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LEO Satellite Constellations Network Routing Algorithms

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Abstract- The drive for information globalization has led to the rapid development of communication technologies. The main battlefield for competition for next-generation communication is gradually shifting from terrestrial to satellite communication systems, which have the advantages of wide coverage and less demands on the physical environment. The low-orbit (LEO) communication satellite is close to the planet, has a small communication latency, and can transfer large amounts of data. The rapid advancement of terrestrial and Internet technologies has negatively impacted the conventional geostationary orbit communication business, and low-orbit satellite communication development has become a widespread trend. The integrated circuit industry's rapid expansion has allowed for ever-smaller and more affordable satellites performing the same functions. Moreover, the creation of a LEO communication satellite network can become more feasible and economical with the help of the new technology symbolized by the reusable rocket, which can further reduce the cost of launching a LEO satellite. When compared to the terrestrial communication network, the low-Earth orbit (LEO) satellite network can offer global communication services and more affordable communication in remote locations, high-altitude regions, and maritime areas. However, there are a number of ways in which the LEO satellite network is very different from the terrestrial network. To the best of our knowledge, this research is a survey paper that focuses on routing protocols algorithms for LEO constellations networks.

*Keywords- **Satellite Constellations networks, Routing algorithm, challenges, LEO, Star-link, Delta.***

I. INTRODUCTION

SATELLITE network is One of the essential technologies for future communications. One of the essential technologies for future communications is the satellite network. Traditional geostationary orbit (GEO) satellite systems, on the other hand, suffer from severe delay and high launch costs. As a result, low-earth orbit (LEO) satellites have emerged as a viable alternative to GEO satellites' inherent flaws. The intersatellite connection (ISL) has been created to deliver increased system performance and more dependable service in tandem with the advancement of LEO technologies. Furthermore, because of its high data rate and compact terminal size, the optical ISL has been highlighted. Varied constellation designs will result in quite different satellite connection situations and topologies. The most basic need in terms of constellation design is to attain global coverage. There are two traditional. topologies for regular constellations at the same altitude: The Walker star or polar [1], [2], and the Walker or Rosette [2], [3]. The Walker Delta constellation, which uses inclined orbits, and the Walker Star constellation, which uses polar orbits, are the two principal LEO satellite constellations. In this study, four areas of security technologies in contemporary satellite networks are evaluated based on the function features of satellite networks. Furthermore, we examine vulnerabilities to satellite networks based on routing processes and discover safe routing methods. We also compare and contrast the results, as well as outline future research areas and difficulties concentrating on secure routing issues based on many routing protocols.

II. METHODOLOGIES

Satellite constellation networks in low earth orbit (LEO) have resurfaced in recent years as a result of their capacity to deliver ubiquitous broadband communication [4]. LEO satellite constellations are divided into Walker star and Walker delta constellations based on their orbit inclination. Many modern commercial constellations, like as Starlink and Kuiper, have chosen Walker-delta constellations because they give superior coverage in mid-latitudes, where the majority of the human population resides [5]. Existing LEO satellite constellations have either deployed or are proposing to install intersatellite connections (ISLs). ISLs can help the system become more self-sufficient and less reliant on terrestrial infrastructure. In addition, ISLs can assist improve system throughput and delay performance [6].

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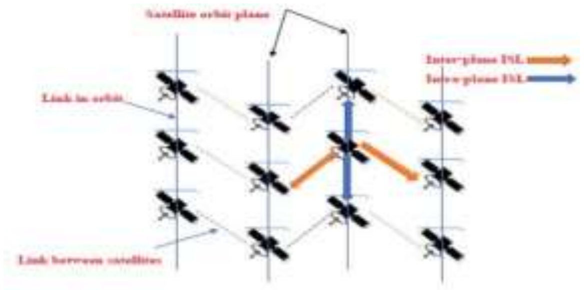

Fig. 1: Routing Architecture

III. LITERATURE REVIEW

In this paper [4], we investigate the prospect of striking a balance between overcoming the challenge of creating intermesh linkages in Walker delta constellations and enjoying the benefits of doing so. A technique for scheduling inter-mesh links is suggested that takes into account several limitations such as link distance, rotational velocity, link setup time, and link switching frequency. Simulations on the Starlink constellation demonstrate that with moderate system complexity, average E2E latency may be greatly reduced. Suddenly, For Walker delta constellations, we suggested an inter-mesh link scheduling mechanism. We showed how inter-mesh networks may dramatically reduce end-to-end delay while maintaining acceptable system overhead in terms of antenna required and topology update frequency [7]. In future constellation networks, we expect that our technique will serve as a starting point for more complicated ISL pattern construction. Another project underway is the development of routing algorithms for the planned ISL pattern, with the goal of lowering storage overhead and jitter between snapshots. Analysis of Inter-Satellite Link Paths for LEO MegaConstellation Networks [8] is another study. The following is a list of the work's contributions: For MCNs, an explicit technique for estimating the ISL hop-count between any ground users is presented, providing a theoretical approach to hop-count analysis and routing design. The algorithm's correctness is confirmed by comparisons with simulation results. Based on the suggested approach, several connections and symmetries between hop-count and user pair placement are obtained. The theoretical study shows that the hop-count in a given constellation is governed solely by the users' latitudes and the absolute value of their longitude difference, but not by their relative orientation. The hop-count distribution properties of Starlink are explored, as well as the influence of constellation parameters on them. We show that by adjusting the phasing factor, the total average hop-count in Starlink may be efficiently reduced. Similar findings may be obtained in the regional example of the United States and Europe. When users switch to a neighboring access satellite, significant differences in hop-count and routing can be discovered. The hop-count discrepancy in Starlink can be up to 45 hops. Finally, The ISL hop-count is investigated in this work in relation to Walker Delta mega-constellations. The purpose is to use ISL relay analysis to get insight into the topology and routing architecture of MCNs. A simple and fast hop-count estimate method is given, which avoids the need for sophisticated and expensive simulations. The hop-symmetry counts and certain explicable features are then derived. It is discovered that the hop-count value in a particular constellation is solely defined by the users' latitudes and the absolute values of their longitude difference. Comparisons with high-resolution MCN simulations are used to validate the suggested technique. The ISL hop-count has been explored in various settings using our suggested technique and derived attributes. When users swap access satellites, we saw a considerable change in hop counts. Furthermore, we discovered that the hop-count has a geographical distribution that is dependent not only on the spherical distance between users, but also on their latitudes. On ISL relays, the effects of constellation settings have also been investigated. The findings demonstrate that adjusting a phase factor is a potential method for lowering hop-count values without sacrificing other performance parameters. In specific US-to-Europe user scenarios, similar consequences have been discovered. Phase II's Starlink constellation will be far bigger than phase I's [9]. Although this research focuses on a single Starlink constellation layer, our suggested hop-count analysis method may be used to each layer of the future multiple-layer Starlink constellation. Based on this research, we want to do a follow-up study on the influence on routing design, in which not only hop count but also other factors such as route stability will be examined. A routing strategy that selects the route mode with the longest sustainable duration and the fewest hops will be an attractive field for further research. The research of latency for MCNs with routing in the sky will be addressed in this regard.

The paper is structured as follows: section I gives an introduction to LEO SatCon. The routing operation of LEO SatCon are summarized in Section IV. Then, Section III describes the state-of-the-art routing algorithms in LEO SatCon and Routing Challenges and Future Research Directions are discussed. Further, a case study on multihop routing algorithms is presented in section V. Finally, Section VI concludes the paper.

IV. OVERVIEW ON ROUTING OPERATIONS IN LEO SATCON

Many satellites have recently been deployed to provide individual users with global internet broadband connectivity. As satellite networks become more widely used, security concerns become more prominent, particularly with regard to the satellite network routing protocol, which ensures the regular forwarding of network data. When the routing protocol is attacked, routing discovery and maintenance are not completed, resulting in communication disruption and data leakage.

1. *SDPs algorithms (the shortest distance path (SDP) and minimum hop path (MHP))*

The satellite constellation network (SCN) in Low-Earth orbit (LEO) has emerged as a potential alternative for non-terrestrial networks (NTNs). The shortest distance path (SDP) and the minimal hop path (MHP) are two essential pathways in LEO-SCNs. This study investigates the conditions under which the

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statement that all SDPs belong to the MHP set holds true or not [29]. This study proves various reduced equivalent statements and creates a discriminant function to assess if the proposition holds in an arbitrary constellation based on topological regularity and link distance fluctuation patterns. Simulations confirm the judgement technique, revealing that all SDPs in constellations with short inclinations (less than 68 degrees) or substantial phasing offsets belong to the MHP set. The suggestions may make it easier to calculate SDP. This study intends to propose a generic approach for determining if all SDPs in a particular LEO-SCN belong to the MHP set. The original proposition is transformed and simplified in the same way. Then, to determine whether or not the statement holds, an explicit discriminant function is generated. The judging criteria are both sufficient and required. Numerical simulations are then used to validate the approach. The following is a summary of the major contributions: • In a typical constellation network architecture, determining whether all SDPs belong to the MHP set is as simple as determining if all SDPs belong to the single-hop vertical detour situation. • A discriminant function and analytical criterion based on ISL variation are suggested to determine whether all SDPs in a particular constellation network belong to the MHP set or not. • Simulations back up the suggested judgement approach, and the results demonstrate that the inclination of the orbit and the phasing factor are the most important factors in determining if the proposition holds. All SDPs in constellations with modest inclinations (less than 68 degrees) or substantial phasing offsets belong to the MHP set. When all SDPs belong to the MHP set, this work derives several simplified equivalent statements and gives a discriminant function to determine whether or not the propo- sition holds. The notion holds in constellations with modest inclinations (e.g., less than 68 deg) or substantial phasing offsets, according to a theoretical model and simulations.

2. *Binary Tree Search Based Routing Algorithm for LEO Satellite Networks*

Although low earth orbit (LEO) satellite networks have advantages in terms of quick response times, extensive coverage, and adaptable networking, end-to-end (E2E) transmission has faced significant difficulties as a result of frequent topology changes [22]. In order to decrease the E2E transmission delay and enhance network quality of service, a time-varying graph and binary tree search based routing method for LEO satellite networks is suggested in this research. In order to describe the topological structure and resource allocation of LEO satellite networks, a coordinate graph (CG) model is used first. Then, a minimum-hop binary tree (MHBT) is built after an E2E minimum-hop region is identified based on the CG model. After obtaining all minimum-hop pathways by the pruning traversal of MHBT, the E2E path with the least latency is identified. The suggested routing method, according to the findings of the simulation, increases the file delivery ratio while simultaneously cutting down on route delays.

3. *Interruption Tolerance Strategy for LEO Constellation with Optical Inter-Satellite Link*

To solve the inadequate bandwidth of microwave ISL, optical inter-satellite connection (ISL) of tens/hundreds Gbps is implemented into LEO constellation [23]. Additionally, due to its lower orbital altitude than GEO/MEO constellations, the LEO constellation experiences more frequent topology flipping. The most common method of topology flipping between nearby topology snapshots is ISL handover (delete or construct ISL). However, it is crucial to manage the service disruption brought on by ISL handover during topology change. Isolated topology and sluggish route convergence, which are caused by a long ISL delay and the distribution of the updated message over hundreds or thousands of satellites, may result in significant service interruptions after ISL handover. To reduce route convergence time for each ISL handover, a predictive update routing strategy based on Open Shortest Path First (OSPF-PUR) is also suggested. In the OSPF-PUR scheme, the forwarding table is refreshed without flooding in order to provide predictable ISL handover based on locally stored ISL handover information. Based on the findings of the simulation, it is clear that the grouped optical ISL handover strategy guarantees topology connection while speeding up route convergence during topology changeover. The OSPF-PUR scheme effectively reduces the ISL handover route convergence time. Additionally, the OSPF-PUR scheme's packet loss rate stays constant even as topology switching frequency rises.

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6. *Simulation Analysis of LEO Constellation Augmented GNSS (LeGNSS) Zenith Troposphere Delay and Gradients Estimation*

Low Earth Orbit (LEO) satellites move more quickly and can significantly enhance the viewing geometry compared to the present global navigation satellite system (GNSS), which is made up of medium- and high-altitude orbit satellites [?]. This paper examines LEO constellation enhanced GNSS (LeGNSS) troposphere estimate and analyses the effects of key variables in great detail. When the standard deviations (STDs) of phase and pseudorange observations at the zenith direction are 0.005 and 0.5 m, respectively, and the temporal resolutions of zenith troposphere delay (ZTD) and horizontal gradients are 1 and 2 h, the accuracy of ZTD, north gradient, and east gradient augmented by LEO constellation improves by 15.7 percentage, 29.6 percentage, and 16.4 percentage, respectively, compared with GNSS solution. After include LEO data, the findings of troposphere estimate in an obstructed environment and utilising inexpensive dual frequency sensors also become more reliable. Most importantly, analysis results for times when tropospheric parameters are rapidly changing suggest that the contribution of the LEO constellation increases as ZTD and horizontal gradient temporal resolutions increase, suggesting that LeGNSS can be used to extract tropospheric parameters with higher accuracy at higher temporal resolution. As a result, LeGNSS observations can increase the capacity to quickly capture severe weather occurrences, and the performance can get much better with more LEO satellites. All of these findings point to LeGNSS as a potential tool for enhancing troposphere estimate performance and advancing GNSS use for water vapour monitoring.

7. *Earliest Arrival Routing Algorithm for LEO Satellite Net- works*

Low Earth Orbit (LEO) Satellite Systems have traditionally been a research hotspot in space adventures due to the world- wide coverage, rapid communication, affordable launch, and high survivability of these space-based components of space- air-ground integrated networks. However, the quality of service (QoS) for LEO satellite networks will suffer due to the high dynamics of the network architecture and the time-varying distribution of link resources [24]. In this research, a combined minimal hop and earliest arrival (MHEA) routing algorithm for LEO satellite networks is suggested in order to decrease communication time and guarantee end-to-end (E2E) data transfers. First, a coordinate graph (CG) model is developed to precisely characterise both the topological structure and link resource distribution of time-varying networks in the two-dimensional Cartesian coordinate system, based on the networking mode of Walker constellations. The minimal E2E hop count and the area of the minimum hop path are then calculated using a CG-based minimum hop (MH) routing model. The shortest latency next hop node is then determined using an earliest arrival (EA) approach. Simulation findings show that the proposed MHEA routing algorithm increases the file delivery ratio while lowering the route count, hop count, and time of the E2E link.

8. *Routing Algorithm for AD Hoc Networks of LEO Satellites based on OSPF*

Due to the high density of nodes in the same orbit plane, the enormous number of satellites, and the rapid satellite motion speed, the static routing protocol is challenging to implement in the Low-Earth-Orbit (LEO) satellite network. This research suggests a routing method for AD hoc networks of LEO satellites based on OSPF to address the dynamic change problem of satellite topology [25]. Network connec- tivity scenarios and routing table data are established based on the periodicity and predictability of satellite topology. We dynamically compare the received predicted link status notice and LSDB to the proper routing information for routing node loss.In order to complete the trustworthy transfer of information, we also build the route reconstruction method at the same time. In comparison to OSPF, our method can cut the route convergence time by 94.22 percentage, the end-to- end delay by 56.17 percentage, and the packet loss rate by 64 percentage. STK and NS3 are used for simulation verification, and the results reveal that.

9. *A Multi-Region Division Routing Algorithm Based on Fuzzy-Shortest-Path-First for LEO Satellite Networks*

Low Earth Orbit (LEO) satellite network is anticipated to deliver higher-quality communication services in conjunction with terrestrial network and is a major addition to the terrestrial network and a crucial part of the upcoming 6G. It also garners considerable research attention. Balancing the network load has emerged as one of the major challenges for LEO satellite networks since the uneven distribution of terrestrial services may result in inter-satellite link (ISL) congestion. We suggest a multi-region division routing algorithm based on fuzzy- shortest-path-first

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(FSPF-MDR) for LEO satellite networks in order to avoid ISL congestion [26]. To reduce congestion, we partition the satellite network into a number of compact zones and communicate connection information among them. Simulation findings demonstrate that the suggested technique greatly reduces computation complexity at the modest cost of slightly increasing average hop count. Additionally, it can minimise congestion while utilizing less resources. The level of computational complexity can be decreased by 45 percentages to 70 percentages with various LEO network sizes.

IV. CASE STUDY:

In this section, we provide a system-level evaluation of one of the promising multi-hop routing technique for edmonds algorithm that make maximum matching G = (V, E) be a undirected graph, The links in the maximum matching is then the expected inter-mesh links [5].we are only concerned about assigning inter-mesh links to satellites in S.

Proposed Routing Algorithms:

This section proposes two inter-mesh scheduling algorithms to select suitable inter-mesh links that satisfy several constraints, save memory and power, and reduce the end-to-end delay. We consider the uniform cost search (UCS) and the Bellman-Ford (BMF) algorithms, respectively. Each one can be followed by using the Dijkstra algorithm to find the end-to-end route between two satellites, as shown on the block diagram in Fig 6. This investigation follows the same technique used in [32], where a combination of Edmonds and Dijkstra algorithms was used for routing. For the sake of completeness, we summarize the four algorithms as follows:

- **Dijkstra's (DIJK) Algorithm**: is a shortest path algorithm, shown in Algorithm 1, that is used in [32] to find the end-to-end route between any pair of satellites. However, there are several drawbacks to Dijkstra's algorithm, including the high CPU memory requirement, especially for a large number of nodes. Additionally, it cannot handle negative edges and is limited to positive weight graphs.
- **Edmonds' (EDM) Algorithm**
The authors in [32] formulated the link assignment problem as a maximum matching problem in a general graph to guarantee that each satellite is assigned at most one inter-mesh link. In graph theory, the EDM algorithm, also known as Blossom's algorithm, is an efficient algorithm for finding maximum cardinality matching on general graphs G = (V, E) [13]. It finds a matching M such that each vertex in V is incident with at most one edge in M and |M | is maximized. By incrementally
enhancing an initial empty matching along enhancing paths in the graph, the matching is created as shown in Algorithm 2. The time complexity of Edmonds' algorithm is O(V2),

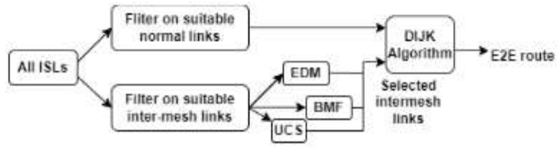

Fig 2: the block Diagram of the system

Algorithm 1 Dijkstra's Algorithm

```
procedure DIJKSTRA(G, s)                    ▷ G is the graph, s is the source vertex
    dist ← array of distances initialized to ∞
    dist[s] ← 0
    Q ← priority queue of vertices with dist as the key
    Insert s into Q
    while Q is not empty do
        u ← vertex in Q with minimum dist[u]
        Remove u from Q
        for all neighbors v of u do
            alt ← dist[u] + weight of edge (u, v)
            if alt < dist[v] then
                dist[v] ← alt
                Decrease key of v in Q to dist[v]
            end if
        end for
    end while
    return dist
end procedure
```

where V is the number of vertices in the graph. However, with the use of efficient data structures and optimizations, the algorithm can often run much faster in practice.

Algorithm 2 Edmonds' Algorithm

```
procedure EDMONDS(G)                        ▷ G is the graph
    M ← empty matching
    while there exists an augmenting path P in G do
        M ← M ⊕ P
    end while
    return M
end procedure
procedure ⊕(M)                              ▷ Augmentation operation
    M' ← copy of M
    for all edges (u, v) in the augmenting path P do
        if (u, v) ∈ M' then
            Remove (u, v) from M'
        else
            Add (u, v) to M'
        end if
    end for
    return M'
end procedure
```

- **Uniform Cost Search (UCS) Algorithm**:

UCS is an algorithm in artificial intelligence to find the cheapest path to a goal node in a weighted graph. It expands the node with the lowest cost so far, keeping track of the total cost from the start node to each node on the path. The UCS algorithm shown in Algorithm 3 can be used to determine the shortest path between a source vertex s and every other vertex in graph G. UCS starts with s only at the priority queue (Q), as in step 2, and then gradually adds other vertices from the adjacent vertices. We select the vertex whose distance from s is lowest in each expanding step. The time complexity of the UCS algorithm is O((|V | + |E|)log|V |), if we use a min-priority queue to implement Q. The following formula, dist[v] = min(dist[v], dist[u] + w(u, v)) is used to update the distance value of each vertex. The main difference between UCS and the Dijkstra algorithm is how we store vertices in Q. The UCS algorithm initially only stores the source vertex and stops expanding once we reach the destination vertex. Therefore, the UCS algorithm may only store a partial graph at the end. On the other hand, Dijkstra's algorithm initializes Q with all vertices in G. Therefore, the DIJK algorithm is only applicable for explicit graphs where we know

Algorithm 3 Uniform Cost Search Algorithm

```
procedure UNIFORMCOSTSEARCH(G, s, goal)      ▷ G is the graph, s is the source
vertex, goal is the goal vertex
    dist ← array of distances initialized to ∞
    dist[s] ← 0
    visited ← array of booleans initialized to false
    Q ← priority queue of vertices with dist as the key
    Insert s into Q
    while Q is not empty do
        u ← vertex in Q with minimum dist[u]
        Remove u from Q
        visited[u] ← true
        if u = goal then
            return success
        end if
        for all neighbors v of u do
            if visited[v] = false then
                alt ← dist[u] + cost of edge (u, v)
                if alt < dist[v] then
                    dist[v] ← alt
                    Insert v into Q with dist[v] as the key
                end if
            end if
        end for
    end while
    return failure
end procedure
```

all vertices and edges. However, the UCS algorithm starts with the source vertex and gradually traverses the necessary graph parts. Therefore, it applies to both explicit and implicit graphs. Additionally, Dijkstra's algorithm has more memory requirements as we store the entire graph. Bellman-Ford (BMF) Algorithm: Another proposed algorithm for further improvements in this system is the BMF algorithm shown in Algorithm 4. BMF algorithm is a shortest-path algorithm that finds the shortest path between a source vertex and all other vertices in a weighted graph with negative edge weights. These enhancements include preventing negative cycles, dealing with negative edges, reducing E2E delay, and improving system performance in terms of several metrics including the cost, power requirements, memory usage, and E2E delay. While BMF uses the concept of area relaxation, unlike Dijkstra's method, it does not do so in a greedy manner. BMF offers several benefits including its dynamic nature, ability to compute both positive and negative directed edges, and the ability to identify the shortest path between two nodes to minimize network construction costs. Additionally, BMF can discover the lowest path weight with great efficiency and accuracy and does not require complex data structures for applications.

Algorithm 4 Bellman-Ford Algorithm

```
procedure BELLMANFORD(G, s)      ▷ G is the graph, s is the source vertex
    dist ← array of distances initialized to ∞
    dist[s] ← 0
    for i ← 1 to |V| − 1 do      ▷ |V| is the number of vertices
        for all edges (u, v) in G do
            if dist[u] + weight of edge (u, v) < dist[v] then
                dist[v] ← dist[u] + weight of edge (u, v)
            end if
        end for
    end for
    for all edges (u, v) in G do
        if dist[u] + weight of edge (u, v) < dist[v] then
            return "Negative cycle exists"
        end if
    end for
    return dist
end procedure
```

Results and Simulations:

In this work, we consider phase 1 of Starlink constellation for comparing the performance of different link scheduling algorithms [16]. The constellation consists of 1584 satellites distributed across 72 orbits with an inclination of 53 degrees and a height of 550 km. The connection setup time (tsetup) is set to 30 seconds, while the connections are planned for 5800 seconds or approximately one orbit cycle. The satellite Scenario object in Matlab, which represents a 3 dimensional (3D) arena consisting of satellites, ground stations, and their interactions, is used for simulation as shown in figure 3. To implement the different routing algorithms, all possible links between satellites need to be identified according to the relative coordinates between satellites during each snapshot. Figure 4 shows a sample of Starlink SatCon network and their actual coordinates extracted from the two-line element (tle) files of Starlink's. Figure 5 is declared the side view and top view of all satellites using Dijkstra Algorithm to find the shortest path.

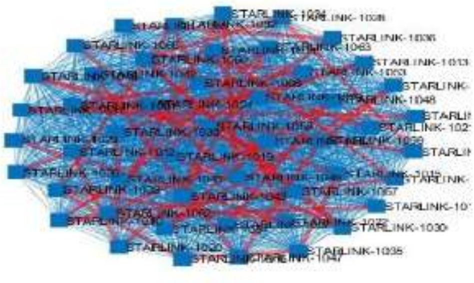

Fig 3: the network of satellites with intra and inter ISLs

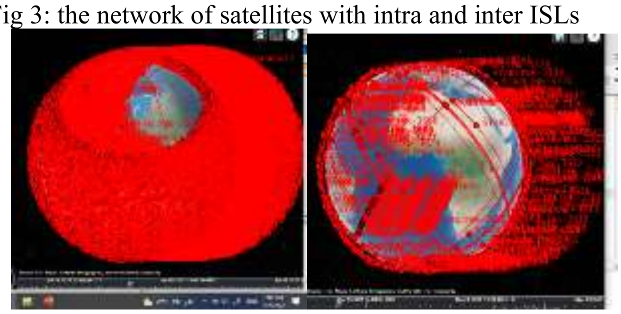

Fig 4 : satellites with its orbits using MATLAB simulation

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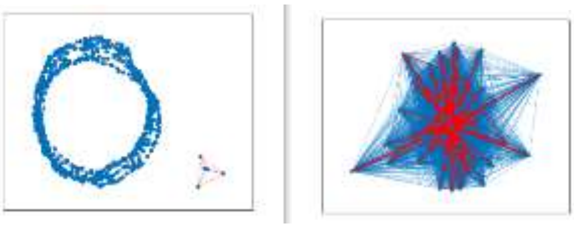

Fig 5 : the side view and top view of the satellites

VI. CONCLUSION

since of their ability to supply ubiquitous broadband connectivity, satellite constellation networks in low earth orbit (LEO) have revived in recent years. Based on their orbit inclination, LEO satellite constellations are split into Walker star and Walker delta constellations. Walker-delta constellations have been selected by many current commercial constellations, such as Starlink, because they provide improved coverage in mid-latitudes, where the bulk of the human population dwells. Inter satellite links have been implemented or are being proposed by existing LEO satellite constellations (ISLs). ISLs can aid the system's self-sufficiency and reduce its reliance on terrestrial infrastructure. ISLs can also help increase throughput and delay performance in systems. Inter-satellite links have been implemented or are being proposed by existing LEO satellite constellations (ISLs). ISLs can aid the system's self-sufficiency and reduce its reliance on terrestrial infrastructure. ISLs can also help increase throughput and delay performance in systems.

VII. REFERENCES

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