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Interference Management in Hybrid Satellite Networks: From Localization to Machine Learning Strategies

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Abstract

Our research study looking for the interference challenges when using GEO and LEO satellite together in communications, to use both technology we are improving the coverage but also increasing the signal interference due to the overlapping and orbital path, we study different ways to detect the interferences including traditional methods and advanced techniques like AI also review the spectrum regulation and guidelines (ITU) , we find that we need for real-time interference control and coordination to maintain satellite networks.

Chapter 1:

Introduction

Satellite communication is a critical key for world communications. GEO satellites provide wide and stable coverage, while LEO satellites more faster and lower latency ,this combination make a strong feature for communications world but also facing a big problem which is the interference when their signals overlap in space and frequency it can interrupt the connections and make a service outage .old methods struggle due the fastmoving and changing to modern satellite networks .the new solution (AI-,smart radios) help spot and avoid interference in real time. advanced technique adjusts signals based on satellite movement, optimize transmission power, frequency and direction, international guidelines (ITU) help to manage fair spectrum use.

Background

GEO satellite systems work like a train on fixed schedule but now with the LEO satellite systems interference changes per minute, speed, weather and overlapping coverage all make the problem anarchism, the modern AI and signal tech can track and fix the issues in real time.

Problem Statement

The existing methods today for handling the interference in hybrid satellite networks are difficulty or too slow due to the LEO satellites move quickly and increase the number of LEO's ,which is increase the interference and change the level of this problem to be complicated ,there is no smart or real time system can detect quickly and reduce the impact of the interferences.

Research Objective

As we face degrading on service quality, increase packet loss, and lower spectral efficiency.

The existing methods fail to operate under dynamic real-world conditions. Then our research objectives will be as follows:

- To Propose a Doppler- technique leveraging FOA and satellite kinematics.
- To Design a deep learning model for real-time interference detection using attention mechanisms.
- To Develop a cross-orbit coordination strategy integrating intra- and inter system management.
- To Modeling hybrid network behavior using stochastic geometry under shared-spectrum conditions.
- To Evaluate the system using localization accuracy, detection latency, and compliance metrics.

Research Scope

In this research focusing on Hybrid Satellite networks GEO and LEO operating within shared frequency bands, we are looking to the downlink interference in Ku and Ka bands, we simulate interference impact in satellite networks scenarios and evaluate the performance using machine learning.

Chapter2:

Literature Review

Several studies have contributed to understanding interference in satellite networks:

[1] Kalantari et al. (2022) this paper proposes a novel method for localizing intentional and unintentional RF interference sources by utilizing the frequency of arrival (FOA) to enhance interference detection and reduce dependency on multi-satellite systems. It's based on satellite motion to estimate the location of interference.

[2] Yang et al. (2023) This paper proposes to develop a real-time robust interference detection system for satellite communications between LEO and GEO satellites overlapping frequency bands..

[3] Elbir et al. (2022) This Paper proposes a Coordinated Intra-and-Inter-system interference Management (CIIM) algorithm for Integrated Satellite-Terrestrial Networks (ISTNs) to address co-channel interference and interference between GEO and LEO. The primary goal of this tech. It is to maximize downlink throughput while minimizing interference.

[4] Wang et al. (2021) This paper proposes to develop an analytical model for hybrid GEO-LEO satellite networks and evaluate coverage performance under frequency sharing using stochastic geometry. Hybrid Satellite modeling both sets (GEO and LEO) are modeled using Poisson Point Processes (PPPs).

Coverage probability derivation:

- 1- Biased-received-power (BRP) association policy
- 2- Satellite antenna gains
- 3- Nakagami-m fading and directional antenna assumptions.
- 4- Interference from both GEO and LEO satellites.

[5] Zhang et al. (2022) This Paper proposes a novel framework for modeling and analyzing (GEO) networks using stochastic geometry, unlike (LEO) models. This work accounts for the (GEO) satellites, which are stationary relative to Earth.

[6] Tang and Wu (2020) This paper proposes to enhance service efficiency and manage co-channel interference in a heterogeneous dual-layer satellite by integrating LEO and GEO with mobile edge computing in the network caching and SDN.

[7] Ali et al. (2024) This paper propose a hybrid CNN-RNN framework for satellite spectrum (pattern detector and memory tracker) the AI combination helps the satellites filter out junk signals.

[8] Hassan et al. (2023) This paper proposed an ADMM-based resource allocation technique (automatically share the channel fairly without a referee) to reduce co-channel interference works for satellite, 5G and IoT (crowded signals)

[9] Li and Zhou (2023) This paper proposed an unsupervised learning for anomaly-based interference detection in real-time satellite data streams. universal interference detector for satellites no training needed.

[10] Reddy et al. (2025) This paper proposed AI applied on graph neural networks (GNNs) to model interference in hybrid networks helps to stop signal crashes in complex networks.

The above studies support the viability of integrating localization, deep learning, and cooperative frameworks in satellite interference management.

Chapter3:

Research Methodology

This research follows a mixed-method approach:

1. Simulation We simulate hybrid GEO–LEO satellite topologies using stochastic geometry.
2. Localization Algorithm FOA-based estimation is implemented to detect interference sources.
3. Machine Learning DualAttWaveNet and GNN models are trained on synthetic and real-world satellite interference data.
4. Coordination Protocol Design the CIIM protocol is modeled to coordinate frequency reuse among layers.
5. Evaluation The framework is tested across metrics like latency, false alarm rate, and throughput improvement.

Expected Outcomes

- A robust interference localization mechanism using FOA and deep learning.
- Demonstrated improvements in detection accuracy ($\geq 90\%$) and spectrum efficiency.
- A scalable coordination protocol (CIIM) for multi-layer satellite networks.
- Published results and framework adaptable to real-world hybrid satellite scenarios

Gantt Chart

See table below for timeline overview.

Task	Start Date	End Date	Duration	Milestone
Literature Review	19/07/2025	25/07/2025	7 days	Yes
Methodology Design	26/07/2025	30/07/2025	5 days	Yes
Data Simulation	01/08/2025	10/08/2025	11 days	No
Model Training	11/08/2025	15/08/2025	5 days	Yes
Evaluation & Writing	16/08/2025	21/08/2025	6 days	Yes

References

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