Modelling Low Earth Orbit Constellations for Networking

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I, Joseph Law McGuchan of King's College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose.

Signed

Date

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Contents

1 Introduction

SpaceX are planning to launch a constellation of 4,425 low Earth orbit communication satellites in the next few years. The objective of this constellation, called Starlink, is to provide low-latency internet connection across the world. It will do this using lasers, which, in the vaccum of space, travel 47% faster than in glass.

The satellites in this network will be in constant motion, not just relative to the ground, but relative to one another, creating a network with a constantly changing topology and associated latencies. The question of how to structure such a network, and what the resultant properties of said network will be, has not been thoroughly explored, but it will become increasingly relevant as more and more companies build similar constellations. If these

Constellations prove to provide significant gains in latency while providing competetive bandwidth, they might render previous submarine optical cables obsolete.

My goals are:

1. To create visualisations of the SpaceX conselations and test it's paths for latency.

This network, and networks like it, are the future of the internet.

1.1 Why Focus on Starlink?

Theoretically, my goals would allow me to focus on any constellation, and focusing my attention on Starlink runs the risk of creating algorithms that are specific to it, which might not perform as well on other networks. However, the vast amount of legislation on satellites makes it hard to know what a normal network would look like. By using Starlink we get a confirmed legal and physically possible network, on which we can build our routing algorithms.

There is another reason for focusing on Starlink. As I progress through this dissertation, I will

1.2 Existing Research

In

2 Preparation

2.1 Starting Point

2.2 What is Starlink?

As of 21/11/18, there are two companies offering sattelite internet services, Excede[**?**], and Hughes, whose 9202 BGAN Land Portable Satellite Terminal offers connection speeds up to 464kbps[2]. These companies largely target domestic use in rural areas which dont have a faster coverage, and corporations, providing internet connections to airplanes and cargo ships. Currently, Sattelite Internet connection is a last resort, something turned to when conventional means of connection are not available, Starlink intends to invert this, turning sattelite internet into the premium option,

Figure 1: The layout of Starlink

SPACEX SYSTEM CONSTELLATION					
Parameter	Initial Deployment (1,600 satellites)	Final Deployment (2,825 satellites)			
Orbital Planes	32	32	8	5	6
Sattelites per Plane	50	50	50	75	75
Altitude	1150km	1110km	1130km	1275km	1325km
Inclination	53°	53.8°	74°	80°	70°

SpaceX have already sent up two test sattelites, and according the Elon Musk, they are working very well, providing a latency of only 25ms[3].

2.3 The Structure of Starlink

There is a lot we do not know about Starlink, but this is what we can infer from SpaceXs application to the FCC[4], and their technical attachment[5].

2.4 Modelling Sattelites in Orbit

Typically, an orbit around the surface of the earth is described by:

Distance Above the Surface

Inclination This is the angle between the orbital plane, and the equatorial plane, (the plane on which the equator lies).

Longditudonal Offset If inclination ¿ 0, then the orbital plane and equatorial plane will intersect at a line, the angle between this line and the plane described by the great circle at longditute 0 is the longditudonal offset. In other words, the Longditudonal offset is the Londitudute of the point where this line passes through the surface of the earth.

Eccentricity The eccentricity coefficient describes the squashness of the orbit. For the time being, we will be ignoring this...

Retrograde A retrograde orbit is one that goes against the rotation of the earth, typically these are described by orbits with a longditudonal offset ¿180. It is significantly more expensive to put a sattelite into a retrograte orbit, and is essentially never done.

Furthermore, an individual satellite's position in an orbit can be described by:

True Anomaly This is the angle of its arc along its orbit. Where the start of its arc is the point with londgitude equal to its longditudonal offset.

Phase Offset This is the satellite's true anomaly at time 0.

In our model, true anomaly is the only variable that changes. The way it changes is uniquely determined by the other 6 variables. The rate of change of true anomaly, the anglular velocity, is given by

$$\sqrt{\frac{GM}{r^3}}$$

Where r is the distance from the origin, or altitude + radius of the Earth.

Note that while altitude is constant (eccentricity = 0) velocity is unchanging, and true anomaly can be described as a linear function of time.

The position of a sattelite is calculated by taking its true anomaly and adding its angular velocity multiplied by the timestep (real timesince last frame update * some factor). The location is then calculated through a series of transformations performed on the true anomaly:

1. We take a vector (r, 0, 0) where r is the distance above the surface + the radius of Earth.
2. We rotate this point around (0, 1, 0) (the line through the poles) by the true anomaly.
3. We rotate this point around (1, 0, 0) (the line from 0 longditude to 180 longditude through the equator) by the inclination.
4. We rotate this point around (0, 1, 0) agian by the longditudonal offset.

Because the only variable that is changed is the true anomaly, and the x, y, and z coordinates are determined by only this variable and a series of fixed variables, we do not run thesame risks normal discete physics models face when describing continuous behaviour, such as unredictable behaviour when sped up, at extreme forces, or the steady moving of orbits.

For the rest of this document, a sattelite will be denoted by $x_{i,j,k}$. Where i demotes the orbital sphere, s_i, and j denotes the orbital plane $o_{i,j}$. n_i will be used to denote the number of satellites per plane of obital sphere s_i (50 or 75).

2.5 Variables

While we can learn a lot from SpaceX's applications, there are still a number of variables that are left undetermined.

Distribution on Orbit SpaceX only specifies which orbital planes it requires, and how many satellites will be on each plane, it does not specify where sattelites will be positioned on those planes. This leads us to speculate as to how sattelites will be distributed. I will describe the distribution of $o_{i,j}$ by the normalised n_i-dimensional vector d_i, where $(2\pi d_i)_k$ gives the arc between $x_{i,j,k}$ and $x_{i,j,k+1}$. For simplicitys sake, I will use non-normalised vectors as shorthand for normalised vectors, and vectors that are too short as shorthand for repeatind patterns. For instance:

$$d_i = [1]$$

Is shorthand for:

$$d_i = \frac{1}{n_i}[1, 1, ..., 1]$$

And:

$$d_i = [1, 3]$$

Is shorthand for:

$$d_i = \frac{1}{n_i}[0.5, 1.5, 0.5, 1.5, ...]$$

Phase Offset As we do not know for certain how satellites will be positioned in orbits, we also do not know how they will be positioned relative to other orbits. The phase offset of an obit $o_{i,j}$, $po_{i,j}$, can be described as a number from 0 to 1, where, $\forall k$, 0 indicates that $x_{i,j,k}$ will cross the equator at the same time as $x_{i,j+1,k}$, and 1 indicates that satellite $x_{i,j,k}$ will cross the equator at the same time as $x_{i,j+1,k+1}$. This number will have to be some fraction of the total number of orbits, to garuntee that the first and last orbits are properly aligned.

Each of the orbital spheres can also be offset from each other. The phase offset of each sphere will be described relative to central sphere (initial deployment) s_0, so the offset of s_i, ps_i, is 0 when $x_{i,0,0}$ crosses the equator at the same time as $x_{0,0,0}$,

Link usage Each satellite will have a maximum of 5 links, however, we do not as of yet know which arrangements of links are the most optimal.

In his study Mark Handley uses two links to connect $x_{i,j,k}$ to $x_{i,j,k+1}$ and $x_{i,j,k-1}$. He then uses two more to connect $x_{i,j,k}$ to $x_{i,j+1,k+h_i}$ and $x_{i,j-1,k-h_i}$, where h_i is a variable that describes how "diagonal" these sideways links should be. The final link connects to the nearest unconnected satellite. However there a number of different ways to connect up the sattelites, for a given sphere s_i I will catagorise the different link usage methods as.

Handley(h) Mark Handley's method where $h_i = h$.

OneFree(X) A generalisation of Handley, described by a 2*2 matrix X. Where $x_{i,j,k}$ connects to $x_{i,j+X_{0,0},k+X_{0,1}}$, $x_{i,j+X_{1,0},k+X_{1,1}}$ and visa-versa.

ThreeFreeBasic In which $x_{i,j,k}$ connects to $x_{i,j,k+1}$ and $x_{i,j,k-1}$, and the other three links connect to nearby satellites.

ThreeFree(v) A generalisation of ThreeFree, described by a 2d vector v, in which $x_{i,j,k}$ connects to $x_{i,j+v_0,k+v_1}$ and visa versa.

FiveFree In which all 5 links are free links, connecting dynamically to the closest nodes.

Response to Failiure One thing not examined by Mark Handley's study is how the SpaceX network should be expected to respond to failure.

2.6 Why Create a Visualisation?

When it comes to understanding a network such as starlink, a visual description is incredibly valuable. By visualising the network we can develop an intuition for how it operates, and use that intuition to develop ideas for new algoritms and structures for testing.

To create the visualisation I will be using the open-source game engine Godot. Using a game engine struck me as the simplest way to create a visualisation tool, and Godot, being powerful, open-source, and capable of runningeasily on many devices, seemed like the ideal choice.

3 Implementation

3.1 Repository Overview

3.2 Difficulties of modelling orbits

On Implementation, I found that my planned method of implimenting orbits was flawed, being able to simulate only 500 sattelites in motion before slowing down. Because of this, I changed to a precomputed method. In this method, orbits are precomputed as a number of points, and the position of sattelites is calculated by interpolating adgacent points, this sacrifices some accuracy, but castly increases the computation speed.

4 Evaluation

4.1 Analysis of Variables

For each of these variables, I modeled a variety of different possibilities, examining the latency of connections with each of these.

5 Conclusion

References

[1] `https://www.exede.com`

[2] `https://www.hughes.com`

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[4] `licensing.fcc.gov/cgi-bin/ws.exe/prod/ib/forms/reports/related_filing.hts?f_key=-289550&f_number=SATLOA2016111500118`

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[6] http://nrg.cs.ucl.ac.uk/mjh/starlink/

[7] http://stuffin.space/

[8] http://ece466.groups.et.byu.net/notes/smf28.pdf

A Appendix A