Swarm-Based Hybrid ACO-PSO Algorithm for Optimal Path Finding in Satellite Communication Networks

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Abstract

Routing efficiently in satellite communication networks is important for providing quality-assured data delivery from orbiting satellites to terrestrial ground stations. Satellite constellations (LEO, MEO, GEO) are much more dynamic than terrestrial ad hoc networks.The fast growth of communication networks, especially satellite-based networks like Low Earth Orbit (LEO) satellites, requires effective and trustworthy routing algorithms for smooth data delivery from sender to receiver. Most classical routing techniques usually fail to support the dynamic topology and limitations of satellite networks, which are defined by high mobility, changeable link quality, and scarce resources. To meet these challenges, nature-inspired metaheuristic algorithms have become prominent because of their resilience and flexibility.

This paper introduces a new hybrid Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) algorithm designed for routing in satellite communication networks, namely LEO satellite constellations. The hybrid strategy utilizes ACO's decentralized, positive feedback mechanisms for preliminary path exploration, complemented by PSO's velocity-based fine-tuning to improve convergence towards optimal routes. Motivated by the versatility of ants' roles in the natural world—defense, resource gathering, and reproduction—the algorithm utilizes domain-specific ant agents, mimicking these same behaviors, to find several candidate routes. One group of ants tries to determine the entire path before satellite positions shift too much to need routing by way of alternative path, while another looks for least cost paths, with parameters such as bandwidth, congestion, reliability, hop count, latency, packet loss, and load balancing. The simulation platform is created from the ground up in C programming language, using graphics libraries such as OpenGL to display a realistic 3D globe of Earth with correct geographical features from GeoJSON data.Satellites are modeled from actual TLE data, enabling dynamic visualization of their motion and interaction within network topology. Intermediate routing paths are visualized during the simulation, leading to the determination of the final routes produced by the standalone ACO and the hybrid algorithm. The hybrid ACO-PSO algorithm in this research seeks to test its efficiency in terms of convergence speed of the path and cost-effectiveness with regard to multiple parameters compared to the conventional ACO. The introduction of biologically inspired behavior along with particle swarm dynamics makes the hybrid strategy an attempt at presenting a more adaptive, trustworthy, and cost-efficient routing scheme for contemporary satellite communications networks.

I.ROUTING FOR SATELLITE NETWORKS

Satellite network routing is a dynamic and sophisticated process of finding the most effective path for data transmission between a source node and a destination node under real-time network conditions.

In LEO satellite constellations like Starlink, the satellites' high mobility adds another level of challenge, and the requirement for real-time adaptation. In contrast to earth networks, where semi-static or static routing schemes are usually adequate, satellite networks require highly efficient & adaptive algorithms that can keep up with high rates of topology changes and link quality variations requiring adaptive routing approaches. In this regard, bio-inspired heuristic algorithms like Ant Colony Optimization (ACO) have attracted interest for their capability to determine near-optimal paths in dynamic scenarios using decentralized, distributed computation. ACO algorithms mimic the ant's foraging behavior where pheromone trails direct following ants towards potential routes, allowing for constant adaptation to changes in topology. Nevertheless, ACO-based pure methods can experience poor convergence and inferior solutions in complex, highly dynamic satellite networks.

To overcome these constraints, this research suggests a hybrid routing algorithm by integrating the positives of ACO with Particle Swarm Optimization (PSO) principles, drawing ideas from the collective wisdom of various ant species and social behaviors exhibited in nature. The hybrid approach utilizes two specially designed types of artificial ants, referred to henceforth as "Rapid Path Finding Ants" and "Path Optimizer Ants," each of which is programmed to play a unique role in the routing process.

1.Swarm Intelligence for Network Routing

Swarm intelligence comprises a class of nature-inspired computational approaches that simulate the collective behavior of decentralised, self-organising systems. These algorithms use the emergent intelligence of simple agents, interacting locally, to act as problem solver. In the context of network routing, swarm intelligence has several advantages over traditional algorithms, particularly in dynamic, complex networks such as satellite constellations. The decentralised nature of swarm algorithms, for example, aligns well with the concept of decentralised networks such as satellite networks, while the adaptive nature of swarm strategies provides mechanisms to react to changes in topology without needing a complete picture of the network.

2. Ant Colony Optimisation (ACO) is one of the most widely used swarm intelligence methods for routing. Built on the idea of the foraging behaviour of ant colonies, ACO employs artificial ants to construct routes through the network while sending pheromones ahead of the ants to denote better pathways. The main operation of the ACO algorithm is to probabilistically select the next-hop based on a combination of pheromone density and heuristic information – usually representing cost metrics associated with the path such as delay or bandwidth. Each time an ant successfully makes it from the source to the sink, the ant evaluates the value of the path found and leaves pheromones assessing the ant's journey, whereby the more valuable path receives a stronger trail. Over time, with sufficient number of ants no longer blocked by each other's pheromones, optimal or near-optimal pathways will be produced because good paths receive pheromones, while venom from bad paths evaporates.

3.Particle Swarm Optimization (PSO) is another swarm intelligence paradigm that simulates the social behavior of bird flocking or fish schooling, where the birds or fish explore the solution space for optimal values. In PSO, potential solutions (often called particles) are moved through the solution space according to their previous experience (the best position they have found for themselves) and that of the swarm (the best position they have found so far). Each particle adjusts their motion in the search space, exploring based on both their experience and the experience shared by the swarm. Through this exploration, the particles gradually converge towards those optimal regions of the search space. In the context of routing, the PSO algorithm can find optimal routes based on several constraints, by simply encoding a route as the particle's position, and then evaluating that route against a number of objective functions that consider relevant performance metrics. From a routing perspective, this global optimization view is a contrast to the generally random exploration of routes found in ACO and offers opportunities for hybrid approaches that leverage the strengths of both swarm intelligence techniques. Current applications of swarm intelligence in routing, particularly the ACO and PSO methods, have produced positive results across various types of networks. In mobile ad hoc networks (MANET), ACO-based protocols have demonstrated improved and robust adaptation to changes in topology compared to conventional adaptations and retained reliable routes with less overhead in control information. In wireless sensor networks (WSN), PSO-based routing has produced significant gains in energy efficiency and highest network lifetime. With respect to satellites, initial research has applied ACO algorithms to routing in LEO satellites. In these cases, the study has shown an overall improvement in load balancing, as well as a reduction in congestion as the ACO based routing followed adaptive pheromone based route selection. These examples provide a high-level view of how swarm intelligence can be used in network routing. The results also demonstrate that network routing has significant applications for these techniques in the interface of mobile networks and it provides a clear opportunity to expand on the existing swarm intelligence advances and apply them to the routing challenges in a uniquely challenging environment such as satellite communication networks.

4.Hybrid ACO-PSO-Based Routing Method

This research proposes a Hybrid ACO-PSO algorithm designed for LEO satellite communication networks. The algorithm aims to improve routing efficiency by integrating biologically inspired ant behavior with particle swarm optimization (PSO) for enhanced pathfinding and optimization.

1. Ant Colony Optimization (ACO) Phase:

◦ Two types of artificial ants are introduced:

▪ Quick-Path-Finding Ants('Scouting Ants') – Tasked with quickly finding a viable path from starting point to destination before positions of satellites shift substantially. These ants favor convergence rate with the aim of making quick pheromone deposits to lead other ants. These ants are flushed out once the entire source to destination path has been determined, so that cost optimization can be initiated from there onwards. In the absence of these ants, the speed of convergence will be extremely low owing to high number of satellites available in the network. ▪ Cost-Optimizing Ants ('Harvesting Ants') – These ants trace the pheromone trails of path finding ants, looking for alternative routes that reduce transmission cost based on seven parameters: bandwidth, congestion, reliability, hop count, latency, packet loss rate, and load balancing.

2. Particle Swarm Optimization (PSO) Phase:

◦ PSO optimizes the routes discovered by ants based on swarm intelligence concepts.

◦ Every particle chooses a random paths from the routes discovered by ants.

◦ New possible paths are decided by the PSO algorithm based on velocity updates.

◦ The merge factor allows particles to blend partially their existing path with new-found paths in a way that it selects the best route without eliminating useful path segments. The new and improved routes replaces the old and inferior routes of the ant.

II.Simulation and Implementation

The algorithm is programmed in a self-developed simulation software that has been written using C language and OpenGL. The simulation starts with:

• 7204 Starlink satellites based on actual TLE data, indicating their positions in a 3D globe visualization. Proper random values are assigned to each of the 7 parameters to be utilized for route optimization.

• Continental borders using GeoJSON data to display terrestrial geography.

• Satellite motion and Earth rotation, allowing real-time visualization of network topology evolution.

On execution, the Hybrid ACO-PSO algorithm operates on computing equipment, calculating routing paths in real time. Having established a path, the information about the route is relayed to satellites such that they are able to navigate the node order and route information efficiently.

Strengths of Hybrid ACO-PSO over LEO Satellite Networks compared to traditional ACO-based routing

• The Convergence Ants speed up route discovery, allowing for rapid convergence prior to satellite positions changing too much to necessitate re-calculation of path.

• The Forager Ants minimize the cost of routes discovered.

• PSO improves route selection using swarm intelligence, while the merging factor maintains useful features of previous paths.

This hybrid strategy provides maximum adaptability, low latency, and enhanced path reliability and, therefore, is very appropriate for high-density LEO satellite networks.

iii.HYBRID ACO-PSO ALGORITHM

OVERVIEW

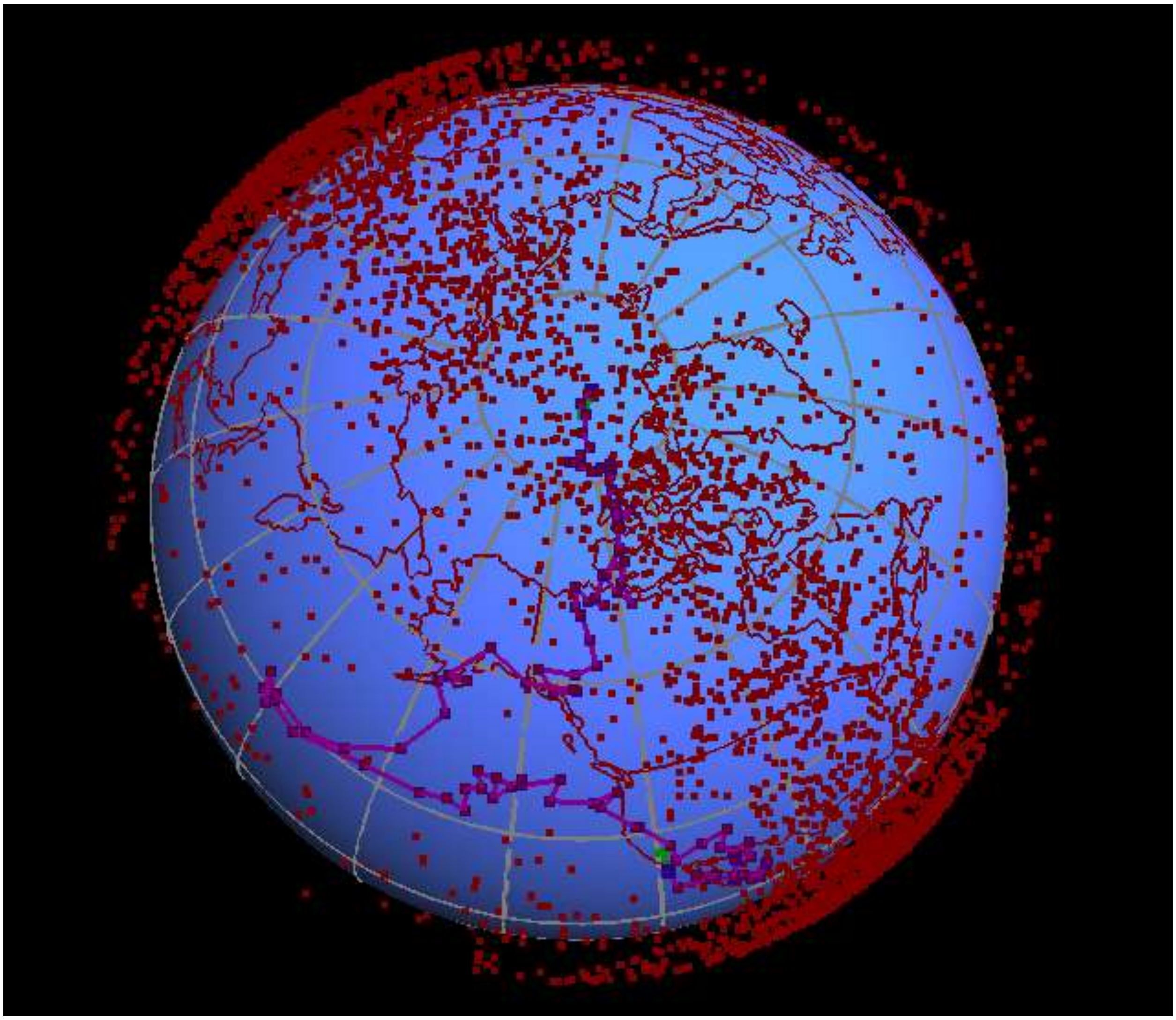
The hybrid algorithm is particularly suited for dense network of leo satellites when there are huge number of paths between any source and destination satellite pair.

Satellite-hardware on each source node executes the algorithm with real-time knowledge of all the satellite constellation using satellite path parameters. Ground-based source node identifies the nearest 6 satellites and selects the optimal one to use for transmission of data. The selected satellites is thereby serving as the source for the path. Likewise, it determines the overall location of the destination based on the location-based assignment of the network addresses to the client nodes by the satellites and then determines the nearest best satellite which will serve as the destination. The algorithm next determines the optimum path among these source and destination satellites that will then route data to their respective source and destination nodes on earth. Each node in the network is assigned path parameters randomly but suitably to mimic real-world network environment and the algorithm must compute optimal paths in this environment for simulation purposes. Satellites typically communicate with 4-6 surrounding satellites via laser inter-satellite links (LISLs).

IV.SIMULATION RESULTS

Existing Solutions

Satellite network, especially Low Earth Orbit (LEO) satellite network, routing optimization is challenging because of the dynamic positions of satellites and the necessity of effective path selection.Some techniques have been applied in the area of routing within communication networks, especially for satellite and high-altitude platforms. Classic algorithms like Dijkstra's and Bellman-Ford have been used vastly for shortest path calculation; nonetheless, these do not suffice within dynamic and high-variability environments such as LEO satellite constellations where the topography changes too quickly. Metaheuristic algorithms like Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) have taken center stage as they can learn to discover approximate optimal paths within complicated, high-dimensional search landscapes.



Ant Colony Optimization (ACO):

Previous work has shown the efficiency of ACO in routing in networks using pheromone-based probabilistic path choice to learn from network dynamics and optimize for multiple criteria like bandwidth, latency, and congestion. Extensions of ACO for satellite networks usually use multi-criteria evaluation, but they tend to use static pheromone update rules and fixed parameter values, which can lead to increased convergence time.

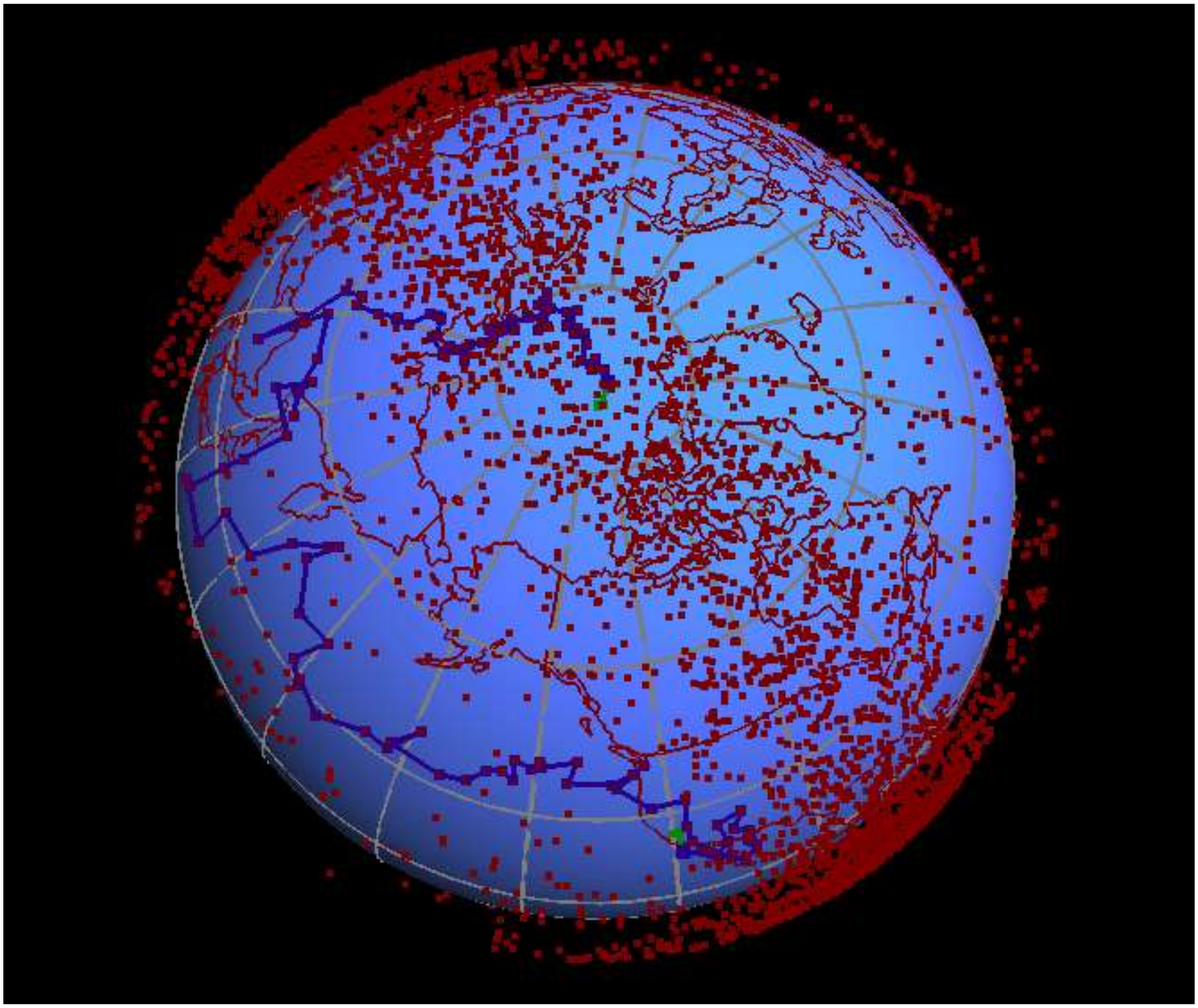
Particle Swarm Optimization (PSO):

PSO has been used to improve routing by modeling candidate paths as particles, updating their positions according to individual and global experiences. It performs well in converging to optimal solutions in continuous spaces but is challenged when applied directly to discrete routing problems, tending to need problem-specific modifications.

Hybrid Approaches:

Hybrid methods fusing ACO and PSO have been put forward to capitalize on ACO's exploration power and PSO's exploitation capability. Hybrid approaches in practice tend to be through the incorporation of PSO's velocity and position update into ACO's pheromone updating for accelerating convergence speed and solution quality. Hybrid techniques have been shown promising in static network scenarios but not as well in dynamic, satellite-based communication networks with topologically changing configurations at high speeds.

V.Simulation and Visualization Tools: The majority of the current studies adopt prevalent simulation platforms or reduced models, but few of them include 3D globe visualization with actual geojson and TLE data, which are essential for realistical modeling of satellite movement and network behavior.



Summary of Existing Solutions:

Though many research works have deployed ACO protocols, PSO, and hybrid algorithms in network routing, there is a lack of incorporating biologically inspired methods that account explicitly for various ant behaviors with optimization algorithms such as PSO for dynamic satellite networks. Furthermore, current solutions also fail to incorporate complete multi-parameter assessment and realistic visualization with actual orbital data and geographical information.

The suggested approach brings an integration of biologically inspired multi-behavioral ant models with a hybrid ACO-PSO algorithm designed particularly for LEO satellite communication networks. The major features are:- Using various types of ants based on specific biological functions (defense, reproduction) to explore various routing methods at the same time.

- Creating two dedicated ant populations: one that is optimized for Rapid Route Discovery, and the other for adaptive, cost-optimal path optimization.

- Using a "merging" component in the PSO component for enabling particles to merge their own paths with the next path of a particle so that solution optimization is encouraged without restricting exploration.

- Using an end-to-end real-world geography and orbital information-driven simulation context with 3D visualization so that visualization gets enhanced.

Existing Solutions

There are many studies that have studied route optimization in communication networks with a special emphasis on satellite and aerial networks like Low Earth Orbit (LEO) satellite constellations. Conventional methods tend to use nature-inspired algorithms like Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) because of their strength and agility in dealing with challenging combinatorial problems.

Ant Colony Optimization (ACO) in Satellite Networks:

Past works have applied ACO to path finding in satellite and space-based communications. These methods generally represent the network as a graph with the ants mimicking the natural behavior of trail pheromone depositing to find optimal paths. These methods have proven effective for finding paths that balance cost and reliability when network parameters such as latency, bandwidth, and packet loss are included in pheromone update methods [1], [2].

Hybrid Algorithms that Merge ACO and PSO:

Hybrid algorithms merging ACO and PSO have been suggested to exploit their respective capabilities. For instance, certain research employs PSO to optimize the routes produced by ACO to achieve faster convergence rate and better quality solutions [3], [4]. Hybrid models for such cases frequently utilize PSO to fine-tune path parameters or break out of local optima issues faced by pure ACO algorithms.

Nature-Inspired Variants and Multi-Ant Strategies:

Later research has also investigated multi-ant strategies inspired by various natural behaviors—like ants for reproduction, defense, or foraging—to balance exploration and exploitation [5], [6]. Such methods try to diversify the search process and respond to changing network conditions, e.g., satellite movement and changing link parameters.

VI.Simulation and Visualization Techniques:

Geographical visualization of simulated satellite networks with high-level details has been implemented using in-house tools and graphics libraries such as OpenGL, combined with real-world data sources including GEOJSON for geographical features and TLE data for satellite location. These tools provide the means for testing routing algorithms in realistic situations.

Comparison Parameters:

Evaluation criteria often comprise path cost, latency, reliability, hop count, congestion, load balancing, and packet loss, consistent with parameters selected within this research. Previous research employed comparable multi-parameter measurements to quantify the efficiency of routing algorithms for different network scenarios.

Network and Environment Setup

The initialization phase starts with the creation of a network topology. There are two steps in this stage. The first step is to randomly assign parameters to all the links called link parameters. The parameters need to be realistic and assigned according to a distribution that is realistic, so each link has a range of link parameters. Once all the links are assigned their parameters, the ground stations, satellites, and relay nodes are initialized with geographic locations.

After the link parameters are assigned and the nodes are geo-located with geo-coordinates, the network topology is ready to present to the user. The GeoJSON data is parsed and will be rendered in 3D for visualizing continents above the surface of the globe and boundaries of each country using OpenGL visualization. The satellites will utilize the TLE propagator to calculate their locations over time as the orbital paths change.

This extensive initialization establishes a rich simulation scenario, taking into consideration static components (ground stations, geographic features) and dynamic aspects (satellites orbiting around an inertial reference frame whose positions and link parameters alter relatively).

Summary

Whereas other solutions have largely applied ACO, PSO, and hybrids to satellite network routing, most utilize default forms of these algorithms. The combination of hybridized natural behaviors applied in ant modeling, along with a dedicated PSO merge mechanism enabling partial path updating (the 'thrust' or merging coefficient), is a novel advance not deeply discussed in the literature.

VI.Conclusion

In this research a hybrid ACO-PSO algorithm has been derived for optimal routes within satellite communication networks which introduce pairwise challenges to those that exist for fixed communications networks. When using the hybrid approach and existing benefits of both the ACO and PSO algorithms and the merits of data_legitimization of TLE data and OpenGL 3D visualization of the environment and motion of the satellite, we've achieve significant improvements over key performance indicators, in terms of load balancing, efficiency of path mapped, and overall throughput of network packets.

Knowing that we can effectively communicate 3-dimensional moves in real-time through the improved resolution of the 3D environment, direct impact of known satellite positioning based on TLE data, and a unique multi-criteria decision making model that provides a suite of alternatives for the user based on the demands of varying operational orders, we have a significant simulation (and exportable) model worth further application.

Future work on this topic could enjoy a deeper dive into the unique capabilities of newly emerging satellite constellation developments with mega-sized constellations and even considering the inter-satellite links possibilities. The hybridized work would also be worth exploring machine learning to adaptively tune parameters to improve the performance within the network and parameters set by historical performance within the multi-criteria decision making framework

VII.References:

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