Research Progress Report

MAI Project 16/17

CubeSat Networks: Balancing Energy Consumption with Data Throughput Through Protocol Optimization

(working title)

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Background

Due to prohibitive costs and technical requirements, access to low earth orbit (LEO) (160 – 2,000km) 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 into LEO. In 2001 NASA's Space Transport System's space shuttle's unit cost to LEO, with a fully loaded cargo bay, was approximately $60,000 (usd). 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. 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].

The CubeSat standard, as the name suggested is based on a 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 primarily 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 systems for: 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 vital sub-systems, a CubeSat may carry a small 'payload' which is often a scientific instrument. Payloads may also be comprised of some previously 'unflown' implementation of a sub-system such as an experimental antenna [13]. CubeSats have become increasingly popular within the space industry both for testing new technologies and for commercial applications however, the majority of applications remain within the educational and academic domain [14].

CubeSats, and other small form factors, have an advantage over other larger form factor satellites due to 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, vehicles fitted with primary payloads will have some spare volume and available lift capacity. Multiple auxiliary launchers have be devised which can make use of such unused space and deploy CubeSats alongside the vehicle's primary payloads [15, 16]. For instance, 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 deployer.

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 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 by introducing varying degrees of autonomous cooperation and coordination between CubeSats. It is this cooperation and coordination that presents new CubeSat applications. CSNs present new possibilities such as the collection of greater volumes of scientific data per mission, 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].

Objectives

In many regards CSNs are similar to terrestrial networks such as wireless sensor networks (WSNs) and mobile ad-hoc networks (MANETs). This work aims to examine the applicability of state of the art concepts from both of these fields to CSNs. Existing CSN state of the art is already strongly based on work in these fields [9]. Work in academic domains prior to the design and launch of the first CSNs covered many aspects of interest to this work. However, such prior works were 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 works and adapt future approaches.

The general motivation of this work is to assess CSN network and MAC layer protocol design in light of 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 applications of CSNs. This work seeks to examine a generalised scientific application. The chosen application employs a number of CubeSats each of which has an identical scientific instrument. This scientific instrument periodically produces some data and it is then objective of the CSN to coordinate in order to communicate this data to ground. Even in this highly simplified case there are many complications to consider such as the differing power consumptions of S2G communications and satellite-to-satellite (S2S) communication, which is often referred to as crosslinking.

For scientists on the ground the core concern is typically 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 core metric for success. This leads to more specific objective of this work; to explore CSN communication protocol design in order to identify approaches which may increase overall data throughput to ground. This general objective forms the basis for similar work in this area by Radhakrishnan et al. [24]. 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 and energy consumption. Proposed protocols are assessed through several simulations scenarios constructed using the discrete event network simulator, OMNeT++ [25].

Literature Review and Scope

The relevant literature for this research project can be roughly divided into three broad categories: CubeSat missions, CubeSat communications and wireless communications. The majority of the literature review performed thus far in the project relates to the former two categories. As the development of simulation scenarios progresses further investigation into the state of the art of wireless communications will be performed.

CubeSat 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 Node 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 [26]. The second work, authored by three of the four authors involved in [26], examines the development lessons learned throughout the mission [27]. These works provide insight extensive insight into the missions S2G and S2S communications hardware and capabilities 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 communication protocol 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 [28, 29]. 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 [30]. The technology used to implement inter-satellite networking, "Gamalink" was supplied by Tekever. The details of which are difficult to obtain despite the fact that the Gamalink project was funded by the European Commission's CORDIS project [31]. Clearly, there is intellectual property 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 [32], GomX-4 [33, 34] and Proba-3 [35], NASA's CPOD [36] and TROPICS [37], QB50 [38] and OLFAR [39]. These missions are, at the time of writing in development or awaiting a launch date with the exception of COPINS which was defunded.

CubeSat Inter-Satellite Communications

Even before missions implementing CSNs began 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 [40-44]. These works are out of the scope of this project as they deal more with applications running upon CSNs rather than the implementation 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 [45]. The authors detail relevant prior art in these areas and provide analyses of the relevant efficacies of various approaches. Another work involving authors of the aforementioned survey paper provides the starting point for simulation development. The work examines potential optimal MAC protocol implementations for small satellite systems [24].

Although the work by Radhakrishnan et al. is by far the most relevant, although 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 [32]. Another survey style paper on inter-satellite links 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" [31] technology owned by Tekever is prevalent in the design of many recent missions involving CSNs and, in fact, small satellite S2S communications in general. The technology is employed in the design of the aforementioned Tianwang-1, Proba 3, QB50 missions. Gamalink is mentioned in several works with varying degrees of relevancy to this project [46-50]. The technology is unquestionably the current state of the art in "turnkey" S2S communications for small satellites. Unfortunately, the implementation details of Gamalink are carefully restricted, perhaps to protect IP but also as a result of the technology's potential military applications. Considerable effort was dedicated to attempting uncover 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.

Wireless Communications

At present, this portion of the literature review is the least explored. Nonetheless, some key works have been identified as well as potentially relevant sub-fields within the large domain of Wireless communications. 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 unknown prior to communication.

WSN data collection is examined by Francesco et al. in their extensive survey paper of 2011 [51]. 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, and power management. 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 [52]. The work approaches WSNs in more general terms. Its value, in a similar manner to the aforementioned survey, stems from the exploration of the many dimensions of energy conservation across several WSN topics such as routing, radio duty cycling, mobility and so on.

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" [53] 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 [54] provides a detailed view of many of the aspects alluded to 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) [55]. A survey by Bekmezci et al. introduces FANETs in the context of both MANETs and VANETs. The authors deal primarily with Unmanned Aerial Vehicles (UAVs). As expected, FANETs, are a sub-class of VANETs which handle many of the same challenges, restrictions and properties of CSNs.

Dissertation Structure

Chapter 1: Introduction

The Introduction chapter offers a basic overview of the project background and the motivations and objectives thereof. This chapter aims to provide enough material for lay-readers to understand the general context and scope of the project.

Chapter 2: State of the Art

The State of the Art chapter reviews relevant literature in the categories discussed in this report's literature review as well as including additional technical background material. This additional material explores relevant areas about which there is little published literature, such as proprietary industry technologies.

Chapter 3: Proposed Protocols

The Proposed Protocols chapter follows on directly from the state of the art chapter by focusing on relevant network and MAC layer protocols detailed by existing literature. In each case, the protocol's suitability for use with CSNs is explored. Modifications to existing protocols are presented in this chapter in order to provide context for the simulations chapter.

Chapter 4: Simulations

The Simulations chapter describes the simulations carried out using the network simulator OMNeT++. Each section of the simulation chapter describes a different simulation scenario, with each successive section adding a degree of complexity or adjusting the protocol under examination. This chapter also provides justifications for the key metrics of interest.

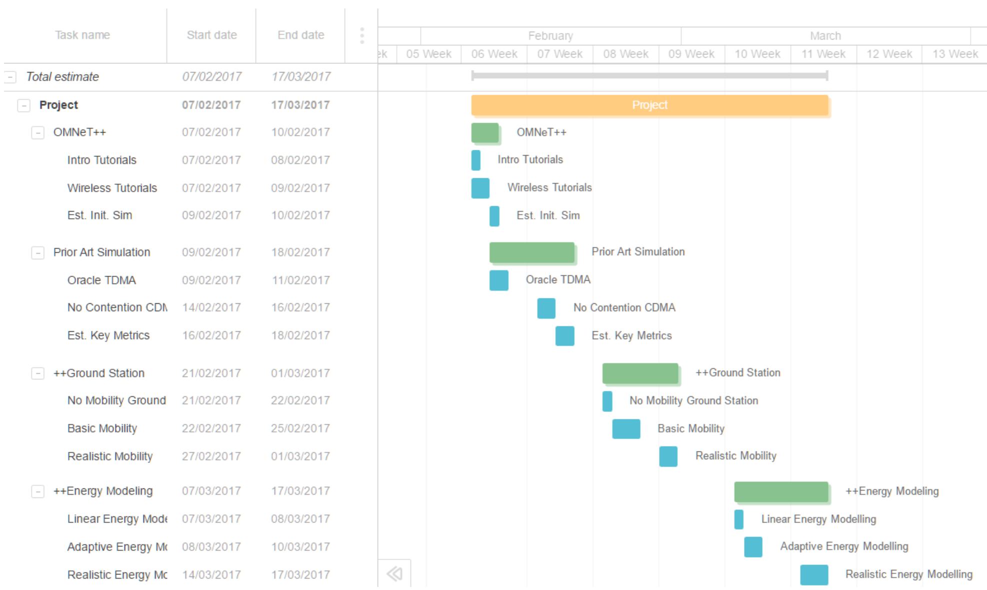
Chapter 5: Results

The Results chapter follows directly from the simulations chapter in that it is broken up into a number of sections each describing the results collected and analysed from differing simulation scenarios. The results chapter concludes with an overall comparison of the key metrics described in the simulations chapter across all simulation scenarios.

Chapter 6: Conclusions

Finally the Conclusions chapter provides a critical analysis of the results collected and discusses potential future work. The chapter also includes a broader discussion of key points from the proceeding chapters within the context of the collected results.

Bar/Gantt Chart



The accompanying figure shows a projection of the current work plan from the deadline of this report up to and including the last week prior to the allotted project demonstration period. The critical path analysis is straightforward as each major task relating to simulation development relies directly on the previous making the critical path: OMNeT++, Prior Art Simulation, ++Ground Station and finally ++Energy Modelling.

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