GLOrbit: A 3D satellite orbit propagator for network topology analysis

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Resumen—Los protocolos de redes tradicionales fueron desarrollados para redes terrestres, caracterizadas por topologías altamente estáticas. En este escenario, los errores de enlace aleatorios han sido el cambio más demandante que una configuración de red podía enfrentar. Por otro lado, los protocolos de redes móviles se ocupan de topologías dinámicas pero asumen trayectorias desconocidas y muy alta conectividad. Ninguna de ambas se aplica al paradigma para las redes de constelaciones satelitales donde su naturaleza orbital describe topologías temporalmente variables pero altamente predecibles. Para estudiar este tipo de redes tolerantes a demoras, proponemos GLOrbit; una herramienta de análisis de topologías y redes de satélites, capaz de propagar nodos espaciales en el tiempo, en un ambiente visual 3D mientras registra la topología en diferentes formatos para estudios analíticos posteriores. Para esto implementamos el algoritmo de propagación orbital SGP4, evaluadores de enlace entre nodos, y un motor gráfico de OpenGL. Esto permite obtener salidas precisas para graficar la red satelital y el análisis físico mientras se va ganando intuición visual para diferentes configuraciones orbitales. Se demuestran las capacidades de la herramienta con un primer trabajo de análisis con GLOrbit de tres topologías de orbitas bajas representativas. Escenarios lineales, transversales y diferentes escenarios de altitud son estudiados concluyendo que los lineales poseen una gran fortaleza en los enlaces inter-satelitales, mientras que los segundos en los contactos tierra-espacio. Finalmente, pero no por ello menos importante, debido a que los gráficos tradicionales representan redes estáticas, una novedosa estructura gráfica para topologías evolutivas temporalmente, es presentada como un resultado para el diseño topológico de redes tolerantes a demoras predecibles y sus estrategias de asignación de enlaces.

Palabras clave—Redes de Satélites, Redes Tolerante a Demoras y Disrupciones, Protocolos de Comunicaciones.

Abstract—Traditional networking protocols were developed for earth-based networks characterized by highly static topologies. In this scenario, erratic link failures were the most demanding change a network configuration could face. On the other hand, mobile networking protocols cope with dynamic topologies but assume unknown trajectories and high connectivity. Neither of these applies to satellite constellations network paradigm where their orbiting nature describes an opportunistic but highly predictive topology. To study this kind of delay-tolerant networks we propose GLOrbit, a satellite network and topology analysis tool, capable of propagate space nodes in time in a 3D visual environment, while recording the network topology in different formats for further analytical studies. For this we implemented SGP4 propagation algorithm, inter-node links evaluators, and OpenGL graphic engine. This allows obtaining precise outputs for satellite network graph and physical analysis while gaining visual intuition for different orbital configurations. We demonstrate the tool capabilities with a first work on three representative low earth orbit topologies analysis generated by GLOrbit. Lineal, transversal, and different altitude scenarios are studied concluding that the first evidence an important strength in inter-satellite links, while the second excels on ground to space contacts. Last but not least, since traditional graphs represents static networks, a novel time evolving topology graph structure is presented as a key outcome for predictive Delay Tolerant Networks (DTN) topological design and link assignment strategies.

Keywords— Satellite Networks, Delay and Disruption Tolerant Networks, Communication Protocols.

INTRODUCTION

Inter-networking is an old practice and knowledge area with many development throughout the years deriving in complex networks such as Internet. Recently, Inter Planetary Network [1] droved the attention to expanding these concepts to space, where satellite communications could benefit from evolving from simple data relays to intelligent constellation of routers capable of directing information to its destination. Despite this is a widely evolved area of science in earth applications, expanding packet networking to space environment implies several challenges. Dealing with highly dynamic -but predictive-satellite topologies is one of them and is the investigation proposed in this paper.

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In a first approach to time varying topologies, the challenge is to physically understand how the real nodes (orbiting satellites) behave in time for a given orbit path. For this we developed a OpenGL [2] based 3D environment to visualize the network. The environment allows rotating the camera, move around space, and controlling time speed. The value of visualizing orbiting elements is discussed in [3].

Secondly, we implemented SGP4 (Simplified General Perturbations) [4] algorithm as mobility model in order to propagate the position of network nodes on a given time. This models takes NORAD TLE (Two Line Element) [5] files as inputs and generates satellite orbit state vectors relative to Earth-Centered inertial coordinate system (ECI). It also predicts the effect of perturbations caused by Earth's shape, drag, radiation, and gravitation effects from other bodies such as the Sun and Moon. SGP4 model is solved via algorithms described in [5], whose implementation is provided by Celestrak [6].

In third place, during GLOrbit simulation execution, nodes position is updated on a configurable regular basis. The position can be processed on demand and stored in DOT, DTF (Dynamic Topology Format, a novel data structure detailed in Section V), and CSV format output files for further processing. The former allows to study possible ISL (Inter Satellite Links with visibility), and ground station links, while the latter allows for physical measurements.

This three work-phases form the architecture of GLOrbit illustrated in Figure 1. The rest of the paper is organized as follows: Background, previous tools, and similar studies are summarized in Section II, then, we describe the visual environment in section III; the Mobility model implementation details are discussed in Section IV; in Section V we review the topology output graphs and processing, providing the first topologies results for linear, transversal and different altitude orbits configuration and their corresponding analysis; finally, we conclude in VI.

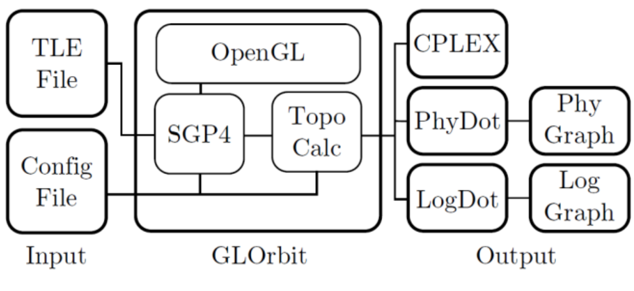

Fig. 1: GLOrbit Architecture

II - BACKGROUND

Many free and paid tools are available for evaluating orbiting nodes position, attitude, distances, and coverage, among others. Satellite Toolkit [7] is one of the most complete commercial software available in the industry with an important legacy of supporting flight missions for many agencies. Others commercial tools are ESA's Space Trajectory Analysis Tool [8], NASA's GMAT General Mission Analysis Tool [9], Nova [10], and Visualyse [11]. All of them are designed for real missions so that prove rather expensive for academic purposes. Freeware alternatives include SaVi [12], based on Geomview [13] engine, but are mainly focused on visualization.

Most of the referenced implementations include add-on packages for visualization and communication modules capable of simulating wireless links including antenna, propagation, channel and interference models. This allows for evaluating link budgets for different scenarios, but they are limited for a point to point link, whether Earth to and from space, or bend-pipe (relay) based inter-satellite links. However, none of them allows for packet-oriented delay tolerant network topology analysis.

Regarding research field on topology design for space networks, the related work is scarce. In [14] a LTD algorithm for LEO satellite networks is proposed, but does not treat the problem of delay tolerance; and [15] deals with link assignment, but for non-predictable DTN.

The authors are not aware of commercial or free simulation tools capable of analyzing scenarios with several nodes linked in a packet oriented switched delay tolerant network fashion. Moreover, the scarce research on topology design field for space networks opens the way for GLOrbit to contribute on the topological study of the of the sparse connections generated in a moving space constellations.

III - VISUAL ENGINE

The visual environment of GLOrbit is based on OpenGL graphics library version 1.4. OpenGL is a widely known open API standard for 3D visualization. Older version was chosen for implementation for sake of compatibility with non-GPU (Graphic Processing Unit) capable computers and Windows OS whose OpenGL support is way behind Khronos [16] (currently maintaining the library) releases. Figure 2 shows a screenshot of a simulation of Iridium constellation [17].

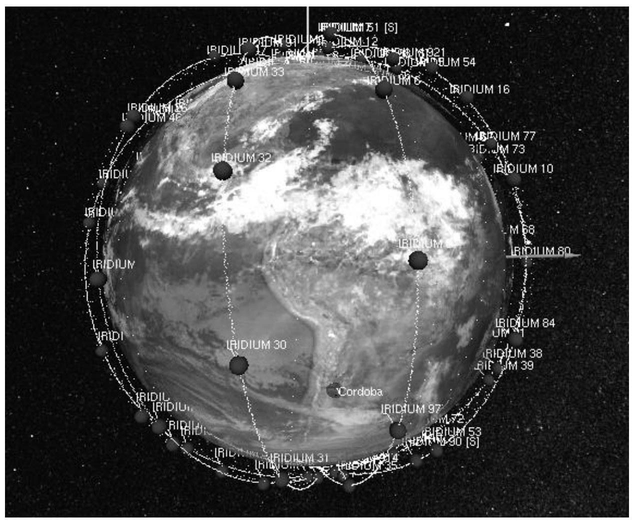

Fig. 2: Iridium Simulation

The Free-glut (free GLUT) library [18] was chosen for windows management, context creation and configuration, and providing basic user I/O operations using mouse and keyboard functions. The main reason driven the use of Free-glut is the fact that is cross-platform allowing GLOrbit to be

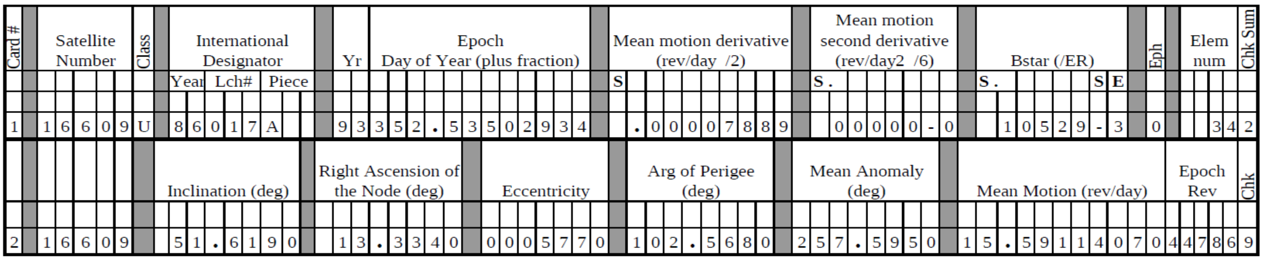

Fig. 3: NORAD TLE format

available for Linux, Windows, Mac OS, and others systems. The same reason derived in using GLEW [19] (OpenGL Extension Wrangler Library) as well, which provides easy OpenGL Core and Extensions access. GLU [20] Utility library is used for generic OpenGL functions, and SOIL [21] (Simple OpenGL Image Library) for loading images as textures.

GLOrbit main loop is based on two functions: *postRedisplay* for drawing the scene and *idle* -for processing when not drawing-. The former takes ECI coordinates of all satellites, Earth stations, sun, moon, camera position, and strings containing simulation data and plot them on the screen. The latter performs time advance control, orbital mechanics calculation, including satellite propagation, earth rotation, sun and moon position, user I/O, and topology calculations. Time is kept along the simulation Julian Date (easily converted to Gregorian time) while Sun and Moon angles are derived from Vallado's algorithms [5]. Integration of this libraries and APIs allowed GLOrbit to provide a user friendly interface to intuitively understand the analytical topologies outputs provided.

IV - MOBILITY MODEL

Simplified General Perturbations models such as SGP, SGP4, SDP4, SGP8 and SDP8 provide orbital state vectors for satellite and space debris referenced to Earth Center Inertial (ECI) coordinate system based on classic orbital elements. SGP4 was developed by Ken Cranford in 1970 [22] and includes gravitational and atmospheric models for near-earth (period less than 225 minutes) orbiting elements. Later on 1977, deep space models were developed, where solar/lunar perturbations have a larger effect than atmospheric drag; these came to be known as SDP4. Current code libraries have merged SGP4 and SDP4 algorithms into a single codebase handling the range of orbital periods which are known as SGP4. David Vallado working through the Center for Space released an AIAA paper in 2004, which attempted to unify the many codes into one standardized code. This new code was made available to the public through [6]. In [23] it is stated that SGP4 model has an error of ~1 km at starting epoch (TLE accuracy) and grows at ~1–3 km per day, providing enough accuracy for topology analysis, the primary objective of GLOrbit.

GLOrbit reads a list of concatenated TLE from a text file in order to feed SGP4 model. TLE format is specified in [23] as well and illustrated in Figure 3. In the first line, column *Satellite Number* indicates a unique NORAD catalog number, and repeats in both lines; *Class* field indicates classification (U is unclassified); *International Designator* is an additional unique number assigned by WDC-A-RS; *Epoch* is the base time for the element onto which the rest of time-varying fields are referenced; *Mean motion derivates* are in revolutions per day units, and give information on the mean motion variation, however this is not used by SGP4; *BStar* is a drag coefficient representing how susceptible an object is to drag; *Eph* represents the ephemeris type used to generate the data, in general is zero representing SGP4/SDP4 orbital model; *Element Num* increments with each TLE generation for a given element; *Chk Sum* is a modulo-10 checksum equal to the last number of the sum of all numbers of the line (minus signs get a 1 value). The second line contains elements calculated using SGP4/SDP4 orbital model. All units are in degrees and range from 0 to 360, *inclination* is the angle between the orbital plane and the equatorial plane, it only goes up to 180 degrees. *Right Ascension of the Ascending Node* (RAAN) is the angle from Aries as a reference longitude to the direction of the ascending node (point where the body crosses the equator from south to north) measured in a reference plane (equatorial); *Eccentricity* is a unit-less value with an assumed leading decimal point that determines the amount by which the orbit drift from a perfect circle (0 is perfectly circular and 1 is parabolic); *Argument of Perigee* is the angle between the orbit perigee (closest point to the center) and the ascending node; *Mean Anomaly* relates position and time of a body in a Kepler orbit, goes from 0 to $2 * \pi$, and it is not an angle, but proportional to the area swept from the focus to body line from perigee which is equal in equal time intervals; *Mean motion* is measured in revolutions per day, if eccentricity is different than 0 it is rather an average value than an instantaneous angular velocity; and *Revolutions at Epochs* specifies the number of orbits the body has made since its launch (not real usage for SGP4).

These parameters are taken as inputs in GLOrbit on a per satellite basis. All existing satellites TLEs are publicly available and custom orbiting body can be manually created by using parameters illustrated in Figure 4. TLEs to be simulated in GLOrbit should be concatenated in TLE File. \# is considered comment in the file (\# name: SAC-D specifies *SAC-D* as name for the following satellite). An example can be seen in Figure 5. There is no limit on the number of bodies to propagate in GLOrbit.

V - SIMULATION RESULTS AND ANALYSIS

Physical Analysis

In order to demonstrate the results and output files GLOrbit provides for analysis we propose a comparison between different orbital configurations. These scenarios must be described with a series of TLE files to feed GLOrbit propagator engine. For sake of simplicity we evaluate all 4 nodes sized networks in what we define as *linear*, *transversal*, and *different altitude* configurations. Figure 6 illustrates graphically each of these.

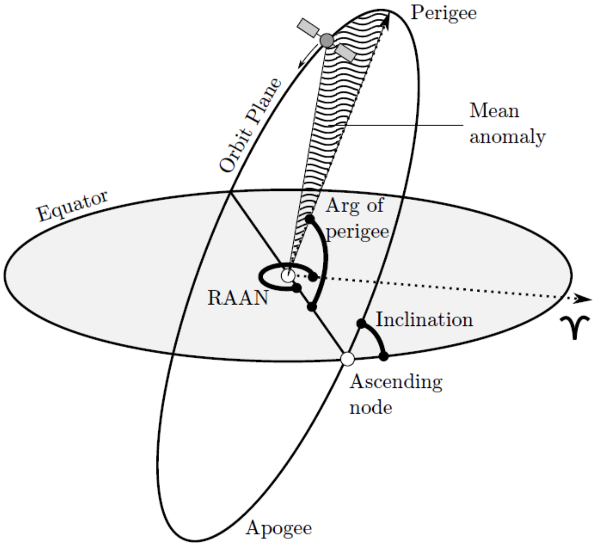

Fig. 4: Orbital Parameters

```
# name: SAC-D
1 37673U 11024A   12223.10521307 -.00000049  00000-0  00000+0 0  3822
2 37673 098.0108 228.9936 0001039 074.9222 285.2135 14.72289895 62753
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Fig. 5: TLE File Example

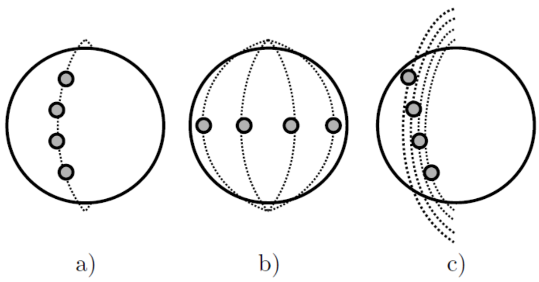

Fig. 6: a) Linear, b) Transversal, and c) Altitude Topologies

Linear topology is essentially a *train* of nodes in the same circular orbit plane, with a 5 degree *perigee argument* difference resulting in an inter-satellite distance of 603Km at 570Km average height. This flight configuration implies no complication from a launcher point of view since it can be achieved by a multi payload adapter with successive satellite releases. Inter-satellites communications can be easily accomplished by fixed antenna alignment thanks to the constant relative distance and angle. NASA A-train protect [24] proposes a similar configuration for earth observation mission (it does not use inter-satellite links though) with separations of a few seconds between each node.

Transversal topology aims at nodes in different orbital planes separated by 10 degree in the equatorial plane (right ascension of the ascending node) deriving in an inter-satellite distance of 1207Km at 570Km average height. This is the further the ISL distance can get and it happens at the moment when the nodes travel through the equator. However, in the pole, all satellites get very close to each other, generating a likely scenario of medium access competition. One of the main drawbacks of this configuration is that in both, poles and equator, mechanical or electrical inter-satellite antenna alignment is required for proper communication. Also, from a launcher point of view, the maneuver for RAAN shifting is considerably more complicated than perigee shift for linear topology [25].

Both linear and transversal topologies suppose all nodes at the same height. As a consequence, a third scenario of different altitudes is proposed. Here, all satellites remain on the same plane but at 10Km of incremental height distance (550, 560, 570, and 580Km). Mean motion (μ) decreases with altitude by equation (1), where h_p is perigee height, provoking different revolution time, deriving in an out of sync topology. Inter-satellite antenna alignment requires mechanical or electrical pointing as well. Also, the launcher will require performing orbital transfer maneuvers such as using Hohmann transfer elliptical orbits [26].

$$\mu = 86400 / h_p \tag{1}$$

The three topologies proposed TLE parameters are summarized in Table 1. Basically, the linear scenario can be generated by shifting the perigee argument, the transversal topology by shifting RAAN, and different altitudes involves different mean motion values.

TABLE 1: Topologies Parameters

	Linear	Transversal	Altitude
Inclination	90°	90°	90°
RAAN	0°	0°, 10°, 20°, 30°	0°
Eccentricity	0°	0°	0°
Arg Perigee	0°, 5°, 10°, 15°	0°	0°
Mean Anomaly	0°	0°	0°
Mean Motion	15.07561	15.07561	15.7090, 15.4285, 15.1578, 15.8965

Once the TLE parameters are defined for each scenario, we can configure them as inputs for GLOrbit, who can provide two types of results files for topology analysis: comma separated values file (CSV) with relative nodes distances and DOT [27] based language file for topology graph generation. Time resolution can be configured for short and precise, or long and relaxed analysis. GLOrbit manages two time dimensions: a topology time and visualization time. The former, is a high resolution (small time steps) used to record topology both in CSV and DOT format. Topology recording can be enabled and disabled on real time since it demands processing and storage resources proportional to the complexity of the network. The latter is a rather relaxed time with highly dynamic time steps that adapts to the visualization speed the user requires during the simulation. Very high time ratio speeds can be reached even while recording topologies. For example, we executed a 60 day long simulation period with topology time step of 1 second for the three scenarios proposed in less than 20 seconds in a

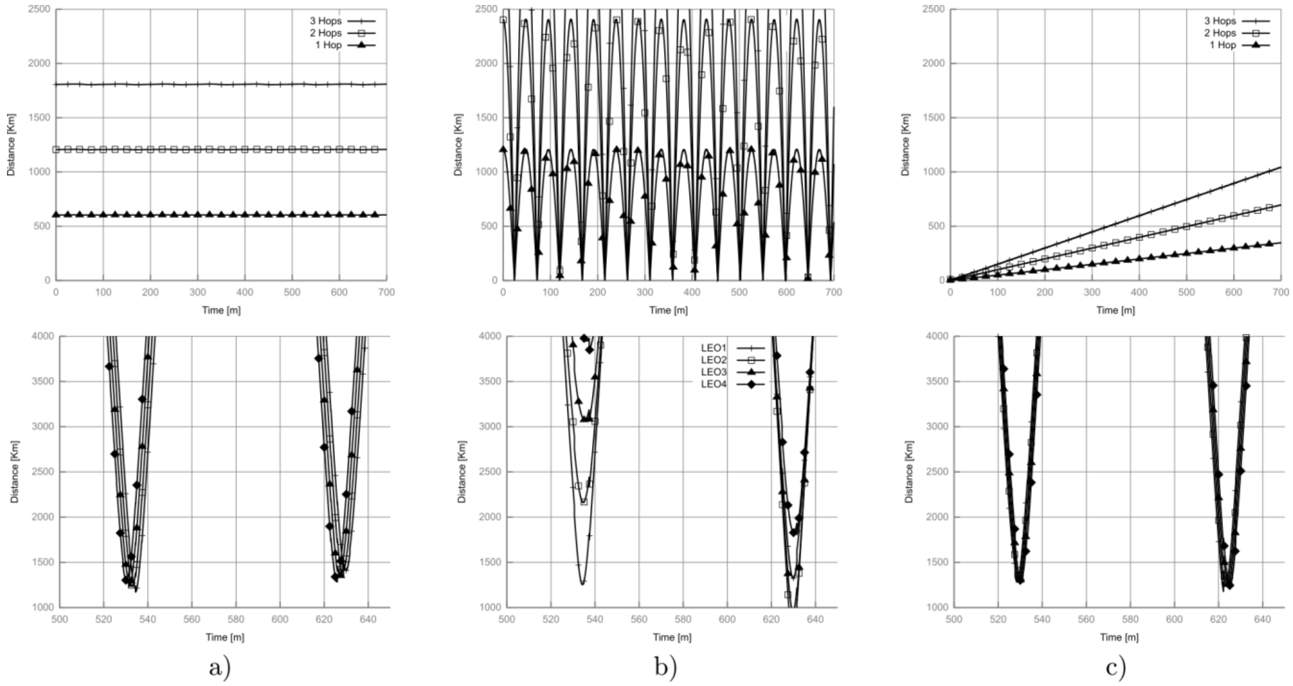

Fig. 7: ISL (up) and GS (down) distances for a) lineal, b) transversal, and c) different altitude topologies

mobile Intel Core i3 processor (simulation speed of 360000% approx.). Such a vast data can be complex to work with, but having standard outputs such as CSV or DOT allows to easily focusing the analysis and process the information. However, the user should consider that a 60 day propagation might incur in several km of position uncertainty.

A first result to analyze is Inter-satellite distances. They are resumed in Figure 7 for the scenarios proposed in the first 12 hours of simulation. Regarding inter satellite distances, as expected, lineal topology shows constant ranges between satellites with minimum variations probably provoked by earth oblateness in SGP4 model. ISL distances increases in steps with each hop increment. Transversal topology results clearly evidence the zero distance in pole zone while reaching around 1200km in equator for adjacent nodes, 2400km for second adjacent nodes, and further apart for the third adjacency links. Different altitude topology might look very promising with the lowest relative inter-satellite distance at the very beginning of the simulation. However this remains true for a limited period of time when all nodes are aligned together in the same earth centered radial line, since as the time advances, the difference in relative velocity separates them apart considerably. This effect is hardly seen in a 12 hour plot, so with the same CSV output from GLOrbit we can further study longer periods of times such as the graph of Figure 8 describing ISL distances along the 60 simulation days. This plot allows us to conclude that different altitude topology provides very large windows (contact opportunities) but between very long periods of time. In this scenario we determined that every 10km in height increment, the inter contact opportunity time among adjacent nodes is around 60 days, 30 days for 20km, 15 days for 30km and so forth. The bigger the altitude distance, the shorter the contact period, but shorter the window time frame as well.

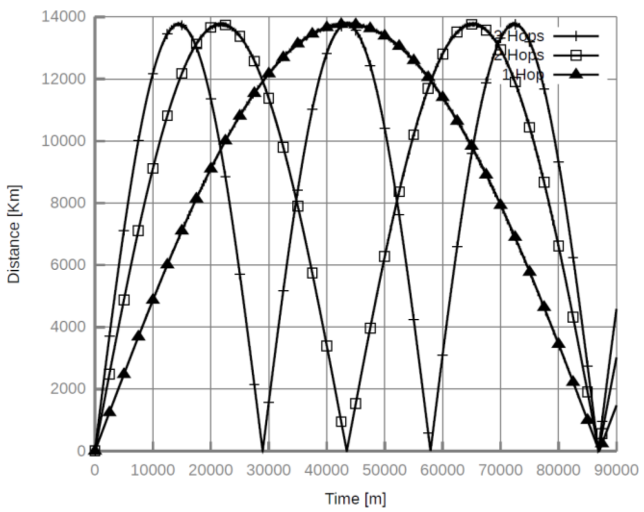

Fig. 8: ISL distances for Altitude Topology

Another interesting result to analyze is the distance to the Earth or Ground Station (GS) shown in the bottom of Figure 7. Figure 9 shows the cumulative distribution function (CDF) of the distance of the closest node to the GS on each topology (i.e. earth to network distance). CDFs expresses the probability that the distance is below the value given in x (CDF(x)=P(X<x)). This plot is based on the 60 day simulation period, with a resolution of 1 minute, and GS placed in Córdoba, Argentina, where this work is taking place. Linear topology evidence equally spaced time slots of contact with earth with a slight offset (1 minute 23 seconds) product of the small geographical movement of the earth on satellites paths. Linear topology has the less GS to network contact probability. Moreover, in transversal topology, contact possibilities are very different between each flying node and earth due to the different RAAN described by their "tracks". This implies that in a given window there is a node considerably closer (with a longer contact period as well) to the ground station. The latter suggest that the

transversal topology is beneficial from a space to earth contact point of view. This twist becomes more important when considering the topology nature of covering larger equatorial distances, provoking higher distribution of network to GS contact than the linear scenario. On the other hand, different altitude topology initially provides highly overlapped contact to ground at initial phase, but separates beneficially over time becoming the topology with higher network to GS distributed and probable contacts. However, as demonstrated previously, this configuration lacks of sustained ISL capabilities. Table 2 summarizes the qualitative characteristics concluded from the simulations on the three topologies proposed.

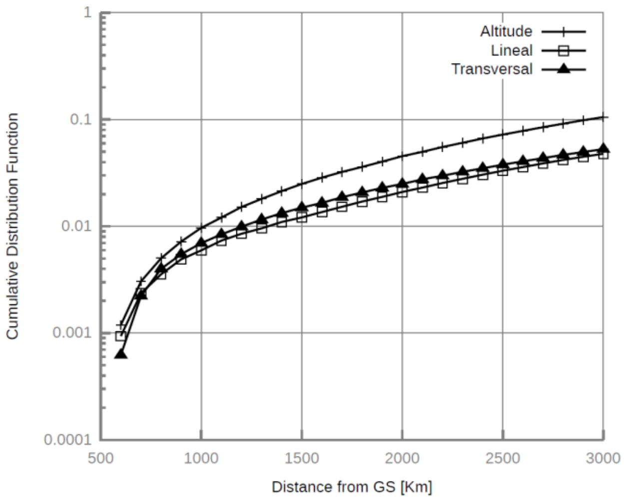

Fig. 9: CDF for GS distance

TABLE 2: Topologies Summary

	Linear	Transversal	Altitude
ISL contact	Permanent	Frequent with short duration	Infrequent with long duration
GS contact	Highly overlapped	Distributed	Highly distributed

Topological Analysis

In order to manage the evolving and predictive nature of the networks described, we propose a novel graph type able to represent the changing of links possibilities over time. Figure 10 shows an illustrative example for a satellite network graph with 4 nodes and 3 subsequent topology states. Such scenario might stand for nodes with proximity able links (used near the poles) and node 1, 2 and 3 equipped with directional antennas transponders enabling long directed links in the equator zone. This physical topology can be represented by a three dimensional visibility matrix $V_{k,i,j}$ whose $v_{k,i,j}$ elements represent unidirectional arcs from node *i* to *j* at state *k* and can take integer values of 0 if no link possible, and *a* if link possible via interface *a*, where *a>1*.

On the example network restrictions might be specified. For instance: the maximum number of interfaces enabled in a given node at the same time. This restriction may be either by the existing hardware in the node, energy limitations, or interference requirements. Assuming 1 as the maximum interface numbers for the case of Figure 10, a decision must be taken for node 2 at k=2. The question is: which is the most appropriate link to enable in this case? Or in other words: which is the most appropriate link set to disable? $v_{2,1,2}$ and $v_{2,2,1}$? Or $v_{2,2,3}$ and $v_{2,3,2}$? This kind of analysis requires appropriate logical topology design algorithms for which GLOrbit can provide realistic simulated scenarios [28]. We leave as further work the creation of a module of GLOrbit specifically devoted to the resolution of communication resource conflicts.

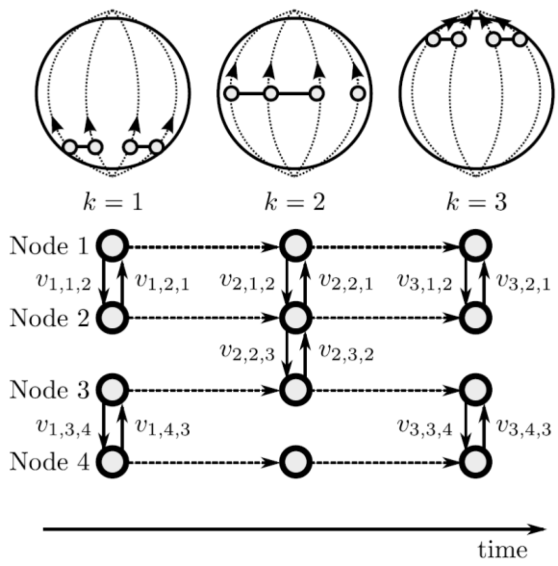

Fig. 10: Graph for time evolving topologies

GLOrbit provides topology output in DOT format, and DTF (Dynamic Topology Format) which essentially is the referred time evolving visibility matrix [V]. DOT can be used to easily plot the topology graph as in Figure 10, and DTF to easily serve as inputs for LTD (logical topology design) algorithms or procedures. Figure 11 illustrates a DOT plotting of an iteration of the transversal topology assuming a single omnidirectional antenna interface on each node.

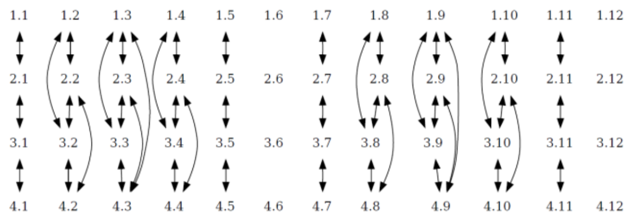

Fig. 11: GLOrbit Transversal topology Graph

VI - CONCLUSION

In this work, GLOrbit, a 3D satellite orbit propagator for network topology analysis was introduced. Its architecture accounts for different available libraries, algorithms, and models to provide a powerful tool able to generate precise output files for dynamic satellite networks with a 3D visual interface for intuitive understanding of the values generated.

The tool capability we demonstrated by evaluating three different constellations configurations: lineal, transversal and different altitude. Considering the physical outputs generated by GLOrbit we derived interesting qualitative and quantitative properties from an inter-satellite and ground station contact perspective. Lineal approach evidenced important advantages in the former while transversal in the latter.

Finally, an initial topology analysis was performed using the tool providing interesting results. It was shown that by posing interface restrictions (very common in energy limited satellite networks), the need of logical topological design procedures arise. Developing such algorithms is left as further contribution to future satellite networks.

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