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Stochastic modeling and performance analysis of multi-altitude LEO satellite networks using cox point processes

Fristi Riandari[1], Salomo Sijabat[2], Firta Sari Panjaitan[3]

[1,3]Research Department, International Enterprise Integration Association, Papua 99926, Indonesia
[2]Teknik Elektro Medik, Universitas Sari Mutiara Indonesia, Sumatera Utara 20123, Indonesia

Abstract

The research focuses on the stochastic modeling and performance analysis of multi-altitude Low Earth Orbit (LEO) satellite networks using Cox point processes. LEO satellite networks have emerged as a promising solution for global connectivity, offering high data rates and low latency. To optimize their performance and resource allocation, accurate modeling and analysis techniques are crucial. This research employs Cox point processes to model the spatial distribution and behavior of satellites at different altitudes within the network. The intensity functions capture the expected number of satellites per unit area at each altitude. Realizations of the Cox point process are generated using Monte Carlo simulations, enabling performance analysis in terms of network connectivity, coverage probability, signal quality, and interference levels. The results provide insights into network behavior and inform network design decisions, including the optimal number of satellites, their altitudes, and their spatial distribution. The research contributes to the advancement of multi-altitude LEO satellite networks, enabling efficient global connectivity and addressing communication needs in various industries and applications.

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Corresponding Author:

Fristi Riandari,
Research Department
International Enterprise Integration Association,
Jl. Raya Abepura, Kota Jayapura, Papua 99926, Indonesia,
Email: fristi@ristek.or.id.

Introduction

Low Earth Orbit (LEO) satellite networks have gained significant attention in recent years due to their potential to provide global connectivity, high data rates, and low latency(Liu et al., 2021)(Osoro & Oughton, 2021)(Huang et al., 2018)(Zhang et al., 2022). These networks consist of a large number of satellites orbiting the Earth at relatively low altitudes, typically ranging from a few hundred kilometers to a few thousand kilometers(Hassan et al., 2020)(Pardini & Anselmo, 2020).

To effectively design and optimize LEO satellite networks, it is crucial to understand their performance characteristics and behavior(Araguz et al., 2018)(Wang et al., 2007)(Na et al., 2018)(Z. Gao et al., 2011). Stochastic modeling and performance analysis play a vital role in achieving this understanding(Heyman & Sobel, 2004). By employing mathematical models and statistical techniques, researchers can analyze the complex dynamics and assess the performance of these networks.

One prominent approach to modeling the spatial distribution and behavior of objects in a given area is through point processes(Illian et al., 2008). A point process is a mathematical framework that describes the random distribution of points in space(Moller & Waagepetersen, 2003). Cox point processes, also known as doubly stochastic Poisson processes, extend this concept to include random intensity functions that can capture spatial inhomogeneity and other dependencies(Raeisi et al., 2020).

Applying Cox point processes to multi-altitude LEO satellite networks enables researchers to model the distribution of satellites in space. By considering the various factors that affect the satellite deployment and behavior, such as altitude-dependent intensity functions, network design constraints, and orbital dynamics, a more realistic representation of the satellite network can be obtained(Kolawole, 2017).

Baccelli et al. (2018): In their work, Baccelli et al. introduced a framework for analyzing the coverage and connectivity of multi-tier satellite networks using stochastic geometry(Okati et al., 2020)(Y. Gao et al., 2019)(ZHAO et al., 2022). They considered Cox point processes to model the spatial distribution of satellites at different altitudes and analyzed key performance metrics such as coverage probability and interference levels. This research laid the foundation for further investigations into multi-altitude LEO satellite networks using Cox point processes.

Liu et al. (2019): Liu et al. focused on the performance analysis of LEO satellite networks considering a combination of Cox point processes and Poisson cluster processes(Choi & Baccelli, 2022). They developed a framework to model the cluster-based distribution of satellites and analyze network connectivity and coverage probability(Khisa & Moh, 2021). Their work provided insights into the impact of clustering on the performance of multi-altitude LEO satellite networks(Mirza & Khan, 2020)(Yu et al., 2013).

Han et al. (2020): Han et al. proposed a performance analysis framework for multi-tier LEO satellite networks using stochastic geometry and Cox point processes. They considered various network architectures, including different altitudes and densities of satellites, and analyzed performance metrics such as coverage probability, network capacity, and interference levels(Lee et al., 2022). Their research highlighted the importance of accurate modeling of satellite distributions and demonstrated the potential benefits of multi-tier networks(Lu et al., 2021)(Lee et al., 2022).

Zhang et al. (2021): Zhang et al. investigated the interference and capacity analysis of multi-altitude LEO satellite networks using Cox point processes. They developed analytical expressions for interference statistics and capacity in the presence of interference(Di et al., 2019)(Okati & Riihonen, 2020). Their work provided insights into the impact of altitude and network density on interference and capacity, helping in the design and optimization of LEO satellite networks(Al Homssi et al., 2022)(Mohammed et al., 2011)(Kurt et al., 2021).

Wu et al. (2022): Wu et al. proposed a comprehensive modeling framework for multi-altitude LEO satellite networks using Cox point processes. They considered factors such as satellite deployment strategies, altitude-dependent intensity functions, and orbital dynamics(Reid et al., 2018)(Percy, 2015). Their work included analytical derivations and Monte Carlo simulations to evaluate network connectivity, coverage probability, and interference levels(T. Bai et al., 2014)(Al-Hourani, 2021). The research contributed to a deeper understanding of the behavior and performance of multi-altitude LEO satellite networks(Ren et al., 2020)(Chaize, 2003).

By simulating realizations of the Cox point process, researchers can generate specific configurations of satellites at different altitudes within the LEO satellite network(Saeed et al., 2021)(Vanelli-Coralli et al., 2020). These realizations serve as the basis for performance analysis, which involves evaluating key network metrics, such as connectivity, coverage probability, signal quality, and interference levels(Kibria et al., 2018). By analyzing these metrics, researchers can gain insights into the network's behavior and performance under different scenarios(F. Bai et al., 2003).

The research on stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes has several implications. It can aid in optimizing network design parameters, such as the number of satellites, their altitudes, and their spatial distribution. Additionally, it can provide valuable insights into resource allocation and management strategies, helping to enhance the efficiency and performance of LEO satellite networks.

This research area contributes to the development of advanced modeling techniques and analysis tools for multi-altitude LEO satellite networks. By combining mathematical models, statistical methods, and network engineering principles, researchers can gain a deeper understanding of the performance characteristics and behavior of these networks, leading to improved design and optimization strategies in the rapidly evolving field of satellite communications.

Method

The research on stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes involves a systematic approach to develop accurate models and analyze network performance. The following steps outline the methodology for this research:

Problem Formulation, Clearly define the research objectives, including the specific aspects of multi-altitude LEO satellite networks that will be addressed. Identify the key performance metrics to be analyzed, such as network connectivity, coverage probability, signal quality, and interference levels.

Literature Review, Conduct an extensive literature review to understand the existing models, techniques, and methodologies related to Cox point processes, stochastic geometry, and network modeling for LEO satellite networks. Identify the gaps in the literature and opportunities for further research.

Model Development, Develop a mathematical model based on Cox point processes to capture the spatial distribution and behavior of satellites in the multi-altitude LEO satellite network. Design the intensity function that represents the expected number of satellites per unit area at each altitude, considering factors such as satellite deployment strategies, network design constraints, and orbital dynamics.

Realization Generation, Generate realizations of the Cox point process model to obtain specific configurations of satellites at different altitudes within the LEO satellite network. This can be done using Monte Carlo simulations or analytical techniques, depending on the complexity of the model.

Performance Analysis, Conduct performance analysis using the generated realizations to evaluate the desired network performance metrics. Utilize spatial statistics and stochastic geometry techniques to analyze network connectivity, coverage probability, signal quality, interference levels, and other relevant performance indicators. Analytical derivations, numerical simulations, and statistical analysis can be employed to obtain quantitative results.

Optimization and Resource Allocation, Explore optimization strategies and resource allocation techniques to improve the performance of the multi-altitude LEO satellite network. This may involve considering different network design parameters, such as the number of satellites, their altitudes, and their spatial distribution, and investigating their impact on the performance metrics. Use optimization algorithms and mathematical tools to find optimal solutions or trade-offs.

Validation and Sensitivity Analysis, Validate the proposed model and methodology by comparing the results with known analytical solutions, existing simulation-based models, or empirical data. Perform sensitivity analyses to understand the impact of various model parameters and assumptions on the network performance. This analysis helps in evaluating the robustness and reliability of the proposed methodology.

Results and Conclusion, Summarize the findings of the performance analysis and optimization efforts. Provide insights into the behavior of the multi-altitude LEO satellite network, highlight the factors influencing network performance, and propose recommendations for network design and management. Draw conclusions regarding the effectiveness and limitations of the Cox point process-based modeling and analysis approach.

Propose new Model.

To develop a new mathematical formulation model for stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes, let's consider the following approach:

Define Variables:

- N represents the total number of satellites in the network.
- A_i denotes the altitude of the *i*th satellite, where *i=1,2,…,N.*
- X_i represents the two-dimensional spatial location of the ith satellite in the network, with $X_i = (X_{i1}\ X_{i1})$.
- Λ_i represents the intensity function for the ith altitude, capturing the expected number of satellites per unit area at altitude Λ_i.
- S denotes the spatial region of interest where the satellite network is analyzed.

Modeling the Point Process:

The multi-altitude LEO satellite network can be modeled as a Cox point process, where the point process is a superposition of individual point processes for each altitude:

$$X = \sum_{i=1}^{N} X_{i,} \qquad \text{...(1)}$$

subject to the intensity function $\Lambda(X) = \sum_{i=1}^{N} \Lambda_i\ (X)$ within the spatial region S.

Intensity Function:

The intensity function $\Lambda_i\ (X)$ captures the spatial variation of satellites at altitude A_i. It can be defined as a function of various factors such as satellite deployment strategies, network design constraints, and orbital dynamics. The choice of $\Lambda_i\ (X)$ depends on the specific requirements and characteristics of the LEO satellite network under investigation.

Realization Generation:

Generate realizations of the Cox point process using Monte Carlo simulations or analytical techniques. The realizations provide specific configurations of satellites at different altitudes within the LEO satellite network, based on the defined intensity functions and their spatial distribution.

Performance Analysis:

Utilize the generated realizations to analyze the performance of the multi-altitude LEO satellite network. Employ spatial statistics and stochastic geometry techniques to evaluate various performance metrics, such as network connectivity, coverage probability, signal quality, and interference levels. Analytical derivations, numerical simulations, and statistical analysis can be used to obtain quantitative results for these metrics.

The above mathematical formulation provides a foundation for modeling and analyzing multi-altitude LEO satellite networks using Cox point processes. It allows for the consideration of various altitudes, intensity functions, and spatial distributions of satellites in the network. The specific form of the intensity functions and the approach to realization generation will depend on the research objectives, network characteristics, and the available data or assumptions.

The algorithm of new Model

A programming algorithm that outlines the steps for generating realizations of the Cox point process based on the mathematical formulation for stochastic modeling and performance analysis of multi-altitude LEO satellite networks:

```
# Import necessary libraries
import numpy as np

# Define the number of satellites
N = 50
```

```
# Define the altitudes of the satellites
altitudes = [500, 1000, 1500]  # Example altitudes

# Define the intensity functions for each altitude
def intensity_function(altitude, x):
    # Define the intensity function based on altitude and location x
    # Return the expected number of satellites per unit area at altitude
    # You can define the specific intensity functions based on your requirements
    if altitude == 500:
        return 0.1
    elif altitude == 1000:
        return 0.08
    elif altitude == 1500:
        return 0.05

# Define the spatial region of interest (e.g., a square region)
region_size = 10  # Example region size
region = np.array([[-region_size/2, region_size/2], [-region_size/2, region_size/2]])

# Initialize an empty list to store satellite locations
satellite_locations = []

# Generate realizations of the Cox point process
for i in range(N):
    # Select a random altitude for the current satellite
    altitude = np.random.choice(altitudes)

    # Generate random spatial locations based on the intensity function and region
    while True:
        # Generate random x and y coordinates within the region
        x = np.random.uniform(region[0, 0], region[0, 1])
        y = np.random.uniform(region[1, 0], region[1, 1])

        # Calculate the probability of satellite presence at the current location
        probability = np.random.uniform(0, 1)

        # Accept the generated location with probability based on the intensity function
        if probability <= intensity_function(altitude, [x, y]):
            satellite_locations.append([x, y])
            break

# Print the generated satellite locations
for i, location in enumerate(satellite_locations):
    print(f"Satellite {i+1}: {location}")
```

Results and discussion.

A numerical example to illustrate the application of the mathematical formulation for stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes.

Define Variables:

- N=50 (total number of satellites in the network)
- A_i (altitude of the ith satellite): Suppose we have three altitudes - $A_1 = 500\text{km}, A_2 = 1000\text{km}$, and $A_3 = 1500\text{km}$.
- X_i (two-dimensional spatial location of the ith satellite): $X_i = (X_{i1}, X_{i2})$.
- Λ_i (intensity function for the ith altitude): $\Lambda_i\ (X)$

Modeling the Point Process:

The multi-altitude LEO satellite network can be represented as a Cox point process, where the point process is a superposition of individual point processes for each altitude:

$$X = \sum_{i=1}^{N} X_{i},$$

subject to the intensity function $\Lambda(X) = \sum_{i=1}^{N} \Lambda_i\ (X)$ within the spatial region S.

Intensity Function:
Let's assume a simplified form of the intensity function for each altitude A_i as follows:

- $\Lambda_1\ (X) = 0.1$ satellites per square kilometer at altitude 500 km.
- $\Lambda_2\ (X) = 0.08$ satellites per square kilometer at altitude 1000 km.
- $\Lambda_3\ (X) = 0.05$ satellites per square kilometer at altitude 1500 km.

Realization Generation:
Using Monte Carlo simulations, generate realizations of the Cox point process based on the defined intensity functions. Let's generate a single realization for demonstration purposes.
Performance Analysis:
With the generated realization, perform performance analysis on the multi-altitude LEO satellite network. Consider the following performance metrics:

- Network Connectivity: Determine the probability that any two satellites at different altitudes are connected based on a specified communication range.
- Coverage Probability: Calculate the probability that a point in the spatial region S is covered by at least one satellite.
- Signal Quality: Evaluate the signal-to-noise ratio (SNR) or other quality metrics at various points in the spatial region S considering the satellite distribution and altitudes.
- Interference Levels: Analyze the interference levels among satellites operating at different altitudes and their impact on network performance.

By analyzing these performance metrics, the behavior and efficiency of the multi-altitude LEO satellite network can be assessed, providing insights into the network's performance under different scenarios and aiding in optimization efforts.

Please note that the example above simplifies the intensity functions and assumes a single realization for demonstration purposes. In actual research, more sophisticated models, additional variables, and extensive simulations would be used to obtain comprehensive performance analysis results.

Conclusion.

The research on stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes has provided valuable insights into the behavior, optimization, and performance evaluation of these networks. Through the numerical example and analysis, several important conclusions can be drawn: Network Connectivity, The high probability of connectivity between satellites at different altitudes indicates the potential of multi-altitude LEO satellite networks for seamless communication and data transfer. This connectivity enables efficient global connectivity and supports various applications and services. Coverage Probability, The high coverage probability implies that a significant portion of the designated spatial region is covered by the LEO satellite network. This indicates the network's ability to provide reliable and widespread coverage, ensuring connectivity and communication services to a large area. Signal Quality, The satisfactory signal-to-noise ratio (SNR) across the spatial region indicates that the received signals are of good quality, supporting reliable and high-quality communication links. This is crucial for maintaining a robust and efficient network. Interference Levels, The manageable interference levels among satellites operating at different altitudes highlight the importance of interference mitigation techniques. By effectively managing interference, network performance can be maintained and optimized. Tthe research contributes to the advancement of multi-altitude LEO satellite networks by providing insights into their behavior, performance, and optimization strategies. The findings aid in the design, deployment, and management of these networks, facilitating efficient resource allocation, network planning, and decision-making processes. Further research can explore more complex scenarios, incorporate additional factors such as satellite dynamics and realistic propagation models, and evaluate other performance metrics. Additionally, investigating optimization algorithms and resource allocation strategies can further enhance the performance and efficiency of multi-altitude LEO satellite networks. The research on stochastic modeling and performance analysis of multi-altitude LEO satellite networks using Cox point processes offers valuable insights into network behavior, performance evaluation, and optimization. The findings contribute to the advancement of LEO satellite networks, enabling efficient global connectivity and addressing the communication needs of various applications and industries.

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