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Pop-up 5G Standalone Non-Public Networks (SNPNs) for Live Broadcast Production

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Abstract – A portable, pop-up private standalone 5G network has been developed and deployed around the world in a series of successful proof-of-concepts for outside broadcast production in remote locations. The flexible software-defined radio (SDR) allows us to rapidly customise the network to the environment and requirements, with low-latency configurations and heavy uplink biasing in the bi-directional RF channel to support multiple wireless camera feeds. We used shared spectrum available in the n78 and upper n77 bands (3.3 – 4.2 GHz) in UK, Ireland, Kenya and New Zealand to deliver live-to-air footage. We explored the use of bonding multiple low Earth orbit (LEO) satellites and cellular backhaul, which allowed us to broadcast the Pitlochry Highland Games live from rural Scotland into the IBC 2022 show in Amsterdam. This paper will discuss the critical technical capabilities of the pop-up private 5G network and how broadcasters have rapidly deployed the technology to support historic and sporting events, including the final journey from Scotland of Queen Elizabeth II and the Danish parliamentary elections. We will also explore how to configure connectivity for optimum performance.

1. Introduction and Motivation

The use of 5G technology is of great interest to the broadcast industry, as it can offer the low latency and high bandwidth requirements for outside broadcast (OB) programme making.

There are two main scenarios that should be considered in the deployment of 5G technologies for programme making. The first are contribution feeds, which are characterised by the current use of bonded cellular devices on a public network, that are typically constrained in terms of latency and bandwidth but offer advantages in ease of deployment and large coverage areas. The second scenario is the use of production links that are characterised by low latency, high bandwidth local connectivity dedicated to a single wireless camera channel. Private 5G networks have the ability to impact on both of these scenarios. The main focus of this paper is to look at the production links workflow, but the technology has also been deployed to support contribution workflows at large scale events.

There are many deployment options for 5G Radio Access Networks (RANs). The most well-known implementations are those used commercially as public networks by Mobile Network Operators (MNOs). These nationwide networks generally have good coverage and capacity all throughout urban and suburban environments. While the use of public networks offers a straightforward and readily-available connectivity option in, there can be challenges with real-world implementation of bonded cellular approaches when thousands of people with mobile handsets flood a venue or in areas with poor coverage (resulting in network congestion). Moreover, much 5G network infrastructure runs as non-standalone (NSA), where it actually relies on a 4G LTE core. These networks cannot support the low latency and uplink bandwidth advantages offered by 5G New Radio (NR).

In addition, existing MNO infrastructure is almost entirely hardware based – custom silicon chips that define and run the mobile network hardware and are capable of supporting thousands of attached devices. Public mobile networks are fantastic at serving their customer base, but this hardware-defined approach does not allow for much flexibility to modify network configuration or performance. Many of the newer ‘midband’ cellular bands use a Time Division Duplexing (TDD) approach, where basestations transmit and receive in the same frequency band. MNOs are required to deploy a permanent TDD downlink bias (*i.e.,* more downlink resource slots than uplink slots) in order to satisfy their customers’ data consumption requirements and not interfere with neighbouring networks. While these are suitable for fast deployment contribution use cases, they are not really suitable for the uplink-heavy demands of the production workflow, particularly as we move towards a cloud-based workflow where all video feeds need to be available in remote or cloud-based production studios.

In contrast, a standalone non-public (private) network (SNPN) can be deployed that is totally independent of the MNOs [1]. These can be customised to meet the coverage, capacity, latency, or quality of service and performance requirements at specific geographical locations. A detailed discussion on NPNs can be found in the white paper produced by the 5G PPP Technology Board [2]. In the future, it may be possible for MNOs to offer private network slices using their RAN infrastructure or Public Network Integrated Non-Public Networks (PNI-NPNs).

Due to the limitations of hardware-based networks, we are particularly interested in the development and deployment of software-defined SNPNs with highly flexible configuration that can be popped up in a location to rapidly provide connectivity for devices in a hyper local area. Unlike conventional broadcast wireless cameras using COFDM radio technology, where spectrum licences must be applied for and managed for each camera as well as all of the telemetry and additional communications channels, the IP connection established by 5G not only allows for two-way communication and control, but it also allows for multiple cameras (and other devices, for example microphones) to be connected under a single spectrum licence. Additional cameras can be added *ad hoc*, within the constraints of the bandwidth available in the allocated channel.

With that in mind, one of the key factors for the deployment of a SNPN is spectrum access. In the UK, and a growing number of other countries, the upper n77 frequency band (3.8 – 4.2 GHz) has been reserved for shared access. While the licensing models are not currently in place for spectrum access similar to programme-making and special events (PMSE) to allow for 5G SNPNs to be readily deployed, we have conducted a number of trials using test and development licences in the UK and abroad, which we discuss presently.

In order to demonstrate the readiness and use of 5G SNPNs for the broadcast industry, since August 2021 we have undertaken a series of proof-of-concept trials exploring the deployment and performance of private 5G networks for the challenging use of video transport.

2. Early Proof-of-Concept Trials

The use of 5G networks for video feed contribution was attractive, but MNO network slicing had not sufficiently matured commercially and broadcasters are concerned about the available uplink bandwidth and spectral efficiency, where unused downlink capacity would need to be deployed in order to achieve suitable uplink bandwidth. Moreover, production feeds often need to sit alongside traditional OB productions and would therefore need output to be available on location [3], and the latency penalty for going up to the cloud and back needed to be carefully considered. With the emergence of viable 5G SNPNs and shared access spectrum made available in the UK, there was an interest in using these SNPNs for production links (as well as contribution feeds), but the technology needed to be tested and contrasted with existing COFDM solutions.

MotoGP (Silverstone, UK)

Aim: *Demonstrate the use of a pop-up 5G SNPN for video contribution.*

In August 2021, the University of Strathclyde and its spin-out company, Neutral Wireless Ltd., were invited by BT Sport and Dorna to deploy a SNPN at the Silverstone racecourse in the UK, in a trial to connect wireless cameras for a MotoGP race. A single-cell gNodeB was used to flood the pitlane from a high-gain 60-degree sector antenna, with a 50 MHz channel centred on 3870 MHz using 30 kHz subcarrier spacing. The cell ran in SISO with 26 dBm transmit power, and the antenna gain was 17 dBi giving a downlink EIRP of 43 dBm. While running SISO in the transmit path, 4 receive paths were configured to exploit receive diversity and increase performance. The AW2S Panther remote radio head was collocated with the antenna and connected to the gNodeB using single mode fibre. The system ran using the Amarisoft standalone 5G core and vRAN implementation on a single machine with an Intel i9 processor. The flexible software-defined radio allowed for the physical layer TDD configuration to be biased slightly more to uplink, with the frame structure configured to use 5 slots for uplink and 4 for downlink.

FIGURE 1: VISLINK 5G-ENABLED ENCODERS IN THE PITLANE AND MOUNTED TO A SAFETY BIKE.

Multiple cameras provided by Vislink were connected to the SNPN, including the HCAM5 and a motorbike-mounted camera shown in Figure 1. Cameras capturing full HD (1080i50) were connected by SDI to 5G-enabled H.264 encoders connected to the SNPN using modems configured to transmit at 23 dBm, where they were compressed to 12.5 Mbps streams delivered over the 5G network to the corresponding decoder situated in the production gallery, which provided SDI back out into the broadcast chain. End-to-end (SDI-to-SDI) latency was estimated to be around 200 ms. The 12 Mbps video feeds were easily accommodated even at low signal-to-noise ratios (SNRs) ~15 dB and low modulation depth (16-QAM).

This trial was intended as an internal test that ran alongside the tradition OB production. However, the director was impressed by footage coming back from the pitlane, and the cameras were used as part of the live-to-air production, capturing interviews and imagery live from the pitlane. We believe this is the first live-to-air video contribution using a SNPN.

UK Premiership Rugby (StoneX, UK)

Aim: *Demonstrate multiple low latency 5G-connected cameras with direct COFDM comparison.*

Following some internal development work by Neutral Wireless, the 5G technology used at Silverstone was integrated into a wheeled rack flight case to make it more suitable for transportation and rapid deployment at events. The Neutral Wireless “Network-in-a-box” (NIB) featured the AW2S software-defined radio head and a new compute platform, which was configured to run the Amarisoft 5G core and vRAN software. The first outing for the NIB was at the Saracens versus Northampton Saints Gallagher Premiership Rugby match (at the StoneX stadium, UK) where two cells running 50 MHz channels in n77 were configured to increase coverage range (although it was found that the pitch was sufficiently covered by a single cell). Neutral Wireless also developed a heavily uplink-biased 2:7 (DL:UL) frame structure to significantly increase uplink bandwidth and support more camera feeds.

FIGURE 2: NEUTRAL WIRELESS NIB PITCH-SIDE AT STONEX (LEFT), AND THE 5G AND COFDM CAMERA FEEDS (RIGHT).

Working with BT Sport, BT Media and Broadcast, Vislink and Broadcast RF, the n77 NIB was deployed at the stadium, and integrated into the wider OB that was provided by Broadcast RF. Two wireless pitch-side cameras were fitted with Vislink encoders with COFDM and 5G transmitters, and 12 Mbps feeds were simultaneously sent back over both COFDM and 5G radio links to Vislink decoders to allow for a comparison of the technologies, side by side, as can be seen in Figure 2 (right). There was a latency of a few frames with the 5G feed, as would be expected for the IP-based network. The OB producers used the video carried over the 5G network as part of the live feed, in a UK first. Never before had key match day cameras used as part of a consumer broadcast been enabled in this way.

3. IBC Accelerator Project – Remote Production in the Middle of Nowhere

Based on the successful early trials discussed above, the University of Strathclyde and Neutral Wireless pitched an IBC Accelerator project exploring 5G-enabled “remote production in the middle of nowhere”. The concept was to take a pop-up 5G SNPN to remote locations around the world where internet connectivity was not assured, and use it to explore new production models based on HD wireless camera feeds and tailored to available backhaul.

The goals were to explore the use of an SNPN to provide the communications backbone for high-bandwidth and low-latency media broadcast applications, and to demonstrate that the technology could be made highly portable and low power for rapid deployment anywhere in the world, including off-grid. In addition, the trials aimed to investigate different backhaul connectivity (and bonding) using fibre, cellular, and low Earth orbit (LEO) satellites infrastructure.

The project was very successful, and recently received the **IBC 2022 Accelerator Project of the Year award.**

Fleadh Cheoil – Traditional Music Festival (Mullingar, Ireland)

Aims: *– Demonstrate multiple SNPN-connected camera feeds;*
– Investigate SNPN bonding.

In August 2022, the Neutral Wireless NIB was deployed at the Fleadh Cheoil Traditional Music Festival in Mullingar, Ireland. The 32kg flight case was transported by car and ferry from Scotland. Working with the national broadcaster RTÉ, two LiveU wireless encoders (LU300 and LU600) were equipped with SIMs for the SNPN and used around the streets of Mullingar. The production ran out of an RTÉ OB van, with the 5G antenna and a Starlink for backhaul mounted on the roof as shown in Figure 3.

FIGURE 3: LEFT: RTÉ OB VAN WITH RADIO HEAD AND ANTENNA MOUNTED WITH STARLINK TERMINAL ON THE ROOF. RIGHT: CAMERA OPERATOR ROAMS THE STREETS TESTING THE COVERAGE PROVIDED BY THE SNPN.

A 20 MHz channel was used in the lower n77 (n78) band with an uplink biased 2:7 (DL:UL) frame structure. The 12 Mbps FHD HEVC video streams broke out on the local user plane where there was an LU2000 server on premise. The feeds were routed through an SDI video distribution switch before being re-encoded at 6 Mbps using an LU600 and streamed back to a decoder at RTÉ headquarters in Dublin to enter their live production chain. The backhaul was bonded over Starlink and dual 4G SIMs. The LiveU encoders were using a latency of 2 s. Full network and signal workflows are shown in Figure A1 in the Appendix.

LiveU video encoders are regularly used to bond multiple MNO connections to maximise uplink bandwidth by intelligently splitting the video stream over multiple routes and recombining on the decoder – something possible due to the high-latency workflow. In this trial, we explored bonding using two SIM cards *on the same SNPN*, and the results were better than expected. While the camera with a single modem could maintain its video feed while in line-of-sight of the cell antenna, we found that the bonded camera was able to go much further including exploring the streets of Mullingar *without* line-of-sight. Since frequencies up at 4 GHz can scatter widely in an urban environment, we could actually make use of the reflections off buildings to maintain connectivity. Since the stream is split over two interfaces with their antenna physically separate spatially, and the load on each dynamically adjusted to accommodate the available bandwidth, the bonded solution was very stable and robust.

Ol Pejeta Conservancy (Kenya)

Aim: *Demonstrate NDI|HX workflow with YouTube Live stream production using renewable energy.*

FIGURE 4: SNPN DEPLOYED IN THE BACK OF A VAN IN THE OL PEJETA CONSERVANCY WITH THE HOSTS OF SHENG TALK.

Also in August 2022, the Neutral Wireless NIB made its way by aeroplane to Kenya, where it joined WhatsGood Studios in the Ol Pejeta Conservancy – a large nature conservation area in central Kenya.

Spectrum was agreed with the Communications Authority of Kenya for a 50 MHz channel in n77 with a 2:7 (DL:UL) frame structure.

Production ran in the back of a 4x4, using solar panels through an inverter to provide power. Two Magewell Ultra Encode SDI NDI|HX encoders were connected to the 5G SNPN through a 5G-ethernet bridge configured by Neutral Wireless, which streamed 16 Mbps H.264/HEVC to their counter-part Magewell Pro Convert SDI decoders to feed into a Blackmagic ATEM. An NDI Discovery Server ran on the baseband unit that allowed the decoders to discover the encoders, or the NDI|HX feeds could be configured by manually specifying the source IP address on the private 5G network. The cut feed was presented to an Apple Mac mini computer via USB, and was then streamed live to YouTube. As seen in Figure 4, the presenter drove around the conservancy, showing their large YouTube audience the wildlife there and discussing the 5G workflow they were using. The SDI-to-SDI latency in this workflow using the off-the-shelf Magewell encoders and decoders was around 150ms. In this case, fibre backhaul was available at a nearby mobile cell mast, while the production was powered using solar panels feeding a 600W inverter. Full network and signal workflows are shown in Figure A2 in the Appendix.

Interim Māori Spectrum Commission and Whakaata Māori TV (New Zealand)

Aims: *– Rural deployment for live newsgathering;*
– Full NDI over 5G.

To complete the trip around the world, Neutral Wireless worked with the Interim Māori Spectrum Commission (IMSC) to deploy a NIB in rural New Zealand. Spectrum was made available in the n78 band (3.4 – 3.8 GHz) for a 50 MHz channel.

FIGURE 5: SNPN DEPLOYED AT A SCHOOL IN RURAL NEW ZEALAND, WITH MĀORI CHILDREN PERFORMING A MAU RĀKAU TRADITIONAL MĀORI MARTIAL ARTS CLASS.

The 5G SNPN was set up at a rural school, where cameras captured live video feeds of the schoolchildren performing a Mau Rākau traditional Māori martial arts class, as shown in Figure 5. LiveU LU300 encoders were used, with the 6 Mbps feeds backhauled over Starlink to a decoder at the Māori TV in Auckland studios for post-production and live broadcast. Full network and signal workflows are shown in Figure A3 in the Appendix.

In this trial, a BirdDog NDI encoder was used to send an 80 Mbps full NDI video feed over the 5G SNPN to a decoder on the user plane. Again, the NDI Discovery Server ran on the baseband unit. We believe this was the first time that full NDI video has been delivered over a private 5G network.

Pitlochry Highland Games (Perthshire, Scotland)

Aims: *– Multiple camera OB at rural location with programme feed produced on site;*
– Programme feed (and multiviewer) delivered live to IBC show floor (cloud distribution);
– Talkback over 5G;
– Bonded Starlink terminals and MNO SIMs for backhaul.

The traditional Highland Games are a long-standing celebration of Scottish culture. The Pitlochry Highland Games is one of the busiest weekends of the year for the small rural town in Perthshire, Scotland. The Pitlochry Highland Games were inaugurated in 1852, and we were welcomed by the Chieftain to use the 170th anniversary Games as a testbed for 5G production in a remote location.

This trial aimed to demonstrate a full multiple camera production with an on-site vision mixer to deliver a cut programme feed from a location with poor backhaul connectivity. While rural Pitlochry has partial 4G coverage from public networks, the arrival of several thousand people made this unfeasible as a backhaul option. We therefore wanted to test the performance when bonding multiple Starlink units, in principle attached to different satellite flights, to combat the video drop experienced at handover when using a single terminal.

Working with the Scottish production company QTV, a four-camera production was deployed with the Neutral Wireless NIB to Pitlochry. The 5G antenna was mounted on the pavilion overlooking the Games field, along with the two Starlink terminals. The network ran a 100 MHz channel in n77 with a 2:7 (DL:UL) frame structure. Production ran out the back of a Land Rover parked next to the pavilion, shown in Figure 6.

Figure 6: Left: QTV camera operator with 5G-connected encoder and antenna mounted on camera.
Centre: On site production in the back of a Land Rover.
Right: The multiviewer feed received and displayed at the IBC 2022 show in Amsterdam.

The four JVC cameras captured full HD 1080p50, which was passed to H.264 encoders provided by Open Broadcast Systems. These small form factor encoders were powered from a battery bank and carried in a small satchel by the camera operator. An external 5G modem and dual antenna were connected to the encoders by a 2m USB extension cable, allowing for them to be mounted to the camera well above head height and ensuring line-of-sight visibility with the 5G SNPN cell.

The encoders encoded 4:2:2 10-bit video at 20 Mbps, and these streams were packaged using the Zixi protocol and transported to a Zixi Broadcaster server, which distributed them to the Open Broadcast Systems decoder as well as making stream and 5G network statistics available. The local SDI-to-SDI latency was around 160 ms, including a 50 ms Zixi stream buffer. The four camera feeds passed through a Blackmagic ATEM for local multiview and on to a local vMix instance provided by QTV, where they were cut to produce a live programme feed. This was sent from vMix to the Zixi Broadcaster using SRT, before being transported to Zixi ZEN Master using the Zixi protocol with the stream bonded over the two Starlink units and two 4G SIMs. In addition to the programme feed, a single static camera feed was sent to ZEN Master, and the multiviewer was encoded and sent to Net Insight (unbonded) using SRT. Full network and signal workflows are shown in Figure A4 in the Appendix.

To demonstrate the flexibility of cloud-based distribution, the programme feed was shared from Zixi to Net Insight, before being delivered to the IBC show floor at RAI in Amsterdam using SRT. Unfortunately, during the on-stage live interview from Pitlochry, we experienced some packet loss that degraded picture quality and was originally attributed to the Starlink bonding at such a northern latitude. However, it was later found that the inter-cloud connection between Zixi and Net Insight did not have a sufficient latency buffer to account for the round-trip time and jitter for an inter-continental cloud hop over public internet. This was corrected by simply increasing the Zixi stream buffer by an additional 100ms for the remainder of the show. The statistics available through Zixi ZEN Master for each leg of the stream journey allowed us to identify the source of the packet loss.

In this trial we also demonstrated the use of 5G for talkback. The Open Broadcast Systems C-100 encoders were configured to produce a small protected WiFi hotspot that provided the camera operators with internet access over the 5G network. Since half of the production team were remote (at the IBC show in Amsterdam), we decided to use the low-latency voice platform offered by Discord. This allowed for low-latency communication between the director and camera operators (on site) as well as the remote team. We note that the Blackmagic ATEM could be operated remotely from Amsterdam, but the increased latency when using bonded backhaul meant that cuts made live at the IBC show did not appear in the received programme feed for a few seconds.

4. Live-to-Air Broadcasts

The IBC Accelerator exposed the broadcasters and production companies involved in the events to the capabilities of a pop-up 5G SNPN for programme making, and inspired the confidence to use the emerging technology on real-world live-to-air broadcasts that we discuss in this section.

Her Late Majesty Queen Elizabeth II's Final Departure from Scotland

Aim: *Provide a single 5G wireless camera feed at Edinburgh Airport for a live-to-air world feed.*

On Thursday, 8th September, 2022, Her Majesty Queen Elizabeth II passed away at her Balmoral home in rural Scotland. When this happened, Operation Unicorn – the codename for the transport of Her Majesty's body if she were to pass away in Scotland – came into effect. The plan had originally been that the Royal coffin would be transported by rail from Edinburgh Waverley station, but it had been recently changed to an RAF C-17 Globemaster aircraft from Edinburgh Airport. A shortage of availability of traditional wireless cameras systems – bonded cellular or COFDM – in the UK left BBC Scotland (as the world feed provider) and the Glasgow-based production company QTV, who had been tasked with delivering the outside broadcast, without an option to deploy a traditional wireless camera at the airport. A cable trailing across the runway was not a possibility for an angle shooting towards the congregation, and therefore these significant shots could not have been captured.

At the IBC show in Amsterdam, QTV had partnered with Neutral Wireless, Open Broadcast Systems and Zixi to deliver the multi-camera production over private 5G that was being displayed live on the IBC Accelerator stand. The question arose – why could we not deploy this solution at the airport? The only impediment was spectrum. Working with colleagues at the BBC, a short-term short-notice spectrum licence for n77 at Edinburgh Airport was granted by the UK regulator, Ofcom, allowing for the Neutral Wireless NIB to be deployed at the airport on Tuesday, 13th September 2022, as shown in Figure 7.

Figure 7: Left: Neutral Wireless NIB at Edinburgh Airport. Right: 5G-connected camera is set up.

The airport was a very challenging RF environment to operate in, particularly with the high-power radar transmitter operating nearby. The shared spectrum licensing for n77 is low power transmit, which is well suited to the broadcast application where we are primarily concerned with listening for the video stream uplink. We found that our antenna was saturated by the radar signal, significantly reducing our receive sensitivity and leading to a large amount of packet loss at a regular periodic interval. We describe this as trying to listen to our user equipment whispering while the radar shouted at us.

To overcome this challenge, we did three things. First, we reduced our channel to 50 MHz, since the narrower bandwidth increases the power spectral density as the same power is transmitted but across a smaller range of frequencies. This increases the signal-to-noise ratio (SNR) at the receiver and improves the uplink channel quality. Secondly, we turned the antenna architecture “the wrong way round” and used our large high-gain directional sector antenna at the user equipment (UE), and the lower gain omni-directional antenna at the cell. This allowed us to whisper a bit louder and improved our SNR while reducing the sensitivity of the receive antenna to the radar, resulting in less (but still noticeable) packet loss. Finally, we increased the Zixi stream buffer up to 250 ms to allow for sufficient packet recovery between radar bursts. With these changes, we were able to deliver a stable 20 Mbps H.264 1080i50 stream as a contribution to the OB production, with an SDI-to-SDI latency of around 18 frames (360 ms). This was noticeable but very workable in an otherwise entirely wired production. We note that the latency was nothing compared to that of the feed provided by the helicopter, which was delayed by several seconds and suffered from low bitrate artifacts and packet loss.

As a backup option, a second copy of the video stream from the same Open Broadcast Systems encoder was taken out using Zixi bonded over dual 4G dongles to an AWS cloud instance. This was then brought back down to the production using a 4G customer premise equipment (CPE). In our testing, this worked well, albeit with a noticeable delay compared to the private 5G feed. However, as the procession approached the airport, the 4G backup feed dropped and could not be maintained. Interestingly, it was not the uplink that failed, but rather the downlink back to the OB van.

The video feed contributed using the 5G SNPN received around 10% air time in the live world feed provided by the BBC, which is estimated to have been viewed by over 1 billion people around the globe. We believe that this was the first public live-to-air international broadcast using private 5G network technology without a traditional failsafe in place.

National Ploughing Championships 2022 (Ratheniska, Ireland)

Aim: *Deliver a live-to-air feed at a large event with significant network congestion.*

Neutral Wireless partnered once again with RTÉ and LiveU to deploy a NIB and wireless HEVC encoders at the National Ploughing Championships in Ratheniska, Ireland – an event attended by 300,000 people every year. The workflow was similar to the music festival in Mullingar, with an on-site decoder as well as a feed being delivered to RTÉ headquarters for a live-to-air feed. In this trial, the LiveU LU800 encoder used to re-encode the feed for delivery to the production facility bonded the stream over two Starlink terminals with excellent results. The workflow is presented in Figure A5 in the Appendix. Using the 5G SNPN-connected wireless camera, a live weather report was delivered from the fields at the ploughing championships, as seen in Figure 8.

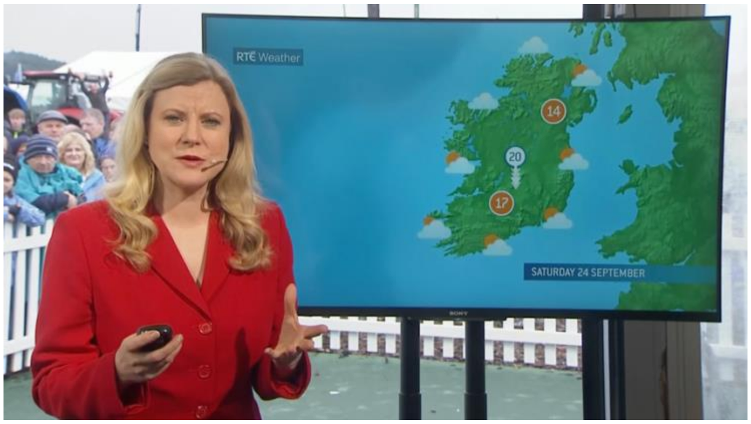

Figure 8: RTÉ weather report delivered live from the fields at the National Ploughing Championships.

With 300,000 people attending the event, MNOs faced significant network congestion issues and, to overcome this, additional temporary cells were brought in to cover the rural location. The presence of this concentrated MNO activity created a challenging RF environment for our low power system, and once again we found that our antenna was being saturated. With TDD, the basestation transmits and receives in the same frequency band, with transmit and receive alternating in time. The uplink-biased 2:7 (DL:UL) frame structure that we were running, which used 2 downlink slots followed by 7 uplink slots, clashed with the MNO frame structure of 7 downlink slots followed and 2 uplink slot (7:2). Our send and receive were out of phase, resulting in us attempting to listen to our low power UE while the MNO cells were transmitting.

In order to overcome this, Neutral Wireless engineers reconfigured the network to match the MNO frame structure, and used GPS to frame-lock with the MNOs to ensure that we were all listening at the same time. This really highlights the flexibility of the software-defined radio approach, allowing the network configuration to be readily adapted to local RF conditions. Since we were only attempting to contribute one wireless camera feed, the reduced uplink bandwidth caused by the downlink-biased frame structure was not a problem, but usable range whilst maintaining the modulation coding scheme (MCS) to support the required bitrate was reduced.

Danish General Elections (Copenhagen, Denmark)

Aims: *– Multi-cell network deployment with cell handover;*
– Ultra-low latency video contributions;
– SMPTE 2110 IP-based workflow to delivery.

As a final 2022 international outing for the Neutral Wireless NIB, in October the SNPN travelled to Copenhagen (Denmark). Working with Danish national broadcaster TV 2 and Haivision, low-latency 5G wireless cameras were used at the historical Christiansborg Palace to capture the events surrounding the Danish Parliamentary Elections.

Two cells running 50 MHz channels in n77 were deployed at the palace – one outside in the courtyard to provide coverage for the arrival of the new Prime Minister (PM), and a second inside the building to provide coverage as the party made their way through to the PM's new office. The outdoor cell was fitted to a bicycle for portability, as captured in Figure 9. Cameras could move around and handover between cells. However, due to the very low latency encoder being used, cell handover did result in a dropped frame. A small buffer could have prevented this dropped frame occurring, but at the expense of an additional latency of 1-2 frames.

Figure 9: Left: Network ~~in a box~~ on a bike – outdoor cell deployed for maximum mobility.
Right: Measuring the RF constellation (QAM-16).

The baseband unit was located in the basement of the building, where a fibre patch panel provided connectivity throughout the palace and grounds. The two radio heads were both located with their antenna (to minimise RF cable length) and connected to the baseband unit using single mode fibre capable of supporting the 10 Gbps radio fronthaul. Backhaul to the TV 2 studios was dedicated dark fibre.

Two low latency HEVC video streams were encoded by Haivision Pro 460 units directly connected to the Neutral Wireless SNPN using their internal Sierra Wireless EM9191 5G modems. They were transported over the 5G network to a Haivision StreamHub on the local user plane, which decoded the streams and pushed the video out to the TV 2 production facility over dedicated fibre in a fully SMPTE 2110 IP-based production workflow [4,5]. TV 2 measured end-to-end latency of less than 100 ms from camera to their production studios. The resulting feed was looped back to the palace, where it broke out as SDI for local display. At the palace, the SDI-to-SDI latency (including the trip through the TV 2 production workflow and back) was measured as approximately 115 ms.

5. Key Learnings

When we started on this journey, the potential benefits of 5G SNPNs for the broadcast industry were understood, but whether the technology was mature enough to use in practice and whether it ultimately delivered on its promises in real-world application remained to be seen. Our biggest take home from the trials and events described here is that the technology is absolutely ready to find use in broadcasting, and will continue to improve with adoption and experience.

The benefits of the software-defined radio (SDR) approach should also not be overlooked, as it allows for complete network flexibility and rapid adaptation to local RF environments. Without this on-the-fly reconfigurability, several of the events above could have failed to deliver on their desired outcomes. The ability to tune the network for uplink bias is significant for broadcasters trying to support as many cameras onto a private network as they can, especially as we move towards 4K content. The SDR solution used here allows for the frame structure to be highly uplink biased, such as 8 upload slots and 1 download slot (1:8). With this configuration, we have been able to sustain over 400 Mbps in the uplink with round-trip time (RTT) of 10ms in single-input single-output (SISO) mode with a 100 MHz channel (over 4 bits/Hz). This can be significantly improved running in multiple-input multiple-output (MIMO) but requires the UE to support uplink MIMO. The frame structure can even be changed to 2:2 or even 1:1 to support very low latency network transit with extremely low jitter (*e.g.,* for audio workflows).

Receive diversity differs to MIMO as the downlink and uplink transimission are both still SISO, however multiple receive paths are used to listen and aggregate the signal. This can be used to significantly increase SNR. At Silverstone for the MotoGP, this led to an improvement of over 3 dB. Using receive diversity allows for different RF polarisations to be received or different spatial locations, which prevent the (regular) situation where the polarisation of a UE's SISO antenna is not well aligned with, or obstacles prevent loss of line-of-sight to, one single-polarisation receive antenna. For example, if a UE transmitting with polarisation +45° and being well received by a +45° antenna were to turn 180° around, its polarisation would now be -45° and orthogonal to the receive antenna. With no receive diversity, the signal quality for this UE will drop drastically. Whereas, with receive diversity using both +45° and -45° polarisations, a good connection can be maintained.

For video streaming applications using protocols with error correction (such as SRT and Zixi) we found that running with unacknowledged mode (UM) on the radio link control (RLC) layer can improve latency and jitter. Since the streaming protocols already include packet recovery (such as forward error correction (FEC) and automatic repeat request (ARQ)) we do not need to do this on the RLC layer as well, and it can actually interfere with the retransmission and in sequence delivery. Acknowledged mode (AM) is typically desirable for TCP-like applications. Retransmission at the medium access control (MAC) layer can be minimised, but we recommend not to disable completely.

Likewise, quality of service (QoS) can be defined to managed resources and reduce latency (as the UE do not need to request resources from the scheduler). Static QoS flow and resource priority for particular traffic or IP addresses can be used to ensure particular UEs take priority over others for resources, or RLC UM bearers to reduce retransmission latency for UDP-based video streams with error correction. These can be mapped to access point names (APNs) to restrict access by SIM card. This can be used to guarantee resources to high priority devices. Indeed, UEs with unprotected resources (not QoS guaranteed bearers) can benefit significantly from variable bitrate (VBR) encoders. When resources become constrained or the UE is close to the cell edge with reduced SNR and MCS, rather than drop frames as the bearer can no longer support a specified constant bitrate (CBR) there is a reduction in bitrate (and quality) to match the available resources. It would be preferable for a live feed to reduce in quality than glitch or drop altogether. Both CBR and VBR devices can be accommodated and coexist peacefully on the network.

NDI-based workflows can be configured to run over the 5G network, either using an NDI Discovery Server or mDNS mirroring across interfaces. Like on a wired IP network, for NDI and NDI|HX it is necessary that both the encoder and decoder have clear IP routes to one another, and this should be borne in mind when designing the wider network topology.

While encoders that perform bonding over multiple interfaces are regularly used to bond over multiple MNOs to maximise throughput and reliability, we have found that bonding multiple UE on the same SNPN provides significant benefits to the stream robustness and reliability. These results have been repeated at the University of Strathclyde's rural 5G testbed on the banks of Loch Lomond using LiveU LU300 encoders with dual external 5G modems and SIMs on the same SNPN.

It is often tempting to run a full 100 MHz channel to maximise uplink bandwidth – more is always better, right? But if the application does not require the full bandwidth, then network performance (including range and reliability) can be improved by reducing the channel width and increasing the power per subcarrier.

We showed how multiple (consumer) Starlink terminals could be bonded and used together to avoid the frame drop often experienced by the hard handover from one Starlink satellite to another. The Starlink units were started up physically separated and offset in time, which appears to be sufficient to coax them into connecting to different satellite trajectors and therefore detaching and reattaching at different times. For the Pitlochry IBC event, we used Zixi to bond over two Starlink terminals and two 4G MNO SIMs, but as the crowds arrived we found that the contribution over the 4G links was almost nothing.

In addition to our own learnings, we would like to highlight the findings of the EBU 5G-RECORDS project [5] that investigated the integration of 5G SNPNs in media production workflows [6].

6. Conclusions and Future Outlook

5G offers many potential advantages over traditional wireless camera systems used within the broadcast industry, from its high data rates to low latency. For many of these advantages to be realised, it is necessary to look beyond the mobile network operator (MNO) offerings to standalone non-public networks (SNPNs) that offer the user the ultimate in network configurability to tune the network as necessary, such as highly uplinked biased or low latency frame structures. Software-defined radio solutions, as used here, are highly flexible, and in this paper we have demonstrated many different devices and production workflows.

One of the biggest advantages that 5G brings is the bi-directional IP connection to the user equipment, which in the broadcast market allows for talkback, tally, return video and camera control to all be performed with low latency over the one network connection. In this paper, we have demonstrated carrying two-way audio communication over the 5G network to facilitate an OB with off-site participants. While not used in the trials above, we have also developed and demonstrated tally lights integrated with traditional tally hardware, and performed full camera control (exposure, shutter, iris, white balance, *etc*.) with cameras from Grass Valley and ZCAM. Finally, we have provided return video over the 5G network directly using RTP/SRT or using webRTC to web browser clients. In principle, if a device can be connected and controlled over ethernet, it can be connected and controlled over 5G using a 5G-to-ethernet bridge. 5G is ready to facilitate all of this essential OB functionality.

This two-way connection has a significant impact on licensing, since the successful application for one 5G spectrum licence can be used to support multiple cameras and all of the control, comms. and telemetry required. With traditional broadcast systems, these each require dedicated spectrum and therefore around 4 individual spectrum licences must be managed and maintained *per wireless camera* for each event. However, access to shared spectrum is not straightforward or universal, nor are the procedures and licensing models currently in place to support PMSE-like access for agile and reactionary deployment. Spectrum access may be a major bottleneck to SNPN adoption.

The successful proof-of-concepts that have been undertaken and discussed here have demonstrated that 5G SNPNs are capable and ready to support live outside broadcasts. They can be taken anywhere and be used to supplement on site production resources with multiple wireless cameras at latencies that can be used as part of a traditional cabled production. Over the 5G SNPN, we have successfully run low latency feeds (as low as 70 ms SDI-to-SDI) using encoders from Open Broadcast Systems, Haivision, Vislink and Nulink, as well as high latency bonded cellular devices from LiveU, Haivision, and Mobile Viewpoint. We have run multi-camera productions and demonstrated multi-cell deployment with handover. With a heavily uplink-biased frame structure, we can sustain over 400 Mbps in the uplink with a round-trip time latency of around 10ms, although this can be reduced at the expense of bandwidth using low latency frame structures.

This paper also discusses live-to-air events where this technology was successfully used as part of real broadcasts. Of course, the technology is still in its infancy and will improve with investment and experience. In fact, there are a number of new features in release 16 that will be beneficial but are as yet unsupported by the majority of 5G modems. Some important ones include configured grants, ultra-low latency frame structures, and soft handover.

This is an exciting time for 5G and particularly SNPNs as their potential role in broadcast is explored further, and we will continue to engage and push the boundary of what can be achieved with SNPNs and the ultimate creative freedom that wireless production can deliver.

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Appendix: Workflow diagrams

This appendix contains the full network and signal flow diagrams for the trials discussed above.

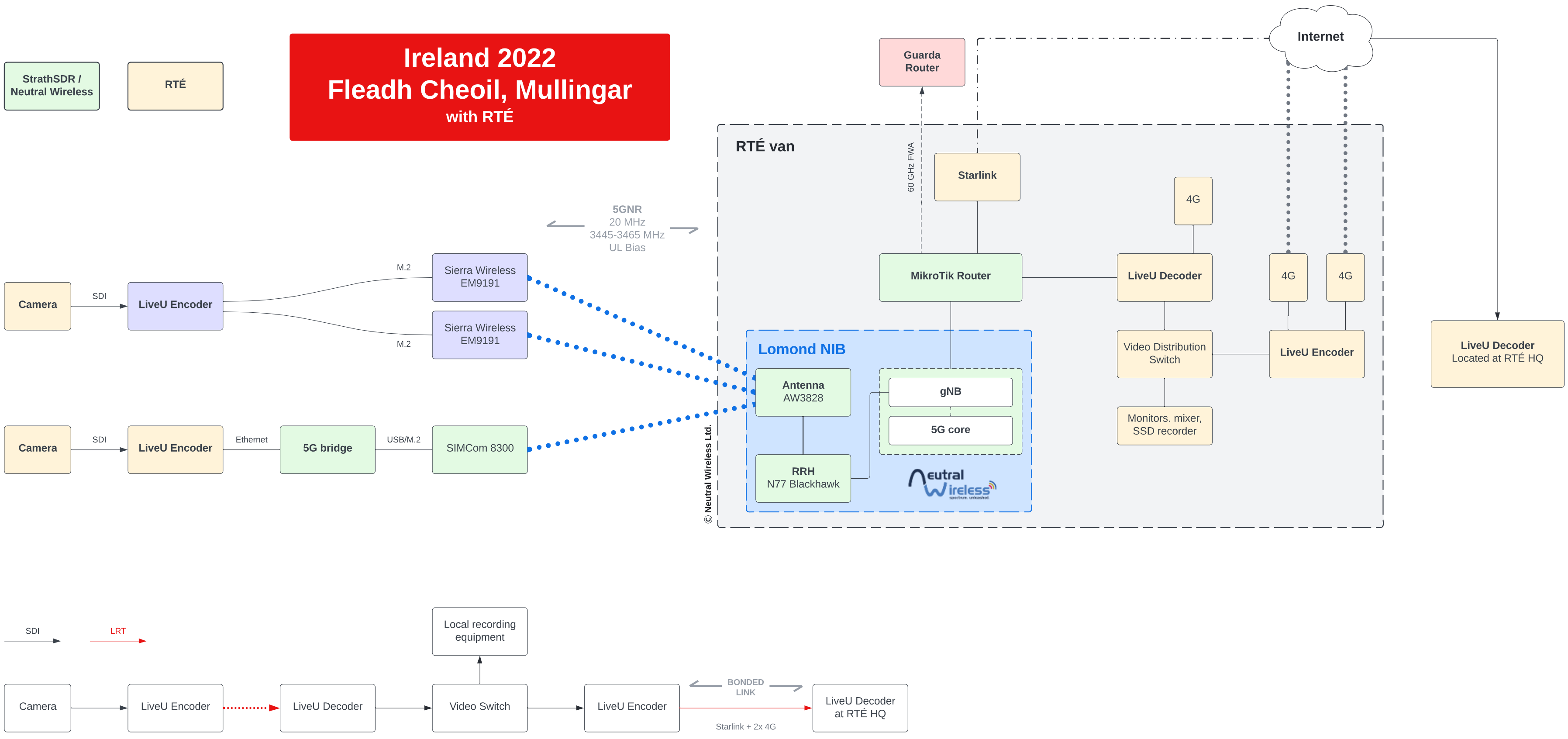

FIGURE A1: NETWORK DIAGRAM FOR THE WORKFLOW USED IN IRELAND (SECTION 3), WITH SIGNAL FLOW DISPLAYED LOWER-LEFT.

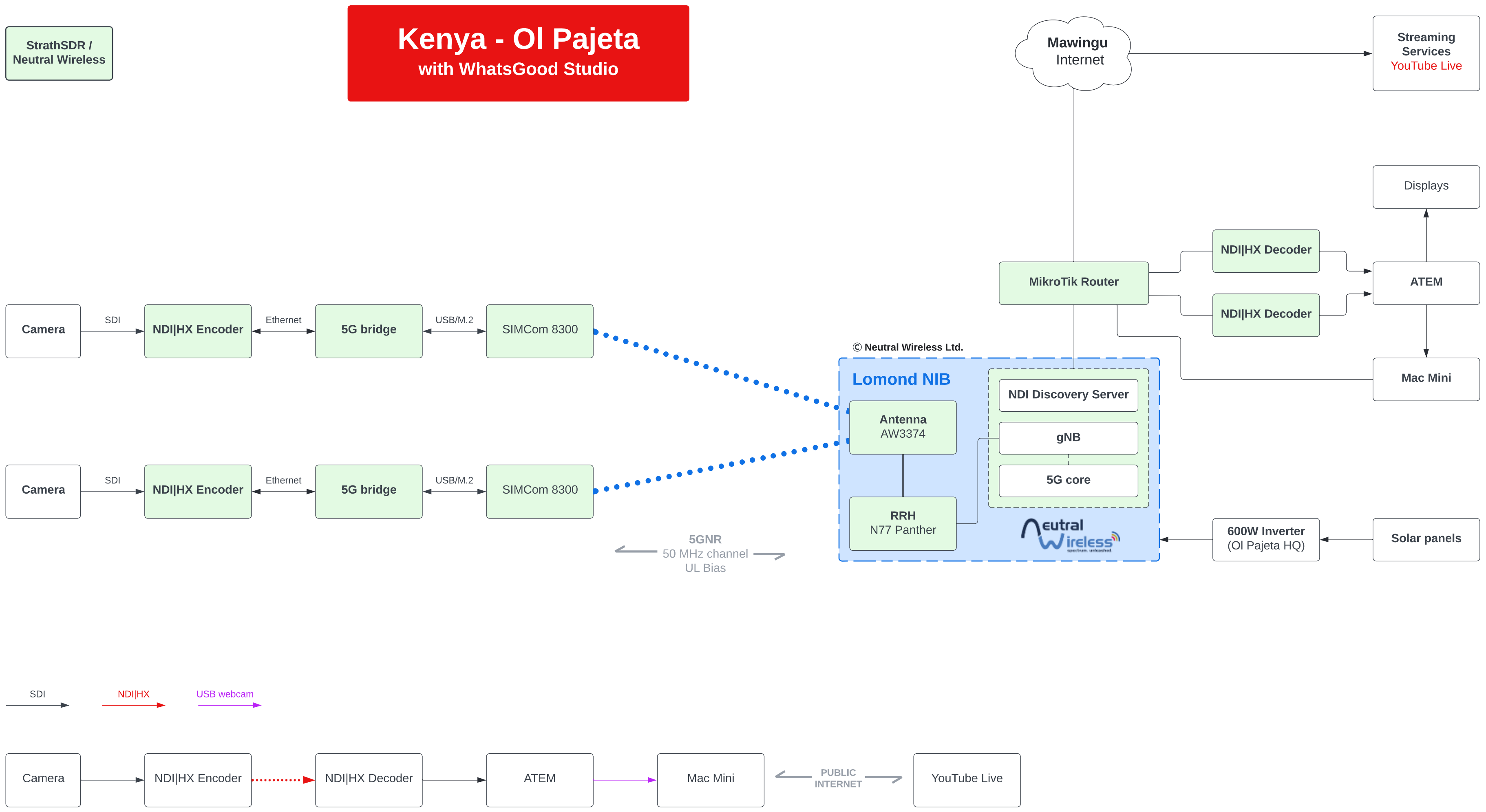

FIGURE A2: NETWORK DIAGRAM FOR THE WORKFLOW USED IN KENYA (SECTION 3), WITH SIGNAL FLOW DISPLAYED LOWER-LEFT.

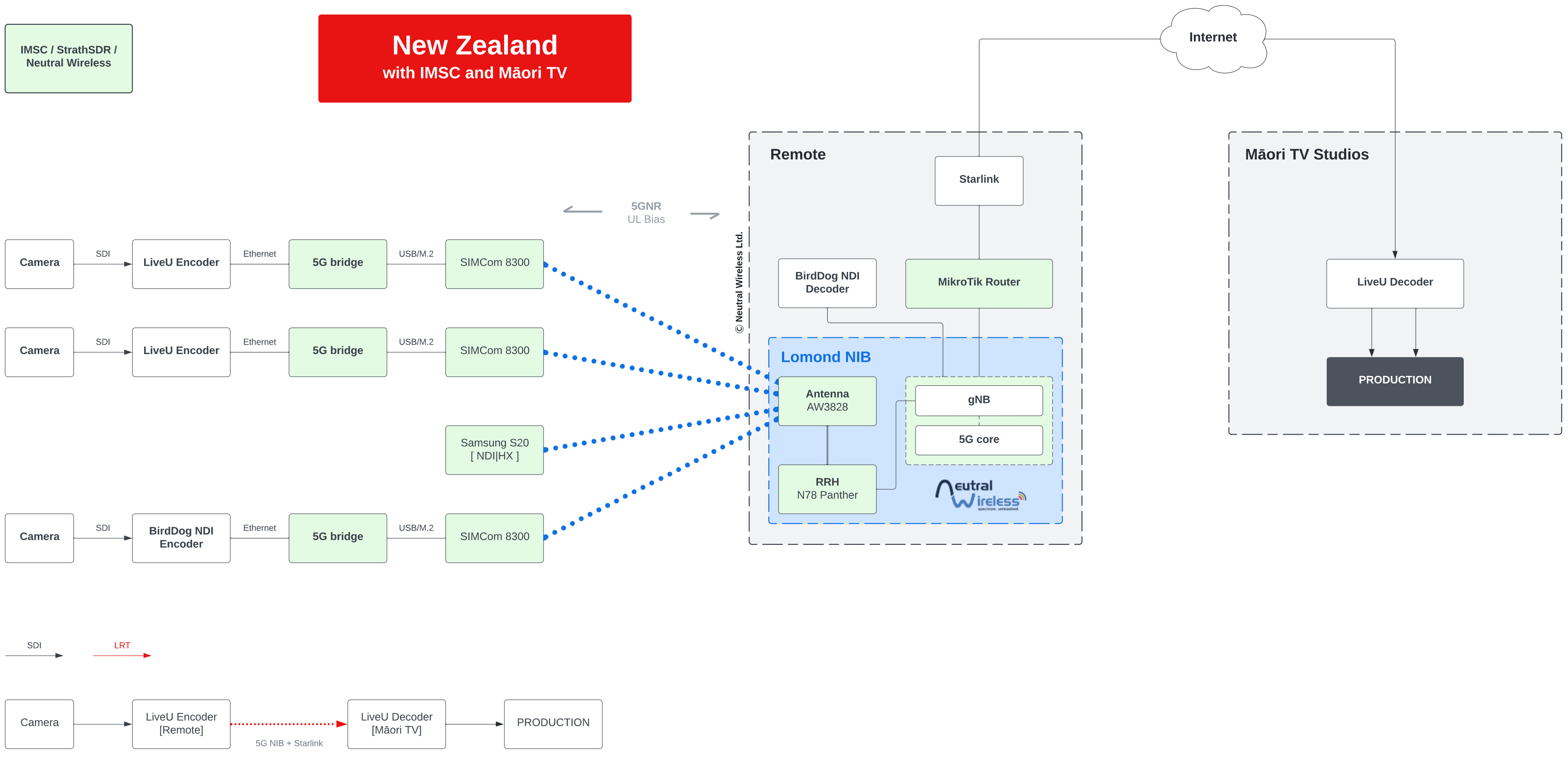

Figure A3: Network diagram for the workflow used in New Zealand (Section 3), with signal flow displayed lower-left.

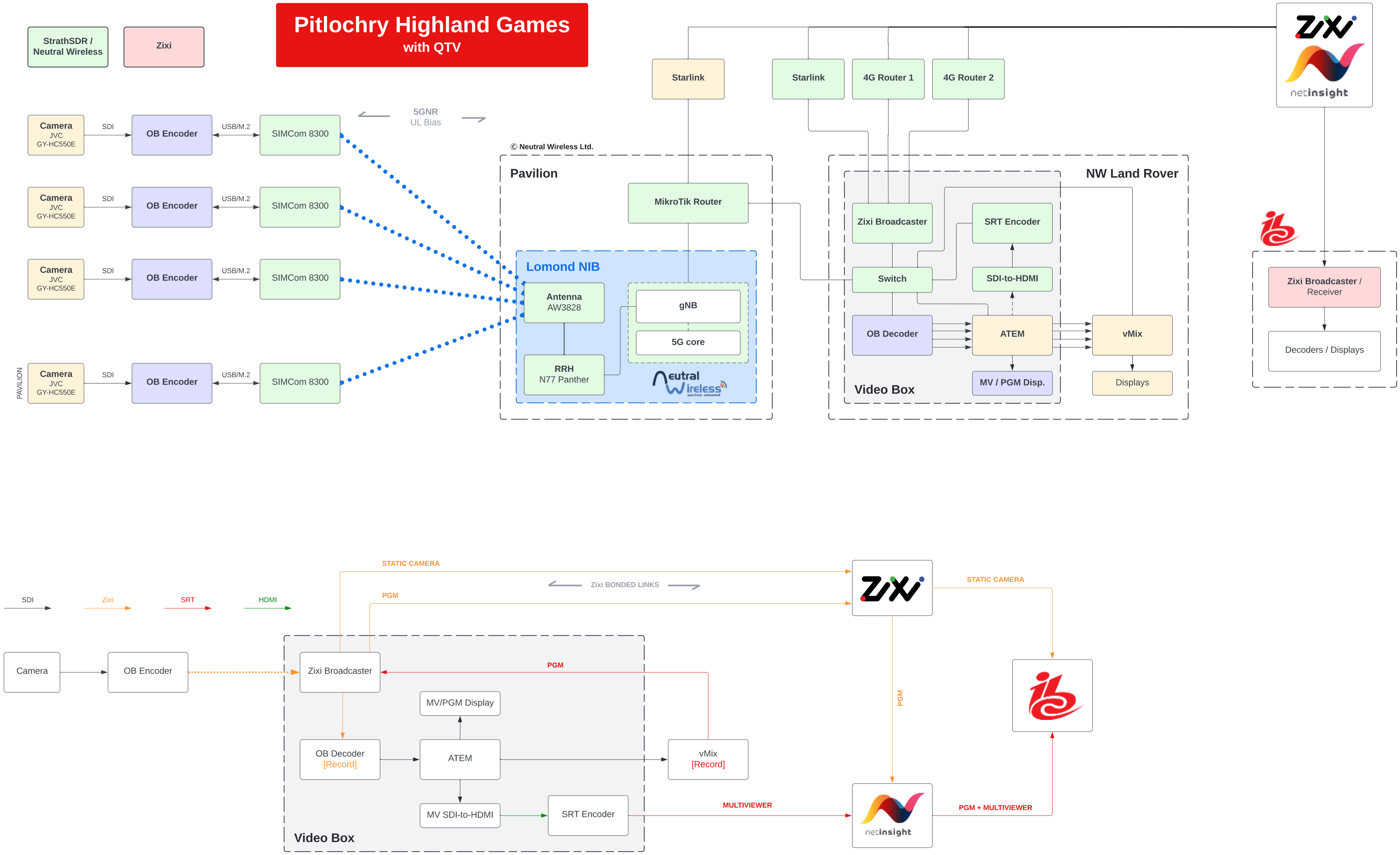

FIGURE A4: NETWORK DIAGRAM FOR THE WORKFLOW USED IN SCOTLAND (SECTION 3), WITH SIGNAL FLOW DISPLAYED LOWER-LEFT

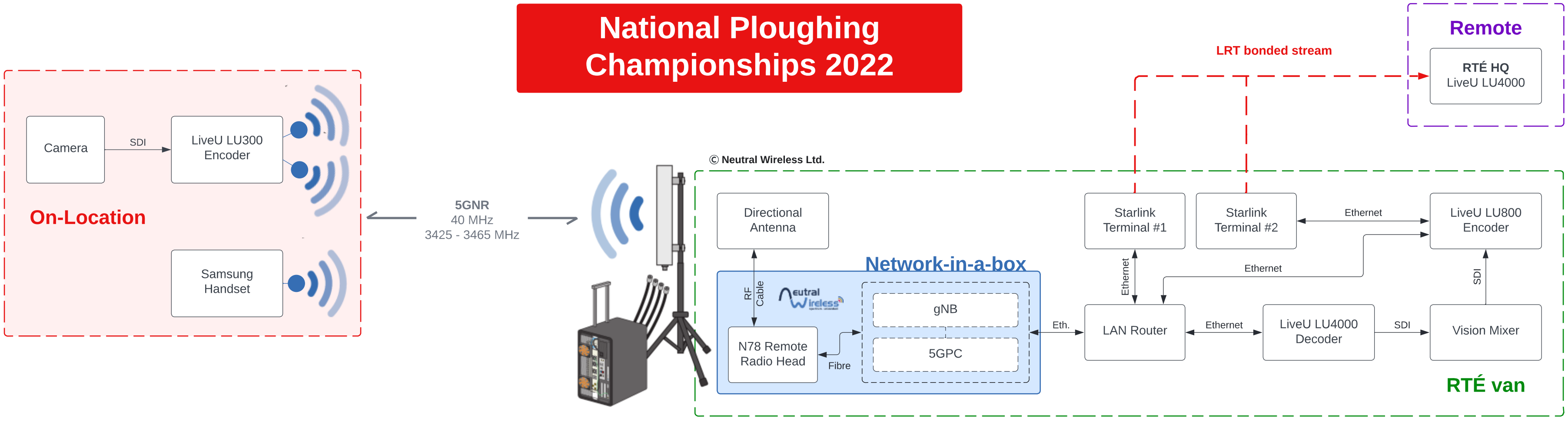

FIGURE A5: NETWORK DIAGRAM FOR THE WORKFLOW USED FOR THE NATIONAL PLOUGHING CHAMPIONSHIP (SECTION 4).