Empirical Analysis of 5G Deployments: A Comparative Assessment of Network Performance with 4G

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The advent of 5G networks has introduced new challenges for network operators, particularly in terms of coverage, capacity, and service quality. Consequently, it is crucial to monitor and assess network performance to detect irregularities and enhance functionality and deployment efficiency. This is especially important for Non-Standalone (NSA) 5G networks, which rely on existing 4G infrastructure and may not fully utilize the advanced capabilities of 5G technology. This study evaluates wireless system/network performance, focusing on key quality indicators and data throughput within typical town settings featuring various operational scenarios. To achieve this, portable smartphone devices were employed to simultaneously measure real-world data from all 5G and 4G networks, providing a comprehensive analysis of service delivery across all (three) cellular network providers in the area.

Results highlight differing 5G rollout strategies and performance across operators, revealing that broad coverage may struggle with congestion issues, while a tailored deployment approach could yield better results. Additionally, the analysis pinpoints significant performance challenges related to throughput, resource utilization, and interference, guiding enhancements in 5G network deployments.

Keywords— 5G, 4G, system measurements, field trials

I. INTRODUCTION

The deployment of 5G technology marks a significant leap in the evolution of mobile communications, offering unprecedented improvements in network capacity, data rate, and quality of service. 5G networks are characterized by their ability to deliver high-speed data, extremely low latency, and support for a vast number of connected devices. To achieve these capabilities, 5G employs cutting-edge technologies such as millimeter-wave (mmWave) frequencies, large-scale multiple-input multiple-output (MIMO) antennas, and network slicing. However, these advancements come with their own set of challenges, including significant path loss, interference issues, and a rise in network complexity, which could impact the actual performance of the system in real-world scenarios. In [1], Shafi et al. offer an in-depth tutorial on the standards and deployment challenges of 5G networks, providing insights into the practical applications and trials of 5G. The authors emphasize key technical aspects and performance metrics essential for 5G deployment. Hosseinian et al. in [2] examine the role of blockchain technology in future wireless networks, discussing its potential applications, challenges, and research directions. Their review highlights how blockchain can enhance security and efficiency in wireless communications. Zhao et al. in [3] focus on the latency characteristics of 5G, presenting findings from extensive field trials. Their analysis demonstrates practical latency performance and identifies critical areas for improvement in 5G network deployment. In [4], Pan et al. conduct a comparative study of 5G and 4G performance in high mobility scenarios, showcasing the reliability and efficiency of 5G networks under extreme conditions. Their findings provide useful data for future enhancements in 5G technology.

The transition from 5G Non-Standalone (NSA) to Standalone (SA) networks is evaluated in [5]-[6], using field trials to compare their performances. The findings in [5] show that SA networks have a slightly higher uplink rate than NSA networks, with comparable latency for both, underlining the importance of assessing these networks to meet 5G use case requirements. In [6], practical deployment and operational challenges faced in real-world scenarios are discussed.

The objective of this work is to carry out empirical evaluations of 5G system performance in various typical operational environments, ranging from urban, sub-urban to industrial environments, focusing particularly on key performance indicators (KPIs) related to signal quality, interference, and data throughput. Concrete measured data from operational 5G and 4G networks are essential for the effective implementation and maintenance of these technologies, as well as the efficient deployment of the new networks. Additionally, this research takes a comprehensive approach by examining service delivery from all cellular network operators in a given area, thereby presenting a complete view of measured results for all three operators under typical operational conditions.

In this context, section II presents the measurement methodology, section III the measurements performed in a real operational scenario and their analysis, while section IV presents the conclusions from the field trials.

II. Measurement Methodology

A primary challenge for 5G network operators is the adoption of new frequency bands, necessitating operators to ensure effective utilization of the radio spectrum to enhance network capacity. Moreover, the intricacies of 5G networks exceed those of earlier wireless network generations, making them more difficult to pinpoint the root causes of network issues. Lastly, the integration of different technologies in NSA 5G networks, complicates the process of identifying the specific technology contributing to various network problems.

To assess the performance of a 5G network, a variety of metrics are typically employed, as outlined in [1]. One key metric is the Reference Signal Received Power (RSRP), which refers to the linear mean of the power contributions (Watts) from the resource elements that convey secondary synchronization signals:

$$RSRP = \frac{1}{N}\sum_{i=1}^{N_{RE}}|S_i|^2 \qquad \textit{(Equation 1)}$$

where N_{RE} is the number of resource elements that carry cell-specific reference signals within the measurement bandwidth, and S_i is the received signal on the *i-th* resource element.

RSRP is a measure of the power level that a device receives from a specific cell in 4G or 5G networks. It is related to the CRS (Cell Specific Reference Signal) in 4G. However, CRS is not utilized in 5G, and instead, SS (Synchronization Signal) and CSI (Channel State Information) are used. RSRP aids in cell selection, power control, mobility, and beam management. The reporting range of RSRP is defined from -140 dBm to – 44 dBm, with 1 dB resolution. Typically, values above -80 dBm are considered excellent, while below -100 dBm are considered weak (cell edge).

The signal-signal-to-interference-plus-noise ratio (SINR) is also a key performance metric in wireless networks that measures the quality of a received signal at the user equipment (UE). It is defined as the power of the desired signal power (e.g. the Secondary Synchronization Signal) divided by the sum of the interference power (from other signals) and noise power in the received signal over the same frequency range. The SS-SINR is used by the UE to measure and report the quality of the received signal from different beams transmitted by the base station (gNodeB). SINR is derived from RSRP and RSRQ measurements and is used to determine the modulation scheme and coding rate for data transmission:

$$SINR = \frac{RSRP}{I_{tot}+N_o} \qquad \textit{(Equation 2)}$$

where I_{tot} is the total received interference power and N_o is the noise power spectral density. Values above 20 dB are considered excellent, while below 0 dB are poor (cell edge).

The Secondary Synchronization Reference Signal Received Quality (SS-RSRQ) is another critical metric. It is determined as the ratio of N_{RB} times the SS-RSRP to the 5G carrier's RSSI, where N_{RB} is the number of resource blocks in the 5G carrier RSSI measurement bandwidth:

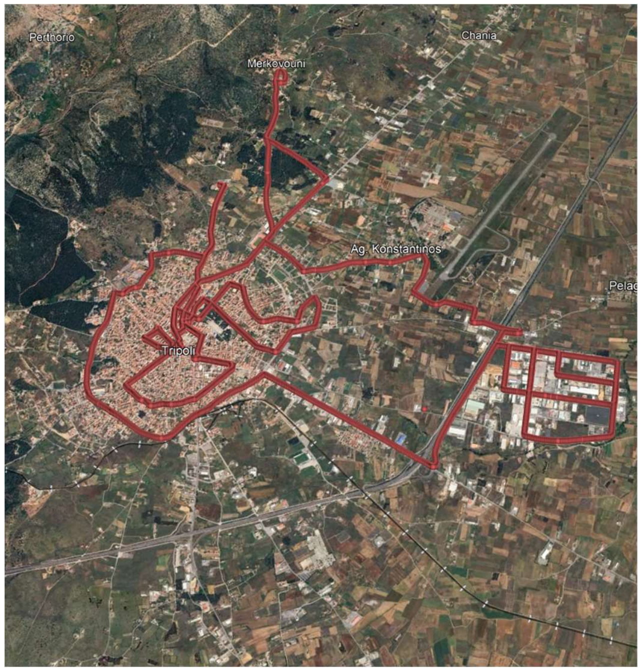
$$RSRQ = \frac{N_{RB}\,RSRP}{RSSI} \qquad \textit{(Equation 3)}$$

The carrier's RSSI is the linear average of the total received power (Watts), perceived in specific OFDM symbols of the measurement time resource(s) across N_{RB} resource blocks from serving and non-serving cells on the same channel, interference from adjacent channels, thermal noise, and others.

In this study, Echo One from Enhancell was used to perform the measurements [7]. It is a handheld cellular protocol (Layer 1-3) measurement tool, including customizable end-to-end testing. The measurement is based on the GPS location, and the UE device (smartphone) can measure all cellular networks (2G-5G), software, and measurement parameters (for example, Uplink-Downlink bandwidth, Beams, Cell ID, Channel Frequency, Connectivity Mode, Modulation, SS-RSRP, SS-RSRQ, SS-SINR, neighbor SS-RSRP, etc.) that can be configured through the cloud.

III. MEASUREMENTS

The study area is in southern Greece, the town of Tripoli, with a population of around 30,000. This town is home to the Wireless and Mobile Communications Laboratory, in the Department of Informatics and Telecommunications at the University of Peloponnese. The approximately 12-kilometer route chosen for measurements, shown in Figure 1 (a), encompasses a variety of operational environments, including the urban area of the town center, as well as suburban and industrial areas. Figure 1 (b) also shows the locations of the base stations for the tree operators in the area, which are colored differently to aid in the understanding of the field trial findings.



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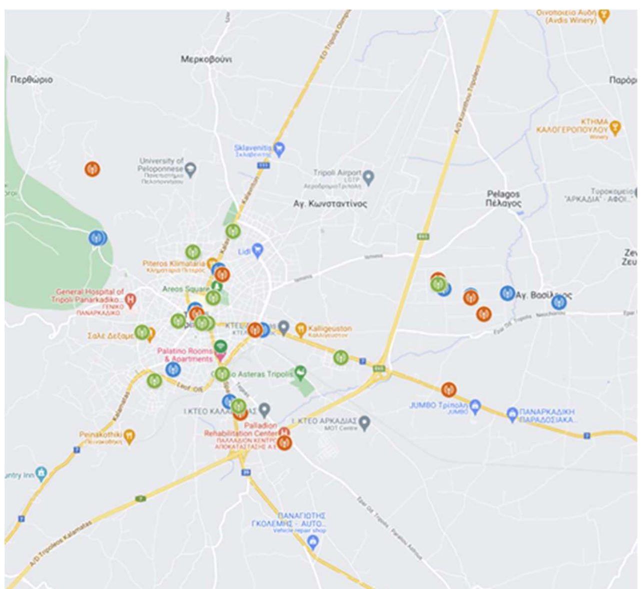


(b)

Figure 1: The field trials route (a), and the locations of the base stations of the three network operators (b).

The employed measurement system was the Echo Suite by Enhancell [7], which comprises:

- Echo One, that can be installed in any cell phone,
- Echo Cloud, a web service for automatic synchronization, storage, and route visualization,
- Echo Studio, a desktop application used for detailed analysis.

The setup involved three (3) Xiaomi 11 Pro 5G handsets, all with Echo One installed, and each connected to a different network provider. During the measurement process, three mobile phone holders were utilized to secure the test mobile phones on the car's dashboard (Figure 2). These phones were used to simultaneously perform measurements for the three wireless networks. The primary parameters measured and discussed in this paper are signal quality parameters such as RSRP, SINR, and RSRQ and their statistics, along with the achieved uplink and downlink throughputs.

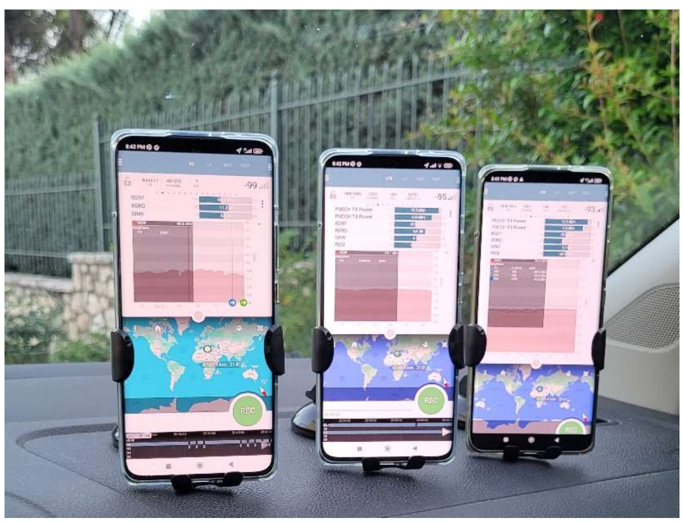


Figure 2: Measurement setup for the placement of the mobile handsets during measurements

IV. RESULTS

Figure 3, Figure 4, and Figure 5 depict in color-coded diagrams the measurement outcome along this path for the three network operators in Greece (identified as A, B, and C in the following), both for 5G and 4G. These figures offer an initial overview of the cellular networks performance in the area, in terms of RSRP, SINR, and RSRQ, revealing varying levels of 5G adoption among the three operators during the period of the measurement campaign, which took place in the summer of 2023. It can be noticed from these figures that operator A was the best in terms of 5G system availability, while for operator B, 5G availability was limited, while operator C has no 5G network deployed in the area under investigation.

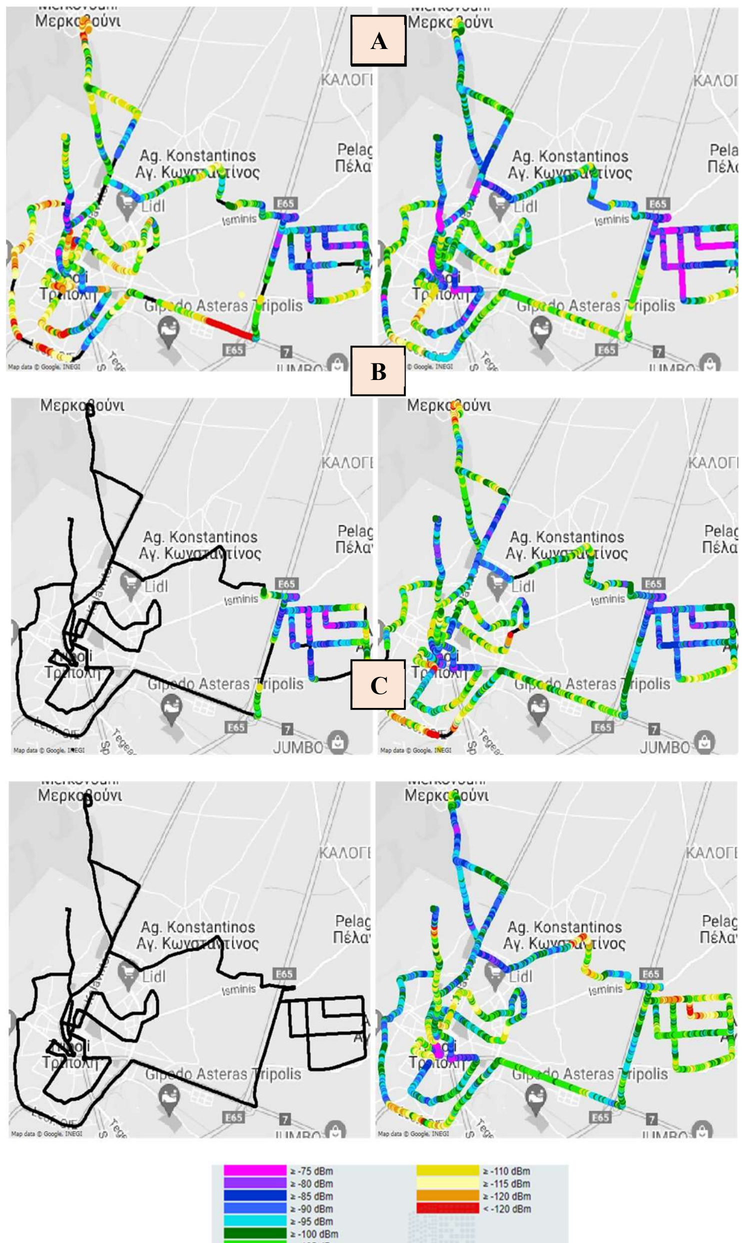


Figure 3: 5G (left) and 4G (right) RSRP for the three operators.

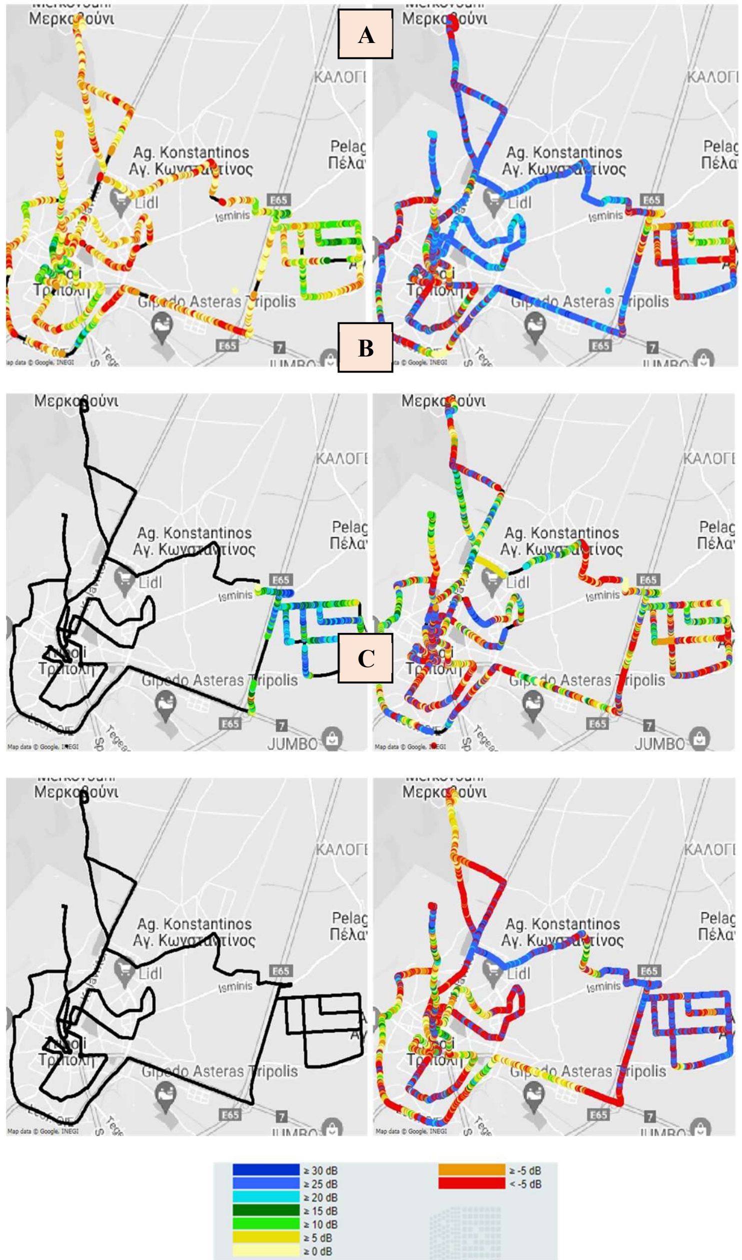


Figure 4: 5G (left) and 4G (right) SINR for the three operators.

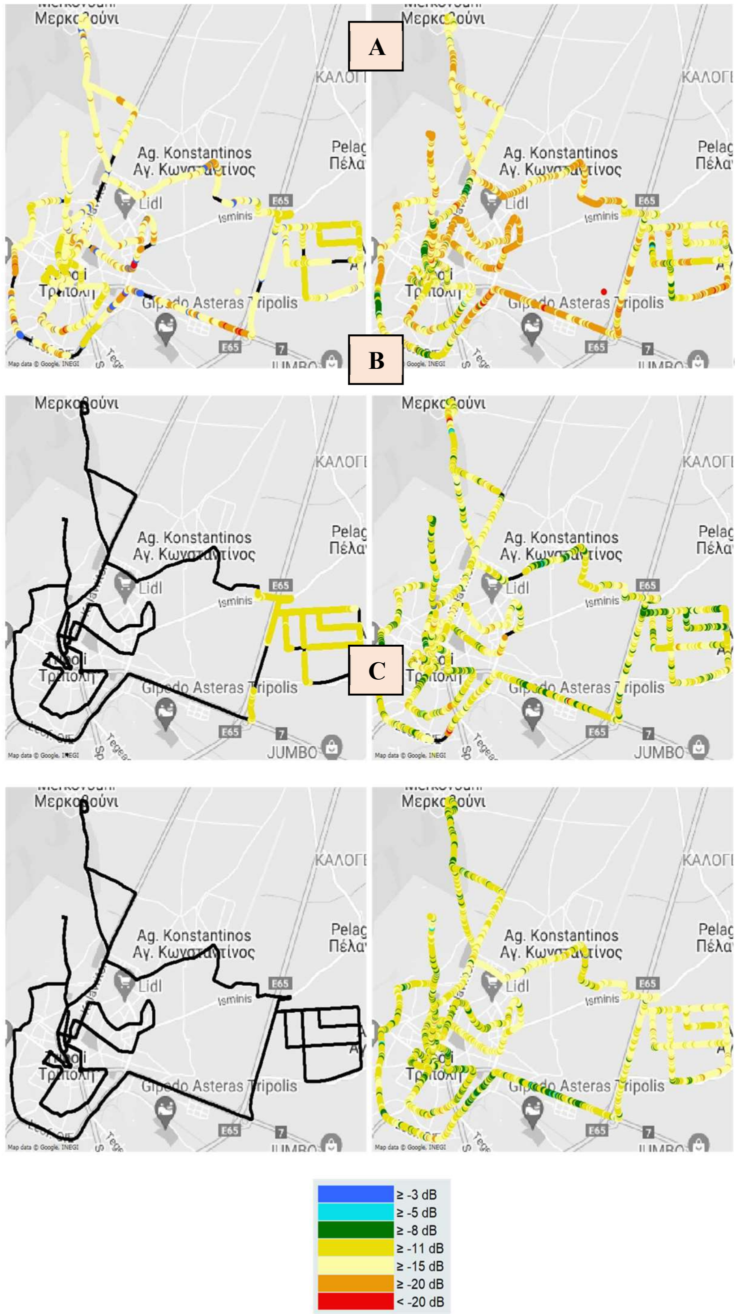


Figure 5: 5G (left) and 4G (right) RSRQ for the three operators.

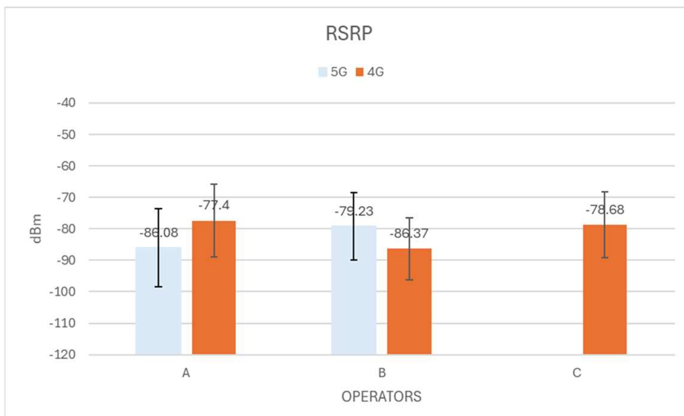
Table 1 offers a closer look at the system availability throughout the route. Operator A provides 5G coverage on 86% of the route, operator B on 17% of the route, while operator C has no 5G availability. Operator's C lack of deployment highlights the fact that different operators adopt 5G technology and roll out 5G networks at different paces. All three providers have fully developed 4G networks, with operator B reaching 94% of 4G availability, operator A 99%, and operator C 100%.

Table 1: System availability for the three operators

Operator	5G Availability	4G Availability
A	86%	99%
B	17%	94%
C	0%	100%

Figure 6 shows the spatial statistics (average and standard deviation) for RSRP, SINR, RSRQ, and 5G/4G networks (the light blue/orange bars, respectively). First, focusing only on operators with 5G networks (A and B), we notice that operator B performs better both with respect to coverage (RSRP) and to quality (SINR). Moreover, operator B also shows better statistics for its 5G network compared to 4G (~7dB better). Both observations are justified by the operator's B limited deployment (merely 17%). Nevertheless, this targeted deployment approach yields better performance in the early stages of its 5G network roll-out. For operator A, despite the widespread support for 5G along most of the measurement route, its SINR is on average ~12.7dB lower than that of 4G (~1.5dB worse for RSRQ). It should be noticed that (for all operators) there are quite large values for the std of 4G SINR, which points to large fluctuations. Furthermore, operator A demonstrates the best average 4G SINR, followed by operator C and then B. The best SINR is shown for operator B, but as also mentioned above, this is due to the limited deployment of 5G.

Another interesting observation is the interrelated behavior of RSRP, RSRQ and SINR. Generally, RSRQ depends on the RSRP (increases with RSRP), the interference levels (estimated by the SINR), and the load of the home cell. A higher RSRQ with lower SINR suggests efficient resource utilization but challenges in maintaining strong signal quality due to interference or noise. This scenario requires targeted strategies to mitigate interference and enhance overall network performance. The opposite scenario with a higher SINR but lower RSRQ indicates strong signal conditions but potential issues with network resource utilization or cell congestion, necessitating targeted network optimization strategies. Now, for operator A, while both 4G RSRP and 4G SINR show good performance (better than the respective 5G measurements), for the RSRQ applies the opposite, i.e., 5G RSRQ outperforms 4G RSRQ. This indicates that the home cell experiences strong signal conditions, the 4G network mitigates interference effectively, but there is an issue with cell resource utilization that possibly drives the 4G system into cell congestion.



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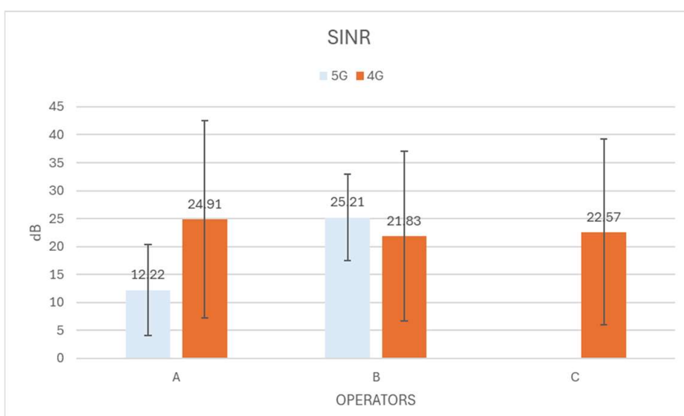

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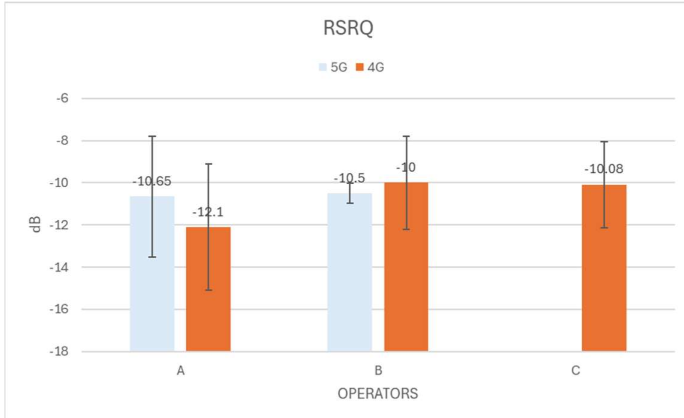
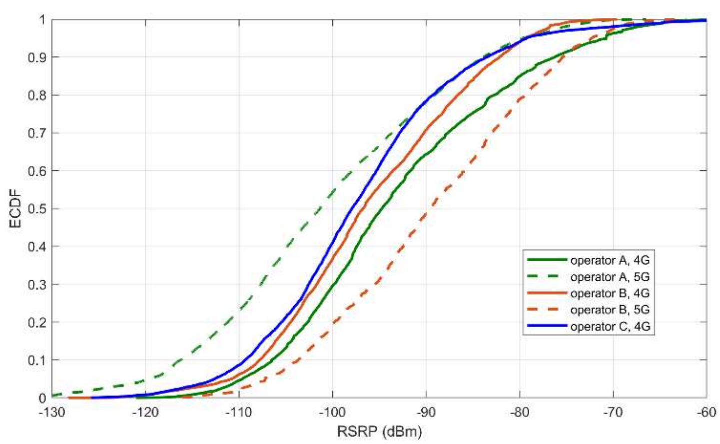


(c)

Figure 6: Spatial statistics for a) RSRP, b) SINR and c) RSRQ, 5G/4G and the three operators

Figure 8 illustrates the Cumulative Distribution Function (CDF) of the RSRP (a) and SINR (b) for all operators, and offers a better overall visualization for the observations made above with regards to the 5G performance difference between networks A and B both for RSRP and SINR (notably, for operator B, the median SINR for 5G is approximately 19dB higher than its 4G counterpart), and shows the steep change in the CDF curve for the 4G systems.



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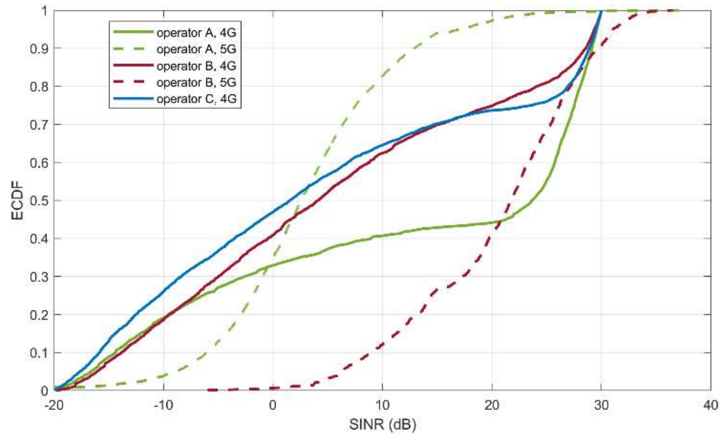


(b)

Figure 7: Empirical CDFs for the RSRP (a) and SINR (b) parameters, for the three operators

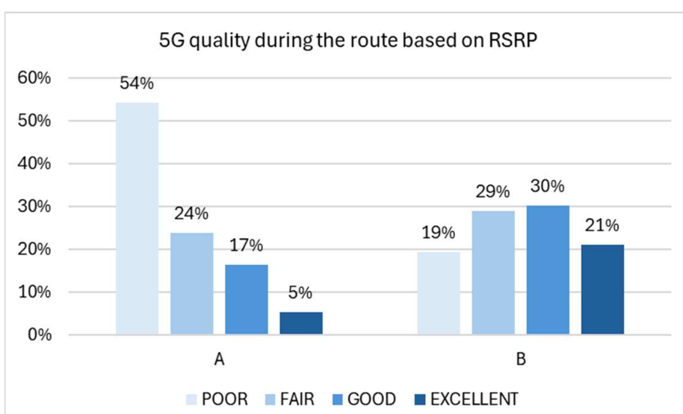
For a more detailed examination of coverage and quality, four (4) ranges are defined for the RSRP, the SINR, and the RSRQ (see Table 2). Each of these ranges is mapped to a quality indicator. The threshold values for these parameters were derived from insights gained from previous measurement experiences and additional analyses found in the literature [8].

Table 2: Quality Statistics

Quality Indicator	RSRP (dBm)	SINR (dB)	RSRQ (dB)
POOR	$-\infty < \text{RSRP} \leq -100$	$\infty < \text{SINR} < 0$	$\infty < \text{RSRQ} < -20$
FAIR	$-100 \leq \text{RSRP} \leq -90$	$0 \leq \text{SINR} < 13$	$-20 \leq \text{RSRQ} < -15$
GOOD	$-90 \leq \text{RSRP} < -80$	$13 \leq \text{SINR} < 20$	$-15 \leq \text{RSRQ} < -10$
EXCELLENT	$-80 \leq \text{RSRP} < \infty$	$20 \leq \text{SINR} < \infty$	$-10 \leq \text{RSRQ} < \infty$

In Figure 8 and Figure 9, the percentage of locations along the measurement route where the relevant parameter fell within these ranges is calculated, leading to a more qualitative categorization of performance. Firstly, operator A with higher 5G system availability (86%), shows a deployment that is still in early stages, with only 5% and 17% of locations reaching excellent and good coverage, respectively (Figure 8 (a)), while at the same time only 7% and 3% of locations offer good and excellent signal quality (Figure 9 (a)). This clearly shows that further development and optimization are required to get to the anticipated 5G capabilities. For operator B, 5G locations with Good and Excellent quality are comfortably above 50% (see Figure 8 (a) and Figure 9 (a)), but as mentioned before, this is mostly due to the network's limited deployment scope.

For the 4G networks, in Figure 8 (b) and Figure 9 (b), operator A shows the highest percentage in good and excellent categories, indicating a good network foundation that could possibly facilitate a smooth transition to a fully developed 5G NSA network. Somewhat high percentages are noted in the "Poor" category, indicating that all networks face challenges in providing consistent service quality. However, at the same time, all networks show similar "Fair" coverage metrics, ranging between 34 and 38%. This uniformity shows that even though there are variations in excellent and poor performance, there is also a consistency in the average service quality offered, showing that there is a benchmark against which 5G improvements can be evaluated.



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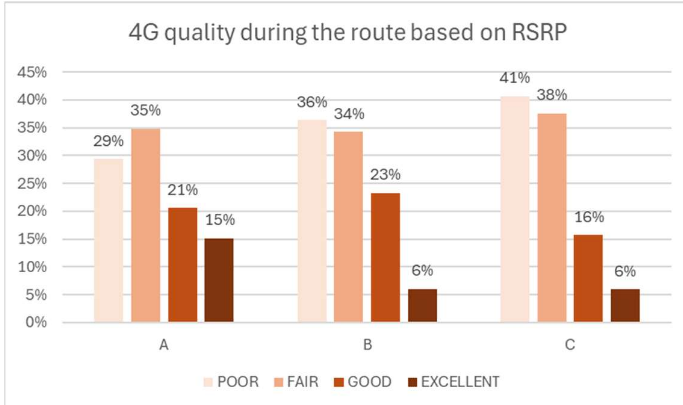

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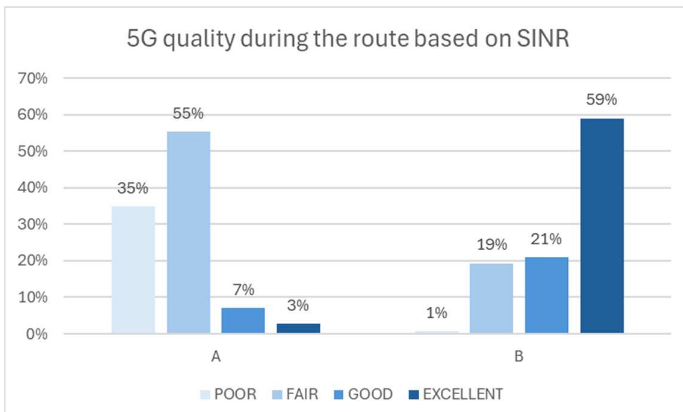
Figure 8: 5G (a) and 4G (b) coverage quality



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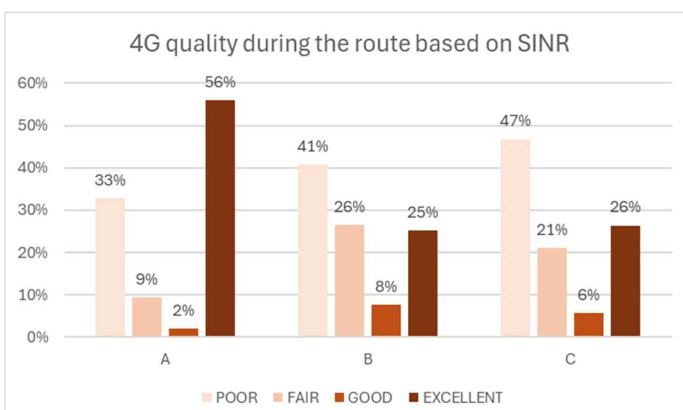

(b)

Figure 9: 5G (a) and 4G (b) SINR quality

Finally, Figure 10 presents the average calculated throughput along the measurement route. There is a clear boost in the throughput when it comes to 5G networks, especially for the downlink. Approximately 28 times increase in the DL throughput for operator A and 7 times for operator B. The respective improvement in the UL is negligible for operator A, while it is rather similarly low for operator B. Clearly, we are not even close to the 100fold increase that 5G goals have been set. Also, the different strategies of the two operators are evident, since operator A focused on a large downlink improvement with 5G (~93 times) instead of a small in the uplink (~4 times), while operator B offers pretty similar up/downlink improvement with 5G (~4 to 6 times).

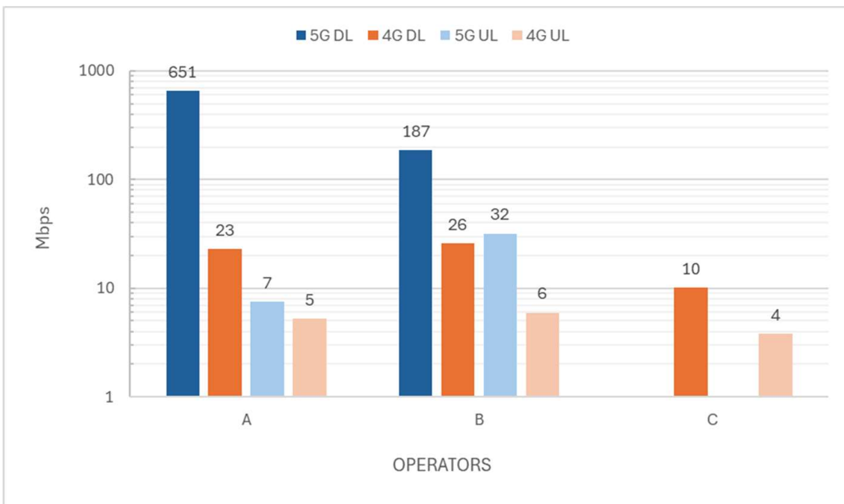

Figure 10: Average throughput (Mbps) for 5G/4G and downlink (DL)/uplink (UL)

V. Conclusions

Using the operating environment of Tripoli in Southern Greece as a case study, the work presented in this paper adds empirical evidence to the discussion on the relative performance of 4G and 5G systems across three cellular networks. The analysis highlights the different stages of 5G technology deployment and its varied performance across different operators. Operator A leads in 5G system availability, covering 86% of the measured area, while operators B and C show a mere 17% and 0% coverage, respectively. Despite its limited 5G deployment, operator B exhibits superior performance metrics in both coverage (RSRP) and quality (SINR) when compared to operator A, suggesting that a targeted deployment might be advantageous during initial 5G rollouts. Moreover, while all operators show well-developed 4G networks, the differences in their 5G strategies are evident from their service quality and performance statistics. For instance, operator A, despite wide 5G coverage, faces challenges such as lower SINR compared to its 4G service, indicating issues with network congestion. Additionally, spatial statistics reveal that 4G networks consistently demonstrate higher SINR values across all operators.

The identification of scenarios with different SINR and RSRQ values shows a possible path forward: addressing resource utilization and cell congestion in scenarios of high SINR but low RSRQ and mitigating interference in the opposite scenario. Moreover, the noticeable improvements in 5G throughput compared to 4G underscore the transformative potential of 5G for data transmission speeds. Nevertheless, despite these gains, the improvements fall short of the anticipated increase projected for 5G networks.

Further work will focus on enhancing 5G deployment strategies to optimize network performance and resource utilization. Adaptive network management techniques that address the observed discrepancies in SINR and RSRQ between 4G and 5G networks will be explored. These will be combined with the development of advanced analytical models to predict network behavior under various user densities and service demands, facilitating more strategic deployment and operational decisions by network operators. Also, it is necessary to monitor the evolution of these networks as 5G adoption expands and stabilizes.

Acknowledgements

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