… CubeSats … Novel … Networks …



Stephen Ennis

Supervisor: Jonathan Dukes

School of Computer Science and Statistics

Trinity College Dublin

*M.A.I. Computer Engineering*

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Thanks be to Dr. Jonathan Dukes for his seemingly infinite patience and wisdom.

Abstract

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Abbreviations

LEO Low Earth Orbit

SMB Small to Medium Business

COTS Commercial Off-The-Shelf

ADCS Attitude Determination and Control Sub-systems

C&DH Command And Data Handling

ISS International Space Station

CSN CubeSat Network

NASA National Aeronautics and Space Administration

EDSN Edison Demonstration of Smallsat Networks

CNSA China National Space Administration

S2G Space To Ground

WSN Wireless Sensor Network

MANET Mobile Ad-hoc Network

ISC Inter-Satellite Communiction

# 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 CubeSat satellite platform and networks thereof. The core objectives of this work and the general structure of this document are also covered.

## 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 which 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 (usd) 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 rise of small satellites. Small satellites, in a general sense, refers to a group of satellite weight classes: ‘Small’, ‘Micro’, ‘Nano’, ‘Pico’ and ‘Femto’. 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 exceptional popularity over the past decade [3].

The CubeSat standard, as the name suggested is based on cube form factor. Cubes are 10cm in dimension and often referred to as units. Multiple units are often combined in order to form larger CubeSats, with 6 unit configurations typically being the largest form factor [4, 5]. CubeSats are unique in that there is considerable open-sourcing of design and implementation thereof which has been historically rare in the satellite industry. 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, their primary applications remain within the educational and academic domain [14].

What gives CubeSats, and other small form factors, an edge on other larger form factors is that the accepted size and weight constraints allow CubeSats to ‘hitch’ a ride alongside larger launch payloads. Effectively all modern launch payloads are designed to match the capabilities of the launch vehicle. Frequently, vehicles will have some spare volume and available lift thrust. In these cases multiple launchers have be devised which can make use of unused space and launch CubeSats along with the vehicle’s primary payloads [15, 16]. In cases where cargo and/or personnel are being delivered to the ISS, CubeSats often hitch a ride to be 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 added redundancy of multi-CubeSat missions addresses the platforms limitations on power and durability. Missions which involve CSNs advance the platform one step further by introducing varying degrees of autonomous cooperation and coordination between CubeSats. It is this cooperation and coordination that presents exciting new CubeSat applications. CSNs open numerous new possibilities such as the collection of greater volumes of scientific data per mission, CubeSat interferometry [20], increased fidelity sensory data, inexpensive low-data rate 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 builds upon the mission and flight data from the aforementioned missions and seeks to explore certain fundamental aspects of the networking approaches employed in CSNs. In particular, this work attempts to identify how scientific CubeSat mission applications may approach CubeSat networking in order to optimize space to ground (S2G) data throughput with network power consumption.

## Objectives

In many regards CSNs are similar to networks to which computer scientists and engineers are accustomed such as wireless sensor networks (WSNs) and mobile ad-hoc networks (MANETs). This work aims to take state of the art concepts from both of these fields and apply them to CSNs. This is not to say that the existing CSN state of the art is not strongly based on work in these fields, as it most certainly is. Work in academic domains prior to the design and launch of the first CSN covered many aspects of interest but was forced to make several assumptions as to the capabilities and dynamics of CSNs. Now that CSN missions have successfully flown there is clear opportunity to assess the assumptions made by previous work and adapt future approaches.

The general motivation of this work is to assess CSN **network layer protocol design** in light of both existing academic work relating to WSNs, MANETs, CubeSat networking, and the design, implementation and flight data of CSN based missions. As mentioned, there are numerous varied applications of CSNs. As such, this work seeks to examine a generic and common scientific application. This chosen application employs **a number** of CubeSats each of which has an identical scientific instrument. This scientific instrument produces some data and it is then objective of the CSN to coordinate in order to communicate this data to ground. Even in this simplified and general case there are many complications to consider such as the power consumed by S2G communications and inter-satellite communication (ISC), which is sometimes referred to as crosslinking. For the scientist on the ground the core concern is the quality and the quantity of the data received. In this work we assume that the issues of data quality are fully addressed by the scientific instrument. This leaves the quantity of data received as the metric for success for this hypothetical scientific mission. This leads to more specific objective of this work; to explore CSN **network layer protocol design** in order to identify approaches which may increase overall data throughput to ground. As alluded to, this may be achieved by increasing the longevity of the missions and/or the rate at which data is transmitted to ground. This exemplifies the core problem which this work attempts to address; the balance of S2G throughput versus power consumption.

In terms of CubeSat power, ISC is expensive however, S2G communication is considerably more so. This presents an optimization problem. Increasing the amount of S2G communication will increase S2G throughput of course but it will also consume more battery overall and reduced the amount of possible sensing. ISC 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 ISC will be wasteful in scenarios where all CubeSats have enough battery and suitable S2G windows to perform S2G communications. It is in this context that the core technical objectives are framed. Any solutions proposed by this work intend to address the primary objective with direct consideration to balancing CubeSat power consumption with S2G throughput.

## 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 just enough material for lay-readers to understand the context and general scope of the project but stops short of introducing in depth the CubeSat platform, LEO environments and NanoSat applications.

The State of the Art chapter …

The Proposed Protocols chapter …

The Simulations chapter …

The Results chapter …

Finally the Conclusions chapter …

# State of the Art

## Introduction

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## CubeSats

…

### CubeSat Capabilities

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### CubeSat Applications

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## Inter-Satellite Communications

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### Gamalink

… *Introduce with press release material – SP7 etc.*

## Wireless Sensor Networks

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## Mobile Ad-Hoc Networks

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## Missions

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### Previous Missions

…

### Future Missions

…

## Summary

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# Proposed Protocols

## Introduction

… *Objectives, Requirements, Restrictions*

## Objectives

…

## Assumptions

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

## Restrictions

…

## Summary

…

# Simulations

## Introduction

… *Include formations/scenarios examined*

## Simulation Workflow

… *Pretty pictures*

## Simulation & Analysis Tools

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### Systems Tool Kit 11

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### Satellite Network Simulator 3

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## Constellation Dynamics Simulation

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### Overview

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## Constellation Network Simulation

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### Overview

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## Discussion

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# Results

## Introduction

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## Network Performance

…

### Approach 1

### Approach 2

### Approach 3

### Approach Comparisons

## Design Considerations

## Summary

# Conclustions

## Discussion

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## Future Work

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