Using a Private 5G Network to Support the International Broadcast of the Coronation of HM King Charles III

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Abstract – Wireless cameras for news contribution feeds regularly use "bonded-cellular" devices, which connect to and split the encoded video across multiple public mobile network SIMs. However, in high demand density environments with large crowds, the public networks can quickly become saturated and unable to sustain the necessary bitrates to support high-definition video. To overcome this and provide uncontested wireless connectivity, the largest pop-up 5G standalone non-public (private) network of its type was deployed outside Buckingham Palace and along The Mall to Admiralty Arch to support news contributions for domestic and foreign broadcasters at the Coronation of HM King Charles III, without changing the contribution workflow.

Introduction

Wireless camera feeds are an integral source of video content for programme making. This is typically done using specialist point-to-point radio frequency (RF) links, or via "bonded-cellular" devices that connect to more than one public mobile network operator (MNO) and split the encoded video traffic over them. Direct point-to-point radio link implementations are generally derived from Coded Orthogonal Frequency Division Multiplexing (COFDM) technology and deployed in custom frequency bands [1]. These offer low latency and robust constant bitrate video streams, but only support a single camera per channel with one-way connectivity. Multiple cameras therefore require many licences to be managed, and additional or return connectivity requires further spectrum licences. Instead, bonded-cellular devices use variable bitrate encoding, and allow the encoded video stream to be distributed across multiple public networks, reducing the required resources from each and adapting to network conditions on each path. These devices have higher latency than dedicated point-to-point links, but require no specific RF licensing and are straightforward to deploy. In recent years, news organisations have invested heavily in these devices, which have become a mainstay replacing satellite trucks for on-location reporting and contribution feeds.

In high demand density (HDD) environments with many devices all competing for resources, the public mobile networks can become saturated and unable to sustain the necessary bitrates to support the live

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streaming of high-definition (HD) video. The issue with relying on the public mobile networks for media contributions is that these HDD events tend to be newsworthy, and wireless remote contributions offer value to broadcasters and viewers. Despite the heavy investment by news organisations in bonded-cellular devices, they cannot be relied upon at events where there are large crowds or multiple organisations all competing for the same finite network resources.

In February 2023, BBC News identified a requirement to provide continuous mobile coverage for news teams on part of the procession route during the Coronation of Their Majesties King Charles III and Queen Camilla, after experiencing significant difficulties during the state funeral held for Her Late Majesty Queen Elizabeth II. It was expected that the large crowds would present a similar problem for public mobile networks and bonded-cellular contribution devices, not just for themselves but all domestic and foreign broadcasters. Wireless cameras were essential for their planned coverage, as crowds would begin to gather and camp along The Mall in the run-up to Coronation Day.

BBC News and BBC R&D approached Neutral Wireless, a Scottish software-defined radio (SDR) company and spin-out from the University of Strathclyde. BBC R&D have previously worked with University of Strathclyde and Neutral Wireless on several private radio network projects, including TV White Space and the award-winning IBC 2022 Media Accelerator Project of the Year [2]. The aim was to deploy an ambitious large-scale 5G standalone non-public network (SNPN, often referred to as simply a *private network*) to provide seamless uncontended coverage in the vicinity of Buckingham Palace and along The Mall to Admiralty Arch, guaranteeing uplink connectivity for use with existing bonded-cellular devices without changing the workflow or day-to-day operations for the news teams. This paper discusses the benefits of a private 5G network for broadcast production and the decisions taken to deploy the world's largest pop-up private 5G network for media contributions [3, 4, 5].

(Private) 5G for Broadcast Production

Wireless equipment to facilitate Programme Making and Special Events (PMSE) has been in common use since 2002 [6], and are usually based on COFDM technology in dedicated single-camera frequency channels [1]. While 5G is also based on COFDM technology, it provides a native bi-directional TCP/IP network, which can easily integrate with modern IP studio infrastructure and systems. This can provide several advantages over conventional technology. 5G allows a single wireless network to support many connections, servicing multiple connected devices with the same spectrum. Moreover, the nature of the network allows for bi-directional data, such as audio communications, return video feeds, camera control and tally lights – or any service that can be encapsulated in IP. This is achieved in conventional PMSE deployments by using separate radios and spectrum licences for each service, which quickly proliferates and requires coordination and management. The ability to do all these services under a single 5G spectrum licence is attractive.

In the UK, Ofcom recently introduced several *shared spectrum* bands, which can be used for private networks through the shared access licence (SAL) scheme [7]. This includes the (upper) n77 frequency band, 3.8–4.2 GHz, which is also being made available as shared spectrum elsewhere in Europe and under consideration in many countries worldwide. Commercial off-the-shelf modems natively support many 3GPP-defined spectrum bands, including the SAL spectrum, which significantly reduces cost and complexity when compared with traditional wireless PMSE techniques. In addition, they also support and can operate in wider bandwidths than conventional PMSE channels, increasing link capacity to enable multiple devices and/or enhanced services, such as ultra-high definition (UHD) video.

While the MNOs provide an excellent and widespread service, they are not optimised for uplink-heavy traffic, such as HD video contributions. Typically, around 75% of a public network's resources are dedicated to downlink connectivity in order to satisfy customer demand to *consume* content. In fact, the UK regulator, Ofcom, stipulates that all mobile networks use the same allocation of downlink and uplink resources and are time-synchronised, such that they all "march in step" to avoid interfering with one another. Bonded-cellular devices address this issue by reducing the uplink resource requirement on each individual network.

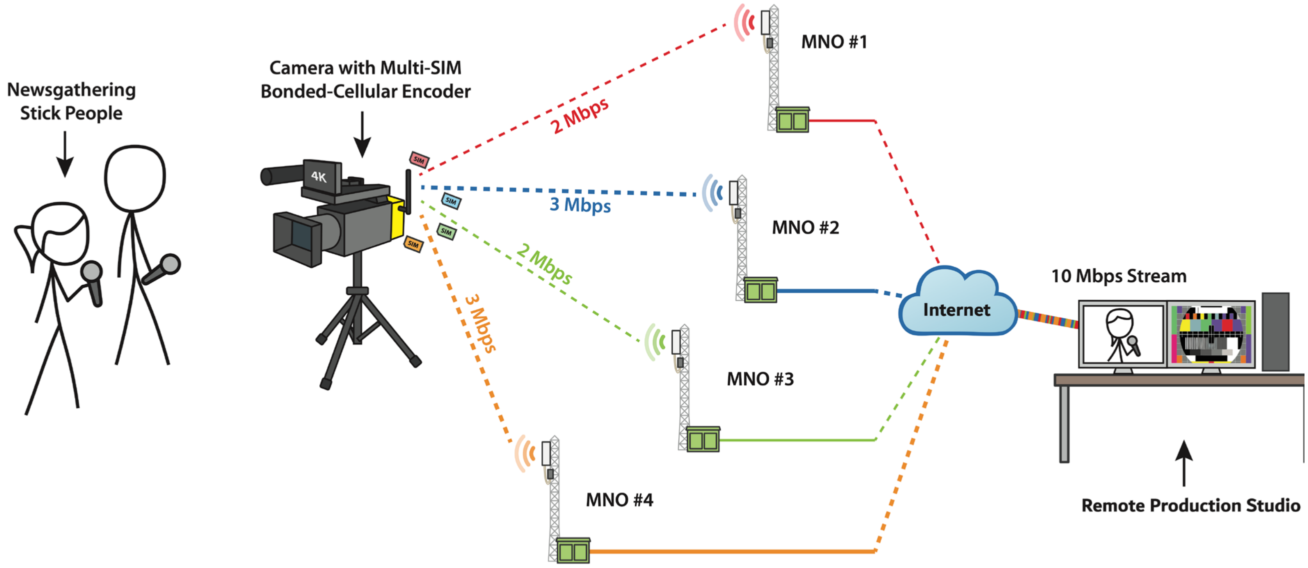

FIGURE 1: THE BONDED-CELLULAR WORKFLOW – ENCODED VIDEO DATA ARE SPLIT ACROSS MULTIPLE PUBLIC MOBILE NETWORKS TO REDUCE REQUIRED RESOURCES AND INCREASE RESILIENCY.

As shown in Figure 1, the encoded video data is distributed across several public mobile networks and recombined at a decoder, either in the cloud or a production gallery. Using bonded 4G/5G non-standalone public networks is becoming increasingly common for electronic newsgathering (ENG) in preference to traditional point-to-point radio links. In the UK, contribution broadcast feeds are typically produced as interlaced full HD at 50 frames per second (1080i50) compressed with H.264 or HEVC (H.265) to 6–12 Mbps. Under normal network load, these bonded-cellular streams can usually be carried on public MNO infrastructure. However, since resources are provided on a best-effort basis, even bonded systems can fail in HDD environments with large crowds, where the public mobile networks are likely to become congested by the volume of traffic.

Spectrum is a finite resource, and all wireless radio communications require spectrum to operate. Unlike WiFi, which operates in unlicenced frequency bands around 2.4 GHz, 5 GHz, and now 6 GHz, standalone non-public networks operate in regulated spectrum for which a licence must be obtained. This means that spectrum licensed to you should not be in use by anyone else, providing uncontended resources. WiFi is completely unregulated – there is nothing to prevent anyone from creating WiFi hotspots congesting the spectrum, and the presence of thousands of devices with WiFi enabled and scanning for networks can easily saturate the spectrum.

For bi-directional communication, two parties both need to talk to the other. The spectrum resources can either be shared in time (time division duplexing, TDD) or frequency (frequency division duplexing, FDD). In the former, the two parties take it in turns to use all the resources, whereas, in the latter, they talk at the same time but using half the resources each. Networks in the n77 band use TDD, where resources are shared between downlink and uplink in time. In LTE and 5G, the downlink/uplink slots are organised into a repeating pattern called a frame – see Figure 2, reproduced from [3]. Using the 15 kHz subcarrier in LTE, in the UK it was decided that public mobile networks operating in TDD bands should adhere to a 3:1 downlink:uplink ratio [labelled (a)] to serve the needs of consumers. When 5G came along, despite access to higher numerologies, this ratio needed to be maintained to prevent interference with nearby LTE networks.

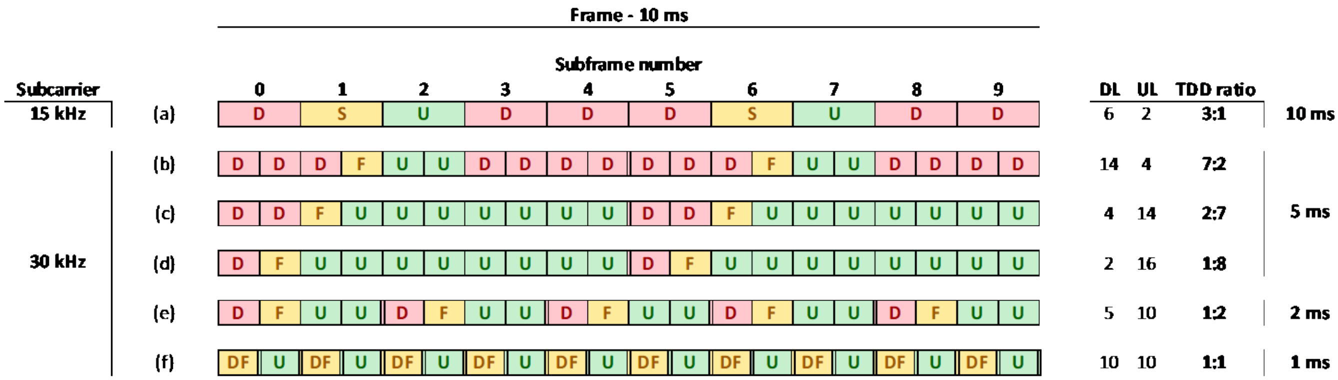

FIGURE 2: A SUBSET OF 5G TDD FRAME CONFIGURATIONS

Currently, in the UK there is no restriction on TDD configuration for private networks operating in shared spectrum, such as n77. This allows for networks to be configured to be uplink-biased instead, such as the 2:7 configuration shown in part (c) above, or for lower latency as shown in (e) and (f). This flexibility allows private 5G networks not only to provide dedicated resources, but also be optimised for the broadcast use case.

The advantages presented by private 5G networks for PMSE have been studied in several large European collaborative research projects [8, 9]. Previous private 5G network deployments for broadcast production trials have looked at both low-latency production workflows [10, 2, 11, 12] and contribution workflows [13, 2] using one or two macro cells, but the cell handover mechanism in mobile technology allows the network to be readily extended using additional radio equipment.

Network Planning

One of the key requirements for BBC News was that the solution could not change the bonded-cellular contribution workflow – it needed to be business as usual for the news teams on the ground. BBC News also recognised that all broadcasters were going to be in the same position, and from the beginning wanted to develop a solution that they could open up to the national and international broadcast community. As such, they were expecting a large number of devices and potentially simultaneous video streams – more than had been previously demonstrated on a private 5G network and were naturally cautious as to whether a private network could provide the connectivity they needed.

FIGURE 3: TESTING 20 1080P50 LRT STREAMS USING 12 LIVEU BONDED-CELLULAR DEVICES AT LOCH LOMOND.

Initial testing was conducted at the University of Strathclyde's Scotland 5G Wave1 rural test-bed on the banks of Loch Lomond, Scotland. Twelve *LiveU* LU300, LU600 and LU800 devices were updated to support 5G standalone networks and connected to a Neutral Wireless Lomond network-in-a-box (NIB) running two adjacent test cells with 50 MHz channels in the shared spectrum n77 band. Twenty simultaneous HD video (1080p50) streams with bitrates 8–12 Mbps were carried on a single cell, with some feeds landing on a local decoder and others streamed to international locations. Network capacity, range and cell handover were stress-tested, with different camera operator configurations and devices on the cell edge. The test-bed has a tree-lined driveway that was used to model The Mall, and HD streaming was maintained to a distance of 875m before line-of-site to the antenna was lost.

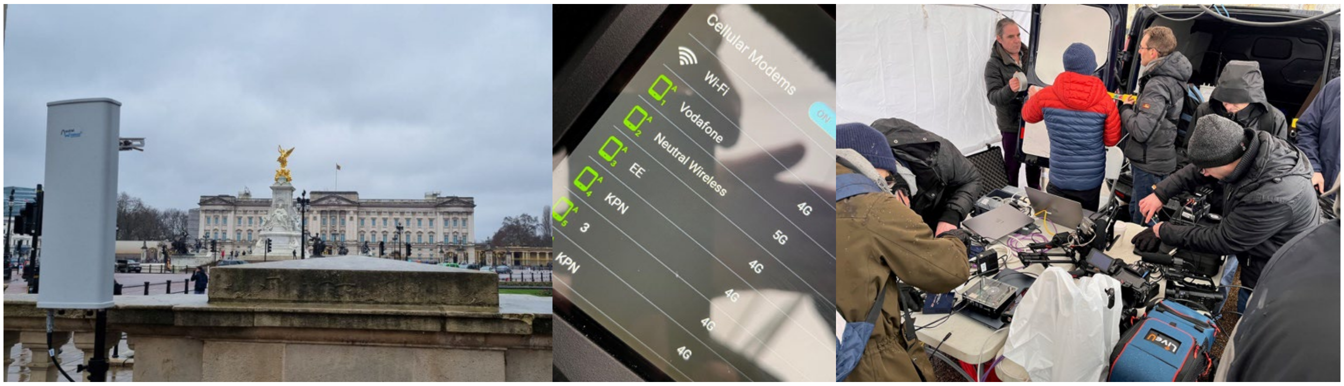

FIGURE 4: ON-SITE TESTING AT CANADA GATE WITH INTERNATIONAL BROADCAST TEAMS AND TECH SUPPORT.

After the very successful tests in Scotland, network planning on The Mall started. Spectrum surveys revealed that the upper n77 spectrum band was relatively clear at that location, A 100 MHz n77 test and development (T&D) shared spectrum licence was applied for at Canada Gate, situated next to Buckingham Palace. Working with the Foreign Broadcaster Service, domestic and international broadcast partners were invited to join forces, and bring their devices to two test days in March 2023. Commercial bonded-cellular encoder vendors have previously worked to ensure that their devices attach to networks provisioned by Neutral Wireless, but experts from LiveU and Haivision were on-site to assist with updates and any connectivity issues.

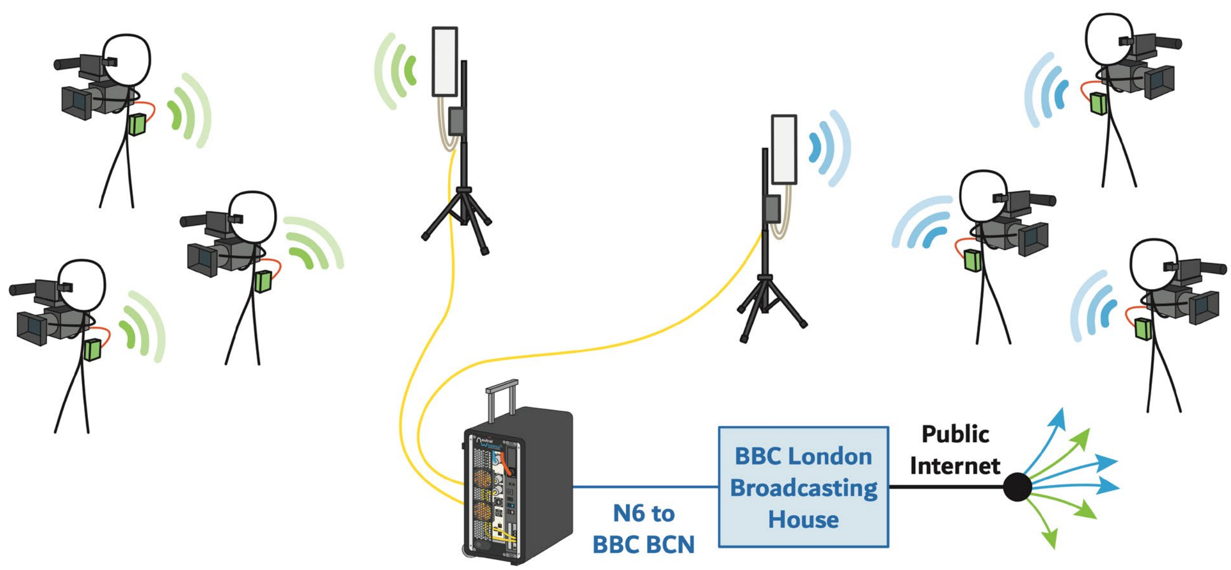

FIGURE 5: ILLUSTRATION OF THE TESTING WORKFLOW AT CANADA GATE.

The tests again ran two cells with handover, and range tests demonstrated uplink connectivity all the way to Green Park (around 400m). Internet connectivity was achieved through the BBC Broadcast Contribution Network (BCN) – a dedicated 10 Gbps fibre network back to BBC London Broadcasting House. During the tests, more than 20 devices were connected to a single 50 MHz channel, with video streams landing back at their broadcast bases. Walking tests demonstrated how bonded-cellular devices could successfully bond over public and private mobile networks, and how bonding on two private network SIMs could increase range and resiliency [2].

With the interest and support of the international news broadcast community, full preparation for the network began. An RF site survey along The Mall was conducted to identify locations of broadcast infrastructure that would make suitable sites for 5G network cells and provide continuous network coverage over the 1km route from Buckingham Palace to Admiralty Arch, which leads on to Trafalgar Square. This needed to account for the tree canopy growth and crowds that might attenuate the 3.8–4.2 GHz frequencies intended for use. Four sites were identified to locate seven network cells to cover the area using an alternating A/B channel plan.

In addition to the main contribution network, BBC R&D and Sony expressed an interest in using the opportunity to also test low latency UHD broadcast production workflows and test cell co-location. A separate single-cell network was added at Canada Gate to cover the area outside Buckingham Palace, using a different core network with functionality to allow dynamic quality-of-service (QoS) control and device prioritisation.

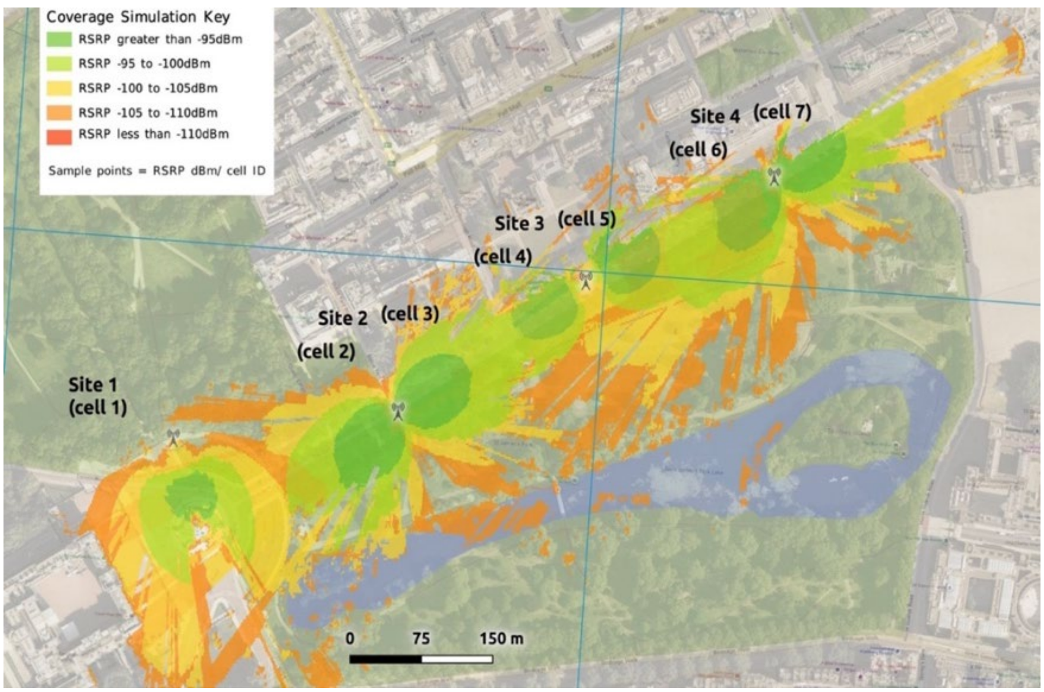

FIGURE 6: RADIO FREQUENCY MODELLING TO PREDICT PRIVATE 5G NETWORK COVERAGE.

A series of RF propagation simulations [14, 15] were conducted to inform cell orientation and parameters, and to indicate expected coverage. RF simulations were performed using the Irregular Terrain Model (ITM) v7 (known as the 'Longley Rice' model) with the CloudRF engine [14, 15]. As shown in Figure 6, the modelling suggested good coverage of the procession route could be achieved from the four sites and was presented to Ofcom to support a shared access licence application for 8 cells using two 50 MHz channels in an alternating A/B channel plan. Site 1 would be a trailer mast in the media compound rigged with one cell at 8m to provide coverage across the front of the Palace. Sites 2, 3 and 4 would use fixed camera platforms to locate two cells with antenna at 4m pointing in opposite directions.

Network Delivery

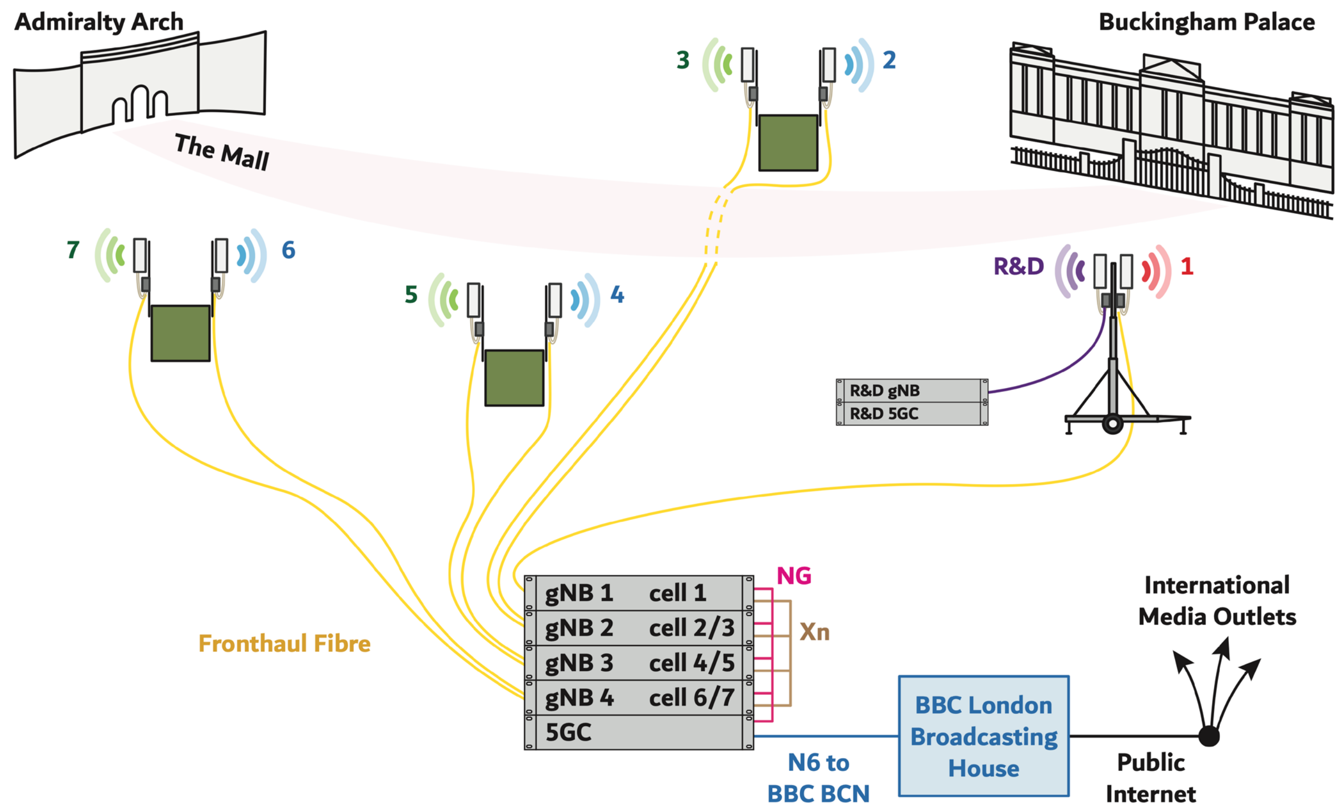

FIGURE 7: MEDIA CONTRIBUTION PRIVATE NETWORK ARCHITECTURE.

At the end of April 2023, the radio heads and antennas were rigged at the agreed camera platform and radio booth locations, with fibre runs back to the base stations in the media compound for the radio fronthaul. A trailer mast was rigged and erected at Canada Gate, providing coverage outside the Palace and across the media compound. This cell was complemented by an additional cell designated for low-latency UHD testing with dynamic QoS control. The main contribution network compute was comprised of five 2U servers: one ran the software-defined 5G network core, and the remaining four ran up to two cells each of the software-defined radio access network (RAN) stack. While each compute was technically capable of running four cells, additional computers were used to reduce the load and provide redundancy should there be a failure. The cells were configured to allow handover between the cells and enable seamless connectivity from one end of The Mall to the other. The core network was backhauled over the BBC BCN to London Broadcasting House, where it joined public internet.

Ofcom granted a licence for 80 MHz of spectrum centred at 3855 MHz. This was used as two 40 MHz channels:

- **A** – 3815–3855 MHz [ARFCN 655666] and
- **B** – 3855–3895 MHz [ARFCN 658334].

In addition, a third channel was available at Canada Gate under the original testing licence:

- **C** – 3895–3935 MHz [ARFCN 661000].

Cells 3, 5, 7 and the R&D cell used channel **A**, while cells 2, 4 and 6 used channel **B**. Channel **C** was only used by cell 1 at Canada Gate. The agility of the Neutral Wireless software-defined radio deployed meant that changes to the radio parameters were easily accommodated. The network was brought up and tuned to optimise handover at the cell edges and maximise coverage. Downlink transmission powers were configured within the licence specification.

Coverage Validation

Once the network was operational, on-the-ground measurements were taken to verify the RF model predictions. This was performed using RSRP and GPS logging on a mobile handset, and using a 5G modem connected to a Raspberry Pi computer equipped with a GPS receiver. Paddle-type monopole antennas with gain ~2 dBi were used on the Raspberry Pi modem, which typically reported values 12 dB greater than the mobile handset. This would be consistent with the phone having an effective antenna gain of approximately –10 dBi.

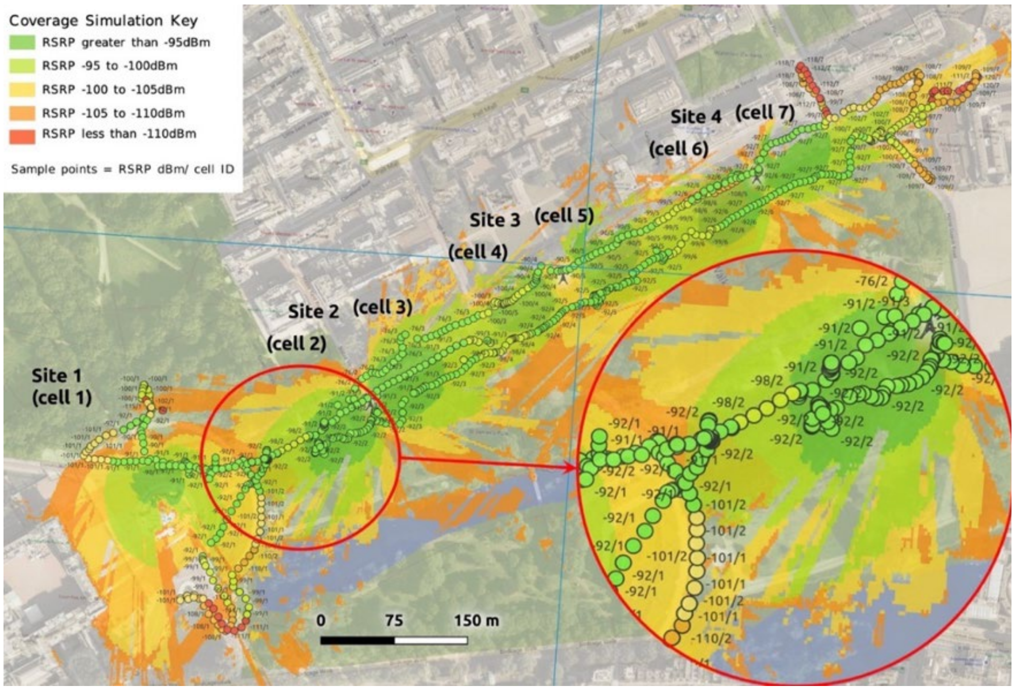

FIGURE 8: COMPARISON OF PREDICTED COVERAGE AND ON-THE-GROUND MEASUREMENTS.

Figure 8 shows the predicted downlink signal strength given in Figure 6, with logging data overlaid. The agreement between the predictions and on-the-ground measurements is excellent, accounting for the limited antenna gain of the handset. Measurement data values are presented as X/n, where X is the receive signal strength (downlink channel) in dBm and n is the serving cell. Note that the handset automatically hands over between cells as it travels along the procession route, based on neighbour cell channel signal strength. In fact, actual coverage outperformed the predictions, with connectivity demonstrated up Duke of York Steps and down to Horseguards, and live broadcasts were delivered from these locations.

Performance of the Main Contribution Network

The cells of the main network operated in SISO mode, as most of the user equipment (UE) used only have single antenna configurations, limiting them to SISO operation. The cells used dual channel receive diversity to combine both +45° and -45° polarisations simultaneously, giving resiliency to UE antenna orientation. An uplink-biased 2:7 TDD frame structure [Figure 2(c)] capable of supporting 4 bits/s/Hz was used to maximise uplink throughput, resulting in a capacity of 160 Mbps for each 40 MHz cell. Across the seven cells, over 1 Gbps of wireless uplink connectivity was provided along The Mall to the broadcasters, at a time when the public mobile networks were saturated beyond capacity.

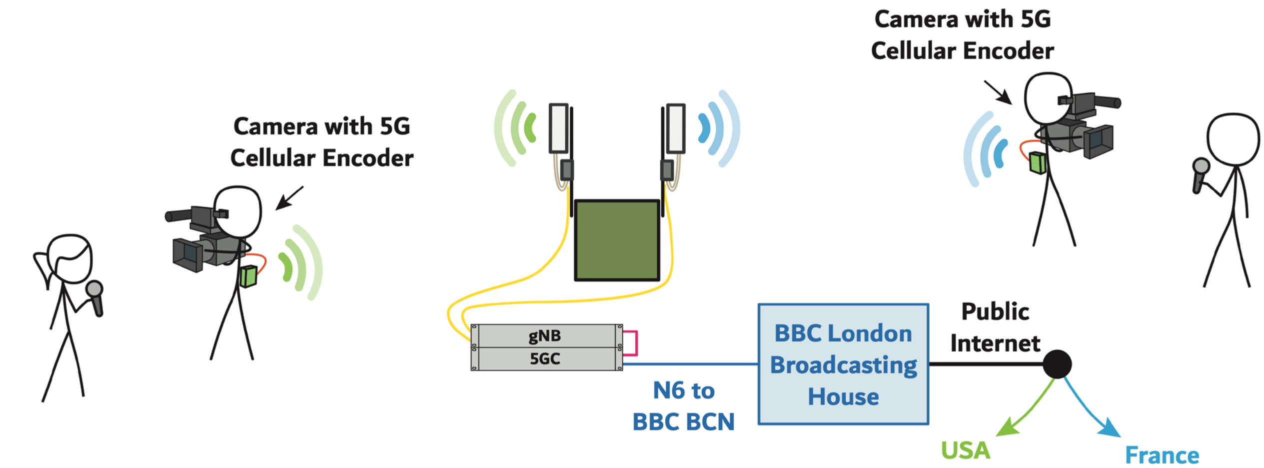

FIGURE 9: ILLUSTRATION OF BONDED-CELLULAR USERS OF THE CONTRIBUTION WORKFLOW.

The typical contribution workflow is illustrated in Figure 9. News teams were free to roam The Mall and go live to air for updates or interviews with attendees. The bonded-cellular encoders contained two SIM cards for the private network and additional SIMs for public networks, and the data travelled across public internet to the (remote) gallery for that broadcaster for inclusion in linear feeds and over-the-top streaming services. Cell handover ensured that teams were always connected, and users reported uninterrupted handover and continuous bitrate when walking the length of The Mall. During testing, Haivision recorded a live video stream walking the entire length of The Mall and crossing all seven network cells with no video drop. Moreover, the round-trip time (RTT) from their encoder on The Mall to their Streamhub decoder in France was measured to be 37ms. The impressive one-way transit time of less than 19 ms includes the 5G network (not optimised for latency), fibre backhaul to London Broadcasting House, and public Internet.

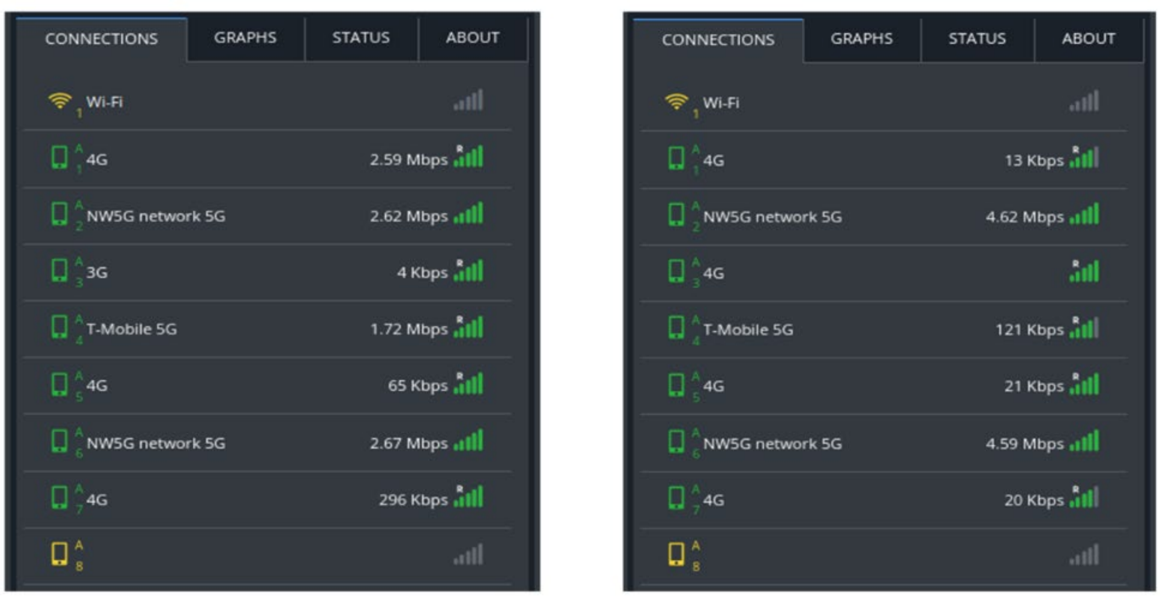

FIGURE 10: BONDED-CELLULAR ENCODER DEVICES EXPERIENCED PUBLIC NETWORK CONGESTION.
(LEFT) UNCONGESTED MNOS PRE-CORONATION; AND (RIGHT) CONGESTION ON CORONATION DAY.

Bonded-cellular encoders were loaded with two Neutral Wireless SIM cards, along with their standard public network SIM cards. Before the Coronation, news teams started going live to air, providing updates of events at the Palace and interviewing dedicated campers securing their spot for Coronation

Day. Monitoring these live streams, symmetric bonding over the private and public networks is observed. Figure 10 shows the LiveU Central dashboard for a device streaming 9 Mbps. The left-hand panel was captured before Coronation Day, with roughly equal traffic on the each of two Neutral Wireless SIMs and two of the public network SIMs. This was exactly as intended. As Coronation Day approached and the crowds gathered, as expected the public mobile networks became heavily congested and bonded-cellular devices started to lean more heavily upon the private network. When King Charles III appeared on The Mall on the afternoon of Friday 5th May, the public networks reached saturation and news teams relying solely on the MNO networks lost connectivity. However, broadcasters with access to the 5G SNPN maintained their video streams. This led to additional broadcasters requesting SIM cards for the Neutral Wireless private network.

The right-hand panel in Figure 10 was captured on Coronation Day itself. We observe that the full 9 Mbps is split (evenly) across the two Neutral Wireless connections, while the public networks are only able to sustain kbps. The response from broadcasters was unanimously positive, and has increased the appetite for systems like this at large international events.

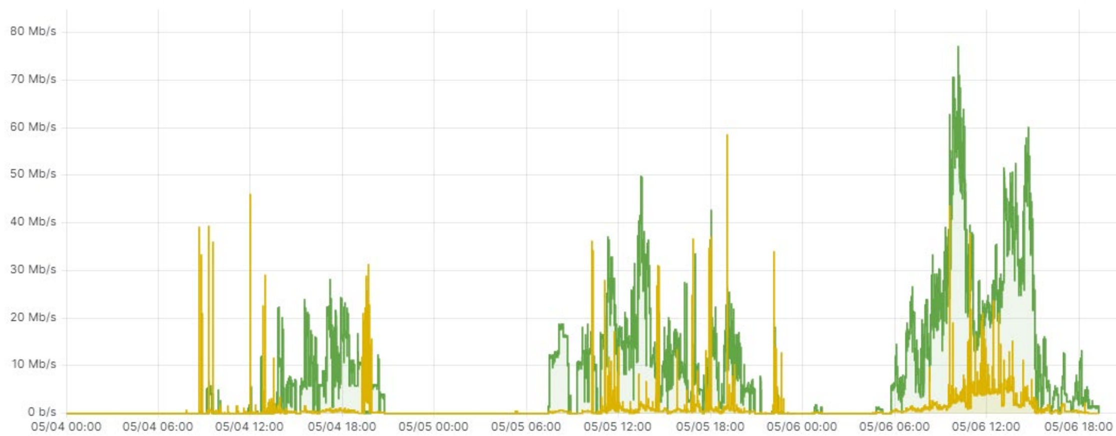

FIGURE 11: PRIVATE 5G NETWORK TRAFFIC – UPLINK BITRATE (GREEN) AND DOWNLINK BITRATE (YELLOW).

During the week, the private 5G network carried 54.4 GB of uplink video, with the majority of this being on Friday 5th May and Saturday 6th May. On Coronation Day itself, as the public networks became saturated, 60 devices from 20 domestic and international media outlets, including BBC (News and Radio), ABC, ARD, CBC, CBS, CNN, RTL and TV 2 Denmark, were all using the 5G private network to deliver live news contribution content. The private network was used to carry over 25 GB of data – over 9 hours of continuous video at 6 Mbps – to broadcasters around the world. In addition, 2.3 GB of downlink data (return audio communications and device control data) were delivered to devices. Since live news contributions typically do not air at the same time across broadcasters, the peak uplink was only 80 Mb/s, well below the network's capabilities.

Performance of the R&D Network

The R&D cell used a low latency 1:2 TDD frame structure [Figure 2(e)] to support low latency UHD camera feeds using constant bitrate encoders. This used a low gain omni-directional antenna for downlink transmission, allowing for connectivity within the media compound, with additional receive diversity on a high gain sector antenna facing the area outside the Palace. Since the mobile handsets and modems used support MIMO, this cell was configured to provide 2x downlink MIMO.

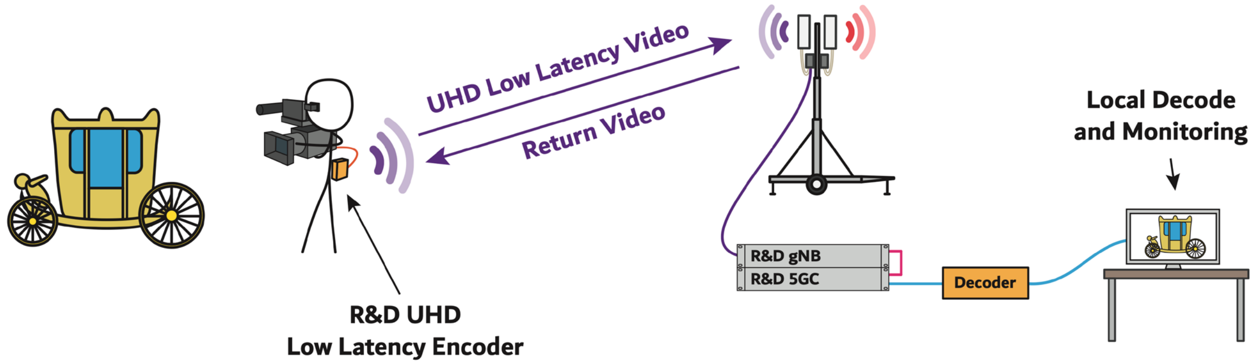

FIGURE 12: ILLUSTRATION OF THE LOW-LATENCY WORKFLOW.

The low latency workflow is illustrated in Figure 12. Constant bitrate low latency UHD encoders were connected to the network and delivered HEVC video to local decoders on the user plane for low latency monitoring. An encoder developed by BBC R&D was tested, using SRT to transport the video stream. In addition, a prototype encoder developed by Sony using a mobile handset as its 5G modem demonstrated a 55 Mbps UHD video feed with sub-100ms latency. This encoder can also provide a HD return video feed back to the camera, as well as camera control and tally functionality. Quality of service was managed on-the-fly using the VideoIPath media orchestration platform [16], prioritising particular device(s) to guarantee resources and protect program/preview feeds over non-bus feeds.

Last minute licence restrictions from the UK regulator meant that only 80 MHz was granted out of the planned 100 MHz. This meant that there was insufficient spectrum for a guard band to be put in place between the two networks. Using SDR techniques enabled us to quickly reconfigure the radio to accommodate the changes, however the collocation of antennas for networks running different TDD configurations, without sufficient guard band, led to poor performance of the cells in front of the Palace, and had a negative impact on handover with cell 2. The decision was taken to match the 2:7 TDD structure and GPS lock the two networks. The cell then performed as expected, providing an additional 160 Mbps connectivity for low-latency test devices. With this configuration, the UHD camera feed reported a glass-to-glass latency of 115 ms.

Conclusions

The use of private 5G networks for broadcast production has previously been investigated and reported [2, 8, 9, 10, 11, 12, 13], but the deployment of the largest standalone non-public network to support media contributions at such an international, high-profile and high demand density event was an ambitious and innovative collaborative effort. This industry-leading project, pioneered by the BBC, successfully delivered private 5G connectivity using shared spectrum in the n77 band to an international coalition of broadcasters, providing untethered freedom to roam The Mall and deliver high-definition video and radio contributions when the public mobile networks were saturated, and with no change to their workflow.

The private media contribution network provided over 1 Gbps of uncongested uplink capacity over seven network cells covering 1km of the procession route, from Buckingham Palace to Admiralty Arch. The network was used by over 60 devices from 20 international media outlets (including ABC, ARD, CBC, CBS, CNN, ITV, TV 2 and RTL) to deliver live news broadcast contributions. This was mainly 1080i and 1080p video streams, typically using H.265 compression at bitrates in the range 6–12 Mbps, but also included MiFi-type devices to enable radio contributions for BBC local and national stations. The UK spectrum regulator, Ofcom, approved the use of 80 MHz of spectrum in the upper n77 band under a shared access licence (SAL), and themselves commented,

> *“Shared spectrum being put to great use here!”*

The sharing of a single non-public network to support so many broadcasters and devices is considered innovative and very efficient use of radio spectrum.

The network (which was the largest to date [3, 4, 5, 17, 18, 19]) received very positive feedback from broadcasters, who delivered live video and radio content that could not have otherwise been broadcast. Jens Christoffersen (Technical Solutions Architect, TV 2 Denmark) described their experience, saying:

> *"Our team have been doing around 25-30 live shots, and without this [private] network we could not have done this because all the public networks have been down."*

Meanwhile, *Deborah Turness (CEO, BBC News) noted:*

> *"For the first time we were able to broadcast a major national event by deploying an innovative, private 5G network that enabled our teams – and a coalition of 15 other broadcasters – to connect devices via secure 'protected' cellular technology instead of using satellite. It meant that, no matter how many thousands of public mobile devices were in use in the area, our LiveU technology would still work. It's a massive step forward and congratulations to the BBC team for leading the industry with this innovation."*

As well as facilitating the successful delivery of media contributions to viewers around the world, the private network also removed the broadcast media load from the public networks. Available resources were highly constrained, and these public resources could be used to best serve the crowds. This has potential benefits for availability should emergency assistance be required.

This highly successful trial of 5G standalone technology for large-scale broadcast production demonstrates a useful application of the SAL scheme developed by Ofcom, an initiative that has pioneered spectrum sharing in the UK and is influencing spectrum policy across Europe. However, the manual interventions required in the current licensing processes introduces significant delays. These may be workable for large events planned well in advance, but do not serve expedited temporary deployments. Solutions for automated shared spectrum access and real-time monitoring are being explored and would be desirable to facilitate day-to-day and ad hoc usage.

Ofcom requires the use of a particular TDD frame structure in many 3GPP bands in order to prevent interference between adjacent radio networks, but there is (currently) no restriction in the upper n77 band. Our deployment of networks running 2:7 and 1:2 configurations introduced issues to both networks, despite the 40 MHz guard band between the cells, possibly due to the base station antennas being co-located. These were (unsurprisingly) overcome by matching frame structure and GPS time *synchronisation. Coexistence of pop-up and static networks is the subject of ongoing further studies.*

It is important to stress that for 5G networks there is a trade-off between reducing latency and increasing capacity. Software-defined private 5G networks can support both requirements. The bonded-cellular workflow used by video devices on the media contribution network at the Coronation is not considered low latency, with devices typically using latencies of 1-2 seconds to accommodate bonding over multiple public networks and distribution over public internet. Standalone private networks have been used to transport ultra-low-latency HEVC UHD video with "glass-to-glass" latency of 80ms using commercial off-the-shelf hardware, and Neutral Wireless has demonstrated latencies as low as 30ms using lab-based development encoders. Private 5G networks will be used to support low latency video for a major sporting event during the summer of 2024 [20].

Commercial off-the-shelf modems are readily available from numerous vendors, which natively support many 3GPP bands including n77. These devices offer affordable connectivity, particularly compared with conventional point-to-point hardware. Mobile handsets are an important modem-based user equipment (UE), but connecting standard handsets to standalone private networks remains challenging. Many 5G handsets do not support standalone networks, or require custom firmware or network whitelists to allow access. This landscape is improving, with newer models and operating systems from vendors including Sony, Samsung and Apple now supporting standalone networks and working to open up access to private networks using the mobile country code (MCC) 999. Better support for handsets would easily facilitate talkback and video monitoring capabilities for productions, as well as offering direct audio and video contributions. Unfortunately, the move to eSIM presents a possible obstacle for private network vendors due to regulation surrounding eSIM provision and management.

5G standalone network technology is relatively new. In the UK, the technology has not been widely deployed by Mobile Network Operators (MNOs). Operator Vodafone is the first in the UK to have started distributing 5G SA-capable hardware and partnered with broadcaster ITN to deliver a 5G SA network slice at the Coronation. This provided ITN with guaranteed uplink resources to support a programme feed from Canada Gate to their London HQ [21]. MNOs could have the capability to deploy SNPNs or public network integrated NPNs (PNI-NPNs) for this type of use case, but by self-deploying we were able to take advantage of existing broadcast infrastructure, such as cable runs, power and platforms for antenna mounting, reducing cost and complexity. This highlights the potential of 5G SA and how SNPNs and slicing are, in fact, complementary technologies servicing different parts of the broadcast puzzle – an entirely 5G-based production could use a private network for (ultra-)low latency acquisition and then use a network slice for the contribution link.

5G technology continues to evolve, and the use of private standalone networks is becoming more common across many market verticals. Developments in networks for broadcast production have now demonstrated ultra-low-latency UHD video with return feeds, full camera control, push-to-talk communications, and tally signalling, as well as improved cell handover. The potential role of these networks for outside broadcasts and in studio environments is an active area of exploration. As 5G continues to develop, it is anticipated that the PMSE use case will continue to expand and facilitate the transition from traditional broadcast technology to IP operation in the wireless domain integrating with cloud production services.

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