration of the dedicated secondary payload deployers built into the “Orion Stage Adapter” of NASA’s upcoming Space Launch

System. Existing launch vehicles are generally retroactively fitted with such deployers. Image Credit: NASA.

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 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 [35]. 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 [36].

There are some notable outliers to the trends in CubeSat S2G communications which denote advancements in the domain. In particular, NASA's Dynamic Ionosphere CubeSat Experiment (DICE) mission achieved a remarkable S2G maximum data rate of 3Mbps [37]. Such rates were achieved using a custom SDR based sub-

system consuming roughly 9W of power and operating within the UHF band. The DICE mission holds the current record for the highest S2G data rate achieved by a CubeSat. At present there are few missions that attempt S2G rates in the order of Mbps, with the notable exception of JPL's ISARA mission [38]. The majority of upcoming missions aim to operate communication rates in the order of hundreds of kbps.

In order to approach protocol design for the PvTP challenge, 'baseline' state of the art S2G characteristics were chosen. One of the primary inspirations for these characteristics is the Tianwang-1 (TW-1) mission [39]. This mission is an ideal candidate to use as a baseline for S2G communication modelling as the mission was designed specifically to test CubeSat inter-communications. 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 [40] 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 comparatively 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 of S2S CubeSat capabilities: The NASA's Nodes mission and Gamalink [41]. As will be discussed, 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 basic approach 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 [42], DelFFi [43] and ESA's Proba 3 [44].

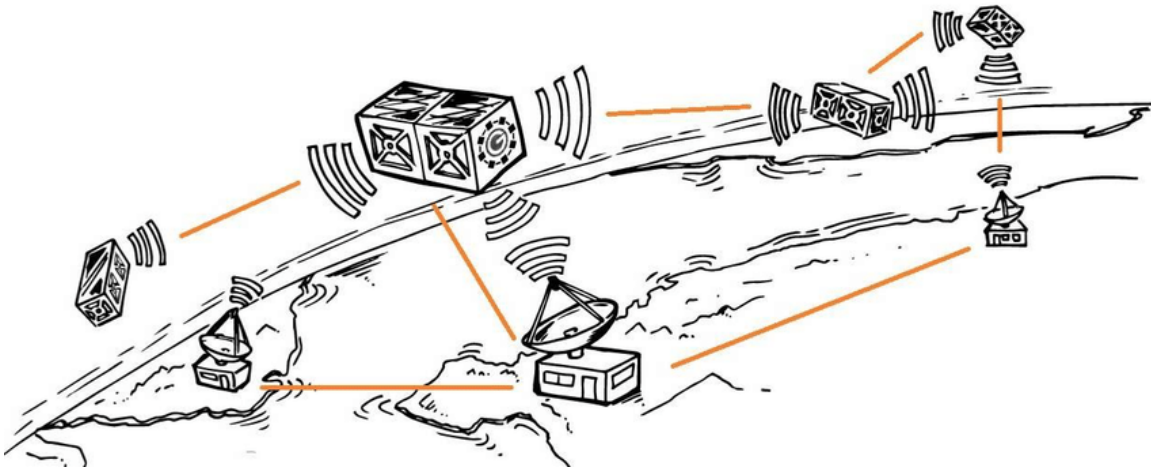


Figure 7 Unlike with NASA's EDSN approach, Gamalink seeks to establish multi-hop CubeSat networks capable of communicating with multiple ground stations. Image Credit: [45]

Due to the Gamalink's proprietary nature and its likely use for military applications details regarding Gamalink are exceptionally sparse. During research no information regarding protocol use or design was discover. Tekever make several allusions to MANETs even stating that Gamalink implements an "SDR-based Ad hoc Space Network" (SASNET). This is an 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 [42]. Gamalink operates in the S-Band, between 2.40 and 2.45 GHz, with a bandwidth of 40Mhz making the advertised data rates appear feasible. Gamalink consumes a peak of 1.5W while transmitting and up to 200mW while receiving [43]. Using these details

and assuming a maximum data rate of 2Mbps, a state of the art baseline can be established for CubeSat S2S communications. This baseline is used alongside the S2G baseline in the design of this work's simulations.

2.1.1.3 Other Capabilities

Although the most 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 CubeSat equivalent.

Attitude determination and control sub-systems (ADCS) are implemented to ensure correct spacecraft orientation. ADCS are critical to insuring correctly positioned solar panels, 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, 46, 47] including several which are available COTS (Figure 8). 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.



Figure 8 An off-the-shelf CubeSat attitude control unit. The rotational velocity of the three reaction wheels shown above can be altered in order to adjust attitude. Image Credit: Clyde Space.

The determination of accurate time and position are two classic challenges for spacecraft that have been long solved in the domain of CubeSats. By communicating with Global Navigation Satellite System (GNSS) a CubeSat may acquire precise GPS time, velocity 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 potential beneficial CubeSat capabilities within multi-CubeSat missions [48].

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 mission objectives. Two categories of application are considered, sensing missions and CSN missions. This is not intended to assert that sensing missions and CSN missions are disjoint. CSN missions are highly suited to collaborative sensing applications.

2.1.2.1 Sensing Missions

When approaching the CSN PvTP challenge, 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 multi-CubeSat mission. 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 the communication of 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 [49] and RAVAN (Radiometer Assessment using Vertically Aligned Nanotubes) [50]. 3Cat-2 is 6U CubeSat developed at the Universidad Polit cnica de Catalu a. 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 also make it an interesting case

for the application of CSNs. 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 informs the baseline chosen 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 adaption for a CSN. 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.

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 [51] (Figure 9). Unfortunately, The spacing of the forty proposed RAVAN craft prohibits S2S communication using current technologies. Nonetheless, RAVAN is strong example of the growing interest in multi-CubeSat missions.

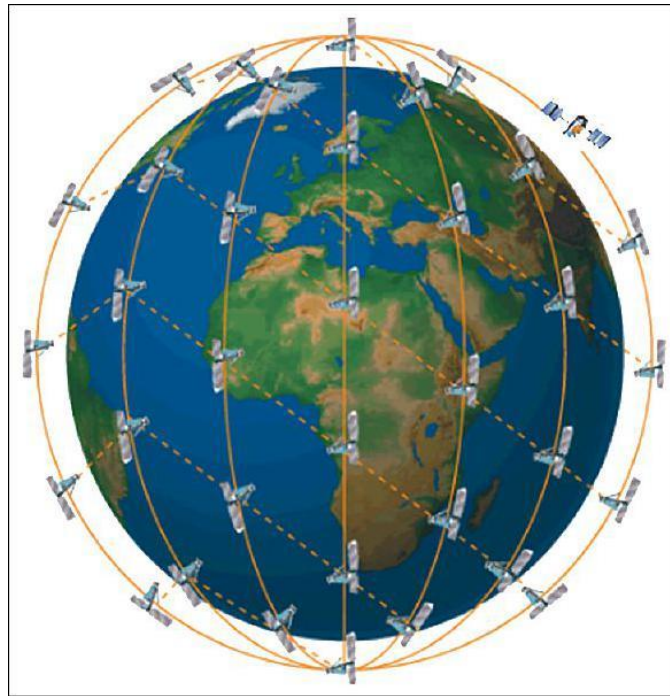


Figure 9 A conceptual illustration of the proposed RAVAN constellation.
Image Credit: John Hopkins University Applied Physics Laboratory.

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) [52], LAICE (Lower Atmosphere/Ionosphere Coupling Experiment) [53], and SOCON (Sustained Ocean Observation from Nanosatellites) [54] seek to

advance the already diverse applications of CubeSats. In several regards, it is these advanced applications that drive interest in CSN based missions. As applications develop, so too does interest in advancements such as multi-point measurements, in-orbit interferometry [55] and synchronized observation. These advancements 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: EDSN, Nodes, and Tianwang-1 (TW-1). Of these missions, both Nodes and TW-1 have successfully flown. NASA's 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 [56]. While the second work details lessons learned during development [57]. 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 activity scheduling and execution for each craft. Several secondary COTS micro-controllers handle various activities involving GNSS, data handling, scientific measurements, 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. EDSN’s sensing objective are not entirely dissimilar from those of 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 North American Aerospace Defense Command (NORAD)). The AstroDev transceiver enables S2S communications at 9.6kbps with 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 capabilities are not provided.

Each EDSN craft carries four lithium ion batteries which combine to provide a maximum energy capacity 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 a AX.25 link layer for S2S communication. The link layer, as detailed by the OSI reference model [58], 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 [36]. However, S2S communication introduces new challenges which warrants more involved approaches. In the case of EDSN a custom “Captain – Lieutenant” (Cpt/Lt) protocol was designed on top of AX.25.

The 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 (Figure 10). The Cpt then communicates as much of this data to ground as possible. Lt communication in EDSN is triggered solely by the Cpt. 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 communications can occur on the shared S2S frequency.

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 FIFO manner. After ending a communication session with an Lt, the Cpt will then proceed to ping each remaining Lt in a fixed order (Figure 10). The Cpt will wait up to four minutes for

a response from a pinged Lt before giving up and moving onto pingging the next Lt.

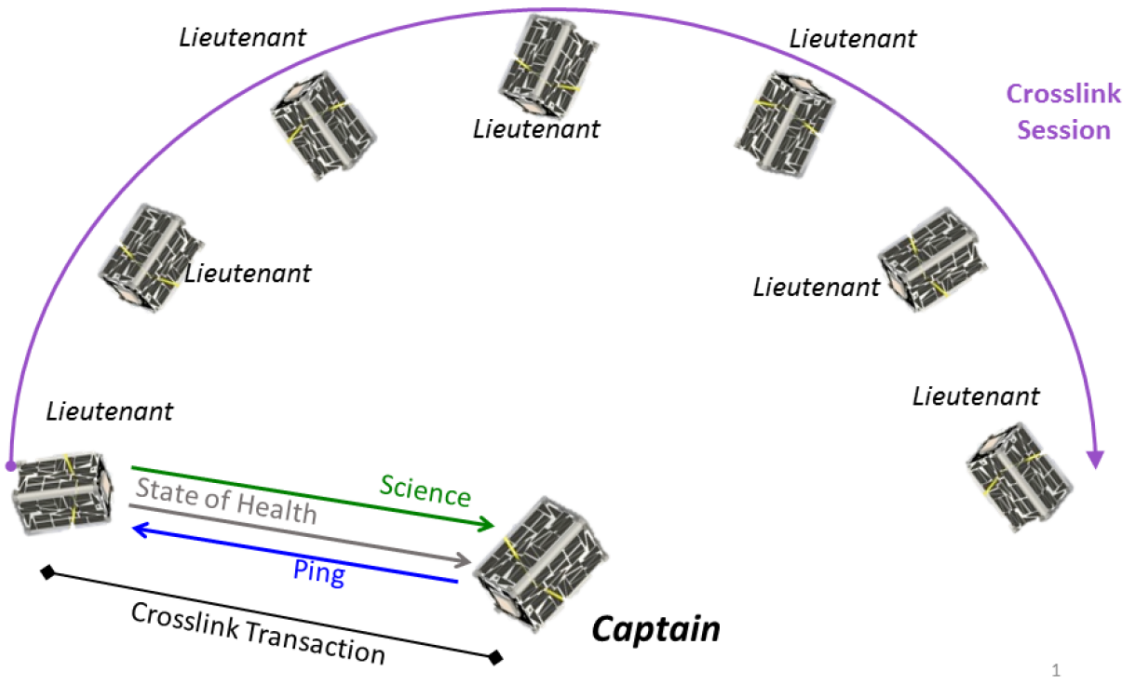


Figure 10 The Cpt/Lt protocol. EDSN designers refer to S2S communication as crosslinking. The Captain pings a Lieutenant before receiving state-of-health and science data packets. Image Credit: NASA Ames Research Centre

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. 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 their S2S transceivers continually on and in receiver mode. As such, along with the Cpt pinging scheme, all S2S sessions follow a fixed schedule. 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 its 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 continue listening 30 seconds after the expected final, sixth, ping. Each session start time is determined by a table of offsets. These 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 employed 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. Some small changes were made to mission objectives and there were 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 to demonstration of Ground-to-Space (G2S) remote commands. In Nodes, the objective was set to communicate a command to the elected Cpt. The Cpt would then forward this command to the Lt for execution. Unlike with science and state-of-health packets, command packets are implemented along with 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 of CubeSats 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 (Figure 11) . A default Cpt craft compares metrics relating to battery voltage, amount of science data collected and the predicated duration of the next ground station fly over. At the start of each minor cycle the selected default Cpt 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 only demote itself to the Lt role once the promote command has been acknowledged. 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.

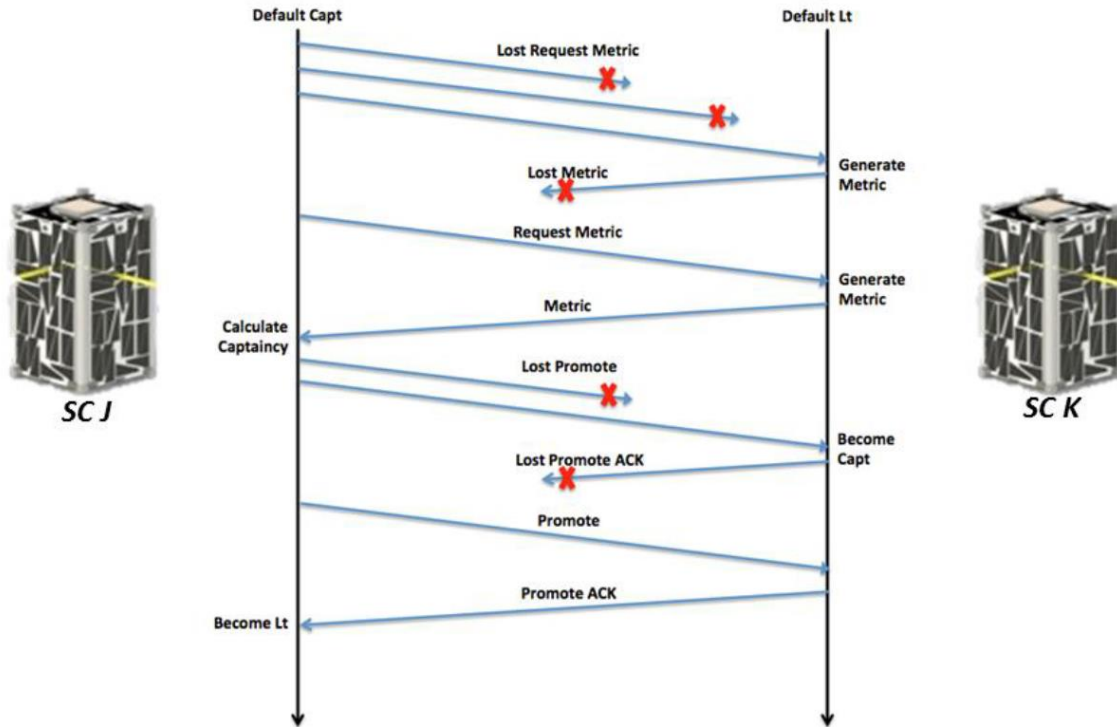


Figure 11 A timeline of the Captaincy negotiation process carried out between the two Nodes spacecraft. Image Credit: NASA Ames Research Centre

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 successful S2G session
- One successfully executed indirect command
- Two successful captaincy negotiations
- 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 designers 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 [46, 59]. A presentation by Wu et al. during the 30th Annual AIAA/USU Conference on Small Satellites in 2016 offered a brief overview of the mission's Gamalink communication system [39]. 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" subsection. 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, primarily a technology demonstration mission. TW-1's objectives were to flight test Gamalink, a novel ADCS and a novel 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 also carried out 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 no further relevant information available 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 [60], GomX-4 [61, 62] and Proba-3 [44], NASA's CPOD [63] and TROPICS [64], QB50 [65] and OLFAR [55]. 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

When approaching the design CSN communication protocols inspiration can be drawn from the state of the art in similar terrestrial fields of research. In this section we examine two such fields, both of which bear numerous similarities to the domain of CSNs. These fields are Wireless Sensor Networks (WSNs) and Mobile Ad-Hoc Networks (MANETs). Both fields have considerable depth, as such a

focus is placed on survey and review style publications. More focused publications are examined in the following section which examines works related directly CubeSat communications.

The following sections on WSNs and MANETs attempt to identify the most relevant sub-domains within each field. Within the field of WSNs works relating to data collection and energy aware protocols are of most interest. As discussed the primary application of CubeSat is sensing which leads to obvious similarities to terrestrial WSNs. MANET related works are relevant in their treatment of the mobility of network members. Particular attention is paid to Flying Ad Hoc Networks (FANETs). FANETs share many of the same properties as CSNs. Like CSNs, ANETs are expected to experience intermittent, potentially unpredictable, access to a greater and more 'static' network. In the case of CSNs, this static network is represented by one or more ground stations.

2.2.1 Wireless Sensor Networks

Common WSNs challenges relate to the unpredictable or intermittent failure of network elements and resource and/or capability constraints. These challenges impact, to varying degrees, a WSN's ability to perform data collection or data dissemination. The sink (collection) or originator (dissemination) of data in the context of CSNs is the earth based ground station. In this work we are concerned with energy efficient data collection (the PvTP challenge) with the added complication of node (CubeSat) mobility.

A survey by Rault et al. focuses on energy efficiency in WSNs [66]. The authors approach the domain by examining a number of areas of WSN application such as

healthcare, transportation and industry. For each area the authors outline characteristic WSN application requirements such as scalability, mobility, security and so on (Table 1). Table 2 extends this table with a number of application cases relevant to CSNs.

Table 1 The requirements of several WSN application domain. RT – Round Trip, QoS – Quality of Service. Credit: [66]

		Scalability	Coverage	RT Delay	QoS	Security	Mobility	Robustness
Healthcare	Vital status monitoring	--	--	++	+	++	++	+
	Remote surveillance	--	--	+	+	++	++	-
Agriculture and environment	Precision agriculture	++	++	--	--	--	--	+
	Cattle monitoring	++	-	-	--	--	+	-
	Environment monitoring	--	--	+	+	++	++	-
Public safety and military systems	Active intervention	--	--	++	+	++	++	++
	Passive supervision	--	+	++	+	++	--	-
Transportation systems	Traffic control	--	-	++	++	++	++	-
	Safety system	--	-	++	++	++	+	+
	Services	--	--	-	+	+	+	-
Industry	SCADA systems	--	-	++	+	++	--	++
	Smart grids	+	-	++	+	++	--	++
Requirement importance								
--								Very low
-								Low
+								High
++								Very high

Table 2 An extension of Rault et al.'s table shown in Table 1 to include a number of CSN applications. ET – Extra-Terrestrial. ET Science examples: measuring solar radiation, performing astronomical measurements etc.

		Scalability	Coverage	RT Delay	QoS	Security	Mobility	Robustness
Space	CSNs – Earth Observation	-	+	--	+	-	++	+
	CSNs – ET Science	--	-	--	+	-	+	+

Rault et al. address several aspects of low-power WSNs and the trade-offs required when attempting to increase energy efficiency. Several low power WSN standards are explored such as IEEE 802.15.4 [67], Bluetooth Low Energy (BLE) [68], and

Routing Protocol for Low power and lossy networks (RPL) [69]. No one standard presents itself as being an obvious choice for the CSN PvTP challenge. However, clear benefits can be seen in elements of RPL and ISA100.11a [70], one of many extensions of 802.15.4.

Beyond low power WSN standards, several core WSN approaches are highlighted by Rault et al. Although all of these areas are relevant in some regard to CSNs, the areas of highest relevancy to this work are: Duty cycling schemes, cluster architectures, energy as a routing metric and sink mobility. Each of these areas are explored, to some extent, in the Proposed Protocols chapter.

Rault et al. discuss a number of approaches to the trade-offs involved in the implementation of energy efficient WSNs. Three techniques are discussed: Multimetric protocols, Cross layer approaches, or cross layer optimization (CLO), and Multi-objective optimisation (MOO). Of the three techniques, CLO bears the most relevance to CSNs.

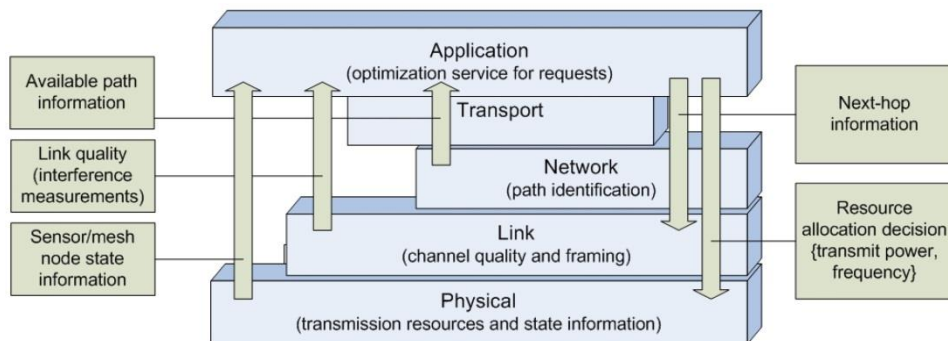


Figure 12 An illustration of information that may be passed between layers. This is a departure for the treatment of each layer as an isolated black box. Image Credit: [71]

The authors define CLO as “solutions exploit(ing) interactions between different layers to optimise network performances” (Figure 12). Here ‘layers’ may refer to several communication models, but it can be safely taken as relating to the OSI reference model [58]. This work adopts Rault et al.’s definition of CLO from here on. Two particular surveys are cited as being authoritative on the CLO domain [72, 73]. Rault et al. highlight the communication of the energy metrics by the Physical layer to the MAC and network layers as being a key example of the application of CLO. Other examples given include: Communicating clustering formations achieved at the MAC layer and to higher layers and the explicit scheduling of communications at higher layers allowing lower layers to reduce activity.

No one approach or standard is singled out as the obvious choice for energy efficient WSNs. Rather, Rault et al. point to the importance of adapting approaches to applications. The authors state clearly that regardless of the application or approach, the introduction of greater CLO is expected to advance the field. CLO is a common and favoured theme throughout recent literature relating to WSNs and MANETs. The exact meaning of CLO differs somewhat depending on the author, application and domain. Despite this, it is clear that it is an active topic in both WSN and MANET energy efficiency research.

WSN data collection is examined by Francesco et al. in extensive survey paper published in 2011 [74]. The work is particularly useful as it focuses on WSNs with Mobile Elements (WSN-MEs). The authors concentrate on mobility while maintaining and referencing the existing relevant state of the art in WSN routing and energy management.

Francesco et al. lay out a number of WSN mobility scenarios the most relevant of which is the “Mobile Peer” scenario (Figure 13). With CSNs, there is no appreciable difference whether one considers the ground station as moving into range of a satellite or a satellite moving over ground. In either case, a network of satellites in some formation must contend with a finite but predictable communication window with ground.

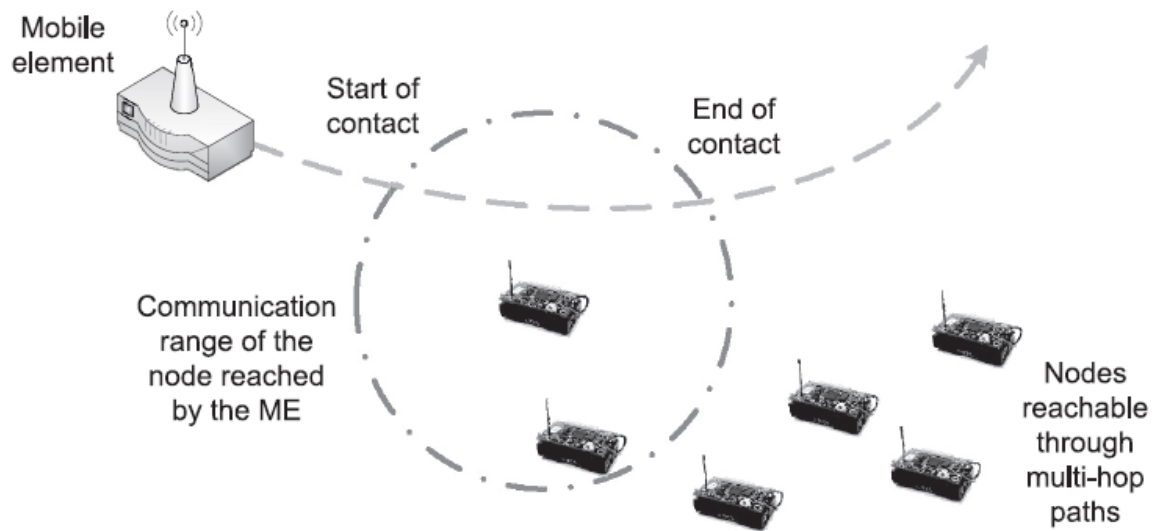


Figure 13 A mobile peer architecture which bears clear similarities to CubeSats in orbiting passing over a ground station. Image Credit: [74]

Data collection is divided by Francesco et al. into three distinct phases ‘Discovery’, ‘Data Transfer’ and ‘Routing’. The authors outline that the treatment of the Discovery phase is critical to the performance of WSN-MEs. In particular, the authors highlight issues with discovery protocols which rely on schedule based discovery of reachable nodes. The timeliness of the discovery of a mobile element defines the maximum windows for communication. Schemes based on periodic or scheduled discovery attempts are liable to suffer from reduced communication

windows due to ill-timed discovery attempts. The authors highlight an approach that utilizes low-power short-range radios to asynchronously waken nearby nodes prior to data communication using a longer range higher power radio [75]. Other methods involving learning are noted for their potential to avoid the pitfalls of periodic/scheduled listening. Such methods may, with or without prior heuristics or topology knowledge, converge on optimal discovery schedules over time [76]. In the case of CSNs, CubeSats can easily determine their next communication window with ground through the use of GPS time, position and velocity. However, discovery of S2S windows closely mirrors the challenge of WSN node discovery.

The data transfer phase, which follows the discovery phase, is primarily concerned with the quality of communications and MAC schemes. The authors clearly identify WSN-ME data transfer as a field that requires further work. The authors note a stop-and-wait protocol [77] as well as an automatic repeat request (ARQ) scheme [78]. Further references to specific well-established MAC schemes are sparse. Francesco et al. make a clear recommendation that network coding schemes require greater attention in relation to WSN-ME data transfer. MANETs and WSN-ME bear numerous similarities. Work on data transfer within the domain of MANETs tends to be broadly applicable to WSN-MEs. Why Francesco et al. avoid the direct evaluation of relevant MANET related work is unclear. It is possible the authors intend to stress the importance of adapt approaches for WSNs.

Routing in WSN's, as highlighted by Francesco et al., is considerably more developed than discovery or data transfer. The authors make an assumption that the motion of network elements is not controlled. In this regard, the works

discussed are relevant to S2S communications of CubeSats which have no orbital control capabilities (In simulating CSN communications this work assumes no orbital control capabilities). Routing for uncontrolled mobile WSN elements is classified by the authors into flat routing and proxy-based routing. In flat routing schemes all nodes behave in the same fashion whereas in proxy-based schemes certain nodes may take on routing or proxy style roles.

Several approaches to routing are discussed by Francesco et al. Three are worth noting in brief: A modified Optimized Link State Protocol (OLSR+) [79], Energy-Aware Routing to Mobile gateway (EARM) [80], and a cluster based approach by Somasundara et al. [81]. OLSR+ adapts to the mobility of element by passing velocity information between nodes. With this added information nodes can estimate the future stability of a link and avoid unnecessary abandonment or predict upcoming suitability. EARM implements an adaptive approach wherein node may boost their transmission power to a mobile node as the node moves out of reach. EARM's core logic allows nodes to decide the point at which a direct link should be abandoned in favour of an multi-hop route. Somasundara et al.'s approach employs adaptive clustering. Nodes collaboratively and dynamically form clusters and elect a cluster heads based on their distance from a mobile sink. These cluster heads act as routers to the mobile sink and manage inter-cluster communication. Somasundara et al.'s approach is similar to the cluster based MAC approach developed by this work. This work does not employ a cluster based routing strategy such as the Cluster Based Routing Protocol (CBRP) [82] (Figure 14). Rather, this work adapts a routing protocol known as the "Dynamic

MANET On-demand routing protocol" (DYMO) [83] for use with the cluster based MAC approach.

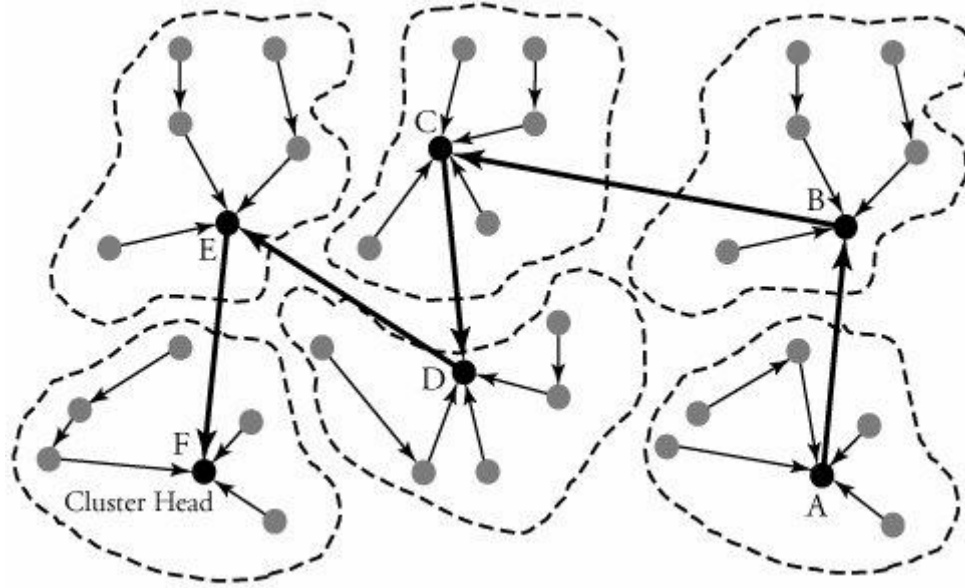


Figure 14 An example of network cluster forming with the election of cluster heads. With the introduction of a mobile sink clustering can be adapted to insure election of optimal cluster heads in order to maximize throughput [81]. Image Credit: [84]

Finally, to compliment the discussed WSN survey materials a more targeted work is considered. "Efficient data collection in wireless sensor networks with path-constrained mobile sinks" by Gao et al. approaches the PvTP challenge directly through the design of novel routing protocol [85]. Increasing the relevancy of this work to the CSN domain is the focus by Gao et al. on WSN's with mobile sinks. Each mobile sink can be considered analogous to a CSN ground station. The proposed protocol is given the name "Maximum Amount Shortest Path" (MASP). The authors determined the formal properties of MASP and used OMNeT++ to simulate and analyse its performance.

MASP outperforms a common approach to the determination of the most efficient routes to adopt called Shortest Path Tree (SPT). There are several implementations of SPT, but a common approach is to construct a tree of possible routes to a destination. This tree can then be search with an algorithm such as A* while using a heuristic cost function which represents the energy cost of using a given route. MASP beats SPT by provided a genetic algorithm which solves a multi-dimensional optimization problem based on known and computable routes and route heuristics.

The work of Gao et al. represents a state of the art approach to the PvTP challenge in WSNs. Energy as a routing metric was clearly noted by Rault et al. as critical when attempting to optimize data collection with energy efficiency. MASP develops on this concept of energy as a routing metric and introduces a complex yet performant solution. However, MASP can only determine efficient routes given successful and timely discovery. Without the introduction of an appropriate discovery scheme MASPs performance is fundamentally limited. This lack of development in the area of discovery is noted by Francesco et al.

From the analysis of WSN based prior art one can identify several similarities to the CSN PvTP challenge. There are clear recommendations for further development CLO and discovery in the area of energy efficient data collection. Although the CSNs diverge in certain regards from WSNs, prior art therein provides a considerable basis for the development of the CSN domain.

2.2.2 Mobile Ad-Hoc Networks

MANETs bear obvious similarities to CSNs. MANET research tends to be less concerned with the constraints, such as power and bandwidth, placed upon network members. Rather, a focus is placed on the capability of a given approach to efficiently and reliably enable self-organization and communication. Although there are many areas of overlap between MANETs and WSNs their differing objectives merit their joint investigation.

In MANETs no initial shared knowledge of the network is assumed. With CSNs, although several CubeSats may be deployed together, countless factors could cause unpredictable failure or orbit perturbations. LEO is an environment of extremes with intermittent flares of radiation, hazardous solar winds, fluctuating magnetic activity and temperatures ranging from -170 to 150 degree Celsius. MANET technologies which will prove most valuable are those which are mature, adaptive to failure and topology change and energy efficient.

The most discussed and active topic within MANET research is that of routing. MANET routing protocols are generally divided into three primary classes: reactive, proactive and hybrid. Reactive protocols attempt to establish routes only as required whereas proactive protocols attempt to establish routes in-advance of communication. Hybrid protocols implement a mix of reactive and proactive approaches, generally by restricting reactive or proactive behaviours to certain areas of a network. The methods by which protocols maintain and discover routes may or may not differ between protocols of differing classes. This section places a focus on reactive protocols. Generally, proactive and hybrid protocols are

unsuitable for CSNs. Proactive protocols are typically designed for low mobility networks with reliable links. Hybrid protocols can provide a ‘best of both worlds’ between reactive and proactive protocols. However, hybrid approaches are typically best suited for larger networks wherein the additional overheads of more complex protocols scale more favourably.

Several routing protocols are examined by Mohseni et al. in their survey of MANET routing protocols [86]. The conclusions of the authors reinforce the assertion that reactive protocols are better suited for CSNs. The authors state that, comparatively proactive protocols tend to require more power, bandwidth and incur larger overheads. The primary benefit of proactive protocols is the constant availability of routes which lowers latency and increases the consistency of communication throughout the network.

Mohseni et al. discuss a number of the most well-known reactive protocols such as “Dynamic Source Routing” (DSR) [87], Ad hoc on Demand Distance Vector (AODV) [88], Temporally Ordered Routing Algorithm (TORA) [89] and CBRP [82]. Of these it is worth providing a brief overview of DSR and AODV. In DSR, a node (the originator) broadcasts a route request (RREQ) for a given target. Non-target nodes add their address to an incoming RREQ and rebroadcast it. Loops are avoided by nodes dropping RREQs to which they have already added themselves. Once an RREQ reaches its target it contains a list of nodes representing one possible route from originator to source. An attempt is then made to use this route to send a unicast route response (RREP) from the target to the originator. Through this approach, DSR is capable of building up multiple routes for a given target. In DSR, due to the construction of routes within packets, packet sizes grow in

proportion to overall network size. AODV builds upon concepts from DSR and a proactive protocol known as Destination-Sequenced Distance-Vector routing (DSDV) [90]. Unlike DSR AODV only specifies that the originator and target addresses must be contained within a route packet. AODV borrows route packet sequences numbers from DSDV in order to avoid infinite loops and determine the ‘freshness’ of a route. AODV also introduces features such as ‘intermediate-RREPs’ and ‘Hello’ messages. An intermediate-RREP may be generated by a non-target node in response to an incoming RREQs if said node has a route to for a given target. ‘Hello’ messages may be periodically generated in order to detect broken routes.

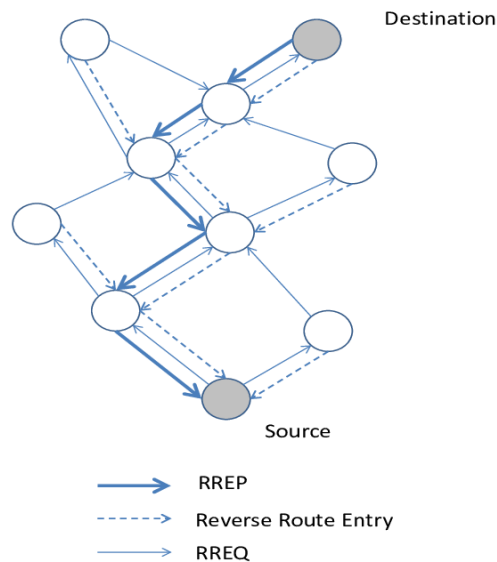


Figure 15 An illustration of the broadcast RREQ unicast RREP approaches used by DSR and AODV. An added feature above allows nodes to add routes to neighbours when receiving route packets. Image Credit: [91]

The routing protocol utilized by this work, DYMO, is a modification of AODV. In fact, recent IETF specification drafts have begun to refer to DYMO as “AODV version 2”. This work’s implementation of DYMO within OMNeT++ is based on an older IETF specification draft [83] which uses the DYMO naming convention and as such it is retained. The primary differences between DYMO and AODV relate to implementation. The core route discovery and maintenance approaches of AODV are largely unchanged by DYMO. DYMO is discussed further in the Proposed Protocols chapter.

Vehicular Ad-hoc Networks (VANETs) are a sub-domain of MANETs. There are notable parallels between CSNs and VANET such as the separation of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) concerns. Despite initial similarities, a survey of the protocol stacks in the domain by Mohammad et al. reveals several undesirable facets of VANETs [92]. As mentioned, there is generally less focus in the field of MANETs placed on resource constraints. VANETs, generally, follow this trend as the majority of applications focus on planes, trains, and automobiles [93]. Also, security is a central topic in recent VANET research. Although security has relevance to CSNs, security related topics are beyond the scope of this work.

Mohammad et al.’s survey shows the strong preference of VANET protocol stacks towards mobile IPv6 capable technologies and flavours of the 802.11 stack. Implementing a stack which supports IPv6 enabled RPL [69] for CSN communications is potentially feasible. However, in broad terms, the power use, overheads and low mobility basis of 802.11 flavours are generally unfavourable. Mohammad et al. point to C2CNet (Car-to-Car Net) as the emerging state of the

art standard within VANETs. C2CNet's protocol stack makes heavy use of 802.11 standards making it generally unsuitable for use with CSNs.

FANETs (Flying Ad-Hoc Networks), a sub-domain of VANETs, have a higher level of relevancy to CSNs. A survey by Bekmezci et al. [94] introduces FANETs in the context of MANETs and the VANETs. The authors deal primarily with unmanned aerial vehicles (UAVs). Capability and resource constraints are more central within the field of FANETs. This is particularly true where long haul UAVs and small scale drone based applications are concerned. Bekmezci et al. highlight the departure from the use of standard 802.11 MAC layer protocols for FANET applications as the field has developed. The authors point to the development of tailored FANET MAC protocols, many of which aim to take advantage of advancements in antennae. At the network layer, both DSR and a modified AODV [95] are noted along with other well-known MANET routing protocols such as GPSR [96] and OLSR [97]. Interestingly, due to the use of time slots for route discovery, the aforementioned modified AODV protocol has similar properties to the combination of protocols proposed by this work.

Bekmezci et al.'s work provides an overview of FANETs which details the use of customized MAC protocols and mainstream MANET protocols. One FANET related project cited by Bekmezci et al. called the Cooperative Autonomous Reconfigurable UAV Swarm (CARUS) project [98] is worth mentioning briefly. The project focuses more on application layer coordination and formation flying. Due to several notable parallels with CSNs the project merits investigation for future developments on CSN formation flying and cooperative observation.

Bekmezci et al. place value on cross-layer architectures (CLO) within in the field of FANETs. CLO, as discussed, is an important topic within WSNs and its applicability within FANETs further reinforces its importance to CSNs. Bekmezci et al. note works that take advance of cross-layer clustering and scheduling and the sharing of attitude and antennae related information in order to improve performance [99, 100].

The state of art in MANETs provides an insight into several potential routing protocols which may be employed in addressing the CSN PvTP challenge. It is clear that FANET sub-domain contains the highest relevancy work. Examining MANET prior art augments and reinforces the findings relating to WSNs and provides important background when addressing CubeSat communications and this work's proposed protocols.

2.3 CubeSat Communications

Prior to the development and flight of the first CSN related mission several academics produced works examining the inter-communication and networking of CubeSats. Most notably Challa and McNair of University of Florida provide extensive explorations of distributed applications implemented upon CSNs [36, 101-104]. These works are somewhat out of the scope of this project as they deal more with applications running upon CSNs rather than communications within the CSN itself.

The most relevant work in this area is a survey by Radhakrishnan et al. [9]. This work focuses on MAC (data link layer) and routing (network layer) protocols

when approaching the PvTP problem. Radhakrishnan et al. detail several relevant works in these areas and discuss the relative efficacies of the various approaches.

Prior to the examination of communications Radhakrishnan et al. provide an overview of some of the common terms used when referring to CSN formations. A trailing formation, sometimes referred to as 'leader-follower', involves a single orbit chain. A cluster is more broad and generally refers to a collection of satellites in multiple orbits which maintain an in-orbit and inter-orbit topology. The term constellation is often misused. A constellation formation focuses on coverage of the earth's surface. Communications and GNSS constellations typically seek to achieve complete coverage or 'visibility' of the earth's surface. The term swarm, is again often misused. A swarm is not a satellite formation in the same sense as a cluster or constellation. To quote Sundaramoorthy et al. "a satellite swarm is a group of identical, minimal, self-organised (self-functioning) satellites in space that achieve a common objective with their collective behaviour" [105]. Radhakrishnan et al. adopt the same definition as Sundaramoorthy et al. Similar to the concept of a swarm is the concept of a fractionated network wherein "the functionalities of a single large satellite are distributed across multiple modules, which interact using wireless links" [105] (Figure 16). In this work we consider CSNs which fly in cluster formations and operate as swarms.

2.3.1 Physical Layer

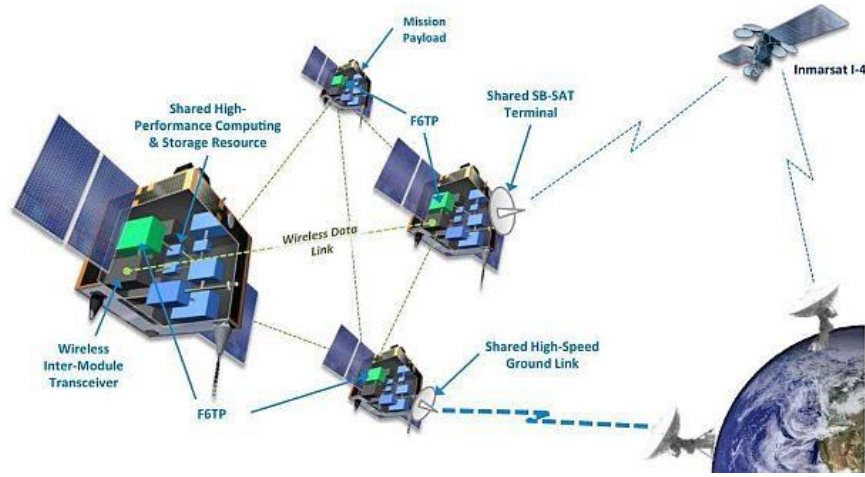


Figure 16 DARPA fractionate satellite concept. It can be seen that the mission payload exists independently of other core systems such as compute and communications. Image Credit: DARPA

Although the physical layer of OSI model is not core interest in this work it is nonetheless worth noting some of the findings of Radhakrishnan et al. When referring to the maximizing data rates Radhakrishnan et al. recommend the increase of bandwidth rather than the reduction of the S2N ration. They also cite that higher S2G data rates can be achieved by transmitting in burst rather than continually [106]. This intermittent S2G communication approach is adopted by this work. In terms of modulation and coding schemes employed at the physical layer Radhakrishnan et al. cite Binary Phase Shift Keying (BPSK) as the current state of the art for small satellites. Quadrature Phase Shift Keying (QPSK) and offset-QPSK are noted for potential future development provided additional bandwidth is balanced by the increased power requirements.

In comparison to other areas of CubeSat communications, there has been notably more work published relating to antenna design. Radhakrishnan et al. point to Gamalink [41] for its use of an advanced antenna. Unfortunately, no further information regarding Gamalink is offered. Single patch S-band (2 – 4 GHz) antennae are highlighted as the current state of the art. Also, the authors state that “a maximum distance of 1000 km between satellites can be achieved using a 3 W transmit power” using UHF (300 MHz and 3 GHz) radios [45]. This assertion seems dubious considering the work previously discussed in relation to CubeSat communication capabilities. Radhakrishnan et al. express doubts regarding the applicability of complex MIMO and multi-patch antenna, instead recommending the use of multiple antennae. To conclude the discussion of the physical layer aspects of small satellite communication Radhakrishnan et al. state that links between satellites are typically full duplex typically favouring Time Division Duplex (TDD) over Frequency Division Duplex (FDD).

2.3.2 Data Link Layer

Thus far the data link, or simply ‘link’, layer has been referenced in relation to Medium Access Control (MAC). Although the focus in this work will continue to be placed on MAC protocols, it is worth noting some of the other duties of the link layer: framing, synchronization, error control, flow control and MAC addressing. MAC protocols determine how multiple agents share a common radio medium. As such MAC protocols have a considerable effect on energy efficiency, network scalability, channel utilization, latency and throughput. There are two main classifications of MAC protocol: contention based and contention free. Contention based protocols such as Carrier Sense Multiple Access (CSMA) rely on detecting

when the medium is in use and when two signals have collided on the medium (contention). Contention free protocols seek to completely avoid the need to detect medium use or collisions. Such protocols generally achieve this by allowing multiple agents to communicate at once without collision such as with Code Division Multiple Access (CDMA) or by logically dividing the medium such as with Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) (Figure 17).

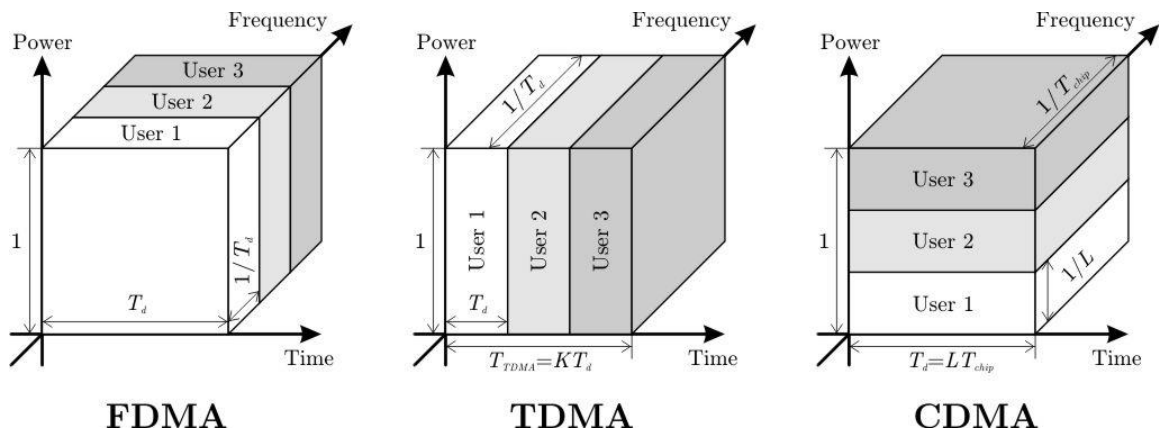


Figure 17 A comparison of common contention free MAC schemes. In CDMA a 'chip' is used to insure that signal on the medium are orthogonal and therefore cannot collide. Image Credit: IEEE Wireless Projects

Several MAC protocols are discussed by Radhakrishnan et al. in relation to small satellite communication. One approach attempting to adjust the IEEE 802.11 physical and MAC standard for communications in LEO [107]. As discussed in relation to VANETs several aspects of 802.11 based standards are unsuitable for space based communications. The modified 802.11 based approach addresses issues relating to inter-frame spacing (IFS). In LEO networks propagation delays may be in the order of milliseconds and can often be difficult to predict prior.

Using known propagation models and GNSS based information the modified 802.11 approach adjusted contention windows to fit communication delays. The distributed adjustment of IFSs and contention windows introduces considerable complexity at scale. The designers of this modified 802.11 approach assert its feasibility for use in LEO communications. However, it is this Author's opinion that the modifications introduced solve a problem left-over from terrestrial communications that need not exist in the first place.

A work, also led by Radhakrishnan, explore the use of a CSMA style MAC protocol [108]. A protocol using CSMA with Collision Avoidance (CSMA/CA) is examined. The proposed protocol makes use of control packets to address problems such as the hidden node problem. In the hidden problem some node B can hear nodes A and C. However, nodes A and C cannot hear one another. Both A and C may see the medium as free and attempt to communicate to B. Request To Send (RTS) and Clear To Send (CTS) packets control packets can ameliorate this issue. A and C can avoid communication with B until receipt of an appropriate CTS packet from B. In their assessment of this CSMA/CA approach Radhakrishnan et al. conclude that the protocol is best applied in situations with low frequency communications within tightly grouped formations. Generally, CSMA and other contention based schemes are liable to introduce unnecessary and wasteful communications adversely affecting power consumption.

Researchers at the University of Delft propose a CDMA based MAC protocol for use in "Precision Formation Flying" (PFF) missions [109]. The proposed protocol employs a form of half-duplex CDMA which allows for the networks to adaptively scale and reconfigure as new members are introduced. The CDMA scheme was

shown to have adverse effects on the ranging and navigation required for PFF missions. As such, the protocol's designers recommend the use adaptive transmission power control mechanisms. PFF missions require high frequency low latency communications. Given this, CDMA may be the best approach. However, for the CSN PvTP challenge, the additional power requirements of CDMA are not matched by obvious benefits in throughput.

Radhakrishnan et al. discuss a protocol proposed by Chen et al. dubbed "Load Division Multiple Access" (LDMA). LDMA is a hybrid MAC protocol which utilizes a mix of TDMA and CSMA in an attempt maximize channel (medium) utilization and therefore throughput. LDMA allows network elements to operate in two different modes High Contention Level (HCL) and Low Contention Level (LCL). HCL mode is used in response to high levels of communication which may result in numerous collisions whereas LCL is used in inverse situations. In HCL mode TDMA is used. TDMA protocols rely on a schedule of time slots shared among network members. Each time slot is assigned an owner. During a time slot only the slot owner may transmit (Figure 17). There are many different flavours of TDMA. For instance schedule and slot ownership may be fixed or may be negotiated between nodes in a distributed manner. LDMA uses a fixed TDMA scheme.

In LCL mode, a version of CSMA is used. Nodes in LDMA may be in differing modes at any one time. As such, when a node is in LCL mode it gives priority to the owner whenever collisions are detected on the medium. In response to collisions nodes will generate conflict frames. Nodes switch from LCL to HCL based on the number of conflict frames received. Nodes will revert to LCL mode

as their communication demand drop sand the number of overhead conflict frames reduces.

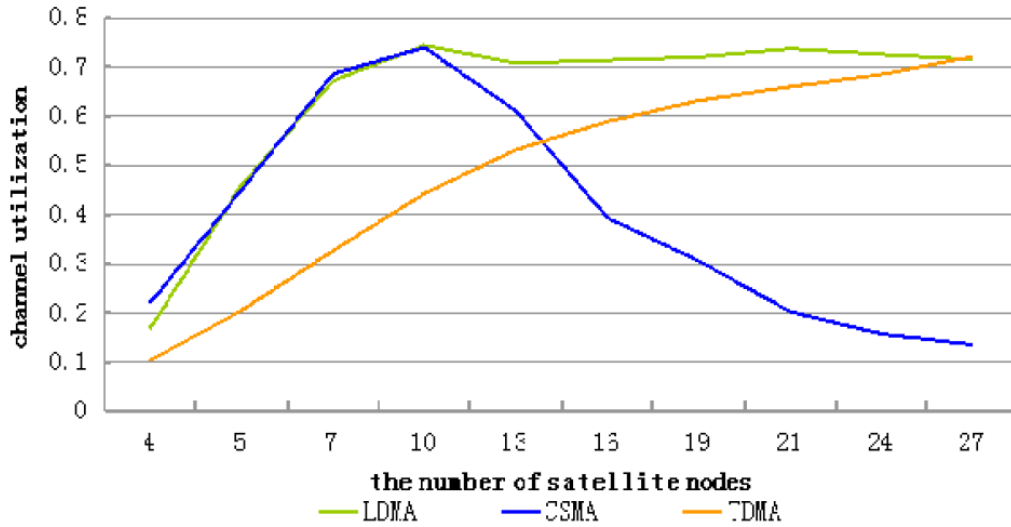


Figure 18 Cannel utilization (Vertical axis), measured from 1.0 (100%) to 0, compared to network size (Horizontal axis) for LDMA, pure CSMA and pure TDMA.

Cannel utilization generally refers to the percentage of time for which the common radio medium is used for communication of data. The communication of data being distinct from the communication of protocol control information. Cannel utilization is best measured under steady state heavy loading conditions wherein a node always has a data pending to send. When correctly measured cannel utilization is a key indicator of the overall throughput performance of a network. Chen et al. compared LDMA to pure TDMA and CSMA protocols through simulation. One graph representing their findings is shown in Figure 18.

LDMA presents itself as strong candidate for use in attempting to optimize throughput for CSNs. As communication activity falls the protocol mirrors a pure

CSMA approach and conversely it approaches pure TDMA as activity increases. The power consumption profile of the protocol merits further investigation. The protocol requires nodes to be promiscuous in order to overhear conflict frames and mode change broadcasts. Leaving radios constantly in a receiver mode will incur a power consumption penalty over time. In comparison, certain TDMA protocols allow nodes to sleep their radios for periods within slots which they do not own.

Two further hybrid approaches are discussed by Radhakrishnan et al.: An FDMA/TDMA (F/TDMA) hybrid and a CDMA/TDMA (C/TDMA) hybrid. The F/TDMA protocol, based on WiMedia [110] and proposed by Heidari et al. is only worth mentioning briefly. The protocol introduces the distributed management of heterogeneous network state as well as two-dimensional super frames in place of TDMA time slots. The C/TDMA protocol takes a cluster based approach to the division of CDMA and TDMA [111]. Comparatively the C/TDMA protocol provides many of the same properties as the aforementioned F/TDMA protocol without the prohibitive levels of complexity.

The C/TDMA protocol was chosen as the starting point for the MAC protocol proposed by this work. As such, the details of the protocol will be discussed at length in the Proposed Protocols chapter rather than within this section. The protocol was chosen as it makes explicit allowances for energy awareness and the improve of throughput. For a given scenario involving a trailing formation, simulations of the protocol show outperforming the previously discussed CSMA/CA approach (Figure 19). The protocol's formation of clusters is based on the energy available to nodes. Node's with higher levels of remaining power are

elected as cluster “Masters” which act as routers between clusters. This allows other nodes within the cluster to conserve energy.

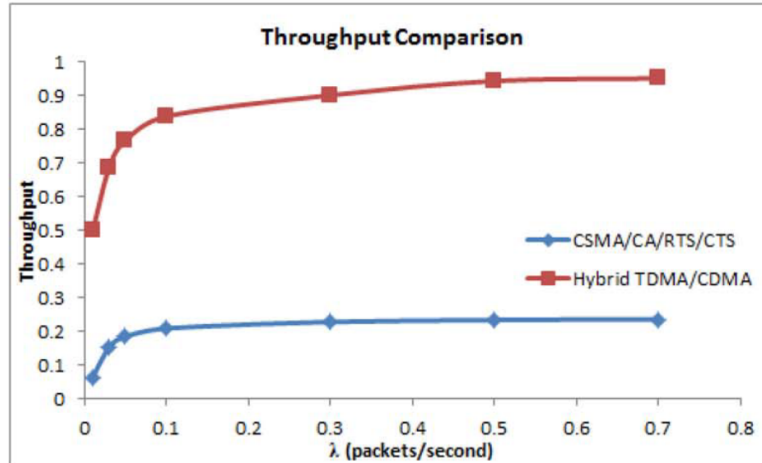


Figure 19 Throughput here is measured as the amount of time spent transmitting data divided by the amount of time available to transmit data. Considering the findings in Figure 18 It is likely that the experimental setup and the traffic simulated naturally favoured the T/CDMA protocol. Image Credit: [111]

2.3.3 Network Layer

The primary responsibility of the network layer is routing, although packet forwarding and address handling are also important activities. Routing protocols effect the discovery and selection of optimal routes within a network. There are several generally applicable approaches to the discovery of routes discussed in the context of MANET routing protocols. Unlike discovery, the selection of optimal routes is often highly application dependent. For instance, in the context of this work, there may be benefits in avoiding routes which involves nodes with a low amount of remaining power. The approaches to determining and maintaining optimal routes differentiates many of the routing protocols proposed for small

satellites. It should be noted that there has been less published work relating to the routing protocols than to MAC protocols. As evident from the Nodes and Tianwang missions, the current state of the art for CubeSats are small one-hop networks. Such networks do not require robust approaches routing. In these networks rarely need to perform route discovery or chose between multiple routes. As such, the network's performance is predominantly determined by the layers below the network layer.

Radhakrishnan et al. discuss a number of routing protocols in their survey of inter-satellite communication for small satellites [9]. The authors highlight routing approaches which have been adapted in the past for use with larger satellites such as the Border Gateway Protocol (BGP) [112] and Multi-Layered Satellite Routing (MLSR) [113]. Unfortunately, the authors make no comment on suitability of these approaches for small satellites. This is a theme throughout the author's discussion of routing protocols which reflects the scarcity of relevant research in this area. For instance the authors discuss delay tolerant networking (DTN) at length. DTN has been proposed recently by some for small satellite applications but no notable works thereon have yet to be produced.

An approach proposed by Bergamo et al. involves each node classifying its neighbours as either 'new' or 're-occurring' [114]. The approach is similar to that of AODV however the classification of neighbouring nodes reduces the overall frequency of route discovery. The protocol mainly focuses on synchronization of larger satellites with regular control orbits. However, this protocol may have benefits in situations involving CSNs composed of multiple swarms in disparate orbits.

Of the routing protocols discussed by Radhakrishnan et al. few are obviously suitable to CSNs and none deal directly with the balance of energy efficiency and throughput. As such, prior art relating to MANETs and WSNs informs the choice of proposed routing protocol.

Radhakrishnan et al. recommend further work on cross-layer optimization (CLO) and the introduction of protocols which adapt naturally to predictable topology changes. Not recommendation that further work be carried out on routing however, it there is clear need for such work. Radhakrishnan et al.'s survey is a valuable resource when approaching the domain of CubeSat communications. The authors cover the physical and data link layers well but fail to discuss and identify the gaps in relation to network layer protocols. Also, worryingly, the authors provide considerably more content for works on which one or more of the authors were involved.

2.3.4 Other Works

Wong et al., operating mainly out of NASA's Goddard Flight Centre, examine a potential future for CSNs. Wong et al. propose that space to ground communications be performed indirectly through relay with existing space bound communication networks [10]. This concept is further explored for deep space missions in the preliminary development of the ESA's COPINS mission [60].

Another survey style paper on inter-satellite link for CubeSats by Budianu et al. [8] published in 2013 provides a somewhat out of date overview of the field. However, Budianu et al. pay more attention to antenna design and link budget analysis than Radhakrishnan et al.

2.4 Other Areas of Note

Alongside the primary areas of concern there are secondary areas which are deemed to be less relevant to this work. These secondary elements illustrate further the considerable context which must be considered when approaching issues relating to CubeSat networking and communications.

2.4.1 Energy Aware Scheduling

Energy aware scheduling is an active area of research in the terrestrial domain, especially in relation to WSNs [115]. Despite the growing popularity of small form factor satellite missions, there are few related notable publications in the domain. However, new insights into the area was produced 2016 the technology demonstration focused GomX-3 [116] mission. GomX-3 was designed by private Danish company GOMSpace and flown by ESA. Following the mission's succession, mission designer published a work entitled "Battery-Aware Scheduling in Low Orbit The GomX-3 Case " [61]. The work outlines the approach taken to adaptively model and predict battery usage in order to produce a activity schedule which optimized power consumption. In relation to long duration CSNs, one might consider an energy conservation scheme which entails generating an optimal schedule for each CubeSat. Through distributed consensus these schedules could then be used in order to generate final desired activity schedules.

2.4.2 Delay Tolerant Networking



Figure 20 An illustration of several NASA Tracking and Data Relay Satellites (TDRS) which make the primary backbone of NASA's deep space network. Some of the most advanced space bound radios enable the relay of signals from spacecraft throughout the solar system.

Interplanetary communication presents many novel problems. Delay tolerant networking (DTN) approaches have been employed successfully solved many of these [117]. A notable success case is NASA's deep space network [118] (Figure 20). Although CSN's don't face the same magnitude of challenges presented by inter-planetary communication many, including Radhakrishnan et al., point to DTN as important to the future of CSNs. DTN has the obvious advantage in this regard of being tested on-board larger satellites and developed by experts within the space industry.

Chapter 3: Proposed Protocols

3.1 Introduction

...

3.2 Assumptions

... Large sections covering basis, defence and compromise of all relevant assumptions

3.3 Restrictions

...

Chapter 4: Simulation

4.1 Introduction

... Include formations/scenarios examined

4.2 OMNeT++

...

4.3 Protocol Implementation

...

4.4 Simulation Design

... Assumptions, simplifications etc.

4.5 Simulation Analysis

...

4.6 Discussion

...

Chapter 5: Results

5.1 Introduction

...

5.2 Key Metrics

...

5.3 Simulation Results

...

5.3.1 Scenario 1

...

5.3.2 Scenario 2

...

5.3.3 Scenario 3

...

5.4 Discussion

Chapter 6: Conclusions

6.1 Discussion

...

6.1.1 Space Junk

...

6.1.2 Mission Design

Those familiar with mission planning and satellite technology will note that there is little treatment of mission operational requirements and technology readiness. These omissions allow a focus on the PvTP challenge by ignoring many of the realities mission design. In reality, space bound technology must be thoroughly understood, tested and generally as simplified as possible. There are hints of this in the design of NASA's EDSN and Nodes missions. Mission designers opted to design a protocol rather than implement an existing one. This has two clear benefits; It allows for complete knowledge of the protocol by mission designers and operators and it greatly reduces the risk of the existence of unknown bugs or flaws.

Once a satellite is in orbit there is little that can be done to fix issues. As such, mission designers tend to focus on simple, easily-understood and if possible space-tested approaches. Both CubeMac and DYMO are less complex than some

current MAC and Routing protocols but, there are definitely less complex approaches in existence. For instance, why not adopt pure TDMA and DSR? The approach may not be as performant but it would be simple to test in simulation prior to launch and issues in orbit would be easily understood.

This preference towards simplicity provides part of the motivation behind protocol design choices, especially with CubeMac. There are several protocols such as ... and ... which could have provided a basis for CubeMac [9]. However, it was not felt that the added complexity of these protocols added suitable benefits.

...

6.2 Future Work

...

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