DRL-based Intellectual Spectrum Planning and Interference Management in 6G Terrestrial and Non-Terrestrial LEO Satellite Constellation

I. Introduction

Many contemporary infrastructures use a multitude of sensors and actuators linked by wireless communications via the use of IoT and WSN technologies (Benaddi et al 2020).In recent days, communication using IoT (Internet of Things) devices has been mounted to the peak. Hence, sixth-generation (6G) networks aimed to aid in the rapid network traffic that comes from broadband services, IoT-based applications, and so on (Stergiou et al 2021). The ability to distribute files via existing terrestrial networks is often contingent upon several factors, primarily an extensive infrastructure or a large number of intermediary nodes. The wherever-ever manageable competence with the expansion of large data volume, however, cannot be successfully provided by depending on the present terrestrial systems in these locations due to low node density and poor organization in distant places and catastrophe circumstances. The above-mentioned problems may now be effectively addressed because of the quick advancements in LEO constellation technology, which also offers the following benefits of LEO satellites. First off, the wide coverage provided by the LEO constellation's inter-satellite linkages will serve as a useful supplement to insufficient infrastructure in distant areas and in some crises. In addition, customers' access delays to file distribution services may be reduced by the low orbital height of Low Earth Orbit (LEO) satellites, guaranteeing improved performance. Additionally, further, than fifth-generation movable infrastructures (B5G), the broadcasting potential may be completely used for large groups of users, like satellite IoT. Therefore, to guarantee excellent data access and task off-loading wherever at any time in the future networks, the incorporated LEO satellite-TN has been playing a significant character in a range of contented scattering facilities. However, in such integrated networks, it is very difficult to discover subsequent end-to-end pathways because of the clear topological divisions from regularly sporadic connections (Yang et al 2020). Further, the other hand, the rise of terrestrial IoT devices is expected to 25 billion by 2028. As IoT gadgets are related by wireless communications links, it is predictable that spectrum scarcity will be a daunting one that can affect connectivity issues (Menaka et al 2021)

(Santana et al 2021).To address the spectrum scarcity issues, Cognitive Radio (CR) is preferred for effective spectrum sharing (Tarek et al 2021).CR helps in full spectrum utility by allowing secondary users to utilize idle channels of primary users and vacant the connection if primary users are present (Devi et al 2021). On the other hand, satellites play a vital role in offering elongated network coverage and capacity to terrestrial networks as they cannot offer global coverage concerning the increasing demand (Darwish et al 2021). Thereupon, satellites help the terrestrial network by covering a huge number of users and serving in remote and rural areas too, and. Several space-borne platforms exist like as,

- Geostationary Equatorial Orbit (GEO)
- Medium Earth Orbit (MEO)
- Low Earth Orbit (LEO) (Fish et al 2019) (Paek et al 2020).

These are man-made artificial bodies that orbit around the Earth for various purposes such as defense reconnaissance, communication, imaging, and so on. They are differentiated by their altitude from the earth's surface. Among all, the LEO satellite constellation ensures low propagation delay, minimum transmission power, high coverage, and service density with good throughput (Leyva et al 2019) (Cai et al 2020). The reason behind offering such benefits is that the LEO is positioned 50 times closer to the Earth. So, it is attracting researchers to do deeper investigations on that. Therefore, the incorporation of satellite networks and terrestrial networks promises to ensure reliable communication (Chen et al 2020. The LEO satellites communicate with each other by establishing Intersatellite Links (ISL).

II. LITERATURE SURVEY

This chapter illustrates a brief explanation of Spectrum Planning and Interference Management in 6G Terrestrial and Non-Terrestrial LEO Satellite Constellation. In DRL is also employed. A detailed literature review relating to the proposed work is explained.

Literature shows the reader how the researcher can: design a Spectrum sharing in LEO satellite, LEO satellite in 6G, Terrestrial and non-terrestrial in LEO satellite, and interference management in LEO satellite constellation that has been proposed. Each process method is discussed in depth.

In a GEO and LEO satellite system based on NOMA, this research examines a combined operator pairing and power distribution strategy. In particular, a new NOMA framework is constructed whereby the NOMA sets are generated based on the subcarrier task of ground users and comprises two transmitters' receivers, namely the GEO and LEO satellites. Next, an optimization problem is developed, taking into account the power consumption and decoding threshold, to exploit the scheme capacity. They break down the defined issue into user pairing and power distribution techniques since it is non-convex and theoretically unsolvable. To convert the multi-user pairing issue into a matching issue, virtual GEO consumers are created in the user pairing scheme. A max-min pairing method is then used to guarantee equity between NOMA groups. The non-convex issue in the power allocation scheme is split up into many convex subproblems, each of which is then solved iteratively using an algorithm. The outcomes of the simulation verify the efficiency and dominance of the suggested plans in contrast to many current plans(Bian et al 2021).

For a cognitive radio (CR) capable non-geostationary orbit (GEO)-LEO coexisting satellite network, they suggest rate splitting multiple access (RSMA). Specifically, this study intends to limit the temperature interference to GEO satellite users while enhancing LEO satellite communication's power allotment and subcarrier beam assignment at a similar time to exploit the scheme's total rate. It is difficult to discover a global optimum response to the non-convex issue of sum-rate maximization. To simplify and make the issue more manageable, They first use the sequential convex approximation approach. Next, they make use of the "Karush–Kuhn–Tucker (KKT)" condition for their distribution, and they use an effective method based on the greedy method for the subcarrier beam task. As a baseline, They also provide 2 suboptimal methods with random subcarrier beam tasks and fixed power allocation. The suggested system outperforms the benchmark schemes, as shown by the results(Khan et al 2022).

In this work, they provide in-depth analyses of cooperative orthogonal multiple access and NOMA's uplink transmission performance. The diversity ordering is also given and the analytical formulations of outage probability are developed as a generic metric. Based on the assumption of ordered channels, NOMA is more promising and can achieve impressive performance in low signal-to-noise ratio areas, as shown by the simulation results(Li et al 2023).

They look at several DM-MIMO-based satellite systems scheme topics, including the advantages of this style, related difficulties, and possible keys. Furthermore, They suggest a strategy called "distributed joint power allocation and handover management (D-JPAHM)", which works by simultaneously optimizing the cross-layer power allocation and handover management procedures. This framework takes into account the QoS supplies of UT and the power capacities of the satellites to exploit network data and minimize the handover rate. Additionally, They provide a method based on AI to effectively implement the suggested D-JPAHM framework in a way that is appropriate for the dynamic SatNet environment and real-time operation. This is the first paper that They are aware of that introduces and examines DM-MIMO tools in LEO SatNets. Comprehensive results of simulation demonstrate the superiority of the suggested design and results above traditional methods found in the literature(Abdelsadek et al 2022).

An approach to partitioning the beam coverage region from the outdoor to the interior is presented in this letter. It meaningfully enhances the overall effectiveness of current beamforming techniques by achieving the ideal attention of is flux of numerous beams to the ground with constant transmitter production power when combined with the subarray multibeam forming approach. Meanwhile, to lessen common interference among nonuniform multiple beams, a frequency reprocesses color separation technique based on the depth-first hunt is developed(Zhong et al 2021).

In this study, they suggest a cognitive LEO satellite organization, in which the Internet of Things users exploit the legacy LEO users' spectrum cognitively as the SU to access the LEO satellites. They employ code division multiple access to facilitate CIoT interaction because of its versatility in multiple access and its widespread usage in LEO SatCom. They are absorbed in the attainable rate investigation and source allocation for the CLEO satellite scheme. Especially, They especially utilize the "random matrix theory" to analyze the asymptotic SINR and derive the feasible rates for both legacy and IoT schemes, taking into account the unpredictability of propagating codes. Subject to the maximum received power limits and the legacy satellite scheme performance requirements, the power of the legacy and IoT communications is jointly assigned at the mouthpiece to exploit the sum rate of the IoT interaction. They establish that the optimum receive powers for these 2 organizations are obtained from the fact that the total rate of IoT consumers is quasi-concave terminated by the satellite to obtain power. Lastly, thorough simulations have validated the resource distribution plan presented in this research(Cai et al 2023).

They have conducted a thorough study of the ISTN in this paper using interference situations and LEO constellations from the network ideal. Following that, channel state information (CSI) estimate method based on DL algorithms is established, which includes the forecast of atmospheric attenuation and interference period, taking into account the stringent requirements of IRA for network state perception. A resource allocation strategy driven by deep reinforcement learning (DRL) is designed with the assumption of a thorough perception of CSI. The suggested DRL-driven resource allocation scheme's efficacy in reducing interference and enhancing constellation capacity is shown by the simulation results (Zhang et al 2023).

In this study, they concentrate on the uplink, where terminals may create a direct connection at the Ka-band with the NTN. They research a grant-free entry strategy, “resource sharing beamforming access (RSBA)”, to mitigate the crash risk when a big terminal demographic is broadcasting concurrently. Their research focuses on RBSA for huge MIMO satellite communications in LEO. The objective is to decode several overlapping signals by making use of the geographical variety. They have developed an open-loop, blind beamforming system in which neither the terminals nor the receiver needs to provide channel status information or do a “brute-force search in azimuth and elevation”. After calculating the hypothetical throughput, they demonstrate that RBSA is suitable for grant-free entry to LEO satellites since it lowers the likelihood of an impact and, as a result, upsurges the number of terminals that may receive media. Aspects of the applied implementation, including estimating the necessary data and figuring out the user base, have been addressed (Caus et al 2021).

To assess the coverage likelihood and average attainable rate of any given airplane, they provide an analytical methodology. The Laplace alters of the interference plus-molecular absorption sound and interference is used to represent the analytical findings. In particular, They calculate the odds that a meddling satellite is congested by the Earth and give the probability distributions of the distances to the target airplane from an arbitrary satellite, the serving satellite, and any non-serving satellite, all while taking into account a frequency reuse strategy. The correctness of the analytical formulations is confirmed by numerical findings, which also demonstrate that improved coverage and rate performance are caused by fewer orthogonal channels and a lower LEO satellite altitude. There is an ideal number of satellites since it is a crucial network design parameter with two opposing impacts on coverage and rate. In the above process, the results offer theoretical recommendations for the deployment and scheduling of THz satellite constellations (Wang et al 2023).

Their article focuses on the dependable creation and identification of RA preamble, to optimize accessibility effectiveness in highly changing LEO situations. A lengthy preamble sequence is created in the RA technique by adding the conjugated and circularly gets rid of copies of a solo root ZC command to evade extra signaling overhead during the recognition process. Additionally, they suggest brand-new LDCC-based impulse-like timing terms that may lessen the result of noise on timing approximation and are resistant to “carrier frequency offset (CFO)”. The outcome of the SNR power ratio may be value-added by increasing the correlation length, according to the statistical investigation of the suggested metric, and the 1st path recognition threshold is self-governing of noise statistics. Comparison output in various LEO situations confirms that the suggested method is robust against severe channel distortion and demonstrates that, when compared to the current RA methods, their method can attain a significant improvement in timing approximation accuracy, first access success probability, and mean normalized access energy (Zhen et al 2020).

An improved technique for estimating TA is presented in this paper for the LEO satellite interaction system. First, a user-side time-frequency pre-compensation approach is presented. This method uses regularity offset dimension on organization signal blocks that satellites broadcast during the first stage of cell search. The maximum limit of the interpreamble interference made happen by partial-period cross-correlation operations during the RA phase is computed for a preamble format recommended by 3GPP, and it is exposed that the interference level is directly proportional to the square of the number of like operations. Motivated by this outcome, a longer guard period, differential power allocation, and variable preamble organization are included in the design of a cyclic prefix-free preamble format (Zhu et al 2023).

In this study, they propose a DNN beamformer for wideband LEO satellite messages in sub-TeraHz bands, which will eliminate Phase changers, which are required for a vast assortment of antenna parts used at ground stations. They demonstrate that, despite the LEO satellite's fast movement, the signal processing technique used with DNN can equal the recital of a true-time interruption beamformer when it comes to the angle of the influx of the wideband signal received at the ground station. The use of DNN beamformers will be able to lower receiver costs and open the door to an effective, small-footprint vast array beamforming system for wideband low-Earth orbit satellite applications (Kumar et al 2022).

In this work, they examine the multi-satellite cooperative processing mechanism in the context of the random access issue in huge MIMO-based LEO satellite systems. To address faulty synchronization, they specifically designed a preparing the order padded multi-carrier system at edge satellite nodes. The keep-fit sequence is used to monitor the activity of the devices and estimation of their channels. They approximate the delay coefficients and UT activity using the orthogonal approximation data passing-multiple capacity vector approach, taking into account the intrinsic sparsity of TN-satellite connections and the intermittent traffic characteristic of IoT terminals. A 2-D estimate of signal parameters using the rotational invariance approach is carried out to improve channel estimation and make further use of the receive array's structure. Lastly, they suggest a majority voting system at the central server node to improve activity detection by the consolidation of backhaul data from many satellites. Furthermore, to deal with perfect and quantized backhaul, correspondingly, 'multi-satellite cooperative linear data detection and multi-satellite cooperative Bayesian dequantization data detection are suggested'. The efficiency of their suggested techniques for "quasi-synchronous random access" in satellite systems is confirmed by simulation results in footings of channel estimation, activity detection, and data detection (Ying et al 2023).

III. Research Methodology

The motto of this research work is to offer global network coverage to the 6G terrestrial network with the help of LEO satellites. When compared to 5G, the incorporated 6th generation technology offers wider network coverage, higher data rates, as well as high network speed. Along with this, a Cognitive Radio (CR)-enabled hybrid wireless communication model is proposed in which Free Space Optical (FSO) and Terahertz (THz) are taken into account to ensure reliable communication with higher data rates to the terrestrial users. Here, CR is used for ground-to-ground communication, whereas FSO is used for air-to-air communication. On the other hand, THz is used for ground-to-air communication, and hybrid links are used for air-to-ground communication. The entities getting involved in this work are LEO satellites, satellite gateway, 6G core, terrestrial base station, user equipment, and spectrum planning framework. Eventually, we have also unified artificial intelligence, and optimization algorithms to realize our ultimate objective. Fig: 1 depicts the overall proposed architecture

A. Co-operative Clustering

Initially, the clustering process is performed for two entities such as user equipment (UE) and LEO satellites by the terrestrial base station and satellite gateway respectively using the Molecules. The parameters considered for user equipment are distance and location whereas for satellites mobility, position, energy, and distance are taken into account. Here, the initial number of UE clusters determination is as follows. In the clustering process, the primary number of clusters is required to be optimally determined while a center selection of the initial cluster thus minimizes overhead in clustering and enables the bandwidth sufficiently.

B. Initial Cluster Center Selection

An initial center of cluster $\mathfrak{C}_1$ is arbitrarily chosen from the set, ensuring the uniform distribution. The lowest distance, explicitly the lowest value in Euclidean distance among points and the presently chosen clustering centers is indicated as $\mathcal{D}(ue_i)$After that, we calculate the probability of point ue_i in chosen as following clustering center by utilizing the subsequent equation:

$$\mathcal{P}(ue_i) = \frac{\mathcal{D}(ue_i)^2}{\sum_{ue_i \epsilon UE} \mathcal{D}(ue_i)^2} \quad (1)$$

We have chosen the point with the uppermost probability as the next center$\mathfrak{C}_i$. Next, we recap the overhead process until total k^* centers have been selected, which can be described as set$\mathfrak{C} = \{c_1, c_2, \dots, c_{k^*}\}$. The center might be utilized as a unique cluster center for k-means++ clustering.

C. Cluster Formation

While performing this process, the definite number in cluster k could be less than the primary number of clustersk^*. The motive behind this is that the procedure of adaptive clustering merges the clusters near to each other, for mitigating the cluster along with secluded or minimal numbers of nodes. In each cluster, cluster members are denoted as daughter nodes whereas the cluster head is labeled as the mother node. Fig 2 portrays the cooperative clustering using MoLoClus.

D. Cluster Head Selection

The main reason behind clustering is to ensure cooperative communication among users & satellites as well as among clusters to improve network performance in terms of reconfigurability, adaptability, flexibility, energy conservation, link stability, and selforganizability. The incorporated algorithm has the benefits of performance enhancement, high throughput, high packet delivery ratio, minimum energy consumption, and mother node changing ratio.

E. Intellectual Spectrum Planning

After the clustering process, cognitive radio-assisted intellectual spectrum planning is performed with the help of deep reinforcement learning agents to ensure full spectrum utility and to realize the mounting demand for wireless bandwidth by utilizing idle licensed channels of primary users. Initially, spectrum sensing is performed by the secondary users using CR wireless communication where Channel Quality Information (CQI), SINR (Signal to Interference and Noise Ratio), and RSRP (Reference Signal Received Power) are gathered and shared with the mother node. A spectrum planning framework is positioned with the terrestrial base station where TD3 is pillared which offers a high convergence rate and superior decisions. The mother node shares the aggregated sensed spectrum details with this framework where the TD3 agents identify the spectrum as unavailable (non-vacant) and available (vacant) based on spectrum holes, and several primary users using a specific spectrum.

F. Optimal Interference Management

After spectrum planning, interferences are managed in two manners spectrum handoff and intellectual channel switching at terrestrial and air-to-ground communication to ensure ceaseless communication. The secondary users continuously monitor the activities of primary users to avoid interference and they intimate the spectrum planning framework through the mother node. The framework maintains the available spectrum details like first grade and second grade in a hierarchical manner. When the first-grade link is in the state of being occupied by the primary user, second-grade channels are preferred for handoff to ensure service continuity and QoS. For air-to-air communication (Inter-satellite Links- ISL), FSO links are utilized as there is a clear line of sight and this technology ensures high antenna gain, high network coverage, and low energy consumption. The LEO satellites work in a self-organizing manner to adapt network dynamics and avoid communication interruptions caused by satellite failures by automatically establishing ISL links thus ensuring robust routing processes.

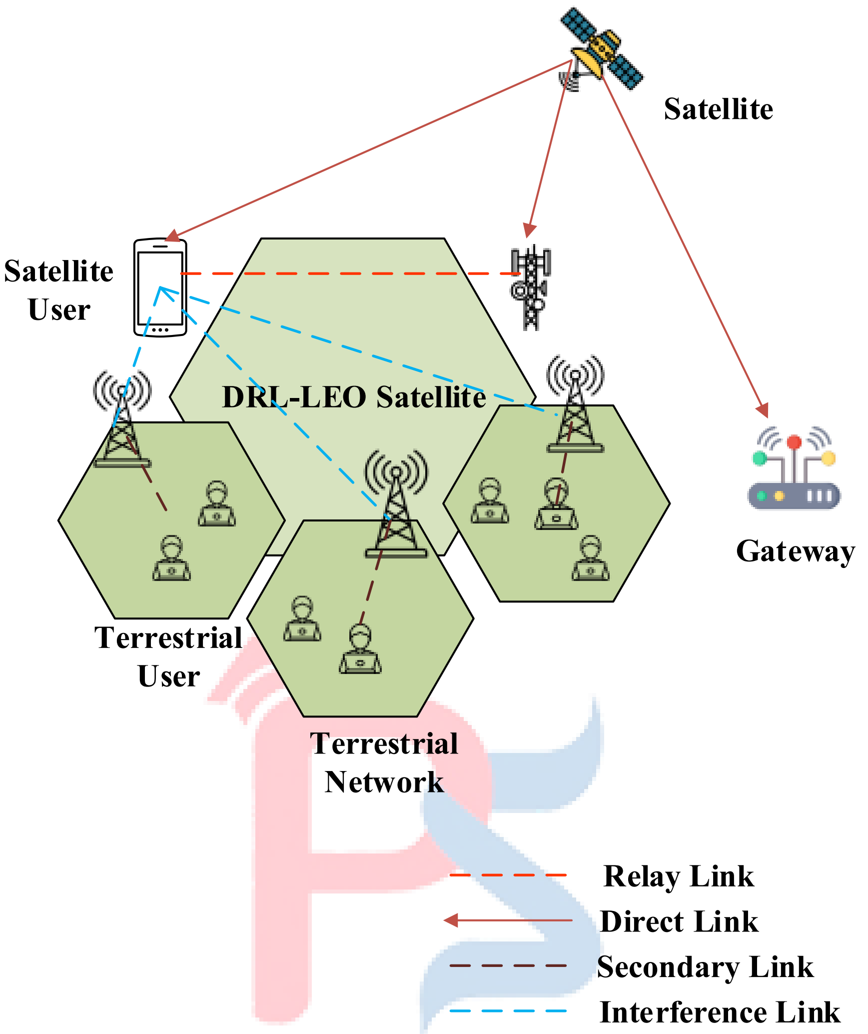

Fig: 1 depicts the overall proposed architecture

IV. Results and Discussions

In this work, we conduct an experimental analysis through simulation to evaluate the efficacy of the proposed methodologies DRL-LEO framework achieves better performance through comparison results. The study overview, the use-case scenario, the comparative analysis, and the simulation setup are the four subsections that make up this section. The proposed method will be tested in a simulated environment, and its efficacy will be shown by comparing its performance metrics with those of prior works. The proposed method is evaluated in a controlled simulated environment that closely models dynamic network conditions, user mobility, and varying traffic loads. Key performance metrics such as Quality of Experience (QoE), throughput, latency, packet loss ratio, spectral efficiency, and convergence behavior are considered for a fair and detailed assessment.

The simulation results demonstrate that the DRL-LEO framework consistently outperforms conventional optimization and learning-based methods by effectively adapting to rapid network variations and resource constraints. The deep reinforcement learning agent learns optimal spectrum allocation and link selection strategies, leading to improved QoE stability and reduced end-to-end delay under high-traffic and interference-prone scenarios. Furthermore, the proposed framework shows faster convergence and higher robustness compared to baseline models, highlighting its capability to make intelligent decisions in real time. the DRL-LEO approach achieves noticeable gains in throughput and spectral efficiency while maintaining lower packet loss and jitter. These improvements directly contribute to enhanced user-perceived video quality and seamless communication. Overall, the results validate the effectiveness and scalability of the proposed DRL-LEO framework, confirming its suitability for next-generation 6G-enabled satellite-terrestrial integrated networks and real-time multimedia applications.

V. Conclusion and Recommendation

Ineffective spectrum planning and interference management remain the major concerns in LEO satellite communication. To neutralize these issues, we have proposed DRL based spectrum planning and interference management system. For that, initially, we have clustered two entities such as user equipment (UE) and LEO satellites using MoLoClus which enhances high packet delivery ratio and minimum energy consumption. After that, cognitive radio-assisted intellectual spectrum planning is executed with the help of DRL agents to ensure full spectrum utility thereby identifying whether the spectrum is available or unavailable using the TD3 algorithm. Then, the interferences are managed in two manners spectrum handoff and intellectual channel switching at terrestrial and air-to-ground communication by utilizing the H2O algorithm. Here, the link of interest is identified using the H2O algorithm based on significant parameters. The proposed DRL-LEO framework is simulated in the NS-3.26 simulation tool where the proposed works performed better than other existing works. The proposed DRL-LEO framework outperforms other prior works in terms of bit error rate, energy efficiency, packet error rate, and sum utility of the LEO satellite.

VI. Chapter Summary

The DRL-LEO framework for intelligent spectrum planning and interference control in 6G terrestrial and non-terrestrial LEO satellite constellations was experimentally analyzed and provided in this chapter. Network Simulator (NS-3.26) was used to build up the simulation, and performance indicators were compared to previous studies, namely IM-SCo and HST-NCC.

BER, Energy Efficiency, PER, and Sum Utility of LEO Satellite were the main subjects of the comparison investigation. The results showed that, with a reduced rate of 38.4%, the DRL-LEO framework surpassed the previous efforts in terms of BER. Furthermore, the suggested structure exhibited an increased Energy Efficiency of 1.18 bit/J, which was ascribed to cooperative clustering and efficient interference control. Additionally, the Packet Error Rate dropped to 49%, demonstrating the advantages of cooperative clustering and effective interference control.

Last but not least, the Sum Utility of LEO Satellite showed significant improvement, with the DRL-LEO framework outperforming HST-NCC and IM-SCo by attaining a higher rate of 2.08 bps. The suggested approaches produced a better overall performance by successfully reducing interference and optimizing spectrum use. The major performance parameters are concisely summarised in Table III, which further supports the effectiveness of the DRL-LEO architecture in 6G communication settings.

VII. FUTURE WORK

In the future, we have planned to incorporate effective security measures through significant authentication and anomaly detection approaches for also ensuring data privacy while spectrum sharing and communication. In addition, advanced cryptographic techniques and lightweight security protocols will be explored to protect real-time video data without introducing excessive latency or computational overhead. The framework will be further extended by integrating AI-driven intrusion detection systems capable of identifying malicious behaviors, spoofing attacks, and unauthorized access in dynamic 6G environments. Moreover, privacy-preserving learning methods such as federated learning will be investigated to enable collaborative QoE optimization while maintaining user data confidentiality. Finally, the proposed system will be validated in large-scale heterogeneous network scenarios to evaluate its scalability, resilience, and impact on Quality of Experience under diverse security threats and network conditions.

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