5G in the Wild: Performance of C-Band 5G-NR in Rural Low-Power Fixed Wireless Access

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***Abstract*—In this paper, we have evaluated the performance of one of the first community-led rural applications of standalone 5G for fixed wireless access on the n77 band in the UK. This was achieved through a full-stack holistic monitoring platform, evaluating the overall performance and quality of experience of connections in the network. Our results show that 5G n77 networks can provide sub-gigabit connectivity in line of sight applications in rural areas, even when accounting for the impact stemming from infrastructural constraints. We have evidenced that our platform has identified opportunities to improve performance and capacity.**

***Index Terms*—5G-SA N77 C-Band Rural Broadband**

I. Introduction

The UK has seen a recent resurgence of ”alt-net” community-led programmes deploying Internet connectivity to premises in local rural communities [1], often with fibre. These initiatives require collaboration from many local parties to build, but still have a large cost for the end user [2]. The use of wireless technology for the last mile can help reduce overheads, and is known as Fixed Wireless Access (FWA).

Rural application of wireless - especially cellular - technology is challenging because the technology is predominantly deployed at scale by large communications providers with business models aligned to higher user densities [3]. Rural connectivity remains a persistent challenge since the high cost of deploying infrastructure may not deliver a return on investment to motivate large scale operators [4]. This has led to community-led projects - such as the Mobile Access North Yorkshire (MANY) consortium - that seek to use emerging vendor-neutral and open standards to deliver service.

There are now several options for FWA, each with benefits and drawbacks. Our research has previously monitored systems providing FWA to rural areas utilising TVWS (Television White Space) and mmWave 60GHz. We developed a technology-agnostic monitoring stack as part of 5GRIT, to allow for analysis of performance across layers to compare sites and deployments [5].

Spectrum availability in the UK is limited for standard cellular equipment. 5G New Radio provides for new spectrum in C-band, of which n77 is one such band. The industry partners within the MANY consortium opted to invest in hardware capable of 5G-NR n77 largely due to special availability in the 3.7 to 4.2GHz range for small-scale testbeds and operators. The licence is limited in both bandwidth (50MHz) and EIRP (20W), which results in a tighter link margin than typical cellular systems due to the intended use for FWA - where user equipment will be equipped with high gain antennas and fixed in place [6], [7].

This paper evaluates the performance of this n77 5G system in a rural valley environment in North Yorkshire, UK. We demonstrate how our cross-layer analytical approach has allowed us to measure performance and pin-point causes such as weather-related events and core network issues. We:

- Show the real-world performance and experience for users on our network using our cross-layer approach.
- Link performance degradation to physical-layer impacts - such as snowfall - or backhaul impacts - such as core network congestion.
- Identify architectural constraints that limit investigation due to the tunnelled nature of 5G traffic and dependency on tight integration with vendor-specific telemetry to understand network load.
- Argue that there is space for user experience and capacity improvement if regulators would increase the EIRP in similar deployments.

The remainder of the paper is organised as follows: Section II describes the motivation and design of the deployed network. Section III describes our measurement framework and how we evaluate the performance of the system on trial. Section IV details our early findings and challenges specific to the rural application of this technology. Section V concludes.

II. Testbed Background

Mobile Access North Yorkshire (MANY) is a consortium of community groups and regional communications service providers (CSPs) in the North of England funded initially as part of the UK Government 5G Testbed and Trials programme. Our primary role is to provide independent monitoring and evaluation of the technologies and implementations used.

A focus in MANY is vendor neutrality and application of open standards and implementations. Due to security concerns, the UK Government policy restricted the vendors that the consortium were allowed to procure core network (CN) and radio access network (RAN) equipment from. As such, MANY primarily looked to vendors that were UK based and could offer solutions providing interoperability.

The CSP selected the CableFree Emerald solution for the gNB, providing two sectors with cross-polarised MIMO antennas on the n77 5G New Radio Standalone band. Each sector points in opposite directions along a glacial valley. The antennas provide 18.8dBi gain, have a horizontal HPBW (Half Power Beam Width) of 63° and vertical HPBW of 6°, and are aligned in such a way to cover as many potential customers as possible in the challenging terrain. Channel allocations are at C-band (between 4.1 and 4.2GHz) with 50MHz per sector and operating in Time Division Duplex (TDD) mode. EIRP is limited by the license to 20W EIRP.

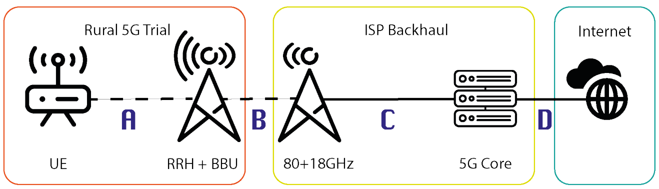


Fig. 1. Network Architecture Diagram (Simplified)

The 5G Core is operated by the CSP in one of their core data centres, with the backhaul (segments B and C in Figure 1) implemented over a mixture of high capacity (40+Gbps) fibre links, leased 10Gbps Ethernets, and 80/18GHz point-to-point microwave links providing upto 10Gbps into the remote valley.

TABLE I

Manufacturer	Model	Type	Antenna Configuration
D-Link	DWR-978	Desktop	External
D-Link	DWR-2101	MiFi	Integrated
ZyXel	NR-5101	Desktop	External
ZyXel	NR-7101	External	Integrated

The User Equipment (UE) was not subject to procurement restrictions. Equipment from several vendors was tested and the ZyXel NR-7101 selected. It is mounted outdoors and has an integrated antenna with 10dBi gain. The CSP installed equipment for consumers and was responsible for antenna alignment. We tested other modems to eliminate performance differences (beyond the scope of this paper).

III. Measurement Framework

Our custom end-to-end measurement framework (outlined in Figure 2) measures and combines data streams from multiple tools into one holistic data set. Project participants are able to view data on dashboards and our researchers can explore data to analyse issues which may otherwise be missed. This approach allows for a dynamic, reactive and iterative design approach to build and expand our dataset and draw more context into our analysis. We can expand and contract data sources to ensure that we can accurately investigate numerous QoS and QoE metrics using wider context [8], [9].

We have expanded the data sources considerably since the 5GRIT project [5] and made it easier to deploy and scale

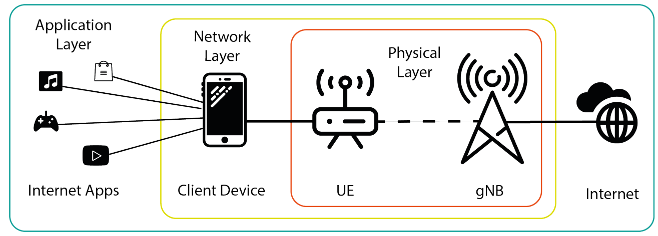


Fig. 2. Monitoring Framework Overview

through containerisation [10]. Software deployed on edge nodes is platform agnostic to allow for deployment on low-power small form-factor GNU/Linux systems, but also on other platforms (such as ARM) to provide opportunities to integrate with existing hardware operated by partners [11].

Our framework is divided into three principal areas: the physical, network, and application layers.

A. Physical Layer

The physical layer is a collection of wireless link parameters passively measured by networked devices. Some parameters are vendor-specific, whilst others are standardised by 3GPP, such as RSSI (strength indication), RSRP (average reference signal power), RSRQ (reference signal quality) and SINR (signal plus interference to noise).

These values give context about the radio link and allow us to establish whether or not the user experience is due to a fundamental channel constraint rather than network congestion or some other issue outside the RAN. We can also establish if the link quality is consistent with the coverage model.

The modulation and coding employed at a given point in time also provides insight into the maximum theoretical throughput. How these metrics vary over time can also offer unique ways to analyse the behaviour of the network as it responds to changes in channel conditions.

Furthermore, there are other metrics which are useful to collect, such as statistics from the UE or gNB like the CPU load. Our framework does not inherently try to limit the data collected and we work to record all metrics available. Even if their relevance may appear dubious, we have found that evidence can often be found in unexpected metrics.

B. Network Layer

Our network statistics come from active QoS monitoring tests, which operate at regular intervals. These determine real-world throughput and latency experienced by the customer.

We conduct measurements against both public and private endpoints because the results can be subject to external influences such as contention in backhauls and the wider Internet, depending on how traffic is managed by the CSP and others.

Public testing utilises existing services such as Ookla Speedtest.net and the Fast.com service provided by Netflix. These provide a helpful overall indication of the performance that the user would likely experience when using popular Internet services because they have algorithms that mitigate

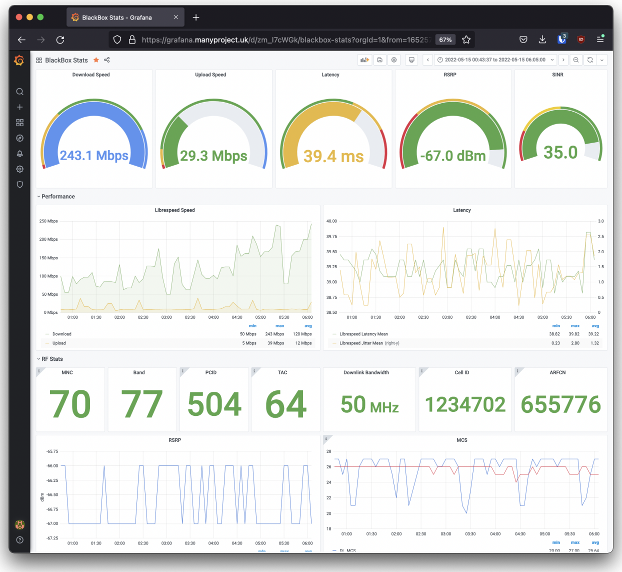


Fig. 3. Monitoring Framework Dashboard

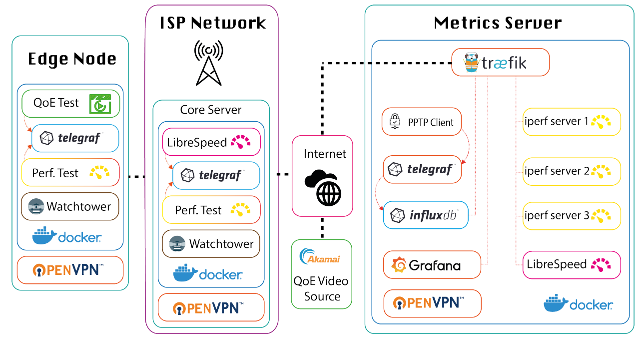


Fig. 4. Monitoring Framework System Diagram

transient errors through automated selection of servers and content delivery networks.

Private testing utilises tools such as LibreSpeed, iPerf3 and ICMP ping. This uses endpoints deployed within the core network and externally on the Internet. We modify the design and configuration of these as required. This approach allows us to test specific portions of the network to isolate performance results and eliminate potential external influence. This is important in topologies involving multiple wireless links, differing backhaul technologies and potential contention.

C. Application Layer

We emulate how users will experience the network by deriving QoE measurements automatically from open source implementations of typical applications. Video streaming is one of the most resource intensive uses of networks, and these metrics when combined allow for an accurate representation of how the network is performing at a user experience level.

We use gStreamer to stream MPEG DASH video streams periodically and gathered metrics including timings of how long the video stream appears in each available resolution, the duration that the stream was buffering for, a count of how often the stream stalls, and a count of how many times the resolution changes throughout the stream.

D. Other Metrics

Our framework can also gather and present other data which can be used in conjunction with network parameters to help draw further conclusions as well as aid in debugging issues. We can monitor weather data (for example using the UK Met Office API) and data monitored by consortium partners from IoT devices. This allows visibility of weather events which impact radio links. We also monitor internal system telemetry (such as CPU load) to verify that nodes are healthy and rule out faults as a cause of poor performance.

E. Data Gathering

Data is stored in the time-series database InfluxDB, while data is transmitted between edge nodes and the server via Telegraf, with Traefik proxying the traffic. Telegraf acts as a buffer as well as a collector of statistics which aids reliability. Real-time visualisation of the metrics is achieved via dashboards created with Grafana. This allows for real time visualisation of data by researchers, the CSP and community participants, which was not previously possible without offline analysis.

IV. Results

We discuss data from two UEs - both utilizing NR-7101 hardware but on two different deployments of n77 5G FWA using the same gNB technology and connected to the same 5G Core:

- **Idealised Case:** This UE is approx. 0.4km from the gNB with zero relative elevation and line-of-sight. The location is in the plains of East Yorkshire.
- **Representative Case:** This UE is approx. 3.7km from the gNB, with a relative elevation of approx. 150m and line-of-sight. This location is in the Yorkshire Dales National Park, an area known for highly variable and inclement weather and, due to the heritage of the area, there are severe restrictions on planning applications for network infrastructure.

These connections were used by users as their primary broadband connection, consequently the performance measurements may be impacted by concurrent consumer data load and from other users sharing the same infrastructure. Both sites previously displayed an on/off peak pattern in throughput, which is addressed in subsection IV-D. We have undertaken measurements over the full period to account for periods where the system load differs and have measured the infrastructure itself to help separate out the RAN performance.

The maximum downlink modulation for each gNB is 256-QAM. See Table II for modulations referenced in figures 5(c) and 5(f).

TABLE II
DOWNLINK/UPLINK MODULATION SCHEME INDEX VALUES

DL Index	Modulation Scheme	UL Index	Modulation Scheme
0	QPSK	0	PI/2 QBSK
1	16 QAM	1	QPSK
2	64 QAM	2	16 QAM
3	256 QAM	3	64 QAM
4	1024 QAM	4	256 QAM
-	-	5	1024 QAM

A. *Typical Performance*

We evaluate three key statistics recorded by our monitoring framework over the period of a month: download throughput, uplink throughput, and SINR. We also consider RSRP and the utilised modulation scheme where this is relevant. Throughput described relates to site-to-5G-core Librespeed testing (i.e. not an Internet endpoint).

1) Idealised Site: In Figure 5(a), our statistics demonstrate peak downlink throughput of 246mbps, dropping to 46mbps at minimum and an average of 231mbps. Upload performance was 46mbps, 4mbps and 15mbps respectively. Downlink modulation described in figure 5(c) is predominantly 256-QAM, but occassionally drops to 64-QAM. Uplink modulation was more varied and while it is still mostly 256-QAM, 64-QAM and 16-QAM were reported.

Figure 5(b) demonstrates the RSRP is strong, at between -65dBm and -69dBm, and should give a SINR of around 55dB for the sensitivity given a measured sensitivity of approx. -123dB on the UEs. This corresponds with the consistent performance expected for a link with such a wide margin. We note that the SINR is around 35dB and does not often track the RSRP, which may indicate an elevated noise floor or an issue related to gain control.

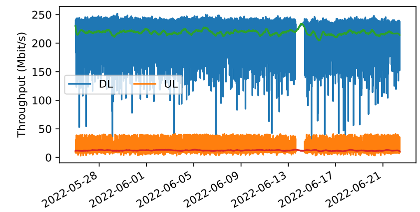
2) Representative Site: Figure 5(d) shows the representative site. Peak downlink throughout is 151mbps, while the minimum was 18mbps, with a mean of 113mbps. Upload throughput was 13mbps, 5mbps and 10mbps respectively.

SINR and RSRP are closely correlated as shown in figure 5(e). SINR averages around 20dB and RSRP around -102dBm, with a total range of about 6dB. Downlink modulation is predominantly 16-QAM. These figures are consistent with the coverage model and is thus a consequence of the link margin afforded by the base station EIRP.

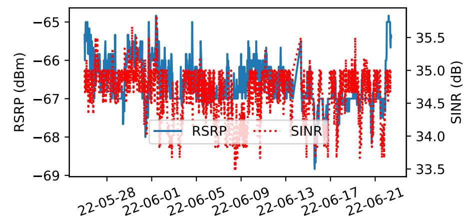
B. *5G Latency*

From our monitoring we observed that latency introduced from the 5G portion of our network appears to be sizable. Figure 6 compares the latency from the UE at our representative site to the 5G Core (network segments A, B and C in figure 1) versus the latency from the gNB to the 5G Core (segments B and C only). A mean increase of latency of 36ms is observed. This is repeated at the idealised site where a mean increase of 28ms is detected (shorter backhaul distances are involved).

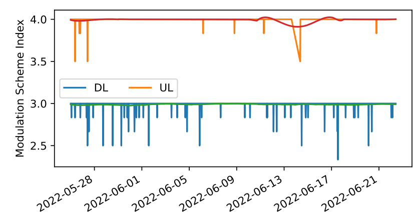
It is uncertain whether this latency overhead originates from the user plane handling in the 5G core or an issue with the gNB



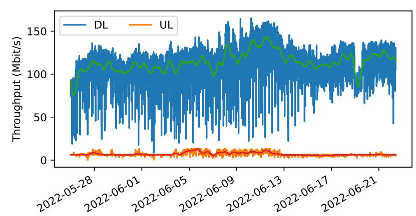
(a) Idealised Site: Throughput



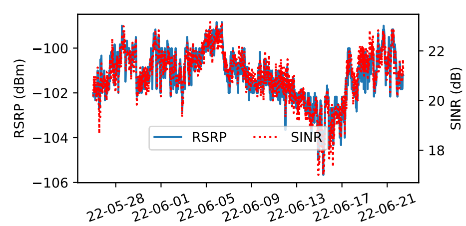
(b) Idealised Site: RSRP/SINR



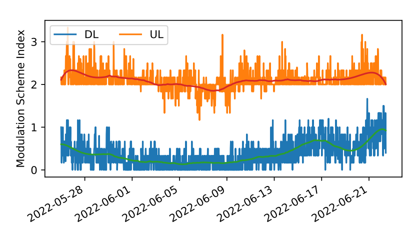
(c) Idealised Site: Modulation Scheme



(d) Representative Site: Throughput



(e) Representative Site: RSRP/SINR



(f) Representative Site: Modulation Scheme

Fig. 5. Typical Performance

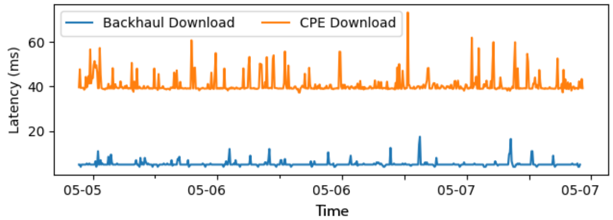


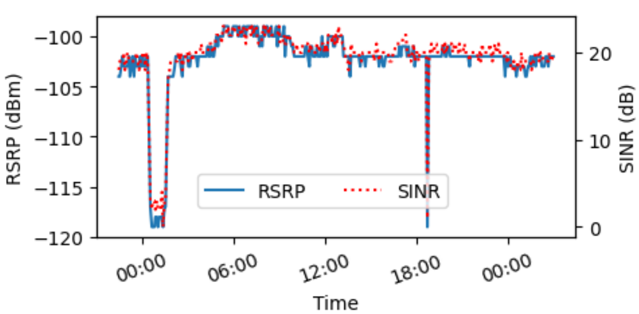
Fig. 6. Representative Site UE vs. gNB Backhaul Latency

however we were able to rule out a specific issue with the NR-7101 UE because alternatives (such as the D-Link DWR-978) generate similar latency. This remains under investigation, but our data rules out a relation to backhaul performance.

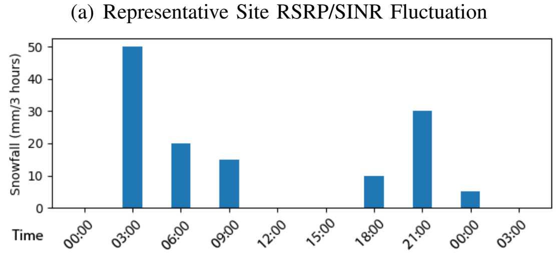
C. Weather

Recall from Section I that the regulator allocated spectrum in C-band with an EIRP forcing a smaller link margin than a typical cellular system as to account for FWA terminals with high gain antennas. We observe above that the achievable SINR is insufficient to maximise 5G performance and this is further degraded by real-world propagation where the continually changeable environment causes variation in SINR.

Variation is not a problem on condition that a sufficient margin is available to support modulation providing an acceptable QoE, however events such as heavy rain or snow cause significant impact or stop service completely. This is unlikely in a wired connection, unless infrastructure is damaged. Figure 7(a) demonstrates variation in RSRP over a 24 hour period.



(a) Representative Site RSRP/SINR Fluctuation



(b) Representative Site Snow Accumulation

Fig. 7. Weather Impact

The nearest Met Office weather observations site is outside the dale's micro-climate, however it does give an indication of humidity, barometric pressure, and temperature. We recorded precipitation accumulation values for the area based on doppler radar imagery, and combined this with temperature data recorded to determine the type of precipitation over time.

Whilst rainfall is more common than snow in this area of the UK, it does occur. Figure 7(b) demonstrates estimated snow accumulation over a 24-hour period, and correlation can be seen between high levels of snowfall and transiently low RSRP/SINR results (Figure 7(a)). Through correlating this data with network layer statistics, we were able to determine that during these transient events no TCP/IP traffic was able to be routed. The impact on the user during these events would be perceived as a loss of internet connectivity. The customer reported that during the night in question they had received over 100mm of snowfall.

Research exists on the rain fade phenomena on mmWave technologies [12], [13], and on the attenuation of 4GHz communication networks in heavy rain [14], further investigation is needed into the impact of weather, and in particular snow, on rural N77 5G networks where there is a constrained link margin and a tendency towards more inclement weather. The regulator might need to consider increasing the gNB EIRP limit, particularly given the natural RF isolation provided by the valley environment.

D. Contention

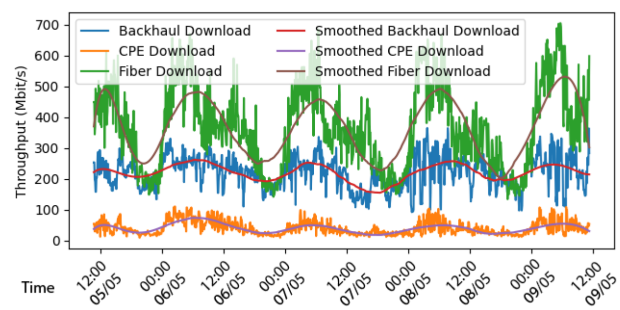


Fig. 8. Representative Site versus Fibre Performance (from 5G Core)

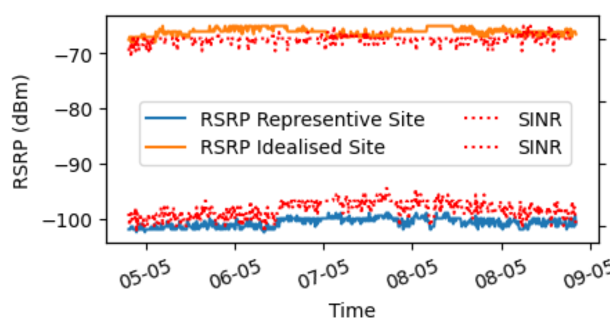


Fig. 9. Representative vs. Idealised Site RSRP

Figure 8 shows a cyclical on/off peak performance variation. A measurement node was installed at the gNB to test backhaul segments B through C (Figure 1). It is not possible to test only segment A as traffic is encapsulated to the 5G Core.

We evaluated data in our dashboard to check (a) whether or not an impact was obvious on the physical layer, and (b) whether not not a similar impact was seen elsewhere in the network. We were able to eliminate the air interface given a lack of change to RSRP and SINR as demonstrated in Figure 9 for the same time period. Our investigation shifted to the core network given that our statistics showed similar variance at other locations, including some without a radio link.

Figure 8 compares the throughput from the UE at the idealised site to the 5G Core (segments A, B and C) as well as from the segments B through C unencapsulated to the 5G Core. The green and red plots utilise a Savitzky-Golay filter to provide smoothing, and are similar. We examined results from other sites and nodes connected directly to the CSP fibre network. The same cycling was observed. We were thus confident that the cycling is not related to the air interface. This information was fed back to the CSP who performed investigation work to deterine the cause, and was later rectified. This led to a large increase in performance and reliability for the end users - compare the orange plot in figure 8 which averaged 43mbps with the blue plot in figure 5(d) averaging 113mbps with no on/off peak cycling.

E. QoE

The QoE metrics (see Table III) are not statistically different to our data from alternative network types - a dataset which includes data from a 1Gbit/s LAN, a 500Mbit/s DOCSIS 3.1 connection, and a 70Mbit/s VDSL connection. We will be improving our QoE analysis [5] as future work.

TABLE III
QoE Results (Representative Site), 3 months)

Metric	Min	Max	Mode
HD Time	99.7%	99.9%	9.8 min
Buffer Events	1.2	1.0	1.0
Resolution Events	2.0	2.3	2.0
Average Buffer Time	0.8s	1.2s	0.7s
Total Buffer Time	0.8s	2s	0.8s

V. Conclusion

Our monitoring framework provided the metrics and insight needed to determine the performance of the 5G technologies trialled in this project for the rural use case in question. This paper has demonstrated the merit of analysing data from the physical layer and external data sources such as weather to contextualise network performance. For the longevity of these systems, we propose that fixed wireless access UE devices should have monitoring functionality accessible via a standardised protocol such as SNMP to allow those without access to gNB telemetry to measure and optimise their network, and provide the best possible QoE for their communities.

Despite the issues that we have observed, n77 5G SA networks can be suited to rural fixed wireless connectivity. It is a good use of underutilised spectrum to provide connectivity, but there is space for improvement in performance if regulators would increase the EIRP constraint on gNBs in environments where signal propagation is naturally limited by terrain. This would provide a link margin supportive of smaller UEs with less ideal antennas, faster modulation to improve user experience, and optimise channel capacity.

Users reported that their primary requirement was fast and dependable Internet access, and that they were less concerned about the type of technology used to achieve it. We have seen some evidence that the complexity of 5G technologies can lead to difficulties and performance problems that are hard to diagnose and address. In some cases these issues appeared to be related to backhaul when in fact they were linked to the design and implementation of 5G technology. This should be a consideration when communities select technologies and is worthy of further investigation.

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