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5G STANDALONE NON-PUBLIC NETWORKS: MODERNISING WIRELESS PRODUCTION

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ABSTRACT

New spectrum opportunities that facilitate the deployment of 5G Standalone Non-Public Networks are of increasing interest to broadcasters. Modern IP workflows can integrate seamlessly with such networks and the technology is finding an increasing number of applications for wireless production. The cost of 5G network equipment is reducing and a single 5G deployment can potentially replace a plethora of traditional wireless production equipment.

This paper explores the characteristics of current 5G implementations, detailing the strengths and challenges of deploying this new technology. For wireless cameras, many alternative streaming technologies can be used and the trade-offs between reliability, quality, network load and latency are explored. The BBC's experience of trialling the technology at the Coronation of HM King Charles III is discussed.

INTRODUCTION

The opportunities presented by 5G Non-Public Networks (NPNs) for programme making have been the subject of several collaborative research projects (1), (2). Mobile spectrum has traditionally been available only for public network bought at auction. Identifying the value of smaller private networks, spectrum in the 3.8–4.2 GHz is now licensed by Ofcom UK using the shared access licence (SAL) (3). This spectrum forms part of the 5G n77 band.

Advantages of 5G compared to traditional Wireless PMSE

Wireless Equipment for Programme Making and Special Events (PMSE) has been in common use since 2002 (4). Implementations are generally derived from Digital Video Broadcast – Terrestrial (DVB-T) Coded Orthogonal Frequency Division Multiplexing (COFDM) technology, deployed in custom frequency bands with unified tuning ranges (5). 5G also uses COFDM technology but can potentially benefit from recent advances including Multiple Input Multiple Output (MIMO). Unlike traditional digital wireless cameras links, 5G provides native bi-directional TCP/IP network connections which integrate easily with modern IP studio architectures. The radio modems operate in wider bandwidths enabling higher throughput for enhanced services like UHD.

Unlike conventional PMSE, where separate radios are deployed for audio and video applications in forward and reverse directions for each service, 5G allows a single base station to support multiple connections. This can include audio, video, camera control, tally light, or any service that can be encapsulated in IP. The 5G radio modems natively support the SAL spectrum without the need to modify them to use a custom PMSE band. These aspects reduce complexity and cost when compared to traditional wireless PMSE techniques.

PREVIOUS 5G TRIALS

Several 5G trials have taken place in the UK since 2021 (6), (7), including the IBC Media Accelerator Programme 2022 Project of the Year (8), and the technology is steadily maturing. Trials initially used one or two macro cells, but the cell handover mechanism in mobile technology allows the network coverage to be readily extended using additional radio units. Software-defined radios have been used in most trials supplied by small vendors.

5G network optimisation for programme making

For programme making, the uplink performance is paramount, so networks must use the 5G standalone (SA) mode; Non-standalone (NSA) 5G networks use 4G technology for the radio uplink and core network and have insufficient capacity for video PMSE applications. Networks in the n77 band use time division duplex (TDD) and the parameters can be tuned to optimise performance, such as biasing for uplink-heavy operation to support video traffic from the camera terminal. While LTE was restrictive in the available frame structure configurations, the 5G New Radio (NR) waveform is highly configurable.

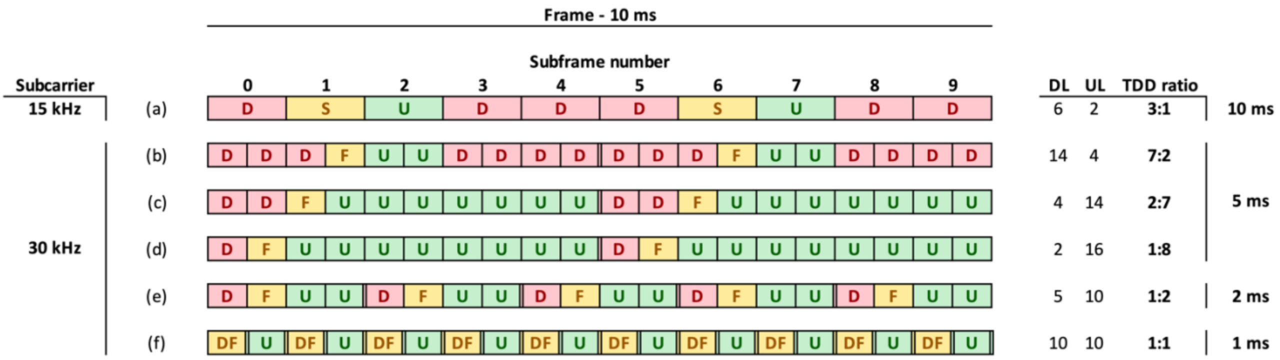

Figure 1 – A subset of 5G TDD configurations

Public mobile network operators are restricted to using a synchronised 3:1 (downlink:uplink) TDD ratio (Figure 1(a)) to ensure that networks transmit and receive at the same time and avoid interfering with one another. Of the 10 subframes that make up a single 10 ms frame, there are six for downlink, two for uplink, and two ‘special’ subframes, during which the transition from downlink to uplink takes place. 5G NR supports more numerologies (subcarriers) than LTE, depending on the frequency band. When using 30 kHz subcarriers (available in the midband, including n77) there are 20 time slots, allowing for 14:4 (7:2) shown in Figure 1(b), increasing downlink bandwidth. Note that this frame structure has been shifted to remain synchronised with the 3:1 frame structure employed by the MNOs.

This restriction does not currently extend to the n77 band. A typical PMSE application will instead use a reversed TDD ratio of 2:7, whereby 14 radio slots are allocated for uplink and 4 for downlink, illustrated in Figure 1(c). This can be pushed further to 1:8 to maximise uplink throughput (Figure 1(d)), or reduced to 1:2 or even 1:1 to minimise latency (Figure 1(e) and (f), respectively). The special subframes ‘S’ can be defined arbitrarily in 5G NR, and are known as ‘flexible’ slots. They contain a mixture of uplink and downlink symbols, separated by gap symbol(s). The 1:1 frame structure makes use of the flexible slot to provide the uplink or downlink (for example, ‘DF’ in Figure 1(f)).

5G network capacity

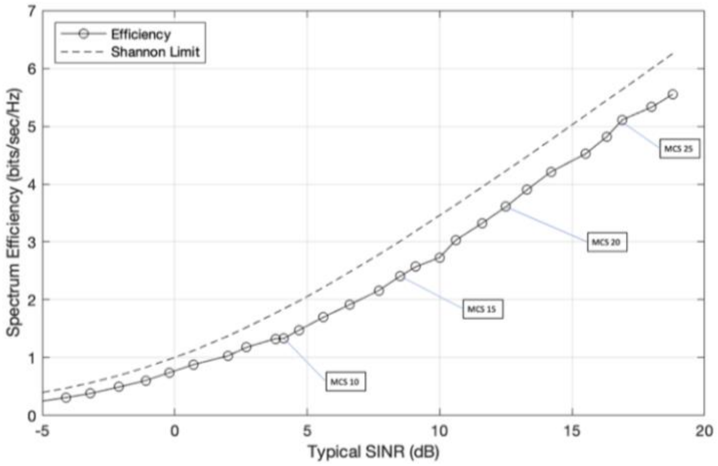

Figure 2 – Typical 5G Capacity vs SINR

Like all radio systems, 5G is constrained by the Shannon-Hartley theorem and capacity is a function of the signal to interference and noise ratio (SINR) on the radio link. At high SINR, a higher order modulation and coding scheme (MCS) can be supported with a reduced level of forward error correction. For 5G NR links, modulation up to 256-QAM in the Physical Uplink Shared Channel (PUSCH) is defined with 2x2 MIMO (9). Practical implementations tend to be limited to 64-QAM and many commercial terminals have a single antenna, limiting the system to SISO operation. The typical relationship between SINR, MCS and capacity is shown in Figure 2.

Bitrate requirements for video streams

The bitrate requirement for broadcast content video distribution is a matter for debate. Ideally, the streams would be lightly compressed to minimise cascading artefacts in the codec chains within a typical broadcast system. This would advocate the use of a mezzanine video codec with a bitrate requirement of around 190 Mb/s for HD. In practice, this is far too high for practical 5G implementations, and most video links will make use of H.264 (AVC) or H.265 (HEVC) compression.

The bitrate requirements for artefact-free video will be dependent on the nature of the content. Noise-like material with fine-scale detail (such as running water, smoke and large crowd scenes with considerable motion) is particularly hard to encode. Talking heads against near-stationary backgrounds are much easier as there is considerable temporal and spatial redundancy that can be exploited by the codecs to reduce the bitrate.

The precise requirements are usually evaluated by expert viewing panels on specially selected test sequences. This is a time-consuming process. The use of perceptual codec evaluation methods, such as VMAF (Video Multi-Method Assessment Fusion (10)), provide useful indicators and a set of hardware-accelerated H.265 encoders were evaluated ahead of the Coronation event. For simple material like the EBU “park dancer” sequence (1920x1080p50, 8-bit 4:2:0 chroma), H.265 implementations tend to give similar results. VMAF scores exceeding 90 at bitrates as low as 4 Mb/s can be achieved. Demanding material, like the SVT open content “crowd run”, requires higher bit rates and exaggerates the implementation differences between vendors; up to 20 Mb/s can be necessary to achieve VMAF geometric mean scores exceeding 90. This is summarised in Figure 3, where three codec implementations are compared with a software reference (FFmpeg).

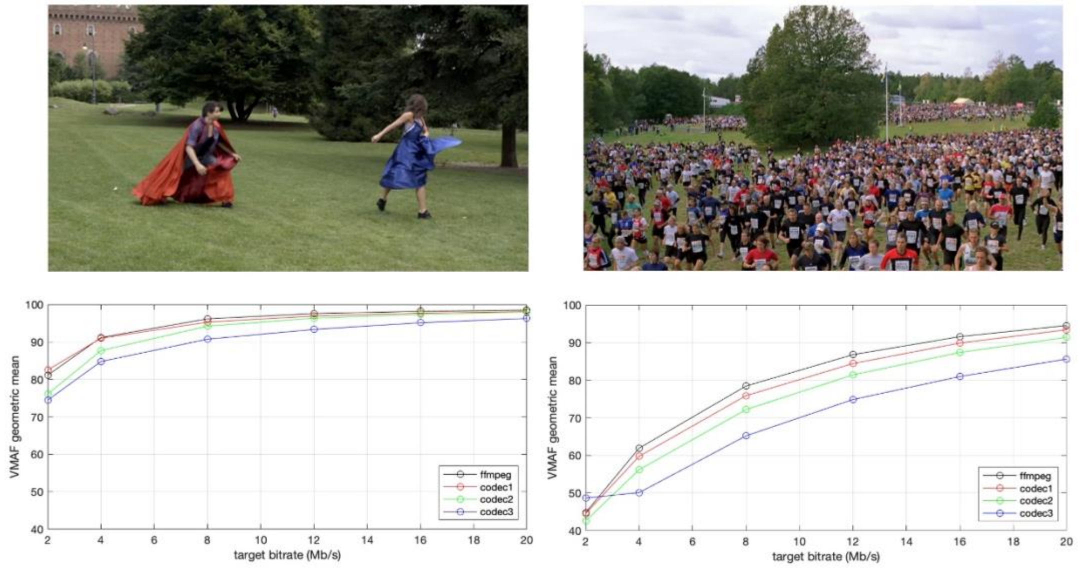

Figure 3 – Video quality vs Bitrate for typical H.265 codecs

Interlaced HD video, used for broadcast, halves the pixel rate compared to progressive HD. A bitrate ceiling of 12 Mb/s was set for News contributions, with codecs adapting according to the available bandwidth and network conditions. Many broadcasters either chose to set their maximum bitrate lower or were restricted by licences on their devices.

ELECTRONIC NEWS GATHERING USING MOBILE NETWORKS

Elecronic News Gathering (ENG) increasingly makes use of mobile systems utilising 4G and public 5G NSA networks in preference to the traditional private point-to-point radio links. The required uplink traffic for live HD broadcast video can, under normal network load, usually be carried on mobile network operator infrastructure. Systems are now readily available from a number of vendors that bond multiple MNO connections for resiliency and reduced individual network resources, which are cost effective and convenient. Since the mobile capacity is provided on a best-effort basis, even bonded systems can fail at large events with big crowds as the mobile networks are likely to be congested by the volume of traffic.

NEWS LINKS FOR THE CORONATION OF KING CHARLES III

In February 2023, BBC News identified a requirement to provide continuous mobile coverage for News teams on part of the Coronation procession route between Admiralty Arch and Buckingham Palace (“The Mall”).

Previous experience suggested that bonded public 4G/5G NSA systems, that would normally be used, were likely to fail due to the network congestion that is common at big public events. Investigations and trials to deploy a private 5G SA network in the n77 band started and spectrum surveys revealed that the target spectrum band was relatively clear. A Shared Access Licence of 100 MHz was requested from Ofcom and granted in March.

Commercial bonded-cellular encoder vendors have previously worked to ensure that their devices attach to 5G standalone networks provisioned by Neutral Wireless. The aim was to provide private 5G SA coverage to support such devices for their News operations, while also opening up the resources to other domestic and foreign broadcasters. Initial tests in March 2023 at the proposed media compound at Canada Gate were conducted using a downlink EIRP of 41.7 dBm. Stable operation over a cell radius of up to 350 m was confirmed.

5G coverage planning

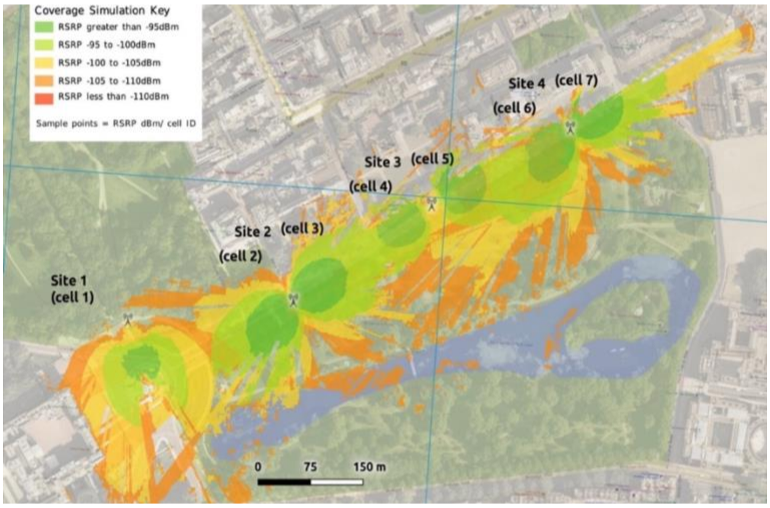

Figure 4 – Predicted RSRP values for the 5G network

To enable coverage along the 1 km length of The Mall, a network of four cell sites was planned using 100 MHz of radio spectrum. Site 1 provided blanket coverage in the vicinity of the Palace using an omni antenna, while sites 2, 3 and 4 used directional panel antennas pointing in opposite directions deployed at the fixed camera platforms. The coverage prediction (11) for the downlink received signal reference power (RSRP) is shown in Figure 4. Site 1 used a trailer mast in the media compound with antennas rigged at 8 m. Sites 2,3 and 4 were camera positions along The Mall with antennas at 4 m height.

5G network deployment

Rigging for the Coronation began one week prior to the event. Fibre was used to connect the remote radio heads (RRHs) at the cell sites to the baseband units (BBU) at the media park.

Tuning of the network began on the 3rd May, 3 days ahead of the Coronation. Cell 1 was complemented by an additional cell in non-overlapping radio channels. The lower frequency channel was configured in a low latency mode to support tests on experimental, low-latency UHD cameras from BBC R&D and Sony. The antenna arrangements for the cell sites are shown in Figure 5.

Figure 5 – Antenna arrangements for (left) Site 1 (“Media Compound”) and (right) Site 2 (“The Mall South”)

Spectrum Measurements

A 100 MHz block of radio spectrum was initially licensed from 3835–3935 MHz and used for trials at Canada Gate. The block was split into two 50 MHz channels for A/B channel reuse along The Mall. After successful testing, a licence application for spectrum along The Mall was submitted, resulting in a licence for the spectrum 3815–3935 MHz. This supported 40 MHz A/B channels at 3835 MHz and 3875 MHz (as well as a 40 MHz channel at 3915 MHz at Canada Gate covered by the original licence) but reduced the guard band to the nearest mobile allocation (3760–3800 MHz) from 35 MHz to 15 MHz. The software-defined radio architecture allowed for easy reconfiguration to accommodate the licence changes. The spectrum observed at the media compound is shown in Figure 6 – see also Table 1. Note that, in practice, the uplink-heavy traffic meant that there was little downlink traffic, and the basestation transmitted power was well below maximum.

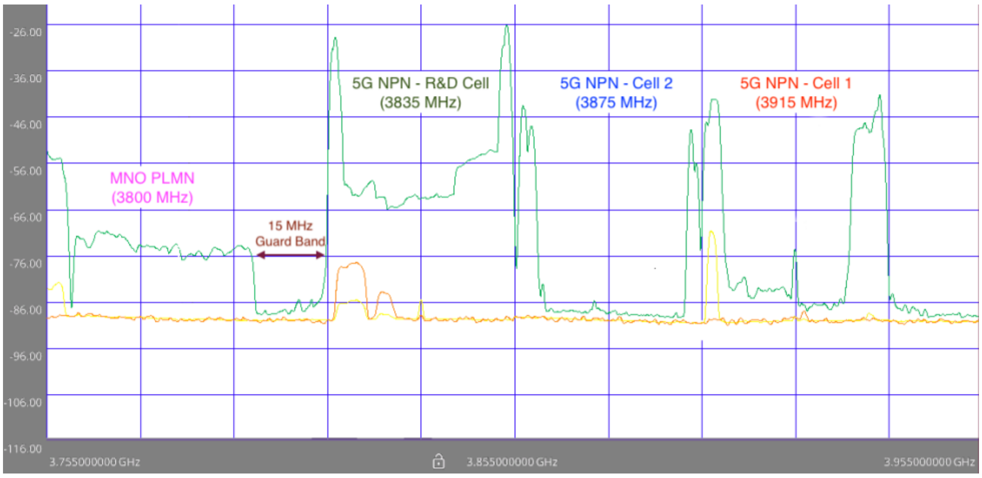

Figure 6 – Radio spectrum (dB) of 5G NPN and Mobile services measured at Site 1.

Network configuration

The network was designed to provide seamless coverage along The Mall. Four antenna sites were identified to host seven cells, with a classic A/B channel plan for spectrum reuse. The network was run on a custom-built rack located in the BBC News area of the media compound. To provide hardware redundancy, each site (hosting two cells) was hosted on individual hardware. Cell neighbours were fully specified to enable inter-gNB handover. Each cell used the uplink-biased 2:7 TDD frame structure (Figure 1(c)) with a 40 MHz channel and SISO transmission mode. For the uplink, dual channel receive diversity was used to receive and combine both +45° and -45° polarisations simultaneously. Downlink transmission powers were configured within the licence specification.

The 2:7 TDD frame structure implemented across all cells was capable of supporting 4 bits/s/Hz, resulting in a capacity of 160 Mb/s for each 40 MHz cell. Across the seven cells for the main network, over 1 Gb/s of wireless connectivity was provided along The Mall to the broadcasters, at a time when the public mobile networks were saturated beyond capacity, despite the provision of additional temporary cells. We note that, despite this wireless capacity, the allocated Internet backhaul over the BBC Broadcast Contribution Network (BCN) to New Broadcasting House was restricted to 450 Mb/s.

Cell	**Channel**	**TX power** (dBm)	**TX gain** (dBi)	**RX gain** (dBi)	**Radio Head TX/RX Mode**
1	C	26	14.0	14.0	1Tx 2Rx (diversity)
2	B	26	15.7	15.7	1Tx 2Rx (diversity)
3	A	26	14.0	14.0	1Tx 2Rx (diversity)
4	B	26	15.7	15.7	1Tx 2Rx (diversity)
5	A	26	14.0	14.0	1Tx 2Rx (diversity)
6	B	26	15.7	15.7	1Tx 2Rx (diversity)
7	A	26	14.0	14.0	1Tx 2Rx (diversity)
R&D	A	26	3.0	3.0 + 14.0	2Tx 4Rx (diversity)

Table 1 – Network cell properties. Channels: A – 3815-3855 MHz [ARFCN 655666]; B – 3855-3895 MHz [ARFCN 658334]; and C – 3895-3935 MHz [ARFCN 661000].

An additional “R&D” network designed to support low latency UHD camera feeds using constant bitrate encoders was deployed at Canada Gate alongside cell 1. This cell was configured to run the lower-latency 1:2 TDD frame structure, which significantly reduces latency and network jitter. 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.

Coverage validation

The coverage was checked by making mobile measurements at ground level using a phone running an RSRP logging app and using a 5G modem interfaced to a raspberry pi equipped with a GPS receiver. Paddle-type monopoles (~2 dBi) were used on the raspberry pi modem which returned signal strength values typically 12 dB greater than the phone. This would be consistent with the phone having an effective antenna gain of approximately –10 dBi.

Due to logistical complications onsite, the position of site 3 was moved from the intended camera platform to a BBC radio booth located nearby. In addition, the omni-directional antenna used for cell 1 at Canada Gate, which provided blanket coverage over the media compound during testing, was changed to a sector antenna the day before the event, as the coverage overlap with cell 2 was interfering with cell handover. RF simulations using the CloudRF engine (11) were repeated to model coverage on the Coronation Day itself. Simulations were performed using the Irregular Terrain Model (ITM) v7, known as the ‘Longley Rice’ model, with the parameters presented in Table 1.

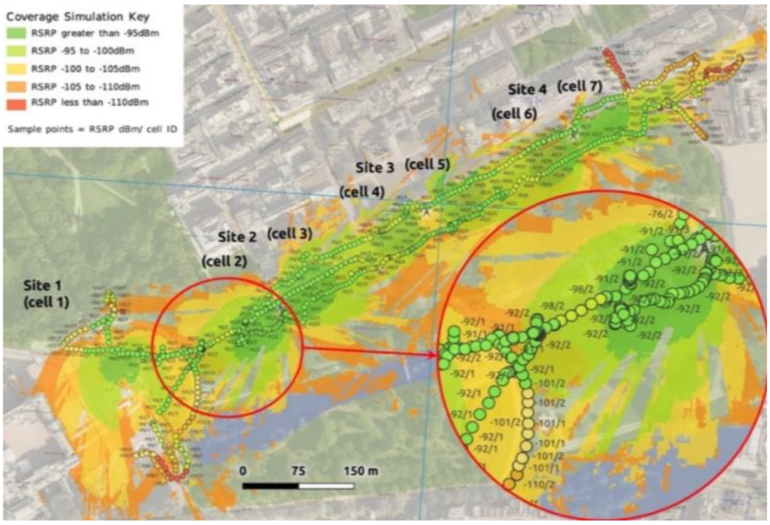

Figure 7 – Predicted and measured RSRP values for the 5G network

Figure 7 shows the predicted downlink signal strength, with logging data collected on a mobile handset overlaid. The agreement between the predictions and on-the-ground measurements is excellent, taking into account 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.

Observed performance and throughput

In the days leading up to the Coronation, bonded cellular units started live news contributions. These devices were loaded with two SIM cards for the NPN, but also various SIMs for the public MNOs. The devices worked as expected, splitting the stream bitrate over

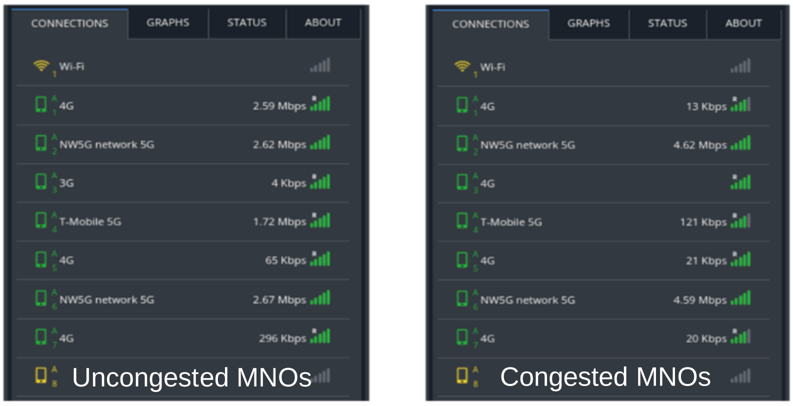

Figure 8 – Monitoring screens on bonded cellular UE

the public and private networks (left panel of Figure 8). However, as the crowds gathered and the public networks became congested, the device adapted to push the majority of the data over the private network (right panel of Figure 8).

While low latency was not the design goal for the newsgathering contribution network, one vendor reported a packet round trip time (RTT) of 37 ms from their encoder on The Mall to their decoder located in France; the transit time of 19 ms includes the 5G network (not optimised for latency), fibre backhaul and public Internet connectivity and is impressive.

Users reported uninterrupted handover and continuous bitrate when walking the length of The Mall, with usable coverage found in unexpected and unplanned locations, such as Duke of York Steps and outside Horse Guards. The response from broadcasters was unanimously positive.

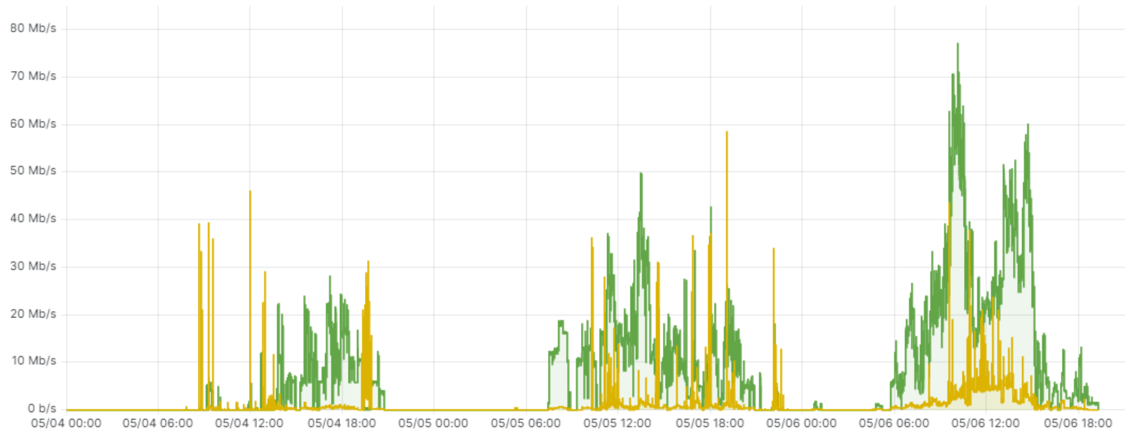

Figure 9 – 5G private network uplink bitrate (green) and downlink bitrate (yellow) traffic

Over the course of the week, over 60 devices accessed the NPN. The 5G SA network carried 54.4 GB of uplink video, with the majority being on Friday 5th May and Saturday 6th May. On Coronation Day itself, 24.8 GB of video data were streamed – over 6 hours 50 minutes of continuous video at an average of 8 Mb/s (over 9 hours at 6 Mbps). 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 (see Figure 9). In addition, 2.3 GB of downlink data (return audio communications and device control data) were delivered to devices.

Testing of the complementary low-latency "R&D" network within the media compound resulted in excellent performance. An experimental low latency UHD camera operating at 55 Mb/s (CBR) was attached to the network using a handset configured as a USB 5G modem with HD return video. Quality of service was managed on-the-fly for each SIM.

The collocation of antennas for networks running different TDD configurations led to poor performance of the R&D cell in front of the Palace, which 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 performed as expected, providing an additional 160 Mb/s connectivity for low-latency devices, including a BBC R&D prototype. The increased network latency and jitter required increased data buffers to facilitate stable performance, with the UHD camera reporting a glass-to-glass latency of 115 ms.

CONCLUSIONS

By successfully deploying a large-scale 5G Standalone Non-Public Network (SNPN) for the Coronation of King Charles III (12) – (15) we demonstrated that shared spectrum in the n77 band could be used to implement a pop-up multicell network. This network covered 1 km of the procession route along The Mall, providing wireless connectivity with a total uplink capacity of over 1 Gbps. An additional 40 MHz channel supported a low latency 4K R&D test cell outside Buckingham Palace.

The network was used to support live broadcast contributions for news teams from several international broadcasters. This included 1080i and 1080p video streams, typically using H.265 compression at bitrates in the range 6-12 Mb/s. We also connected several MiFi-type devices, which enabled radio contributions for BBC local and national stations. The network received very positive feedback from broadcasters, who delivered live video and radio content that could not have otherwise been broadcast. The sharing of a single non-public network to support over 20 international broadcast outlets (including ABC, ARD, CBC, CBS, CNN, ITV, TV 2 and RTL) is considered an innovative and very efficient use of radio spectrum, with the UK regulator Ofcom themselves commenting, *“Shared spectrum being put to great use here!”*

This trial of 5G standalone technology demonstrates a useful application of the Shared Access Licence (SAL) scheme developed by Ofcom. Ofcom’s SAL initiative has led the way for innovative spectrum sharing and deployment of 5G private networks, but we feel the mechanisms for obtaining licences need to be streamlined if SALs are to be used regularly by the broadcast sector. The manual processes currently required introduce significant delays that may be workable for large-scale events planned well in advance, but do not suit short-notice or reactionary deployments. A dynamic spectrum access model 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 (Figure 1(c) and (e), respectively) 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 requires further study.

It is important to stress that for 5G networks there is a trade-off between low latency and high capacity. The jitter introduced by a typical uplink-biased 2:7 TDD frame structure is not suitable for ultra-low-latency applications, such as sub-100ms video. Methods to reduce the latency or jitter unfortunately carry a capacity penalty, reducing the available bandwidth for connected devices; 5G SNPNs can support ultra-low-latency video – BBC R&D and Neutral Wireless have demonstrated 2 frames (at 50 fps) glass-to-glass latency over 5G SNPN – but using configurations with reduced capacity. The bonded cellular workflow used by video devices on the main network at the Coronation is not considered low latency. In order to accommodate the bonding and recombining of streams split over several routes traversing public Internet, devices typically run with a latency of around 1-2 seconds.

Commercial off-the-shelf modems that can access the 5G n77 band are readily available. Some issues with modem attachment delays were encountered, which typically depend upon modem configuration and the firmware release used by the vendor. We also find that the efficiency benefits of using MIMO are not easily realisable, as MIMO operation can lock-out some modems (rather than establishing SISO connections with those devices) and, while increasing bandwidth, MIMO also increases jitter. Enhancements to firmware and MIMO implementations are anticipated to address these shortcomings. Commercial implementations often only support SISO and have broadband, low gain antennas. Products with external antenna ports and MIMO support would help improve spectrum efficiency.

Unfortunately, attaching standard mobile handsets to 5G SNPNs remains challenging. Many 5G handsets do not support standalone networks at all, or custom firmware or network whitelists are required. There is movement in this area, however, with newer models and operating systems from vendors including Sony, Samsung and Apple now supporting standalone networks and working to open up access to NPNs 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.

The cell handover characteristics of mobile are generally inferior to existing COFDM diversity receiver installations using maximum ratio combining. The process of cell handover takes around 40 ms, which is adequate for News contribution using bonded cellular. This will improve as the technology develops, but currently results in dropped frames for ultra-low-latency feeds. Release 16 supports dual active radios, allowing for “soft handover”, but this is currently not implemented in any UE. Release 16 does not support Time Sensitive Networking and is not yet capable of carrying PTP traffic with the precision required for camera synchronisation. This is a potential barrier to multi-camera live production.

5G standalone network technology is relatively new and 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 (16). 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 – one could envisage an entirely 5G-based production, with (ultra-)low latency acquisition over a SNPN and then use of a network slice for the contribution link.

As 5G develops further, 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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