… CubeSat Networks …

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Acknowledgments

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Abstract

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Contents

Figures

Tables

No table of figures entries found.

Abbreviations

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

Chapter 1: Introduction

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

1.1 Background

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

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

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

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

As a result of the lowering unit costs to LEO and the increasing affordability, availability and capabilities of CubeSat components, CubeSat mission have become increasing ambitious [17-19]. This project focuses on a particular subset of emerging CubeSat missions which involve networked swarms of CubeSats; these will simply be referred to as CubeSat networks (CSNs). The multi-CubeSat missions offer greater redundancy which addresses the platform's limited power and durability. Missions which involve CSNs seek to advance the platform by introducing varying degrees of autonomous cooperation and coordination between CubeSats. It is this cooperation and coordination that presents various new CubeSat mission applications. CSNs stand to enable the collection of greater volumes of scientific data, novel interferometry [20], high fidelity sensory data, inexpensive low-data rate terrestrial communications and improved air traffic monitoring [21]. The space industry has taken the first crucial steps into designing and testing CSNs with missions such as NASA's EDSN [22] and Nodes [12] and CNSA's Tianwang-1 [23].

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

1.2 Objectives

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

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

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

1.3 Thesis Structure

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

The State of the Art chapter …

The Proposed Protocols chapter …

The Simulations chapter …

The Results chapter …

Finally the Conclusions chapter …

Chapter 2: State of the Art

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

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

2.1 CubeSats

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

CubeSats were first proposed by Bob Twiggs of Stanford University and Jordi Puig-Suari of California Polytechnic State University in 1999 [24]. In 2000 the first published work detailing a new CubeSat standard was published [25]. The platform was intended as an answer to the prohibitive costs and challenges involved in low-resource academic satellite development. At the time, there were effectively no standard approaches or components for the design and implementation of small satellites. Researchers relied almost entirely on acquiring a place for instruments on larger satellites or pursuing the development of research satellites as lengthy collaborations across multiple research institutions. Frequently, research only required satellites with basic capabilities.

2003 saw the first launch of a CubeSat on-board a Russian Eurorockot [24]. At the time of writing there have been 487 CubeSats launched [25] since 2003. Spread across 14 years this number may seem unimpressive however, approximately 75% of all these launches have taken place during the previous 5 years. This is due almost entirely to the recent boom in the private space industry which has greatly lowered the cost of access to LEO [1].

Thanks in large part to a San Francisco based company named Planet Labs [26], roughly 40% of all launched CubeSats were developed by commercial entities. Comparatively, academic/research institutions have developed approx.. 40% and the remaining 20% is divided between civilian and military institutions. In terms of use cases, roughly 60% of all missions are dedicated to earth imaging, 20% to technology demonstration, 10% to education, and the remaining 10% is divided between various commercial, military and science applications [25].

Unsurprisingly, the core motivation behind the recent popularity of CubeSats is their cost. Costs are driven down by three factors, the use of COTS components, open sourcing, and reduced launch costs. Effectively every component of a modern CubeSat is available in COTS form. Retailers such as Clyde Space offer a wide range of products from power to attitude determination and control systems [27]. COTS components reduce costs significantly by removing the need to develop or source custom components from third parties.

Combined with COTS components open sourcing lowers costs further by reducing development time and the need for expertize. Open and often proven approaches for both soft and hard CubeSat systems are becoming widespread as the platform develops [3]. Although this may seem intuitive, such sharing and open-sourcing of work in the satellite industry has been historically rare. To date, there is no accepted standards body for the domain. Researchers such as Puig-Suari at the California Polytechnic State University (CalPoly) have driven the domain forward since its inception, creating a number of pseudo-standards. Crucially, CalPoly lead the development and design of standard CubeSat deployers [28]. Such deployers became common place have come to defined the de-facto standards for the domain. A similar pattern can be seen elsewhere in the domain such as with the development of a pseudo-standard satellite bus design [29]. Recently, "OpenOrbiter" by Straub et. al from the University of North Dakota is a prime example of open pseudo-standard framework for CubeSat development [30].

Depending on the complexity of the CubeSat, development costs may range anywhere from $50,000 to $250,000 [31]. This can be compared to a development cost in the order of millions of dollars for larger satellites weighing over 100kg. A similar gap has emerged in terms of launch costs. Satellites over 100kg may see launch costs in the order of hundreds of thousands if not millions of dollars, depending on the launch vehicle and orbital requirements. CubeSats avoid these costs by 'hitching' a ride alongside larger payloads using volume and lift capacity not required by primary or secondary payloads. Providers such as SpaceX have disruptive the satellite industry further by offering greatly reduced cost access to LEO [32]. These factors have led to CubeSat launch costs as low as $10,000 [31]. With recent development towards multi-CubeSat and CSN mission, multiple CubeSats may take the place of their larger counterparts at a fraction of the cost. CubeSats are also making the move beyond LEO with new developments towards deep space and lunar applications [16, 18].

2.1.1 CubeSat Capabilities

… *1-2 pages*

2.1.2 CubeSat Applications

… *1-2 pages*

2.2 Terrestrial Communications

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

2.2.1 Wireless Sensor Networks

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WSN data collection is examined by Francesco et al. in their extensive survey paper of 2011 [33]. The work is particularly useful as it focuses on WSNs with mobile elements (WSN-MEs). It places a strong focus on mobility while maintaining and referencing the existing relevant state of the art in WSN routing, data collection, power management and so on. In many respects, this work by Francesco et al. represents an ideal overview of WSNs topics which are relevant to CSNs. Complementing this work is another survey by Rault et al. published in 2014 which examines energy efficiency in WSNs [34]. The work approaches WSNs in more general terms. It's value, in a similar manner to the aforementioned survey, comes from the exploration of the many dimensions of its focus covering relevant elements across several WSN topics such as routing, duty cycling, mobility and so on.

2.2.2 Mobile Ad-Hoc Networks

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There is, as suggested by the existence of WSN-MEs, often considerable overlap between paradigms within the fields of MANETs and WSNs. This overlap is quite obvious when comparing the work of Aung et al in their review of “group mobility models for mobile ad hoc networks” [35] and the aforementioned work of Francesco et al. In general, the most discussed and active topic within MANETs is that of routing. In this regard the work of Mohseni et al. in their survey of routing protocols in MANETs [36] provides a more detailed view of many of the aspects mentioned in brief by Francesco et al.

Finally, the area of VANETs, contains many parallels to CSNs. In fact, there is a further concentration of VANETs dubbed FANETs (Flying Ad-Hoc Networks) [37]. A survey by Bekmezci et al. introduces MANETs and VANETs and in the context of both fields FANETs. The authors deal primarily with unmanned aerial vehicles (UAVs). As expected, FANETs, as described, are a sub-class of VANETs which include many of the same challenges, restriction and properties of CSNs.

2.3 CubeSat Communications

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Even before missions implementing CSNs had begun development the academic community produced several works examining the inter-communication of CubeSats. Most notably Challa and McNair of University of Florida provide extensive explorations of distributed applications implemented on CSNs [38-42]. These works are somewhat out of the scope of this project as they deal more with applications running upon CSNs rather than the operation of the CSN itself. Despite this, these works provide an insight into potential future applications of CSNs .

The most relevant work in this area is the extensive survey of “Inter-Satellite Communication for Small Satellite Systems” by Radhakrishnan et al. [9]. The survey provides an overview of the state of the art as well as a roadmap for exploring numerous areas within the field. The survey focuses on the physical, data link and network layers of the OSI networking reference model [43]. The authors detail relevant prior art in these areas and provide analyses of the relevant efficacies of the various approaches. Another work involving authors of the aforementioned survey paper provides the starting point for simulations. The work examines potential optimal MAC protocol implementations for small satellite systems [44].

Although the work by Radhakrishnan et al. is by far the most relevant there are other works worth mentioning which inform the current state of the art. Wong et al., operating mainly out of NASA’s Goddard Flight Center, examine a potential future for CSNs where space to ground communications are performed through relay with existing space bound communication networks [10]. This concept is explored for deep space missions in much of the preliminary development of the COPINS mission [45]. Another survey style paper on inter-satellite link for CubeSats by Budianu et al. [8] published in 2013 provides a broader overview of the field with more attention to antenna design and link budget analysis. The authors only touch briefly on networking protocols making the work less relevant in this case.

Lastly, the SDR based “Gamalink” [46] technology of Tekever is prevalent in the design of many recent missions involving CSNs and, in fact, small satellite crosslink communications in general. The technology is employed in the design of the aforementioned Tianwang-1, Proba 3, QB50 missions as well as several others. Gamalink is mentioned in several works with varying degree of relevancy to this project [47-51]. The technology is unquestionably the current state of the art in “turnkey” inter-satellite communications for small satellite form factors. Unfortunately, the implementation details of Gamalink are carefully restricted, perhaps to protect IP but also perhaps the technology may also see use for military applications. Considerable effort was dedicated to attempting learn the implementation details of Gamalink. Despite contacting various persons involved in the development of the technology and examining all relevant literature no concrete details as to the MAC and network protocols used by Gamalink were obtained.

2.3.1 Space-to-Ground

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2.3.2 Satellite-to-Satellite

… Gamalink, introduce with press release material – SP7 etc.

2.4 CubeSat Network Missions

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2.4.1 Previous Missions

There are three major missions to consider in the area of CSNs: NASA's EDSN and Nodes, and CNSA's Tianwang-1 (TW1). Of these missions, both Nodes and TW1 have flown. The EDSN or "Edison Demonstration of Smallsat Networks" was unfortunately lost due to a failure during launch. The mission is still worth investigating however as remaining EDSN craft we used during the successful Nodes missions.

The two most informative works on the EDSN mission were both published in 2014, prior to the loss of the mission payload in November 2015. The first work, authored by Hanson et al. examines the inter-satellite communications architecture of the mission [52]. The second work, authored by three of the four authors involved in [52], examines the development lessons learned throughout the mission [53]. These works provide insight extensive insight into the missions S2G and crosslink communications hardware and capabilities thereof as well as the energy profile of each CubeSat.

"Nodes" is the direct follow on from the EDSN mission which uses leftover CubeSat's from the EDSN mission. In general all the salient details regarding the EDSN mission still apply. The changes made to the Nodes mission relate primarily to on-board software and are detailed by Hanson et al. in a work published in 2016 following the mission's successful launch, deployment and conclusion [12]. As many of the changes were software based the paper provide useful insight into the communications protocols utilized. To date this is the only published work relating to the mission.

The CNSA's Tianwang-1 (TW1) mission, also referred to as STU-2, is a 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 [54, 55]. A presentation by Wu et al. during the 30th Annual AIAA/USU Conference on Small Satellite (2016) offers an brief overview of the mission's communication systems [56]. The technology used to implement inter-satellite networking, "Gamalink" was supplied by Tekever. The details of which are difficult to come by despite the fact that the Gamalink project was funded by the European Commission's CORDIS project [46]. Clearly, there is IP relating to Gamalink that belongs to parties such as Tekever which is restricted from publication.

There are other mission other than those ones details here that can provide an insight into the general development of CSNs: ESA's AIM COPINS [45], GomX-4 [57, 58] and Proba-3 [59], NASA's CPOD [60] and TROPICS [61], QB50 [62] and OLFAR [63]. These missions are, at the time of writing in development or awaiting a launch date with the exception of COPINS which was defunded.

2.4.2 Future Missions

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2.5 Other Areas of Note

...

2.6 Summary

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Chapter 3: Proposed Protocols

3.1 Introduction

… Objectives, Requirements, Restrictions

3.2 Objectives

…

3.3 Assumptions

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

3.4 Restrictions

…

3.5 Summary

…

Chapter 4: Simulation

4.1 Introduction

… Include formations/scenarios examined

4.2 OMNeT++

…

4.3 Protocol Implementation

…

4.4 Simulation Design

… Assumptions, simplications etc.

4.5 Simulation Analysis

…

4.6 Discussion

…

Chapter 5: Results

5.1 Introduction

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5.2 Key Metrics

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5.3 Simulation Results

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5.3.1 Scenario 1

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5.3.2 Scenario 2

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5.3.3 Scenario 3

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Chapter 6: Conclusions

6.1 Discussion

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6.2 Future Work

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References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[28] J. Puig-Suari, J. Schoos, C. Turner, T. Wagner, R. Connolly, and R. Block, "CubeSat developments at Cal Poly: the standard

deployer and PolySat," in *Proceedings of SPIE-The International Society for Optical Engineering*, 2000, pp. 72-78.

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

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

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

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

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

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

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

[36] S. Mohseni, R. Hassan, A. Patel, and R. Razali, "Comparative review study of reactive and proactive routing protocols in

MANETs," in *Digital ecosystems and technologies (DEST), 2010 4th IEEE international conference on*, 2010, pp. 304-309.

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

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

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

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

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

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

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

[44] R. Radhakrishnan, W. W. Edmonson, F. Afghah, J. Chenou, R. M. Rodriguez-Osorio, and Q.-A. Zeng, "Optimal multiple

access protocol for inter-satellite communication in small satellite systems," in *4S Small Satellite Systems and Services Symposium*, 2014.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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