

Resilience Analysis of Multichord Peer to Peer IoT Satellite Networks

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Abstract— The world is witnessing a dramatic shift in usage of social networks from being a passive network to an active one. This will incorporate all types of information and devices that require scalability and resilience in network operations. With Internet of Things (IoT), the challenge is doubled with the limited capabilities of such devices in addition to being self-organizing and self-configuring topologies. Some research started proposing the use of satellite networks as a carrying medium of the information in IoT networks. In this paper, we focus on analyzing the resilience of such networks in the presence of frequent disconnections that may lead to a significant delay in discovering, connecting and organizing IoT devices. This facilitates mechanisms to collect, aggregate, filter, process, store and retrieve data. In particular, we present the mathematical model of the proposed novel peer to peer multichord-based protocol for IoT over LEO satellite networks. Preliminary results show that multichord IoT satellite networks can provide the required high-speed connectivity with low latency and high robustness to failure.

Keywords— Satellite Internet of Things, Multichord Peer to Peer networks, Starlink LEO Constellation

I. INTRODUCTION

Internet of Things (IoT) is a new paradigm in the field of networking that consists of a massive number of sensors and computing devices with the capability of interacting with one another autonomously. This requires new concepts in the network structure as well as new techniques to manipulate data. Consequently, in this paper, we present a two-fold contribution. First, we propose the Chord concept for logical networking to provide IoT services and modify its standard operation to work in a multichord architecture. We show that our proposal allows for scalability, differentiability and robustness to failure. Second, we propose an overlay network for IoT services based on multichord for Low Earth Orbit (LEO) based satellite networks. For our simulations, we choose the Starlink LEO constellation as a reference.

Chord protocol for peer to peer network

Nowadays, data that we produce through our devices is processed and stored by centralized Internet service providers in a cloud computing structure. Although data is distributed among different servers, there is a single point of control and access to them. This approach of entrusting people data to centralized Internet service providers may challenge the implementation of mechanisms to preserve people privacy [1].

This is even more certain in the context of the IoT, whereby billions of devices will continuously collect fine-grained personal information. Therefore, we propose a distributed hashing in a multichord peer to peer network for data storage and manipulation in a decentralized manner. Specifically, we focus on designing an overlay management architecture based on the chord protocol, i.e., given a key (data item), which maps the key onto a node (peer) using consistent hashing [2] to assign keys to chord nodes.

Our proposal is an extension of the successful chord technology [3] to cope with the dynamism of IoT networks given the physical orbital constraint of an IoT network over satellite.

The advantages of using the chord protocol as a distributed peer-to-peer lookup system are:

- Load balancing: due to the usage of distributed hash function, keys are spread evenly over nodes.
- Decentralization: chord is fully distributed; no node is more important than another, thus improving system robustness.
- Scalability: logarithmic growth of lookup costs with number of nodes in network, even very large systems are feasible
- Availability: chord automatically adjusts its internal tables to ensure that the node responsible for a key could always be found.

However, chord protocol for peer to peer networks have the limitations of not being able to distinguish type of data stored. No control on process of modifying data that is stored. The lookup delay increases significantly with the growth of nodes in chord and also robustness may be jeopardized in case of simultaneous failure and/or add-join of nodes. To overcome such limitations, our proposed solution consists of multichord networking as an extension to the existing chord peer to peer network. Each chord represents a type of data collected from sensors that provide this kind of data. The architecture of the proposed multichord consists of a main chord network of edge devices that branch from them sub-chords of specialized nodes. We also bring new commands (operations) to the standard chord network commands such as: remove shared node, merge shared chords, split shared chords, leave from shared node to single node, join shared chord, sleep single node, sleep shared

node, awake single node and awake shared node. Our proposal differs from the existing solutions as follows. In [4], the authors focused on designing an overlay management architecture based on Chord algorithm. The architecture is a collection of multiple peer Chord rings, and thus, each of these rings is considered as a smart context. Their architecture is evaluated by simulating a large-scale environment with a large number of nodes and sensors to evaluate performance and operation costs of the entire system with various topologies and properties. The achieved results proved that our proposal has the operability and feasibility to apply to practice [5]. On the other hand, the proposal in [6] is a direct extension to chord concept, where there is no interconnection clear between the chords. On the contrary, our proposal developed the concept of shared nodes that will facilitate the operations between the chords.

Starlink

SpaceX plans to launch up to 42,000 LEO communication satellites, which can provide up to gigabit Internet with latency in the tens of milliseconds [7]. It uses phased array antennas for up and downlinks and laser communication between satellites to provide global low-latency high bandwidth coverage [8]. These filings provide a great deal of detail about the RF links between the satellites and the ground, including how phased-array antennas can steer narrow transmission beams for both uplink and downlink. The filings do not discuss in detail satellite to satellite communications. No radio spectrum for satellite-to-satellite communication is requested, so, lasers must be the primary communication link between satellites. Starlink represents a new category of wide-area backbone, where thousands of satellites move and connect in a predictable pattern, but due to orbital constraints the network is far from a simple static mesh.

We ground our study on the basic properties of the Starlink deployment and proceed by overlying multichord approach on such a network. In Starlink initial phase, 1,600 satellites in 1,150 km altitude orbits provide connectivity to all except far north and south regions of the world. A second phase adds another 2,825 satellites in orbits ranging from 1,100 km to 1325 km altitude, increasing density of coverage at lower latitudes and providing coverage at least as far as 70 degrees North [8] as shown in Fig. 1 [9]. In contrast, we are mostly concerned with satellite to satellite communication. A good working assumption is that each satellite will have five free-space laser links to connect to other Starlink satellites. The orbital data for the LEO constellation is presented in Table 1

Table 1. Specification of Starlink system

	Initial phase
Number of satellites	1600
Orbital planes	32
Satellites per plane	50
Altitude (km)	1150
Inclination	53

Accordingly, the question that now needs to be addressed is how to mathematically model the proposed peer to peer over

such satellite network, especially in the situation of frequent disconnections and failure.

SpaceX currently relies on the Linux operating system for running over dual core x86 processors implemented in its constellation that has more than 30,000 Linux nodes (and more than 6,000 microcontrollers) in space right now. Updates on software on all the satellites are done nearly once a week generating more than 5TB [5 tera bytes] a day of data.

This introduces many instances, where a satellite on orbit had a failure we had never even conceived of before but was able to keep itself safe long enough for us to debug it, figure out a fix or a workaround, and push up a software update. Doing the detection of problems onboard is one of the best ways to reduce how much telemetry we need to send and store.

Accordingly, we can model the satellite as a (Linux) software-driven node, which is an appreciable novelty of these satellites with respect to the state-of-the-art: most of traditional on-orbit satellites do not yet allow what SpaceX say; they are able to do such as on-orbit debugging.

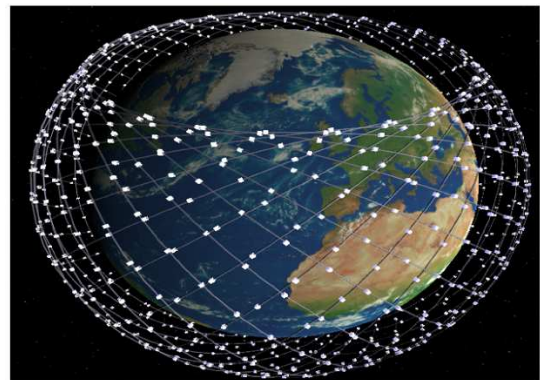


Figure 1. Initial phase Satellite orbits

The paper is structured as follows. Section II introduces the proposed multichord IoT satellite network and its projection over the starlink satellite constellation. Section III presents the mathematical model analysis. The obtained results are elaborated and discussed in Section IV and we conclude the paper in Section V.

II. MULTICHORD IoT SATELLITE NETWORKING

M. De Sanctis et al. in [10] focused on the use of satellite communication systems to support IoT. The authors highlighted the enabling factors of IoT through satellites: 1) the interoperability between satellite systems and sensors/actuators and 2) the support of Internet Protocol Version 6 (IPv6) over satellite. They also provided an integrated solution among MAC protocols for satellite routed sensor networks, efficient IPv6 support, heterogeneous networks interoperability, quality of service (QoS) management, and group-based communications.

In [11], authors used a constellation of five Molniya satellites and one-dimension electronic scanning phased array ground terminals. The obtained result is a baseline concept that meets customer needs for IoT data connectivity and for consumer high data rate Internet access. Molniya orbit satellites provide the benefits of available bandwidth, lack of interference with other satellite links, and less crowded orbital paths. A drawback is that they are not geostationary since they have elliptical orbits.

Authors in [12] focus on LEO satellite constellation-based IoT services for their irreplaceable functions. They provide an overview of the architecture of the LEO satellite constellation-based IoT including LEO satellite constellation structure, efficient spectrum allocation, heterogeneous networks compatibility, and access and routing protocols.

To the best of our knowledge, the proposed satellites IoT networks in the literature have not yet considered peer to peer connectivity based on the chord concept, which has the advantage of being distributed, scalable and robust to failure.

P2P satellite networks are classified to unstructured and structured networks. Unstructured P2P networks organize nodes in random graphs, while structured P2P networks are based on fixed rules, where nodes' links share common structured patterns. The existing structured P2P networks are developed on DHTs support efficient exact key lookups [3]. They map keys of data items and peers into the same identifier (ID) space and assign each content's key to a set of peers whose IDs are closest to that key and have the coupling between keys of data items and peers on the graph and thus ensure that queries are resolved.

A typical chord protocol for peer to peer networks is shown in figure 2 where figure 2a shows the concept of successor nodes and figure 2b shows finger table concept. The successor nodes concept represents the nodes that are directly after the node in consideration (v) and they are the nodes that hold duplicate data of node v while the finger table represents the forwarding mechanism used to lookup data requested from node v . The chord protocol for peer to peer network is illustrated in [3].

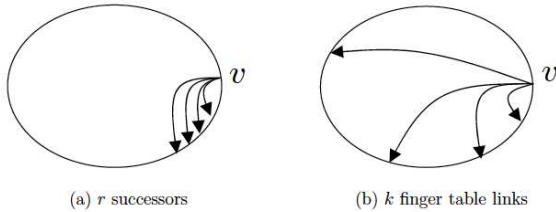


Figure 2. User v 's successors and neighbours in Chord

In Multichord maps, each satellite and key use a uniform hashing function into the identifier (ID) space $\{0, 1, \dots, 2m - 1\}$, where m is number of bits that represents the binary notation of all satellites without conflict. Each key is assigned to the successor satellite, i.e., the first satellite whose identifier is larger than the key in the clockwise direction along the ring. As illustrated in Fig. 3, each satellite v in Chord builds a successor list and a finger table. Assuming n satellites in each orbit and m orbits in the system, the former set contains $r = \Theta(\log n) + 3$

$\Theta(\log m)$ nodes immediately following satellites v along the ring. The latter set consists of $k = \Theta(\log n) + 3 \cdot \Theta(\log m)$ neighbour pointers, where the i -th neighbour in same orbit is the owner of the key $\text{id}(v) + 2^i$.

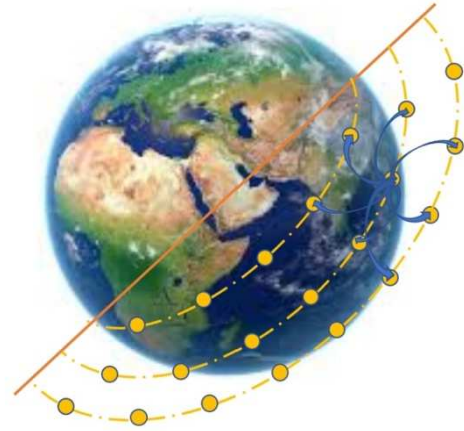


Figure 3. Multichord Protocol over satellites network

Finger tables are used during key lookup where the originating node performs jumps of exponentially decreasing length until it finds the node responsible for the key. Inconsistent states in finger tables and successor lists are periodically repaired using a stabilization technique, which allows multichord to fix links broken during satellites down or link disconnections and/or new satellites joining the system. The stabilization process ensures the correctness of the operations of multichord networks. The process is required to the successor nodes up to date on regular basis.

In the following section, we will present the mathematical model of this process and show that it tolerates multiple nodes failing simultaneously and only requires that no successor list sustain a failure of all r satellites within a given stabilization interval. Similarly, node v learns of new arrivals during its stabilization process and properly adjusts its successor list to include the new peers.

III. MATHEMATICAL MODEL ANALYSIS OF MULTICHORD P2P SATELLITE NETWORK

We follow a probabilistic approach in modelling the resilience behaviour of multichord P2P satellite network. Consider a Multichord P2P satellite network as in Fig. 3 with n satellites in m orbits, where each satellite i is either available, i.e. on, or unavailable, i.e. off. This behaviour can be modelled by an ON/OFF right-continuous process $\{Z_{i,j}(t)\}$ for each satellite i in orbit j as shown in Fig. 4, where random variables $L_{i,j} > 0$, $D_{i,j} > 0$ are durations of satellite i ONs and OFFs, respectively.

$$Z_{i,j}(t) = \begin{cases} 1, & \text{satellite } i \text{ IS ON AT TIME } t \\ 0, & \text{OTHERWISE} \end{cases} \quad 1 \leq i \leq n, 1 \leq j \leq m \quad (1)$$

Where i is the index of satellite and j is the index of orbit

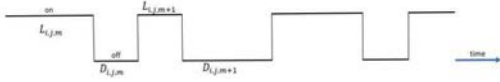


Figure 4. Life cycle Process $\{Z_i(t)\}$ depicting ON/OFF behavior of satellite i in orbit j

ON/OFF is the lifecycle of satellite in operation. It again may occur when the satellite lose connection for a certain period of time and that is considered the OFF state. Otherwise, it is in the ON operational state. In our work, we considered the ON/OFF distributions that are well known to model the behaviour of telecommunication sessions. They are the exponential distribution, $F_i(x) = 1 - e^{-\mu_i x}$, $\mu_i > 0$, with mean $1/\mu_i$ and Pareto distribution $F_i(x) = 1 - (1 + x/\beta_i)^{-\alpha_i}$, $\alpha_i > 1$, $\beta_i > 0$, with mean $\beta_i/(\alpha_i - 1)$. Thus, the probability that a satellite is in the system at an arbitrary instance, t is given by

$$A_i = \lim_{t \rightarrow \infty} P(Z_i(t) = 1) = \frac{l_i}{l_i + d_i} \quad (2)$$

where l_i is the mean ON time of satellite i and d_i is the mean OFF time of satellite i averaged over all time cycles. The distribution of the number of satellites in the system $N(N, T) = \sum_{i=1}^n Z_i(T)$ the number of satellites in the network at any time and based on central limit theorem it will be approximately Gaussian for large n with a mean $E[N(n)]$ given by

$$E[N(N)] = \sum_{i=1}^n E[Z_i] = \sum_{i=1}^n A_i \quad (3)$$

and a variance of $N(n)$ given by

$$\text{VAR}[N(N)] = \sum_{i=1}^n \text{VAR}[Z_i] = \sum_{i=1}^n A_i(1 - A_i) \quad (4)$$

We then model the process of actively switch links to new satellites before the current satellite goes OFF in order to balance the load and ensure consistency. As defined from standard chord protocol, the network maps keys and satellites in same orbit into the same identifier (ID) space. Each satellite is responsible for a fraction of the DHT space from its predecessor to itself as well as a set of near satellites in other orbits which is called satellite zone. To facilitate routing, each joining satellite v selects and then monitors using some stabilization technique k links in the DHT space as shown in Fig. 5 (a).

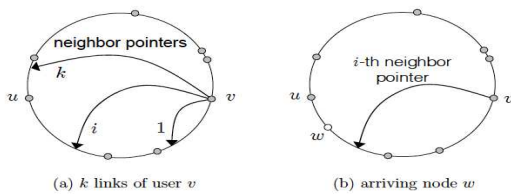


Figure 5. User v 's neighbours in the DHT

It is worth mentioning that the analysis of any link in any orbit will be identical to any other link or orbit and the neighbours adjacent to it during the v 's online session. As satellite v

continues to stay in the system, the identity of its neighbours (i.e. successors of its neighbour pointers) may change over time as satellites join and leave the system. There are two types of changes in neighbour tables – explicit handoffs of an existing zone to another satellite handoff without explicit notification of v . Explicit handoffs occur when a new arrival takes ownership of a link by becoming the new successor of the corresponding neighbour pointer. This is shown in Fig. 5(b) where a new arrival w splits the zone of an existing neighbour u and becomes the new neighbour of v . Handoff without explicit notification occurs when an existing neighbour leaves and the successor of the failed neighbour takes over that zone to become the new neighbour of v .

This model is elaborated in the time diagram shown, in Fig. 6. Thick horizontal lines represent online presence of peers that own v neighbour pointer in the DHT space. The topmost line is the original neighbour with a residual lifetime Z_i acquired by v during join. As satellites split the zone of the current neighbour, the link switches to a new additional satellite. Switch is complete after a new satellite performs all join tasks.

Once the last satellite leaves at time R_i , the link is considered unavailable and a replacement process is initiated. Specifics of detecting failure are not essential to our results because the repair delay is not studied in this paper as shown in Fig. 6.

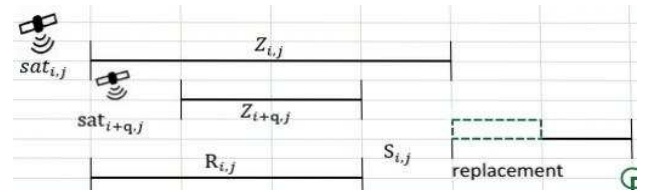


Figure 6. Satellite link connectivity model

Recovery is finished after S time units when another node takes over the zone of the dead peer and is selected as a v 's new neighbour. Thus, one can define a conditional link lifetime $R(y)$ as the duration of the link conditioned on the fact that the remaining zone size Y_j is $y > 0$ and the cumulative distribution function of link lifetimes R_j can be written as:

$$P(R_j < x) = \int_0^\infty P(R(Y) < x) f_{Y_j}(y) dy \quad (5)$$

where $f_{Y_j}(y)$ is the PDF (probability density function) of the remaining zone size Y_j (note that the distribution of Y_j depends on cycle number j). Similarly, one can obtain the expectation of R_j as:

$$E[R_j] = \int_0^\infty E[R(Y)] f_{Y_j}(y) dy \quad (6)$$

Thus, the task of deriving link lifetime R_j is reduced to analysing the properties of conditional link lifetime $R(y)$ and the distribution of remaining zone size Y which can be done by simulation due to the dynamic nature of the links.

When all r successors of any satellite, Fig. 7, fail simultaneously, we call the event satellite isolation and note that it determines the likelihood of graph partitioning:

$$P(\text{GRAPH DISCONNECTS}) = P(X > 0) \quad (7)$$

where X is the number of satellites that are isolated in the system.

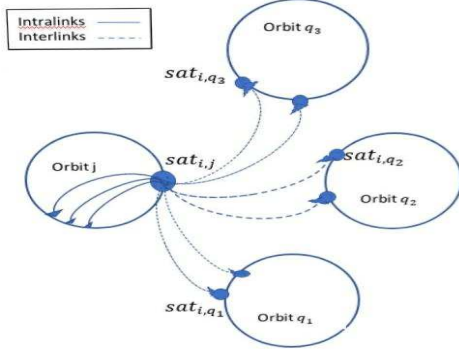


Figure 7. Satellite successor list

As there is a dependency among successor lists of consecutive satellites along the same orbit and between different orbits, we perform the analysis for both static and dynamic node failure when each node independently fails with a certain probability p .

It can be easily shown that if $r = c \log_2 n$, where $c > 0$ is a constant, $n \rightarrow \infty$, the probability that network remains connected approaches 1, if $p < 2^{-1/c}$, and 0, if $p > 2^{-1/c}$.

We define a Bernoulli random variable X_i indicating whether satellite i is isolated due to the fact that its r successors all fail while i survives:

$$X_i = \begin{cases} 1 & \text{satellite } i \text{ is alive and its } r \text{ successors failed} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

Then, the number of isolated satellites X in the system is the sum of a large number of dependent random variables :

$$X = \sum_{i=1}^n X_i \quad (9)$$

where n is the number of satellites in a single orbit.

It is clear that the probability that orbit remains connected (i.e., is not partitioned) is equal to $P(X = 0)$, where

$$\lim_{n \rightarrow \infty} \frac{P(X=0)}{E^{N(1-p)^R}} = 1 \quad (10)$$

From the fact that $P(\text{orbit is connected}) = P(X = 0) \approx E^{N(1-p)^R}$

IV. SIMULATION RESULTS

We carried out three experiments to evaluate the proposed model. The satellite is modelled as a (Linux) software-driven node [13]. Thus, multichord satellite network may tackle node software failures at different time scales. We can easily identify two-time scales:

- Time scale 1 - weekly connectivity software failures (as there is a weekly software update) that are debugged in-orbit.
- Time scale 2 - weekly connectivity software failures (as there is a weekly software update) that cannot be debugged in-orbit.

We will consider the first-time scale in experiments shown in Fig. 8 and the second-time scale is experiment shown in Fig. 9.

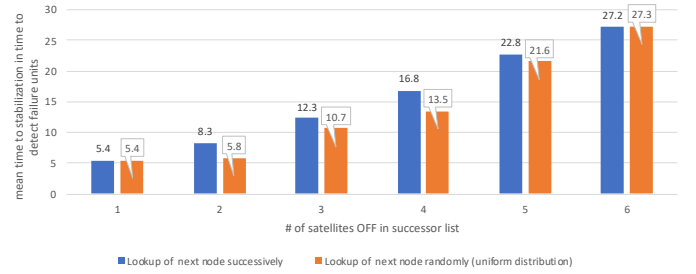


Figure 8. Number of satellites OFF in a successor list

The first experiment measures the ability of multichord satellite network to respond to failure in satellites listed in the successor list. The second experiment measures the response of the system to failure in connecting with a complete orbit. The third experiment measures the ability of the system to keep the connections alive during a complete lifetime of the satellite session.

Since calculations of real time of operations, processing, detection of failure and recovery is highly dependent on the network architecture and software used. We performed our simulation model on the basis of an abstract time unit. This time unit represents the time the satellite will need to detect failure in connections with one of its successors.

Figure 8 shows the mean time to achieve stabilization if the satellites listed as successors suffers from failure. The experiment is carried in two situations. The first situation assumes the lookup in the successor list is done in order and the second situation when the look up is done randomly. As the figure shows, there is a nearly linear increase in the meantime with the number of satellites in failure in first situation compared to the situation when the lookup is done at random. It also confirms that random lookup is superior when the number of failure nodes is low.

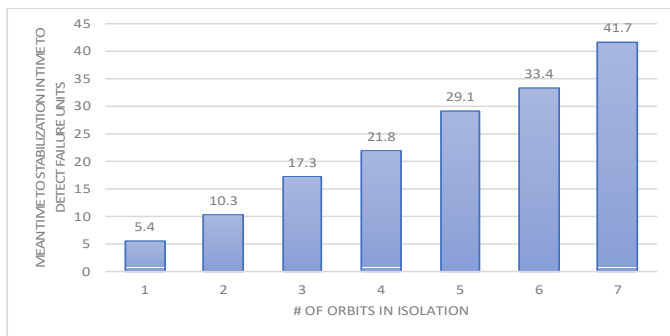


Figure 9. Mean time to stabilization

Figure 9 shows the mean time to achieve stabilization when the failure is in the orbit rather than the satellites. It is noticed that the growth in mean time is nearly exponential. This is due to the increase in lookup time for an alternative orbit and a satellite that can be used as a successor node in that orbit.

The last experiment is shown in Fig. 10, which measures the percentage of keeping the link alive versus the remaining time available in the ON session of a satellite. The figure shows that there is at least 50% chance of success to keep the link alive if the remaining time of ON session is more than half its overall time.

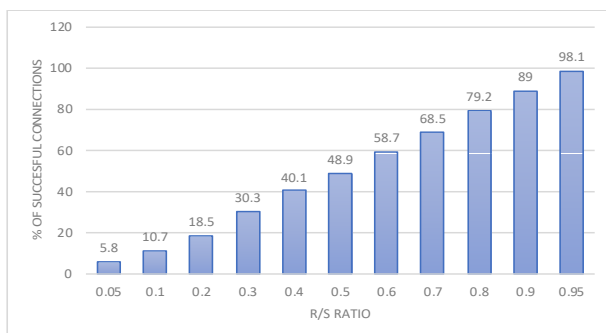


Figure 10. Number of successful connections

V. CONCLUSION AND FUTURE WORK

In this paper, we presented a mathematical model for peer-peer IoT satellite network based on the well-known chord concept. The mathematical model is based on a probabilistic approach that models the life time of a satellite in an orbit and the resilience of the network to satellite failure. It is shown that the time response to satellite failure is nearly linear which confirms the scalability of the model. However, it is not the same for orbit failure as it follows an exponential growth in time. Future work will investigate other types of intermittent

disconnectivity in inter-orbit communication and the robustness to cascaded large number of satellites failure in one and multiple orbits.

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