Report

Technology Evolution in the PMSE Sector

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Executive Summary

This report evaluates future demand for radio spectrum in the Programme Making and Special Event (PMSE) sector, setting out to answer the key question: **"What are the key technological and working practice changes that may impact both radio spectrum demand for PMSE and its supply?"**

Demand for PMSE spectrum was estimated over the next 10 years, for wireless equipment including programme-quality radio cameras, radio microphones, personal audio ('in-ear') monitor devices, and communications equipment that uses the relevant spectrum. Demand was assessed across six key PMSE activity areas:

1. Television light entertainment programme making
2. Outdoor music events
3. Major theatre productions
4. Television sport programme making
5. Feature film making
6. Television news gathering

Questionnaire-driven interviews and data collection were done with technical experts and senior management representative in each PMSE activity area in order to assess current, mid-term (5 years) and longer-term (10 years) trends. In each activity area a forecast was made for the number of simultaneous instances of each type of device. It was ascertained that:

- Outdoor music events and large TV light entertainment shows use the highest simultaneous number of programme-quality wireless audio devices (radio microphones and in-ear monitors) both now and for the next decade.
- Television sport currently uses the highest simultaneous number of wireless video devices (mainly radio cameras), and is forecast to do so for the next decade; Formula One motor racing representing the highest instances.
- Some future television light entertainment or sport productions may make use of considerably larger numbers of radio cameras, technology permitting.
- In all cases, high definition video is supported today, and there is a high probability that ultra-high definition ('4k' or higher) radio cameras will be required within the next decade.
- The greatest number of radio frequencies used for communications equipment (non-programme audio) is expected to appear in London's West End in one of the clusters of larger theatres.
- About 30% of the 'UHF TV' spectrum available today, which is shared between TV broadcast and programme-quality wireless audio devices, may be re-allocated to other primary users.
- For video devices, 42% of the available frequencies in the range 2GHz – 4GHz will be re-allocated to other primary users, requiring many PMSE users to move up to the band at 7GHz.

Technical interviews were carried out with designers and makers of audio and visual equipment used in the PMSE field to understand the current technology capabilities and development roadmaps. This data was supported by interviews with research organisations and by in-house technical analysis, to gauge the expected improvements in spectral efficiency for each equipment type. Technical findings were:

- Radio microphones and in-ear monitor equipment is now available that can use spectrum around 2.5 times as efficiently as current practice for analogue transmission, and 3 times as efficiently for digital transmission (up to 8 times in restricted cases). At the moment this performance is offered only by top of the range equipment, but could reasonably be expected to be available at lower cost in the next five years.
- Radio camera equipment exists now that operates in the 7GHz band mentioned above and works satisfactorily, though some issues of universal applicability need to be addressed.
- Radio camera equipment is being developed now that will be twice as efficient spectrally as current practice, and should be available within the next five years. Video compression (codec)

technology is being developed now for ultra-high definition transmission within the same spectrum as today's high definition, and this should be available for radio cameras within 5-10 years.

It is concluded that, in general, technology advances will make possible deployment of the predicted simultaneous instances despite proposed reductions in available spectrum, so long as equipment manufacturers, hire companies and other users have sufficient incentive to invest in them. This means, as a minimum, a long-term guarantee of the spectrum available to PMSE, so that the high development costs and equipment costs can be amortised over time, for the relatively small manufactured volumes of professional equipment.

It is also noted that mitigations only become effective once a significant majority of its users has deployed the new technology!

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Abbreviations used

Abbreviation	Meaning
16-QAM	16-state Quadrature Amplitude Modulation
3G	Third Generation of mobile telecommunications technology standards. (Note that, in broadcast video, '3G' can also refer to a 2.97Gbit/s Serial Digital Interface wired connection.)
3GPP	Third Generation Partnership Project standardising complete systems, including radio access, service capabilities, codecs, security, quality of service etc.
4G	Fourth Generation of mobile telecommunication technology standards
4k	Ultra-high-definition television, 3840 x 2160 pixels, at least 50 frames per second.
APWPT	Association of Professional Wireless Production Technologies: an independent association working for the benefit of all professionals using radio spectrum in Europe, including PMSE
BEIRG	British Entertainment Industry Radio Group: an independent association working for the benefit of UK professionals using radio spectrum (mainly concerned with audio devices)
CAGR	Compound Annual Growth Rate
Codec	COder-DECoder, referring to hardware and signal processing algorithms to compress the data rate of video or audio content for transmission or storage, and then decompress it for viewing.
COFDM	Coded Orthogonal Frequency Division Multiplex
C-PMSE	European Cognitive project for Programme Making And Special Events
DAB	Digital Audio Broadcast
dB	Decibel (logarithmic power ratio)
dBm	Decibels relative to a power of 1 milliwatt
dBW	Decibels relative to a power of 1 watt
DECT	Digital Enhanced Cordless Telecommunications
DSP	Digital Signal Processing
DVB-T	Digital Video Broadcast Terrestrial, a series of ETSI standards (EN 300 744 etc.) for television broadcast from terrestrial transmitters (as opposed to satellite or cable) to home TVs
FCC	Federal Communications Commission: the US government agency responsible for regulating interstate and international communications (wire, cable, radio, TV and satellite)
FDMA	Frequency Division Multiple Access
H.264	ITU-T Recommendation for Advanced Video Codec standard designed for HD video
H.265	ITU-T Recommendation for High Efficiency Video Coding standard designed for a range of applications from handset viewing all the way to 8k ultra-high-definition video
HD	High Definition, 1920 x 1080 pixels, at least 25 frames per second
HDTV	High Definition Television
HEVC	High Efficiency Video Coding (see H.265)
IEM	In-Ear (personal) audio Monitor, generally wireless today
IP	Internet Protocol (set of standards)

Abbreviation	Meaning
ITU-T	International Telecommunications Union, Telecommunication Standardization Sector
LED	Light Emitting Diode
LTE	Long-Term Evolution standards from the 3GPP mobile communications standardisation activity. New releases of LTE are made every 1-2 years.
MIMO	Multiple Input Multiple Output radio modem.
MNO	Mobile Network Operator (wireless telecommunications)
MVNO	Mobile Virtual Network Operator: provides a communications service hosted on networks owned by others
OB	Outside Broadcast: programme origination from outside a studio building, often using production control rooms built into a suitable vehicle, and temporary communications links back to the broadcaster.
OFDMA	Orthogonal Frequency Division Multiple Access
PA	Power Amplifier
PCM	Pulse Code Modulation – simple linear encoding of an analogue signal into digital form.
PIN diode	P-type/Intrinsic/N-type semiconductor layer structured device, used for RF switching
PMSE	Programme Making and Special Events
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SIM	Subscriber Identification Module
SLA	Service Level Agreement, for example between a network operator and a customer
SPMF	Spectrum for Programme Makers Forum: an independent association working for the benefit of UK broadcast programme makers using radio spectrum
TCP	Transmission Control Protocol (part of the Internet Protocol set of standards)
TETRA	Terrestrial Trunked Radio: ETSI standards for a digital trunked mobile radio standard developed for Professional Mobile Radio use
UAV	Unmanned Aerial Vehicle
UHD	Ultra High Definition, generally synonymous with 4k (q.v.) or higher definition
UHF	Ultra High Frequency: frequencies between about 300MHz and 1GHz, in this document. (UHF is elsewhere taken to mean frequencies between 300MHz and 3GHz)
VCO	Voltage Controlled Oscillator
VHF	Very High Frequency: frequencies between 30MHz and about 300MHz

1 Introduction

The purpose of this report is to evaluate future demand for radio spectrum in the Programme Making and Special Event (PMSE) sector. Our study set out to answer the following key question:

"What are the key technological and working practice changes that may impact both radio spectrum demand for PMSE and its supply?"

We addressed this key question though subsidiary areas of investigation, as described below. Information was collected principally through questionnaire-driven interviews with experts and key stakeholders in PMSE, on both the 'demand' and the technology/working practice (or 'mitigation') sides of the sector.

Future radio spectrum demand trends and forecasts over ten years were assessed, principally in terms of increased production quality and quantity of demand by the PMSE sector. General spectrum demand trends are described, followed by a summary of activity-area demand trends (i.e. forecasts of peak instances) in terms of 'programme-quality' audio and video links (Chapter 2). Key activity areas studied were:

1. Television light entertainment programme making
2. Outdoor music events
3. Major theatre productions
4. Television sport programme making
5. Feature film making
6. Television news gathering

Technology and working practice trends and forecasts are identified and analysed to derive a set of common mitigations (Chapter 3).These mitigations in spectrum demand for audio devices (radio microphones, in-ear monitors) and video devices (radio cameras and other links) are applied to a set of scenarios for each of the above PMSE activity areas. The outcomes, in terms of gross spectrum demand, are described in Chapter 4.

General PMSE-related observations that are considered outside the main scope of this study, but which were nevertheless considered significant, are captured in Chapter 0.

Finally, the broader conclusions of the study are discussed in Chapter 6.

Further background material may be found in the Appendices to this report. These sections are as follows:

- Appendix A – Methodology for the study
  (including the engagement strategy and a list of stakeholders interviewed)
- Appendix B – Straw-man reference for a co-ordinated wireless audio system
- Appendix C – Link budget calculations for a ground-top-air video link at 2.5GHz and 7.1GHz
- Appendix D – Analysis of highest carrier frequency feasible for a body-worn radio microphone

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2 Analysis of future radio spectrum demand trends in PMSE

In this chapter we present our analysis of future radio spectrum demand trends in PMSE. Section 2.1 gives an overview of general spectrum demand trends with respect to wireless video (including radio cameras) and audio links (including programme quality equipment such as radio microphones, personal audio monitors and communications equipment). Section 2.2 provides a more detailed analysis of the PMSE demands of the six key activity areas that we have studied, including forecasts for their peak instances of wireless devices.

2.1 Analysis of general spectrum demand trends in PMSE

A summary of general spectrum demand trends, derived from an analysis of our stakeholder interview programme, is provided in Table 1, below. Each of the key points in the table is expanded upon in the remainder of this section.

Spectrum demand trends	
Video links (radio cameras)	1. Steady but modest growth in number per event, for the largest events 2. Some new production formats and/or business cases could appear that use a much larger number of radio cameras. 3. Trend to increase resolution as broadcasters demand it, or if the content is likely to have a long market life. 4. Trend to increase sample depth, at least for content acquisition
Audio links (radio microphones and personal audio monitors)	1. No requirement for higher audio quality 2. Steady but modest growth in number per event, for largest events 3. Trend to provide in-ear monitor and wireless microphone to each performer

Table 1 Summary of spectrum demand trends

2.1.1 General spectrum demand trends – video links

General spectrum demand trends with respect to broadcast-quality video links including radio cameras are discussed below.

For today's largest events, steady but modest growth is predicted in number per event

In most activity areas, only modest growth in radio cameras is likely, due to:

- The relatively high cost of radio link equipment compared with cabled cameras in many cases (especially when rigging time for antenna systems is included),
- Radio cameras not yet being fully reliable, and still requiring a degree of expertise in deployment and operations,
- There being limited further spectrum available for expansion, given expected near-term developments in radio link technology and spectrum allocations.

""In 5 to 10 years I see HD moving to Ultra HD (4k)…but this will not be mainstream in 1 to 2 years' time. It is for exceptional events at the moment."

CTO, Independent TV programme maker

The UK is a class leader in provision of facilities and expertise for staging and televising major events – including the provision of radio spectrum and expertise in its use – and its continuing growth benefits the economy and culture. Where we compete with other countries for activities like feature film and major television drama production, the relevant stakeholders were concerned that the UK should not detract from this excellence through the lack of a resource like spectrum.

Some new production formats and/or business cases could appear that use a much larger number of radio cameras

However, some new programme formats have been envisaged that could engender significant growth in radio camera usage, in applications like in-vehicle, on-bicycle, concealed camera or 'point of view' applications. Some activity areas were mentioned that could use many tens or even hundreds of radio cameras, cost and resource permitting.

There may be further growth in radio cameras for outdoor events carried on unmanned aerial vehicles (UAV) once suitable aircraft have been developed that can be demonstrated to be safe under various fault conditions. Current designs fall rapidly on the failure of the control link or the power source, and regulation prohibits their use within 150m of any crowd of people; this may be relaxed for future designs with autonomous control, making UAV attractive for many sporting events.[1]

There is a trend toward increased resolution, as demanded by broadcasters

Today's radio camera links deliver 1080i50 4:2:0 (1920 x 1080 pixels, 25 full frames per second, colour information sent once per 4 pixels) with reasonable link budget

However the desirable standard is 1080p50 4:2:2 (50 full frames per second, colour information sent once per 2 pixels) for content origination, especially if it is to be archived. Radio camera links can do this now, at a cost of reduced link budget (hence potentially more fragile links than those carrying 1080i). The higher frame rate reduces perceived judder of the picture, especially of fast-moving picture elements, and the higher sample rate for colour data gives greater scope for subsequent processing of the pictures, as well as a slight improvement in perceived resolution on some types of content.

We can confidently predict a demand for '4k' or Ultra High Definition[2] picture resolution (3820 x 2160 pixels, 50 or 100 frames per second) over 10 years, as the consumer electronics industry is already doing a hard-sell of screens for this resolution. BSkyB (via satellite) and NetFlix (internet) are launching 4k services imminently.

There is a trend to increase pixel sample depth and colour gamut, at least for acquisition

Increasing the sample depth to 10 bits or even 12 bits per colour per pixel is arguably more valuable than a move to 4k and cameras are capable of it now. On all but the very largest screens, the perceived quality will improve a lot more with better contrast ratio than with more pixels;[3] current TV distribution (DTT, BluRay etc.) is not capable of more than 8-bit sample depth per colour, but the newer codec standard described below will have this capability.[4]

"The bigger 'wow' factor [than increasing spatial resolution] is to provide higher dynamic range. Displays support 8 bits now … could soon move to 10 or 12 bits"

Director, TV camera manufacturer

In addition to greater contrast ratio, an improved colour gamut is also being defined. For standard definition and HD television, the choice of the three primary colours (red, green, blue) was limited by available phosphor materials and camera sensors, and the ITU-R 709 gamut can display about 70% of the colours that can be reflected by the surface of an object in nature.[5] For UHD, a new standard ITU-R 2020 defines different primary colours which can display 99% of reflected colours, and requires either 10 or 12 bits per colour to encode it.

However, the designers of the next generation codec (H.265 High Efficiency Video Coding) standard expect that this additional colour data will not contribute significantly either to the amount of processing required to encode a picture, or to the rate of the encoded data.[6]

[1] INT-026 UAV manufacturer
[2] UHD strictly refers to '4k or higher' resolution. 8k (7680 x 4320 pixel) cameras are already in production, mostly for cinema.
[3] INT-007 Camera manufacturer: suggested that to get a useful improvement from 4k, the screen would have to be well over 100, and possibly as much as 200, inches diagonal, at the average 2.7m viewing distance.
[4] Current LED-backlit TV sets are specified to accept up to 12 or even 16 bits per colour per pixel. This report does not study whether the displayed colour gamut in these TVs is actually greater.
[5] "Pointer's gamut" an enumeration of the gamut of real surface colours – research by Michael R. Pointer, 1980
[6] INT-025 BBC R&D, HD video specialist

2.1.2 General spectrum demand trends – audio links

General spectrum demand trends with respect to PMSE wireless audio devices are discussed below.

Quality of radio microphones and IEM is now as good as is required

The audio signal to noise ratio, frequency response, distortion etc. of analogue radio microphones and in-ear (personal) monitors (IEM) is generally today regarded as being as good as necessary. This sets the standard for current and future digital designs.

"Price point [of radio microphones] dropped at the end of the 1990s and the quality of low-end gear improved"

Chief Engineer, Radio microphone manufacturer

Steady but modest growth in number per event, for largest events

Very significant growth in radio microphones and IEM has been experienced over the last 5-7 years in live or 'as-live' television shows, music events of all sizes, theatre and film making, such that many shows, film/TV shoots etc. use about as many of these devices as they require.

But no spectacular show ever gets smaller, and modest growth is predicted in most areas.

Although not affecting peak spectrum demand in most cases, there is considerable growth in the number of live music events overall, as musicians now get most of their income here (rather than from recorded content).

Trend to provide in-ear monitor and wireless microphone to each performer

Radio in-ear monitors (IEM) are arguably safer than monitor speakers, avoiding trip hazards and possible high acoustic levels. Many performers have got used to IEM and demand them for live or TV performances. In a contest show, each performer can also be wearing a microphone with a body-worn transmitter, and also using a hand-held microphone. Major live music bands provide IEM to every performer (including backing singers and instrumentalists) and also to the musicians' technicians (typically 3-4 in number) for communications; it is not unusual in this case for each individual to receive their own mix and therefore use one RF channel. For large events with dancers and chorus, and for most feature film shooting, a larger number of IEM receivers can be used, but sharing only a few RF channels

"Six major [mostly outdoor] events over the last year have used between 60 and 100 PMSE audio devices.'

Chief Engineer, Radio microphone manufacturer

TV white space spectrum is already very limited in some locations

Bristol, Manchester and East Grinstead were cited as being examples of locations where TV band white space for outdoor events was very limited, since they fall into the effective coverage area of several TV transmitters.

For example, in parts of Manchester three transmitters[7] can be heard (as shown on a TV coverage map[8]), and this could represent 18 occupied TV channels out of the total 27 that will be available after a possible re-allocation of the 700MHz band (694-790MHz), leaving theoretically up to 72MHz for professional PMSE, in practice known to be reduced as other TV transmitters are also fairly close.[9]

In the case of East Grinstead, parts of the terrain are also shown with 'good' coverage by 18 channels from three TV transmitters.[10] A check of a slightly-elevated location with the Arqiva PMSE

"There are several places where it is today impossible to stage a large music festival [for example] because there is not enough UHF spectrum for the radio microphones – insufficient propagation loss from the TV transmitters with which PMSE shares"

Senior Director, Equipment hire company

[7] For Disley, south of Manchester: Winter Hill, Saddleworth, Birch Vale
[8] http://www.digitaluk.co.uk/coveragechecker
[9] INT-032 Sound Supervisor, TV light entertainment
[10] Crystal Palace, Heathfield, East Grinstead

availability checking tool[11] showed 111.5MHz available today, which – depending on the way in which TV transmissions are re-planned – could reduce to 24MHz or less after any re-allocation of the 700MHz band.

It was mentioned by several audio practitioners[12] that the Arqiva PMSE tool – which has the primary purpose of protecting DVB-T reception – does not always predict channel quality well for radio microphones in some locations. In some cases some ad hoc re-planning has been required when Arqiva PMSE allocations have not turned out to work well on site.

2.2 Analysis of PMSE activity area-specific spectrum demand trends

This section reviews our analysis of PMSE activity area-specific demand trends, including forecasts for peak instances of wireless devices and a supporting narrative on trends within each activity area. The activity areas examined are:

1. Television light entertainment programme making
2. Outdoor music events
3. Major theatre productions
4. Television sport
5. Feature film making
6. Television news gathering

In each case, the term 'peak instances' means the maximum number of concurrent spectrum-using devices in use at a single location.

11 https://www.pmse.co.uk/jfmgecom/wireless/private/microphone.aspx
12 INT-027 Radio mic hire/supply company

2.2.1 Spectrum demand trends in television light entertainment programme making

Key demand trends and forecasts for peak instances of wireless devices in television light entertainment, derived from an analysis of the demand-side interview programme, are summarised in Table 2, below. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section.

Activity area: Television light entertainment programmes					
User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	Growth	Peak instances	Growth
Programme audio devices	109 *Sound Supervisor, TV talent show*	115	1% per year *Sound Supervisor*	140	30% total *Commissioning Editor, Light Entertainment*
Video links (high-definition)	5 Lambing Live *outside broadcast*	30 *Head of Entertainment, TV broadcaster*		100 *CTO, TV production company; Commissioning Editor, Light Entertainment*	
Video links (ultra-high-definition)	0	0 *RF Consultant*		*NB Cannot predict whether or not Light Entertainment will adopt UHD by 2024*	
Comms	10 *Sound Supervisor, TV talent show*	10	0% *Comms kit hire company*	10	0% *Comms kit hire company*

Table 2 Forecasts for peak instances of wireless devices in television light entertainment.

In the TV light entertainment industry the popularity and growth of large talent shows has been rapid over the last 10 years. In the next 10 years growth in size of these shows is predicted to be 30% by TV commissioners. One entertainment show today, *Last Choir Standing*, would benefit from having 120 radio microphones to provide good capture of all the choirs.[13] On this and some other shows, radio microphones (or frequencies) are shared between contestants, but this is risky for live TV where the sound supervisor cannot always be sure that the microphone is with the correct performer (or, for a shared frequency, that the correct microphone is switched on).[14]

Currently, *X Factor* (including its crossover show, *The Xtra Factor*, which adds 15 more performers to the main show[15]) is the largest talent show with 109 peak instances for programme audio devices, 3 radio cameras (one Steadicam, one backstage and one rail-mounted) and about 10 UHF channels used for intercom. Production costs are approximately £1 million per show and it draws a weekly audience of over 15 million viewers. However, the growth in production size of *X Factor* has been fairly static over the last couple of years, possibly because there is a limit to the number of people that can be physically accommodated on the show. Based on recent history this format is predicted to continue to grow very slightly – *X Factor*'s sound budget increases by 2-3% per year which includes inflation, suggesting a 1% real annual growth.[16]

[13] INT-029 Commissioning Editor, TV LE
[14] INT-006 Commissioning Editor, TV LE, INT-029 Commissioning Editor, TV LE
[15] INT-029 Commissioning Editor, TV LE
[16] INT-032 Sound Supervisor, TV light entertainment

The Brit Awards runs a close second with 104 programme quality audio devices, last year comprising 53 microphones, 17 guitar transmitters and 34 radio channels for in-ear monitors. Each of the multiple bands uses around 12 transmitters (microphone or guitar) and 12 IEM channels, so some sharing of spectral resource is done.[17]

In the figures above, no account is taken of other audio devices on the same site (for example, in an adjacent studio). An example from 2012 indicated that for *Children in Need* together with other programmes being made simultaneously at BBC Television Centre needed a total of 152 allocations for audio devices.[18]

The *X Factor* plans to move to all-digital audio devices over the next 10 years[19] to minimise the risk of spectrum and channels required not being available. Last year the show introduced digital radio microphone technology from Sennheiser, which showed improved adjacent channel and intermodulation performance. As a bonus this equipment provided very precise management of its rechargeable batteries, as well the benefit of its encryption capabilities for the judges' deliberations (as journalists had been rumoured to be using radio microphone receivers outside the building to get this information early!). There is a preference for lower latency than the current ~2ms for digital radio microphones: 1ms for the total signal chain from microphone – mixing desk – in-ear monitor would be ideal.

"We expect to go digital to minimise the risk of spectrum not being available for all the channels we require"

Sound supervisor, TV light entertainment

The growth in large talent shows is not expected to cause significant growth in numbers of non-performing staff in the short or long term, as production budgets are squeezed every year – therefore the growth in wireless communications equipment is expected to be negligible.[20]

In general, TV light entertainment will use radio cameras more as technology develops to improve the reliability of the link and minimise the latency, simply to make acquisition more flexible, and to give a greater range of shots.[21] An entertainment show shot outdoors, *Lambing Live*, used 5 co-located radio cameras.[22] In *Splash* (which used a lot of cameras following the individual participants), radio camera range was not always very good in the swimming pool building where the show was shot. Use of UAV-mounted cameras would always be of interest, if the aircraft can be made safe enough to operate in built-up or crowded areas, and this would require further radio links for the cameras.[23]

"The quality is increasing and the cost of cameras etc. decreasing, so we'll be able to shoot in more interesting places and take better shots. In 5 years' time using 100 cameras will be the norm"

CTO, Independent TV programme maker

There will be an increase in Reality TV shows such as *Educating Yorkshire, Educating Essex*, and a new series about educating a platoon of Royal Marines, where up to 100 small, sometimes concealed, cameras are employed to capture fly-on-the-wall content and action shots. For flexibility of deployment at minimum rigging cost, many of these could be radio cameras over the next 10 years, especially as the quality of these cameras increases and their cost decreases.[24] In the more immediate future, a new 'reality game show' is being piloted on Channel 4, in which several groups of contestants play the game over 8 hours through the streets of London, and where 10 radio cameras (including 2 on helicopters) are used. If the show continues after the pilot, it could make good use of 30 radio cameras as there is no possibility of planning most of the camera locations.[25]

Other outdoor shows including *Saturday Night Takeaway, Bedtime Live* and *Embarrassing Bodies* make use of cameras in viewers' homes using (up to 6) mini-outside broadcast units, and this is expected to

[17] INT-036 Sound supervisor / designer
[18] Arqiva PMSE (formally JFMG) allocations for Television Centre, ~16 November 2012
[19] INT-032 Sound Supervisor, TV light entertainment
[20] INT-010 Communications equipment supplier
[21] INT-006 Commissioning Editor, TV LE, INT-015 Technical head, TV news organisation
[22] INT-028 Outside broadcast sound supervisor
[23] INT-006 Commissioning Editor, TV LE
[24] INT-029 Commissioning Editor, TV LE, INT-016 Independent TV producer
[25] INT-022 Head of Entertainment, UK broadcaster

drive the need for further radio cameras and audio devices. Skype video has been used in the past on this type of show to communicate with viewers in the home but has not delivered good quality to date.[26]

Requirements for UHD radio cameras will remain small over the next five years as there is no predicted demand from broadcasters for it in light entertainment; sport is likely to lead in UHD content. One respondent considered 3D in television to have been a flop with audiences and that it is unlikely to be taken beyond last year's pilots.[27] Beyond 5 years, it is difficult to ascertain whether UHD content will be the norm for light entertainment.

The use and demand for second screen content to enhance the audience experience is growing, allowing viewers to express their opinions, take part in voting surveys and use gaming content during advertisement breaks.[28] For example, ITV offer five shows with second screen content including some video: *X Factor, Coronation Street, Emmerdale, Britain's Got Talent* and *The Only Way Is Essex* – in the latter show a separate sponsor,[29] production team and commissioning plan are dedicated to producing second screen video content. Second screen is unlikely in the medium term to affect the number of wireless PMSE devices needed, as content can be taken from the main show equipment. Game shows like *Million Pound Drop* deliver a smartphone or tablet app for home viewers to play, but do not deliver video content.

New show formats such as singing talent show *Rising Star* will provide a smartphone app, for both the studio audience and home viewers to vote, and the *Brit Awards* pioneered allowing the studio audience to tweet. Many smartphones are likely soon to use the 790-862MHz band (and may in future also use 694-790MHz if this band is re-allocated). These bands are adjacent to the PMSE band for radio microphones, and LTE user equipment is permitted to radiate a small amount of energy into adjacent bands, which may present an interference hazard to radio microphones in the same studio. There may also be picocell base stations in the studio which have a higher technical specification but potentially higher transmitted power, therefore also a possible risk for radio microphones. It may be possible to provide Wi-Fi access for this communication, but it may be too complex to instruct all the studio audience to enable the Wi-Fi on their smartphone and connect to a particular SSID.

[26] INT-016 Independent TV producer, INT-022 Head of Entertainment, UK broadcaster, INT-029 Commissioning Editor, TV LE
[27] INT-006 Commissioning Editor, TV LE
[28] INT-029 Commissioning Editor, TV LE, INT-022 Head of Entertainment, UK broadcaster, INT-006 Commissioning Editor, TV LE
[29] Current second screen content sponsor is match.com

2.2.2 Spectrum demand trends in outdoor music events

Key demand trends in outdoor music events are summarised in Table 3. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section..

Activity area: Outdoor music events

User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	Growth	Peak instances	Growth
Programme audio devices	251 *Spectrum plan for Glastonbury 2013 event*	~260	~0% except a few 'specials' *Glastonbury organiser*	~260	~0% except a few 'specials' *Glastonbury organiser*
Video links (high-definition)	17 *Spectrum plan for 2013 event*	~20	~0% except a few 'specials' *Glastonbury organiser*	~20	*~0% except a few 'specials'* *Glastonbury organiser*
Video links (ultra-high-definition)	0	0	~0% except a few 'specials' *Glastonbury organiser*		*NB Cannot predict whether or not outdoor music events will adopt UHD by 2024*
Comms	10 in UHF TV band (+182 in 'business radio' band) *Spectrum plan for 2013 event*	~10	~0% except a few 'specials' *Glastonbury organiser*	~10	~0% except a few 'specials' *Glastonbury organiser*

Table 3 Forecasts for peak instances of wireless devices in outdoor music events

The Glastonbury Festival is the largest outdoor music event in the world, held every 1-2 years. In 2013, a total of 721 wireless device allocations[30] was made for all audio, communications and video links.

In the 470-790MHz TV band many of the (505) allocations were for a limited period (9% for 2 hours or less; 64% less than 1 day, 81% less than 3 days) within the festival, and the peak number of simultaneous frequency allocations was calculated to be 270.

At the time the peak occurred, 9 of these 270 were multiple instances on the same frequency and were spatially separated or flagged 'Must Be Switched Off When Other Artists Are Performing'. This leaves a peak of 261, of which **10** were marked 'In-Band Talkback', and the remaining **251** marked either 'UHF Coordinated Wireless Mic/IEM' or 'Audio Link.' The number of different frequencies in the 470-790MHz TV band that were used at least once was **374**.

The festival has around 10 major stages with up to eight acts a day, with the headlining act (The Rolling Stones) using an estimated 42 audio devices.[31] Broadcasters and film units also had audio device allocations, and a number of allocations were for fixed audio links (for example, linking speaker positions within the audience to the main sound system).

[30] Analysis of Spectrum Manager's spreadsheet from Arqiva PMSE for Glastonbury 2013.
[31] INT-037 Spectrum planning consultant

The UHF TV spectrum used for Glastonbury 2013 comprised a total of 28 x 8MHz channels, 20 are shown as usable outdoors on the Arqiva PMSE planning tool.[32] Of these 28, a TV coverage tool[33] showed 6 channels as having good TV reception from other transmitters,[34] so these probably had a higher noise floor for PMSE than the others. A number of mitigations were used in order to fit the allocations into this spectrum, including:

"Unlikely to fit more into Glastonbury in future"

Event planner

- Temporal sharing of radio mic frequencies. In an ideal set up this would require, per stage, the largest sum of audio channel requirements of two adjacent acts (so that one act can be performing whilst the next is kitted up with their microphones, IEMs etc). Another example of this practice was at the Olympic opening and closing ceremonies, where all performers including bands shared an allocation of about 40 frequencies for radio microphones and 24 for in-ear monitors, with a high level of management of individual devices, transferring them between performers.[35]

  In practice, some performers wish to use their own equipment which may not include the allocated frequencies in its tuning range, and so would require additional allocations. The fact that in the UHF TV band 379 separate frequencies were used to service a peak demand of 266 allocations is possible evidence of this. In the *Brit Awards* this latter problem has in some cases been mitigated by performing an 'electronics transplant' to the performer's equipment, replacing the radio transceiver with the boards from a mainstream product.[36]

- Spatial re-use of the same frequency at the same time is possible over a large site, as interference is unlikely to occur at distances in excess of a few hundred metres. Table 4 shows some of these simultaneous applications for Glastonbury 2013 – they are for the total duration of the festival, and not correlated with the peak allocations.

Simultaneous allocations where two or more allocations were made at the same frequency or close together in frequency[37]					
Same frequency	Within 100kHz	Within 150kHz	Within 200kHz	Within 300kHz	Within 400kHz
44	**49**	**49**	**78**	**95**	**164**

Table 4 Overlaps in time and frequency for Glastonbury 2013 (quantities cumulative left to right)

  Around 78 allocations possibly fall within the passband of a standard FM system: in the allocation chart, these were generally marked as being spatially separated or otherwise managed. The further 86 allocations with a frequency difference between 200 and 400kHz could work with a smaller spatial separation (at least 30m apart) so that intermodulation effects between transmitters do not occur.

- The use of 'grey space' TV channels (i.e. with a higher noise / interference floor) is possible with careful placement of radio microphone receive antennas or IEM transmit antennas to minimise the range that the radio signal needs to cover.

Arqiva PMSE provides a spectrum allocation service for all visiting acts and other users, for audio devices and radio cameras. Arqiva also implements its own on-site management and an investigation service if unplanned radio users turn up at the event, but has no powers of enforcement[38].

[32] https://www.pmse.co.uk/jfmgecom/wireless/private/microphone.aspx
[33] http://www.digitaluk.co.uk/coveragechecker/main/trade
[34] Stockland Hill, Wenvoe transmitters. The main TV transmitter is Mendip, 9km away.
[35] INT-048 Sound designer, large outside events
[36] INT-036 Sound supervisor / designer
[37] Spectrum Manager's spreadsheet from Arqiva PMSE for Glastonbury 2013.

It is expected that, if available UHF spectrum should reduce, more mitigating activities will be needed year on year for Glastonbury, including wider tuning range, ability to function with smaller carrier to interference ratios and better back intermodulation performance. In particular, if the 694-790MHz band is re-allocated, about 16 TV channels will remain – about 120MHz when guard spaces are included – allowing a peak 300 instances when spaced 400kHz, which is more than the 2013 actual peak allocation (266), but considerably less than the number (379) of individual frequencies that were allocated in 2013.

The bulk of the on-site communications used equipment that did not use PMSE frequencies: only 10 frequencies were allocated in the UHF TV band, compared with about 189 allocations in VHF or UHF business radio bands. A total of 17 radio cameras were used between BBC Technology and SIS Outside Broadcasts; no other broadcasters had radio camera allocations.

Significant growth is not predicted for the Glastonbury Festivals, as it is limited by the site and environmental considerations. Similarly, its organiser does not expect proliferation in the number of broadcasters on the site.[39]

Overall the total number of separate music concert events is predicted to increase steadily as this is now the main revenue stream for music bands, now that recorded music is either given away or sold at low prices: the total number has quadrupled over the last 5 years.[40] Large outdoor music concerts, which included British Summer Time Hyde Park event, One Big Weekend at Carlisle Airport, and Take That's concert at the Sunderland Stadium of Light, use typically 60-100 wireless devices, and it was estimated that 40-50 wireless devices can be used for the largest band in a concert[41].

Historical growth in wireless audio devices has been significant, from just a few devices for a typical band a decade ago, up to current levels.[42] The growth for musicians has been in

- wireless guitar links (a Bruce Springsteen set at a past Glastonbury Festival included 8 guitars each with its own radio pack[43]). The wireless link must be of sufficient quality to be indistinguishable from a cabled one, and this is generally achieved.[44]
- IEMs, which are often supplied to the musicians' support technicians (usually 3-5 in number) as well as to all performers including backing singers and instrumentalists. A health and safety case is often made for IEMs: both in reduced trip hazard and in the chance to reduce audio levels on stage. For singers, there is a maximum tolerable delay between their own microphone and what they hear in an IEM, which is about 3ms on average, with some exceptions where the singer will not tolerate any delay at all in excess of a fraction of a millisecond.[45] This precludes the use of many current digital devices.

A typical band will use at least 12 portable transmitting devices (either radio microphones or guitar transmitters) and 12 IEMs, each using a separate frequency.[46] Now, following this considerable rise in device numbers, almost everyone who could be using a wireless audio device is doing so, and further growth is likely to be organic only.

[38] INT-037 Spectrum planning consultant
[39] INT-061 Glastonbury organiser
[40] INT-010 Communications equipment supplier
[41] INT-010 Communications equipment supplier, INT-008 Radio mic manufacturer
[42] INT-008 Radio mic manufacturer
[43] INT-037 Spectrum planning consultant
[44] INT-031 Radio mic manufacturer
[45] INT-036 Sound supervisor / designer
[46] INT-036 Sound supervisor / designer

2.2.3 Spectrum demand trends in large theatre productions

Key demand trends in West End and other large theatre productions – principally musical – are summarised in Table 5, below. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section.

<table>
<tr><th colspan="6">Activity area: Major Theatre Productions</th></tr>
<tr><th rowspan="2">User service</th><th>2014</th><th colspan="2">2019</th><th colspan="2">2024</th></tr>
<tr><th>Peak instances</th><th>Peak instances</th><th>Growth</th><th>Peak instances</th><th>Growth</th></tr>
<tr><td>Programme audio devices</td><td>74
‘Charlie and the Chocolate Factory’ - Radio mic hire/supply co.

‘up to 80’
Radio mic manufacturer</td><td>84</td><td>Negligible
Producer, West End musicals</td><td>94</td><td>Negligible
Producer, West End musicals</td></tr>
<tr><td>Video links (high-definition)</td><td>0
No use of wireless video mentioned</td><td>0</td><td>0%</td><td colspan="2" rowspan="2">0
Unlikely that large theatre productions will adopt significant wireless video (HD or UHD) by 2024</td></tr>
<tr><td>Video links (ultra-high-definition)</td><td>0</td><td>0</td><td>0%</td></tr>
<tr><td>Comms</td><td>70, across worst case group of 4 theatres
Radio mic hire/supply co.</td><td>70</td><td>0%
Radio mic hire/supply co.</td><td>70</td><td>0%
Radio mic hire/supply co.</td></tr>
</table>

Table 5 Forecasts for peak instances of wireless devices in major theatre productions

The West End musical industry plays an important role in the UK’s tourist industry and is an important contributor to the economy. The West End is a high density user of spectrum, and growth in the size of the largest West End and national touring productions is predicted to average 5% per year[47] on average over the next 5-10 years, with the proviso that the industry is somewhat cyclic in nature.

Currently, the West End production of *Charlie and the Chocolate Factory* at the Theatre Royal, Drury Lane is the greatest user of wireless devices. A total of 74 programme-quality audio channels (64 radio microphones and 10 reverse radio links to deliver sound effects from speakers in movable pieces of theatre set) and 28 UHF frequencies for intercoms[48]. Around ten other shows in London’s West End use between 40 and 68 radio microphones, and up to 22 channels of intercom.

There are several groups of theatres in the West End that are close enough together to require some frequency co-ordination. Because radio microphones and other programme-quality equipment is generally used only on stage or in the auditorium, the local transmitter is usually received at a much higher level than the one from an adjacent theatre, but this is not true of intercom systems where

[47] INT-027 Radio mic hire/supply company
[48] INT-027 Radio mic hire/supply company

coverage is needed throughout the building; therefore intercoms need inter-site co-ordination.[49] The prediction in Table 5 for intercoms is for one of these groups[50] – a total of 70. UHF remains popular for intercom equipment as the range is greater than with systems at higher frequencies. (Whilst some of the higher frequency equipment is cellular, theatre productions invariably use temporary installations, where multiple base units add an undesirable level of cost and complexity.)[51] No interviewees were aware of any radio HD or UHD video links in theatres.

Opera in the UK uses radio microphones mainly for its own audio-visual acquisition (for archive recordings and live relay to cinema) and for occasional special effects, and in general the number of devices is small – the Royal Opera House owns 16 radio microphone channels which cover 95% of its requirements. Some more modern 'musical-like' shows use a few more: Turnage's *Anna Nicole* used 18. No radio cameras are used by the ROH (which has its own TV production facility) except by visiting broadcasters when other events are run in the theatre.[52]

In Europe the practice with radio microphones is different: the opera houses at Malmö and Darmstadt operate 65 and 64 channels respectively (both using digital systems),[53] and this practice may migrate to the UK.

There is a limit to growth in the theatre set by the number of people that can be present on stage and therefore ultimately to the use of radio microphones. However, with high audience expectations of quality and reliability, a growing number of lead performers are wearing double radio microphones to ensure continuity through equipment failure or interference – for example, *Les Misérables* was re-equipped recently with 8 leading performers wearing dual transmitters. Also, in some instances a further radio microphone is built into another costume to allow for quick costume changes, but in general there is not someone back-stage to manage switch-on and -off of transmitters, meaning that another radio frequency is required. Uneven growth is expected for radio devices, averaging perhaps 5% per year.[54] Growth in backstage staff is small, and the expected growth in intercom systems is zero.[55]

"There are more new shows and existing shows continuing in the West End. The greater growth has been in the touring productions, now requiring similar channel counts to West End."

Radio microphone manufacturer

The use of IEM is not common in theatre today, but the next generation of performers with a background in music concerts may demand them in the future.

In general, spectrum is not a problem today for West End theatres. However, the trend for one-off shows and national touring productions[56] is growing and these productions are becoming as complex as West End shows in terms of spectrum requirements. PMSE spectrum planning in some locations can be difficult, particularly when more than 40 radio microphone frequencies can in practice be hard to locate in certain cities such as Edinburgh.[57]

[49] Novello, Lyceum and Aldwych Theatres and Theatre Royal Drury Lane make one such group; Prince Edward and Palace Theatres make another
[50] Theatre Royal Drury Lane: *Charlie and the Chocolate Factory* (28); Lyceum: *The Lion King* (22); Novello: *Mamma Mia* (10); Aldwych: RSC repertory, followed by *Dance 'Til Dawn* from October 2014 (guess 10)
[51] There are systems on the market at 1.9GHz using DECT technology, and at 2.4GHz using a range of designs.
[52] INT-053 Theatre head of sound and broadcast
[53] INT-024 Digital radio microphone manufacturer
[54] INT-027 Radio mic hire/supply company
[55] INT-010 Communications equipment supplier
[56] INT-031 Radio mic manufacturer
[57] INT-027 Radio mic hire/supply company

2.2.4 Spectrum demand trends in television sport programme making

Key demand trends in television sport are summarised in Table 6, below. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section.

Activity area: Outdoor sporting events

User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	Growth	Peak instances	Growth
Programme audio devices	97 *Arqiva PMSE assignments: NFL, Rams vs. Patriots, Wembley Stadium. 2012*	116	20% *Director, IMG Sport*	140	20% *Director, IMG Sport*
Video links (high-definition)	42 *Formula One*	50-60 *Formula One*		67 *Formula One* (200 for Tour de France) *CEO, Sports prod company*	
Video links (ultra-high-definition)	1 *Ryder cup – CEO, Sports rights-holder*	1	*Probably none*		
Comms	26 *Arqiva PMSE assignments: NFL, Rams vs. Patriots, Wembley Stadium. 2012*	30	Probably small in UHF TV bands	35	Probably small in UHF TV bands

Table 6 Forecasts for peak instances of wireless devices in television sport programme making

Over the past decade radio cameras and radio microphones have become crucial to televising sporting events, to the extent that some of them (e.g. the Boat Race, marathon and cycle races) could not be done in their present form without these radio devices, whilst others (e.g. golf, horse racing events) could only be done at significantly more cost. TV audiences have become used to 'the best seat in the house' that is made available by this technology. Today's radio cameras cannot yet be deployed 'plug and go' (in the way that wireless audio devices invariably can), and the radio link for video is expensive; once technology overcomes these two hurdles, we can expect considerable growth, possibly replacing cabled cameras in any temporary installations,[58] for all but the most critical applications (like finish lines).[59]

The largest radio camera usage area is Formula One motor racing, where the typical arrangement of broadcasters is shown in Table 7, below:

[58] Larger football stadiums, Wimbledon etc. have cable infrastructures, therefore no advantage to radio links for fixed cameras.
[59] INT-052 Director of Sport, TV broadcaster

Formula One – application	Wireless video	Wireless audio
4 'host' broadcasters each with 2 roving crews, each using 2 radio cameras, 1 reverse video link, up to 6 radio microphones	24	40
6 guest broadcasters (which includes Formula One's content provider for the trackside screens) each with 1 radio camera and up to 3 radio microphones	6	18
On-car cameras, linked to multiple receive sites around the track, max.	12	-
TYPICAL TOTAL TODAY	**42**	**58**
Future growth over next decade: another 3-4 broadcasters, of whom one might be dual crew (as per hosts above)	15	32
Additional on-car cameras (which will require allocations at a higher frequency than the 7GHz band)	10	0
EXPECTED TOTAL IN 10 YEARS (in 2GHz, 7GHz and higher frequency bands)	**67**	**90**

Table 7 Radio camera and audio device usage for Formula One motor racing

(Some other wireless links, feeding the trackside displays etc. are also deployed, but Formula One is discouraging this practice.) Over the next few years, Formula One is developing and testing its own radio link equipment for car-to-trackside communications; this will replace up to six existing on-car radio systems used for telemetry, voice communications etc., and will support one video link from each car (i.e. an increase from the 8-12 cars currently supported for video). The equipment will have the capability of using frequencies above 7GHz, and Formula One is working with regulators globally for suitable allocations.[60]

Once the in-car camera development is complete, Formula One's requirement for radio cameras in the 2GHz and 7GHz bands over the next 10 years could decrease to **45**, This assumes that PMSE spectrum could be made available in bands above 7GHz for up to 22 on-car links. It is not yet known what radio channel bandwidth will be required per car. [61]

Other events using significant numbers of radio cameras by the host broadcaster are the Grand National horse race, 11 (including a van-mounted jib camera recently added to the line-up); the Boat Race, 10; London Marathon, 10 (5 on motorcycles, 2 on helicopters, 3 shoulder-carried).[62] For marathon and bicycle races the video from motorcycles is generally uplinked to aircraft; in some cases in two steps from motorcycle to a helicopter, and then onward to a fixed-wing aircraft at higher altitude, before being relayed back to the studio centre. At each of these events there are varying numbers of guest broadcasters, typically with 1-2 radio cameras each.

"Production budgets are going down all the time and this may counter against radio cameras with them being more expensive than cabled: this may restrict growth"

CEO, sports programme maker and content owner

Major golf tournaments have considerable guest broadcaster interest, with 9-11 cameras for the host, and up to 26 (Ryder Cup) or 22 (British Open) in total.[63] Because of the different games and different stages of each game in golf, the full complement of cameras is in use all the time, with little chance of mitigation from sharing spectrum between cameras. For Wimbledon tennis, there can be up to 50

[60] INT-051 Formula One
[61] INT-051 Formula One
[62] INT-052 Director of Sport, TV broadcaster
[63] INT-023 Radio camera supplier

guest broadcasters but only about 6 will typically deploy one radio camera each, the host using 2.[64]

For most sports, radio camera deployment has reached a natural level (reached before there was pressure on spectrum).[65] In the USA, most sporting events use comparable or smaller numbers of radio cameras (e.g. 30 for motor racing, 2 for an NFL football game, 6 for golf games)[66] so significant changes in practice are not expected to come from that source. Because production budgets are being reduced all the time, radio camera deployment may not increase significantly unless equipment costs fall significantly. That said, no event has ever used fewer cameras than its predecessor, and it is common to add one camera or so per year.[67] In the USA, 'spider' cameras on wires are becoming popular and may be adopted in the UK, adding another radio camera to the total.[68]

The demand for televised outdoor sports broadcasting is expected to continue to grow in the next 5 to 10 years, predicted to be driven by increasing coverage of American sports like National Football League, more online content and the expectation that all non-premier league football will be captured for TV using small OB facilities.[69] However; the peak usage of wireless devices is expected to remain at current levels for televised outdoor sports: in football, tennis and cricket only 1-2 radio cameras are typically used as roving cameras for interview or touchline (or equivalent) views.

Future trends in the sporting industry include the increased use of mini-cameras, almost all radio linked, for 'point of view' pictures – for example, within riders' helmets in horse racing events, within cricket stumps, or attached to the bikes of cyclists (although the weight of current or foreseeable equipment is unlikely to be attractive to the cyclist![70]). In this latter case a business case has been proposed in which viewers could pay a subscription to gain access to content from their favoured competitors. However, there has generally not been much interest from potential subscribers in paid-for speciality feeds.[71]

Another future probable trend is the adoption of 4k video in the next 10 years for major sporting events, starting with the Olympics and the World Cup – UK broadcasters are not yet committed to 4k adoption as it would require an upgrade of the camera interfaces and links, the connection back to the broadcast centre, and the production workflow[72] – so it may be slower in the UK compared with the USA or Japan and other Asian countries,[73] although BT Sport may be launching some 4k content,[74] and the one 3D camera already used at the Ryder Cup this year is likely to be replaced in future with a 4k one.[75] We could certainly expect a mix of HD and 4k acquisition within 5 years.[76]

Programme-quality audio devices include in-ear monitors for commentators and radio microphones: a host, or larger guest, broadcaster might use up to 6 devices per crew. The estimated total for Formula One is 58 today, growing to a possible 90 by 2024, but a larger number was used for a multi-broadcaster NFL event at Wembley Stadium in October 2012, as shown in Table 6.

Some comms-quality devices in the UHF TV bands are also used (in addition to 'walkie-talkie' type equipment partitioned within business radio bands): the number shown is based on the same NFL allocation.

[64] INT-040 CEO, TV sport producer
[65] INT-050 Technical head, sports broadcaster
[66] INT-055 Technical head, sports broadcaster
[67] INT-052 Director of Sport, TV broadcaster
[68] INT-055 Technical head, sports broadcaster
[69] INT-040 CEO, TV sport producer
[70] INT-058 Technical head, sports broadcaster
[71] INT-052 Director of Sport, TV broadcaster, INT-051 Formula One
[72] INT-059 Sports Technical manager, UK broadcaster
[73]INT-040 CEO, TV sport producer
[74] INT-058 Technical head, sports broadcaster
[75] INT-023 Radio camera supplier
[76] INT-059 Sports Technical manager, UK broadcaster

2.2.5 Spectrum demand trends in feature film making

Key demand trends in film making are summarised in Table 8. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section.

Activity area: film-making					
User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	Growth	Peak instances	Growth
Programme audio devices	36 max on one film set; *Les Miserables filming* 40 average 10 with 4 co-located productions	100 (average 10 x up to 10 co-located productions) *Film recordists*		200 (average 10 x up to 20 co-located productions) *Film recordists*	
Video links (high-definition)	0 –confidence monitors only [non-PMSE[77]] *Film recordists*	0 *Film recordists*		0 *Film recordists*	
Video links (ultra-high-definition)	0 –confidence monitors only [non-PMSE] *Film recordists*	0 *Film recordists*		0 *Film recordists*	
Comms	0 *Almost all comms is partitioned in business radio band*				

Table 8 Forecasts for peak instances of wireless devices in film-making

Currently the British film industry is buoyant; experiencing strong growth and attracting much overseas business supported by favourable UK government tax incentives. The number of wireless devices used in film production has increased significantly over the last 6-7 years, with the key driver being the transition from wet film to digital camera use.[78] With digital cameras there is no expensive consumable like film stock, so it is today common practice to use 4-6 digital cameras on a single scene, recording the entire scene at once. (Film camera practice used to be that each scene was shot a number of times, with the camera set up in the various positions required.) This has meant that directional microphones on booms or poles can no longer be the primary source of audio, since the device and its operator cannot be kept out of shot of all the cameras.

““The move from wet film to digital cameras has meant that there is no major cost to running 5-6 cameras on a shoot”.

Freelance film production mixer

The primary sound in film production is now from radio microphones used on actors (although boom and pole-mounted microphones are still used, but usually with a radio transmitter to avoid trailing cables). Film production mixers (sound recordists) license and make use of the uncoordinated PMSE allocation of TV channel 38 (606-614MHz), and each production mixer owns a number of radio microphone and IEM kits

[77] Film confidence monitors generally use licence-exempt spectrum at 2.4GHz or 5GHz, or at 1389-1399MHz – an allocation entitled ‘video distribution for private use’

[78] INT-046 Film production mixer, INT-044 Film production mixer

which include this allocation in their tuning range – and most of which currently have a tuning range of around 24-25MHz. Where necessary, production mixers license other coordinated PMSE frequencies.

"The demand is ever expanding, especially with the UK's tax incentives for film making"

Freelance film production mixer

For the filming of *Les Misérables*, 32 wireless programme audio devices were used[79] simultaneously. In a recent TV 'crossover' programme that was shot in film style, *Masterchef* fed the cast of *EastEnders*, 40 radio microphones[80] were used. These represent the peak instances for PMSE spectrum demand in a single shoot, and a further significant increase in the number of wireless devices is not expected per production in film making; only small numbers of microphones being added for occasionally larger casts, capture of sound atmosphere and effects etc.[81]

Since film shots and scenes are often 'designed on site' by the director, there is often little chance to plan frequency requirements in detail. Production sound mixers work on the basis that they will initially use frequencies in channel 38, and they license other frequencies where they can predict their need, from the film's shooting schedule. This generally works for shooting on location, except when last-minute schedule changes are made (often due to the weather or other influences external to the sound recording process).

However, in large film production studio complexes (Pinewood, Shepperton, Leavesden etc.), a number of films can be shooting at the same time on the site. These studio complexes are growing since the UK's tax incentives for feature film production are to be expanded to support high-end TV drama too, and the larger complexes can accommodate 10 or more film or TV productions, of which several could be using in excess of 20 radio microphones.

Shooting in a studio complex like this can lead to spectrum coordination issues with multiple shoots in progress; in this case the use of channel 38 is coordinated informally between the production mixers working on the different films, but they can run out of frequencies in channel 38 despite this informal coordination,[82] requiring the licensing of additional PMSE frequencies, often at short notice. The studio centres generally 'dry hire'[83] their facilities to film producers, who themselves bring in all the equipment required for the shoot, and therefore do not feel that they are in a position to assist with such coordination.[84]

In addition the predominantly American-based film industry does not expect to be charged for spectrum (since in the USA radio microphone use is licence-exempt) and there is often no provision for production mixers to be reimbursed by the client for any PMSE licence fees, nor for the hire cost of additional radio microphone equipment when the PMSE allocation is not within the tuning range of their own equipment. Therefore a shortage of channel 38 spectrum can be a direct financial hit on the production mixer him/herself.[85] A mitigation of the hiring-in issue is to procure equipment with a wider tuning range, and at least two of the manufacturers[86] popular with film production mixers now make equipment with tuning span between 75MHz and 232MHz; but this investment is again a cost to the individual. These additional costs to production mixers might serve to make their services less competitive than those of their peers in other countries.

It would be very helpful to production mixers to have a smartphone app which allowed very rapid licensing with Arqiva PMSE, to avoid the need to 'go illegal' in order not to hold up the film shooting schedule.[87] Another uncoordinated block of frequencies like channel 38 would be even better!

Channel 38 radio microphones have been reported[88] to be more susceptible to back intermodulation than ones in the previous uncoordinated allocation at channel 69, so that production mixers have been able to

[79] INT-046 Film production mixer, INT-044 Film production mixer
[80] INT-042 Film production mixer
[81] INT-046 Film production mixer, INT-044 Film production mixer
[82] INT-046 Film production mixer, INT-044 Film production mixer
[83] 'Dry hire' means provision of equipment or facilities without associated staffing.
[84] INT-060 Technical director, film studio
[85] INT-044 Film production mixer
[86] Lectrosonics, WisyCom etc.
[87] INT-042 Film production mixer, INT-046 Film production mixer

use fewer audio channels: in one case only 4 reported possible, compared with 6-8 at channel 69. However, a difference in 'back intermodulation' performance (see section 3.3.1 for details) for the same basic design at different frequencies is highly improbable with current transmitter designs. There is a slightly greater probability of receiver intermodulation effects at particular frequencies, for example at harmonics of the IF (which is 110MHz in most current designs – not obviously related to 606-614MHz).[89] Further investigation would be needed to exclude the effects of either external interference or some other artefact of the design being used. Channel 38 has also been reported as having a higher noise floor than channel 69, but other reports suggest that it has improved in the last few years.

The UK has a limit of 50mW transmitted power for body-worn radio microphones (and 10mW for non-body-worn types). This power limit restricts the distance over which audio can be recorded, which in turn may affect the scenes that can be shot on location. It was suggested that for filming in the UK power limitation should be updated or revised in line with other countries. For example, in the USA the power limit is generally 250mW, whilst another opinion was that the 50mW limit was a good incentive to optimise antenna and receiver performance instead.

Often actors are fitted with a radio microphone at the start of the day that can be turned on and off remotely as required (especially if costumes are complex); several designs offer control via licence-exempt radio or ultrasonic link. This capability allows spectrum not to be occupied when not required.

Digital radio microphones are not popular with most production mixers, with cited issues including reduced range, audio output quitting without warning (where in an analogue system the audio noise floor would first increase and warn the user), and delay being a problem when mixing a number of microphones some of which might be non-digital wireless, or cabled. In this case phase differences between microphones can arise and be a problem, especially as the audio mixing equipment used in the field does not currently offer control of delay to correct this. Film production mixers are expected to deliver a mix of the film's dialogue on the day of filming, so correcting phase issues in post-production, whilst possible, is not desirable.[90]

[88] INT-046 Film production mixer, INT-049 Film production mixer
[89] INT-057 RF designers' panel
[90] INT-042 Film production mixer, INT-049 Film production mixer

2.2.6 Spectrum demand trends in television news gathering

Key demand trends in television news gathering are summarised in Table 9, below. Derived figures (e.g. from a % growth forecast) are shown in pale grey. These forecasts are discussed in more detail in the remainder of this section.

Activity area: News gathering					
User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	Growth	Peak instances	Growth
Programme audio devices	30 *Technical head, news organisation*	35 *Technical head, news organisation*		45 *Technical head, news organisation*	
Video links (high-definition)	10 *Technical head, news organisation*	12 (due to 1-2 added broadcasters) *Technical head, news organisation*		15 (due to 1-2 added broadcasters) *Technical head, news organisation*	
Video links (ultra-high-definition)	0 *Currently no UHD for news*	Probably 0 *Technical head, news organisation*			
Comms	0 *UHF TV band comms requirements negligible*				

Table 9 Forecasts for peak instances of wireless devices in television news gathering

Radio links have become the normal way of transmitting news from camera to news-gathering vehicle or infrastructure, with the owners of many locations no longer permitting cables on their property on health and safety grounds. Similarly, broadcasters are concerned about public safety liability when cables are laid across streets and pavements, and generally avoid this.[91]

News gathering in the UK for day-to-day news is done by five main broadcasters; BBC, Sky News, ITV, BBC Regions, and ITV Regions. Each of these organisations licenses, long-term and country-wide, one 10MHz wide radio camera frequency for low-power operation between an on-camera transmitter and an outside broadcast vehicle, and a second 10MHz wide frequency (in BBC's and ITV's case shared between their two operations) which can be used at higher power to link from vehicle back to a central receiver point. Both frequencies are in the 2.0-2.1GHz or 2.2-2.3GHz band. All these organisations also operate satellite news gathering vehicles which can receive from the radio cameras and uplink to a satellite, when a ground-based central receiver point is not available within range.

[91] INT-035 Spectrum policy manager, TV broadcaster, INT-056 Technical head, TV news organisation

When additional cameras are required for more complex events, these are licensed either in these 2GHz bands or in the 7.1-7.3GHz band. For a major news item such as a film premiere in Leicester Square, the peak use of wireless devices can be 10 or more on-camera links and 30 or more radio microphones[92]. The use of radio cameras in the 7GHz band requires more planning due to the 'near line of sight' properties of signals at this higher frequency; therefore 2GHz is always favoured for ad hoc news gathering.[93] On the other hand, the spectrum at 7GHz is generally cleaner than at 2GHz.[94]

"Radio cameras work best in the 2GHz region, where there is no control of camera location and we have no control over the "sharp end" of the link. We prize links that are able to go around corners"

Technical head, TV news organisation

UK broadcasters have agreed informally to limit the transmitted power from radio cameras to 100mW (up to 1W ERP is permitted by the licence) within the M25, in order to secure both co-existence when they use channels adjacent in frequency and maximum re-use of the channels from one location to the next.[95]

By the end of 2014 all news gathering will be in 1080i50 HD (i.e. 25 full frames per second as described in section 2.1) – this trend was initiated by Sky News in 2010 for the General Election. Today's codec and radio modem technology makes it feasible to transmit 1080i50 with reasonable robustness, but there is a production desire to move to 'full HD' of 1080p50, which will require further technical development, with one operator suggesting that improved modem technology (e.g. HalfRF, described in section 3.2.3) might be used in some cases for full HD rather than to increase capacity.[96] In 10 years' time there may be pressure to move to 4k resolution, but this will be led by television sport ahead of news.

A new news service, London Live, has recently started up, and its operations to date use entirely 3G/4G MNO services, using aggregator boxes with multiple modems from manufacturers like LiveU or Dejero. This equipment is also used by the other news organisations for rapid deployment where timely content is more important than picture quality: the best data rates achieved over cellular networks are currently around 8Mbit/s (an example from the USA, where Verizon has deployed 4G networks widely)[97] which is about half that achieved with the standard PMSE video links. Good cellular coverage is required, and in some cases multiple news crews in one location have found that together they overload the networks, and have to schedule their contributions co-operatively to avoid this.[98] Cellular services are also used for uploading recorded content (not in real time). Several news organisations would be interested in cellular links with a guaranteed quality of service for their live contributions, but have not found much interest from the MNOs yet in providing this.[99]

London Live is currently procuring city-wide connectivity using a 'wireless Ethernet' type service from operator UK Broadband, which is providing a ~50Mbit/s IP link to multiple access points. The service is line-of-sight, and London Live has built a truck with a telescopic antenna, and with a local link to a radio camera using the Cobham Communications NETNode MIMO radio – a PMSE allocation will shortly be required to operate this latter link.[100] Other news organisations are also procuring fixed receiver infrastructure, in one case allowing direct connection from a radio camera to the network. This will not require additional PMSE licences for many of their operations.[101]

In addition to the six news organisations above, foreign broadcasters use radio cameras from time to time, including CNN and NBC from the USA. These latter broadcasters license PMSE frequencies short-term as required. Otherwise significant growth in normal news gathering is not expected, with the important exception of major events like royal weddings or state funerals, where special planning is required.

[92] INT-015 Technical head, TV news organisation
[93] INT-035 Spectrum policy manager, TV broadcaster
[94] INT-054 Technical head, TV news organisation
[95] INT-056 Technical head, TV news organisation
[96] INT-056 Technical head, TV news organisation
[97] INT-056 Technical head, TV news organisation
[98] INT-015 Technical head, TV news organisation
[99] INT-056 Technical head, TV news organisation, INT-015 Technical head, TV news organisation
[100] INT-054 Technical head, TV news organisation
[101] INT-015 Technical head, TV news organisation

Radio microphone usage is typically 2-3 per camera crew, and intercom is generally done either with push-to-talk transceivers (which use PMSE allocations that are generally partitioned within business radio bands) or mobile phones.[102] Radio microphones in news are generally used with a receiver on a camera close by, but there are cases where the separation is greater, and a need was expressed for equipment with good range; therefore UHF devices are desirable.[103]

A current trend for news gathering at large venues, like political party conferences, is the provision of broadband IP connection from the venue, but there are substantial costs associated with running a cable for this. The possibility of utilising a radio link for this IP link would be more favourable in cost, and news organisations have conducted trials using the 5GHz licence-exempt band. However, for this to be a reliable option, broadcasters would need to have protected spectrum.

News gathering broadcasters are beginning to offer ‘second screen’ services to enhance home audience experience. ITN, for example, is already providing a separate feed for a football customer who delivers extra content to mobile phones. However, this is not expected to increase radio camera usage.[104]

[102] INT-015 Technical head, TV news organisation
[103] INT-035 Spectrum policy manager, TV broadcaster
[104] INT-015 Technical head, TV news organisation

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3 Analysis of technology and working practice trends in PMSE

In this chapter we present an overview of technology evolution and changes in working practices taken from an analysis of our interview programme. We begin with a summary of technology and working practice mitigations, which are derived from an analysis of key trends. We then discuss technology and working practice trends with respect to video and audio links, anchored in terms of today's state of the art.

3.1 Development of technology mitigations

A set of technology and working practice mitigations was developed, based on the trends identified throughout the course of our stakeholder interview programme. These mitigations are summarised in Table 10, below, and will be applied to a set of activity area-specific mitigation scenarios (Chapter 0).

Technology and working practice mitigations	
Video links (radio cameras and some fixed links)	V1. Codec technology should improve roughly in step with demand for resolution V2. HD video will be possible in 5MHz bandwidth in the near future using HalfRF or similar modem. V3. Higher-order MIMO and H.265 codec should over 10 years provide UHD in a 5MHz bandwidth, or HD in 2.5MHz bandwidth V4. 7GHz radios are available now, but will need a lot more care in deployment and may not be applicable everywhere.
Audio links (radio microphones and personal audio monitors)	A1. Top of the range analogue kit can deliver 400kHz raster, with care A2. Digital equipment offers raster down to 350kHz (and 125kHz in optimum conditions) A3. In the long-term a change to digital OFDMA systems could provide levels of spectral usage equivalent to 250kHz (or smaller) raster

Table 10 Summary of technology and working practice mitigations

3.2 Technology and working practice trends - video links

Technology and working practice trends with respect to video links (including radio cameras and some fixed links) are discussed below.

3.2.1 Today's technology

Today's medium-distance radio camera technology invariably uses a video codec which is developed from the ITU-T H.264 standard (which is used for today's high-definition TV transmission and for Blu-ray discs, etc.). Radio camera equipment manufacturers carry out further development so as to reduce the end-to-end latency to a maximum of two frames; in most cases less than 1 frame (40ms in Europe) latency is achieved.[105]

The radio modem technology is again based on an established standard, the DVB-T system which specifies a coded orthogonal frequency division multiplex (COFDM) system which was originally designed to fit into an 8MHz channel bandwidth in the UHF TV band (470-790MHz). The allocated channels for PMSE are 10MHz wide, so there is some guard-space when using this modem. Two manufacturers make alternative modems which fill the full 10MHz bandwidth: Cobham UMVL and Gigawave UMST, delivering either higher data rates, or more robust operation.

[105] INT-012 Radio camera link equipment manufacturer

The data rate over the radio link is between 12 and 16Mbit/s,[106] using a 16-QAM constellation. RF output power is usually 100mW for handheld, and up to 2W for vehicle mounted, or 5W for aircraft-mounted transmitters. At this rate, the codec delivers broadcast quality at a 'half-HD' rate of 1080i50 (or 768p50).[107] With careful deployment of a radio camera system, it is possible to transmit 1080p50 with reduced link budget – this is done, for example, for the backstage cameras for *Strictly Come Dancing*.[108] Current DVB-T based modem implementations are claimed to achieve performance within 2dB of theoretical,[109] suggesting that there is not significant scope to improve performance using the current standards. In addition, they are spectrally efficient in the sense that they can be used back to back[110] in adjacent 10MHz radio channels. Tuning span of current equipment is around 750MHz.

The frequencies at 2105MHz and 2095MHz have been reported unusable in some places due to adjacent 3G downlinks. The frequencies at 2395MHz and 2495MHz are also expected to become similarly affected by the future award of the 2350-2390MHz band and roll-out of LTE at 2.6GHz . It was mentioned that cellular network base stations are permitted to emit much higher powers in the channels adjacent to a radio camera than its own transmitted power (which is generally between 100mW and 1W). Radio camera modems need better than 20dB signal to interference + noise ratio in their 10MHz band to function reliably.[111] A future change in use of mobile satellite band at 1980-2010MHz to use LTE technology (or other transmissions with similar RF characteristics) might also affect the radio camera frequency allocation at 2015MHz.

The cost of radio camera link equipment has dropped from some £70,000 ten years ago to nearer £20,000 today, and the performance has improved to the level that it is now unusual to have problems with a radio camera.[112]

Shorter range radio camera systems operate in the 5GHz bands, and make use of high-order MIMO techniques – mostly using silicon from Amimon Ltd.[113] in Israel – to deliver several hundred megabits per second over the link. These systems use much simpler and lower (typically <1ms) latency codecs, and occupy typically 20MHz or 40MHz of spectrum. In general they function well indoors over distances of a few tens of metres.[114] These systems can be operated in the licence-exempt allocations at 5.15-5.35GHz (at 100mW, indoors only), 5.47-5.725GHz (at 1W)[115] and at 5.725-5.875GHz (at 25mW). The total licence-exempt allocation is 605MHz, which could – in cases where there are few other users in the location – accommodate a fair number of short-range video links. Alternatively these systems can make use of a number of PMSE allocations (totalling 291MHz) within the range 5.472-5.925MHz which allow higher power.

Some TV shooting has also been done by the BBC with a TV camera attached to a standard Wi-Fi terminal, which can deliver 2-way video, but with longer latency than systems described above.[116] This radio link equipment costs less than £1,000, and is also compatible with an enterprise Wi-Fi network, which could provide a solution to some of the high demand scenarios described in section 2.2.1, etc.

3.2.2 Codec / modem technology is improving, roughly in step with demand for resolution

Single manufacturers in the broadcast market do not have the resources to develop specialist codecs,[117] since the amount of research and development work is too large: the H.264 and upcoming H.265 (High Efficiency Video Codec, HEVC) codecs are both the result of big international cooperative research and development programmes. Therefore it is expected that radio camera development will continue to use

[106] Two figures from INT-043 Radio camera link equipment manufacturer; INT-009 Radio camera supplier
[107] INT-009 Radio camera supplier
[108] INT-012 Radio camera link equipment manufacturer
[109] INT-012 Radio camera link equipment manufacturer
[110] INT-023 Radio camera supplier
[111] INT-009 Radio camera supplier, INT-023 Radio camera supplier
[112] INT-013 Radio camera supplier
[113] http://www.amimon.com/mimo-ofdm
[114] INT-045 MIMO on-camera link equipment manufacturer
[115] Operating licence-exempt devices requires detection of radar signals before and during operation in the allocations 5.25-5.35GHz and 5.47-5.725GHz – requirements are set out in EN 301 893
[116] INT-035 Spectrum policy manager, TV broadcaster
[117] INT-012 Radio camera link equipment manufacturer

these mainstream codecs, using profiles that minimise latency (at the cost of lower compression ratios than would be achieved for broadcast distribution).

The H.265 codec standard is being defined currently, and implementations are being developed and trialled. H.265 will deliver 4k (UHD) video over DVB-T2 carriers, and might – with an appropriate profile – be reasonably expected to encode a 4k picture in 15-20Mbit/s with a sub-40ms latency, even with 10-bit (per colour) sample depth.[118] It is expected that the decoder will have similar complexity to H.264, but that the encoder will require around one order of magnitude more computational power. This is not a problem in the broadcast distribution network (where there are few encoders and no limit to space and power available), but radio camera-sized encoders will not be feasible until a Moore's Law increase of tenfold in computation throughput and processor power consumption has occurred. Based on these performance parameters doubling every 18 months, this will take about 5 years. The development work to implement a suitable version of H.265 for radio cameras may be too much for a single organisation, and require collaborative work between several design organisations.[119] The development may also rely on suitable silicon and other technology becoming available from mainstream electronics (e.g. consumer TVs and cameras, and LTE data modems) in a suitable form.[120] It is possible that 4k will become popular for some broadcasts before a radio camera codec / modem is available that can deliver the content in a 10MHz bandwidth.[121]

H.265 may also become a suitable vehicle to deliver full HD (1080p50) over a standard radio link, in place of 'semi HD' (1080i50) at the moment, since it has been shown to offer a 25-50% reduction in output data rate for a given quality of picture.[122] However, if the technology allows it, most (but not all) broadcasters would in most cases prefer to use more 1080i50 radio-cameras rather than have the increased quality per camera.[123]

3.2.3 An HD picture in a 5MHz channel will be possible in the near future

Changing the radio modem from DVB-T to DVB-T2 will increase by about 20-25% the data rate over the link. This will not be sufficient to increase spectral efficiency of radio cameras usefully but could offer better quality if rolled out.[124]

BBC R&D has developed a reference design called 'HalfRF' which is designed to deliver today's (half-) HD pictures in a 5MHz RF bandwidth. Using the same H.264 codec, a 4x4 MIMO (non-adaptive) modem uses two pairs of cross-polarised antennas and offers 20Mbit/s over the air in a 5MHz bandwidth, adapting to both line-of-sight and high-multipath environments. Prototypes have been demonstrated and the BBC is offering HalfRF for commercial licensing now.[125]

Cobham Communications has also developed MIMO modems, in its NETNode mesh system, which currently offer up to 18Mbit/s in a 6MHz RF bandwidth. This is a military and security product, but could be adapted for broadcast. With current equipment there are some cases where there is insufficient multipath for NETNode to deliver its full data rate.[126] Cobham is confident that reliable radio cameras delivering HDTV in a 5MHz bandwidth will be commercially available within 5 years.[127]

HalfRF type solutions will only be useful when a significant number of them have been bought and deployed.[128] Useful growth in this roll-out might be prompted by licensing 5MHz wide RF channels for radio cameras.[129]

[118] INT-025 BBC R&D, HD video specialist
[119] INT-041 BBC R&D, RF projects
[120] INT-012 Radio camera link equipment manufacturer
[121] INT-041 BBC R&D, RF projects
[122] INT-012 Radio camera link equipment manufacturer
[123] INT-043 Radio camera link equipment manufacturer
[124] INT-043 Radio camera link equipment manufacturer
[125] INT-041 BBC R&D, RF projects
[126] INT-043 Radio camera link equipment manufacturer
[127] INT-043 Radio camera link equipment manufacturer
[128] INT-023 Radio camera supplier
[129] INT-013 Radio camera supplier

3.2.4 Higher-order MIMO should over 10 years provide UHD in 5MHz, and HD in 2.5MHz

Today's short-range 5GHz MIMO (typically up to 6x6) modems can deliver several hundred Mbit/s indoors, over distances of a few tens of metres as mentioned at the end of section 3.2.1.

MIMO technology in general will add complexity and cost, as well as power consumption, due to additional signal processing and the need for both ends to be transceivers, but may offer a big step change in spectral efficiency.[130]

BBC R&D is also working on a UHD HalfRF design, which will use more MIMO channels (up to 8x8) including the use of four antenna polarisations (vertical, horizontal, clockwise and anticlockwise circular – which does provide some useful performance gain over the two polarisations) as well as multiple receive sites. The aim is to deliver 100Mbit/s over the link.[131]

Current MIMO designs from BBC R&D and the equipment manufacturers are targeted at 2GHz. It has been suggested that MIMO is likely to offer less performance gain at 7GHz, at least within 5 years,[132] but MIMO demonstrations have already been made at considerably higher frequencies (for example, 25GHz) in support of research for 5th generation mobile communications.[133]

In the further future, techniques that will be developed by the designers of LTE mobile systems, including interference cancellation (which has the potential of allowing more than one radio camera to share a frequency at a location) might become feasible – depending upon the state of LTE research and development. BBC R&D follows this research in published papers, but does not generally get useful access to LTE silicon technology.[134]

This will be expensive R&D, requiring as a minimum the incentive of a guaranteed spectrum allocation over 10-15 years.[135]

3.2.5 Radio links are available for 7GHz, but will need a lot of care in deployment

The use of 7GHz was reported by several designers and practitioners as being about as far as it is possible to go with portable equipment, with rapidly diminishing returns above this band,[136] although one manufacturer makes 8.6GHz links for other markets and also offers a '500-carrier' modem (in place of the usual DVB-T '2000-carriers') which improves 7GHz performance, but is still well below that for 2GHz.[137] The design of the very linear amplifiers required for COFDM gets more difficult as frequency increases, and higher power (up to 10W for links to/from aircraft) will often be needed than at 2GHz.[138] For the same RF output, 7GHz needs about 20% more battery power than 2GHz (which is 7-10W for the link transmitter).[139]

In general, 7GHz is more difficult to deploy than 2GHz – the link budget was reported to be up to 20dB worse for a given transmit power, and the polar patterns of antennas have been found unpredictable.[140] For uplinks from motorcycle cameras to aircraft, 7GHz offers particular problems with patch antennas, and also with the RF shading effects as the motorcycle passes under trees. Some sample link budget calculations are attached to this report in Appendix C, and we concur that for an example uplink from motorcycle to aircraft – including likely attenuation due to foliage and tall buildings, and assuming the best practical antennas that could be made within the space available at each end – would have at least 10dB less margin at 7GHz than at 2GHz.

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130 INT-012 Radio camera link equipment manufacturer
131 INT-041 BBC R&D, RF projects
132 INT-043 Radio camera link equipment manufacturer
133 Example http://www.commnet.ac.uk/documents/comment_5g_workshop_130314/2_Samsung_5G.pdf
134 INT-041 BBC R&D, RF projects, INT-012 Radio camera link equipment manufacturer
135 INT-023 Radio camera supplier
136 INT-012 Radio camera link equipment manufacturer
137 INT-043 Radio camera link equipment manufacturer
138 INT-023 Radio camera supplier
139 INT-043 Radio camera link equipment manufacturer
140 INT-009 Radio camera supplier

Golf would generally be adequately covered at 7GHz, apart from needing more receive antenna sites to be deployed.[141] BBC R&D believes that 7GHz can be made to work, with a suitable number of antennas.[142] It might be necessary in some cases at 7GHz to transmit 1W power from shoulder-mount cameras rather than the 100mW currently used to achieve the required link margin, and concern was expressed that this might have health effects over a long operating shift.[143]

Two suppliers expressed a strong preference to keep some allocation at 3.5GHz (3.41-3.60GHz, which has included eleven 10MHz channels for PMSE, and is currently being released by MoD for possible award), in place of the 7GHz space promised, for the foreseeable future.[144]

Industry would like to see a scheme to compensate incumbents when they need to replace or modify equipment, similar to that done by the FCC in the USA (and for Channel 69 [854-862MHz] in the UK).[145]

3.3 Technology and working practice trends – audio links

Technology and working practice trends with respect to audio links (including radio microphones and personal audio monitors) are discussed below.

3.3.1 Today's technology

Audio link equipment considered in this section is of programme quality (audio bandwidth at least 20Hz to 15kHz and typically to 20kHz) with latency (end-to-end delay of the audio signal) from tens of microseconds for analogue systems up to about 3ms for digital.[146] Most equipment has a tuning span of between 24MHz and 200MHz, somewhere within the UHF TV band 470-790MHz, and uses 'white space' channels where no TV transmitter is operating in the region. Whilst the occupied bandwidth of each device is nominally 200kHz or less, it is generally not possible as explained below to place devices on a 'raster' of, say, 400kHz – meaning one device at frequency *f*, the next at *f*+400kHz, the next at *f*+800kHz and so on – without limit. (Technical mitigations of this limitation are described in sections 3.3.2 and 3.3.3 below.)

The main equipment types are

- Radio microphones which are either compact body-worn units with a miniature microphone capsule on a cable, or handheld types comprising the microphone capsule, radio transmitter, batteries and antenna within a single tubular housing. The corresponding receivers are either single portable units with two antennas for space diversity, or rack-mounted systems where a pair of antennas feeds a number of receivers (again each with twin 'diversity' inputs). The transmitter is limited in power in the UK to 50mW for body-worn and 10mW for handheld.
- Personal monitors (or IEMs) which are compact body-worn receivers with audio output feeding one or two earpieces (which can be complex custom-moulded items), generally carrying a 'foldback' programme comprising a personal mix of some of the instruments and singers' voices for a performance. The transmitters for IEM are invariably rack-mounted, with several typically feeding an RF combiner, optional main power amplifier, and antenna system. IEM transmitter power is generally limited to 10mW (with some high-power licences permitting up to 1W).

Similar equipment to that described above is also used for specialised purposes including feeding sound effects to movable scenery pieces in theatre, time-code between recording devices for on-location audio capture, or even when a high-quality intercom system is needed.

Radio microphones are either analogue FM or digital, both occupying a 200kHz nominal bandwidth. When transmitters are placed close to one another, an effect called 'back intermodulation' (sometimes referred to as 'reverse intermodulation,' or 'transmitter to transmitter intermodulation') occurs, where the

[141] INT-023 Radio camera supplier
[142] INT-041 BBC R&D, RF projects
[143] INT-050 Technical head, sports broadcaster
[144] INT-009 Radio camera supplier , INT-013 Radio camera supplier
[145] INT-012 Radio camera link equipment manufacturer
[146] INT-038 Radio microphone designer

output from one transmitter is received at the antenna of another, and the two signals mix: due to non-linearities in the circuitry, various sum and difference signals are generated which can then fall into the pass-band of a third microphone's receiver at a level sufficient to cause unwanted noises (sometimes called 'birdies' or 'spurii') with analogue equipment, or reduced operating range with digital.

With early FM radio microphone transmitters, back intermodulation used to be considerable as the output power amplifier (PA) was generally operated in Class C, which is very efficient in power, but very non-linear. More recent designs improve intermodulation performance by using a more linear PA design; this takes more power, so is a trade-off against battery life. However, back intermodulation remains a problem in many current designs when more than 5 or so microphones could be within a few metres of one another, and a user has to create a so-called 'intermodulation plan' with the aid of charts or a computer program that calculate frequencies where no intermodulation products will fall, and the radio microphones are placed on those frequencies.[147] The effect of this has been to make the spectral efficiency of radio microphones very low, with some types requiring more than 1MHz each when more than about 20 are co-located.

Back intermodulation can occur even more strongly in IEM systems, where up to 20 transmitters (possibly more powerful than radio microphone ones) can be co-located within the same equipment enclosure. This performance can be improved if the transmitter outputs are combined electrically at a much lower RF level, then fed to a very linear PA and then on to an antenna system.[148]

Receiver intermodulation has in the past been another area of concern, in which several strong signals from the antenna appear at the receiver's first mixer, and mix with one another as well as mixing with the receiver's local oscillator. However, modern professional radio microphone receivers include a highly linear amplifier at the front end, together with first mixer operated at high signal levels, all of which are expected to minimise the effect of intermodulation in the circuit.[149]

Analogue radio microphones and IEMs generally need a signal to interference ratio of around 40dB[150] for full quality audio. (The signal path invariably includes a compander[151] in order to deliver around 100dB peak signal to noise ratio for the audio.) Digital systems can work with lower signal to noise + interference ratios: for QPSK around 26dB for pulsed interference.[152]

All IEMs are currently analogue, to avoid some of the latency problems described below.[153]

A recent source of problems has been the growing popularity of LED video walls or video nets, where LEDs are used as the pixels for large video displays, and are driven at high clock rates.[154] One manufacturer saw the noise floor in the UHF band rise in places by 50dB at a recent *X Factor* final in Copenhagen, requiring some rapid re-planning of frequencies for performers' radio microphones.[155]

Finally, audio professionals are very wary of white-space data devices; even when these occupy channels where no radio microphones are in use, the fear reported by a number of practitioners was that when many thousands of white-space devices are in use in a region, the noise floor would rise, limiting the range available for audio devices, especially outdoors.[156]

[147] INT-020 Radio microphone manufacturer
[148] INT-019 Radio microphone designer
[149] INT-057 RF designers' panel
[150] ITU-R BS.412-9 specifies 39dB protection ratio when the interferer is another FM transmitter on the same frequency. For white noise, an FM receiver for audio will generally commence quiet operation with signal to noise ratio exceeds about 12dB, and will then deliver an audio signal to noise ratio equal approximately to ({RF signal to noise}+40dB).
[151] A compander comprises to parts: in the transmitter, circuitry to compress the audio dynamic range, and in the receiver similar circuitry to expand it again. Noise from the radio link is at a level lower than that of the desired audio, and so the expander reduces it further. Analogue compander circuitry has to be designed with care to avoid introducing audio distortion.
[152] See for example *Performance of QPSK System in the Presence of Pulse Interference and Noisy Carrier Reference Signal* – Stefanovic et al., Serbian J. Elec.l Eng. Nov. 2003; for BER of 10^{-6}; for white noise, signal to noise ratio needed is ~12dB.
[153] INT-020 Radio microphone manufacturer
[154] INT-018 Radio microphone manufacturer
[155] INT-019 Radio microphone designer
[156] INT-020 Radio microphone manufacturer

3.3.2 Analogue audio devices can be designed to deliver 400kHz or better raster, with care

Most audio devices occupy a 200kHz bandwidth, which means that with the best feasible RF filtering (within the size and power constraints of practical equipment), the spacing achievable for non-interference between devices is 350-400kHz. However, with many of today's designs, back intermodulation effects do not allow audio devices to be deployed on a 400kHz raster without limit, being limited instead by the need for intermodulation planning as described above.

There are several ways to improve back intermodulation performance, which are already being adopted by several manufacturers:

- Design very linear power amplifiers (PAs) in radio microphone and IEM transmitters. This implies more headroom (i.e. the PA is run at a lower efficiency than otherwise needed) which in turn means that more power is required from the battery.[157]
- Add a directional coupler (also called a circulator) to the RF output, arranged so that any received signal at the antenna is dissipated in a resistor rather than reaching the PA. These couplers are ferrite devices, and have the disadvantage of a fairly narrow frequency band of operation – typically 20MHz or less, which conflicts with the requirement to provide wider tuning ranges. In addition, they are quite bulky and heavy, and have an insertion loss of around 2dB at UHF, which again requires more power in the PA.[158] However, two radio microphone designs use directional couplers, and offer operation on a 400kHz raster across their tuning range.[159]
- Use two identical PAs in phase quadrature, combining them in a phase-shift network at the antenna output.[160] This causes any signal received at the antenna to cancel. The disadvantage is that the PAs have to be closely matched (typically requiring an expensive calibration process in manufacture) as well as the additional component cost and power consumption.[161]
- Use a modulation scheme that requires a smaller signal to interference ratio, so that the effect of intermodulation products on receivers of other microphones is lower. In general this is true of digital modems using QPSK and similar low-order modulation schemes (as described in section 3.3.3).

The addition of intelligent (programmable) distributed antenna systems can improve the performance and coverage of radio microphone systems. In Italy where white space TV spectrum is unregulated, systems like this are necessary in many installations.[162]

Several manufacturers offer a maximum of 16-20 audio channels in an 8MHz block using analogue FM:

- Shure top of the range, remote controllable radio microphone system (via 2.4GHz low-speed digital comms) *Axient* has very highly-specified PA design, and offers 16 audio channels in 6MHz, or 20 in 8MHz.[163] The cost is in power consumption – this product uses a higher capacity battery than the twin primary AA cell used in most other radio microphones for 8 hours' operation.
- WisyCom *MTH400* and other models offers the quadrature signal cancellation circuit technique at the transmitter as described above, together with very accurate receiver filtering. The resulting improvement in back intermodulation performance is about 25dB compared to a single PA, and with care in deployment allows up to 30 audio channels in 8MHz. This care includes ensuring that body-worn transmitters are in place on the person before switching on, as the 25dB improvement

[157] INT-034 Radio mic manufacturer
[158] INT-057 RF designers' panel
[159] INT-020 Radio microphone manufacturer, INT-008 Radio microphone manufacturer
[160] INT-019 Radio microphone designer
[161] INT-057 RF designers' panel
[162] INT-019 Radio microphone designer
[163] INT-018 Radio microphone manufacturer

can be rapidly wiped out by the much higher signal level that can result from a transmitter antenna which has no associated body absorption.[164]

- Sennheiser *Evolution 100G3-1.8GHz* range tunes only 1785-1800MHz, and includes ferrite directional couplers: this equipment offers 400kHz spacing without intermodulation planning.[165]

This is not an exhaustive list – other manufacturers also offer 'top-of-the-range' equipment which offers similar performance, namely 400kHz or better spacing with 200kHz RF channels.

A separate approach for closer spectral packing is to design radio microphones to operate in narrower bandwidths, for example 70kHz (which could fit between channels in the digital audio broadcast (DAB) band at 174-240MHz). For a 70kHz RF bandwidth, the oscillators in the design must have about 8dB better phase noise than for 200kHz at a given offset from the main output, to maintain the same audio performance. In addition, the receiver filters need to be more tightly specified, as an FM system requires a flat group delay across its passband – this is harder to achieve for a narrower passband. These requirements translate into the need for more expensive components, including better varicap diodes, and also higher tuning voltages generated in the circuit, requiring additional power conversion circuitry.[166] In addition, the audio passband may have to be reduced to 15kHz. Designs are being brought to market at the moment.[167]

It was mentioned that in the USA, the FCC may enforce in a future rule-making the ability for a radio microphone system to function with at least 12 channels in a 6MHz band.[168]

3.3.3 Digital equipment offers raster down to 350kHz (and 125kHz in optimum conditions)

Several manufacturers have now launched digital radio microphones, including Zaxcom (which has offered digital for about 10 years), Sony, Shure, Sennheiser and Lectrosonics. All the designs to date offer the same RF bandwidth as analogue, 200kHz.

In most cases the data rate over the link is around 3-400kbit/s, and therefore an audio codec is used in order to compress the digitised audio (generally from a raw rate of up to 1.2Mbit/s from the analogue to digital converter, assuming 20-24 bits, 48kHz sample rate). In current designs the end-to-end latency from the codec and modem is in the range 1.9-3.4ms. The signal to noise + interference ratio for good operation in one model is about 16dB,[169] and 9dB for another,[170] which should allow their deployment in 'grey space' spectrum – shared areas where the noise / interference floor is higher than would be acceptable for analogue FM equipment.

To achieve this data rate within the 200kHz RF bandwidth, the digital modulation needs to achieve at least 2bit/s per Hz occupied – QPSK is common, though there is at least one phase- and amplitude-modulated design on the market. These modulation schemes all require a very linear PA for transmission free of RF distortion (which causes the signal to exceed the desired RF bandwidth), which gives current digital designs intrinsically good back intermodulation performance.

Some current digital systems include:

- Shure *ULX-D* offers two operation modes; Standard Mode, which can be placed on a raster of 350kHz with some intermodulation planning (much less restrictive than today's analogue equipment[171]), and High Density Mode, which runs at lower transmitted power of 1mW and can be

[164] INT-019 Radio microphone designer
[165] INT-008 Radio microphone manufacturer
[166] INT-057 RF designers' panel. Phase noise in a FM system translates directly into noise in the audio; non-flat group delay in the RF passband translates into non-linear distortion in the audio.
[167] INT-019 Radio microphone designer. In fact, two manufacturers mentioned this type of product but one wished to remain anonymous.
[168] INT-038 Radio microphone designer
[169] INT-034 Radio microphone manufacturer
[170] INT-047 Digital radio microphone manufacturer
[171] INT-048 Sound designer, large outside events

operated on a raster of 125kHz without limit, but with a reduced range of up to 30m. This reduced power operation is only feasible if the noise and interference floor is very low.[172]

- Sony *DW* range offers operation on a raster of 500kHz without limit, and also the possibility indoors of working on the same TV channel as a DVB-T transmission.[173]
- Zaxcom *TRXLA2* offers a raster of 700kHz without limit at full power.[174]
- Sennheiser *Digital 9000* series has 88MHz tuning span for the transmitter and 320MHz for the receiver. Directional couplers are used in the transmitters[175] to improve back intermodulation: it is believed to use several directional couplers, switched, to cover the wide tuning span. This equipment has a High Definition mode which transmits audio as linear PCM without a codec, using a higher order modulation scheme (which translates into lower receiver sensitivity and therefore shorter range) than for its other mode, called Long Distance.

This is not an exhaustive list – other manufacturers also offer equipment which offers performance within the range described in the list.

It was reported for one digital design that care was needed in antenna deployment, to avoid an excessively large signal at the receiver, which had been seen to give rise to bit errors.

The additional latency from digital systems – of up to 3.4ms – is not seen by manufacturers as a problem in any application ***except for*** where an IEM is used that takes the signal from the same singer's microphone, in which case the sum of latencies from the microphone, a digital mixing desk and transmission, and the IEM itself, could add up to 5ms or more. This is enough to disconcert a fair proportion of singers, and in this case, using analogue radio equipment may remain the best solution.

Digital radio microphones are now deployed in some major opera houses in mainland Europe, where there is a move toward using radio microphones for every singer; latency has not been seen to be a problem here, as IEM are not used by opera singers.[176]

Current digital designs require more battery power than their analogue equivalents, due to the need for high-linearity PAs, as well as the additional circuitry for digital signal processing. In many cases this has meant a departure from the traditional battery of two alkaline AA-cells (only one for Sennheiser's analogue 3000 and 5000 series), either to more cells[177] or to rechargeable packs (Shure ULX-D, Sennheiser 9000). In the rechargeable case, the opportunity has been taken to include very precise battery management, which one user said could give 'to-the-minute' prediction of operating time (displayed at the receiver or the system's management workstation).[178]

Digital radio microphones are at the 'early adopter' stage, costing the same as the top-end analogue products. Cost drivers include the need for a very clean power supply for the analogue-to-digital converter, better channel filters and highly linear PAs.[179] In the future, PA techniques like feed-forward linearization could be adopted,[180] once the additional power required by the DSP for this function in the transmitter is mitigated by Moore's Law improvements. Digital systems also allow the possibility of a controlled trade-off of spectral efficiency against quality of the spectrum.[181]

[172] INT-018 Radio microphone manufacturer.
[173] INT-024 Digital radio microphone manufacturer
[174] INT-047 Digital radio microphone manufacturer
[175] INT-008 Radio microphone manufacturer
[176] INT-024 Digital radio microphone manufacturer. In opera the singer can be quite a distance from the accompanying orchestra: up to 20m, corresponding to a time difference of around 60ms, is not unusual. In this case the singer hears the orchestra 60ms later than the audience front row does, then the singer's own sound takes another 60ms to reach the front row – a total latency of 120ms.
[177] INT-038 Radio microphone designer
[178] INT-032 Sound supervisor, TV light entertainment
[179] INT-024 Digital radio microphone manufacturer
[180] INT-038 Radio microphone designer
[181] INT-018 Radio microphone manufacturer

Steady improvement, and cost reduction in digital designs, is to be expected, especially as the cost and power consumption of the digital parts reduce with Moore's Law. No other step change is predicted in the next few years in technology for audio devices, above what has been described.

3.3.4 In the long term a change to digital OFDMA systems could provide levels of spectral usage equivalent to 330kHz (or better) raster

No manufacturer has adopted access methods other than frequency division (apart from Shure who have a DECT-based range for industrial / office use). A time division multiplex scheme is seen as driving latency upward (having a longer frame period), as well as having the whole multiplex at risk from a single interferer, and also not providing coexistence with legacy equipment.[182]

In Appendix B Cambridge Consultants describes a possible radio microphone or in-ear monitor system in which much of the processing for this type of system would be done in digital silicon, and so could offer the opportunity of at least equivalent performance to conventional frequency division multiple access, but at a lower component cost. It could be developed with a 5-10 year time-scale, and this straw-man design has been discussed with some manufacturers of radio microphone systems.

It is not a complete design as described, and it is possible that appeal may be needed to Moore's law concerning power consumption and cost of digital elements over the time being considered.

The design aims to borrow techniques from the current-day, or near-future, LTE physical layer, and possibly to use silicon developed for LTE applications. A base station unit provides a common downlink and co-ordinates all connected 'client' units (which will usually be transceivers) in time and frequency, including the allocation of bit-rate per user application. The modem and multiplex system described is OFDMA, designed to fit within an 8MHz (or 6MHz) TV channel, and could offer a total data rate of 9Mbit/s using QPSK, or 19Mbit/s using 16QAM, modulation with a framing latency of about 0.5ms and able to deliver programme quality audio without a codec.

Two responses from established radio microphone manufacturers are:

- "The LTE-like physical layer offers may benefits, resistance to multi-path effects being foremost in my mind. The scheme you present seems to have made reasonable parameter choices/tradeoffs. The symbol period is suitable for the kind of applications targeted from a multipath/ISI standpoint and the link latency is acceptable.
  "The system seems well suited to IFB and intercom applications, where a central base station is ideal. It's the same for a lot of wireless mic applications (stage, house of worship, conference rooms etc.) but not all. In video production and ENG applications, small camera mount receivers are commonly required at different locations in space. A central base station doesn't fit into that use case.
  "Such a system offers a lot of flexibility in configuration and allows for program quality audio when demanded. The potential for adaptive power control etc. is exciting.
  "One concern I have is that the OFDM waveforms have a high crest factor so very linear transmit chains are needed. This can drive cost and power consumption up. Our appeal to Moore's law will need to succeed to realize a body worn transceiver design powered by 2 AA batteries.
  "Another is that that bandwidth must not be assumed to be congruent with a 6 or 8 MHz TV channel. There may be a need to tailor the operating bandwidth (number of carriers) of the system to fit arbitrary spans of spectrum such as guard bands in future fragmented UHF band plans. In any case regulatory and technical rule changes may be needed in many jurisdictions to allow this type of system. If so, the regulatory process may dictate the timetable for marketing such systems. The 5 - 10 year timescale doesn't seem so long in that case!" [183]
- "The proposal is interesting and worthy of further study. We are always studying new technologies and we appreciate the potential merits of 4G technologies like OFDMA. As noted, there are a

[182] INT-038 Radio microphone designer
[183] INT-038 Radio microphone designer

number of technical hurdles that would have to be overcome to implement it. PMSE users demand flawless audio performance, and interruptions are not acceptable. Furthermore, since OFDM is an inherently wideband system, it could be difficult for disparate entities to share a limited amount of spectrum within a venue. On the other hand, today's narrowband transmission technologies are amenable to deployment in a multi-user scenario, and the wireless audio industry has worked diligently to significantly increase spectral efficiency without sacrificing audio quality and link reliability." [184]

3.3.5 RF tuning spans are being extended, but there are practical limits

Over the last 10-15 years, the tuning span of many wireless audio devices has been in the region of 24MHz (=3 TV channels in the UK). In response to the spectrum available to users becoming more fragmented, all manufacturers are designing products with wider span, examples being 66MHz, 75MHz[185] up to 200MHz[186] or more. This extension of span is not strictly an improvement in spectral efficiency, but it can provide technical mitigation of the effects of fragmentation, and an alternative to hiring in more equipment (which can be difficult for ad hoc deployments, such as those found in feature film making).

The tuning span of a radio that uses a phase-locked loop synthesiser is determined principally by

- the antenna and its matching components: a single circuit can usually cover 10% span of a given centre frequency (= 50-60MHz at UHF TV bands) with reasonable radiation efficiency. To cover a wider span, the antenna circuit must contain tunable components, or multiple matching circuits with arrangements to switch between them. For a receiver, the tunable components can be varicap diodes, but these cannot be used at a transmitter output where the signal level is much higher; here PIN diodes would be needed for range switching. Either of these arrangements will require more battery power at the portable end, with PIN diodes switching high-level RF requiring forward currents of 5-10mA each,
- the span of the voltage-controlled oscillator (VCO): it is reasonably straightforward to achieve a 20% span (100MHz) whilst achieving the required phase noise performance. To increase the span requires either
  - a higher tuning voltage (within the limit that varicap diodes can operate over: for the best ones this is about 30V), which requires more components in the design including DC-DC converters and level shifters, and a corresponding increase in power required;
  - a greater VCO gain (in MHz/volt), which will have poorer phase noise performance unless the quality factor (Q) of the VCO can be improved by other means;
  - range-switched components in the VCO, again requiring additional switching components with their cost in power and complexity.[187]

Degradation in phase noise at small offsets from the main output translates into higher audio noise in an analogue system, and into increased jitter and hence poorer receiver sensitivity, in a digital system.

Overall, any attempt to increase the tuning span tends to increase the complexity, size and power consumption of the design, and will be limited by, for example, the market need for a particular battery.

Direct digital synthesisers (DDS, where the oscillator waveform is generated by a digital circuit) are not currently used for radio microphone systems because they invariably produce spurious spectral output at some distance (in frequency) from the desired output, and therefore require filtering. If a wide tuning span is required, then the filter has to be a tracking type – in fact the most popular tracking filter for a DDS is a

[184] INT-018 Radio microphone manufacturer
[185] INT-038 Radio microphone designer
[186] INT-019 Radio microphone designer
[187] INT-057 RF designers' panel

phase-locked loop synthesiser! In addition, DDS are generally more power-hungry than the equivalent phase-locked loop, although Moore's Law improvements in digital circuitry may mitigate this in time.[188]

These considerations together imply that an octave range is probably a practical limit for a radio microphone system's tuning span; therefore it is unlikely that a single equipment could cover both the UHF TV band and bands above 1GHz; separate equipment will almost certainly be needed. Of course, one piece of equipment could effectively contain two transmitter RF sections for different bands, which is the approach taken for modern mobile phone designs. It is worth noting that in order to accommodate wider tuning spans, among other features, the RF performance specifications for mobile phone user equipment has been reduced over time (with correspondingly higher requirements on the infrastructure): this measure would not generally be available for PMSE equipment.[189] (Reference to one specification aspect of mobile UE, and its effect on PMSE, is made in section 3.3.7.)

Although it does not comprise an increase in equipment tuning span, at least two manufacturers are re-evaluating the use of VHF spectrum, e.g. around 174-216MHz, for analogue radio microphones even though the noise floor is higher in this band. As well as the fairly modest PMSE VHF allocations, mention was made of guard-bands between DAB ensembles in the band 174-240MHz[190] (which have a nominal width of 170kHz, though in practice there is some energy outside the nominal 1540kHz DAB transmission which will reduce the quality of this spectrum).

3.3.6 Radio microphones can in principle be operated at frequencies of several GHz, but will be more expensive

We carried out some path loss modelling for a radio microphone using a body-worn transmitter, with four parts to the model:

- Model of FM radio microphone transmitter and receiver system, with 50mW transmitted power, and unity gain (0dBi) antennas. (Higher gain antennas can be used for receivers but not in general for body-worn transmitters since they can change orientation rapidly)
- Short-range propagation losses estimated for outdoor and indoor deployments using ITU-R models.[191]
- Shadowing loss from an adjacent person, taken from published work on shading by human bodies[192] for the outdoor model, and allowances for Rayleigh fading for the indoor model.
- Measured total antenna efficiency of a short wire antenna mounted on to a radio microphone case which was worn by a person. Existing research work was not available for the frequencies and antenna deployment, so a series of measurements was made using an automated antenna measuring system,[193] with a mocked-up transmitting system worn on a canvas belt in the small of the back.

A pragmatic formula for antenna EIRP was used: the total isotropic efficiency (in the body-worn deployment) was multiplied by the worst-case polar efficiency that was sustained over an angle of 30º or more (in plan view), the presumption being that very sharp dips in the polar plot would be mitigated by a standard dual-antenna diversity receiver setup.

Full details of the work, and a set of polar plots, are given in Appendix D.

[188] INT-057 RF designers' panel. DDS are commonly used in an 'inner loop' for equipment that needs very small tuning steps and/or very fast settling to a new frequency, and one or more PLLs comprise the outer loop and tracking filter.
[189] INT-057 RF designers' panel
[190] INT-018 Radio microphone manufacturer
[191] ITU-R P.1411-7 and ITU-R P.1238-7 respectively
[192] Ali Kara: Human body shadowing variability in short-range radio links 3–11 GHz band. *Intl. J. Electronics*, Feb. 2009, etc.
[193] Satimo SG-64: http://www.satimo.com/content/products/sg-64

This total efficiency was found to decrease somewhat in the 1-2GHz band and then to improve, so that the antenna performance at 3GHz and above was nearly as good as at 1GHz.

Frequency	1170	1400	1700	2225	2475	2900	3550	4850	MHz
Antenna type tested (on body)	wire	wire	wire	wire	patch	wire	wire	wire	-
Tx power used for model	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	dBm
Tx measured total antenna efficiency on body	-4.1	-8.0	-4.4	-4.7	-1.9	-3.2	-1.9	-6.4	dB
Polar worst over at least 30deg	-14.0	-19.0	-16.0	-20.0	-17.0	-16.0	-10.0	-10.0	dBi
Pragmatic EIRP	-1.1	-10.0	-3.4	-7.7	-1.9	-2.2	5.1	0.6	dBm
Outdoor model, range	**111**	**60**	**87**	**76**	**80**	**70**	**80**	**34**	**m**
Indoor model, range	**105**	**35**	**58**	**26**	**44**	**37**	**59**	**28**	**m**

Table 11 Predicted ranges of body-worn radio microphones at different frequencies (from Appendix D)

The predicted range is largely determined outdoors (see Appendix D, table 9) by the body shadowing effect, which in the cited research had at 5GHz a standard deviation of 11dB (in a log-normal distribution); mitigation of this would require a number of receive antennas, and even then there could be cases in stage and film shows where a cluster of bodies might be sufficient to stop correct operation. Our experience with systems around 5GHz shows that shadowing of the radio path by objects or people is much more sudden in effect than at lower frequencies. This may again lead to the need for more receivers (multiple antenna diversity) to give performance free of drop-outs.

A clear upper limit is not discernible from this data – rather an expected rise in cost and complexity of deployment mirroring in some ways current experience moving radio cameras into 7GHz from 2GHz. There is certainly evidence to support reasonable performance up to about 3GHz.

In addition, at higher frequencies, these design issues come to the fore:

- For each twofold increase in frequency, the phase noise (at a given offset from the carrier) must improve by 6dB for equivalent audio performance, requiring generally more power for the VCO and amplifier components
- About 3GHz and above, special printed circuit materials are generally necessary since the usual epoxy-fibreglass composite (e.g. type FR-4)[194] becomes too lossy. This increases cost.
- The effective aperture of – and therefore the power collected by – an antenna of given directivity decreases as the square of the frequency, reducing the range for a given transmitted power. To increase this aperture in mitigation produces an antenna with more directivity, which in turn means that to cover a wider angle, more receivers will be needed, again increasing cost.

Sennheiser already has an analogue microphone on the market covering 1,785-1,800MHz and this is licensable in the UK, and with good back intermodulation performance (uses directional couplers) it offers 36 audio channels in that space. It was noted that since the 1,785-1,800MHz band is in a duplex gap, the noise floor is likely to rise as 3G or LTE user equipment is rolled out in the adjacent mobile phone band.[195] (GSM transmissions have tighter spectral masks, necessary for a part-FDMA system.)

Other manufacturers differ in their view of the suitability of frequencies above 1GHz, with two concerned that link budgets, once body absorption and increased free-space propagation loss have been accounted

[194] FR-4 is a printed circuit substrate material designation of the National Electrical Manufacturers Association
[195] INT-020 – 5 Radio microphone manufacturer

for, will not be sufficient for reliable operation over the ranges required by professional users.[196] Others plan products between 1GHz and 2GHz, and there was general consensus that 2GHz represented a practical limit. There is a 1.2GHz PMSE band being allocated in Japan, which might be of interest elsewhere:[197] in the UK this band is allocated to MoD radar and in part to amateur radio. Different antenna design and placement practices will be needed to achieve the desired performance, and it may be better for equipment to be digital.[198]

It was reported that Germany's upper parliament has approved in principle the allocation of 1452-1492MHz to PMSE as recompense for the loss of the 800MHz part of the TV bands, and also that Luxembourg has already legislated for this same allocation.[199] The European Communication Office document ERC 70-03, February 2014 edition, lists 1492-1518 as recommended for PMSE.

3.3.7 'Duplex gap' allocations are risky as more mobile equipment is deployed into the related bands

A duplex gap allocation is possibly available to PMSE in the range 821-832MHz (ERC 70-03 recommends 823-832MHz allocated to radio microphones, with the lowest 3MHz having a lower power limit). However, radio microphone manufacturers expect that LTE (which transmits in the frequencies above 832MHz for this band, referred to as 3GPP Band 20) will raise the noise floor in this band to unusable levels.[200]

The master specification[201] for LTE performance in Band 20 permits terminal stations (user equipment) to emit -6dBm in a 5MHz bandwidth within this duplex gap, rising to +1.6dBm for the top 5MHz.

Frequency range of out-of-band emissions	Maximum mean out-of-band power	Measurement bandwidth
Below 790 MHz	-65dBm*	8 MHz
790 to 791 MHz	–44 dBm	1 MHz
791 to 821 MHz	-37 dBm	5 MHz
821 to 822 MHz	–13 dBm	1 MHz
822 MHz to –5 MHz from FDD uplink lower channel edge	-6 dBm	5 MHz
–5 to 0 MHz from FDD uplink lower channel edge	1.6 dBm	5 MHz
0 to +5 MHz from FDD uplink upper channel edge	1.6 dBm	5 MHz
+5 MHz from FDD uplink upper channel edge to 862 MHz	-6 dBm	5 MHz

Table 6: Out-of-band requirements for FDD TS

This means that a compliant piece of user equipment could emit -20dBm in a 200kHz bandwidth in this duplex gap, rising to -12.4dBm for the top 5MHz – more if some of the emissions are narrow-band rather than noise-like. In the case that a user is wearing both a radio microphone and an LTE user equipment, the signal to interference ratio seen by the radio microphone receiver could be 37dB (marginal for FM operation), dropping to 29dB for the top 5MHz (probably no FM reception). If the LTE user equipment were nearer to the radio microphone receive antenna, then this signal to interference ratio could be considerably lower.

The European Commission had proposed that, in certain locations, an arrangement could be made for the MNOs who are allocated the adjacent spectrum, also to deploy a pico-cell at a different 3GPP band (typically 2.6GHz) to offload any LTE traffic into this different band. However, this would not be legally enforceable if the licences have already been agreed, but a commercial arrangement could be made

[196] INT-047 – 3 Digital radio microphone manufacturer, INT-019 – 8 Radio microphone designer
[197] INT-018 – 14 Radio microphone manufacturer
[198] INT-018 – 9 Radio microphone manufacturer
[199] INT-034 – 1 Radio mic manufacturer. Also found on APWPT website but not elsewhere in WWW search.
[200] INT-034 – 3 Radio mic manufacturer, INT-019 – 6 Radio microphone designer, INT-020 – 6 Radio microphone manufacturer
[201] ECC/DEC/(09)03 *ECC Decision of 30 October 2009 on harmonised conditions for mobile/fixed communications networks (MFCN) operating in the band 790 - 862 MHz.*

between an MNO with the relevant allocation and an organisation using PMSE.[202] Subsequent to this interview, the EC Radio Spectrum Committee has concluded discussions on this Implementing Decision, and the proposal relating to the deployment of pico-cells to mitigate interference from LTE into the 800 MHz duplex gap has been removed.

[202] INTM-001 Mobile network operator

3.4 Technology and working practice trends – production communications

In all the activity areas explored for this report, production (or 'backstage') communications using UHF TV frequencies was in the minority compared with programme audio devices, but in some activities still represented up to 70 frequencies in a location.[203] This equipment generally uses FM in a 200kHz nominal bandwidth despite offering an audio passband of typically 8-10kHz; there are some narrow-band FM and digital versions available too. Because there is not the critical audio quality requirement for this application as for radio microphones, they can be more tightly packed spectrally, with examples[204] spaced on a 500kHz raster.

The bulk of communications at large and complex events uses PMSE allocations which are generally partitioned within the business radio bands, with a mixture of push to talk and continually-transmitting systems, using 12.5kHz or 25kHz RF bandwidth and either analogue narrow-band FM or digital systems like TETRA.

The much longer latency from very spectrally efficient systems like TETRA (which have very high-compression audio codecs, with a latency around 80ms) is subjectively unpleasant when there is a chance of being in earshot of the other end,[205] so a reasonable latency limit needs to be imposed for PMSE type applications: 40ms has been suggested as a usable maximum.[206]

Because production communications does not require the same very high quality and low latency of wireless programme audio devices, there are opportunities to make low-cost digital equipment, using techniques including:

- DECT digital communications – used in at least two production intercom products – can deliver 7kHz or better audio bandwidth by using a simple codec and a DECT long time-slot (which delivers 64kbit/s over the air), and DECT's very low-order (simple FSK) modulation makes it robust to interference. Unfortunately DECT has a correspondingly high symbol rate (1124k symbols/s) and no channel equaliser, which makes it susceptible to multipath interference outdoors or in large indoor spaces like stadia, reducing its useful range considerably.[207]
- Digital systems in the 2.4GHz band – used in at least 3 production intercom products – can use either 'Wi-Fi-like' or purpose-designed modulation and framing systems, and also offer good performance at low cost in many cases. However, in some cases the use of the 2.4GHz band is not possible,[208] ruling out use of this equipment.
- Future systems could be based on TETRA or P25[209] but feasibly with a different codec to deliver lower audio latency: for example, a TETRA radio using all four time-slots for a single transmission could deliver 30kbit/s, which could support some recent codecs[210] which have latencies in the 10-20ms range.

Improvements or further developments on systems like those mentioned should be able to deliver both point-to-point and infrastructure-based (cellular) communications with good quality and acceptable latency.

In the next chapter, the proposed mitigation for production communication equipment is that it can over the next 5 years be re-equipped – only where necessary due to high density – with narrower-band UHF equipment that has become available recently,[211] or relocated to licence-exempt bands. On average, we predict that production communication equipment could use per audio channel approximately half the spectrum of today's equipment.

[203] This was a hypothetical requirement for 'talkback' type comms in four adjacent West End theatres (see § 0)
[204] Comms frequency allocations for West End production of *Charlie and the Chocolate Factory.*
[205] INT-010 Communications equipment supplier
[206] Part of the specification for the Clearcom Freespeak DECT intercom system, agreed with BBC.
[207] INT-048 Sound designer, large outside events
[208] INT-048 Sound designer, large outside events; (anecdotal) that Eurovision 2011 reserved 2.4GHz band for journalists' Wi-Fi.
[209] USA standard covering both analogue and digital comms
[210] An example is open-source OPUS (CELT), originally designed for music, but adopted in several systems for voice communications
[211] An example is Bosch/RTS narrow-band FM analogue system BTR-80N

3.5 Other technology and working practice mitigations considered

Other technology and working practice mitigations were considered but not carried forward for analysis of future spectrum demand since they are improbable. These are summarised in Table 12, below.

Other proposed technology and working practice mitigations – improbable
Combined audio and video mitigations
N1: Integration of radio microphones or cameras with mixer, to demand spectrum only when in use Multiple mixers per event, background recording, difficulty in co-ordination between manufacturers, managing when everything hired
N2: Cognitive use of spectrum Risk averse community, especially when livelihood depends on functioning link
N3: Management of spectrum use in time as well as frequency Done as much as possible today – no significant improvement possible
N4: Use of MNO services for contribution Reliable guaranteed service offering not likely for a while (though an MVNO is offering aggregation of several MNOs' services). Will be used when no other PMSE method available for news etc.
N5: Licensed shared access MNOs with PMSE MNOs do not see incentive to provide this; would be detrimental to their network planning and operations

Table 12 Other proposed technology and working practice mitigation considered improbable

3.5.1 Integration of radio microphones or cameras with mixer, to demand spectrum only when in use

Two manufacturers[212] at least are discussing the possibility of integration of the radio microphone system with the mixing console, so that spectrum is demanded only when the device is in use. Zaxcom already offer this with its portable mixers, but it is not used much as recordists and other users want the confidence that the audio will be there when faded up on the mixer.[213]

However, this is not compatible with a lot of current practice: in a large TV or live performance, each radio microphone goes to several consoles, handling stage monitors, the sound mix heard by the audience, and the sound heard by the TV viewer. In addition, for some TV talent and reality-type shows, all microphones are recorded all the time.[214]

3.5.2 Cognitive use of spectrum

Three radio microphone manufacturers - Zaxcom, Sony and Shure – offer radio microphone equipment that can be remotely controlled at operating distance over an RF link (as opposed to infra-red or ultrasonic local set-up), and receivers (in Shure's case a separate spectrum manager unit) that can perform a spectrum scan, and allocate frequencies. Cobham's IP NETNode mesh for radio cameras has similar capabilities.[215] These therefore have some characteristics of cognitive systems, although self-contained rather than accessing external systems.

[212] INT-018 Radio microphone manufacturer
[213] INT-047 – 6 Digital radio microphone manufacturer
[214] INT-032 Sound supervisor, TV light entertainment
[215] INT-043 Radio camera link equipment manufacturer

A cognitive technical trial and standardisation programme (C-PMSE) project ran in Germany: Sennheiser, Bosch (which owns the Electrovoice radio microphone brand) and Shure participated. Its aim was to preserve audio quality even when audio devices were very tightly packed, but actually cognitive does not improve spectral density on its own. C-PMSE used database lookup as well as local sensing, and claimed to co-exist with non-cognitive equipment, by moving out of its way. The measuring rig deployed for this trial at Berlin Messe has been left in place to collect a year or two's spectral occupancy data. Note that cognitive adds a lot of complexity to the design, needing internet connection for the system, together with a receiver for control of each microphone (or camera), which has a cost in battery power.[216]

Cognitive allocation is seen by professional users – especially those whose livelihood depends on good sound on demand – as too risky.[217] In addition, too many local factors not known to the cognitive system database need to be taken into account, like topology and high user density in some places.[218]

Because of the blind node problem, a cognitive system would have to include an allocation database, and therefore users would need internet access – not always available on a film location. There is also the risk that an incumbent user at, for example, a sports stadium might grab all the good allocations for itself, leaving nothing for a visiting broadcaster, for example.[219]

We are not aware of any current or imminent products to support C-PMSE systems.

3.5.3 Management of spectrum use in time as well as frequency

For large events, this is done already for audio equipment – large music festivals could in principle operate on the principle of one set of audio equipment is in use by the performing act, whilst another set is used to prepare the next act. This becomes complicated when a particular act wants to use its own equipment, which may not tune to the frequencies used by the 'main' kit – requiring more frequencies than the minimum.[220]

For broadcasters, there would be a lot of nervousness about a source of audio or video that can't be checked regularly and tested off-line.[221] For televised sporting events like golf, there are too many different activities being shot, and the full complement of cameras is required for most of the time.[222]

We consider that there is not scope to do significantly more of this than is already done today.

3.5.4 Use of MNO services for contribution is interesting for further expansion in programme making, but would not replace existing PMSE

Two mobile network operators interviewed considered that there was no reason why a broadcasters' contribution link service should not be offered, but had no specific service offering yet.[223] Some exploratory trials are reported without any detail of who or where.

At the moment the 2G and 3G radio access network does not have any means of differentiating quality of service (QoS) between users; however, in LTE, QoS management will be introduced.[224]

Orange (through its EE joint brand with Deutsche Telekom in the UK) plans a QoS-differentiated service to businesses within the next 5 years, and PMSE users could be customers of this. A typical SLA (of original application to telemetry) might be to offer 99% probability of at least 1Mbit/s. An MVNO would not be able to offer any QoS service independent of the host MNO.[225]

[216] INT-034 Radio mic manufacturer
[217] M-020, INT-043 Radio camera link equipment manufacturer
[218] INT-012 Radio camera link equipment manufacturer
[219] INT-047 Digital radio microphone manufacturer
[220] INT-018 Radio microphone manufacturer, INT-020 Radio microphone manufacturer, INT-037 Spectrum planning consultant
[221] INT-043 Radio camera link equipment manufacturer
[222] INT-023 Radio camera supplier
[223] INTM-001 Mobile network operator
[224] INTM-001 Mobile network operator, INTM-003 Mobile network operator
[225] INTM-003 Mobile network operator

Latency end to end through an Advanced LTE network is claimed by network equipment manufacturer Huawei to be 10ms best case, 20ms typical.[226] With 3G, Orange offers 30ms today.[227]

Mobile virtual network operator (MVNO) Stream Communications connects to a number of networks within the backbone, and provides an alternative core network with managed QoS. Today it connects to all 3G networks, and in a year it will also be connected to LTE networks. Stream offers a service to broadcasters today that allows the use of a multiple modem aggregation unit to deliver several Mbit/s for mobile-connected camera use. The cost is £6/Gbyte, which would correspond to about £27/hour for a 10Mbit/s camera link – much cheaper than a satellite link. Stream has been selling to broadcasters for 2 years, and provided video connectivity to several broadcasters for the 2012 Olympics, and also to the BBC for part of the Olympic torch relay.

Stream asserts that the bottleneck is not usually in the radio access network of the MNO, especially when several MNOs' networks can be in the connection. It avoids making any assumptions about shaping the data that it passes (for example, it does not assume that the user data rate can be backed off after a period of connection and/or inactivity), and it also has nodes at the edge of its network which run a TCP optimisation process, to avoid backoff and re-tries.[228]

Stream has a partnership with manufacturer Dejero for modem boxes.

Gigawave also makes a cellular modem for cameras but reckons that with 3G networks it's difficult to get over about 1Mbit/s: it depends on network loading. For LTE, one TV news organisation has made considerable use of Verizon's network services in the USA, which has delivered data rates of 8.1Mbit/s near Washington, DC – this is adequate for breaking news contribution but less than half the data rate required for HD news coverage.[229]

3.5.5 Licensed shared access between MNO and PMSE is improbable

A trial has been performed in Finland in 2013 where some frequencies used in the mobile network are shut off in a particular location, on the request of a PMSE user to provide radio camera services. This showed how an incumbent user, who has the 2.3GHz band for PMSE, can share and use the band together with a mobile broadband operator. To start, the MNO system is operating in the shared band at Ylivieska, Finland. To switch usage, the TV camera crew requests the operator to clear the ASA band for their cameras using a tool called LSA Incumbent Manager to define location, time and frequencies to be cleared, and the MNO deactivates the LTE in the shared band, managing appropriately any existing end users sessions.[230] In Finland it appears that the PMSE user had the primary allocation in the band in question! Where the MNO is the primary licensee, invariably the case in the UK, a commercial arrangement would be needed between the PMSE user and the MNO – Telefonica O2 raised the concern that in many cases the use of PMSE and mobile services are highly correlated (for example, at televised sporting and news events), so the MNO would find any sharing commercially unattractive.[231]

Orange was further concerned that – to it –expected demand for sharing would place serious constraints on the quality of service that it could provide to its customers. In particular, network design practice is based on access to its entire allocated spectrum, and considerable changes would be needed in that practice to accommodate geographic and temporal re-arrangements around PMSE.[232]

It was also reported that conversations are in progress between APWPT (the European interest group for PMSE) and MNOs, and discussions of possible MNO services to LTE, but we could not find any details of these.[233]

[226] INTM-001 Mobile network operator
[227] INTM-003 Mobile network operator
[228] INTM-004 Mobile Virtual Network Operator
[229] INT-056 Technical head, TV news organisation
[230] https://tapahtumat.tekes.fi/uploads/d947b274/Finnish_ASA_trial_030913-3748.pdf
[231] INTM-001 Mobile network operator
[232] INTM-003 Mobile network operator
[233] INTM-002 Spectrum specialist, mobile industry

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4 Mitigations of 2024 radio spectrum demand in PMSE

A series of hypothetical scenarios has been developed for each PMSE activity area in which the outcomes of applying technology mitigations to predicted future spectrum demand are modelled.

We use the forecasts for peak instances of wireless devices in each activity area – as described in Chapter 2.2 – as a starting point for each scenario. These forecasts are summarised diagrammatically as 'index cards'.

An aggregation process deduces the highest demand found for any single location (for example, for radio microphones, this might be the studio recording of *X Factor* which uses many audio channels, or a televised outdoor sporting event in which multiple presenters all use radio microphones and monitors to present their own pieces prior to the main event). For video, demand comprises both the number of units and the quality of video to be sent, which may well increase the uncompressed data rate considerably.

Each aggregation comprises a point for today's demand, points for 5 years in the future and, where possible, also 10 years in the future. At the same time, we incorporate the pressures on spectrum, in which bands at 3.5GHz, 700MHz and others will be lost, and where any replacement spectrum will be at a higher frequency (camera allocation at 7.1GHz rather than 3.5GHz; radio mic allocation at 1.8GHz rather than some parts of 470-790MHz).

The technical mitigations described in Chapter 0, including enhancements to video codecs and to modems, the move from analogue audio to digital, and the possible move from 'PMSE spectrum' to suitable cellular technology, are applied to forecast spectrum demand. To provide a baseline for assessing potential spectrum demand constraints, we apply a 'no mitigation' to forecast spectrum demand.

Outcomes of applying the various mitigations are described in terms of gross spectrum demand. The extent to which gross spectrum demand for audio and video links fits within the constraints of existing spectrum availability is shown as a 'traffic light' system. This is shown in Table 13, below.

User service	Relative constraint of gross spectrum demand (MHz)		
	Unconstrained	Constrained in some locations/applications	Insufficient spectrum
Audio links	**<72**	**72 – 152**	**>152**
Video links	**<390**	**390 – 440**	**>440**

Table 13 Relative constraints of gross spectrum demand within existing radio spectrum availability

These limits for audio devices are based on 9 available 'clean' UHF TV channels, which is the minimum for a number of venues according to an internal study by Ofcom[234] (from the bands 470-606 and 614-694MHz, i.e. omitting channel 38 since users needing high availability in real time generally prefer not to use uncoordinated spectrum),. Outdoors, this quantity of channels may reduce considerably, with concern already expressed for locations including Bristol, Manchester and East Grinstead, Sussex.

[234] Ofcom internal study *UK Theatre Major Touring Venues: Channel Quality as per Minimal Change Scenario* shows for 40 theatres a minimum of 9 TV channels available at full quality, with the exception of one out-lier, Bristol Hippodrome (3 channels), for which it is presumed that some local mitigation (e.g. a built-in distributed receive antenna system) will be needed.

For video links, the presumption is that 19 channels, 10MHz wide, are available in the 2GHz band and 25 in the 7.1GHz band. Within the 2GHz band, nine 10MHz channels are allocated to news broadcasters on an exclusive basis, which would reduce the pool of available spectrum unless suitable arrangements are put in place to access these assignments for events with a high peak demand. Our criterion for 'constrained in some locations/applications' is based on access to up to five channels might be unavailable as a result of these exclusive assignments.

Technology mitigation scenarios for each PMSE activity area are discussed below.

4.1 Mitigation scenario for spectrum demand in television light entertainment

For television light entertainment, the application of technology and working practice mitigations gives rise to peak demand as summarised in Figure 1 below.

Forecasts for peak instances of wireless devices

Activity Area: Television light entertainment					
User service	2014	2019		2024	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	109	115	*1%*	140	*30%*
Video links (high-definition)	5	30	*N/A*	100	*N/A*
Video links (ultra high-definition)	0	0	*N/A*		
Comms	10	10	*0%*	10	*0%*

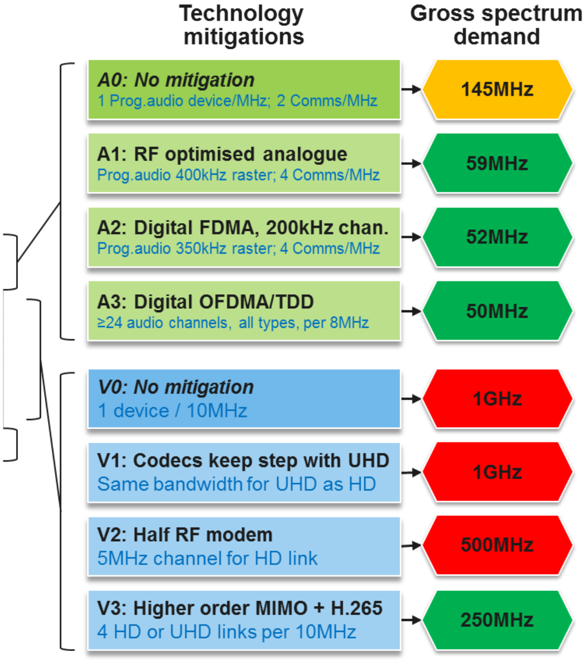

Figure 1 Peak spectrum demand for television light entertainment

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 1, our estimate for current peak instances of wireless audio devices suggests that there are constraints within existing spectrum availability (gross spectrum demand 114MHz, assuming one programme audio device per MHz and two comms devices per MHz). Forecast peak instances of wireless audio devices, without the application of technology mitigations, further compounds gross spectrum demand (150MHz).

Optimisation of analogue audio links (<400kHz raster; mitigation A1) or digital FDMA (<350kHz raster; mitigation A2) yield reductions in gross spectrum demand to 56MHz and 49MHz, respectively, resulting in unconstrained scenarios. Further reduction in gross spectrum demand (to 46MHz) is achieved through the application of digital OFDMA (>24 audio channels per 8MHz; mitigation A3).

Impact of technology mitigations on gross spectrum demand for video links

Our estimate for current peak instances of wireless video links results in limited impact on gross spectrum demand (50MHz, assuming one device per 10MHz). As discussed in Chapter 2.2.1 we understand that there could be a significant leap in the use of wireless cameras within a ten year timeframe (up to 100 devices). Although we cannot predict whether TV light entertainment will adopt UHD in this timeframe, this forecast increase in wireless video links will likely require in excess of 200MHz with outliers as high as 1GHz, in the absence of mitigation.

Assuming codecs keep step with UHD (utilising the same bandwidth as HD; mitigation V1) or the application of HalfRF or similar modems; mitigation V2), these mitigations yield reductions in gross spectrum demand to 1GHz and 500MHz, respectively. Both outcomes yield constraints within existing spectrum availability. However, the application of higher-order MIMO platforms (mitigation V3) reduces gross spectrum demand to 250MHz, resulting in an unconstrained outcome. This latter mitigation relies on Moore's law to get H.265 into a camera within a ten year timeframe; otherwise, potentially greater spectrum impact is possible.

Therefore, given our estimates for forecast peak instances and impact of technology mitigation, spectrum policy will likely limit future production activity in television light entertainment programme making with regards to wireless video links.

4.2 Mitigation scenario for spectrum demand in outdoor music events

For outdoor music events, the application of technology and working practice mitigations gives rise to peak demand as summarised in Figure 2 below.

Forecasts for peak instances of wireless devices

Activity Area: Outdoor music events					
User service	**2014**	**2019**		**2024**	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	251	260	*~0%*	260	*~0%*
Video links (high-definition)	17	20	*~0%*	20	*~0%*
Video links (ultra high-definition)	0	0	*~0%*		
Comms	10	10	*~0%*	10	*~0%*

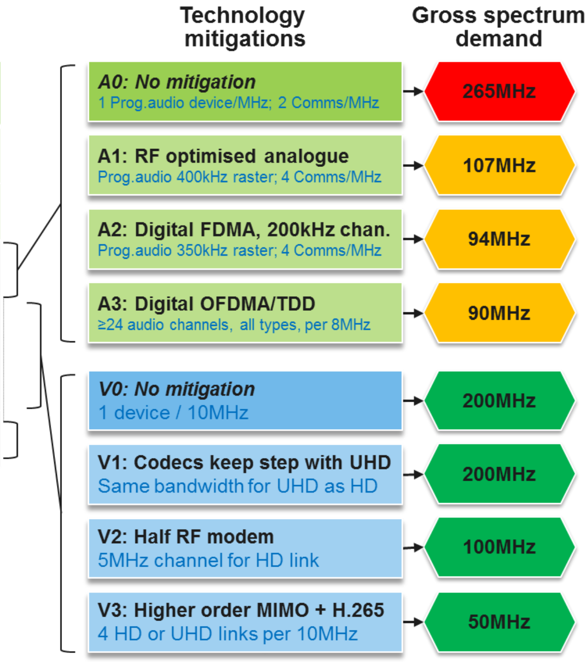

Figure 2 Peak spectrum demand for outdoor music events

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 2, our estimate for current peak instances of wireless audio devices in the field of outdoor music events results in gross spectrum demand of 256MHz, representing insufficient spectrum. Forecast peak instances of wireless audio devices, without the application of technology mitigations, further compounds gross spectrum demand (270MHz). Optimisation of analogue audio links (<400kHz raster; mitigation A1) or digital FDMA (<350kHz raster; mitigation A2) yield reductions of gross spectrum demand to 104MHz and 91MHz, respectively, which both represent moderate levels of constraint. Application of digital OFDMA/TDD reduces gross spectrum demand to 86MHZ, which remains constrainedin some locations/applications.

Impact of technology mitigations on gross spectrum demand for video links

Our estimate for forecast peak instances of wireless video links in outdoor music events results in a gross spectrum demand of 200MHz (assuming one device per 10MHz). As discussed in Chapter 2.2.2 we understand that there is likely to be considerably more cameras in operation at any one time, but the majority of these will be wired. Therefore, given our estimates for forecast peak instances and impact of technology mitigations on video links, we do not anticipate spectrum constraints within a ten year timeframe.

4.3 Mitigation scenario for spectrum demand in large scale theatre productions

For West End theatre and other large-scale productions, the application of technology and working practice mitigations gives rise to peak demand as summarised in **Figure 3** below.

Forecasts for peak instances of wireless devices

Activity Area: Major Theatre Productions					
User service	2014	2019		2024	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	74	84	*Negligible*	94	*Negligible*
Video links (high-definition)	0	0	*0%*	0	*0%*
Video links (ultra high-definition)	0	0	*0%*	0	*0%*
Comms	70	70	*0%*	70	*0%*

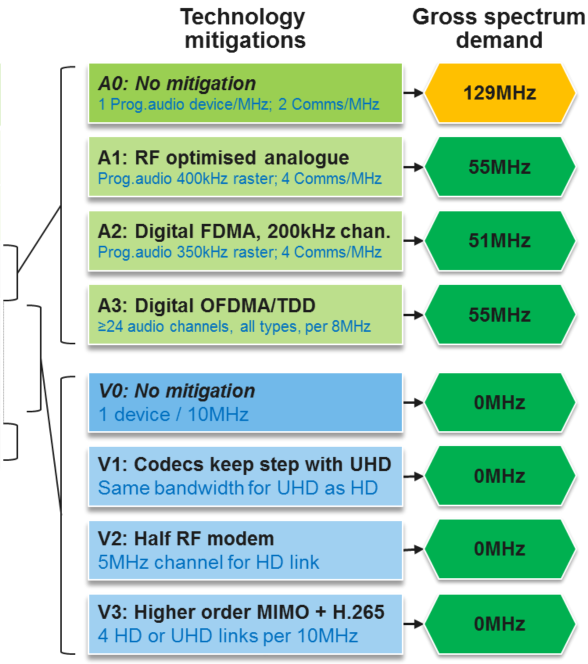

Figure 3 Peak spectrum demand for large-scale theatre productions

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 3, our estimate for current peak instances of programme audio devices in the field of major West End theatre productions results in a moderately constrained gross spectrum demand (109MHz, assuming one programme audio device per MHz and two comms per MHz). Programme audio device frequencies can in general be reused from theatre to theatre, since device use is generally constrained to the stage and auditorium. This is not true for communications, where building-wide coverage is needed and therefore the interference with an adjacent theatre using the same frequency would be probable.

Our forecast for peak instances of wireless audio devices, without the application of technology mitigations, also predicts a moderately constrained outcome on existing spectrum availability (gross spectrum demand 129MHz).

Optimisation of analogue audio links (<400kHz raster; mitigation A1) or digital FDMA (<350kHz raster; mitigation A2) yield reductions in gross spectrum demand to 38MHz and 33MHz, respectively. Similarly, the application of digital OFDMA/TDD (>24 audio channels per 8MHz) reduces gross spectrum demand to 31MHz, thus removing spectrum availability constraints.

Impact of technology mitigations on gross spectrum demand for video links

As discussed in Chapter 0, typically no wireless video links are used in West End theatre production; this is a situation likely to continue within a ten year timeframe, according to stakeholders interviewed.

Therefore, future demand trends in West End theatre production do not appear to present any spectrum constraints, for either audio or video links, based on the above data set.

4.4 Mitigation scenario for spectrum demand in television sporting events

For television sporting events, the application of technology and working practice mitigations gives rise to peak demand as summarised in **Figure 4** below.

Forecasts for peak instances of wireless devices

Activity Area: Outdoor Sporting Events

User service	2014	2019		2024	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	97	116	*20%*	140	*20%*
Video links (high-definition)	42	50-60	*N/A*	67 Formula One	
Video links (ultra high-definition)	1	1	*Probably none*	(200) (Tour de France) -	
Comms	26	30	*Probably small in UHF TV bands*	35	*Probably small in UHF TV bands*

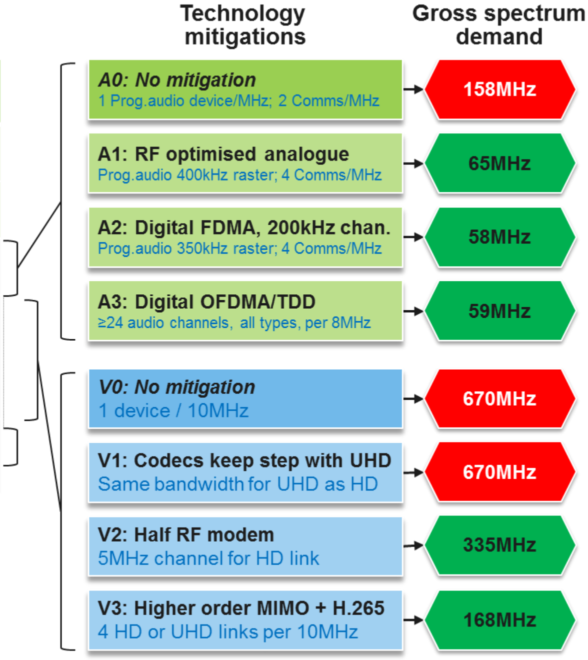

Figure 4 Peak spectrum demand for television sporting events

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 4, our estimate for current peak instances of wireless audio devices in the field of television sporting events results in a gross spectrum demand of 110MHz (assuming one device per MHz and two comms per MHz), which places moderate constraint on existing wireless capacity. Our forecast for peak instances of wireless audio devices, without the application of technology mitigations, predicts gross spectrum demand of 158MHz, which continues to yield a moderately constrained outcome before technology mitigations are applied. All three technology mitigations serve to reduce gross spectrum demand, and creates unconstrained outcomes.

The PMSE audio users at many sporting events can be very fragmented, representing many broadcasters, possibly from a number of countries. The range of audio equipment that they use is correspondingly wide, which means that a longer time could elapse before a significant proportion of the equipment is replaced than, for example, a studio broadcast under the control of a single organisation. The corresponding technology mitigation will therefore also take longer to realise.

Impact of technology mitigations on gross spectrum demand for video links

Our estimate for forecast peak instances of wireless video links in television sporting events – using Formula 1 as a representative example – results in gross spectrum demand of 670MHz (assuming one device per 10MHz). Without mitigation this level of demand yields significant constraint on spectrum availability. Assuming that codecs keep step with UHD (same bandwidth as HD; mitigation V1) gross spectrum demand at 670MHz continues to yield insufficient spectrum. Application of HalfRF modem (5MHz channel for HD link; mitigation V2) or higher order MIMO (4HD or UHD links per 10MHz; mitigation V3) reduces gross spectrum demand to 335MHz and 168MHz, respectively, and removes constraints on existing spectrum availability.

In addition, mitigation being proposed by Formula One is to create its own technology to deliver video, voice and telemetry from its 22 cars to the trackside, with the ability to use spectrum above 7GHz. PMSE allocations may be available for this in the UK at 8GHz (up to 40MHz with geographic restrictions),10GHz (up to 60MHz with geographic restrictions) and at 12GHz (up to 300MHz, subject to non-interference with TV satellite broadcast[235]). Where this mitigation can be applied, it can reduce Formula One's maximum 2024 requirement to **45** video links in the 2GHz and 7GHz bands. It is not yet known what RF bandwidth is required for Formula One's technology.

As discussed in Chapter 2.2.4, Formula 1 and Tour de France has explored use of multiple, participant 'on-board' cameras. Other televised sports – notably horse racing – may adopt this practice. This trend would further increase future spectrum demand and place further constraints upon spectrum availability. Therefore, growth in spectrum demand is likely going to come from the cumulative effect of a combination of televised sporting events that practice 'on board' video links, rather than a contribution from any single event.

4.5 Mitigation scenario for spectrum demand in film-making

For film-making, the application of technology and working practice mitigations gives rise to peak demand as summarised in **Figure 5** below.

Forecasts for peak instances of wireless devices

Activity Area: Film Making

User service	2014	2019		2024	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	36	100	-	200	-
Video links (high-definition)	0	0	-	0	-
Video links (ultra high-definition)	0	0	-	0	-
Comms	No significant UHF TV comms				

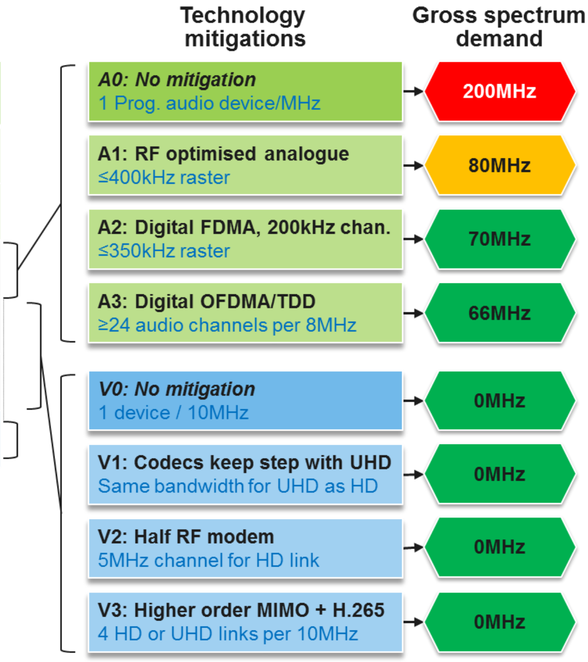

Figure 5 Peak spectrum demand for film-making

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 5, our estimate for current peak instances of wireless audio devices in film-making is unconstrained within existing spectrum availability (gross spectrum demand 36MHz, assuming one device per MHz). However, forecast peak instances of wireless audio devices, without the application of technology mitigations, results in significant constraints within existing spectrum availability (gross spectrum demand 200MHz).

Optimisation of analogue audio links (<400kHz raster; mitigation A1) reduced gross spectrum demand to 80MHz, which yields constraints in some locations/applications. Application of digital FDMA (<350kHz raster; mitigation A2) and application of digital OFDMA (>24 audio channels per 8MHz; mitigation A3) both yield reductions in gross spectrum demand, and result in unconstrained outcomes. Therefore, future demand trends in film-making do not appear to present any spectrum constraints, but will require equipment with wider tuning spans, or a greater amount of hired-in equipment, to take advantage of the available spectrum.

[235] About 11 DVB-S multiplexes are transmitted in this 12GHz band from Astra and Eutelsat satellites, on behalf of UK broadcasters.

Impact of technology mitigations on gross spectrum demand for video links

According to stakeholders interviewed no PMSE wireless video links are used in feature film making, and this is a situation likely to continue within a ten year timeframe.

4.6 Mitigation scenario for spectrum demand in television news gathering

For television news gathering, the application of technology and working practice mitigations gives rise to peak demand as summarised in **Figure 6**, below.

Forecasts for peak instances of wireless devices

Activity Area: Television News Gathering					
User service	2014	2019		2024	
	Peak instances	Peak instances	*Growth*	Peak instances	*Growth*
Programme audio devices	30	35	-	45	-
Video links (high-definition)	10	12	-	15	-
Video links (ultra high-definition)	0	0	-		
Comms	No significant UHF TV comms				

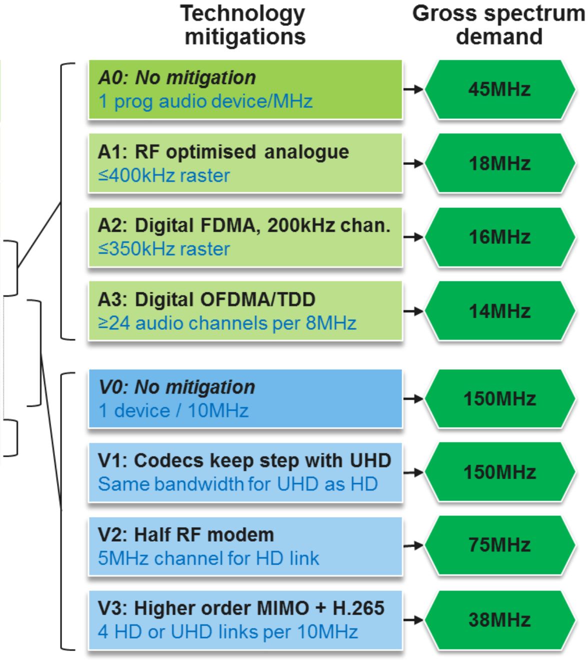

Figure 6 Peak spectrum demand for television news gathering

Impact of technology mitigations on gross spectrum demand for audio links

As shown in Figure 6, our estimate for current peak instances of wireless audio devices in the field of television news gathering results in a gross spectrum demand of 30MHz (assuming one device per MHz), which does not place any constraint on existing wireless capacity. As discussed in Chapter 2.2.6, a higher rate of news gathering and more news organisations contribute key drivers for spectrum demand in this field, according to stakeholders interviewed. Our forecast for peak instances of wireless audio devices, without the application of technology mitigations, predicts gross spectrum demand of 45MHz, which continues to yield an unconstrained outcome before technology mitigations are applied.

Impact of technology mitigations on gross spectrum demand for video links

Our estimate for current peak instances of wireless video links in television news gathering results in gross spectrum demand of 100MHz (assuming one device per 10MHz). Without mitigation this level of demand places no constraints on spectrum availability.

All three technology mitigations for wireless video links yield gross spectrum demand below the level at which it constrains spectrum bandwidth.

Therefore, future demand trends in television news gathering do not appear to present any spectrum constraints for either audio or video links, based on the above data set.

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5 General observations outside main scope of work

5.1 Ten- to fifteen-year assurance of spectrum requested

A strong message received from many stakeholders[236] was the request for a commitment from government and regulators for at least 10 years' – and preferably 15 years' – continuity of any spectrum allocation, due to the high purchase costs of PMSE radio equipment: users expressed a need to sweat these expensive assets for as long as possible. A lot of the equipment cost is amortisation of its development over a relatively small quantity (hundreds in the case of radio camera equipment) of units made: again these investments in development can only be made if there is expectation of an adequate financial return over a reasonable period.

Since most of the manufacturers supply globally, harmonisation of allocations in as many countries as possible is also of great value to them.

5.2 UK has best PMSE spectrum management in the world

A number of stakeholders mentioned, in the context of discussing problems with using or managing PMSE devices, that the Arqiva PMSE organisation provides an excellent service, unrivalled by the equivalent operation in any other country.[237]

One stakeholder, an applications specialist for radio microphones, mentioned that he spent a lot of time training his customers in the requirements and processes for licensing this equipment, and would welcome some type of training service or at least training resources, from either Arqiva or Ofcom.[238]

The film sound community would welcome a quickly-accessible smartphone app to buy short-term licences for PMSE spectrum on the spur of the moment.[239]

5.3 Loan spectrum for large events only useful if in tuning range of existing kit

One stakeholder mentioned that, in order to stage another event approaching the size of the 2012 Olympics, would require a lot of 'loan' spectrum, and that this represents a problem for manufacturers, who will not wish to invest in design of equipment with tuning ranges that can't be used for most of the time. Another reported that at the 2012 Olympics some loan spectrum at 2.9GHz was made available for cameras, but no-one had invested in any equipment that could tune that range.[240]

5.4 The radio deployment process is becoming de-skilled

Another recurring theme was that many broadcast and sound recording activities were moving toward 'plug and go' operation, without using specialists in RF planning available. News cameramen are expected to deploy in short time, with broadcasters providing substantially automated vehicles or infrastructures for relaying their content. Many large theatrical and TV productions make use of the supply company's services[241] for activities like spectrum planning and licensing, with only the largest ones using a radio specialist. One comment was that broadcasters were sleep-walking into a spectrum crisis, and that much of their in-house engineering expertise has been let go or diluted, making them unaware of this.[242]

[236] INT-010 Communications equipment supplier, INT-023 Radio camera supplier, INT-027 Radio mic hire/supply company, INT-028 Outside broadcast sound supervisor, INT-051 Formula One, INT-058 Technical head, sports broadcaster
[237] INT-010 Communications equipment supplier, INT-053 Theatre head of sound and broadcast
[238] INT-008 Radio mic manufacturer
[239] INT-024 Digital radio microphone manufacturer
[240] INT-031 Radio mic manufacturer, INT-023 Radio camera supplier
[241] INT-010 Communications equipment supplier, INT-027 Radio mic hire/supply company, INT-032 Sound Supervisor, TV light entertainment
[242] INT-012 Radio camera link equipment manufacturer

5.5 Germany and Austria are understood not to be releasing the 700MHz band

A report in Germany by IRT states that the Eurovision Song Contest could not be staged again, if the 694-790MHz band were to be lost to PMSE, and one interviewee[243] stated that Germany and Austria have decided not to release this band as a result. We have not been able to confirm this independently.

5.6 LED video walls appear to be an interference hazard at UHF

The use is growing of video walls or flexible meshes/curtains, which comprise matrices of colour LED pixels, with pixel pitch varying from about 2mm to 100mm, and overall size from a few metres width up to a complete stadium backdrop (Texas Motor Speedway in February 2014 built a LED wall screen 66m x 29m).

"The use of video walls is seen to be a problem – there appears to be a lot of interference to both UHF and above which can increase the levels of drop-out in service"

Senior Management, Radio microphone manufacturer

The use of these video walls has become popular indoors as well, and spurious emissions in the UHF TV band was cited as a problem by several practitioners and manufacturers; for example in an *X-Factor* final in Copenhagen in 2013, some rapid re-allocation of radio microphone frequencies had to be done once the video wall had been switched on.[244]

Screens of far Eastern manufacture were mentioned as being more problematic than European. One hypothesis is that it is difficult to suppress voltage transients with the rapidly-switched constant-current drive circuits required for LEDs.

5.7 Sennheiser HD Audio band proposal

Sennheiser has proposed that a band – possibly above 1GHz – should be allocated for 'high-resolution' audio, digital with 24- or 32-bit sample depth and 96kHz or 192kHz sample rate. This would provide capture quality compatible with future immersive audio user systems, as well as for the requirements of classical music recording.[245] However, we did not identify among other stakeholders any market demand for higher-quality audio than can be delivered by existing radio microphone systems.

[243] INT-034 Radio mic manufacturer
[244] INT-018 Radio microphone manufacturer, INT-019 Radio microphone designer, INT-032 Sound Supervisor, TV light entertainment
[245] INT-034 – 7 Radio mic manufacturer

6 Conclusions

6.1 Overall

This report is optimistic about the potential availability of mitigating technology, but any technology development requires investment, initially by the equipment manufacturer, and then by users or hire companies to purchase the new models of devices.

Despite PMSE being an enabler for very significant revenue and employment,[246] PMSE users are not themselves a big industry, and lack the resources of – for example – the mobile terminal or consumer electronics markets.

Requests were heard from many sources, for these incentives:

- Commitment to PMSE spectrum of reasonable quality for a sensible time: at least 10 years and preferably 15.
- Whilst professional users will in general replace their PMSE equipment on a natural 5-7 year cycle, some financial assistance would be welcome to those displaced from a past spectrum allocation. (Examples were heard of the FCC in the USA compensating displaced incumbents.)[247]

Crucially, technology mitigation only takes effect when the great majority of PMSE users in a particular location has invested in the corresponding new equipment. This is especially true for the fragmented user bases found at sporting events and larger music festivals. Financial incentives could speed this investment.

Some public funding for PMSE development is provided via organisations like BBC Research & Development, but this is in the context that PMSE has relies a lot (and always has) on technology transfer from other market sectors, and a lot of that technology is arguably becoming harder to access. For example, it can be very difficult to obtain support for a high-performance communications chip-set, if a manufacturer cannot promise an order of the volume expected for mobile phones. Similarly, it was observed that the development of the H.265 video codec already needed to be done by multiple organisations on account of its size, and that making a portable encoder might be too large a project for a PMSE equipment manufacturer to countenance without some assistance.

6.2 Radio cameras and video links

6.2.1 Sport dominates, and current TV predicts only organic growth in radio cameras

Television sport is the largest user of radio cameras, and relies on them substantially for much of its output. The largest single radio camera user, Formula One motor racing, is in the process of applying its own technical mitigation to part of its PMSE demand; however it is predicted to remain the largest.

No significant step changes are seen in the format of current programmes in sport, light entertainment or news gathering: organic growth from additional 'point of view' cameras is probable, or from small numbers of additional broadcasters. A repeated observation is that no show or event ever gets smaller from year to year in its numbers of cameras!

6.2.2 Some new TV formats might drive much higher growth

However, over 10 years new content delivery methods and new programme formats could drive a demand for up to 200 radio cameras at a single location, if technology advances were to permit that number of devices to be operated in the available spectrum at that time.

[246] "The UK's creative industries are worth £71.4 billion per year to the UK economy and accounted for 1.68 million jobs in 2012, 5.6% of UK jobs." – Department for Culture, Media & Sport, 14 January 2014
[247] One example is access to the otherwise licence-exempt 'UPCS' band 1920-1930MHz, where each manufacturer of UPCS equipment is required to pay a one-time USD 50,000 up-front fee to company UTAM, Inc . whose task was to relocate around 1,100 licensed point-to-point microwave links from the band.

6.2.3 We can be optimistic that technology will ultimately mitigate predicted spectrum constraint

Ultra-high definition and/or greater bit depth and/or wider colour gamut video is unlikely itself to cause more demand for PMSE spectrum, because the same codec that is used for distribution can in principle be used for programme origination (but see 6.2.4 below concerning practice).

In addition, the availability of link equipment to deliver a broadcast picture from a camera in a 5MHz bandwidth is reasonably certain within 5 years. In the longer term advanced signal processing may provide better spectral efficiency than this.

There are growing pains with 7GHz links in some applications which will continue, and it may be 5 years before technology advances deliver solutions to these.

6.2.4 For UHD, there may be a time-lag between demand and mitigation

However, because of the higher computation complexity for a suitable coder for a UHD (4k or above) radio camera, there may be a delay before this is available, and UHD may become popular first, meaning that for an interim period, radio camera operation could need more spectrum per camera than it does today, by a factor between 2 and 4.

Specifically, the H.265 HEVC encoder is estimated to require around ten times the amount of computation of today's H.264, and it is probable that the only part of the TV industry that requires low power H.265 encoding will be PMSE. This low power implementation will be a large project possibly needing multiple partners, or might be able to take advantage of intellectual property created for smartphones (which can be confidently expected to incorporate H.265 encoders in their development – there are already '4k' smartphones on the market today). The coder may also have to rely on Moore's Law improvements in digital circuitry to be achievable.

6.3 Audio devices (radio microphones, in-ear monitors and intercom/talkback)

6.3.1 Large outdoor musical events dominate, with modest growth predicted

Large outdoor music festivals dominate the demand for spectrum for wireless audio devices, and have to operate without the benefit of screening from building structures that TV studios and theatre usually enjoy. Glastonbury is currently the largest event for using wireless audio devices, but other festivals might be expected to grow. Outdoor events and programmes will therefore become very constrained in spectrum, whilst most indoor activities will be able to continue at their predicted scope – with appropriate technology mitigation – after a possible re-allocation of the 694-790MHz band.

6.3.2 Very high service availability needed

It is for many live performances crucial that programme audio devices – especially radio microphones – work to a very high level of reliability, as the effect of an audible splat or gap is more noticeable than almost any other sensory phenomenon. A notional service level agreement for a lead singer's microphone could be maximum of 100ms gap in 4 hours' performance, which is a 'five nines' availability, similar to the requirement for communication backbones or financial IT.

6.3.3 Current 'top of the range' equipment already incorporates enough mitigation

Top-end analogue and digital audio devices using FDMA with a 200kHz or narrower RF channel already provide sufficient mitigation of the predicted spectrum demand for the largest demand scenarios, but they are currently more costly than mainstream equipment. Some of the techniques used in this top-end equipment can be expected to migrate down the equipment ranges.

A device design using a more advanced multiple access technique stands a good chance, over a 5-10 year time, of providing a similar level of mitigation for some activity areas, at lower device cost.

6.4 Could regulators be more proactive in encouraging technology?

Several users and equipment manufacturers were of the opinion that regulators appeared to be reactive to external influences rather than having a proactive PMSE policy, and possibly also over-confident that technology would eventually appear to resolve any contention arising from increasing demand and / or reducing spectrum.

A strong message received from many stakeholders was the request for a commitment from government and regulators for at least 10 years' – and preferably 15 years' – continuity of any spectrum allocation, due to the high purchase costs of PMSE radio equipment: users expressed a need to sweat these expensive assets for as long as possible. A lot of the equipment cost is amortisation of its development over a relatively small quantity (hundreds in the case of radio camera equipment) of units made: again these investments in development can only be made if there is expectation of an adequate financial return over a reasonable period.

News organisations in particular are very concerned that, with their operations crucially dependent on the spectrum at 2GHz (i.e. the two bands 2.01-2.10GHz and 2.20-2.30GHz), if either of these bands were to be re-assigned from the primary incumbent (military in the UK, which makes minimal use of this spectrum in most places where PMSE is required), their availability to PMSE could be at risk. For TV news' ad hoc deployments, it may be a long time before 7GHz technology could provide the required performance.