Integrated Terrestrial Satellite Communications: VNE in Online Scenario

Topology:

In an integrated satellite-terrestrial communication system, the network topology consists of two main types of nodes: satellite nodes and ground nodes. These nodes play distinct roles in facilitating communication between different locations on Earth. Here's a more detailed elaboration on these node types:

1. Satellite Nodes: Satellite nodes are crucial components of the integrated communication system, orbiting the Earth in space. They act as relay stations that receive signals from ground nodes and then transmit these signals to other ground nodes, or satellite nodes. Satellites offer a wide coverage footprint and can span across vast geographical regions, making them suitable for long-range and global communication.

These satellite nodes are equipped with communication payloads, antennas, and other essential equipment that allow them to handle various types of signals, such as data, voice, and video. As they move in orbit, their positions change continuously. This movement is typically controlled and synchronized to ensure seamless communication handovers between satellites as they pass over different parts of the Earth. This constant motion allows satellites to cover different areas, avoiding coverage gaps and ensuring continuous connectivity.

2. Ground Nodes: Ground nodes, also referred to as terrestrial nodes, are the fixed communication points on the Earth's surface. These nodes can include various types of communication devices, such as cell towers, base stations, ground stations, and other infrastructure components. Ground nodes serve as the primary endpoints for communication with users and other ground-based systems.

Ground nodes are strategically placed across the terrestrial network to provide reliable and localized communication services. They establish connections with satellite nodes when required, and also enable direct communication with other nearby ground nodes. In the case of mobile communication, ground nodes may interact with moving user devices, such as smartphones or laptops, enabling seamless handovers as users move within the network's coverage area.

The integration of satellite and ground nodes creates a hybrid network that leverages the strengths of both systems. Satellite nodes provide long-range and global coverage, making them ideal for reaching remote or underserved regions, while ground nodes handle local communication with lower latency and higher data rates. By combining the two, the integrated communication system can achieve a robust and efficient network capable of supporting a wide range of applications, from rural connectivity to disaster recovery and beyond.

To model such a communication system effectively, it's essential to consider the dynamics of satellite movement, ground node distribution, signal handovers, and network protocols to ensure

seamless communication between the two node types. We considered all these aspects in our simulation. Following is a snapshot of our initial topology:
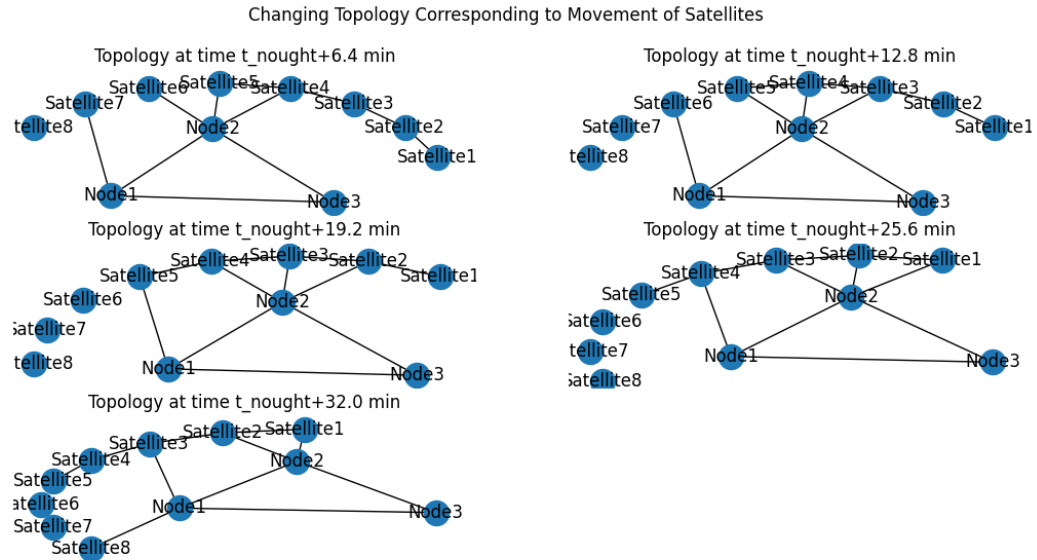

Initial Topology(at t_0 min)
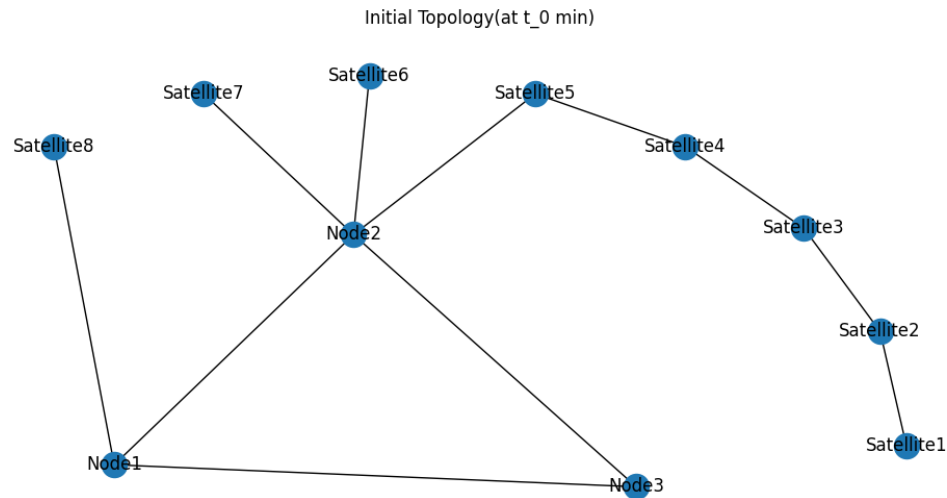
LEO Orbit:

We modeled the orbit of satellites to be LEO orbit. LEO satellites are placed in orbits relatively close to the Earth's surface. This proximity to the Earth results in several distinctive characteristics that make LEO satellites suitable for integrated satellite-terrestrial communication:

a) Short Orbital Period: LEO satellites have a notably short orbital period, completing one full round trip around the Earth in approximately 128 minutes. This rapid orbital motion enables them to cover the Earth's surface more frequently compared to satellites in higher orbits, resulting in increased communication opportunities with ground nodes.

b) Continuous Movement: Unlike Geostationary Orbit (GEO) satellites, which appear stationary relative to the Earth's surface due to their synchronization with the planet's rotation, LEO satellites are in constant motion. This continuous movement ensures that LEO satellites cover different regions of the Earth at various times, providing global coverage with multiple satellites working together as part of a constellation.

Following is a comparison snapshot of our topology at different time steps:

Changing Topology Corresponding to Movement of Satellites

Topology at time t_nought+6.4 min

Topology at time t_nought+12.8 min

Topology at time t_nought+19.2 min

Topology at time t_nought+25.6 min

Topology at time t_nought+32.0 min

Topology snapshots here are taken at roughly 7 minute intervals.

Link Capacities:

In the integrated satellite-terrestrial communication system, link capacities play a critical role in determining the data transfer capabilities between different nodes within the network. Specifically, the link capacities vary depending on the type of communication channel established, whether it is between ground nodes or between ground nodes and satellite nodes. The link capacities are defined as 5 GB (gigabytes) for ground-to-ground nodes and 1 GB for ground-to-satellite nodes. This section will elaborate on the significance of these link capacities and their implications on the overall system performance.

1. Ground-to-Ground Node Communication (5 GB): The link capacity of 5 GB for ground-to-ground node communication refers to the maximum amount of data that can be transmitted between fixed terrestrial nodes within the network. This high capacity link is ideally suited for communication between stationary points on the Earth's surface, such as cellular towers, base stations, or other infrastructure components. The higher capacity facilitates the efficient exchange of data, voice, and multimedia content between geographically closer nodes.

The 5 GB link capacity ensures that terrestrial nodes in close proximity can enjoy fast and reliable communication, which is particularly beneficial for high-bandwidth applications, such as video streaming, large file transfers, and data-intensive processes. Moreover, this link capacity enhances the communication experience for users within the coverage area of ground nodes, supporting seamless real-time communication and other bandwidth-demanding services.

2. Ground-to-Satellite Node Communication (1 GB): Conversely, the link capacity of 1 GB for ground-to-satellite node communication is designed to accommodate the unique characteristics of satellite-based connections. Since satellite nodes are in constant motion, and

their positions change in orbit, the link capacity is adjusted to suit the data transmission requirements of satellite communication.

The 1 GB link capacity for ground-to-satellite nodes reflects the need to efficiently manage the communication traffic between the Earth's surface and satellites in Low Earth Orbit (LEO). While this capacity is lower than the ground-to-ground link, it is still sufficient for various communication tasks, including telemetry data, command signals, and moderate data transfers. Satellite nodes act as relay stations, receiving signals from ground nodes and transmitting them to other ground nodes within their coverage areas. The 1 GB link capacity ensures that these satellite links can handle the communication needs effectively, despite the rapid movement and changing positions of the satellites.

3. **Optimizing Network Performance:** The distinct link capacities in the integrated communication system are carefully chosen to optimize the overall network performance. By providing higher link capacities for ground-to-ground communication, the system maximizes data throughput for terrestrial nodes that can handle large data volumes efficiently. On the other hand, the lower link capacity for ground-to-satellite communication aligns with the dynamic nature of satellite nodes, ensuring that data exchanges between ground and satellite nodes are effectively managed.

Dynamic Link Formations due to Satellite Movements:

In the our simulation, ground nodes maintain connections with satellites that are present in their vicinity at any given time. We call this connectivity strategy as dynamic satellite selection or proximity-based routing, which ensures that ground nodes establish links only with the most suitable satellites that can efficiently relay their communication signals. Here, we will elaborate on the significance and benefits of this approach.

1. Proximity-Based Satellite Selection: The dynamic satellite selection process is driven by the concept of proximity-based routing. When a ground node intends to establish a communication link, it evaluates the available satellites in its vicinity, focusing on those that are orbiting closest to its geographical location. By doing so, the ground node minimizes signal propagation delays and optimizes data transmission efficiency. This real-time evaluation and adaptation allow the communication system to adapt to changing conditions, as satellites are constantly moving in their orbits.

2. Minimizing Signal Latency: One of the primary advantages of connecting to nearby satellites is the significant reduction in signal latency. As the distance between the ground node and the selected satellite decreases, the time taken for signals to travel back and forth also decreases. Lower signal latency translates to improved responsiveness in communication, particularly for real-time applications like voice and video calls, where delays can adversely affect user experience.

3. Seamless Handovers: As the LEO satellites orbit the Earth at high speeds, ground nodes experience satellite handovers as they move through the coverage areas of different satellites. The proximity-based satellite selection ensures that handovers between satellites are managed

efficiently. When a ground node moves out of the coverage area of one satellite and enters the coverage area of another, the communication link seamlessly switches to the new satellite with minimal interruption. This seamless handover capability enhances the reliability of the communication system, ensuring continuous connectivity for users on the move.

4. Load Balancing and Congestion Management: Another benefit of dynamic satellite selection based on proximity is the potential for load balancing and congestion management. By connecting to the closest available satellite, the system can distribute the communication load more evenly across the satellite constellation. This load balancing approach prevents individual satellites from being overloaded with traffic, thereby enhancing the overall network performance and stability.

5. Robustness and Adaptability: The use of proximity-based routing makes the communication system more robust and adaptable to changing conditions. Satellites may experience temporary signal obstructions or interference due to atmospheric conditions or other factors. By dynamically selecting satellites in the vicinity, the ground nodes can quickly switch to alternative satellites, maintaining the continuity of communication even in challenging scenarios.

Disruption-Free Service Mechanism

The Disruption-Free Service Mechanism (DFSM) presented in this research addresses the critical challenge of ensuring uninterrupted communication services in integrated satellite-terrestrial communication systems, even in the face of topology changes caused by the movement of satellites. This section elucidates the components, operation, and benefits of the DFSM.

1. Introduction to Disruption-Free Service Mechanism

The DFSM is designed to overcome the inherent disruptions in communication paths that arise due to the dynamic nature of satellite movements. Traditional communication routing methods are susceptible to interruptions caused by satellite repositioning, resulting in service downtime. The DFSM aims to proactively select communication paths that remain stable during the entire lifetime of a request, thus guaranteeing a seamless user experience.

2. Path Stability Evaluation

The foundation of the DFSM lies in the advanced evaluation of path stability. The mechanism incorporates real-time satellite position tracking and predictive modeling to anticipate potential topology changes. By analyzing satellite trajectories, the system identifies communication paths that are likely to remain intact over the requested duration. This evaluation minimizes the risk of path disruptions, ensuring a high level of service reliability.

3. Dynamic Path Selection Algorithm

The core of the DFSM involves a novel Dynamic Path Selection Algorithm (DPSA) that intelligently chooses the optimal communication route for each individual request. The DPSA takes into account a multitude of factors, including satellite movement patterns, link quality, and latency. It employs sophisticated heuristics to assess the trade-offs between path stability and other performance metrics, thereby achieving an equilibrium between disruption avoidance and efficient resource utilization.

4. Real-time Topology Monitoring

To maintain the effectiveness of the DFSM, a robust real-time topology monitoring system is established. Satellite positions are continuously tracked, and the predicted trajectories are updated accordingly. Any detected deviations from the predicted paths trigger the re-evaluation of ongoing communication routes. The dynamic nature of this monitoring ensures that the system can promptly adapt to unforeseen changes, further enhancing the disruption-free service provision.

5. Benefits of DFSM Implementation

The DFSM offers several substantial advantages for integrated satellite-terrestrial communication systems:

- **Uninterrupted Communication:** By meticulously selecting stable paths, the mechanism guarantees a consistent and disruption-free communication experience for users, irrespective of satellite movements.
- **Enhanced Reliability:** The predictive modeling and real-time monitoring enhance the reliability of the communication network by reducing the potential for service interruptions.
- **Efficient Resource Allocation:** The DPSA optimizes resource allocation by considering both path stability and performance metrics, thereby ensuring efficient utilization of network resources.
- **Future-Proofing:** The DFSM's proactive approach ensures that the communication system is prepared to handle the dynamic and evolving nature of satellite movements, making it resilient to unforeseen disruptions.

Online Traffic Generation

The Traffic Generation component in our integrated satellite-terrestrial communication system is a fundamental aspect that replicates real-world communication scenarios by introducing an online traffic generation mechanism. This section elucidates the architecture, operation, and significance of the online traffic scenario, highlighting the dynamic and real-time nature of request generation.

1. Introduction to Online Traffic Generation

Unlike conventional offline traffic scenarios that involve pre-determined communication patterns, our system incorporates an online traffic generation approach. This approach mimics the unpredictable and continuously evolving nature of communication demands in real-world environments. The primary objective is to validate the performance and robustness of our Disruption-Free Service Mechanism (DFSM) under real-time conditions, providing a more accurate representation of system behavior.

2. Real-time Request Generation Architecture

The heart of our online traffic scenario lies in the real-time request generation architecture. A separate request generator thread operates alongside the main thread responsible for implementing the DFSM. The request generator thread continually generates and introduces communication requests into the system as if they were arriving from external sources. These requests are then added to the "Request Store" container within the main thread, reflecting a dynamic inflow of traffic.

3. Dynamic Request Characteristics

The online traffic scenario encompasses dynamic request characteristics to emulate various real-world communication scenarios:

- **Randomized Arrival Patterns:** Request generation is based on randomized arrival patterns to replicate the inherent uncertainty of communication demands.
- **Variable Bandwidth Requirements:** Requests exhibit a range of bandwidth requirements, allowing the system to adapt to varying communication needs.
- **Duration and Intervals:** Each request is associated with a specific duration and intervals, capturing the transient nature of communication sessions.

4. Benefits and Significance

The implementation of online traffic generation brings several noteworthy benefits to our research:

- **Realism and Relevance:** By generating requests in real time, we create a simulation environment that closely mirrors real-world communication dynamics. This authenticity enhances the validity of our results and conclusions.
- **Dynamic Performance Evaluation:** The online traffic scenario enables us to assess the performance of the DFSM under fluctuating and unpredictable conditions, providing a comprehensive understanding of its capabilities.
- **Adaptability Testing:** The system's ability to effectively manage incoming requests in real time is thoroughly tested, showcasing its adaptability and responsiveness to changing network dynamics.

Cost Savings through Disruption-Free Service

One of the key benefits realized through the implementation of the Disruption-Free Service Mechanism (DFSM) in our integrated satellite-terrestrial communication system is the significant reduction in migration costs. This section highlights the remarkable cost-saving implications of the DFSM and presents a graphical representation of the achieved savings.

1. Migration Cost Reduction

Traditionally, the reconfiguration of communication paths to accommodate changes in satellite positions incurred substantial migration costs. As satellites shifted, network paths required adjustments, leading to service interruptions and necessitating reconfiguration efforts. These migration-related expenses, often incurred on a regular basis, contributed to significant operational overheads.

2. Impact of Disruption-Free Service

The introduction of the DFSM revolutionized the management of satellite-terrestrial communication paths. By proactively selecting stable paths and mitigating the disruptions caused by satellite movements, the DFSM significantly minimized the need for frequent network reconfigurations. As a direct result, the disruption-free service approach translated into substantial savings in migration costs.

3. Graphical Representation

The accompanying graph (Figure 1) visually portrays the migration costs saved as the time progresses in the simulation. If a request would have been disrupted, it would take almost 100ms to rerun the virtual network embedding algorithm and re embed the disrupted request. We took this as the cost of one disruption. In simulation, as the time progresses, more and more disruptions are avoided, as a result of which the graph shows an increasing trend of saved migration costs with time.

Migration Cost Saved Over time
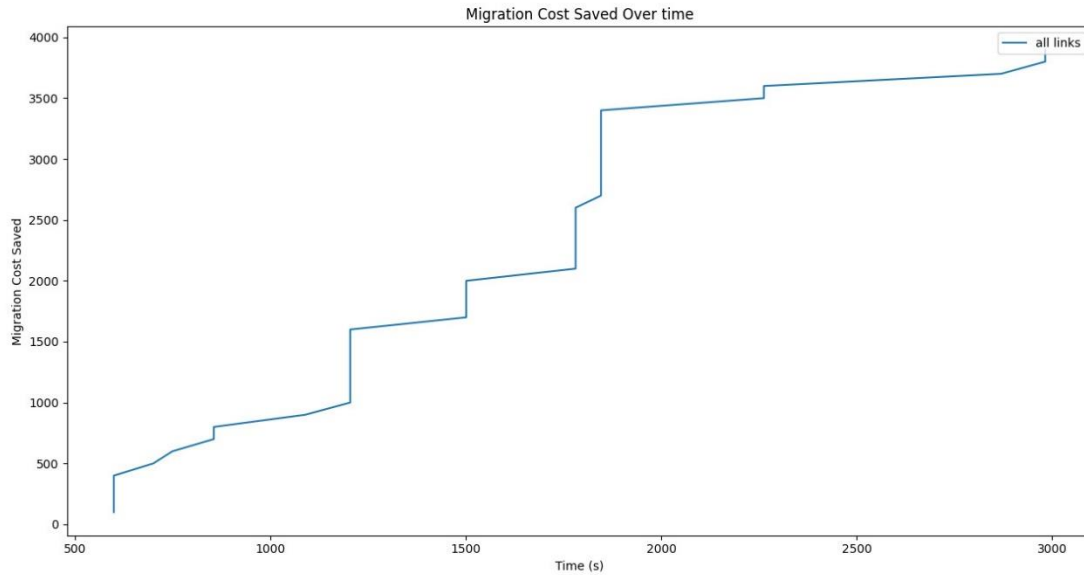
Spectrum Utilization Analysis: Link Types and Traffic Flow

The efficient allocation and utilization of available spectrum resources are pivotal in ensuring the optimal performance of integrated satellite-terrestrial communication systems. This section delves into the insights obtained from a spectrum occupancy analysis, specifically focusing on ground-ground links, ground-satellite links, and satellite-satellite links. The presented graph not only showcases the remaining spectrum occupancies but also offers valuable implications concerning the predominant utilization of satellite-to-ground links.

1. Graphical Representation

The graph depicted in Figure 2 represents the remaining spectrum occupancies for different link types across a given time period. The vertical axis quantifies spectrum capacity remaining, while the horizontal axis represents discrete time intervals. Distinct lines correspond to ground-ground, ground-satellite, and satellite-satellite link types. The declining trendlines denote the progressive consumption of spectrum resources, with varying rates for each link type.

Available Capacity in Network
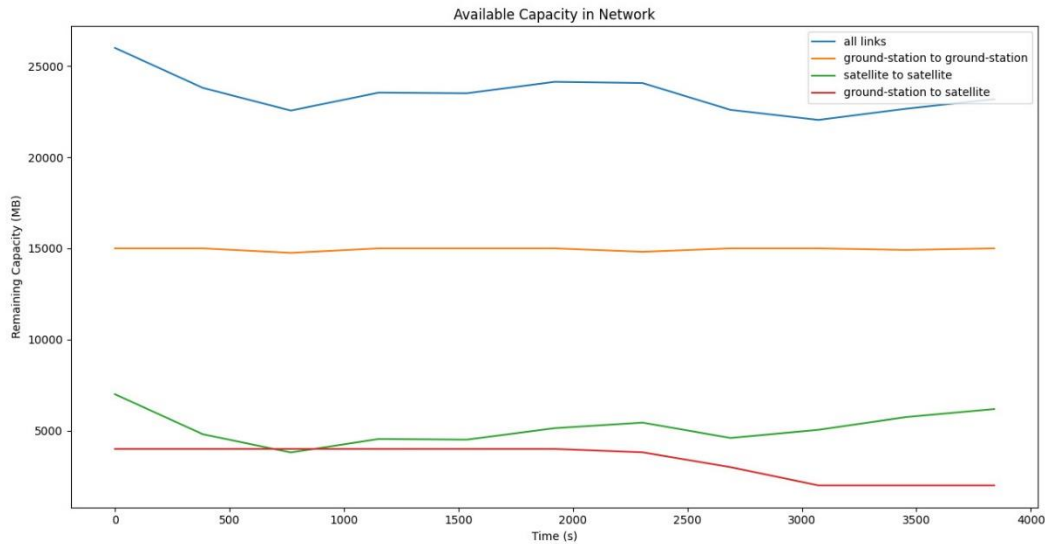
2. Satellite-to-Ground Link Dominance

A noteworthy observation drawn from the graph is the marked prominence of satellite-to-ground links in terms of spectrum utilization. This observation aligns with the inherent nature of internet traffic generation, because it predominantly gets generated from ground-based users and endpoints. The graph's inclination towards satellite-to-ground links signifies the substantial traffic flow from terrestrial sources to satellites for global distribution.

The fundamental explanation for the higher utilization of satellite-to-ground links stems from the origin of internet traffic. With the majority of internet users located on the Earth's surface, ground-based sources generate the bulk of communication demands. Consequently, satellite-to-ground links are prioritized and more extensively employed to facilitate the bidirectional exchange of data between terrestrial users and the satellite network.

3. Impact on Resource Allocation

The graph's representation of spectrum occupancy has significant implications for resource allocation strategies within the integrated communication system. Acknowledging the preference for satellite-to-ground links, allocation algorithms can be optimized to ensure the availability of adequate spectrum resources for these critical links. This strategic allocation can aid in maintaining optimal communication quality and minimizing potential congestion.

4. Enhancing System Efficiency

Understanding the disparity in spectrum utilization among different link types enables communication network designers to fine-tune their strategies. By emphasizing the allocation of spectrum resources in alignment with traffic patterns, the system's overall efficiency is enhanced. This, in turn, contributes to improved user experience, reduced latency, and minimized disruptions in the satellite-terrestrial communication ecosystem.