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Hybrid Terrestrial–Non-Terrestrial Network Architecture for Low-Latency Global Connectivity in Beyond-5G Systems

Harsha Vardhan Reddy Kavuluri

Lead Oracle, Postgres, Cloud Database Administrator, Contractor for Deloitte, USA.

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ABSTRACT

The growing need of smooth worldwide connectivity in Beyond-5G (B5G) systems has also underscored major drawbacks related to latency and small coverage with regards to traditional terrestrial networks. Although wireless communication has advanced, current terrestrial networks do not adequately have the capability to offer trustworthy connectivity in remote, maritime, and high-mobility locales. Non-Terrestrial Networks (NTNs), such as low Earth orbit (LEO) satellites and unmanned aerial vehicles (UAVs) provide longer coverage, but their combination with terrestrial systems is inefficient and results in poor performance and higher latency. To counter these potential issues, the current paper will offer a hybrid terrestrial-non-terrestrial network architecture with a latency-wise optimization framework. The suggested methodology is a hybrid of system-level-based modeling and system-equivalent analysis of communication that is used to efficiently represent both network-layer and physical-layer properties. A delay-aware network selection algorithm and an adaptive resource optimization strategy is built to help direct traffic dynamically across terrestrial and NTN links to enhance the efficiency of the system as a whole. Simulation findings indicate the proposed hybrid architecture can greatly decrease end-to-end latency besides increasing throughput relative to traditional terrestrial-only and NTN-only methods. It is also clear that the performance is enhanced especially in situations where there are high user density and dynamic traffic, which validates the scalability and robustness of the proposed model. The key results of the work are the development of the hybrid terrestrial-NTN architecture design, the design of latency-contrained optimization model with the help of circuit level representation and detailed performance analysis that should prove the efficiency of the suggested system to be used as the next generation wireless communication artifact.

Author's e-mail: 1kavuluri99@gmail.com

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1. INTRODUCTION

The accelerated development of wireless communication technologies to develop beyond 5G (B5G) and sixth generation (6G) systems due to the growing need of ultra-reliable, low-latency, and connectivity on a global scale [2], [3], [4], [5]. The use of autonomous systems, remote healthcare, smart cities, and industrial automation among others nowadays demand the ability to communicate seamlessly in a variety of often challenging environments. Nevertheless, traditional land-based networks have a fundamental constraint in delivering a uniform coverage especially within rural areas, oceans and disaster prone areas thus making it imperative to integrate complementary communication paradigms [2].

The introduction of Non-Terrestrial Networks (NTNs) such as low Earth orbit (LEO) satellites, unmanned aerial vehicles (UAVs) and high-altitude platform stations (HAPS) have become attractive networks to reach beyond traditional network coverage [10]-[12]. These technologies are allowing wide area connections, and facilitating communication where before it was impossible. Although they have benefits, NTNs come with problems like a larger propagation delay and dynamic states of links, which may pose a major threat to the overall performance of the network. Moreover, ineffective routing, and non-coordination among terrestrial and non-terrestrial paths tend to cause inefficient latency and inefficiency of the system [11], [12].

The key constraint on current studies is the lack of a single hybrid architecture that is capable of combining both terrestrial and NTN systems and considerations of physical-layer properties to system-level design. The existing tools are either oriented at network optimization at high level or rather on isolated communication models without considering the interaction between the circuit-level behavior and the network-level interactions. Such a difference limits the ability to attain optimal performance in applications that are latency-sensitive.

In light of these concerns, this paper will seek to create a hybrid terrestrial-non-terrestrial network design, which integrates latency conscious optimization and physical-layer modeling. The main aim is to implement an effective communication network that can reduce the end-to-end delay and provide highly dependable and scalable communication. Some of the contributions to this paper are the creation of a hybrid architecture that is integrated, the creation of a latency-aware optimization model that is backed up by a circuit level representation, and overall performance analysis which indicates a decrease in latency and throughput over the current methods.

2. RELATED WORK

However, even with impressive developments in the 5G technologies, conventional land-based communication networks still have fundamental limitations regarding coverage, scalability, and latency, especially in the remote and mobile high settings [1], [2]. Such restrictions have stimulated a substantial research on other communication paradigms that can expand connectivity to the traditional infrastructure boundaries. Here, Non-Terrestrial Networks (NTNs), such as low earth orbit (LEO) satellites, unmanned aerial vehicles (UAVs) and high-altitude platform stations (HAPS) have become promising alternatives to serve both wide area coverage and enhance communication in underserved areas [10]-[12]. NTN-based systems provide better reach and flexibility; nevertheless, they add issues like the increase in propagation delay, dynamic topology, and vulnerability to environmental factors and these could adversely affect the overall network performance.

In order to address the personal constraints of terrestrial and non-terrestrial systems, recent studies have suggested hybrid terrestrial-NTN systems. These solutions are intended to combine the two types of networks to capitalize on the low latency of the terrestrial connections, as well as the extensive coverage of the NTN systems. Although these hybrid models have shown better connectivity, much of current frameworks is more designed at the level of high-level architecture, and does not provide detailed mechanisms of effective coordination between segments of the network. Specifically, the problem of routing inefficiencies and ineffective resource allocation strategies are still important issues, particularly when dealing with dynamic traffic.

A number of methods to optimize latency have been discussed, such as integrating edge computing, traffic unloading, and adaptive routing schemes [6]-[9]. These strategies strive to minimize the end-to-end delay, through optimization of data routes and locations of processing. Nevertheless, the majority of these schemes can only be applied to optimizing the network-layer, and they fail to consider the underlying physical-layer attributes, which determine the performance of communications.

The key deficiency in the existing literature is that there are no detailed frameworks focusing on a combination of circuit-level modeling and system-level network design. The effects of signal-level behavior, like propagation effects, noise, and channel dynamics, on latency and reliability in general are little taken into account in existing works. Also in most of the studies, adaptive routing strategies employed are either not dynamic enough or do not respond to true network conditions thus the selection of pathways is not done efficiently. To fill these gaps, the design of hybrid architecture, modeling of physical-layers, and intelligent latency-aware routing schemes need to be combined in a cohesive way.

3. SYSTEM MODEL AND DESIGN

3.1 Hybrid Network Architecture

The hybrid non-terrestrial-terrestrial network architecture proposed combines several communication layers to make Beyond-5G systems have low-latency and wide-area connectivity. The architecture has several important elements, such as User Equipment (UE), Base Stations (BS), Edge Computing Nodes, Non-Terrestrial Network (NTN) devices such as low Earth orbit (LEO) satellites and the UAV/HAPS platforms, and Core Network. The UE transmits to the terrestrial infrastructure via radio access links and the Base Station transmits to the Edge Computing Node via fronthaul links. The Edge Node includes local processing, and sends data to the Core Network over backhaul connections, providing efficient data processing and low latency data.

The NTN division increases its reach by adding LEO satellites and UAV/HAPS platforms which are linked to each other by inter-platform aerial links. The terrestrial to NTN layer communication is made possible through NTN access links and aerial relay links, as the two network domains are seamlessly integrated. The architecture includes a latency-sensitive control object that carries out routing and resource optimization and dynamically chooses the most efficient communication route based on the network conditions. This control system improves the overall system performance through reducing the delay and maximizing the use of resources.

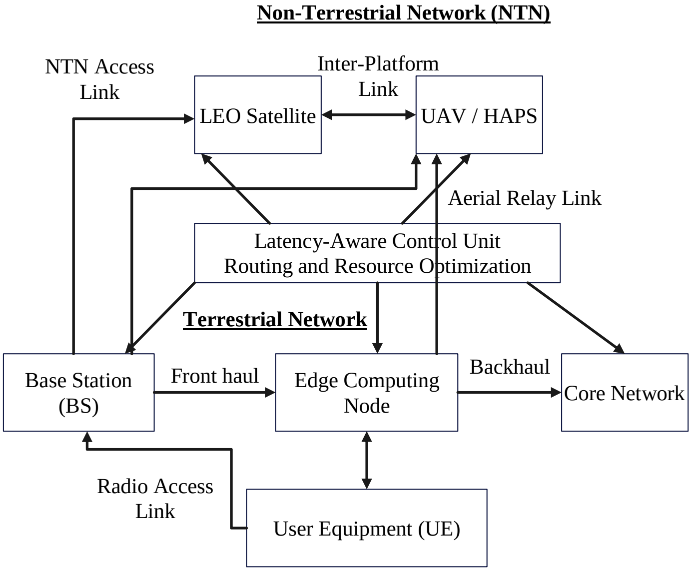

Fig. 1. Proposed Hybrid Terrestrial-Non-Terrestrial Network Architecture with Latency-Aware Control and Resource Optimization

The Figure 1 represents the projected hybrid terrestrial-non-terrestrial network design, emphasizing the correspondence among terrestrial and NTN elements, the consequences of the latency-conscious control unit in facilitating effective and adaptive communication.

3.2 Equivalent Circuit Model

The hybrid non-terrestrial and terrestrial communication system is also expressed as an equivalent circuit to illustrate the inherent physical-layer properties that affect signal propagation, propagation delay and signal noise.The model consists of a source voltage V_s with an internal resistance R_s, representing the transmitter and its inherent losses. The channel of communication is bifurcated into the terrestrial and NTN channels into two parallel composite channels.

The upper branch models the low-delay terrestrial communication path using a resistance R_t and capacitance C_t, which represent signal attenuation, buffering effects, and propagation delay within terrestrial links. The lower branch represents the high-delay NTN path, characterized by resistance R_n and inductance L_n, capturing the extended propagation effects and dynamic behavior associated with satellite and aerial communication links. A latency-aware path selector switch S_1 is incorporated to dynamically choose between the terrestrial and NTN paths based on real-time network conditions, thereby enabling optimized routing and reduced end-to-end delay.

Additionally, a noise current source I_n is included to model channel-induced interference and environmental noise effects, while the load resistance R_L represents the receiver. This equivalent circuit model gives an ultimate representation of terrestrial and NTN communication behaviors that can be analyzed accurately in determining signal degradation, latency characteristics and system overall performance.

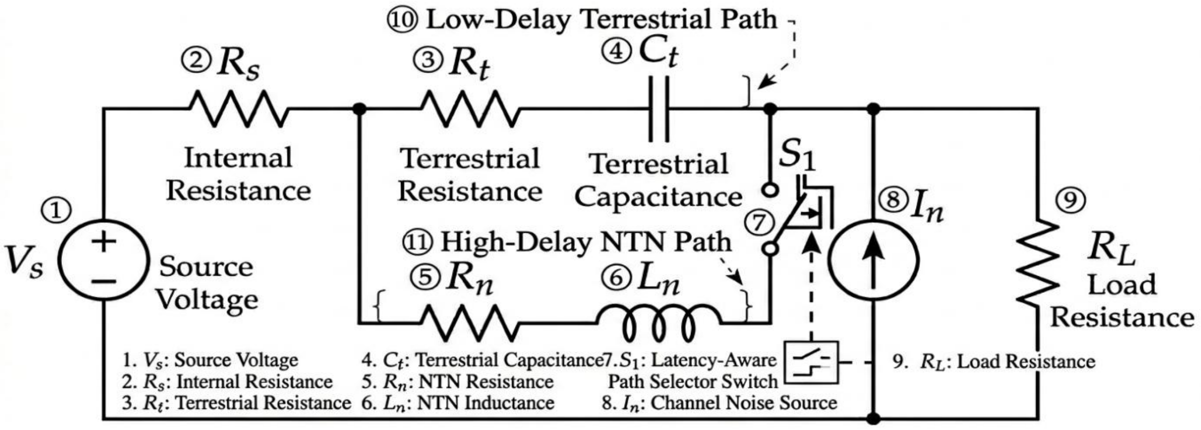

Fig. 2. Equivalent Circuit Model of Hybrid Terrestrial-Non-Terrestrial Communication System with Latency-Aware Path Selection

The equivalent circuit diagram of the hybrid terrestrial-NTN communication link (Figure 2) shows the parallel path arrangement, a mechanism to switch between latency-consciously, and the effect of noise and load on the performance of the system.

3.3 Latency Model

End-to-end latency is one of the parameters that have a significant impact on the overall performance of the proposed hybrid communication system and is a significant parameter in Beyond-5G applications. The overall delay incurred in the transmission of data can be represented as the summation of several delay components as a result of various steps involved in the communication process such as the transmission delay, propagation delay, processing delay and the queuing delay.The total latency D_{total} is given by:

$$D_{total} = D_{tx} + D_{prop} + D_{proc} + D_{queue} \,, \qquad (1)$$

where D_{tx} represents the transmission delay, D_{prop} denotes the propagation delay, D_{proc} corresponds to processing delay at intermediate nodes, and D_{queue} accounts for queuing delay due to network congestion.Equation (1) demonstrates that the overall latency depends on the network- and physical-level considerations, so the optimization of these parameters presents a crucial requirement to realize the low-latency communication in hybrid terrestrial-NTN systems.

4. PROPOSED METHODOLOGY

4.1 Latency-Aware Network Selection

The hybrid communication architecture proposed is designed with a latency-aware network selection mechanism to dynamically calculate the most effective-path of transmission between terrestrial and non-terrestrial network elements. Such a selection enables the reduction of end-to-end delay, under the consideration of the reliable communication under different network conditions. The decision making mechanism tests several parameters as they come to determine the best communication line to transmit data.

The main criterion that will be taken into consideration during the selection process will be the end- to end delay of each of the available paths. The system constantly measures the latency over terrestrial and NTN connections and chooses the route with the least delay. Besides delay, network load is considered to avoid congestions and balance in the use of resources in the network. Traffic conditions on a specific link can create more delays in queuing and hence, the selection algorithm dynamically reallocates traffic to unexploited paths.

Another important parameter that affects the network choice, especially in wireless and NTN settings is signal strength, the conditions of which in a channel may change considerably. Better signal quality guarantees quality transmission of information and minimizes the number of packets lost and hence enhances the overall effectiveness of communication. Through a collective delay, load and signal strength consideration, the latency-aware network selection mechanism proposed will allow the adaptive and intelligent routing mechanism to achieve the best performance in hybrid terrestrial-non-terrestrial communication infrastructure.

4.2 Resource Optimization

In order to increase the effectiveness of the proposed hybrid communication system further, the resource optimization framework is designed to reduce the total latency and effectively use the available resources of the network. The key constraints that are taken into account during the optimization process are band-width availability and transmission power that directly impact system performance and energy efficiency.The objective of the optimization model is to minimize the total latency D_{total} subject to resource constraints, and it is formulated as follows:

$$\min D_{total} \ s.t \ B_i \leq B_{max}, P_i \leq P_{max}, \tag{2}$$

where B_i represents the allocated bandwidth for the i^{th} communication link, B_{max} denotes the maximum available bandwidth, P_i is the transmission power, and P_{max} is the maximum allowable power level.The optimization structure, as specified in Equation (2), is to make sure that the latency is minimized at the cost of bandwidth and power being used at allowable levels. By so doing, the approach will be able to allocate resources effectively both on the terrestrial and non-terrestrial links, thus yielding a better overall performance of the system, reduced congestion and an increased energy efficiency in Beyond-5G communication space.

4.3 Adaptive Routing

The proposed framework is complemented by a latency-aware network selection and resource optimization mechanisms and an adaptive routing strategy that adaptively changes the routes used to transmit data according to real-time network conditions. This is able to use multi-path routing to allow flexible routing of data over both the terrestrial and non-terrestrial paths, leading to increased reliability and minimization of the chances of congestion or delays during transmission. The system will be able to smooth ship between routes by keeping several candidate paths which will allow the smooth switching between routes in order to provide optimal performance under different traffic and channel conditions.

Besides multi-path routing, the suggested model employs the use of edge-assisted decision-making to make routing efficient. The Edge Computing Node is important in measurements of network parameters like latency, load and signal quality and thereafter making a choice of the most appropriate route to deliver data. This deployment of localized decision-making minimizes reliance on centralized control making fast responses and higher scalability possible. Adaptive routing with edge intelligence has ensured that communication system is robust, efficient and responsive even in terrestrial heavy traffic hybrid network environment that is non-terrestrial.

4.4 Algorithm

The proposed hybrid communication framework is deployed via a delay-conscious adaptive algorithm that combines delay assessment, path choice, and allocation of resources. The algorithm is dynamic and optimally routing and optimal usage of the network resources is achieved in real time. The mechanism of the proposed method is explained by the step-by-step algorithm (Algorithm 1) that consists of the steps to choose the most effective path of communication and modify the system parameters in accordance with the current network conditions.

Algorithm 1: Latency-Aware Adaptive Routing and Resource Optimization

Input: Network parameters (delay, load, signal strength)
Output: Optimal path selection and resource allocation

1. Initialize network parameters for terrestrial and NTN links
2. Measure end-to-end delay for all available paths
3. Evaluate network load and signal strength for each path
4. Select the path with minimum delay and acceptable load conditions
5. Allocate bandwidth and transmission power based on optimization constraints
6. Route data through the selected path
7. Monitor network conditions continuously
8. Update path selection and resource allocation dynamically if conditions change

The algorithm suggested provides effective combination of ground and air communication connections, as it constantly adjusts to the change in delay, traffic and signal quality. In a dynamic network environment, the system can offer low-latency communication with the optimal use of resources and a high degree of reliability as outlined in Algorithm 1.

5. SIMULATION SETUP

5.1 Simulation Tools

The effectiveness of the suggested hybrid non-terrestrial-terrestrial communication system is tested with the help of conventional simulation packages, such as MATLAB and NS-3. To implement the mathematical models, optimization framework, and the latency analysis, MATLAB is used, which offers a versatile platform of numerical calculation and algorithm verification. Meanwhile, NS-3 can be used to simulate at the network level to capture the reality of communication situations, as well as dynamic traffic conditions, routing behavior and interaction between terrestrial and NTN components. The integration of MATLAB and NS-3 allows the assessment of the physical-layer and network-layer features of the system, providing the correct analysis of the system performance in the context of latency, throughput, and resource usage in Beyond-5G communication.

5.2 Simulation Parameters

The simulation environment will be set to test the functionality of the proposed hybrid terrestrial-non-terrestrial network in the real operating conditions. Some of the key parameters are chosen as per the system model and latency formulation and resource optimization constraints as discussed earlier. These parameters have a direct impact on delay, throughput, and the overall network efficiency. The user numbers are diversified to examine the system scalability and its effect on the latencies and routing performance. Bandwidth is assumed to be a key resource parameter with the optimization model required in Equation (2), which influences the transmission capacity and congestion. The satellite altitude is also added to the model, to better model propagation delay in NTN links: as it is a great contributor to the total latency discussed in the Equation (1). Table 1 shows the parameters of the simulation carried out to assess the proposed hybrid communication framework.

Table 1. Simulation Parameters

Parameter	Symbol	Value Range / Setting	Description
Number of Users	N	10 - 200	Evaluates scalability and traffic load impact
Bandwidth	B	1 - 20 MHz	Available communication bandwidth (used in Eq. 2)
Satellite Altitude	H_s	500 - 1500 km	Determines NTN propagation delay (used in Eq. 1)
Transmission Power	P	0.1 - 2 W	Power constraint for communication links
Noise Power	N_0	-100 dBm	Channel noise level affecting signal quality
Edge Processing Delay	D_{proc}	1 - 10 ms	Processing delay at edge node
Queueing Delay	D_{queue}	1 - 20 ms	Delay due to network congestion

6. RESULTS AND DISCUSSION

6.1 Latency Analysis

Latency performance of the proposed hybrid terrestrial-non-terrestrial communication system is measured by subjecting the network to varied network load by increasing number of users between 10 and 200 users. The comparison in the analysis is on the end-to-end latency of three communication models that include terrestrial-only, NTN-only and the proposed hybrid framework. Figure 3 shows that the end-to-end latency varies with the number of users of the three approaches to communication discussed. .It can be observed that latency increases with the number of users for all models due to the rise in queuing delay D_{queue} , as defined in Equation (1).

At low user densities (e.g. 15 ms with 10 users), the terrestrial network has initially low latency due to reduced propagation range and efficient local communication. As users grow however, the earth system will see high congestion leading to a dramatic increase in latency that peaks at around 160 ms at 200 users. This is mainly because of the overload of traffic and resource contention in the network. The NTN-based model of communication, on the contrary, shows a steadily increased latency at all user levels, beginning at about 60 ms and peaking at 180 ms at 200 users.This is due to the inherently large propagation delay associated with satellite and aerial communication links, as modeled by D_{prop} in Equation (1). NTN offers coverage over a wide area but the latency performance of the NTN is rather low compared to terrestrial systems.

The suggested hybrid model is far superior to the terrestrial approach as well as NTN approach since the hybrid model dynamically chooses the best communication path (dynamically) based on the latency, load and signal conditions. The hybrid system has the minimal latency in all situations involving users as indicated in Figure 3 with ranges between 12 ms when the system is at low loads and about 90 ms when the system is at high loads. At 200 users, the latency is still lower than the QoS threshold of 100 ms, which indicates the usefulness of the latency-aware optimization strategy. Figure 3 is used to illustrate the latency reduction of the proposed hybrid model when compared to the NTN-based system in the shaded area. This area is a clear indication of the performance improvement achieved in adaptive routing and resource optimization. As the number of users grows, the distance between the NTN and hybrid curves increases, which means that the offered solution is especially beneficial in high-load situations. Moreover, the QoS threshold line at 100 ms offers the reference point of acceptable latency in real-time applications. It is clear that both terrestrial and NTN systems surpass this limit at greater densities of users, but the hybrid model is able to ensure latency remains with-in reasonable ranges. Altogether, the findings confirm that latency-aware network selection, resource optimization (Equation (2)) and adaptive routing have a significant effect on the system performance, which secures the efficient and scalable communication in Beyond-5G hybrid networks.

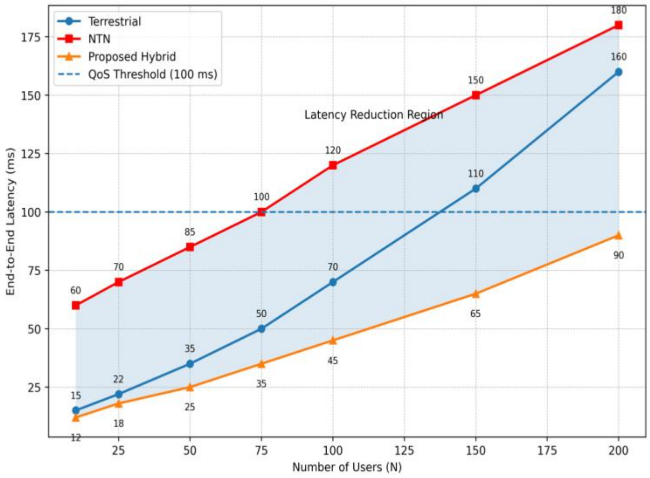

Fig. 3. End-to-End Latency Comparison versus Number of Users for Terrestrial, NTN, and Proposed Hybrid Communication Models

6.2 Throughput Analysis

The performance of the proposed hybrid terrestrial-non-terrestrial communication system in terms of throughput is studied under different conditions of load on the network by adding new users up to a number of 200. This analysis is aimed at verifying the efficiency of the data delivery of the system and proving the efficiency of the suggested strategies of resource optimization and adaptive routing.

Figure 4 demonstrates the changes in throughput versus the number of users of terrestrial-only, NTN-only and the proposed hybrid communication models. Throughput is quantified in the rate (Mbps) of the data delivered successfully, and directly relies on the bandwidth allocation, network congestion, and routing efficiency, as explained in Section 5.2 and Equation (2). When there are fewer users, the terrestrial network demonstrates rather high throughput (e.g., 70 Mbps at 10 users) as a result of effective local communications and a low rate of congestion. With the growing number of users however, the terrestrial throughput is reduced significantly to about 15 Mbps at 200 users. This is mainly due to overload of traffic, bandwidth contention and increased queuing delays, a factor that adversely affects the efficiency of data transmission.

The trend of communication model based on the NTN demonstrates a contrasted trend with moderate values of throughput which steadily rise between 40 Mbps and about 52 Mbps as the number of the users increases. This is owed to the large spatial coverage and reliable connection of NTN systems, despite the restriction in their performance due to increased propagation delays and reduced real-time flexibility. The hybrid model proposed always yields the greatest throughput regardless of the context of the users and commences at about 75 Mbps under no load and sustains at about 50 Mbps even when there are 200 users. This is due to the gain in performance that is a direct consequence of the latency-sensitive network selection mechanism, the resource optimization policy as defined in Equation (2), and the adaptive multi-path routing as outlined in Section 4.3. The hybrid model works to alleviate congestion by dynamically balancing the traffic on terrestrial and NTN routes and ensures that bandwidth is fully utilized. The black area in Figure 4 calculates the throughput gain obtained by the proposed hybrid network over that of the terrestrial network. This region brings out clearly the performance gain that is achieved with regard to intelligent routing of routes and allocation of resources. The better result is achieved with the growth of the number of users, which proves the scalability and stability of the proposed system in the conditions of high load. Also, the QoS threshold line at 40 Mbps can be used to establish a standard of performance in data transmission. It is noted that, even at higher user densities, the terrestrial network will drop below this threshold where the hybrid model will invariably keep the throughput at above the required level, guaranteeing reliable communication of bandwidth intensive applications. On the whole, the findings made in this paper affirm that the combination of latency-conscious selection, resource optimization, and adaptive routing can not only reduce latency (as evidenced in Figure 3) but also can lead to a significant throughput increase, making hybrid terrestrial-NTN communication systems more efficient and scalable.

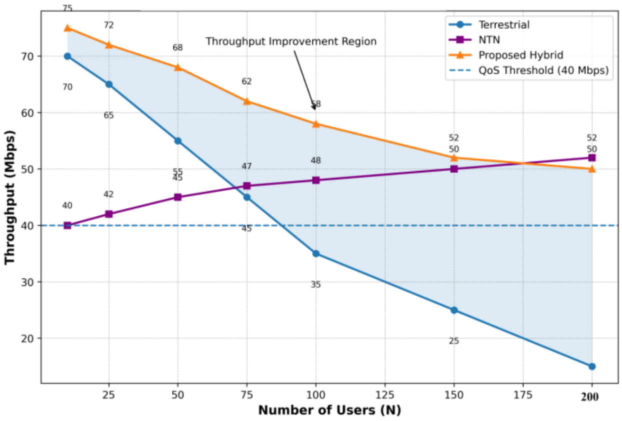

Fig. 4. Throughput Comparison versus Number of Users for Terrestrial, NTN, and Proposed Hybrid Communication Models

6.3 Discussion

The results of the performance analysis shown in Figures 3 and 4 are a clear indication of the benefit of using the proposed hybrid terrestrial-non-terrestrial communication setup as compared to the traditional baseline systems. The hybrid model provides better performance in both throughput and latency measures compared to terrestrial-only systems and NTN-only systems. Terrestrial network, although low latency with low user densities, suffers greatly when overloaded with other users because of congestion and unavailability of resources. On the other hand, the NTN model has a broader coverage and a more constant throughput but it is necessarily limited by larger propagation delays thus has higher latency under all operating conditions.

The suggested hybrid model combines the advantages of the terrestrial system and NTN in a successful way as the system takes the advantage of the latency-aware system of networks selection, resource optimization, and adaptive routing to enhance the working system. As it is evident in Figure 3, the hybrid model would always have lower latency than both baseline methods even during the times with heavy user load, by dynamically choosing the best communication route. Likewise, Figure 4 indicates that the hybrid system maintains a higher throughput level as it effectively balances traffic and maximizing the use of bandwidth, and therefore avoiding congestion and enhancing data delivery performance. These performance improvements confirm the quality of the optimization model given in Equation (2) and adaptive routing mechanism outlined in Section 4.3.

In spite of these strengths, the hybrid approach, which is proposed, also presents some trade-offs, which are important to take into account. Combination of the terrestrial and the NTN introduces complexity in the system demanding complex control systems and real-time decision making capabilities. Moreover, the installation and servicing of NTN facilities, including satellites and UAVs, may also cause increased operational expenses than traditional ground-based networks. Nevertheless, these limitations are compensated with the major gains in latency, throughput and network scalability at large, especially in the applications that need the reliability of communication in dynamic and wide-area networks. On balance, the findings reveal that the hybrid terrestrial-NTN architecture offers a well-balanced and efficient solution to Beyond-5G communication systems and can offer a better performance level with a solution to the drawbacks of separate network paradigms.

7. COMPARATIVE ANALYSIS

In order to further prove the usefulness of the proposed hybrid system of terrestrial-non-terrestrial communication, the framework is compared and contrasted with current communication systems, such as terrestrial-only models, NTN-based and traditional hybrid architectures. These key performance metrics—latency, throughput, scalability, adaptability, and system complexity, are compared. Table 2 gives a comparative analysis of the suggested approach with the current ones and shows its better performance in reducing latency, improving throughput, and having adaptive routing resources.

Table 2. Comparison with Existing Methods

Method	Latency Performance	Throughput Performance	Scalability	Adaptive Routing	Complexity
Terrestrial Network	Low (at low load), High (at high load)	Decreases with load	Limited	No	Low
NTN-Based Network	High (due to propagation delay)	Moderate, stable	High	No	Moderate
Conventional Hybrid	Moderate	Moderate	Moderate	Limited	High
Proposed Hybrid Model	Low (optimized across all loads)	High and stable	High	Yes (latency-aware)	Moderate

The terrestrial network is characterized by low latency but with congestion and performance degradation with increase in the number of users. NTN-based systems have both wider coverage and predictable throughput but have great latency because long-distance propagation of signals is involved. Traditional hybrid solutions enhance performance and coverage to a certain degree but do not have effective adaptive routing and optimization techniques. By comparison, the offered hybrid model exhibits higher effectiveness due to combining the latency-aware network selection, resource optimization, and adaptive routing. The proposed system (Figures 3 and 4) manages to maintain low latency and high throughput even with high network load, and it further offers enhanced scalability and flexibility. Despite the fact that the system increases the moderate complexity of the system since it incorporates control and optimization mechanisms, the efficiency and reliability of the system has been greatly improved compared to the current methods.

8. CHALLENGES AND FUTURE WORK

Although the proposed hybrid terrestrial-non-terrestrial communication framework has shown encouraging performance enhancements, various issues have been noted that need to be dealt with in order to be practically implemented. The management of smooth handover between terrestrial and NTN links is among the major challenges. Changing between various network layers, in particular, in very dynamic environments, can add extra signaling cost and temporary service interruptions without managed effectively.

The other major challenge is the inconsistency in the delays caused by satellites. NTN connections, especially those with LEO satellites, UAV/HAPS platforms, etc., experience dynamic propagation delays, based on orbital motion, atmospheric conditions, and link availability. Such variability can influence the precision of the latency estimation, and it might have an implication on the efficiency of the latency-aware routing mechanism. Energy is another major limitation particularly to UAV-based communication nodes and edge devices. The small battery capacity and power can have a limiting effect in continuous operation and the sustainability of the system in general. The hybrid communication systems should then be deployed with efficient energy management strategies to promote long-term deployment and reliability.

In the future, one can consider certain research directions to improve the proposed framework. The combination of machine learning and artificial intelligence methods of dynamically optimizing networks is a promising direction in improving decision-making processes on dynamic environments. The predictive routing, adaptive resource allocation, and smart congestion management could be facilitated by AI-based models. Also, the future development of 6G communication systems and especially utilization of terahertz (THz) frequency spectrums provides possibilities of extremely fast data rates as well as high-speed communication with minimal latency. Integration of these sophisticated technologies in hybrid terrestrial-NTN architectures can greatly improve the systems and facilitate next-generation wireless applications.

9. CONCLUSION

In this paper, the major challenges, identified in Beyond-5G communication systems namely high latency and poor coverage across the globe were dealt with by suggesting a hybrid terrestrial non-terrestrial network architecture. Traditional land networks experience congestion when there are large users whereas NTN-based networks, despite their ability to deliver wide-area coverage, cannot meet demand due to lengthy propagation delays. Such shortcomings bring about the necessity of a combined communication structure that can strike the right balance between latency, throughput and scalability.

The hybrid model proposed involves network selection based on latency, resource allocation, and adaptive routing where an optimal communication path is selected dynamically based on the efficiency. The equivalent circuit model promotes even more the study by including physical-layer properties like signal propagation, delay, and noise. The outcomes of simulations prove that the hybrid system can significantly decrease end-to-end latency and enhance throughput in comparison with other systems (terrestrial-only and NTN-only). It is important to note that the proposed system does not violate acceptable latency limits under the QoS conditions and even at high network load conditions, the system does not experience a decrease in data rates.

In practical terms, the proposed framework offers an efficient and scalable framework of real-world uses that need reliable and low-latency communications, including autonomous system, remote healthcare, disaster management, and smart cities. The model is differentiated by successfully incorporating both terrestrial and non-terrestrial networks, which guarantee higher connections, better utilization of resources and strong work in dynamic environments. In general, the research confirms the hybrid terrestrial-NTN architecture as an effective solution to develop a new generation of wireless communication networks.

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