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The Role of Legacy Mobile Networks in Infrastructure Resilience: Evidence from the Southern Brazil Flood

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***Abstract*—This paper investigates the resilience of mobile communication networks during the extreme flooding that affected Rio Grande do Sul, Brazil, in May 2024. Based on regulatory data and technical insights from operators, the study identifies the leading causes of network disruptions, primarily related to flooding and prolonged power outages. The results reveal the significant vulnerability of modern networks (4G/5G) during the event and the essential role played by legacy technologies (2G/3G) in sustaining basic connectivity under adverse conditions. The findings underscore the necessity of disaster-aware infrastructure planning, taking into account the ongoing significance of legacy systems, diversified power supply strategies, and resilient network designs to enhance service continuity during future crises.**

***Index Terms*—Resilience, Telecommunications Infrastructure, Climatic Events, Mobile Networks**

I. INTRODUCTION

In May 2024, Brazil's southernmost state, Rio Grande do Sul, experienced an unprecedented climatic disaster that disrupted critical infrastructure and displaced approximately 2.3 million people across more than 400 municipalities. The state capital, Porto Alegre, was particularly affected due to its high population density and prolonged flooding, with parts of the city submerged for over 30 consecutive days. Mobile communication networks—essential for emergency response and public safety—were among the hardest hit services. The flooding caused widespread outages of Base Transceiver Stations (BTSs) and significant degradation of service continuity. At the most critical moments, even basic communication services were unavailable.

To mitigate the impacts, telecom operators adopted emergency measures such as free-roaming agreements. Nevertheless, modern networks (4G and 5G) suffered substantial outages, whereas legacy technologies (2G and 3G)—although limited in capacity—remained operational and played a vital role in sustaining communication under adverse conditions.

This event highlighted the vulnerability of mobile networks to prolonged disasters and raised critical questions about the decommissioning of older technologies. Before the flood, the Brazilian National Telecommunications Agency (Anatel) had already initiated efforts to sunset 2G and 3G networks, aligned with international modernization trends [1]. However, the dependence on legacy technologies during the disaster demonstrated the potential risks associated with this transition.

In this context, this paper investigates two research questions: (i) What were the main factors leading to mobile service disruptions during the 2024 flood? (ii) How would mobile coverage have been affected if 2G and 3G had already been phased out? Addressing these questions is crucial for understanding the resilience of current mobile infrastructures and informing future policies on the decommissioning of legacy technologies.

To answer them, we combine regulatory datasets, operator network snapshots, and interviews with telecommunications professionals. This mixed-methods approach provides insights into the root causes of network failures and highlights the essential role of legacy technologies in supporting mobile network resilience during climate-induced disasters.

The main contribution of this work lies in the empirical observation of a problem not yet explored in the literature: long-lasting failures in mobile networks during an extreme climate disaster. Unlike most studies, which focus on short-term events such as hurricanes or localized blackouts, this article analyzes an unprecedented scenario of prolonged flooding.

Our findings indicate that, under conditions of extended power outages and flooding, legacy technologies demonstrated greater resilience in maintaining minimum connectivity compared to next-generation networks. These results suggest important differences between legacy and modern technologies, and provide valuable lessons for the design of more robust infrastructures capable of ensuring service continuity in the face of increasingly frequent extreme climate events.

II. RELATED WORK

The resilience of telecommunications infrastructure has been extensively studied, focusing on economic impacts, network performance, and recovery strategies [2]. However, most studies address short-duration climatic events, while the 2024 flooding in Brazil stands out as a long-lasting disaster, severely affecting Porto Alegre and surrounding municipalities [3].

Several case studies highlight the vulnerability of telecommunication systems to extreme weather events. Hurricane Katrina (2005) caused extensive damage along the Gulf Coast of Mexico, leaving 70 percent of cellular base stations inoperative due to strong winds and flooding, delaying full service restoration by up to 40 days [4]. Although Porto Alegre did not experience destructive winds, the slow-rising flood resulted in similarly prolonged service disruptions.

Hurricanes Irma and Maria (2017) devastated Puerto Rico, destroying 91 percent of its telecommunications infrastructure and exposing the fragility of aerial networks [5]. This vulnerability is especially relevant to Brazil, where approximately 99 percent of the telecommunications infrastructure is deployed above ground, contrasting with countries such as Spain (25 percent) and the Netherlands, where networks are fully underground [6].

In October 2024, Hurricane Milton disrupted communication services in Florida, impacting emergency response operations [7]. Similarly, floods in Valencia, Spain, affected more than 200,000 users, with 68 percent of mobile lines restored within one week and nearly full recovery achieved in two weeks [8]. In Rio Grande do Sul, recovery was significantly slower, taking over 120 days to restore most services.

In previous work [9], we conducted a broader assessment of this disaster's impact on the state's information and communication infrastructure, focusing on optical networks, data centers, and Internet exchanges. However, the specific resilience and performance of mobile networks, which play a critical role during emergencies, have not been thoroughly examined. This paper addresses this gap by investigating the behavior of mobile infrastructure during the 2024 flood, identifying failure causes, and analyzing the role of legacy technologies in maintaining connectivity.

III. DATASETS

This study employs datasets from Anatel, including information on Personal Mobile Service (SMP) stations, such as location, supported technologies, frequency allocations, and network impact records [10]. Inconsistencies were identified, notably in the coordinates of several Base Transceiver Stations (BTSs), which were corrected using supplementary data provided by a mobile operator in the region.

Additional insights were obtained through consultations with professionals from two mobile operators, including technicians, analysts, supervisors, engineers, and specialists. These interactions provided information on operational conditions, maintenance constraints, and field measurements collected by technician teams. The collected measurements contributed to understanding mobile network performance under adverse conditions in dense urban areas. The flood extent was determined using georeferenced maps from the Hydraulic Research Institute (IPH/UFRGS), corresponding to May 6, 2024, when Lake Guaíba reached its peak level of 5.35 meters [3].

IV. METHODOLOGY

This section describes the methods employed to address the two research questions outlined in this work.

A. Analysis of Factors Contributing to Service Disruption

Natural disasters, such as storms and floods, commonly affect telecommunications systems through fiber cuts, antenna failures, equipment malfunctions, vandalism, and power outages. To investigate the causes of mobile service disruption during the 2024 flood, we combined Anatel's data, operator network records, and the field measurements and observations collected during the emergency. These datasets enabled the identification of affected sites, classification of outage causes, and correlation of failures with infrastructure vulnerability and flood extent.

Mobile sites were classified as affected if their locations intersected the flood polygons provided by IPH/UFRGS and were concurrently reported as offline in the operator's management system. Accessibility constraints were identified based on field reports indicating areas where maintenance activities could not be performed during the flood.

B. Analysis of the Impact of 2G and 3G Deactivation

In the affected regions, particularly the Porto Alegre Metropolitan area, 2G and 3G networks helped maintain minimum service continuity during the flood. Despite their relevance under such conditions, Anatel plans to phase out these legacy technologies in favor of 4G and 5G [1]. However, they still account for over 20% of mobile connections in Brazil. While modernization improves network performance, it may reduce resilience under adverse conditions [11].

To evaluate the potential impact of legacy network decommissioning, a comparative coverage analysis for 2G, 3G, 4G, and 5G was conducted within the flooded regions of Porto Alegre. Each BTS was associated with its nominal coverage radius, defined by its supported technologies, assuming ideal propagation conditions.

V. LIMITATIONS

This study faced two main limitations. First, access to detailed operational data was constrained by compliance and confidentiality restrictions, limiting the granularity of the analysis. Second, spatial analyses were performed using the WGS84 coordinate system (EPSG:4326) without projection to a metric system or modeling terrain and building-related signal losses. These simplifications may have introduced minor distortions in coverage and distance estimations. Future work will address these limitations by adopting projected coordinate systems and fostering partnerships to improve data availability.

VI. RESULTS

This section presents the results obtained from the analysis of: (i) the factors contributing to mobile network disruptions during the 2024 flood, and (ii) the role of legacy technologies in sustaining coverage under adverse conditions.

A. Causes of Mobile Network Disruption

The evolution of Lake Guaíba's water level is shown in Figure 1, providing a temporal reference for the two key snapshots analyzed in this study: the peak disruption phase (May 14, 2024) and the recovery phase (July 9, 2024). These moments were selected as representative of the most critical and recovery periods, respectively.

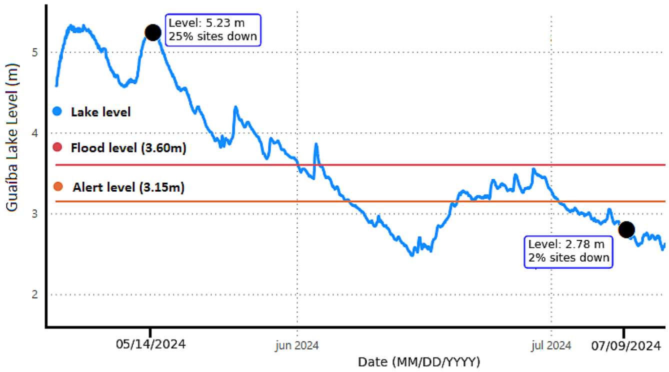

Fig. 1. Evolution of the Lake Guaíba water level in Porto Alegre during the 2024 flood. Snapshots corresponding to the critical (May 14) and recovery (July 9) phases are highlighted. A more complete timeline of events is available in the datasets presented in [9].

The flood had a direct and prolonged impact on telecommunications infrastructure, primarily due to water-induced equipment damage and power outages lasting nearly 30 days [9]. Despite multiple requests, the power utility did not provide detailed information on the geographic extent or duration of the outages.

To quantify the impact, two datasets collected during the event's peak (May 5, 2024) were analyzed. The first, provided by Anatel, aggregated information from all mobile operators in Rio Grande do Sul and indicated that 263 out of the 497 municipalities (53%) experienced disruptions [10]. The second dataset, obtained from a mobile operator, offered a detailed view of site-level disruptions affecting its infrastructure.

The operator snapshot from May 14, 2024, corresponding to the flood's peak water level, revealed severe degradation, with 76 out of 305 sites (approximately 25%) out of service in the capital Porto Alegre, affecting 1,356 base station antennas. Outage causes were classified as shown in Table I: water damage (31.6%), power outages (27.6%), and site inaccessibility (25%), the latter referring to locations where technicians could not perform inspections.

The mobile operator's network comprised (5.16%) of BTSs operating on 2G, (13.97%) on 3G, (72.76%) on 4G, and only (8.11%) on 5G.

The 2G infrastructure assessment revealed that 60 base station antennas (22.06%) were out of service at the peak of the flooding, while 272 (77.94%) remained operational.

For the 5G infrastructure, the analysis showed that 109 antennas (25.47%) went offline, while 315 (73.60%) continued operating, and 4 units, a small fraction (0.93%), had an undefined status due to incomplete management data.

TABLE I
CLASSIFICATION OF OUT-OF-SERVICE SITES IN PORTO ALEGRE DURING THE CRITICAL PHASE (MAY 14, 2024).

Cause	**Quantity**	**Percentage (%)**
Flooded Site	24	31.6
No Power Supply	21	27.6
No Site Access	19	25.0
No Information Available	9	11.8
Fiber Ring Break	2	2.6
Vandalism	1	1.3
Total	**76**	**100**

As shown in Table II, the failure rates varied across technologies. Notably, 2G BTSs exhibited the lowest failure rate (22.0%) compared to newer technologies, despite their lower network share. This finding suggests that legacy technologies made a significant contribution to network resilience during the event.

TABLE II
FAILURE RATE BY MOBILE TECHNOLOGY DURING THE FLOOD.

Technology	**Total Antennas**	**Affected Antennas**	**Failure Rate (%)**
2G	272	60	22.0
3G	737	200	27.1
4G	3838	987	25.7
5G	428	109	25.4
Total	**5,275**	**1,356**	**25.7**

By July 9, 2024, after the water level had dropped below the alert threshold of 3.15 meters, only seven sites (2%) remained inoperative, indicating that the network had almost fully recovered. However, the operator did not clarify whether these sites were pending restoration or had been permanently decommissioned, citing confidentiality restrictions.

B. Service Layer Impact: Internet Access Disruption

Beyond infrastructure-level outages, the flood caused substantial degradation at the service layer, directly impacting user connectivity. Figure 2 presents the evolution of the number of Internet users connected to one of the primary traffic concentrators in Porto Alegre between May and November 2024. During the peak of the flood, a sharp drop of approximately 50% in active users was observed, reflecting the combined effects of site outages, prolonged power failures, and the collapse of local coverage.

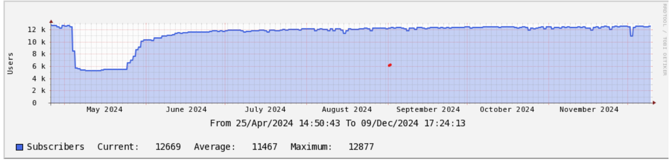

Fig. 2. Internet user count connected to a traffic concentrator in Porto Alegre (May–November 2024). A sudden reduction of nearly 50% occurred during the May flood, followed by a gradual recovery.

Complementary evidence was obtained from end-user measurements collected by a nationwide network quality monitoring system [9]. Table III summarizes the evolution of median Bandwidth (BW) and Round Trip Time (RTT) for mobile network users in the most affected cities. The data confirm a significant degradation in perceived quality: the median mobile bandwidth dropped from 119.5 Mbps before the event to 101.2 Mbps during the critical phase, and further to 69.5 Mbps during the recovery period. Meanwhile, median RTT temporarily decreased during the flood, likely due to reduced user demand, but worsened in the aftermath, suggesting that congestion and capacity limitations persisted even after partial network restoration.

TABLE III
MOBILE NETWORK PERFORMANCE IN THE MOST AFFECTED CITIES.

Period	**Measurements from the total (%)**	**Median BW (Mbps)**	**Median RTT (ms)**
Pre-event	33.5	119.5	28.6
Critical days	22.0	101.2	23.7
Post-event	44.5	69.5	36.7

Taken together, the operator-side data (concentrator user counts) and end-user measurements, bandwidth, and RTT consistently show that the 2024 flood caused not only infrastructure failures but also a severe deterioration of service quality, even in areas where connectivity remained technically available.

These findings illustrate the progressive degradation and partial recovery of mobile network infrastructure in Porto Alegre, affecting both infrastructure availability and service quality. The combined evidence from site outages and end-user measurements highlights the limitations of the current mobile network under extreme events.

C. *Impact of Legacy Networks on Coverage*

To assess the role of legacy networks during the flood, a comparative analysis was conducted between 2G and 5G coverage, focusing on their ability to maintain communication in the affected areas. Some of their technical characteristics are presented in Table IV. Individually, these values are influenced by factors such as obstacles, terrain morphology, antenna height, signal attenuation or interference, and the maximum transmission power permitted by regulatory agencies.

TABLE IV
MOBILE TECHNOLOGY CHARACTERISTICS.

Technology	**Coding**	**Frequency (MHz)**	**Bandwidth (MHz)**	**Range (km)**
2G	GSM	850 / 1800	2.5 / 5	2 – 10
3G	WCDMA	850 / 2100	10 / 20	1 – 5
4G	LTE	700–2600	10 – 20	1 – 4
5G	NR	2300 / 3500	50 / 100	0.5 – 1

Although channel bandwidth does not directly determine the signal propagation distance, it significantly affects link capacity. For a given modulation scheme and equivalent radio frequency (RF) conditions, wider bandwidth channels enable higher connection speeds and support a greater number of simultaneous users.

Modulation schemes dynamically adapt according to propagation conditions: near the site and under line-of-sight conditions, higher-order modulations are typically used, while in distant areas with more attenuated RF signals, lower-order modulations are employed [12].

The coverage ranges adopted in this study were based on practical values calibrated through field measurements obtained via WalkTest and DriveTest procedures [13]. While WalkTest is conducted on foot—typically in indoor environments or densely urbanized areas—DriveTest uses equipment installed in vehicles to cover larger distances. Both methods provide essential data for assessing network performance and identifying faults.

For the map generation shown in Figure 3 and Figure 4, we simulated a worst-case signal coverage scenario, adopting the minimum coverage radius for each technology: 2 km for 2G and 0.5 km for 5G, as specified in Table IV. These maps represent the estimated mobile coverage in Porto Alegre on May 6, 2024, combining flood extent data—corresponding to the peak water level of 5.35 meters [14]—with the technological composition and spatial distribution of each Base Transceiver Station. The data on location, frequency, and supported technology for each BTS was provided by the mobile operator. The red-shaded polygon delineates the flooded area, while the blue circles represent the estimated coverage zones of each active Base Transceiver Station located at the flood boundary, according to the technology in use (2G and 5G). Red markers identify the sites that went out of operation during the event, whereas green markers indicate the sites that remained operational.

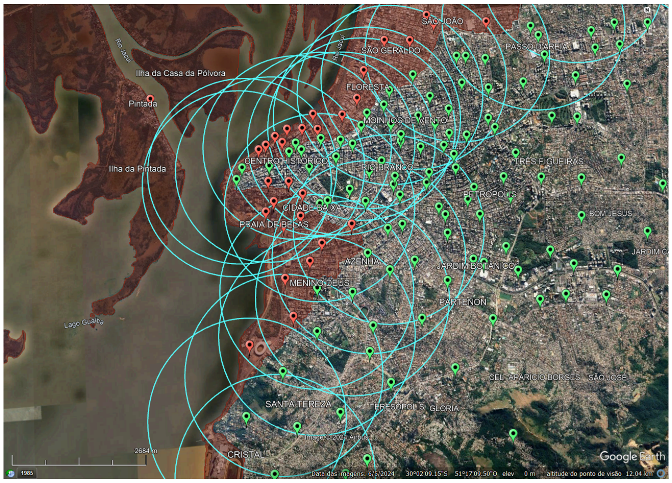

Fig. 3. Estimated 2G coverage maps of a mobile operator's stations in the city of Porto Alegre - (2km radius).

The analysis reveals a significant disparity in coverage between 2G and 5G, with 2G demonstrating a broader signal reach in the flood-affected areas due to its lower operational frequencies. Notably, even in the most severely affected zones, 2G cells remained operational in a higher proportion

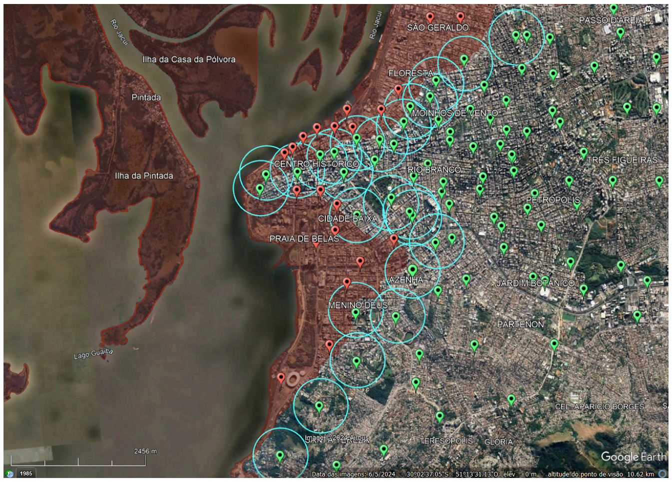

Fig. 4. Estimated 5G coverage maps of a mobile operator's stations in the city of Porto Alegre - (0.5km radius).

compared to 5G, ensuring basic voice and SMS connectivity in the absence of modern data services.

This comparison underscores the vital role of legacy technologies in expanding coverage during emergencies. While modern networks such as 4G and 5G prioritize data capacity and spectral efficiency, their reduced coverage—especially at higher frequencies—limits their resilience under adverse conditions. In contrast, 2G and 3G networks, initially designed for voice and basic data services, offer broader coverage and superior signal penetration, which proved essential during the flood [15].

VII. DISCUSSION

The analysis revealed that approximately one-quarter of the mobile sites in Porto Alegre became inoperative during the flood's critical phase, primarily due to water-induced equipment failures and power outages. Additionally, around 25% of the affected sites could not be assessed due to accessibility constraints, further limiting operators' ability to deploy mitigation measures.

This disruption occurred under an unprecedented hydrological scenario. Historically, between 1899 and 2023, Lake Guaíba surpassed the 3-meter level only four times. However, between September 2023 and May 2024, it exceeded this threshold on three occasions, culminating in the record-breaking flood of 2024 [16]. This trend highlights the increasing frequency and severity of extreme weather events, aligning with global climate change projections.

Although free-roaming agreements between carriers were implemented to mitigate service degradation, connectivity continuity largely depended on legacy technologies, particularly 2G networks. Modern networks, such as 5G, were most affected due to their limited coverage. Coverage analysis showed that if only modern technologies had been available, the impact on users would have been significantly worse.

Beyond technical aspects, the event exposed critical limitations in both energy backup strategies and infrastructure placement. Operators implemented lithium batteries and portable generators to sustain essential sites, but these solutions proved insufficient to endure a power outage lasting nearly 30 days. This highlights the need to reassess backup strategies and to consider deploying alternative energy systems that combine multiple sources, such as solar, wind, and fuel-based generators, to ensure service continuity during prolonged crises. Likewise, the dependence on aerial cabling left critical infrastructure vulnerable to physical damage and hindered field teams' access for repairs during the flood.

Recent regulatory efforts, such as Municipal Law No. 13.402 [17], mandating the underground installation of new utility networks in Porto Alegre, represent an essential step toward improving infrastructure resilience. However, such transitions require long-term investments and coordinated efforts between public authorities and private operators.

Communication via Low Earth Orbit (LEO) satellites emerges as an alternative redundancy option. During the flooding, Starlink equipment was provided to authorities to maintain connectivity in regions with limited or no communication. A future possibility is the Direct Cell service, still under development, which will enable direct connections from LEO satellites to regular mobile phones without the need for parabolic antennas or specialized terminals. In Brazil, this technology is not yet operational, as it depends on approval from Anatel.

Our findings reinforce the importance of legacy technologies during disasters and highlight the need to implement 5G and future technologies in lower frequency bands to enhance signal reach and network availability, particularly in areas with lower infrastructure density. Such measures would improve overall network resilience, particularly in regions vulnerable to extreme weather events. As an alternative, the deployment of more recent technologies, such as 5G operating in the 700 MHz band, can replicate some of the propagation characteristics of legacy systems, providing greater signal reach and improved penetration.

Although the preservation of legacy networks has proven essential to ensuring minimum connectivity in disaster scenarios, in the absence of fully available alternatives — as evidenced in this study — it is essential to acknowledge the technical and operational limitations of their continued use. These technologies have significant drawbacks, including low spectral efficiency, high operational costs, and limited compatibility with modern devices.

VIII. CONCLUSION

This study examined the resilience of mobile communication networks during the 2024 flood in Porto Alegre, highlighting critical vulnerabilities in both the infrastructure and service layers. Legacy technologies (2G/3G) proved essential for maintaining minimal connectivity when modern networks (4G/5G) were severely impacted by equipment damage and long-lasting power outages. However, relying on outdated technologies is no longer viable as they are being progressively decommissioned worldwide.

The results emphasize the urgency of adopting disaster-resilient network architectures, combining robust power backup systems, diversified transmission media, and the flexible deployment of modern technologies. In particular, expanding 5G in lower-frequency bands and improving network densification will be crucial to sustaining communication during future extreme events.

Equally important is the need to establish collaborative frameworks that enable the secure and ethical sharing of operational data among operators, researchers, and public authorities. Such cooperation is fundamental to designing evidence-based strategies that enhance the resilience of critical communication services.

Strengthening mobile infrastructure against climate-induced disruptions is not optional but necessary. The increasing frequency and severity of such events necessitate immediate action to ensure that essential services remain operational when needed most.

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