Evaluating India’s 5G Rollout and Performance

R&D-I Project Report

by

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Abstract

The rollout of 5G in India since October 2022 has marked a pivotal shift in telecommunications, bringing enhanced data speeds, lower latency, and improved network reliability. This study examines deployment strategies by major operators, highlighting the predominance of mid-band frequencies and Non-Standalone (NSA) architectures, alongside the gradual shift to Standalone (SA) networks for enhanced performance. Using tools such as MobileInsight and NDT7, a range of network parameters, including signal strength, throughput, latency, and MIMO configurations, were systematically measured and analyzed. The findings reveal the critical influence of signal quality, carrier frequency, and deployment modes on user experience, with marked variations across operators. This research provides valuable insights into optimizing 5G networks, improving quality of experience, and addressing challenges in achieving consistent and widespread coverage in the Indian telecommunications landscape.

Contents

1 Introduction

The widespread commercial deployment of Fifth Generation (5G) networks represents a pivotal advancement in telecommunications, promising to revolutionize connectivity with unprecedented data rates, ultra-low latency, and enhanced network reliability. In India, 5G was officially launched in October 2022, marking a transformative milestone in the country's digital infrastructure. Since then, the telecommunications sector has witnessed rapid adoption of 5G technology, led by major service providers such as Reliance Jio, Bharti Airtel, Vodafone Idea (Vi), and recently Bharat Sanchar Nigam Limited (BSNL). By late 2024, substantial progress has been made, with 5G services operational across major urban centers and plans underway for nationwide coverage.

1.1 Measuring 5G

The motivation for measuring 5G performance lies in addressing research questions such as:

- What are the primary factors that influence network performance and user experience in real-world 5G deployments?
- To what extent can performance metrics help identify bottlenecks and guide optimization strategies for enhanced QoE?
- How can data-driven analysis aid in predicting network performance under varying conditions?

These questions guide the methodology and scope of our performance measurements Insights gained from these analyses would enable optimization of network performance and guide the development of applications that are aware of 5G capabilities.

Measuring the performance of a 5G network requires capturing a wide range of parameters that influence the User Equipment's (UE) network experience. Network performance can be affected by a variety of factors, which can be categorized into two main types:

- **Operator-specific configurations:** These parameters typically remain stable over time and include factors like the operating frequency band, channel bandwidth, subcarrier spacing (SCS), and duplexing mode (either Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD)).
- **Connection/UE-specific parameters:** These variables can change dynamically based on the UE's location, the received signal strength, network workload, and other factors. They include elements like MIMO layers and Modulation and Coding Scheme (MCS), which directly impact the performance and efficiency of the connection.

1.2 5G Deployment

3GPP specifications [1] define the operation of 5G New Radio (NR) across two distinct frequency ranges:

- **Frequency Range 1 (FR1):** includes low-band (below 1GHz) and mid-band (1 - 6GHz) frequencies
- **Frequency Range 2 (FR2):** comprises high-band millimeter-wave (mmWave) frequencies (above 24GHz)

While mmWave offers greater bandwidth, its adoption has been limited due to challenges like short coverage range, sensitivity to obstructions, and erratic throughput [7]. As of January 2023, only 7% of global 5G deployments were in FR2, according to GSMA Intelligence [5]. Low-band deployment has also been constrained by the limited availability of spectrum, as it is already heavily used for 4G services. Consequently, mid-band frequencies have emerged as the primary choice for deployments in India, aligning with global trends.

5G networks can be deployed in two different modes:

- **Standalone (SA):** Utilizes cloud-native 5G Core and 5G Radio Architecture, offering enhanced performance and ultra-reliable low latency communication (URLLC)
- **Non-Standalone (NSA):** Leverages the 4G LTE Core (Evolved Packet Core or EPC), enabling cost-effective deployment by building on existing 4G infrastructure

Jio has adopted SA deployment, while Airtel and Vi primarily use NSA. However, Airtel is actively transitioning toward SA to enhance its network capabilities.

1.3 PHY Throughput

According to 3GPP standards, the maximum achievable physical layer (PHY) throughput [3] (in Mbps) can be calculated using the following formula:

$$10^{-6} \cdot \sum_{j=1}^{J} \left\{ v_{layers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{max} \cdot \frac{N_{RB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} \cdot \left(1 - OH^{(j)}\right) \right\}$$

where J is the number of aggregated component carriers during CA, and for each j:

$v_{layers}^{(j)}$	Maximum number of MIMO layers
$Q_m^{(j)}$	Modulation order
R_{max}	Code rate
$f^{(j)}$	Scaling factor
μ	Value of carrier configuration ($\mu(i)$ = SCS)
$T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$	Average OFDM symbol duration in a subframe for SCS μ
$N_{RB}^{BW(j),\mu}$	Maximum Resource Block (RB) allocation for a channel with bandwidth $BW(j)$ and SCS μ
$OH^{(j)}$	Overhead for control channels

1.4 Tools

To understand user QoE, various network and application-layer metrics can be measured:

- **Network Throughput:** Directly affects user experience by determining data transfer speed. High throughput ensures faster downloads/uploads and better performance for data-intensive tasks like video streaming. Tools like `ndt7` (M-Lab) and `speedtest` (Ookla) provide download and upload speed measurements. Alternatively, `iperf` can be used for custom server-based speedtests
- **Latency (RTT):** Indicates the responsiveness of the network. Lower latency is crucial for real-time applications. `ping` is commonly used to measure round-trip time (RTT)
- **Video Bitrate/Buffer:** Reflects the perceived QoE during video streaming, a dominant use case for internet services. Video streaming apps like YouTube usually have a stats feature that exposes these metrics, providing insights into the streaming performance

In contrast, measuring physical-layer metrics is more complex, as device manufacturers often restrict access. However, Qualcomm-based Android devices and USB modems support the **DIAG** protocol, which allows developers to access low-level metrics. Devices in Diagnostic Monitor (DM) mode expose metrics through:

- `/dev/diag` (virtual device on Android phones via the `diagchar` kernel module)
- `/dev/ttyUSB*` or `/dev/ttyHSO*` (USB pseudo-serial ports for external devices)

Several tools simplify the parsing and logging of physical-layer metrics using the **DIAG** protocol:

- **MobileInsight** developed by reseachers at UCLA and Purdue
- **GNetTrack** developed by Gyokob Solutions
- **Network Signal Guru (NSG)** developed by Qtrun Technologies
- **XCAL** developed by Accuver

2 Literature Review

2.1 Performance of Cellular Networks on the Wheels

Ghoshal et al. [4] conducted a comprehensive measurement study of 5G networks under driving conditions across the US, covering over 5700 km. The study analyzed network coverage, throughput, latency, and application QoE across Verizon, T-Mobile, and AT&T, with a focus on the unique challenges posed by mobility.

2.1.1 Methodology

- **Measurement Setup:** Smartphones (Samsung S21) were connected to cellular networks via low-band, mid-band, or mmWave services. Accuver XCAL Solo devices logged low-level network KPIs, while AWS EC2 and Amazon Wavelength edge servers were used for end-to-end performance testing.
- **Data Collection:** Throughput and RTT were measured through TCP bulk data transfers and ICMP ping tests. Application QoE was assessed using 360° video streaming, cloud gaming, AR, and CAV apps. GPS and cellular data were logged for geolocation analysis.
- **Handover and Synchronization:** Handover events were tracked using custom Android apps and synchronized with network performance data to assess their impact on throughput.
- **Testing Procedure:** Tests were conducted across urban, suburban, and highway environments, with backlogged traffic in both directions to ensure consistent 5G connectivity.

2.1.2 Coverage Analysis

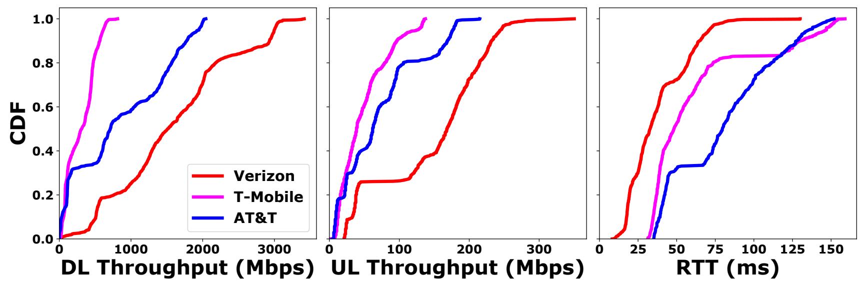
5G coverage was found to be fragmented, with significant differences across operators:

- **T-Mobile:** Achieved the highest overall 5G coverage (68%) due to extensive mid-band deployments.
- **Verizon and AT&T:** Limited to 18 - 22% 5G coverage, with sparse high-speed mmWave connectivity concentrated in urban areas.

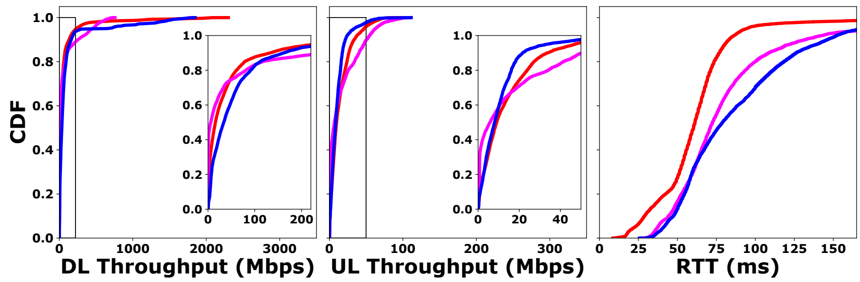
Coverage also varied geographically, with T-Mobile maintaining relatively higher mid-band coverage on highways, while Verizon and AT&T prioritized urban deployments.

2.1.3 Network Performance

The study revealed significant variability in throughput and latency during driving:



(a) Static Measurements



(b) Driving Measurements

Figure 2.1: Throughput and RTT performance during static and driving conditions

- **Throughput:** Downlink speeds exceeded 1 Gbps in ideal conditions (mmWave) but fell below 5 Mbps 35% of the time. T-Mobile's mid-band 5G offered relatively stable performance compared to Verizon and AT&T.
- **RTT:** Median RTTs ranged between 60 - 76 ms while driving, with occasional spikes exceeding 2 seconds.

Figure 2.1 compares the cumulative throughput and rtt distributions for static and driving scenarios.

2.1.4 Handover Behavior

Handover rates were modest, with a median of 1 - 3 handovers per mile. Most handovers were short (median duration: 61 ms) and caused only minor throughput drops, often offset by post-handover performance gains.

2.1.5 Application QoE

Latency-sensitive applications like cloud gaming and augmented reality (AR) were heavily impacted by throughput variability and increased RTTs during driving. While edge servers improved both metrics, QoE remained inconsistent.

2.1.6 Conclusion

This study emphasizes the challenges of achieving reliable 5G performance under mobility, underscoring the need for enhanced mid-band and mmWave deployments, robust handover mechanisms, and adaptive applications to mitigate performance variability.

2.2 Unveiling the 5G Mid-Band Landscape

This study by Fezeu et al. [6], provides a comprehensive analysis of mid-band 5G networks across Europe and the United States. This work represents the first large-scale cross-continental measurement campaign focusing on 5G mid-band performance, with critical insights into network configurations, physical layer (PHY) performance, and application Quality of Experience (QoE).

2.2.1 Methodology

The study evaluated mid-band 5G performance across the US and four European countries (France, Germany, Italy, Spain) using a cross-continental measurement campaign.

- **Measurement Setup:** Smartphones (Samsung S21) were connected to cellular networks via low-band, mid-band, or mmWave services. Accuver XCAL Solo devices logged low-level network KPIs, while AWS EC2 and Amazon Wavelength edge servers were used for end-to-end performance testing
- **Data Collection:** Key network parameters such as channel bandwidth, MIMO layers, modulation schemes, and resource blocks were measured, along with throughput (DL/UL), latency, and application QoE using TCP and ICMP tests
- **Testing Procedure:** Tests were performed in diverse environments (urban, suburban, highway) to simulate real-world conditions, including mobility scenarios.

2.2.2 Deployment and Configuration Insights

The paper highlights significant differences between European and US 5G deployments. European operators predominantly use the n78 band with uniform channel bandwidths of up to 100 MHz. In contrast, US operators rely on fragmented spectrum in the C-band, compensated by Carrier Aggregation (CA), combining multiple channels to achieve higher aggregate bandwidths. Table 2.1 summarizes key operator configurations.

Country	**Spain**			**France**		**Italy**	**Germany**		**Germany**			
Acronym	O_{Sp}		V_{Sp}	O_{Fr}	S_{Fr}	V_{It}	T_{Ge}	V_{Ge}	Tmb		Vzw	Att
SCS (kHz)	30								15	30		
Duplexing Mode	TDD								FDD	TDD		
5G NR Band	n78								n25	n41	n77	n77
Channel Bandwidth (MHz)	100	90	90	90	80	80	90	80	20 + 5	100 + 40	60	40
Max Bandwidth (N_{RBs})	273	245	245	245	217	217	245	217	51 + 11	273 + 106	162	106
Carrier Aggregation	No								Mid + Mid		Mid + Low	Mid + Mid

Table 2.1: Operator Network Configurations

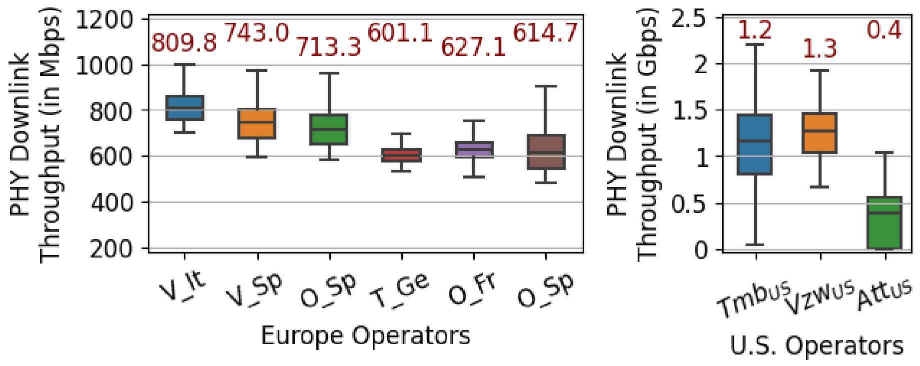


Figure 2.2: Download Throughput of EU and US Operators

2.2.3 Performance and Variability Analysis

Mid-band 5G achieves peak downlink throughput exceeding 1 Gbps, with significantly lower variability compared to mmWave 5G. However, throughput is influenced by factors such as channel bandwidth, MCS (Modulation and Coding Scheme), and MIMO (Multiple-Input Multiple-Output) layers. Figure 2.2 provides an overview of download throughput trends across European and US operators.

- **European Operators:** Vodafone Spain outperforms Orange Spain, despite a narrower 90 MHz bandwidth, due to better MCS utilization and higher consistency in 4x4 MIMO layers.
- **US Operators:** T-Mobile's use of CA enables aggregate channel bandwidths exceeding 100 MHz, supporting higher throughput.

2.2.4 Impact on QoE for Applications

The study examines video streaming as a case study, demonstrating that PHY throughput variability directly affects QoE. Applications experience higher stall times and bitrate fluctuations under conditions of frequent channel reconfigurations. Figure 2.3 illustrates this relationship.

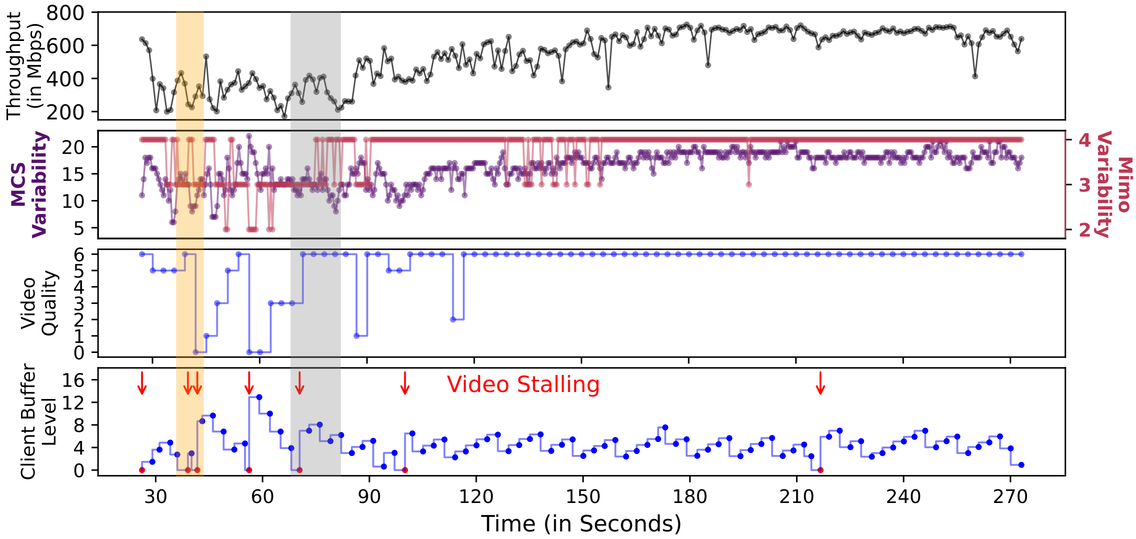


Figure 2.3: Impact of Throughput Variability on QoE

2.2.5 Conclusions

The study concludes that improving performance consistency is more critical than maximizing peak throughput. Operators should focus on enhancing coverage, reducing channel variability, and adopting advanced resource management strategies. For applications, designing adaptive algorithms that respond to real-time network variability is key to improving QoE, particularly for bandwidth-intensive services like video streaming.

2.3 Research Questions

While significant research has been conducted on 5G performance in regions like the US and EU, India's 5G network is still in its early stages, with limited exploration. This raises several key questions:

- **How do Indian operators compare to global counterparts?**
  Given the varying deployment strategies and configurations, comparing Indian operators (Airtel, Jio) to each other and to global operators could provide valuable insights into performance and user experience (QoE).

- **What parameters predict PHY throughput?**
  Identifying critical metrics for accurately predicting physical-layer throughput would enhance network planning and optimization efforts.

- **How is PHY throughput linked to application-layer performance?**
  Understanding how predicted PHY throughput correlates with metrics like video bitrate and buffering could improve QoE models. What additional factors influence this relationship?

- **What impact does mobility have on performance?**
  Given India's unique mobility conditions (e.g., road infrastructure and traffic patterns), understanding its effects on 5G performance and reliability is crucial.

- **How does network congestion affect performance?**
  Investigating how Indian operators manage congestion, particularly during peak traffic, and its impact on throughput and latency will help optimize network strategies.

- **How do regional differences impact 5G performance in India?**
  Exploring how factors such as geographic diversity, population density and infrastructure quality influence network coverage, signal strength, and overall performance across different regions of India.

3 Our Methodology

Our methodology revolves around designing an integrated system to log diverse metrics and automate data collection using a centralized orchestration tool. This approach ensures consistency and efficiency in gathering data from various services and tools.

3.1 MobileInsight

MobileInsight, being free and open-source, became our choice for collecting physical (PHY) layer metrics. Internally, MobileInsight utilizes a C library to read data from a serial port (in this case, `/dev/ttyUSB*`) at a specified baud rate (typically 9600). The parsed signals are structured into packets containing PHY layer metrics. The Python wrapper can then be used to log the packets in user-friendly formats like JSON or XML, or even build custom analyzers.

The format of log packets varies by phone manufacturer and region, requiring parser adjustments. We modified the parser for the `NR_ML1_Search_Meas_Database_Update` packets, which provides:

- **MIMO Layers:** Number of active **MIMO** layers
- **Carrier Aggregation:** Number of carriers
- **Cell Information:** Number of cells, serving cell, and corresponding **RSRP** and **RSRQ** (signal strength) values for each cell
- **Absolute Radio-Frequency Channel Number (ARFCN):** Index number mapped to **Carrier Frequency** and **SCS**

MobileInsight requires several dependencies, including Wireshark, and is compatible with specific (older) software versions. Initial testing was conducted on an Ubuntu 20 virtual machine (VM), the officially supported environment. To enhance portability and ease of use, we containerized MobileInsight using Docker, ensuring a consistent setup.

3.2 NDT7

For network throughput testing, we chose NDT7. The official `ndt7-client-go` is open-source and can be compiled for Android devices using the Go compiler and the Android Native Development Kit (NDK). The tool measures download/upload speeds and latency to a nearest NDT7 server.

3.3 TPing

To collect precise round-trip time (RTT) samples, we developed a custom tool, `tping`, in Rust. This tool sends ICMP echo requests and logs RTT values along with precise UNIX timestamps for each sample.

3.4 Geolocation

For geolocation, we chose the Automate app, which allows users to set up flows that can be triggered via Android Intents. We created a flow to collect geolocation information such as latitude, longitude, and altitude, at regular intervals using Android APIs and store them in a local file on the device.

3.5 Collector

The main orchestration tool, `collector`, was developed to automate and coordinate data collection across tools. It uses Unix timestamps with microsecond accuracy to align metrics from different tools for precise analysis. It operates using four concurrent goroutines:

- *GeoRoutine:* Manages the Automate flow, including starting and stopping it, and transfers log file `geo-{timestamp}.log`
- *PhyRoutine:* Runs MobileInsight logger, storing results in `phy-{timestamp}.log`
- *PingRoutine:* Runs `tping`, storing results in `ping-{timestamp}.csv`
- *SpeedtestRoutine:* Runs `ndt7-client` at regular intervals, parses output, and logs download/upload throughput and latency in `speedtest-{timestamp}.csv`

Upon receiving a stop signal, `collector` gracefully halts all routines and exits. Like MobileInsight, `collector` was also containerized for portability and ease of deployment.

3.6 Setup

We chose the OnePlus 11R 5G for its Snapdragon 8+ Gen 1 chipset and high-performance hardware, ensuring it can handle demanding tasks. Its excellent rooting support, combined with the Qualcomm chipset, made it ideal to use DM mode.

We unlocked the bootloader, and rooted the device using Magisk, then DM mode was activated with the following command:

```
adb shell su -c setprop sys.usb.config diag,adb
```

To connect to 5G network, we used Jio and Airtel SIM cards with unlimited 5G plans, ensuring consistent access to 5G services during testing.

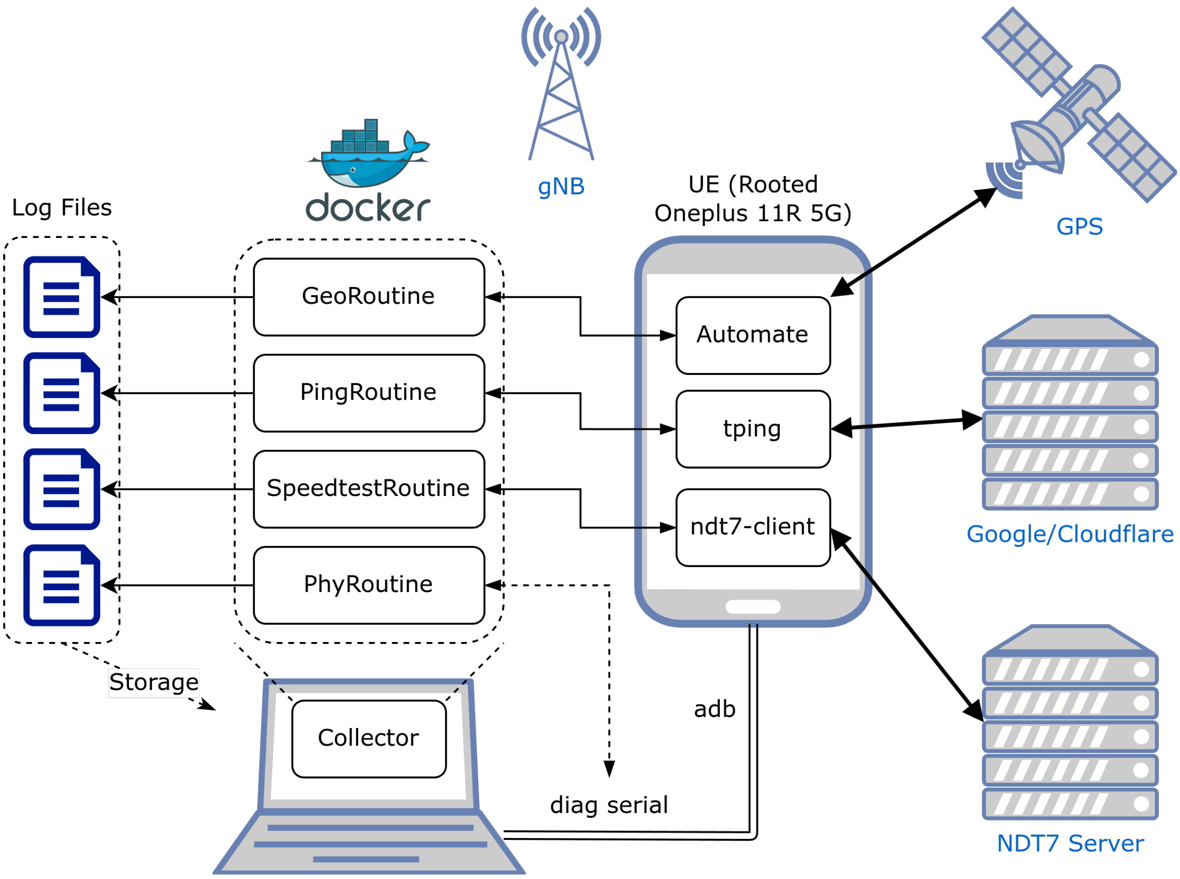


Figure 3.1: Collector Architecture & Setup

4 Results

4.1 Signal Strength vs Throughput

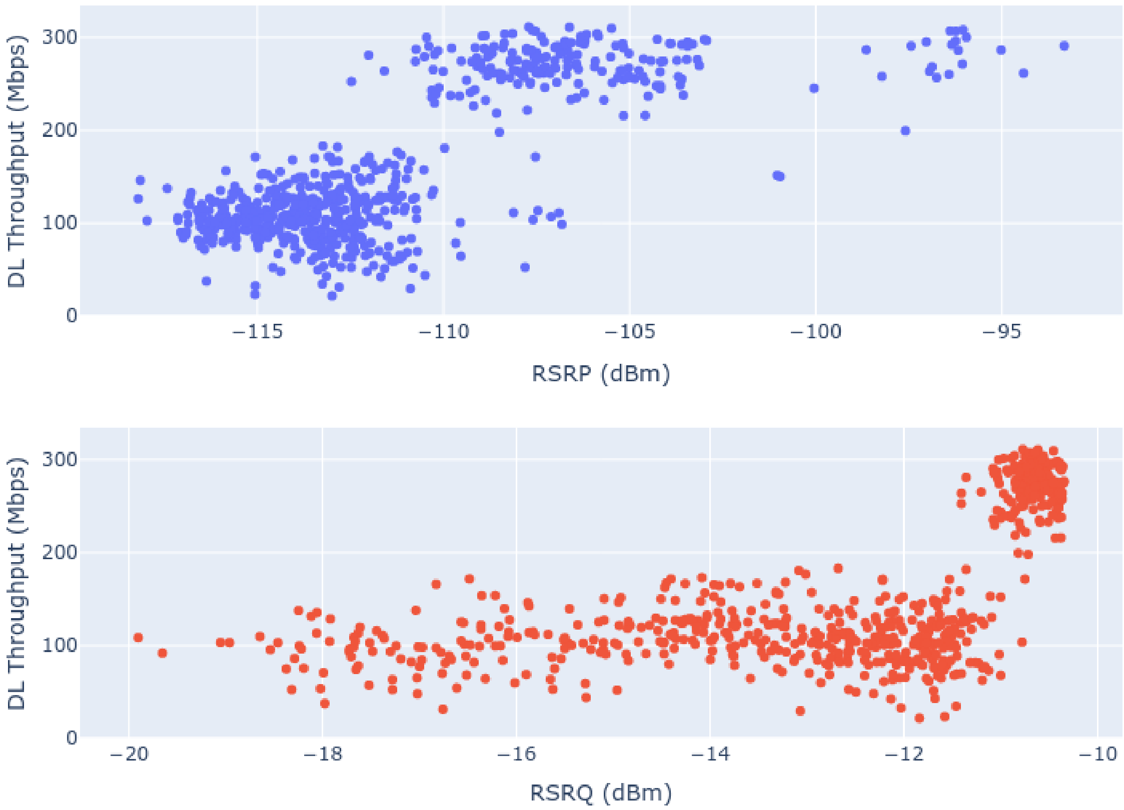


Figure 4.1: Impact of Signal Strength on Download Throughput

Observation (Fig 4.1): Throughput is clearly influenced by signal strength. When $RSRP \geq -110$ and $RSRQ \geq -11$, the throughput is significantly higher (above 200 Mbps) compared to when $RSRP < -110$ and $RSRQ < -11$, where the throughput drops below 200 Mbps.

Signal strength impacts throughput in several ways, one of which is the number of MIMO layers available to the User Equipment (UE).

Observation (Fig 4.2 & 4.3): Two MIMO layers are available only when the signal strength is good, i.e., $RSRP > -105$ and $RSRQ > -12$. With more MIMO layers, throughput improves significantly, with much less variability.

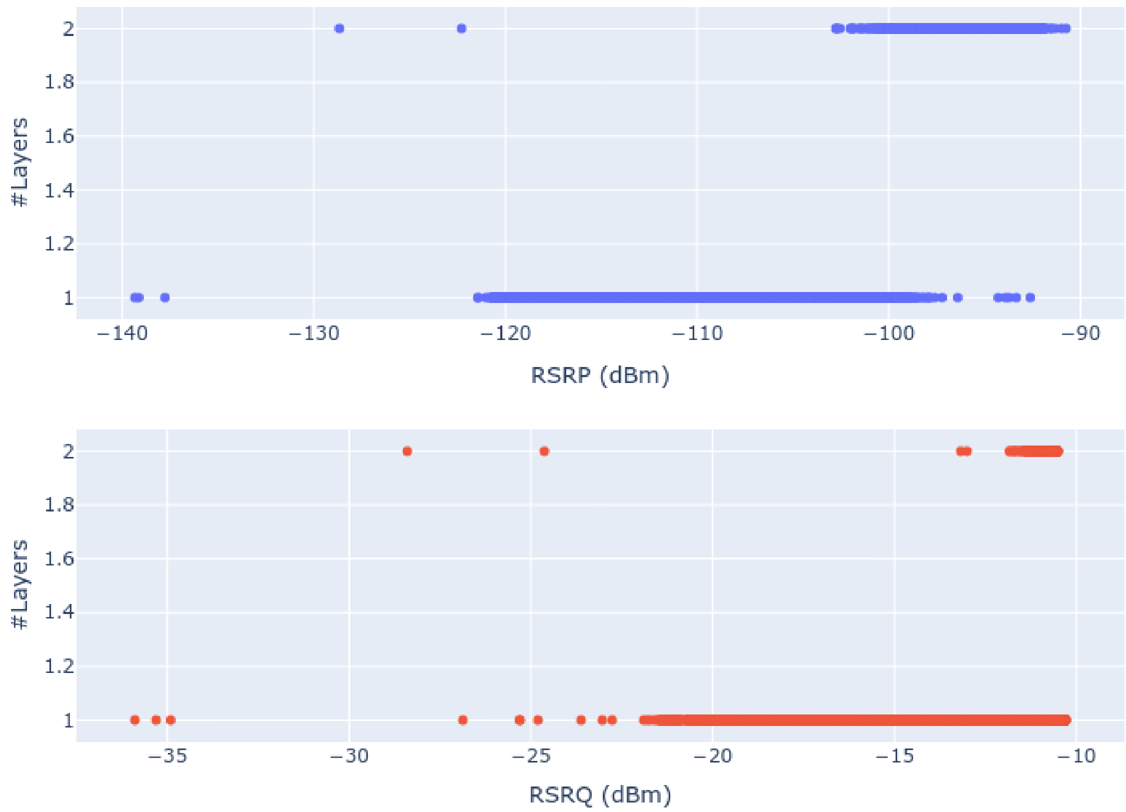


Figure 4.2: Impact of Signal Strength on MIMO Layer Availability

4.2 ARFCN vs Throughput

Observations:

- **n28 vs n78:** Airtel shows better throughput on the lower n28 band due to less signal attenuation and the use of Frequency Division Duplex (FDD), which allows continuous uplink and downlink transmission. In contrast, n78 uses Time Division Duplex (TDD), which has dynamic slot allocation, leading to more variability in throughput
- **Jio vs Airtel (Download):** Jio outperforms Airtel on n78 download throughput, likely due to its use of Standalone (SA) mode, which offers better performance compared to Airtel's Non-Standalone (NSA) mode
- **Jio vs Airtel (Upload):** Airtel has significantly better upload throughput, particularly on the n28 band, likely due to the continuous use of uplink and downlink channels in FDD, compared to TDD used by Jio

ARFCN	Duplexing	NR Band	SCS	Operator
156750	FDD	n28 (758 - 803 MHz)	15KHz	Airtel
625592	TDD	n78 (3300 - 3800 MHz)	30KHz	Airtel
634080	TDD	n78 (3300 - 3800 MHz)	30KHz	Jio

Table 4.1: ARFCN Map [2]

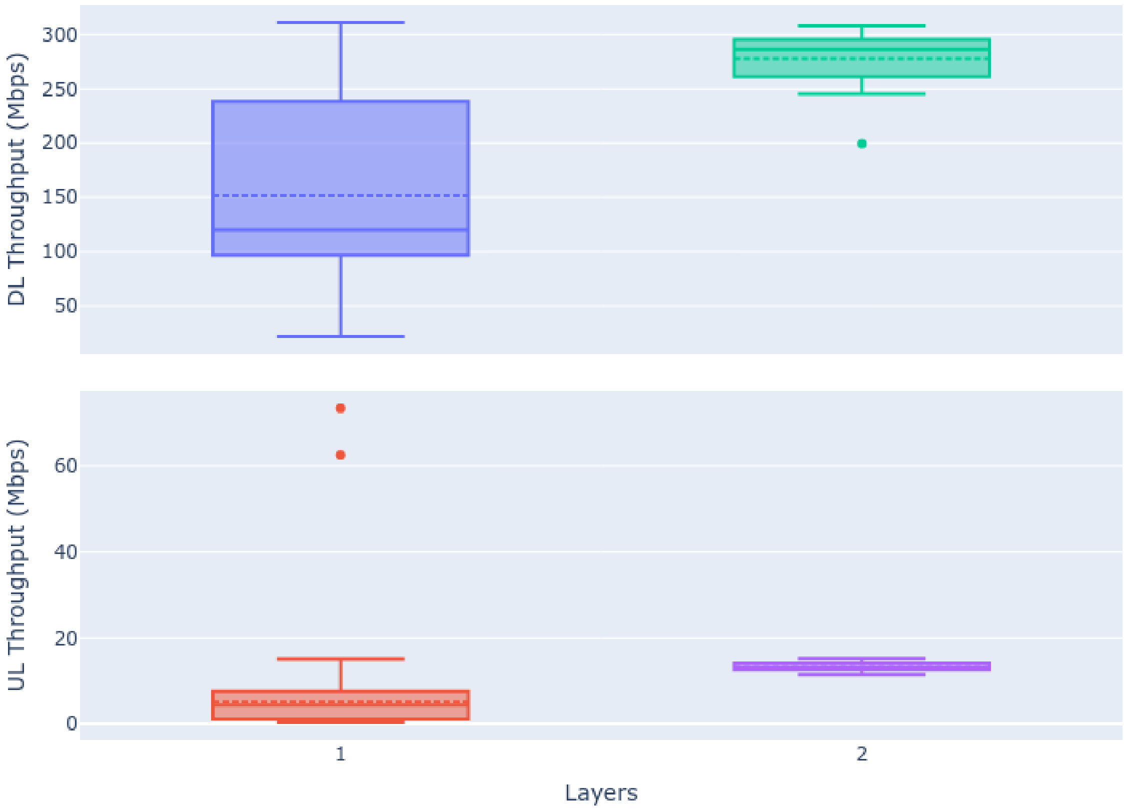


Figure 4.3: Throughput Variation with Increasing MIMO Layers

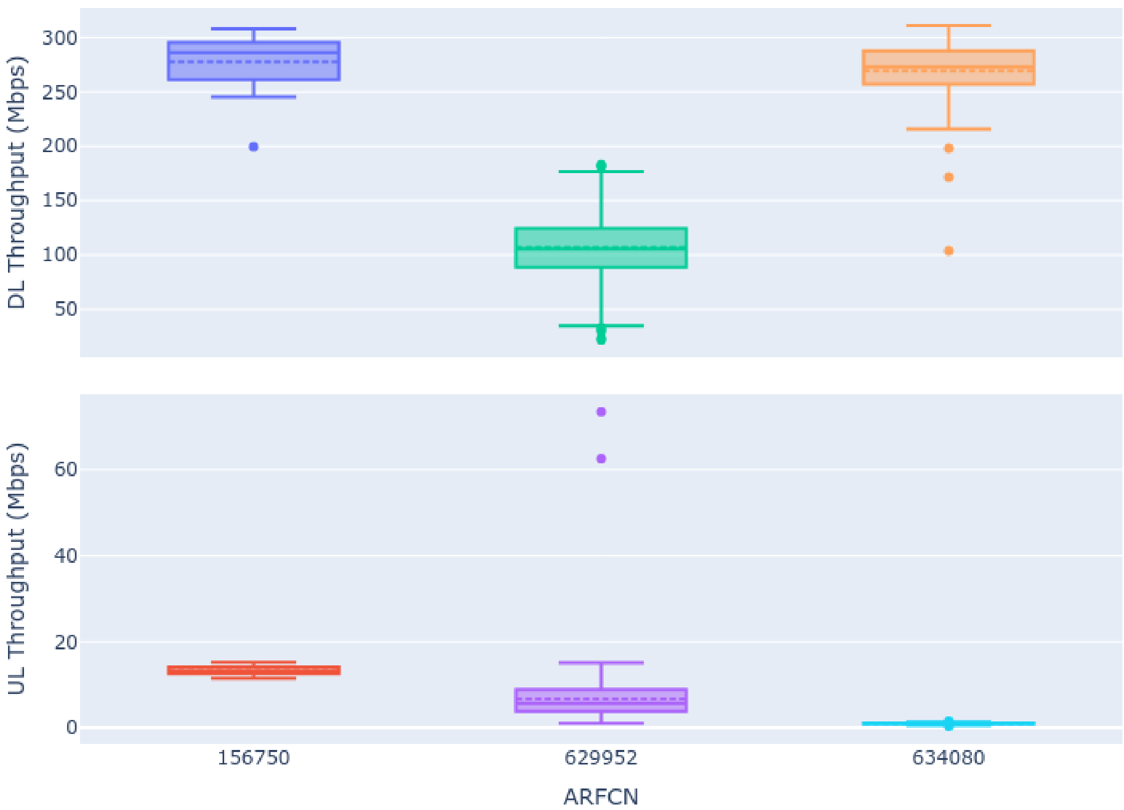


Figure 4.4: Throughput Variation across different ARFCNs

5 Conclusions

Our study provides a comprehensive evaluation of 5G network performance, focusing on the relationship between signal strength, frequency band characteristics, and deployment strategies. Based on the results, here are our key takeaways:

- **Signal Strength as a Critical Determinant**
  Signal strength directly influences throughput and the availability of advanced features such as multiple MIMO layers. Ensuring strong signal coverage should remain a priority for operators to optimize network performance.
- **Frequency Band Trade-offs**
  Lower frequency bands (e.g., n28) are advantageous for their broader coverage and reduced attenuation, making them suitable for improving network reach. Higher frequency bands (e.g., n78), while offering higher capacity, require careful management to mitigate throughput variability.
- **Deployment Modes and Architectural Implications**
  The superior performance of Standalone (SA) deployments compared to Non-Standalone (NSA) highlights the importance of adopting cloud-native 5G cores for future scalability and improved Quality of Service (QoS).
- **Duplexing Mode Impacts**
  Frequency Division Duplex (FDD) delivers consistent uplink and downlink performance, especially in lower bands, whereas Time Division Duplex (TDD) introduces variability that must be addressed through optimized scheduling.

Recommendations for Optimizing 5G Networks:

- *Enhance Signal Coverage:* Invest in additional base stations, especially in low-signal areas, to improve throughput consistency and enable advanced features like MIMO
- *Optimize Frequency Band Use*: Deploy lower bands (e.g., n28) for wider coverage and better signal penetration. Focus higher bands (e.g., n78) in urban and industrial areas, supported by dense small-cell infrastructure. Use a hybrid deployment strategy that balances investments in coverage (low bands) and capacity (high bands) to meet diverse user needs effectively.
- *Transition to Standalone (SA) Networks*: Accelerate the adoption of SA architecture to unlock 5G's full potential, including better throughput, lower latency, and support for advanced use cases.
- *Improve TDD Efficiency*: Optimize TDD scheduling with adaptive resource allocation to reduce throughput variability and enhance reliability in high-demand environments.

6 Future Work

The study provides valuable insights into 5G network performance, but there are several areas for further development and refinement. Below are the key directions for future work:

- **Expanding MobileInsight Parsers for Additional KPIs**
  Currently, MobileInsight parses a limited set of packets to collect physical layer (PHY) metrics. Future work will focus on extending the parser capabilities to include additional key performance indicators (KPIs), such as:
  - *Bandwidth:* Analyzing the available and utilized bandwidth across different frequency bands
  - *Modulation and Coding Scheme (MCS):* Collecting MCS values for more accurate throughput predictions and performance assessments
  - *Resource Blocks (RBs):* Parsing RB allocation data to better understand network capacity and efficiency during different traffic conditions
- **Enhancing the Collector Tool**
  The `collector` tool is essential for orchestrating data collection across multiple measurement routines. Future improvements include:
  - *Feature Expansion:* Adding more functionality to automate the collection of additional metrics, such as user equipment (UE) characteristics, and detailed application performance data
  - *Stability Enhancements:* Improving the stability and fault tolerance of `collector` to handle network interruptions or device failures. This includes refining error handling, reducing data loss during tests, and ensuring smoother coordination between different data collection routines
  - *Video Streaming Performance Metrics:* Incorporating the ability to monitor and analyze video streaming performance by capturing bitrate fluctuations and tracking buffering events during video streaming sessions to evaluate network impact on Quality of Experience (QoE)
  - *InfluxDB and Grafana Integration:* Integrating a timeseries database like InfluxDB to store aggregated logs and developing Grafana dashboards to visualize these logs in real-time. This will enable a user-friendly interface for monitoring key metrics and analyzing network performance trends dynamically
- **Expanding Data Collection**
  To provide more comprehensive insights, future work will focus on broadening the scope of data collection:
  - *Longer Duration Studies:* Extending data collection over longer periods to capture seasonal variations in network performance and the impact of network upgrades or changes in user behavior

- *Geographic Diversity:* Expanding the geographic range of measurements to include more rural, suburban, and remote locations. This will help in understanding how 5G performance varies in less densely populated areas
- *Mobility Scenarios:* Collecting data under a wider variety of mobility scenarios, including different vehicle speeds, different types of transportation (e.g., trains, buses), and other environments (e.g., pedestrian, cycling) to assess how 5G behaves under various mobility conditions
- *Dynamic Network Conditions:* Exploring data collection during periods of high network traffic to better understand how 5G networks manage congestion and prioritize different types of traffic.

References

[1] 3GPP. *5G; NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone*. TS 38.101-2 version 15.4.0 Release 15. ETSI. 2019. URL: https://www.etsi.org/deliver/etsi_ts/138100_138199/13810102/15.04.00_60/ts_13810102v150400p.pdf.

[2] *5G NR ARFCN calculator*. 5G Tools for RF Wireless. URL: https://5g-tools.com/5g-nr-arfcn-calculator/.

[3] *5G NR Throughput calculator*. 5G Tools for RF Wireless. URL: https://5g-tools.com/5g-nr-throughput-calculator/.

[4] Moinak Ghoshal et al. "Performance of Cellular Networks on the Wheels". In: *IMC '23*. New York, NY, USA: ACM, 2023, pp. 678–695. DOI: 10.1145/3618257.3624814.

[5] GSMA Intelligence. *Second wave of 5G*. 2023. URL: https://www.mwcbarcelona.com/press-releases/second-wave-of-5g-30-countries-to-launch-services-in-2023.

[6] Rostand A. K. Fezeu et al. "Unveiling the 5G Mid-Band Landscape: From Network Deployment to Performance and Application QoE". In: *SIGCOMM '24*. New York, NY, USA: ACM, 2024, pp. 358–372. DOI: 10.1145/3651890.3672269.

[7] Arvind Narayanan et al. "A First Look at Commercial 5G Performance on Smartphones". In: *WWW '20*. New York, NY, USA: ACM, 2020, pp. 894–905. DOI: 10.1145/3366423.3380169.