Leveraging LEO SatNets To Bridge Digital Divide In Remote Areas Of Pakistan

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Abstract

This research paper explores the integration of satellite networking with cellular networks as a strategic approach to bridge the digital divide and enhance internet accessibility, focusing on Pakistan's case study. We examine the strengths of Low Earth Orbit (LEO) constellations in providing broader coverage and reduced latency, particularly in rural areas, complementing the high bandwidth and efficiency of cellular networks in urban regions. Through data analysis and simulations, we assess the potential of integrated networks to improve connectivity, foster inclusive development, and enhance network resilience.

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1 Introduction

The digital divide is a persistent challenge, particularly in developing nations like Pakistan, where remote and underdeveloped regions often lack adequate internet connectivity. This gap in connectivity is exacerbated by the uneven distribution of cellular coverage, with highly populated areas enjoying robust network access while lower populated areas face significant limitations. To address these challenges and improve internet accessibility across diverse geographical landscapes, the integration of satellite networking with cellular networks has emerged as a strategic solution. Satellite networks, particularly Low Earth Orbit (LEO) constellations like Starlink and Kuiper, have witnessed significant advancements. These constellations comprise thousands of small satellites orbiting at altitudes ranging from 180 to 2,000 kilometers, providing reduced latency and broader coverage. Their unique advantage lies in their ability to reach remote and geographically challenging areas where traditional terrestrial infrastructure is impractical. In rural areas with less obstruction, satellite coverage is ideal, offering redundancy and resilience critical in scenarios like natural disasters.

In densely populated urban areas, cellular networks thrive due to the concentration of users and the economic viability of investing in robust infrastructure. This results in high-speed data transfer, low latency, and seamless connectivity, supporting a wide range of applications and services. Conversely, the sparse population in rural and remote areas presents a different landscape for cellular network providers. The economics of deploying and maintaining extensive infrastructure in these areas, with fewer potential subscribers, often makes it less financially attractive for service providers. As a result, these regions experience coverage gaps and lower-quality connectivity, exacerbating the digital divide and hindering access to essential services and economic opportunities.

Our research focuses on leveraging the strengths of both satellite networks and cellular networks through integration, using Pakistan as a case study. Pakistan's diverse geographical landscape presents unique challenges and opportunities for connectivity solutions. By integrating satellite networking with existing cellular infrastructure, we aim to extend reliable connectivity to under-served regions while improving network performance and fostering inclusive development.

To understand the existing cellular coverage landscape in Pakistan, we utilized the Global System for Mobile Communications Association (GSMA) database, analyzing coverage across different technologies including 2G, 3G, and 4G. Additionally, simulations were conducted using Cosmic Beats to set up satellites and IoT devices in various locations across Pakistan. This approach allowed us to simulate scenarios

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and analyze the potential of satellite networks in bridging connectivity gaps and enhancing internet accessibility.

Through this research, we aim to showcase the potential of satellite networks integrated with cellular networks and addressing the digital divide. By integrating these technologies strategically, we can unlock new possibilities for connectivity in diverse environments, ultimately contributing to inclusive development and improved network resilience.

2 Data Collection

The OpenStreetMap Dataset

To find the optimal number and placement of base stations for satellite and cellular network integration, we curated a dataset containing a comprehensive list of all cities, towns, villages, and hamlets of Pakistan in JSON format. Each object corresponds to a location with attributes like name, latitude, longitude, and province. This dataset, derived from OpenStreetMap through a Selenium script, comprises 1,229,980 objects tagged with different classifications such as *city*, *town*, *village*, and *hamlet*. The JSON format includes details such as:

- **Name**: Name of the settlement.
- **Other Names**: A dictionary of multilingual alternative names for the settlement.
- **Display Name**: The official name and location of the settlement, including the county and state.
- **Address**: Details about the administrative location of the settlement including city, county, state, postal code, and country.
- **Population**: Population counts for the settlement.
- **OSM Type and OSM ID**: The OpenStreetMap object type and ID.
- **Location**: Geographical coordinates (latitude and longitude) pinpointing the settlement.
- **Bounding Box (Bbox)**: Geographical coordinates defining the outer boundaries of the settlement.

Data Manipulation and Cleaning

This dataset was rich in geospatial and administrative information. However, it did not contain the latitude and longitude values for some entries. For this reason, we used the OpenCage Geocoder API to fill in these missing values of latitudes and longitudes using the postal codes for the settlements. Once we completed the dataset with the missing geographical coordinates, we identified further inconsistencies, such as duplicate values being present for the same settlement. For example, two separate OpenStreetMap (OSM) objects are referred to as "Mohalla Islamabad." In such cases, we processed the data to remove duplicates by utilizing a `removeDuplicates` function from the Geoapify API, which helped us retain the entry with the largest geographical area (this was calculated by mapping a reduce function on the absolute difference of Bbox values of all combinations of duplicates), ensuring that only one representation of "Mohalla Islamabad" remained in the dataset while discarding the redundant entry.

Partitioning The Data

We started reducing our dataset, aiming to identify settlements with no or low cellular network coverage. We defined these categories as follows:

- **No Coverage Settlements**: Areas without 2G/3G/4G coverage.
- **Low Coverage Settlements**: Areas with only 2G and 3G coverage available.

To identify these subsets of areas within our dataset, we first refined our dataset by removing towns, villages, and hamlets that were overlapping with cities by computing the Haversine distance of each city with other locations (for instance, remove "Garden Town" since it is inside the city of Lahore). After refining the dataset, we scraped all locations from Zong and Ufone's publicly available coverage maps. We computed a union to retrieve a list of locations where the cellular networks provided signal strengths in the 2G and 3G range. Another list was similarly computed for signal strengths above 3G, and these locations were removed from our dataset. Using these lists, we partitioned our dataset to retrieve low coverage areas and no coverage areas, the latter by simply computing a set difference.

To further refine our data and guarantee its robustness, we plotted both datasets geographically using ipyleaflet (a Jupyter widget for Leaflet.js, enabling interactive maps in the Jupyter notebook). We overlaid our map on network coverage maps provided by GSMA for other network operators (such as Telenor and PTCL) and manually removed any remaining overlaps. Finally, we further partitioned both datasets based on state boundaries to retrieve no and low coverage areas for each of the six states (Azad Kashmir, Punjab, Sindh, Balochistan, Gilgit Baltistan, and Khyber Pakhtunkhwa).

3 Simulation Platform

In our pursuit to investigate the integration of satellite and cellular networks, a crucial aspect of our research involved finding a suitable simulation platform where we could run experiments and measure satellite performance across various areas. After extensive evaluation of various simulation environments, encompassing tools such as StarryNet and Cosmic Beats[Microsoft], we decided to opt for Cosmic Beats due to its easy setup and its capacity to conduct intricate simulations about satellite networks.

3.1 Understanding Cosmic Beats

Once we decided upon Cosmic Beats, we had to extensively study the whole platform in order to learn how it works and the different components and parameters present in it. Cosmic Beats stands as a sophisticated simulation platform

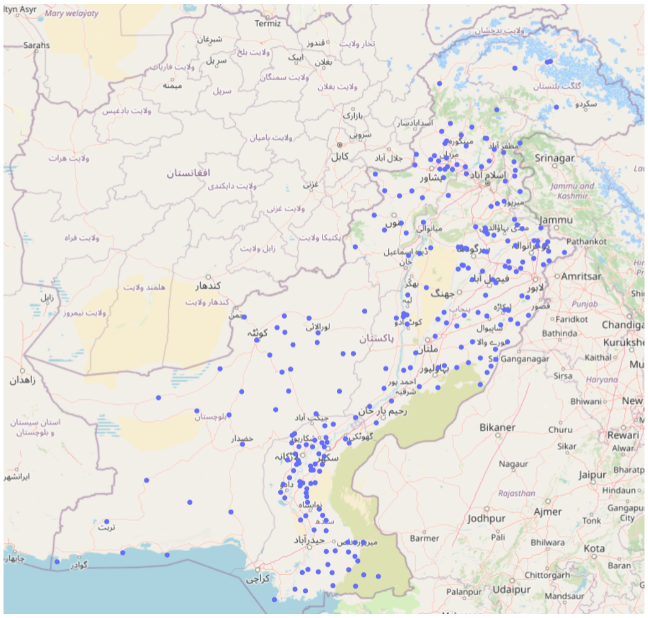

Figure 1. No Coverage Map

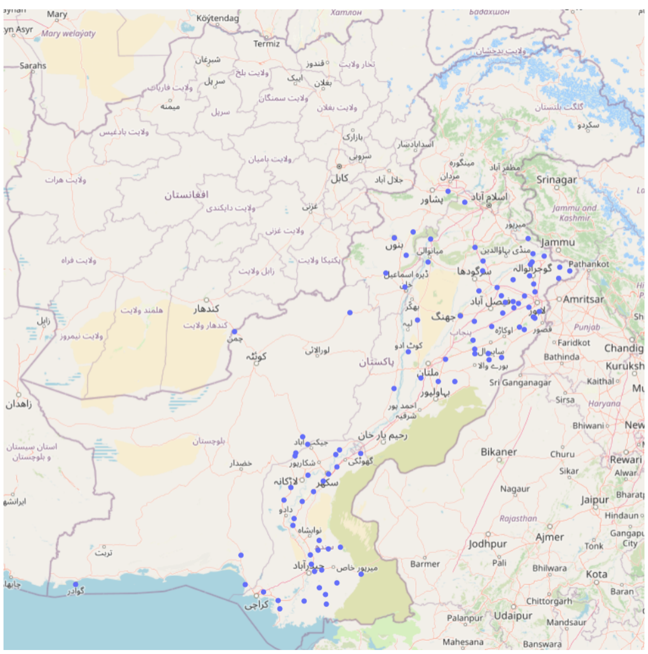

Figure 2. Low Coverage Map

created to replicate the complex interactions among internet devices, satellites, and ground stations within a controlled virtual environment.

The core functionality of the environments simulated within Cosmic Beats is the data transmission process, where internet devices communicate with orbiting satellites that subsequently transmit data to ground stations for further processing and dissemination. The platform encapsulates a range of different parameters that affect the performance of the simulation, ranging from packet generation rates and temporal considerations like time of day to environmental factors such as solar interference and the dynamic orbital trajectories of satellites(Microsoft).

4 Experimental Design and Execution

Armed with a comprehensive understanding of Cosmic Beats' capabilities, we started the experimental stage of our work. Our experimental design was structured into two sequential stages. Initially, we conducted a series of experiments within the province of Sindh. This region was strategically chosen due to its high population density, coupled with areas of proximity and poor cellular coverage. These circumstances made for a perfect testing ground for assessing satellite performance in crowded regions with poor terrestrial connection. These experiments involved the strategic placement of ground stations across various locations, followed by an assessment of how the satellite performed.

Subsequently, we transitioned to the next stage of our experiment, focusing on the province of Balochistan. Contrary to Sindh, Balochistan has a low population density and large areas, offering a stark contrast in geographical characteristics. This choice allowed us to explore satellite performance in regions with sparse populations, thus providing a comprehensive understanding of satellite-network integration dynamics across diverse environments.

In order to simulate a satellite network over the no coverage areas of Sindh, we leveraged real-world satellite data from Starlink, boasting a constellation of approximately 6700 satellites. Now that we had the satellite data, we tried four different approaches where we changed the locations of ground stations in Sindh and Balochistan and then measured the satellite performance.

4.1 Random Placement

In the first phase, we randomly deployed two ground stations across Sindh and Balochistan and conducted simulations to evaluate network performance under these conditions, with particular emphasis on key performance indicators such as latency and packet loss rate.

4.2 Strategic Placement of Ground Stations

Transitioning from the randomized deployment approach, we adopted a staged methodology aimed at progressively increasing the density of ground stations throughout the area. Through a series of four sequential experiments, we systematically increased the number of ground stations, starting from a single station and iteratively introducing additional nodes. We thoroughly examined the satellite performance following each evaluation, providing insightful analysis of network scalability and coverage optimization tactics.

Table 1. Results of Simulations in Sindh

Experiment Type	Packet Loss	Latency
Random Placement	0.6	275.5
Strategic Placement of 1 GS	0.8	400
Strategic Placement of 2 GS	0.25	318.6
Strategic Placement of 3 GS	0.75	315
Strategic Placement of 4 GS	0.85	155
Corners Square Pattern	0.71	288.5
Triangular Pattern 1	0.33	247.5
Triangular Pattern 2	0.83	228
Triangular Pattern 3	0.5	190

Table 2. Results of Simulations in Balochistan

Experiment Type	Packet Loss	Latency
Random Placement	0.3	249.5
Corners Square Pattern	0.3	279.5
Triangular Pattern 1	0.0	169
Triangular Pattern 2	0.5	143

4.3 Triangular Pattern

In the third stage of our study, we deliberately positioned three ground stations in a triangle to examine the effect of spatial arrangement on network performance. We investigated the impact of spatial arrangement on key performance measures by methodically altering the orientation of this triangle across a number of iterations to see whether or not performance increased by shifting the positions.

4.4 Corner Square Pattern

After completing our study of Sindh and Balochistan's topography, we put our planned placement approach into practice by arranging ground stations in a square configuration around the region's four corners. This concluded this phase of our research and gave us important new information on how shifting ground station locations impacts satellite network performance.

5 Results and Analysis

In this section, we present the results and analysis derived from our diverse experimentation. Through a methodical investigation of network performance indicators, including latency and packet loss, across a range of scenarios, we aimed to uncover fundamental ideas that enable successful ground station deployment strategies in satellite-based communication networks.

The initial experiments were conducted with a random placement strategy for ground stations across Sindh and Balochistan, serving as the baseline for subsequent analyses. Under this configuration, the network exhibited a packet loss rate of 0.6 and a latency of 275.5 milliseconds for Sindh and a packet loss rate of 0.3 and a latency of 279.5 milliseconds for Balochistan. This baseline scenario provided a benchmark against which the performance of strategic placement strategies could be evaluated.

Transitioning from random placement, we moved on to position ground stations across Sindh and Balochistan, aiming to optimize network performance. For only one ground station ground station, the satellite network exhibited a higher packet loss rate and latency. However, with the subsequent addition of more ground stations, notable improvements were observed, like the latency in Sindh went from 400 to 155 milliseconds.

Interestingly, different results were obtained when a corner placement method was implemented. Certain configurations obtained reduced latency values with three ground stations deployed in a triangular arrangement across Sindh, confirming the significance of ground station location. However, even with four ground stations, elevated latency persisted in certain configurations, highlighting the complex impact of ground station placement on network performance.

5.1 Analysis

Our research shows interesting patterns in ground station placement tactics and how they affect satellite-enabled communication systems' network performance. We found that network metrics- especially latency- consistently improved when we switched from random to strategic placement. Interestingly, the addition of every ground station placed strategically led to a gradual decrease in latency, demonstrating the effectiveness of focused deployment in improving network performance. Moreover, a notable decrease in latency was seen upon the addition of a fourth ground station, indicating the existence of ideal placement arrangements that optimize satellite coverage and reduce signal propagation delays. This emphasizes how crucial it is to carry out more research on the spatial distribution of ground stations in order to pinpoint high-satellite traffic areas and reduce hotspots associated with delay. Additionally, our analysis of corner placement strategies shows the complex relationship between ground station positioning and network performance, with certain configurations exhibiting lower latency values compared to others. This emphasizes the critical role of spatial arrangement in optimizing network efficiency and highlights the need for strategic deployment strategies tailored to specific geographical contexts. In essence, our findings underscore the importance of strategic ground station placement in mitigating latency and optimizing network performance in satellite-enabled communication systems, offering valuable insights for network design and deployment in real-world scenarios.

Furthermore, our investigation of corner placement tactics highlights the complex correlation between ground station location and network performance, with certain configurations showing lower latency values than others. This shows the necessity of strategic deployment tactics adapted to particular geographic situations and emphasizes the crucial role that spatial organization plays in optimizing network efficiency.

6 Related Works

- Liu et al. (2021) highlighted the potential of Low Earth Orbit (LEO) satellite constellations in bridging the digital divide, particularly in remote rural areas. Their work emphasized the need for focused efforts on integrating LEO satellites with terrestrial networks to achieve comprehensive internet accessibility.
- Wittig (2009) contributed to the discourse by framing the global initiative for digital inclusion, advocating for fast internet access for the unconnected population. This perspective underscores the strategic importance of synergizing SatNets and CellNets to achieve ubiquitous global connectivity.
- Darwish et al. (2021) explored the integration of LEO SatNets, such as Starlink and Kuiper, with emerging 5G and 6G technologies. Their research delved into standardization efforts within 3GPP, focusing on areas like New Radio (NR) impacts and management orchestration to ensure seamless global connectivity.
- Garrity & Husar (2021) provided insights into the significance of integrated satellite-terrestrial network architectures for connecting underserved populations, especially in small island developing states and landlocked developing countries in Asia and the Pacific. Their work underscored the critical role of such integration in extending reliable internet access to diverse regions.
- Charbit et al. (2021) examined the implications of integration on IoT applications, highlighting the diverse distribution of IoT devices compared to human populations. This perspective is crucial for understanding the broader impact of SatNets and CellNets integration beyond traditional connectivity paradigms.
- Zhang et al. (2020) contributed to the discourse on 6G wireless architectures, emphasizing the potential synergies between satellite and cellular networks. Their work focused on leveraging advancements in multiaccess edge computing (MEC) and artificial intelligence (AI) to create more intelligent and efficient network ecosystems.

7 Future Works

The purpose of this paper is to suggest a direction to work towards enabling rural areas of developing countries to become as connected to the world as the urban areas, which welcomes many interesting avenues that warrant further research. In terms of further improving the results we have achieved, exploring newer technologies like beamforming and MIMO (Multiple Input Multiple Output) in satellite systems can help us achieve better speeds and latencies (Fairhurst, Collini-Nocker, Caviglione, 2008). However, it is imperative to note that such explorations must be cognizant of a practical integration of satellite networks in developing regions which would merit serious cost considerations as well as policy development that can help facilitate the deployment of hybrid network infrastructures (Wang et al., 2023). In a similar vein, future works must also investigate optimizing the positioning of base stations with respect to topographical constraints, especially since areas with challenging terrains can increase installation costs to a great extent. One way this can be achieved is through the use of more sophisticated optimization algorithms such as genetic algorithms or other heuristic methods to find the best locations for base stations that minimize costs while maximizing coverage and service quality in rural areas (Li, Xiu, Yang, 2022). Other suggestions may also involve the implementation of Multipath TCP (MPTCP) to leverage both terrestrial and satellite links, enhancing data throughput and reliability, especially from a handover management standpoint (Xu Ai, 2021).

8 Conclusion

With our data collection and simulations we see the potential of LEO satellite networks within remote areas of Pakistan. Comparing our results with cellular networks performance from PTA's data, we see how the satellite networks are way ahead of the normal average latencies of 3G networks and slightly lower than 4g cell networks in Pakistan(PTA) and so this could potentially lead to bridging the digital divide. Even with slightly lower speeds with future research regarding ground station placement there is potential for satellites to be on par with 4G networks of Pakistan. Also with clear satellite network potential, research pathways open to explore multipath protocols and handover management in order to fully integrate the 2 networks to provide strong Internet coverage across Pakistan.

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