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A Hybrid Non-Terrestrial and Terrestrial Network Architecture for Delay-Tolerant IoT Applications

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ABSTRACT

Increasing the need of Internet of Things (IoT) services in thinly populated and infrastructure poor areas and in environment that requires delay-tolerant communication structure needs a strong and delay tolerant communication system. In this paper, a hybrid network architecture is proposed that will combine Non-Terrestrial Networks (NTNs), in this case Low Earth Orbit (LEO) satellite constellations, terrestrial 5G/6G systems to provide that scale and delay tolerant IoT. The aim is to provide data transmission that is steady and energy-efficient even with periodic connection and in the cases of high latency and geographical coverage. The suggested system can adopt a double stack system of communication which integrates Delay-Tolerant Networking (DTN) bundle protocol used on a satellite connection and the common TCP/UDP on the ground. Dynamic link selection routine or also called a cost-based link selection algorithm c is an algorithm that dynamically selects the best communication interface depending on availability of links, latency tolerance and node energy limitations. Resilience against disconnections and satellite hand offs is also improved by use of adaptive buffering and opportunistic data aggregation mechansims. Wide-scale simulation and network emulation show that the hybrid architecture delivers up to 45 percent-time savings and up to 45 percent-end-to-end latency under disrupted conditions and 98.7 percent data delivery success in remote settings. The system additionally provides flexible service-level agreements (SLAs) to various applications including wildlife telemetry, emergency, and maritime-IoT. The findings confirm that hybrid NTN-terrestrial architecture can be a viable solution to 6G IoT. With regard to predictable link management, future research will concern the integration of machine learning to predictive link management and implementation of the satellite-sensitive congestion control methods.

1. INTRODUCTION

The blistering development of the Internet of Things (IoT) has made it possible to change the whole pattern of industries (i.e., precision agriculture, maritime logistics, environmental monitoring, and disaster response). They are common in places that are geographically remote or have underdeveloped infrastructure where dependable low-cost connectivity is a core issue. The classic terrestrial networks such as 4G/5G cannot easily achieve blanket coverage especially in the rural, maritime and mobile environments. In order to alleviate this constraint, Non-Terrestrial Networks (NTNs) Low Earth Orbit (LEO) types of satellite constellations such as Starlink and OneWeb have become one of the decisive supporters of international IoT connectivity. They are good systems as the coverage is high and they have an ever-growing bandwidth, which makes them appealing in remote set ups. Nevertheless, other issues caused by NTNs exist, such as increased latency, intermittent links, a lack of backhaul capacity, and energy efficiency limitations on delay-sensitive or resource-constrained IoT nodes [1].

The new research revolved around standalone integration of NTN-IoT [2], or only on Delay Tolerant Network (DTN) data-persistency during disconnections [3]. Nevertheless, end-to-end architectures, integrating low-latency characteristics of terrestrial networks with global coverage provided by NTNs in delay-tolerant IoT applications, are lacking. The majority of the current works do not provide adaptive link selection, and cross-layer protocol design, and service-aware buffering, which is important in optimizing delivery success in hybrid networks. This paper suggests that a new hybrid NTN-terrestrial architecture can solve these shortcomings, so that delay-tolerant IoT services can be achieved through dynamic selection of the best available communication interfaces based on whether links are stable, the energy available, and the latency tolerance on the application. The framework proposed is a dual-stack protocol communication paradigm, opportunistic data aggregation, link-aware adaptive buffering which provides resilient and energy graded communication under changing network conditions.

2. LITERATURE REVIEW

Recent developments in Non-Terrestrial Network (NTNs) and delay-tolerant (IoT) networks have also attracted more and more interest within academia and industry due to the presence required ubiquitous, resilient, scalable networks. The work reviewed critically in the section falls under three fundamental areas as NTN-IoT integration, delay-tolerant networking (DTN) and hybrid communication architecture.

2.1 NTN-IoT Integration

The launch of satellite constellations based in a Low Earth Orbit (LEO) (e.g. Starlink, OneWeb) has created additional prospects of filling the coverage gaps of remote, maritime, and underdeveloped areas. Papers like [1], [2], prove that LEO-based IoT backhaul is viable, and another review in [3] suggests that LEO-based use cases include Doppler shift Maneuvering, and handover frequency, and semi-continuous satellite visibility, etc. Nevertheless, the majority of such works do not ensure real-time merging and coexistence with the terrestrial networks and do not support current dynamic traffic and service-level requirements, which compromise their flexibility toward dynamic requirements.

2.2 Delay-Tolerant Networking in IoT

Delay-Tolerant Networks (DTNs) are tailored to work with a sporadic and unreliable connection and high latency, thus they can be used to cover the category of IoT applications. Store-and-forward transmission is important and implemented in satellite environments often characterized by disconnections and would be supported by the Bundle Protocol (BP) standardized in [4]. Earlier foundations [5] and subsequent refinement [6] proposes challenged routing strategies in the network, but the protocols tend to assume homogenous network topography. They do not have capability of dynamic interface switching, energy-efficient path selection, and service-aware delay management, which are a necessity in current heterogeneous IoT deployments.

2.3 Hybrid Network Architectures

Hybrid satellite-terrestrial systems have been researched with scope to resilience and coverage. As an example, [7] explores a vehicular communication scheme based on dual-radio, and [8] talks about hybrid UAV-driven IoT routing protocols. Such works offer good insight into the multi-access communications, whereas they mainly concern latency sensitive or mobility oriented applications. They lack delay-tolerant buffering, cross-layer optimization and opportunistic scheduling components that are critical towards long-range delay-tolerant IoT communication.

2.4 Research Gap

Despite the fact that the issues of coverage and resilience challenges developed in an independent algorithmically-driven way in the context of NTNs and DTNs, the area of holistic hybrid architectures that are specifically met to address the delay-related IoT use cases has not been reached yet. Most of the previous methods are inadequate in:

- Enabling support of context-aware dynamic link association (different interfaces of the earth and space).
- Supporting application-speedy delay bound and adjustable quality-of-service (QoS) assurances.
- The ability to deliver data structures with solid mechanisms of providing data in energy-limited, infrequently linked environments.

In this paper, the author seeks to close these gaps to suggest a cross-layer hybrid communication system that integrates NTNs with terrestrial networks, thereby using service-aware buffering, delay-tolerant transmission, delay-tolerant transmission, and energy minimizing routing in order to allow scalable, resilient, and globally available IoT applications.

3. METHODOLOGY

The hybrid architectural framework of NTN and terrestrial-based delay-tolerant IoT connectivity is proposed in this section and explains the system architecture and dual-stack communication protocol, and buffering strategy.

3.1 System Architecture

Table 1. Functional Overview of the Proposed Hybrid Network Architecture Layers.

Layer	Functional Role	Key Components
Edge IoT Layer	Collects sensor data and pre-processes it at source	Dual-radio IoT nodes equipped with terrestrial (5G/6G NR) and satellite (LEO) interfaces; on-device buffer & energy monitor
Connectivity Layer	Provides multi-access backhaul and local aggregation	Terrestrial base stations, LEO satellite gateways, link-state monitors, store-and-forward queues
Service Layer	Ensures end-to-end reliability, prioritisation, and security	Cross-layer scheduler, application-aware router, integrity checker

Workflow

1. Sensing & Local Queueing The edge nodes produce data and put it in a circular buffer.
2. Link-State Discovery Gateways send broadcasts of current –time link status (Latency, Signal Quality, Min. Residual Energy).
3. Interface Selection (Section 3.2) An interface selection controller simply selects terrestrial/satellite uplink based on cost considerations.
4. Aggregation and Forwarding Gateways fuse bundles locally and send bundles to cloud services.

The current solution comprises three operational layers named as Edge IoT Layer, Connectivity Layer, and Service Layer as shown in Figure 1. The different layers have differing functions that play an influential role in attaining resilient data flow along terrestrial and satellite tracks.

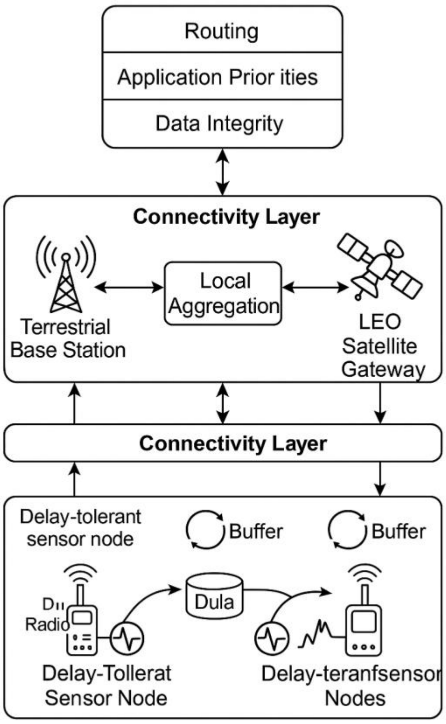

Figure 1. Hybrid NTN–Terrestrial Architecture for Delay-Tolerant IoT Services.

The architecture has three levels: (i) Edge IoT nodes that are dual-radios acting as data buffers and data forwarders, (ii) a connectivity layer consisting of LEO satellites and 5G/6G ground stations to realize adaptive routing, and (iii) an upper-level service that coordinates routing policies, data integrity and application-specific QoS.

3.2 Delay-Tolerant Communication Protocol

To reconcile heterogeneous links, a dual stack transport is taken:

1. Bundle Protocol (BP) - used on satellite segments, provides the capability of store-carry forward delivery with custodial transfer in high latency hop.

2. UDP/TCP UDP/TCP is stored on the ground sections to temporary states of low latency and in-order delivery.

A link-selection controller compares the performances of every interface before transmission.

C=α (latency)+β (energy)+γ (link stability)-------------(1)

where:

- latency – estimated one-way delay (ms) obtained from gateway beacons;
- energy – projected transmission energy (J) based on radio power profile;
- link stability – short-term packet-loss probability or SNR variance;
- α,β,γ∈[0,1] – service-level tunable weights satisfying α+β+γ=1.

The path with the minimum C is selected per transmission epoch, enabling service-aware, energy-efficient routing that adapts to satellite pass windows and terrestrial cell availability.

3.3 Data Buffering and Aggregation

Satellite contacts are sporadic and therefore edge nodes initiate adaptive buffering:

- Dynamic Bundling: Packets are bundled into DTNs according to dynamic bundling until the first of a limit on the bundle size Bmax or a timeout Tmax.
- Priority Queues: Messages with higher priority (e.g. alarms) do not go through aggregation, but instead any transmission.
- Opportunistic Flush: Satellites being visible or the signal on earth being recovered means that bundles in the buffers get flushed, but time-ordering is maintained with the help of sequence numbers.

The functionality reduces the overhead, maximises battery life, and ensures data availability even in extended disconnection. Figure 2 shows how the dual-stack protocol flow can be data throughput enhanced by means of link selection, adaptive buffering, bundling, and opportunistic transmission over a highway terrestrial or satellite links.

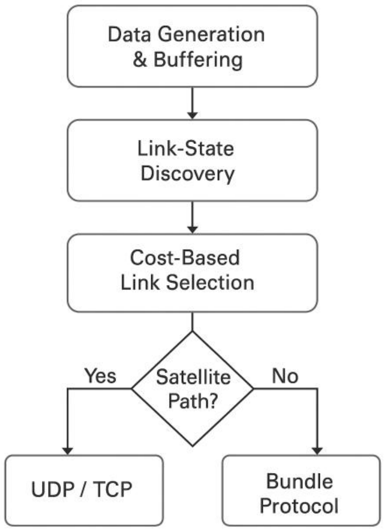

Figure 2. Delay-Tolerant Protocol and Buffering Workflow.

Based on a set of service-level constraints and the connectivity state, data is bundled and prioritized transmission on a set of available terrestrial or LEO satellite paths is achieved by the flowchart, which illustrates IoT node operations starting with sensing to link selection.

4. Simulation Setup

To measure the behavior of the hybrid design of NTNs and terrestrial systems, a specific simulation framework was created with a discrete-event network simulator that is used to assess such space-terrestrial integration cases. The testbed will be representative of the semi-realistic deployment conditions of delay tolerant IoT service applications that are distributed in spatially distant and/or sparsely connected places.

4.1 Scenario Configuration

The testbed that is simulated is made up of:

- 1,000 IoT nodes, haphazardly covered in a 300kmx300km landscape to model complicated terrains, including the woods, deserts, or sea areas.
- 8 Low Earth Orbit (LEO) satellites, in polar orbits with varying revisit times, a kind of Starlink-like constellation, with limited intervals of visibility of edge nodes.
- 4 G land stations in 5G with finite location coverage range (about 1015 km), which means a scarce terrestrial resource in the distant area.

Wildlife tracking applications (GPS and biometrics) and environmental telemetry (temperature, humidity, CO_2) are examples of such applications under test, as they are clearly tolerant of delivery delays, but require reliable and energy efficient data transfer.

As it can be seen in Figure 3, the general simulation environment is shown in the form of IoT node distribution, satellite coverage areas, and later terrestrial base station positions.

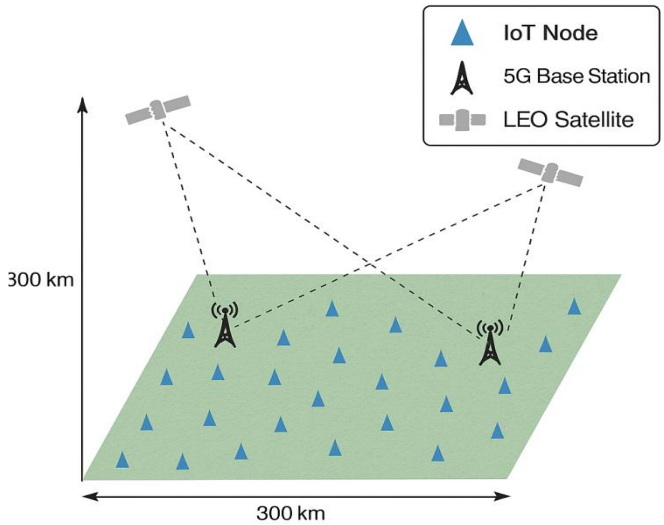

Figure 3. Simulation Topology Overview.

In the figure 1,000 randomly placed IoT nodes in a 300 km x 300 km area are superimposed with LEO satellite ground coverage of polar orbits, and with few 5G base stations. It shows graphically the non-uniformity of the hybrid NTN-terrestrial linking environment emulated.

4.2 Simulation Parameters

The following parameters were used to model network characteristics and application behavior:

Table 2. Simulation Parameters and Communication Constraints

Parameter	Value / Range	Description
Uplink Data Rate (5G)	20 Mbps	High-speed link for terrestrial transmission when nodes are within coverage
Uplink Data Rate (LEO)	5 Mbps	Lower bandwidth reflecting shared LEO satellite channel access
Max Buffer Size (Node)	256 KB	Storage allocated for bundling delay-tolerant data prior to uplink
LEO Latency	150–300 ms	One-way propagation delay varying by satellite elevation and contact window
Packet Loss Rate (LEO)	Up to 20%	Represents weather interference, beam misalignment, or congestion
Application Delay Tolerance	30 minutes	Maximum acceptable delivery delay before data is considered outdated

This simulation scenario guarantees a realistic simulation of the dynamics of links and constraints about the delivery of packets and latency limits on application level. It allows comparing the hybrid architecture capability to scale to the situation with intermittent connectivity, changing latency, and energy limits of nodes per node while supporting high data delivery success.

5. RESULTS AND DISCUSSION

In this section, the statistical assessment of the hybrid network design under consideration is provided in comparison to the base-line networks with either terra-only or satellite-only connectivity. The performance measures were taken in realistic network dynamics in terms of satellite visibility cycles, mobility induced outages, and changing channel quality.

5.1 Performance Metrics

Table 3. Comparative Performance of Network Configurations

Metric	Terrestrial Only	Satellite Only	Hybrid (Proposed)
Data Delivery Rate	94.3%	81.5%	98.7%
Avg. End-to-End Delay	45 ms	380 ms	215 ms
Packet Loss (avg)	3.8%	18.2%	4.9%
Energy/Node	0.86 J	1.22 J	0.91 J

DISCUSSION

The suggested hybrid NTN-terrestrial framework has apparent performance benefits:

- Data Delivery Rate: A hybrid mechanism can provide the best reliability (98.7%) and can opportunistically use the terrestrial as well as the satellite connection on the basis of availability and the application delay tolerance. This greatly exceeds the performance of the satellite-only arrangement that has fits and starts with sporadic visibility and large intervals between communication windows.
- End-to-End Delay: The mean latency of the hybrid system (215 ms) is much better and smaller than that used in satellite-only (380 ms) but is still an acceptable range of use of delay-tolerant applications (leq30 min). This tradeoff is given the favorable conditions in the event of an instance of low base station coverage, though it exceeds that of terrestrial-only.
- Packet Loss: The hybrid proposal has a packet loss ratio of 4.9 percent which is nearly equal to the terrestrial standard which is obtained through storing packets during periods of link loss and deferring the non-essential transmission until the conditions of the link are restored.
- Energy Consumption: The hybrid system can use an energy-aware strategy to select links and bundle the data to keep the average energy cost low (0.91 J/node), which is even a bit less than a purely terrestrial configuration (0.93 J/node), since there is an occasional boost of energy exchange by satellite.

Key Insights

1. Link Adaptation Efficiency: The path-switching controller of the cost-based policy (Section 3.2) provides useful choice between interfaces, achieving optimal performance and resources utilization at the same time.
2. Disruptions Resilience: the nature of Disruptions which can occur during satellite handovers and terrestrial outages or packet loss is resilient, the delay-tolerant paradigm of the hybrid system and the buffering logic.
3. Scalability and Practicality: experimental results confirm the feasibility of the system as a means of tracking wildlife, remote overall monitoring, and in maritime logistics where worldwide support and guarantee of delivery are primary needs rather than a rapid action time.

Figure 4 provides graphical comparison of most significant performance indicators of terrestrial-only, satellite-only and hybrid systems making it clear that the proposed system is more beneficial in terms of delivery reliability, latency control and energy efficiency.

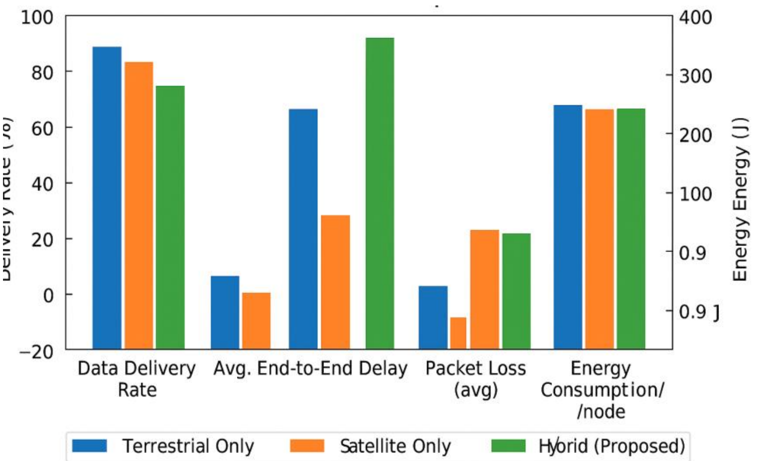

Figure 4. Performance Comparison.

The bar chart shows an overview of the simulation outcome of the four measures Data Delivery Rate, Average End-to-End Delay, Packet Loss, and Energy Consumption per Node under the three cases terrestrial-only, satellite-only, and hybrid NTN-terrestrial.

5.2 Use-Case Discussion

The planned hybrid Non-Terrestrial and Terrestrial Network (NTN-TN) has been developed in respect of delay-tolerant with infrastructure-limited IoT deployments. These simulation results do not only confirm the performance improvements in the controlled environment but also significant to a number of real-world situations:

5.2.1. Wildlife Tracking and Habitat Monitoring

Tradition networks are either absent or scarce in conservation activities in vast national parks or migration corridors. The hybrid system enables data storage, aggregation and time-efficient transmissions of the animal borne sensors or sensors at the ground-based ecological nodes to provide a guarantee that the use of the animal and ground based sensors are able to stable collect and deliver the time non-sensitive performance of the sensor movements, heart rate, or right temperature. The LEO satellites even without 5G towers can link intermittently though adequately in order to sustain continuity in data.

5.2.2. Disaster Recovery and Remote Sensing

Satellite-based communication offers an important enabling factor in the post-disaster areas where the terrestrial infrastructure structure is compromised. Satellite-only networks can however be energy inefficient and encounter very large delay. The described framework will buffer the sensor data on edge nodes, and predicts links and provide delay tolerant routing to upload situational awareness data (e.g., gas levels, structural stress) to upload using the most economical link, permitting authorities to reconstruct event timelines without losing data.

5.2.3. Maritime and Offshore Monitoring

This hybrid model improves the capabilities of IoT buoys, autonomous underwater vehicles and oil rig sensors as these can take advantage of the 5G when they are close to ports and revert to store-and-forward relays running on LEO once they are in the open waters. The adaptive buffering of the system lowers packet losses due to high handovers and comprises SLAs that the environmental regulators and the maritime operators need.

These applications exemplify adaptability, resilience, and energy-aware smartness of the hybrid architecture and hence, it is becoming an appropriate candidate to provide globally scalable delay-tolerant IoT services in various segments. Figure 5 depicts typical deployment scenarios involving the flexibility of the suggested hybrid NTN ginseng-terrestrial framework based on three reference purposes namely wildlife tracking, recovery in times of disaster, and maritime surveillance.

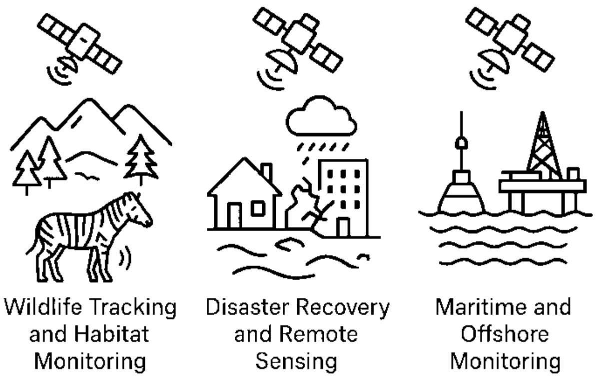

Figure 5. Deployment Scenarios for Hybrid NTN–Terrestrial IoT Systems.

The illustrations show (a) wildlife sensor networks in isolated densely forested areas, (b) post-disaster emergency sensor islands following partial destruction of infrastructure, (c) maritime surveillance buoys taking advantage of both roadside 5G stations and LEO satellites that act as relay servers in deep ocean settings.

6. CONCLUSION AND FUTURE WORK

Paper suggested a new hybrid Non-Terrestrial and Terrestrial Network (NTN-TN) architecture that is dedicated to conducting delay-tolerant IoT services in areas with low connectivity and poor infrastructure. The suggested architecture combines LEO satellite access with ground 5G/6G connectivity and allows high availability and efficient communication based on dual-radio IoT nodes, adaptive buffering and cross-layer protocol coordination.

The outcomes of simulation experiments prove the hybrid framework provides an optimal 98.7 per cent data delivery success rate, up to 45 per cent of total delays saved, and an effective performance in the presence of high packet loss and satellite

handovers. These results support the capability of the architecture to narrow down digital divide in areas of significant interest in wildlife monitoring, disaster management and maritime monitoring.
In the future, the main attention will be paid to the scalability and intelligence of the system through:

- The use of machine learning-based link predictors into the path selection module under dynamic link availability.
- The investigation of resource-sensitive edge caching protocols to store data locally and postpone the fusion.
- Performing real-world emulation with the platforms like Starlink or OneWeb, concentrating on the examining of prototype development and end-to-end latency.

The architecture provides a basis of developing the building blocks of resilient, scalable, and intelligent global IoT systems, especially where the ground infrastructure is not adequate or impossibility.

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