Potential for more efficient spectrum use by wireless microphones

Report prepared for Ofcom by CSMG

CSMG
A TMNG Global Company

04th November 2008

Executive Summary

Ofcom engaged CSMG, a telecoms and media consulting firm, to analyse how wireless microphones, in-ear monitors (IEM) and talkback systems can make efficient use of spectrum in the future. Pete Myring of consulting firm Myrcomm advised CSMG on this analysis.

Context

Digital switchover (DSO) will be complete in the UK in 2012. As a result, 14 channels in UHF Bands IV and V will be nationally cleared of terrestrial television – as will channel 36 of aeronautical radar and channel 38 of radioastronomy – and made available for new uses. Programme-making and special events (PMSE) users of these bands will be affected by both a reduced availability of spectrum interleaved with terrestrial television and changes to the pattern of its availability.

Ofcom wanted to understand better how that use might change in terms of spectrum, equipment and new technology up to and beyond the ten-year period during which users will continue to enjoy protected access to spectrum. The focus of this study is on users of Professional Wireless Microphone Systems (PWMS). Also, the London 2012 Olympic Games and Paralympic Games are not covered specifically in this report – the spectrum requirements for this are being handled separately by Ofcom as a key one-off event.

The timeframes referred to in this report – and focused on – are:
- Short-term: to 2012 (national end of DSO)
- Medium-term: 2012 to 2018

Any implications for the long-term (beyond 2018) were also noted.

PMSE end user characteristics and requirements

Wireless microphones (or radio microphones), which provide short-range reproduction of high quality sound and music, are critical for entertainment and other sectors. These include theatres, concert venues, touring shows and events, sporting events, broadcast TV, TV and film production, businesses, schools and places of worship. PMSE makes a major contribution to the UK's social, cultural and economic well-being.[1]

Firstly, it is important to point out the characteristics and requirements of PMSE end users. While use of spectrum is concentrated among some users, there are thousands of PMSE users of spectrum.

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[1] Ofcom, Access to interleaved spectrum for programme-making and special events after digital switchover, 16 January 2008

Many users need high quality audio in terms of reliability, audio fidelity and 100% duty cycle (spectrum cannot be shared while in use). Low latency (delay) is a critical requirement for most users due to the need for live audio / performer lip synchronisation. Transmission from transmitter-to-receiver for a live performance needs to be virtually instantaneous. Furthermore, wireless microphone-to-IEM and end-to-end system delay must be strictly limited. By comparison, one-way latency for mobile calls is 100-150ms and 300ms-1.4s for digital TV. Interference-free operation is also critical for many PMSE users. This need for high quality, relative to other electronics with audio capabilities, requires high-end equipment.

Strong growth is expected in PMSE organisations as well as PMSE equipment usage and demand for spectrum. A “wild card” in the PMSE sector is adoption of High Definition (HD) audio, which is capable of delivering 192 kHz/32-bit audio quality. Strong take-up of HD audio would result in a step-function increase in spectrum demand.

According to interviewees, as well as licensed and licence-exempt usage, there is also significant illegal PMSE use of spectrum. However, there is little evidence that any such illegal use has had a significant detrimental effect on licensed spectrum users.

Nearly all equipment today is analogue and operates in UHF Bands IV and V (including channel 69). Lifetime for PMSE equipment is typically 6 – 10 years, but can be far longer. PMSE equipment users require and rely on proven equipment – even a short failure or brief reduction in audio quality can have severe implications for an audience and the people associated with an event or production.

As the above indicates, the PMSE sector is diverse. Usage as well as some requirements for equipment vary:

PMSE usage scenarios and equipment performance requirements

	Equipment Used			Relative Requirements			
Usage Scenario	**Wireless Mics**	**IEM**	**Talkback**	**For Portability**	**For Low Latency**	**For Multi-Channel** (Simultaneous)	**Typical RF Transmission Range** (Transmitter to receiver)
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches)	🟩	🟩	🟩	High	Important	High	Up to 200m
Touring performances, concerts and events	🟩	🟩	🟩	High	Important	High	Up to 200m
Studio-based programme making (TV broadcasters, TV production companies, radio)	🟩	*Increasing use due to quality vs talkback*	🟩	High (depending on event)	Important (for live events)	High	Up to 200m
• Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production	🟩	*Increasing use due to quality vs talkback*	🟩	Moderate / High (depending on event)	Moderate / High (depending on event)	Moderate / High (depending on event)	Up to 200m
Community usage (Educational, places of worship)	🟩	🟨	🟨	Varies	Important	Low / moderate (depending on user)	Up to 200m
Short-range audio: • Boardroom conferencing • *Some* community usage	🟩	🟩	🟨	Typically low	Moderate (depending on event)	Typically Low	Up to 20-30m
Short-range ENG / OB audio: Narrator / presenter to camera	🟩	*Increasing use due to quality vs talkback*	🟩	Low / Moderate (depending on event)	Low / Moderate (depending on event)	Low	1.5-10m

Sources: Quotient, Sagentia, CSMG analysis

🟩 = Typically used 🟨 = Occasionally used

PMSE equipment industry

PMSE equipment is developed for multiple national markets due to the relatively low scale of the industry. Therefore it is critical for developments in the UK to take into account general developments in other markets so that UK users have access to appropriate equipment and at the lowest prices possible. PMSE equipment manufacturers will only develop solutions that require significant customisation for the UK market if they are able to recoup the higher costs of doing so through higher prices for UK users.

PMSE straw-man models

Our analysis started with a “blank sheet of paper” constrained only by the “laws of physics” to determine straw-man models that would enable more efficient use of spectrum or use of other spectrum by wireless microphones. To develop these straw-man models, we gathered inputs from PMSE technical experts, previous studies conducted for Ofcom, end user inputs, and industry organisations. We also took into account international developments as well as strategic intent of equipment manufacturers.

Since spectrum below UHF Band IV is currently of limited use for PMSE, the post-DSO interleaved spectrum along with suitable spectrum above UHF Band V are critical. In many cases, accessing this spectrum will require new equipment and even new technology. That said, given digital switchover in the UK and other countries, PMSE equipment manufacturers are focused on developing technology to improve spectrum efficiency and / or access new spectrum.

One technology that has been – and will continue to be – an area of focus for PMSE is digital transmission technology.

During the interviews that we conducted we were told that improvements are needed in the efficiency of chipsets used in digital wireless microphones to achieve the required mix of low power operation as well as low latency and spectral efficiency. Improvements in processing power and power consumption efficiency, coupled with advances in compression algorithms, were expected to improve digital wireless microphone capabilities over the next 5+ years. However, there was uncertainty about whether these improvements would necessarily satisfy the audio performance requirements of high end wireless microphone users, as well as significantly improve spectral efficiency. Relative to most analogue equipment, digital equipment was also considered to be expensive.

However, we note that some Japanese manufacturers appear to be further advanced in producing digital equipment than manufacturers based in Europe and the USA and that at least one West End theatre routinely makes extensive use of such equipment. This demonstrates that some digital wireless microphone technology can already offer a sufficiently high level of performance to be deployed in a professional environment.

Some Broadway and West End theatres already make use of digital equipment, which demonstrates that digital wireless microphone technology can offer a sufficiently high level of performance to be deployed in a professional environment. However, the key uncertainty at present for this report is the ability of digital equipment simultaneously to achieve the performance levels of analogue and to improve spectrum efficiency.

A specific digital modulation technology, ultra wideband (UWB), uses short, precisely timed pulses to transmit large amounts of data at higher frequencies (above 3 GHz). UWB is inherently a short-range technology due to the need to minimise interference. UWB has been approved primarily for use in mass-market consumer electronics applications in the EU[2]. A UWB system is essentially a wideband noise source. It is unlikely that regulatory authorities will permit an increase in transmission power to reach the 100m minimum range required for many PMSE applications, since this would increase noise over a wide spectrum band. The PMSE sector could benefit from R&D being conducted on UWB in other sectors, but it is unclear when any improvements will meet high-end PMSE user needs.

In the long term, frequency hopping spread spectrum, cognitive radio and software-defined radio could be viable options. It must be borne in mind, however, that, in terms of PMSE equipment, the technologies are still at the conceptual / R&D stage.

Some manufacturers and users are starting to trial and transition to new technology and spectrum bands, for specific reasons:

- Some boardroom conference users in the US and other markets can leverage Audio-Technica’s SpectraPulse UWB system (operating at 3 GHz and higher). This particular system uses licence-exempt spectrum and offers encrypted transmission, although the frequency response is only voice quality
- Sony has recently launched a new line of digital wireless microphones specifically for its production-quality digital cameras. Electronic news gathering (ENG) cameras are digital and increasingly HD. Lower audio / transmission ranges and relatively limited need for portability supports use of higher frequencies, especially in presenter-to-camera situations
- Also, some community users such as churches and charities in the US are starting to use equipment that operates in higher-frequency licence-exempt spectrum (such as 2.4 GHz). However, this equipment is not suitable for most professional PMSE users due to its audio quality and the potential for interference.

Given that the PMSE sector consists of a diverse group of users, the potential to use new spectrum and technology will vary. In addition to general requirements such as audio quality, there are some variations in requirements by end user usage scenario.

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[2] Commission Decision 2007/131/EC of 21 February 2007 on allowing the use of the radio spectrum for equipment using ultra-wideband technology in a harmonised manner in the Community

Similarities among these requirements determine potential straw-man models for using new spectrum:

Straw-man models according to PMSE end-user scenarios and equipment requirements

	Equipment Used			Relative Requirements					
Usage Scenario	**Wireless Mics**	**IEM**	**Talkback**	**For Portability**	**For Low Latency**	**For Multi-Channel** (Simultaneous)	**Typical RF Transmission Range** (Transmitter to receiver)	***End User Segments with Similar Requirements***	
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches)	🟩	🟩	🟩	High	Important	High	Up to 200m	• These high-end entertainment and media audio users typically have the most demanding requirements for wireless microphones • These users typically need portable transmitters (non line of sight operation is typical as well as need for long battery life), low latency, multi-channel operation and relatively long transmission range	***Straw-man Model 1:*** *High-end entertainment and media audio*
Touring performances, concerts and events	🟩	🟩	🟩	High	Important	High	Up to 200m		
Studio-based programme making (TV broadcasters, TV production companies, radio)	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	High (depending on event)	Important (for live events)	High	Up to 200m		
• Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Moderate / High (depending on event)	Moderate / High (depending on event)	Moderate / High (depending on event)	Up to 200m		
Community usage (Educational, places of worship)	🟩	🟨	🟨	Varies	Important	Low / moderate (depending on user)	Up to 200m		
Short-range audio: • Boardroom conferencing • *Some* community usage	🟩	🟩	🟨	Typically low	Moderate (depending on event)	Typically Low	Up to 20-30m	• These users tend to have relatively less stringent requirements for transmission range	***Straw-man Model 2:*** *Short-range audio*
Short-range ENG / OB audio: Narrator / presenter to camera	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Low / Moderate (depending on event)	Low / Moderate (depending on event)	Low	1.5-10m	• Camera situations where there is a presenter in front of a camera (or a narrator) have less stringent requirements for portability, latency (although the audio needs to be synched with video), multi-channel operation and audio / transmission range	***Straw-man Model 3:*** *Short-range camera audio*
								• Requirements for Talkback, which is typically used for coordinating production and shows, vary, especially in terms of latency and audio quality for end user	***Straw-man Model 4:*** *Talkback*

Sources: Quotient, Sagentia, CSMG analysis

🟩 = Typically used
🟨 = Occasionally used

For each of these straw-man models, the following spectrum bands could potentially be used. To do this, it is likely that new equipment or technology would be needed:

Potential spectrum bands and technology for PMSE straw-man models

Usage Scenario	***End User Segments with Similar Requirements***		**Short Term (to 2012)**		**Medium Term (to 2012-2018)**	
			Potential Post-DSO / New Spectrum	**Requires New Equipment / Technology?**	**Potential Post-DSO / New Spectrum**	**Requires New Equipment / Technology?**
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches) Touring performances, concerts and events Studio-based programme making (TV broadcasters, TV production companies, radio) • Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production Community usage (Educational, places of worship)	• These high-end entertainment and media audio users typically have the most demanding requirements for wireless microphones • These users typically need portable transmitters (non line of sight operation is typical as well as need for long battery life), low latency, multi-channel operation and relatively long transmission range	***Straw-man Model 1:*** *High-end entertainment and media audio*	UHF Interleaved Spectrum	Likely to need new analogue or digital equipment	UHF Interleaved Spectrum Also depends on technology evolution (antenna, especially digital modulation schemes)	New analogue or digital equipment Also depends on technology evolution (antenna, especially digital modulation schemes)
Short-range audio: • Boardroom conferencing • *Some* community usage	• These users tend to have relatively less stringent requirements for transmission range	***Straw-man Model 2:*** *Short-range audio*	• 1.5 GHz • 2.4 GHz • 3 GHz and higher	• New analogue • Digital? • UWB	• 1.5 GHz • 2.4 GHz • 3 GHz and higher	• New analogue • Digital? • UWB
Short-range ENG / OB audio: Narrator / presenter to camera	• Camera situations where there is a presenter in front of a camera (or a narrator) have less stringent requirements for portability, latency (although the audio needs to be synched with video), multi-channel operation and audio / transmission range	***Straw-man Model 3:*** *Short-range camera audio*	• 1785 – 1800 MHz • 2 – 3 GHz	• Digital	• 1785 – 1800 MHz • 2 – 3 GHz • 3 GHz and higher	• Digital • *UWB?* • *Wireless Personal Area Network?*
	• Requirements for Talkback, which is typically used for coordinating production and shows, vary, especially in terms of latency and audio quality for end user	***Straw-man Model 4:*** *Talkback*	UHF Interleaved Spectrum • 1.5 GHz • 2.4 GHz	Likely to need new analogue or digital equipment • New analogue • Digital?	UHF Interleaved Spectrum • 1.5 GHz • 2.4 GHz	New analogue or digital equipment • New analogue • Digital?

⬚ Initial adoption

☐ Potential for growing / widespread adoption

Implications of this analysis

As the following straw-man model tables indicate, there are opportunities for new spectrum bands to be used by some PMSE segments in the short and medium term. However, for high-end entertainment and media audio users, the opportunities are limited in the short term and, depending on technology evolution, in the medium term:

Straw-man model 1: High-end entertainment and media audio

PMSE segments:

- Fixed-venue performances, concerts and events: Professional theatre, fixed-venue concerts, sporting events, major indoor events and corporate events
- Touring performances, concerts and events
- Studio-based programme making (TV broadcasters, TV products, radio)
- Complex electronic news gathering (ENG) and outside broadcasts (OB) of major events: multiple presenters, participants, and / or interviewees
- On-site TV / film production
- Community users

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

  - **Technological readiness:** Although digital equipment is available, it is not yet widely deployed in the UK. Because of this we did not find evidence that it is able to deliver robust performance across a range of PMSE usage scenarios
  - **Commercial adoption:** Currently, the relatively high costs of digital technology, coupled with the relatively long equipment replacement cycle, suggest that adoption of digital equipment will be limited in this timeframe

Medium-term (2012-2018):

  - **Technological readiness:** We expect the issues concerning the robustness of digital equipment across a range of usage scenarios to be mostly resolved
  - **Commercial adoption:** By the end of this timeframe, we anticipate moderate adoption of digital equipment supported by the market entry of leading equipment manufacturers, which should lead to greater competition and reduction in equipment prices

Straw-man model 2: Short-range audio

PMSE segments:

- Boardroom conferencing
- *Some* community users (with short-range audio requirements and little multi-channel)

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

  - **Technological readiness:** UHF-based analogue and digital equipment are currently available for these end-users, in addition to licence-exempt equipment, although the latter needs to be proven for some community users

- **Commercial adoption:** We expect limited adoption over this timeframe due to the current relatively high costs of UWB equipment targeted at boardroom conferencing applications

Medium-term (2012-2018):

- **Technological readiness:** Improvements are expected to enhance the performance of current UWB audio products by leveraging advances in the technology for other areas of the communications industry
- **Commercial adoption:** We expect UHF spectrum scarcity to drive broad adoption of licence-exempt, alternative technologies such as UWB

Straw-man model 3: Short-range camera audio

PMSE segments:

- Short-range ENG / OB audio: narrator / presenter to camera

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** Digital equipment currently available for ENG usage and there is potential to use higher bands such as 1785 – 1800 MHz , which is being considered for ENG audio, as well as 2 – 3 GHz
- **Commercial adoption:** Continued take-up of existing digital equipment for ENG

Medium-term (2012-2018):

- **Technological readiness:** We expect continued take-up of the above as well as the potential to use spectrum above 3 GHz by utilising digital equipment (embedded audio) and, possibly UWB and Personal Area Network (PAN)
- **Commercial adoption:** Further adoption of the above is expected, assuming current digital equipment improves in performance while decreasing in price. If UWB and other emerging technologies such as (PAN) prove to be robust, they could enjoy limited adoption

Straw-man model 4: Talkback

PMSE segments:

- Talkback (across many usage scenarios)

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** Depending on the transition to IEMs, we expect developments in talkback systems to be broadly in line with those of wireless microphone equipment (UHF-based analogue and digital) due to similarities in the underlying technologies. Current R&D efforts are focused on equipment operating in non-UHF spectrum (1.5 GHz and 2.4 GHz)
- **Commercial adoption:** Depends on the transition to IEMs, but the potential exists for broad adoption of UHF-based analogue equipment and, to a lesser degree, digital, depending on price

Medium-term (2012-2018):

- **Technological readiness:** Depending on the transition to IEMs, we expect

developments in talkback systems to continue leveraging advances in wireless microphone equipment (UHF-based analogue and digital). Equipment operating in non-UFH spectrum (1.5 GHz and 2.4 GHz) may be available
- **Commercial adoption:** This depends on the transition to IEMs, but there is the potential for talkback equipment to be adopted widely, although the price of digital systems would be a significant factor

The key implication of this analysis is that UHF Bands IV and V spectrum will remain critical to many PMSE users (fixed-venue and touring performances, concerts and events, studio-based programme making, complex ENG / OB use, on-site TV / film production and many community users) through to the medium term (2012 – 2018) Over this time frame, it is also understood that analogue technology will remain the preferred choice of many PMSE users because of its cost advantages and the long replacement cycles for wireless microphone equipment.

There is significant capacity available for PMSE use above UHF Band V. However, signal propagation is an issue in most usage scenarios where portability is critical. Therefore, the most useful spectrum, in addition to UHF Bands IV and V, is just above these bands. Improvements in antenna technology may help, but require significant R&D efforts. However, for some users, bands above UHF Band V could start to be used in the short term (by 2012). In some cases, especially with shorter range requirements and line of sight, UWB could enable use of spectrum above 3 GHz for specific usage scenarios.

It is important to note that the transition to a new technology is likely to take approximately 5-10 years, once a technology is viable, due to the timeframes needed for initial take-up, widespread adoption and then sufficient time to recoup investment.

Technology evolution and spectrum are related, in terms of the potential for efficient use of spectrum. For instance, when operating in contiguous UHF channels, digital systems enable more transmitters to be deployed compared to analogue systems. This is because digital systems are less susceptible to the effects of intermodulation distortion. Also, the wider frequency of operation of digital systems allows full use of their switching capability, enabling the same type of transmitter to be used on different channels. It must be noted that this multi-channel advantage of digital systems can only be optimised when contiguous UHF channels are available.

Other countries undergoing DSO are also grappling with how to accommodate the needs of the PMSE industry. International benchmarks indicate use of new spectrum or technology only in certain or limited cases. CEPT has proposed PMSE use, in addition to UHF Bands IV and V, of some spectrum in the ranges of 1452 – 1559 MHz and 1785 – 1800 MHz spectrum. However, CEPT expects this spectrum will be appropriate for only certain usage scenarios. Moreover, usage rights for some of this spectrum have already been awarded in many countries (including the UK).

During this analysis, PMSE manufacturers and users expressed their concerns about security of tenure for spectrum. A greater degree of certainty (within suitable bands) would, in turn, help to support technology developments by manufacturers and investment decisions for new equipment / technology by end users. Also, providers of touring performances, concerts and events are concerned about access to sufficient interleaved spectrum across the UK.

It has been questioned as to why the PMSE industry cannot match or even leverage the capabilities of other wireless audio (and video) equipment; such as TV cameras and mobile phones, which are also examples of equipment where digital technology has made a significant difference in spectrum efficiency:

- TV cameras operate at higher frequencies (above 2 GHz), so why cannot wireless microphones? TV cameras do not have stringent low delay requirements since the signal is being broadcast or saved. Furthermore, TV cameras are mobile, even portable, but do not need to move to the degree a performer must, so line of sight is less of an issue.
- In the case of mobile phones, delay and audio quality requirements are not as stringent as they are for most PMSE users. Audio delay is less of a problem because return echoes are suppressed, so the user is much less aware of the effects of delay. This is demonstrated by the occasional situation where the suppression fails and a return echo of many hundreds of milliseconds can be heard, making conversation very difficult.

The impact of the new technology and spectrum straw-man models on use of UHF Bands IV and V is modest in the short-term. While moving Talkback to new spectrum and/or technology is feasible in the short-term, the impact on UHF Bands IV and V will be limited since most use takes place in the 450-470 MHz range. However, for short-range audio (boardroom conferencing and some community users) and short-range camera audio (electronic newsgathering / outside broadcasting) applications, there is the potential to use new spectrum in the short term (to 2012).

Nonetheless, overall, there are opportunities for improvements in wireless microphone technology to improve spectrum efficiency or enable use of spectrum not traditionally utilised. The consensus of our interviews is that digital is the most promising of the technologies identified. The timescales for the mainstream adoption of digital technology are driven by a combination of technical and commercial factors leading to an expectation that widespread adoption could be in the 7 – 10 year range.

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1. The current situation

1.1 Impact of Digital Switchover

Digital Switchover (DSO) from analogue terrestrial television is taking place in the UK, with all regions to be converted by 2012. This change will have three key impacts:

1. Increase in range and number of terrestrial TV services
2. Spectrum (digital dividend) will become available for new uses
3. The pattern of interleaved spectrum – the frequencies used by terrestrial TV and shared by low-power applications including PMSE – will change

Digital Switchover will have a significant impact on PMSE since these users rely significantly on spectrum in the 470 – 862 MHz range, accounting for 58% of assignments in 2006:

Band	Freq. (MHz)	Assignments during 2006		Applications
Band I	47-62	36	<0.01%	Talkback
Low Band	67-86	65	<0.01%	Talkback
High Band	139-148	181	<0.01%	Talkback
Band III	173-225	1,159 26	2.06% <0.01%	Wireless microphones / IEM Talkback
UHF 1	420-450	1,346	1.77%	Talkback
UHF 2	450-470	23,012	35.23%	Talkback
Bands IV & V	**470-854**	**30,627** **3,344**	**46.89%** **5.12%**	**Wireless microphones / IEM** **Talkback**
Channel 69	**854-862**	**4,243**	**6.42%**	**Wireless microphones**
1.5 GHz	1488-1800	123	0.19%	
2 GHz	2025-2690	2,522	3.82%	
3.5 GHz	3400-3600	146	0.22%	
5 GHz	5427-5925	82	0.13%	
7 GHz	7110-7424	169	0.26%	
8 GHz	8460-8500	4	0.01%	
10 GHz	10300-10360	23	0.03%	
11/12 GHz	11740-12500	1,064	1.61%	
24 GHz	24250-24500	0	0.00%	
48 GHz	48000-48400	0	0.00%	
Total		**66,105**	**100.00%**	

Source: Ofcom, Draft ITT (JFMG)

The specific long-term impact of Digital Switchover and the award of the digital dividend on PMSE users will be:

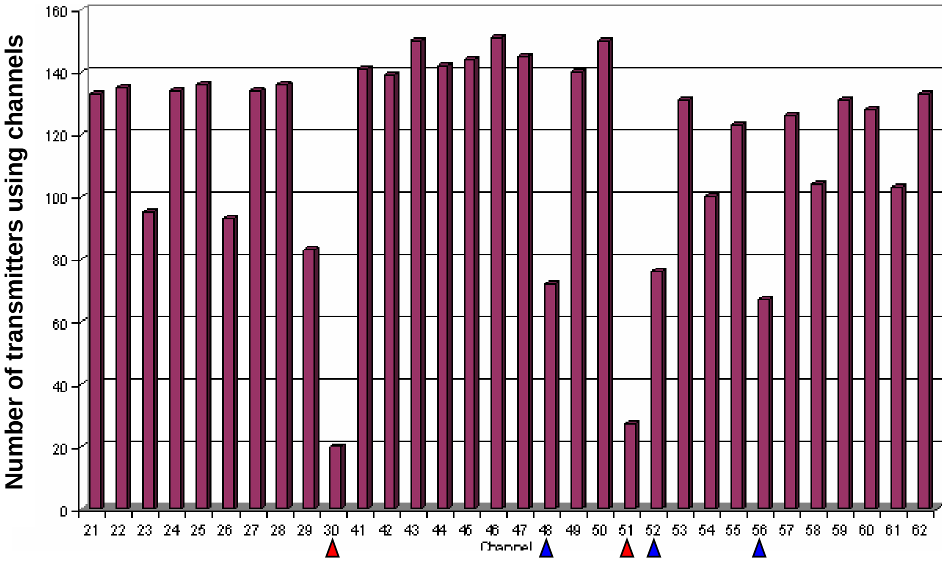
Channel(s)	**Frequency (MHz)**	**Impact**
21 – 30	470 – 550 MHz	▪ Reserved for DTT; continued licensed PMSE use of new pattern of interleaved capacity
31 – 40	550 – 630	▪ Cleared of existing use; award for new use by auction; PMSE use only if a consequence of auction
41 – 60	630 – 790	▪ Reserved for DTT; continued licensed PMSE use of new pattern of interleaved capacity
61 – 62	790 – 806	▪ Reserved for DTT; award of interleaved capacity for new use by auction; PMSE use only if a consequence of auction
63 – 68	806 – 854	▪ Cleared of existing use; award for new use by auction; PMSE use only if a consequence of auction
69	854 – 862	▪ Continued licensed PMSE use

863 – 865 MHz in the immediately adjacent channel 70 will also continue to be available for licence-exempt PMSE use.

Since much *current* PMSE equipment operates only in channels 67 – 69 and channels 67 and 68 are to be auctioned for new use, the implication is that some PMSE users may need to re-equip if channel 69 alone is insufficient to meet their spectrum needs.

DTT will use different frequencies from analogue terrestrial television in the spectrum reserved for it after DSO (Channels 21 – 30 and 41 – 62). The pattern of interleaved spectrum available for PMSE will therefore change. Ofcom has also proposed that the interleaved capacity in channels 61 and 62 be auctioned alongside the cleared spectrum in channels 63 – 68 in order to increase UK spectrum potentially aligned with spectrum available for two-way mobile services elsewhere in Europe.

Nationally, channels 30 and 51 will generally be more available for wireless-microphone use after DSO than other channels in interleaved spectrum. This is because they are outside the nine “standard channel groups” used in the DSO plan. Channels 48, 52 and 56 are also outside those groups and so will also be less heavily used for DTT than other channels, although they are increasingly being used as a group in their own right. It may be possible to use a wireless microphone anywhere in the UK in at least one of channels 28-30 and, separately, in at least one of channels 51-53. The chart below provides further details on the extent of DTT use of UHF Bands IV and V and indicates (with red and blue arrows) channels that may have the greatest availability across the UK for PMSE.



Number of DTT transmitters using digital TV channels (Ofcom)

One point to add relating to the interleaved spectrum is that Ofcom has proposed to allow licence-exempt use of interleaved spectrum for cognitive devices. (However, Ofcom will not be setting aside any of the digital dividend spectrum exclusively for licence exempt use.) Cognitive radio is a new, emerging technology that could detect spectrum that is otherwise unused. It may be able to operate alongside higher power licensed uses. It could be particularly suited to operating in interleaved spectrum, where significant capacity is often unused at any one location at least some of the time. However, it is an unproven technology in early stages of R&D. A critical issue is the potential for cognitive devices to interfere with PMSE (and other services) if operating in the same area of spectrum. Ofcom has stipulated that use of equipment in the UK will need to protect licensed users of this spectrum, including DTT and PMSE, against harmful interference.

Ofcom has decided to award most of the available interleaved spectrum in a way that first and foremost meets reasonable demand from PMSE users. Ofcom analysis suggests that, in most locations, availability of interleaved spectrum is expected to be sufficient to meet historic levels of peak demand after DSO. Ofcom will award – through a beauty contest – a single package of interleaved spectrum, channel 69 and other spectrum outside the digital dividend allocated to PMSE to a licensee that will act as a band manager. The band manager will pay a charge for spectrum based on Administered Incentive Pricing (AIP) and will be able to earn revenue by charging its customers for access. The band manager will be required to meet reasonable demand from PMSE users on fair, reasonable and non-discriminatory terms for a period of 10 years lasting until 2018. These measures will ensure that PMSE users can continue to access spectrum while moving towards a more market-based approach over time. Ofcom is consulting on the detailed design of the award of this spectrum as part of the Digital Dividend Review (DDR) during summer and autumn 2008.

Given the inherently limited capacity of post-DSO channels and interleaved spectrum for PMSE, the potential to use spectrum more efficiently or other spectrum bands is critical.

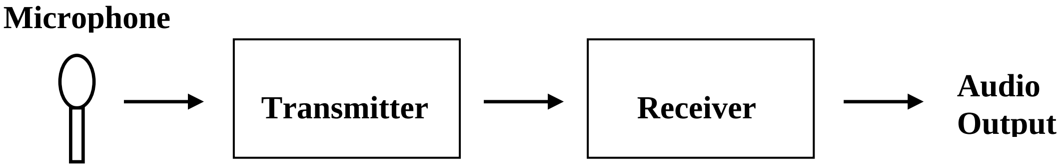
1.2 Overview of current wireless microphones

1.2.1 Basic Description (analogue technology)

The vast majority of wireless microphones equipment currently in use in Europe and the USA are based on analogue design, which facilitates high quality, real-time transmission of audio signals required by applications such as theatres, concerts and television broadcasts.

A wireless or radio microphone system comprises a microphone connected to a miniature radio transmitter and a receiver designed to receive only the microphone's signal. The transmitter and receiver combination are highly specialised radio frequency (RF) and audio electronics which have replaced the high quality audio cable traditionally used to connect a microphone to other audio equipment.

The constituent parts of a wireless microphone system are shown below.



Basic wireless microphone system

Programme making and special events industry (PMSE) makes extensive use of three types of wireless equipment: radio microphones, in-ear monitors (IEMs) and talkback (also known as wireless intercom).

The audio output from the microphone is used to modulate a high frequency carrier wave in the transmitter. Frequency modulation (FM), an analogue modulation technique, is the most commonly used modulation scheme, whereby the transmitter systematically uses the audio signal to vary the frequency of the carrier signal before transmitting it over the air. Modulation refers to the systematic application of an information signal to a high frequency carrier wave in order to achieve efficient transmission of information using radio waves.

At the receiver, the opposite takes place. The carrier signal is de-modulated to recover the original audio information, which is then used to drive other audio components in the system.

Analogue wireless microphones produce undesirable noise artifacts in their outputs due to the use of companding techniques to extend the dynamic range (measure of loudest to softest sounds which can be recorded) of the microphones. Companding is a concatenation of the words "compressing" and "expanding" and it is used to compress the audio signal in the transmitter and expand it in the receiver. The process reduces the dynamic range of the audio signal before transmission using a compander circuit with a 2:1 ratio. At the receiver, the inverse occurs – a 1:2 expander increases the dynamic range of the received audio back to the original dynamic range.

1.2.2 Elements of an analogue wireless microphone system

Wireless microphone transmitters can be grouped into three basic types:

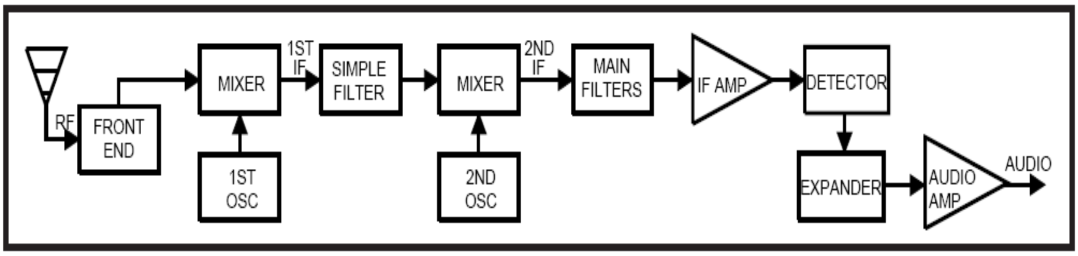
- Handheld models have conventional microphone elements, such as the microphone capsule, mounted to a handle containing a miniature radio transmitter and other electronics.

- Body (Belt) pack models are designed to be used with lavalier microphones, miniature microphones intended to be clipped or pinned to an article of clothing. They can also be connected to mixers and other audio instruments.

- Plug-on models have a female XLR audio connector attached to a compact body containing the transmitter. An internal battery provides power to the microphone. Plug-on transmitters offer extensive flexibility because they allow the use of almost any microphone with an XLR connector and compatible power circuit.

1.2.3 Receivers

The receiver is the single most important component of a wireless microphone system. The choice of receiver is dictated by the application, but, in general, good receivers are required to compensate for the limited range of the microphone output. A standard receiver architecture is shown in the diagram below.



Basic architecture of a wireless microphone receiver

The front-end of the receiver is the first step in a chain of filtering, amplification and conversion processes. The receiver topology shown in the diagram is known as a "double super-heterodyne receiver".

The signals received by the antenna (f_{IN}) are passed to the front end circuit, a filter which attenuates signals outside of its operating range. The desired signals are amplified and fed to the mixer, which is also fed with a high frequency signal (f_{LO}) from the first local oscillator. The mixing or "heterodyning" of these two signals produces "sum" ($f_{IN} + f_{LO}$) and "difference" ($f_{IN} - f_{LO}$) signals of their original frequencies. The purpose of mixing the signals is to derive a constant frequency signal at IF so that fixed frequency filters can be used. They are easier and cheaper to implement using standard circuitry.

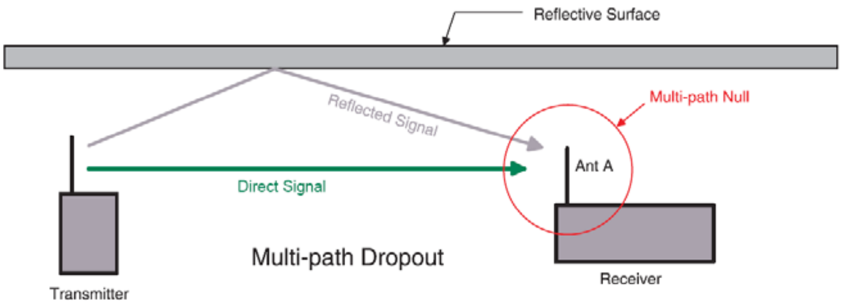
In this example, the "sum" is rejected through filtering, passing only the resulting "difference" signal, which is the "IF" or "intermediate frequency" signal. The heterodyning process is repeated in the second mixer, and the resulting IF signal, which is at a lower signal frequency than the first IF signal, is converted to audio in the detector stage, followed by an audio output amplifier. The radio frequency (RF) signal is therefore converted to an audio signal. The significance of having the second IF signal at a lower frequency is that better channel selectivity can be attained using low-cost, standard filters with sharp frequency cut-off characteristics.

The local oscillator can either be at a frequency (f_{LO}) above the input signal (f_{IN}) or below it. The former is known as *"high-side injection"* and the latter is known as *"low-side injection"*. There are problems and benefits associated with both and the choice depends on which is the most beneficial in a *particular* application.

1.2.4 Antenna Technology - Diversity Reception

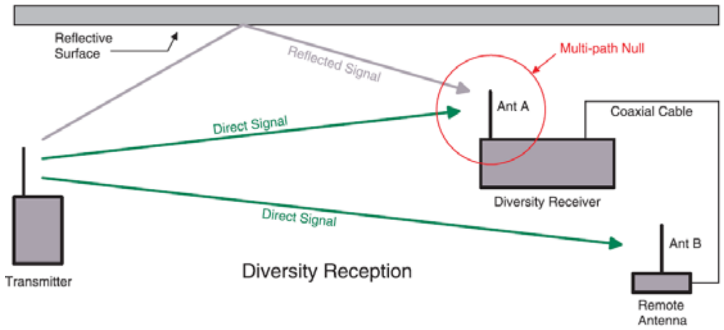
The first wireless microphone receivers had one antenna (non-diversity), but they were prone to multiple path (multi-path) cancellations.

In the example shown below, the signal from the transmitter reaches the receiver antenna via a direct path and a reflected path. The reflected signal path is longer than the direct path, causing the two signals to be out of phase when they mix together at the receiver antenna. The resulting weak signal causes what is known as a "dropout."



Multi-path cancellations resulting in drop-outs

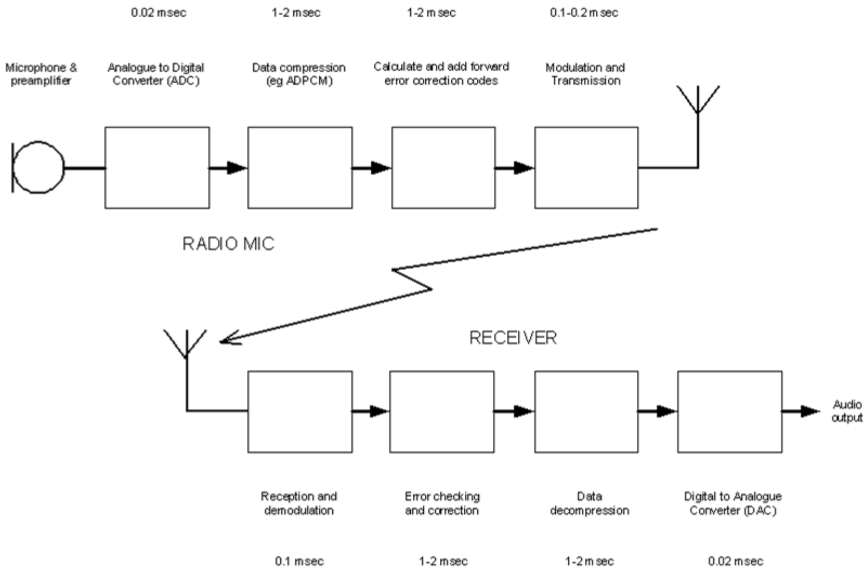
The latest receivers employ a ‘Diversity’ system whereby there are two separate receiver circuits, each with their own antenna and a circuit to analyse which receiver has the strongest signal and noiselessly switches between them accordingly at a set frequency. This avoids audio dropouts where reception is poor.



Diversity reception to prevent drop-outs

1.2.5 Digital Wireless Microphone Technology

Digital wireless microphones are relatively new. A simple digital audio wireless microphone system is shown below[3]. Typical latency values are given for each block. The total system latency is the sum of these individual values and is marginal for high quality PMSE applications.



A simple digital radio microphone system

1.2.6 Digital Modulation and Compression Schemes

Digital modulation schemes appropriate for PMSE equipment include techniques such as the spectrally efficient Gaussian Minimum Phase Shift Keying (GMSK), and Quadrature Phase Shift Keying (QPSK). For example, QPSK involves varying the

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[3] Plextek, 25th April 2008

phase of an analogue carrier signal using a digital bit stream during each phase change. PSK refers to a form of phase modulation which is implemented using a discrete number of states, and “Quadrature” part refers to PSK with four possible states.

Digitising audio signals generates large amounts of data requiring higher transmission bandwidth in order to maintain audio quality. A compression technique termed Adaptive Differential Pulse Code Modulation (ADPCM) is a data reduction technology that offers low latency[4]. ADPCM is a widely used variant of the traditional pulse code modulation (PCM) technique. ADPCM codes and transmits the difference between two sequential audio data samples. This difference is usually small and thus can be coded in fewer bits than a full PCM sample.

Sony has developed a digital audio CODEC which it claims offers the following benefits:

- outstanding sound quality in 24-bit / 48-kHz sampling;
- wide dynamic range of more than 106 dB;
- wide frequency response of 20 Hz to 20 kHz;
- superb transient response performance (that can be a challenge to achieve in an analogue circuit);
- low latency (1.5ms for encoding and 1.5 ms for decoding equating to a spatial distance of 1.2m, although this depends on the distance between the transmitter and receiver antennae during measurement of the latency)
- overall system latency of 3.6ms
- secure transmission

Sony’s digital wireless microphone system is currently focused on electronic news gathering (ENG) and electronic field production (EFP) applications for use with digital wireless cameras, a market in which Sony is understood to be a leading manufacturer.

1.2.7 Common limiting factors in wireless microphone performance

The most common limiting factors in wireless microphone performance are:

- Delay – this is has been applicable to digital wireless microphones, which have suffered delay due to the process of converting the audio signals to digital and applying digital signal processing techniques such as forward error correction. It appears that newer models now coming onto the market do not experience this problem to any significant extent.

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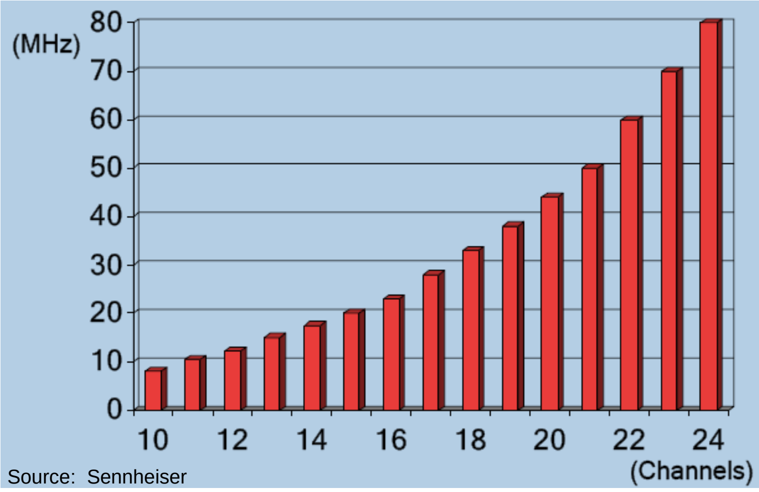
[4] Plextek, 25th April 2008

- Delay (mixed source environment) – Wireless microphones tend to be used in a mixed source environment where many other microphones are wired (zero delay). Signals from all sources are mixed prior to transmission over the public address system and delays lead to undesirable outcomes such as constructive and destructive interference (signal reinforcement or cancellation) arising from mixing a delayed signal with its original.
- Tune-ability (frequency agility) – for large numbers of professional users of equipment operating in UHF bands IV and V, “frequency agility” has become an important factor when purchasing wireless microphones. It refers to the ability to tune the equipment to frequencies in adjacent channels, particularly contiguous banks of channels. However, tune-ability is limited. Generally, the high-end analogue professional microphones can tune over 24 to 36 MHz (about 3-4 TV channels). A phase locked loop (PLL) based frequency synthesiser circuit is the technology which enables frequency agility (see Appendix B for more details).
- Reflections – can lead to signal loss due to signals cancelling each other out
- Range – due to the low power output of the microphones and interference from other signal sources
- Interference – high power signals from high power services such as television broadcasts
- Intermodulation Distortion (IMD) products – occurs when strong signals from two transmitters cause audio noise because of non-linearities in the receiver that forms the intermodulation products.

UHF bands IV and V are shared with other services, mainly terrestrial television broadcasts. Radio microphones are strictly secondary users of the available channels, including the interleaved channels used to prevent interference between adjacent television broadcasts. For this reason wireless microphones are mandated to accept whatever interference occurs, while not causing any (their very low transmitter power means they are unlikely to be sources of interference other than to other wireless microphone systems). It is common, however, for wireless microphones to receive interference, and finding channels where interference will not occur is fundamental to good wireless microphone system performance.

This requires frequency co-ordination, a task currently undertaken by the Joint Frequency Management Group Ltd (JFMG) under statutory contract to Ofcom. Moreover, equipment manufacturers provide and hire companies to provide their users with information and services to ensure interference-free operation. The former usually supply information about frequencies where intermodulation distortion can be avoided, and the latter typically perform tests to ensure intermodulation-free operation when they deploy equipment for their customers.

Intermodulation products serve to reduce the number of useable frequencies within a given block of spectrum. It is the fundamental reason why analogue wireless microphones cannot be used adjacent to each other simply by dividing the spectrum into equally spaced channels. Moreover, the bandwidth required increases disproportionately as the number of channels increases. This is because the increased number of IMD products produced as channels increase. The following chart from Sennheiser provides an indication of bandwidth required to avoid intermodulation distortion:



Source: Sennheiser

Recommended channels per MHz for analogue wireless microphones

According to Sony:

> “digital wireless microphones do not suffer from the same problem. This is because whilst analogue systems require the wanted signal to be better than 40 dB above the interfering signal (the inter-modulation product), Sony digital wireless microphone technology requires only a 20 dB margin.”

and:

> “The advantage of undesired signal tolerability brings about a great improvement in simultaneous multi-channel operation. For analogue systems it is necessary to skip unusable channels where inter-modulation occurs. In contrast, by combining the digital modulation system with an excellent RF circuit, even the inter-modulation channels can be allocated as usable channels.”

However, interviewees pointed out that these claims need to be tested and validated for a full range of PMSE usage scenarios.

In summary, analogue wireless microphones dominate the PMSE market due to their high audio quality and reliability, real-time signal transmission, and relatively low cost. However, they do face limitations, especially with respect to interference and intermodulation distortion. Digital technology is increasingly addressing some of these limitations, but has limitations of its own, which will be discussed later.

1.3 PMSE end user current approach, requirements and usage scenarios

1.3.1 Current approach

Previous work for Ofcom and CSMG research provides context for the current approach for use of spectrum for PMSE.

- Use of PMSE equipment and spectrum is diverse:
    - Professional theatres, fixed-venue concerts and major indoor events
    - Touring concerts and shows
    - Studio-based programme making
    - Electronic news gathering (ENG)
    - Outside broadcasts (OB) of major events
    - Boardroom meetings and presentations
    - Community usage such as educational institutes and places of worship
- For most of the above users, even a short failure or small / brief reduction in audio quality can have severe implications for an audience and the people associated with the event / production
- Although use of some PMSE spectrum is concentrated, a significant portion of use is also fragmented:
    - 50 users account for 50% of all spectrum usage; BBC accounts for 13%
    - Approximately 64,000 individual PMSE frequency assignments are made to around 1,300 different organisations and individuals each year
- Because of the number of different PMSE end users, coordinating spectrum use is critical, especially in urban areas or highly-used, large venues. PMSE spectrum use is coordinated and licences are issued by JFMG Ltd.
- Illegal use of PMSE equipment does take place and is difficult to monitor due to the lower power of equipment. Sagentia[5] has estimated that about two-thirds of channel 69 microphones are operating without licences
    - It is understood that very little enforcement of licences takes place, though it is equally unclear that illegal use creates significant problems in practice for licensed users.
- Freelancers (e.g., for sound design) are important in many PMSE scenarios
    - Freelancers are “only as good as their last job.” Most freelancers will therefore require and rely on proven equipment in order to avoid any potential problems with the audio for a production

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[5] Use of UHF Spectrum for Programme Making & Special Events in the UK, 13 December 2006.

- Hire companies are also an important part of the PMSE value chain since many end users rent their equipment. Equipment hire companies only need one shared licence for all of their microphones

- PMSE equipment is understood to have a lifetime of 6 – 10 years. However, PMSE equipment is often used for far longer time periods

- Secondary markets are important for buying used equipment

- PMSE usage primarily consists of wireless microphones (and in-ear microphones) rather than talkback / wireless intercom

- Indoor use dominates. This is important because of the lack of physical space in theatres for equipment deployment, although spectrum reuse is improved because building structures prevent signals traveling beyond the location in question. Outdoor users typically need a distance of 1km from other users to avoid interference on the same channel[6]

- Local entertainment and events (including theatre, concerts and shows) forms the single largest category of PMSE usage at 41% of assignment days. This category lends itself to wireless transmission as performers often need the full freedom which is not afforded to them by wired microphone usage. Other categories such as news gathering and outside broadcasts, 15% and 4% respectively, rely on wireless transmission as the temporary nature of the coverage means that laying fixed cable infrastructure would be impractical[4]

- Usage varies by geographic region, since urban areas and certain venues are likely to have many simultaneous events. Based on Quotient research, 50% of assignment days were in only 4% of locations. The West End theatre industry is a key example of this, where there are over 25 theatres in close proximity

1.3.2 General requirements

End-users of wireless microphones and talkback equipment have a set of basic requirements from the equipment and systems that they purchase and use. Not all needs apply to all users, but the key needs are:

- *Wireless* – users want freedom of movement, especially important for live performances and concerts. There are also health and safety implications in many situations in using wired microphones

- *Portable* – need varies; equipment for performers must be unobtrusive so as not to hinder the performance

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[6] Quotient, Supply and demand of spectrum for Programme Making and Special Events in the UK, December 2006.

- *Dynamic range* (difference between the softest and loudest sounds) – typically over 100 dB is required for a wireless microphone
- *Frequency response* – ability to respond equally to every frequency within the audible frequency range of 20 Hz to 20 kHz
- *Battery life* – devices must have the capacity to operate for the full length of the performance or show. For a theatre production, including sound checks, this is typically 6 – 10 hours
- *Safety* – the physical equipment and the electromagnetic transmission must both ensure the safety of the user
- *100% duty cycle* – frequency sharing not possible for PMSE use that requires continuous high quality
- *Audio quality* – performances with a significant audio element demand high fidelity from all aspects of its sound system
- *Low latency* – delay must be avoided for a live performances since audio / performer lip synchronisation is critical
- *Reliability / Ease of use* – professional PMSE users in particular demand consistently high performance from their equipment to meet audience requirements for high quality audio and no sound source failure
- *Interference* – the system must not suffer from intermodulation issues, again especially in venues such as a West End show
- *Simultaneous Multi-channel Use* – Many PMSE usage scenarios require the concurrent use of many wireless microphones. A West End show or a major pop concert may require 70-80 wireless microphones. Each microphone must operate in such a way as to avoid causing interference to adjacent channels
- *Potential for HD Audio* – As an example, Intel HD Audio hardware is capable of delivering 192 kHz/32-bit quality. It is understood that ETSI has recently started to consider standards for HD Audio. Due to compression requirements, HD Audio, if it becomes important, is more likely to be used for non-live environments

1.3.3 Usage scenarios and specific requirements

Previous work conducted for Ofcom has identified PMSE usage scenarios, which will be used in this analysis for consistency and to facilitate comparison. CSMG has also noted variations in specific requirements for these usage scenarios:

	Equipment Used			**Relative Requirements**			
Usage Scenario	**Wireless Mics**	**IEM**	**Talkback**	**For Portability**	**For Low Latency**	**For Multi-Channel** (Simultaneous)	**Typical RF Transmission Range** (Transmitter to receiver)
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches)	🟩	🟩	🟩	High	Important	High	Up to 200m
Touring performances, concerts and events	🟩	🟩	🟩	High	Important	High	Up to 200m
Studio-based programme making (TV broadcasters, TV production companies, radio)	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	High (depending on event)	Important (for live events)	High	Up to 200m
• Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Moderate / High (depending on event)	Moderate / High (depending on event)	Moderate / High (depending on event)	Up to 200m
Community usage (Educational, places of worship)	🟩	🟨	🟨	Varies	Important	Low / moderate (depending on user)	Up to 200m
Short-range audio: • Boardroom conferencing • *Some* community usage	🟩	🟩	🟨	Typically low	Moderate (depending on event)	Typically Low	Up to 20-30m
Short-range ENG / OB audio: Narrator / presenter to camera	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Low / Moderate (depending on event)	Low / Moderate (depending on event)	Low	1.5-10m

Sources: Quotient, Sagentia, CSMG analysis

🟩 = Typically used 🟨 = Occasionally used

PMSE usage scenarios and equipment requirements

Key points include:

- Requirements do vary for these usage scenarios:
    - Portability of usage scenarios with actors / dancers means that non line of sight approaches are necessary
    - Low latency is needed where there is a performance with a live audience
    - Need for multi-channel
    - Range (from transmitter to receiver)
- Short-range audio; Boardroom conferencing and some community users (classrooms, small lecture halls) typically have shorter range (and reduced multi-channel) requirements relative to other usage scenarios
- Many of the usage scenarios also include cameras/video. The camera can provide a means in some usage scenarios for capturing audio (with video) and embedding audio in the video stream, although this is a relatively limited usage scenario. Most broadcast-quality cameras in the UK currently operate in the 2-3 GHz range. HD video is becoming important. Sagentia has identified the 7.5 GHz range as another option for video camera transmission, with bands around 7 GHz, 10 GHz and 60 GHz already in routine use in Japan.

  - In some specific cases, range requirements and need for low latency are less stringent than other PMSE usage scenarios (e.g., presenter-to-camera for ENG)

- In addition, there are programme links (point-to-point radio links) used mostly by broadcasters to carry sound for the source back to the studio. Radio microphones operating above 50mW are classified as audio links. All wireless cameras are classified as video links. PMSE spectrum assignments above 2 GHz are mostly for video links (where there is typically line of sight)[7].

- Radio microphones and IEMs tend to share requirements in that they are *one-way* and require high audio quality and low latency (especially for an artist using IEM to hear their voice / musicians during a performance)
  - Many radio microphones sold in the UK are intended for use in channels 67 – 69

- Talkback, also known as wireless intercom, used mainly by theatres, TV production and outside broadcasters for conveying instructions to all those directly involved the production of a programme or event
  - Tends to be used in 450-470 MHz range, where PMR (Professional Mobile radio) and TErrestrial Trunked RAdio (TETRA) use also takes place
  - It is a mixture of one and two-way communications. Since talkback is used to coordinate backstage production activities of a show, the requirements are less stringent relative in some cases to wireless microphones and IEMs
  - However, some users are replacing talkback with IEMs to improve quality

1.4 Manufacturer characteristics and overview of current equipment

Prior to the mid-1980s, there were only five wireless microphone frequencies available for use in the UK, excluding designated BBC and ITV spectrum. These were the VHF frequencies between 173.8 MHz and 175.0 MHz which remain available today. However, the spectrum was insufficient to meet demand at the time and so many wireless microphone users resorted to illegal use of licensed spectrum. The regulatory response was to allocate more spectrum to wireless microphones in UHF bands IV and V, where users of PMSE now operate legally.

Where possible, manufacturers prefer to produce systems which are capable of operating in a broad a range of frequencies in order to enable them to cost-effectively distribute the equipment to multiple markets, or even globally, with limited modification. For the past 20 years, the spectrum designated for use by wireless

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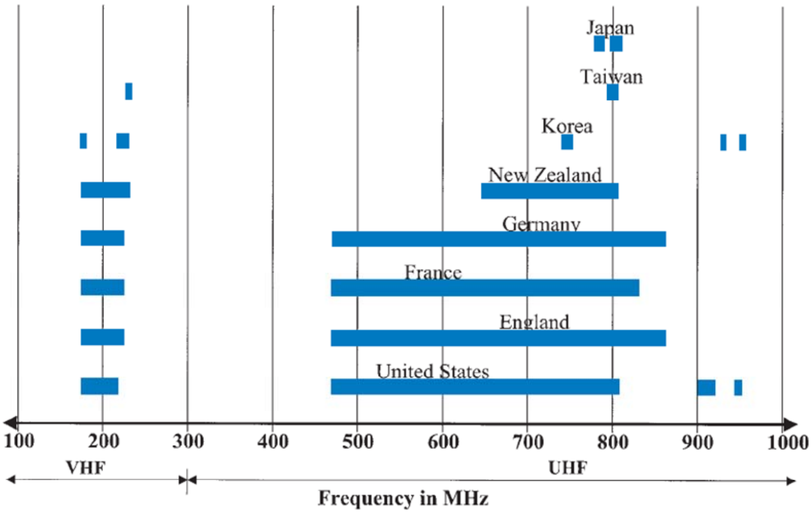
[7] Quotient

microphones and talkback systems has been broadly similar in the major markets of Europe and the US, enabling equipment to be sold and operated internationally. Consequently, the vast majority of high–end wireless microphone equipment produced and in use today is based on analogue transmission and operates in UHF bands IV and V.



Source: Selection and Operation of Wireless Microphone Systems, Shure Inc.

International Wireless Systems Frequencies

As set out in section 3, the realisation of digital dividends in these same countries will inevitably affect this situation. This matters all the more because the PMSE industry is one of limited scale. Estimates prepared for the EU indicate that just under 0.6 million wireless microphone unit shipments in 2006 for the entire EU. By comparison, 169.2 million mobile phones were sold in Western Europe in 2006; and 274.4 million for all of Europe[8]. Sennheiser is one of the larger players in PMSE equipment. Its *overall* revenues in 2007 were £283 million, of which a portion is attributable to PMSE. By comparison with large-scale manufacturers of audio electronics, just Nokia's mobile phone division had revenues of £17.2 billion in 2007 while just Sony's TV division had revenues of £5.2 billion in 2007. Relative to other segments of the electronics industry that manufacture equipment that utilises spectrum, scale and investment for R&D are challenges for the PMSE sector. This is a key reason why manufacturers conduct R&D and develop products for multiple markets.

PMSE manufacturers are a mix of private companies or specialist divisions of much larger multinational electronics manufacturing groups. Due to the limited financial reporting requirements of small private companies, and the lack of fine granularity in the financial reporting of multinational manufacturing companies, detailed

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[8] CIBC, Company annual reports

information on the economics of wireless microphone manufacture is limited. A summary of the main manufacturers and their product ranges is provided below.

PMSE equipment manufacturer	Revenue	Operating Income	Market Presence	Product & Services
AKG	(part of Harman International Industries)	n/a	Austria (part of Harman)	Produces pro audio, microphones and headsets used in stage, live music and other applications
Audio Ltd	(Privately held)	(Privately held)	UK based	Designs and manufactures broadcast-quality radio microphone systems
Audio-Technica	(Privately held)	(Privately held)	Founded in Japan, global presence inc. UK	Designs and manufactures audio equipment including microphones, headphones, wireless systems and mixers, for consumer and professional applications
beyerdynamic	(Privately held)	(Privately held)	Founded in Germany, present in UK, US, Brazil	Manufactures headphones, microphones and conference systems for performance, broadcast, conference and personal users
Lectrosonics	£11m (Privately held)	(Privately held)	US & Canada	Leading developer and manufacturer of wireless audio technology in several industries, particularly film production
Sennheiser	£283m in 2006 (Privately held)	(Privately held)	Founded in Germany, present in US and Ireland	High-end products and tailor-made complete solutions for all aspects of sound recording, transmission and reproduction
Shure	(Privately held, 2,000 employees)	(Privately held)	US, Germany, Hong Kong	Produces audio equipment for stage, studio, and personal use including microphones, wireless systems, digital signal processing, monitor systems and portable audio electronics
Sony	£31b in 2007 (electronics division)	£790m in 2007 (electronics division)	Founded in Japan, global presence inc. UK	Global manufacturer of audio, video, communications and information technology products for consumer and professional markets
Telex	£1b in 2006 (Bosch Security Systems total)	n/a	US (part of Bosch)	Leading manufacturer of dependable, top-of-the-line communication equipment for industries including the aviation industry
Trantec	£3.5m in 2006 (Privately held)	-£184k in 2005	UK	Manufacture digital and analogue wireless systems; as well as selling under own brand, also act as OEM to leading German brand
Zaxcom	£453k (Privately held)	(Privately held)	US	Designs and manufactures professional audio equipment for the television and film industries

PMSE equipment manufacturers and product ranges

The typical wireless audio portfolio contains a variety of equipment; receiver units, bodypack transmitters, handheld transmitters, talkback systems, personal monitors, in-ear monitors (IEM), channels mixers, and so on. Equipment is either sold standalone, or as part of a bundle that provides sufficient equipment to set up a functioning wireless audio system.

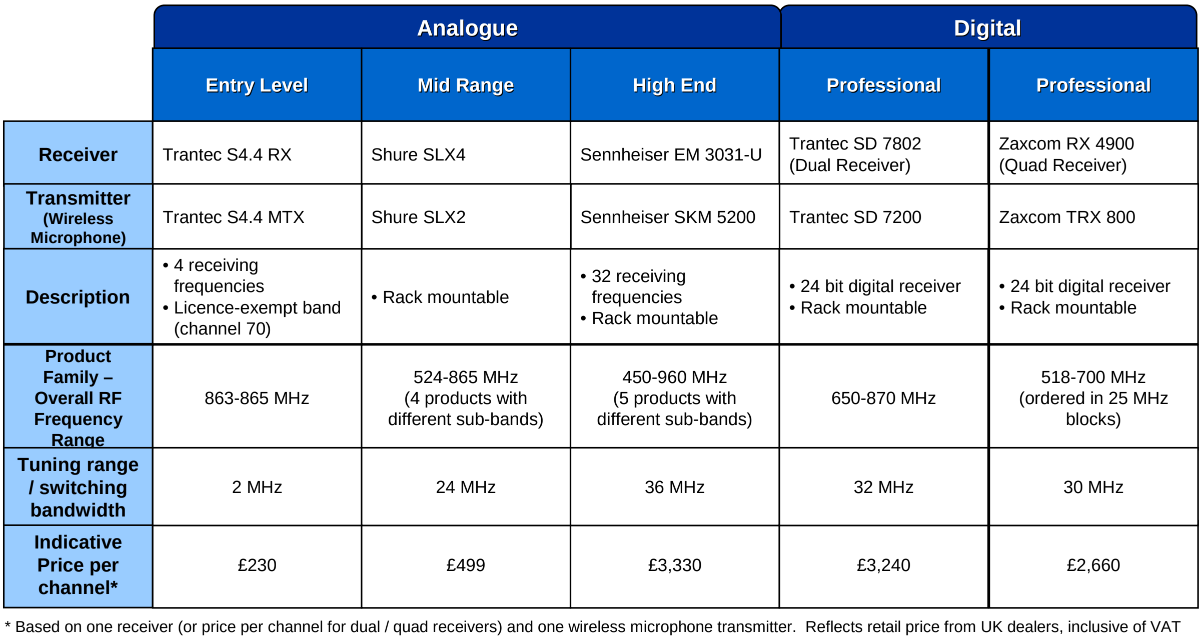
PMSE equipment varies in price and features, reflecting the diverse set of users of this equipment. The following chart provides a few examples of PMSE equipment. A typical system will consist of a receiver and a transmitter (either in the form of a wireless microphone or a bodypack transmitter connected to a microphone). Given that a production or event of any reasonable size will need multiple systems, banks of receivers are typically rack-mounted on specially-made chasses.

Basic receivers are likely to include only a few selectable frequencies; some equipment uses licence-exempt spectrum. Moving up the product range, there tends to be features such as greater frequency coverage, rack mountable units, and at the top end network connectivity.

It is difficult to compare the prices of analogue and digital wireless microphone systems due to varying feature sets and products being developed for specific usage scenarios. In general, digital systems are as expensive as high-end analogue equipment. Indeed, a number of stakeholders we interviewed indicated that digital systems are more expensive than comparable analogue systems.

It is important to distinguish between product family overall RF frequency range, which is typically specified by manufactures, and actual tuning range (or switching bandwidth).

Further details on product lines can be found in the appendix.



	Analogue			Digital	
	Entry Level	**Mid Range**	**High End**	**Professional**	**Professional**
Receiver	Trantec S4.4 RX	Shure SLX4	Sennheiser EM 3031-U	Trantec SD 7802 (Dual Receiver)	Zaxcom RX 4900 (Quad Receiver)
Transmitter (Wireless Microphone)	Trantec S4.4 MTX	Shure SLX2	Sennheiser SKM 5200	Trantec SD 7200	Zaxcom TRX 800
Description	• 4 receiving frequencies • Licence-exempt band (channel 70)	• Rack mountable	• 32 receiving frequencies • Rack mountable	• 24 bit digital receiver • Rack mountable	• 24 bit digital receiver • Rack mountable
Product Family – Overall RF Frequency Range	863-865 MHz	524-865 MHz (4 products with different sub-bands)	450-960 MHz (5 products with different sub-bands)	650-870 MHz	518-700 MHz (ordered in 25 MHz blocks)
Tuning range / switching bandwidth	2 MHz	24 MHz	36 MHz	32 MHz	30 MHz
Indicative Price per channel*	£230	£499	£3,330	£3,240	£2,660

* Based on one receiver (or price per channel for dual / quad receivers) and one wireless microphone transmitter. Reflects retail price from UK dealers, inclusive of VAT

Example PMSE Equipment

1.4.1 Wide tuning range receiver

Wireless microphone receivers employ narrowband filters at the front end to select the wanted frequencies within the receiver's bandwidth. Narrowband filters facilitate signal selectivity to a high degree so that unwanted signals can be prevented from entering the audio system.

Receivers for high-end applications tend to be designed for wide bandwidth operation, and are expensive. It is important to note that a receiver cannot be retuned during a performance. Most receivers have a tuning range of 24-36 MHz. Sennheiser's EM3731 receiver unit, available for £3,872, can be tuned across a bandwidth of 90 MHz. Six selectable fixed frequency banks are available within the receiver between the frequency range 450 – 960 MHz. Lectrosonics has recently developed a wideband tuner (VRM WB) that can tune across 537 – 768 MHz (230 MHz). Although this wideband receiver can be used for high-end applications, in highly congested RF environments, a receiver with such a wide front-end may be more likely to pick up interference than a receiver with a narrow front-end. The West End of London would be an example of a congested RF environment.

1.4.2 Recent equipment developments

Digital has been one area of recent development for manufacturers. Trantec and Zaxcom offer digital wireless microphone systems. Sony recently launched a digital wireless microphone system (DWR/DWT) for ENG (electronic news gathering) and EFP (electronic field production). Sony's digital DWR/DWT series operates in UHF spectrum and utilises licence-exempt spectrum at 2.4 GHz for wireless control of multi-channel system management. It is designed for use with Sony's PDW HD camera for ENG and EFP. As noted above, many HD cameras can embed the audio stream (whether analogue or digital) into the digital video stream for transmission.

Talkback systems are also being developed using digital technology. As an example, Digital Talkback sells a system that uses DECT standards and operates in licence-exempt spectrum at 1.88-1.9 GHz.

Hybrid systems, such as the Lectrosonics Digital Hybrid Wireless system, combine digital and analogue elements to maximise wireless system performance. The system combines *digital* signal processing with *analogue* FM transmission. Therefore, the system will have the same characteristics of any other wireless FM system.

Some manufacturers are developing and producing products outside of the typical spectrum bands used for wireless microphones. Sabine's SWM7000 Series Smart Spectrum Wireless System operates in the 2.4 GHz industrial, scientific and medical (ISM) band and claims it can provide up to 70 channels for simultaneous multi-channel deployments. The 2.4 GHz band is licence-exempt because it is restricted to low power applications, therefore it inherently minimises the chances of high power interference. However, this band is used by Wi-Fi, microwave ovens, cordless phones, lighting systems and several other applications that meet the requirements for licence-exempt operation. The range of existing applications in the 2.4 GHz band means it is heavily congested and, due to the likelihood of inference, professional users are highly unlikely to use equipment designed to operate in this spectrum. Audio quality, reliable operation and the ability to use all 70 channels simultaneously is therefore not guaranteed, a critical drawback for many wireless microphone users. To that end, the market for Sabine's system consists mostly of prosumer/non-professional users. To date, Sabine is understood to be the only manufacturer that produces PMSE equipment for 2.4 GHz.

Audio Technica's SpectraPulse system utilises ultra wideband technology for conference/boardroom environments in the US. The technology uses a series of short nano-second pulses which occupy an instantaneous bandwidth of 500 MHz within the 6 GHz frequency spectrum. Since UWB is a digital modulation scheme, it can provide encryption. It also has licence-exempt operation. The technology is currently limited due to its short range and relatively low audio quality.

The following chart summarises recent technology developments by manufacturer. It is important to note that Sennheiser and Shure, generally considered by many of the stakeholders interviewed to be the leading equipment manufacturers for equipment used by high-end professional users, do not currently produce digital equipment.

Whilst doing R&D in digital, they do not consider digital to offer sufficient performance and commercial advantages, relative to analogue, for high-end users.

PMSE equipment manufacturer	Technologies			Use of Emerging Technology
	Analogue	Hybrid	Digital	
AKG	✓			Fifty year history of innovation in high-end audio
Audio Ltd	✓			Emphasis on audio for studio, theatre, conferencing, location, documentary and ENG
Audio-Technica	✓			Offers a UWB wireless microphone for boardroom conferencing systems
beyerdynamic	✓		✓	Offers digital wireless conferencing systems
Lectrosonics	✓	✓	✓	Developing proprietary technology such as Digital Hybrid Wireless
Sennheiser	✓			Long history of innovation in high-end audio, but reservations about digital technology at present
Shure	✓			Long history of innovation in high-end audio, but reservations about digital technology at present
Sony	✓		✓	Introduced a range of digital wireless microphones in October 2007; strength in ENG / EFP applications
Telex	✓		✓	Digital encryption, spread spectrum transmission
Trantec	✓		✓	Sell under own brand but also OEM
Zaxcom			✓	Frequency agile devices and digital modulation

PMSE equipment manufacturers – recent technology developments

A key planning assumption for PMSE equipment manufacturers is that spectrum will become increasingly scarce, while end user demand will continue to increase. To address these factors, manufacturers are looking to develop the technologies discussed above as well as new technologies. Further details follow.

2. Current and emerging developments for wireless microphone technology

We consulted with industry experts, spoke with manufacturers, and conducted research to understand current and emerging developments in wireless microphone technology. These provided inputs for and helped to validate straw-man models, which are covered later in this report.

2.1 Digital technology

Digital transmission systems are relatively new to the PMSE sector. Although advances in digital technology have resulted in significant performance improvements in most areas of communications, we were told by most UK based interviewees that the needs of the PMSE industry are such that digital technology currently has limited scope to provide significant improvements in spectral performance.

However, we note that according to Sony, "The advantage of undesired signal tolerability of digital systems brings about a great improvement in simultaneous multi-channel operation. For analogue systems it is necessary to skip unusable channels where inter-modulation occurs. In contrast, by combining the digital modulation system with an excellent RF circuit, even the inter-modulation channels can be allocated as usable channels." Further evidence is required about the extent to which digital systems are being used in multi-channel operation in high-end professional usage scenarios, issues encountered and how much spectrum was used.

In order to be as spectrally efficient, digital transmission requires compression since an uncompressed digital signal requires more bandwidth compared to an analogue signal. However, compression introduces latency (delay) into transmission, a critical issue given the audio / performer lip synchronisation required for most PMSE users.

The following chart provides a representative sample of latency tolerances for PMSE (using professional theatre as an example) relative to digitised speech applications:

Speech application	Latency (one way)
Professional theatre	Less than 2ms
Digital television	300 ms – 1.4s
Mobile to mobile voice	100 – 150ms
Voice Over IP (VoIP)	Less than 150ms

Sources and notes:

Professional theatre: for transmitter to receiver (ETSI TR 201 546, Technical characteristics for Professional Wireless Microphone Systems, SRD, Feb 2007)
Digital Television: Varies by encoding technology (Fujitsu)
Mobile to mobile voice: Communications Technology
VoIP: ITU

Digital wireless microphone technology provides a number of benefits for PMSE users:

- *Multi-channel operation* – when operating in contiguous UHF channels, digital systems enable more transmitters to be deployed compared to analogue systems. This is because digital systems are less susceptible to the effects of intermodulation distortion. Also, the wider frequency of operation of digital systems allows full use of their switching capability, enabling the same type of transmitter to be used on different channels. It must be noted that this multi-channel advantage of digital systems can only be optimised when contiguous UHF channels are available.

- *Intermodulation Products* – digital wireless microphone systems have an advantage over analogue systems in that they can tolerate a certain level of interference from intermodulation distortion products. This advantage stems from the fact that intermodulation products, where they occur, have lower signal strength than the desired frequencies. If this difference is sufficiently low, generally digital systems will be capable of extracting the wanted signal without difficulty.
- *Forward error correction (FEC)* – this is a method of error control coding (also known as channel coding) whereby the transmitter adds redundant data to the digital bit-stream to enable the receiver to detect, and often correct, data received in error without the need for re-transmissions. This technique enables digital transmission to be more robust due to the inclusion of additional bits in the data stream designed to allow the receiver to reconstruct corrupted data without the need for re-transmission. However, the use of this technology does result in a slight increase in latency.
- *Encryption* – digital encryption can be used to secure data and prevent eavesdropping. In usage scenarios such as boardrooms, this is an important consideration.
- *Supports HD* – HD audio is another potential development, particularly at the high-end of the market. It is understood that Sony has conducted detailed analysis of HD audio at its research centres in Japan. The fundamental problem it poses is the significantly higher bandwidth requirements for transmitting real-time HD-quality audio signals, and it is possible that this might be as high as 1.2 MHz for a single HD audio channel. AKG offers wireless systems which feature High Definition Audio Performance (HDAP) technology, intended to ensure the best possible sound quality.
- *Dynamic range and frequency response* – for both of these parameters, digital can match capabilities of analogue systems.
- *Capture effect* – the capture effect refers to the ability of a receiver to recover the desired signal when two or more carrier signals with unequal strength are present. According to Sony, digital wireless microphone systems typically require a wanted to unwanted signal ratio of 20 dB, whereas analogue systems require 40 dB.

However, digital technology also has limitations with respect to the PMSE sector.

- *Latency* – the latency problem of digital wireless microphones is a significant drawback in terms of PMSE adoption. For live performances, the transmitter to receiver transmission must be virtually instantaneous. ETSI Technical Committee Electromagnetic Committee and Radio Spectrum Matters (ERM) recommends the delay should be less than 2ms[9]. These stringent measures are to ensure synchronisation between audio output and the lips of performers. Significant delays can materially degrade the quality of the overall performance as well as being unsettling for both the audience and those performers relying on IEMs for checking their own audio output. According to interviewees based in the UK digital wireless microphones have a delay of 3–8ms when the signal is compressed. Sony claim to achieve a latency of 3.6 ms using their proprietary CODEC.
- *Drop-out characteristics* – a potential issue for digital wireless microphones is the so-called "cliff effect". This occurs when a digital wireless microphone transmitter moves out of range of the receiver and, without any indication, the signal is lost and the system is then driven by noise, which is undesirable as it would be audible over the speakers. In contrast, when an analogue microphone moves out of range of its receiver it is possible to detect this in the audio output due to its gradual degradation. This provides sufficient indication to enable remedial action to be taken. A digital wireless microphone receiver could be equipped with telemetry to provide an indication of signal strength using a wireless link on a separate frequency. However, this may not be enough to remedy their relatively poor drop-out characteristics. This is because the audio system will produce an acceptable output as long as reception from the digital wireless transmitter is good. But, as soon as interference causes the bit error rate (measure of the number of bits received in error relative to the total number of bits received in a transmission) to fall below the minimum signal threshold, it leads to a precipitous drop-out whose occurrence could not have been indicated in the audio output. We note that it should be possible for users of digital wireless microphone equipment to conduct tests before using the equipment for a live performance to ensure that the system was not on the limit of its working range.
- *Power consumption* – higher than analogue due to extra processing (digital signal processors (DSPs) and digital to analogue converters). Powerful processors are necessary in order to minimise latency but this is at the expense of increased power consumption. This is due to the extensive signal processing which takes place in order to satisfy the demand for real-time signal transmission.

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[9] Electromagnetic compatibility and Radio spectrum Matters (ERM); Technical characteristics for Professional Wireless Microphone Systems (PWMS); System Reference Document

- *Costs* – It is difficult to compare the prices of analogue and digital wireless microphone systems due to varying feature sets and products being developed for specific usage scenarios. In general, digital systems are as expensive as high-end analogue equipment. Indeed, a number of stakeholders we interviewed indicated that digital systems are more expensive than comparable analogue systems. The PMSE industry is small in scale compared to other sectors of the communications industry. As a result, it has to design its own integrated circuits, which is an expensive process, and the small scale limits the industry's ability to take advantage of the economies of scale provided by embedding these integrated circuits in a large number of manufactured products.

2.1.1 Spectral efficiency - transmitting a single digital wireless microphone channel

Spectral efficiency is complicated in terms of digital transmission technology. The following explains the factors involved.

The transmission bandwidth of an analogue wireless microphone transmitter is typically 125 – 140 kHz (using 200 kHz channel spacing) whereas a digital system typically transmits in a radio frequency bandwidth of 200 kHz. The bandwidth required for digital and analogue systems are therefore broadly similar since both systems require a 200 kHz frequency allocation.

The bandwidth required for transmitting a digital wireless audio signal depends on the data rate and modulation scheme. Pulse code modulation (PCM) is a commonly used digital modulating scheme for transmitting digitised analogue signals. It involves sampling the magnitude of the analogue signal regularly at uniform intervals, representing it as a digital value and finally encoding it into a digital data stream. The data rate is simply a product of the sample size (number of bits used to represent the digital value) and the sampling frequency.

Therefore, if an audio signal with 16-bit resolution is sampled at a frequency of 44 kHz (CD quality, but it must be noted that the compression employed on audio CDs cannot be used in PMSE applications due to the effects of delay) the data rate is 16 × 44 = 704 kbps. This raw, uncompressed data requires the addition of 50%–300% extra data for forward error correction (FEC) and synchronisation[10]. Even taking the best case of 50% forward error correction provides a transmission data rate of 1056 kbps (1.5 × 704).

This data rate has to be transmitted in a bandwidth determined by the modulation scheme employed. Digital modulation schemes such as Gaussian Minimum Shift Keying (GMSK) and Quadrature Phase Shift Keying (QPSK) can reduce the bandwidth required by between 1.24 – 1.66 bps/Hz. For the above data rate of 1056 kbps, this translates to an RF bandwidth of between 636 kHz (using GMSK) and 852 kHz (using QPSK). By contrast, a frequency modulated analogue signal occupies an RF transmission bandwidth of only 140 kHz on a channel spacing of 200 kHz.

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[10] Plextek, 25th April 2008

Therefore a simple, raw digital transmission suffers from poor spectrum efficiency relative to analogue.

Audio data compression can be used to improve the transmission bandwidth of the simple digital system described in the above example. Adaptive Differential Pulse Code Modulation (ADPCM) is an efficient compression technique for data reduction, particularly for low-latency applications such as PMSE. It is a predictive algorithm in which only the *difference* between digital audio samples and estimates that have been made of the samples are recorded. Depending on the accuracy of the predictions, there will only be small differences between the real and estimated samples. This means that fewer bits will be required to represent these samples compared to the original digital audio signals, therefore standard, low cost hardware could be used for implementation. At the decoder the recorded difference signals are added to the predicted signals to provide the reconstructed audio signals.

ADPCM has the advantage of low latency, as required for wireless microphone applications. In practice, to maintain an acceptable audio quality, the minimum ADPCM word length needs to be on average around 4 bits per sample[11].

Assuming ADPCM has been applied to the above example, the parameters become:

- ADPCM sample size: 4 bits (instead of 16 bits uncompressed)
- Sampling frequency: 44 kHz
- Minimum FEC overhead: 50%

Therefore the raw data rate = 4 bits × 44 kHz = 176 kbps

With 50% FEC overhead = 176 kbps × 1.5 = 264 kbps

Using GMSK modulation (1.24bps/Hz) = 264/1.24 = **213 kHz** digital transmission bandwidth

Using QPSK modulation (1.66bps/Hz) = 264/1.66 = **159 kHz** digital transmission bandwidth

High order modulation could improve digital spectrum efficiency. However, higher order schemes are more subject to interference and corruption, and require more error correction overhead, so there is a compromise required for optimum overall performance and efficiency. A modulation technique such as 16QAM provides a bandwidth efficiency of 3.18bps/Hz. However, the overhead will reduce the theoretical gains in efficiency. In addition, the transmitter topology becomes considerably more complex and power hungry, reducing power consumption and increasing size. This is not compatible with small battery powered portable equipment.

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[11] Plextek, 25th April 2008

2.1.2 Spectral efficiency - transmitting multiple digital wireless microphone channels

Digital equipment manufacturers claim that, for an isolated 8 MHz UHF TV channel, digital wireless microphones systems can accommodate 10-16 transmitters (compared to a typical range of 8-12 for analogue systems). This is because it is possible to deploy digital wireless microphones at frequencies where intermodulation products occur due to their ability to tolerate a certain level of interference. As long as the signal-to-noise ratio is at an acceptable level which enables the wanted signal to be recovered, a digital wireless transmitter can be deployed at the frequencies where intermodulation occurs. These frequencies are normally avoided by analogue wireless transmitters, thus enabling a digital system to gain one or two more extra channels of operation in an 8 MHz TV channel. This improvement in spectral efficiency may be at the expense of audio quality and latency (due to compression).

Some digital wireless microphone systems are currently being used in professional applications. It is understood from JFMG data that one West End production using digital equipment in a theatrical show employs 32 digital wireless transmitters using a total of 40 MHz of spectrum.

The chart shows the key performance characteristics of typical analogue and digital wireless microphone systems.

	Parameter	Analogue Wireless Microphones Systems	Current Digital Wireless Microphones Systems
Favours Current Digital Wireless Microphones	Forward error correction	• Not possible	• Possible
	Encryption	• Not possible	• Possible
	Tuning Range	• 24 MHz (3 UHF TV channels)	• 48 MHz (6 UHF TV channels)
	Capture Effect	• Typically require a wanted to unwanted ratio of 40 dB	• Typically require a wanted to unwanted ratio of 20 dB
	Intermodulation Distortion	• Susceptible to intermodulation products	• More immune to intermodulation products
	Supports HD	• No	• Yes
Favours Analogue Wireless Microphones	**Latency (Delay) – Transmitter to receiver**	• Virtually instantaneous	• 3 – 8ms (depending on compression algorithm)
	Power consumption	• Low • Minimal signal conditioning required	• Moderate – due to digital signal processing • Power hungry digital signal processors (DSPs), analogue to digital converters and vice-versa
	Drop-out characteristics	• Signal degrades gradually • Discernible through audio output	• “Cliff Effect” – signal can degrade abruptly
	Cost	• £500 – £3,000 per channel	• Approximately £3,000 per channel
Spectrum Efficiency	Transmission bandwidth	• 125 – 140 kHz (200 kHz channel spacing)	• 125 – 200 kHz
	Transmitters in a single UHF TV channel	• 8 – 12	• 10 – 16 (depending on audio quality and compression) • Actual deployment efficiency may be less
	Multi-channel capability	• Up to 80 – 100 microphones for West End theatres and large, one-off events	• Uncertain, up to 45 reported (US) • Depends on availability of adjacent UHF TV channels

Comparison of key parameters of analogue and digital wireless microphones

2.1.3 Receiver Covering 470–790 MHz

The new pattern of interleaving post-digital switchover makes tuneability more important for many PMSE users who will need to access a wider set of frequencies in order to access enough spectrum for their needs. A potential solution would be a receiver with a switching bandwidth covering the whole of the interleaved spectrum from 470 – 790 MHz. A key limiting factor on the performance of a wideband receiver is the impact of noise, irrespective of analogue or digital technology.

Receiver selectivity is critical in wireless microphone applications, given the low output power of the transmitters.

Designing a wide bandwidth filter to cover the whole of the interleaved spectrum is theoretically possible. However, according to UK-based interviewees, it would be expensive to manufacture and need to take into account a number of technical challenges:

- A receiver employing a filter with an RF bandwidth of approximately 320 MHz would effectively have no selectivity. This would allow interference from digital TV transmissions to enter the receiver; tracking filters could be used to overcome this problem but it would make receivers highly expensive
- Such a wide bandwidth front-end would also leave the receiver susceptible to blocking and the generation of internal intermodulation products due to the high power (TV) emissions over-driving the input. Blocking is where a strong signal over-drives a circuit so that it cannot register any weaker signal on any frequency the receiver is capable of picking up. The difference in power levels between a DTV transmission (several Watts) and a wireless microphone (maximum 50mW) means the former is likely to overwhelm a receiver front-end designed to receive the latter
- Problems arising from intermodulation products could become much worse due to the number of signals entering the receiver
- Such interference would have a debilitating effect on the performance of such a wideband receiver, irrespective of whether it is analogue or digital. An interfering signal would lead to an analogue receiver producing an output with reduced audio quality whereas a digital receiver will suffer a reduction in its operating range. In both cases the impact will be degradation in the overall system performance. It is difficult to estimate the extent of this degradation, not least because a receiver with a bandwidth of 320 MHz does not yet exist and other factors, such as the harshness of the RF environment in which the receiver is deployed, need to be taken into account.
- In congested RF environments where multi-channel systems are deployed, a receiver with a wide front-end may not yield as good a performance as a narrow-band receiver. Given transmitters have limited operating range, better selectivity, and thus performance, can be achieved with narrow-band receivers

Essentially, a greater switching bandwidth provides versatility but it compromises selectivity. This is because wireless microphone receivers employ narrowband filters at the front end to select the wanted frequencies within the receiver’s bandwidth. Narrowband filters facilitate signal selectivity to a high degree so that unwanted signals can be prevented from entering the audio system.

However, we do note that a number of manufacturers produce pen sized analogue and digital TV receivers that connect to and are powered from the USB port of a personal computer or laptop computer. Whilst we acknowledge that these devices are TV receivers rather than wireless microphone receivers, these manufacturers do appear to have overcome many of the issues and challenges highlighted above. However, TV broadcasts have significantly higher transmission energy than wireless microphone signals and the receiver is tuned only to a single channel at a time. In contrast, wireless microphone receivers are designed to receive relatively weak, multiple, simultaneous transmissions.

2.1.4 Summary

Professional quality analogue microphones have been established for over half a century, reaching a point where they have become widely affordable, reliable and, most importantly, can satisfy the demand for high quality, real-time audio performance within the constraints of the ITU stipulated channel spacing of 200 kHz.

In contrast, digital wireless microphone technology is relatively new. Nevertheless, evidence suggests that these devices are already being used in professional production and theatre environments. Whereas analogue technology is now mature, improvements in processing power and power consumption efficiency, coupled with advances in compression algorithms, are expected to further improve digital wireless microphone capabilities over the next 5+ years.

Whether digital devices will see widespread adoption remains to be seen, but in principle a receiver with a tuning range covering the whole of the interleaved spectrum would alleviate the difficulties current PMSE equipment would have in accessing these frequencies post-DSO. Improvements in spectral efficiency would also help to alleviate any capacity complaints.

If digital PMSE equipment can achieve the right combination of tuning range, price, performance *and* spectral efficiency, then the use of digital technology is likely to become increasingly common.

2.2 Other wireless microphone technology developments

2.2.1 Frequency Hopping Spread Spectrum

The term Spread Spectrum describes a class of modulation techniques characterised by its wide frequency spectra – the bandwidth of the transmitted signal is much greater than the bandwidth of the original information signal. It is a digital technique which is used for data transmission.

Frequency Hopping Spread Spectrum (FHSS) technology is at the concept stage and may be a future technology for wireless microphones. It utilises a pseudorandom sequence or code, known to both transmitter and receiver, to transmit signals by periodically switching a carrier signal among a large number of frequencies. The pseudorandom sequence causes the transmitter to jump or hop to a new frequency, transmit information on that frequency for a predefined period of time, then hop to the next frequency and repeat the process. As a result, the original information is distributed over a wide range of frequencies. In other words the spectrum is “spread”, resulting in a wideband signal with very low power spectral density (energy per Hz of frequency) which imbues it with noise-like properties. This means they are unlikely to interfere with other signals, even those using the same frequencies, a significant advantage in relation to spectrum efficiency. Other advantages of Spread Spectrum systems are discussed below.

Bluetooth is an example of a commercially available frequency hopping technology.

The receiver has the task of collecting the spread of frequencies onto its original frequency. One of the challenges of these systems is to synchronise the transmitter and receiver, which must hop to the same frequencies as the transmitter in order to recover the transmitted information. Therefore, the pseudorandom sequence and some synchronisation algorithm must be known at the receiver end of the communications channel. This technology requires duplex communications because the receiver must be able to communicate with the transmitters in order to co-ordinate the hopping pattern. As a result Frequency Hopping Spread Spectrum systems may need additional spectrum.

Spread spectrum systems offer a number of advantages, including the following:

- Signals are hard to detect because of their noise-like properties.
- It is harder to jam or interfere with Spread Spectrum systems because the energy of an interfering signal is spread over a wide band, causing it to become part of the background noise.
- Frequencies can be shared with other services with minimal interference due to the low power spectral density of the Spread Spectrum signals. Also, Spread Spectrum systems are unlikely to be interfered with because the receiver will only demodulate signals matching its pseudorandom code.

The first two advantages are mainly relevant to applications where security is a priority, such as military systems, where Spread Spectrum technology originated. The third advantage listed above is the most relevant to wireless microphone applications. The ability to share spectrum using frequency hopping systems provides a potentially powerful technique to utilise spectrum more efficiently. It may enable more wireless microphone transmitters to be operated in a given block of spectrum and facilitate the simultaneous use of several multi-channel systems. According to UK based interviewees, although Frequency Hopping Spread Spectrum systems for wireless microphone applications could be technically viable, developments are only at the research stage. Commercial systems may not be available for the medium or even long term. Additional issues include the time needed for the hopping process and a means of determining the quality of the next channel before hopping to it.

2.2.2 Ultra wideband

Ultra wideband (UWB) is a wireless digital modulation technology which operates in licence-exempt spectrum. It is used for transmitting large quantities of data over a wide bandwidth across short distances. It uses very short, precisely timed pulses, and the narrow pulses leads to the wide bandwidth. In turn this means the power of the UWB signal is spread over such a large frequency range that, on any given frequency band that may already be in use, the UWB signal has a much smaller power spectral density than the majority of existing communications signal and background noise present in the band. This means that UWB signals do not cause interference to other users of the band. As a consequence, equipment using UWB technology is licence-exempt in the EU.

UWB is inherently a short-range technology due to the need to minimise interference. Its range is limited to less than 10 metres due to its low power. It is unlikely that regulatory authorities will permit an increase in transmission power to reach the 100m minimum range required for PMSE applications, since this would increase noise over a wide spectrum band.

The most well-known UWB product for audio applications is Audio Technica’s SpectraPulse system. It is available in the US where the FCC has authorised a large band between 3.1–10.6 GHz for unlicensed UWB use. The 14-channel SpectraPulse system operates in a bandwidth of 500 MHz and is used for boardroom conferencing applications.

It can be argued that the spectral efficiency of Audio Technica’s SpectraPulse is low, since only 14 channels are available in a bandwidth of 500 MHz, although this spectrum is shared with other services. It also suffers from four significant drawbacks which render it unsuitable for most wireless microphone usage scenarios

- Firstly, it cannot support more than two systems running in the same spectrum in the same location
- Secondly, it operates under licence-exemption and will therefore lack the reliability required by many professional wireless microphone users
- Thirdly, its range of approximately 23m is too low to satisfy the needs of most PMSE users
- Finally, the limited frequency response (100 Hz to 12 kHz) means audio quality will be inadequate for most professional use

The 12 kHz upper frequency limit is dictated by the overall data throughput of the entire system, which is fixed at 8 Mbps for a total of 14 channels, and is a function of several system parameters; including number of channels in the system, audio bandwidth; data sample size (resolution), and forward error correction overhead. If the audio bandwidth is doubled approximately from 12 kHz to 20 kHz (the typical upper frequency limit for professional wireless microphone systems) the data rate per channel will be doubled. However, the total system data rate for all 14 channels is fixed; therefore this increase in the upper frequency response can only be accommodated by reducing the number of channels or the sample size. It must be noted, however, that there is no fundamental restriction on audio bandwidth from using UWB and the limited frequency response of the SpectraPulse system is purely a design compromise imposed by the manufacturer, Audio Technica.

UWB audio systems are not currently practical for many PMSE applications, and so they are not a substitute for existing wireless microphones. Currently available products cannot provide the required audio quality, reliability and range. However, improvements in UWB technology for other sectors of the communications industry could benefit the PMSE sector. It could make wireless microphone systems based on UWB technology feasible for PMSE, but this would require significant advances in R&D work on current UWB limitations. It is difficult to predict when such developments could occur and whether they would lead to affordable, commercially available wireless microphone equipment.

2.2.3 Cognitive Radio

Cognitive radio (CR) is a new technology and as such has diverse definitions. For the purposes of this study it is defined as an intelligent radio which can sense its environment and location and then alter its power, frequency, modulation and other parameters so as to dynamically reuse available spectrum. It employs adaptive software to enable it to reconfigure its communications functions to meet the demands of the transmission network or the user. Conceptually, it should be more efficient in spectrum use than any other system. This is because searching for, then using, any available channels among an unlimited number of channels is better than the dedicated approach of pre-determining the number of useable frequencies within specific bands. It must be borne in mind, however, that the technology is still at the R & D stage and some years away from commercial reality.

Solutions need to be found for a number of performance issues such as:

- Delay (latency) – this arises from the need for a cognitive device to spend time checking the spectrum it is using is still vacant
- Reliability – a cognitive radio device must allow other cognitive devices to share access to its channel, therefore reliability is not guaranteed
- Enabling multiple cognitive radios operating in the same area to detect each other

Delay and reliability could be problematic in cognitive systems. This is because a large number of wireless microphones are likely to be in use at the same time (over 30 in a theatre production, for instance) and each one will need time to determine whether the channel it is using is still vacant. If the channel is occupied and the cognitive device needs to change to another frequency, doing so for over 30 wireless microphones during a live theatre or concert production would be unacceptable.

Cognitive radio suffers from hidden node problems which could hamper its effectiveness. Hidden nodes occur when the cognitive radio device cannot sense the transmissions of other wireless nodes or devices operating in the same area. As a result it intermittently causes interference to them. Additionally, in theory a cognitive device would need to possess diversity reception in order to reliably detect whether a frequency is in use. This need arises from the physics of realistic UHF signal propagation but, given the hidden node problems highlighted, these two issues are potentially intractable since hidden nodes will prevent reliable signal reception. In turn, this would make it difficult to determine if a frequency is in use.

The development of cognitive radio devices is at an early stage, and feedback on tests conducted on prototypes in the US has neither proved the claims of proponents nor disproved the concerns of objectors. The viability of cognitive radio technology for PMSE depends significantly on improvements in processing power and the cost of commercial systems, and is very much a long-term solution. A major manufacturer we interviewed claimed that it could take at least five years for a prototype device to emerge and another 5–10 years for a real product targeted at the general end-user. Therefore cognitive radio experts would require a minimum of 10 years to develop the technology, then to align it to the needs of the PMSE industry – in terms of audio quality – could take another 10 years. It is difficult to predict developments this far into the future but, even if technological barriers were surmounted, cognitive radio devices aimed at the PMSE industry may lack the sophistication the technology promises because they have to be relatively cheap.

In the US, the use of cognitive devices operating in the white space gaps left between DTV channels have been proposed by a coalition including Google, Microsoft, HP, Dell, Intel, and Philips. White Space Device (WSD) is the generic name for these mobile broadband devices being proposed. The National Association of Broadcasters (NAB) is concerned that WSDs will interfere with the DTV transmissions or its members, and PMSE users are also concerned that their wireless microphone and talkback operation will be disrupted. Both stakeholders claim the cognitive abilities (listening and sensing) of the WSDs are not wholly proven and it is not easy to detect usage within the white spaces. Spectrum Sensing is a simplified version of cognitive radio which manufacturers plan to employ in WSDs.

2.2.4 Software Defined Radio (SDR)

The underlying concept of software defined radio (SDR) is the provision of software control of radio functionality. It refers to the use of software programmable hardware to synthesise traditional, hardware-based radio solutions. The technology is characterised by an inherent flexibility since, fundamentally, software defines the radio functionality. Simply modifying or replacing the software embedded in the radio defines the parameters under which it operates in real-time as the user moves from place to place. This enables the needs of a wide range of applications to be accommodated. Although SDR offers a significant degree of flexibility in terms of tuning, it may not necessarily use spectrum more efficiently compared to current PMSE equipment. This is because the digitally synthesised waveforms have to be converted to analogue for transmission, therefore the bandwidth requirements necessary for high quality audio systems will be similar to those of analogue systems. SDR is in its infancy and could prove to be very expensive.

Manufacturers we interviewed are not focused on software defined radio (SDR) as a feasible next-generation technology for wireless microphone equipment. The technology itself may not necessarily produce more efficient use of spectrum compared to current analogue systems, since it is largely a means of attaining flexibility in the choice of modulation scheme and useable channels, and transmission robustness. Appreciable bandwidth will still be required for transmission. Also, the scale of the PMSE industry limits investment in new technology which requires significant R&D investment. However, they are monitoring SDR research and development efforts at universities, other sectors of the communications industry, and military institutions.

2.2.5 Antenna Technology

In the future the wireless microphone industry may be able to take advantage of developments in antenna technology for other applications such as mobile communications and wireless area networks (WLANs). This might enable spectrum in the GHz range to be used for wireless microphone applications because issues such as the requirement for line-of-sight transmission and drop-out problems caused by multi-path cancellation may become less onerous. These developments are focused on adaptive or smart antenna technology such as multiple input, multiple output (MIMO). In general, adaptive antennae provide improvements over conventional antennas by actively adjusting for the radio frequency environment at any given time in order to increase signal strength and quality.

MIMO antennae, for instance, achieve the aforementioned improvements by employing multiple antennae at the transmitter and receiver, in addition to complex control algorithms for processing and monitoring signals and the radio frequency environment. The antennae at each end of the communications link are then combined to improve signal strength, range and quality (by overcoming line-of-sight requirements and signal degradation caused by multi-path cancellation), as well as data rate. It must be noted, however, that these benefits are heavily dependent upon the environment in which a smart antenna is used. Harsh radio frequency environments containing multiple signal sources could provide sufficient interference to undermine the advantages provided by adaptive antennae. Furthermore, adaptive antennae could prove to be extremely expensive, particularly if implemented on wireless microphone *receivers* as well as *transmitters*, although it is highly unlikely with the latter.

2.2.6 Summary

Amongst other wireless microphone technologies, UWB is potentially a key technology for development focus. However, significant advances need to be made in processing power, component costs and audio quality.

UWB will only be viable for the PMSE industry if the current limitations in audio quality and range are overcome. This is a fundamental requirement for many wireless microphone applications which current UWB technology cannot satisfy. These improvements may not become available until well into the medium term.

3. International developments and experiences

The debate on how to balance the needs of PMSE users against those of other spectrum users is also occurring in many other countries. PMSE equipment is developed for multiple markets due to the relatively low scale of the industry. Therefore it is critical for developments in the UK to take into account general developments in other markets so that UK users have access to appropriate equipment and at the lowest prices possible. It is highly unlikely that any manufacturer will have appropriate economic incentives to develop solutions that require customisation – rather than adaptation – for the UK market.

The transition from analogue TV transmission to digital television (DTV) is a common in many markets worldwide, and has raised the same questions about reallocation of the "digital dividend" spectrum freed as a result. In addition to the primary needs of the DTV broadcasters, many other applications are vying for spectrum including PMSE, mobile TV, HDTV and mobile broadband. Many countries are in the process of establishing guidelines on the allocation of this spectrum, or even designing and performing the spectrum auctions that will establish the shape of spectrum usage for many years.

Most European countries have spectrum available in the 470-862 MHz range for wireless microphone and monitoring. However, the spectrum is far from harmonised. The specific bands available within the band vary from country to country, as do the regulations governing use and power level. As a result, equipment providers have often produced frequency-agile equipment capable of operating across a range of frequencies in order to achieve manufacturing scale.

The remainder of this section looks in more detail at how the following countries and regions are using spectrum allocation and technological advances to address PMSE needs:

- US
- France
- Germany
- Sweden
- International developments (ETSI, ITU, EU/CEPT)

3.1 US

Much of the PMSE use in the US is in similar UHF spectrum to that used across Europe. However, some significant amount of US wireless microphone usage is not covered by FCC licensing rules. FCC regulation Part 74, which governs use of UHF and some VHF frequencies, specifies that "low power auxiliary stations," including wireless microphones, are available to broadcast stations and several other types of users, all of whom are involved in production activities in some way. Some parties seeking new uses of the television spectrum have argued that the Part 74 rules do not allow for licensed wireless microphone operations in live theatre productions, live concerts, churches, and conference centres, etc. The FCC has not clarified the scope of its eligibility rules in Part 74. The alternative options are low powered operation in unlicensed secondary spectrum, or obtaining a highly complex and expensive Part 90 license.

As a result, some interests have argued that certain US PMSE usage is unlawful transmission in the "white space" spectrum around analogue TV channels in the UHF band. This usage has been tolerated for years by US TV broadcasters as frequency coordination on the part of wireless microphone users and the natural separation between professional wireless microphone use and television equipment assures that it does not interfere with television signals. This arrangement has become the de facto status quo over more than two decades. However, spectrum in UHF band V has been reallocated as part of the DTV transition, which disturbs the relationship between PMSE and broadcasters. Spectrum in the 700 MHz freed up by the switchover was recently auctioned off for $20 billion with Verizon and AT&T emerging as the main winners. The FCC subsequently published proposals to prohibit the operation of low-power auxiliary stations (including wireless microphones) in this spectrum from the date of switchover – 17 February 2009 – to prevent harmful interference to new services operating there.[12]

New technologies have developed or are in development in the US for the PMSE sector:

Digital PMSE equipment is commercially available in the US. It is important to note that digital in this case is not compressed to avoid latency issues. This, in turn, has implications for bandwidth / spectrum requirements. The US allows up to 800 kHz bandwidth (compared with 200 kHz PMSE channel spacing in Europe) for digital wireless microphones.

Ultra Wideband equipment is available in the market but primarily for applications with lower audio quality requirements such as corporate conferencing rather than professional PMSE use.

Other new applications are emerging which also lay claim to the white space gaps left between television channel transmissions, in particular "White Space Devices" (WSDs). White space is the spectrum left between DTV channels once the DTV transition is complete, and has attracted a group known as the White Spaces Coalition which includes Google, Microsoft, HP, Dell, Intel, and Philips.

Possible resolutions to the conflicting uses of UHF spectrum include:

- *Additional spectrum allocation* – PMSE may be allocated additional spectrum outside the UHF band. However, this change would require new or modified equipment in many cases.

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[12] http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-188A1.pdf

- *Beacons* – are devices in the conceptual stage, which would broadcast a low-power DTV-like signal to protect wireless microphones from WSD usage. The WSDs would use spectrum sensing technology to detect the beacon broadcast and switch to a different frequency accordingly. In effect, the beacon, which would be operating on a designated pilot channel, transmits a "this spectrum is use by PMSE, please use another frequency" signal. Objections have been raised, claiming that the technology is unproven. Moreover, potential cost and spectral efficiency of such a device have been raised as concerns.

- *Geo-location* – is a proposed means to protect broadcast TV from interference from mobile devices. The devices would reference its current location against a database of known DTV transmissions to establish which frequencies are available for in the area. The technology is currently being discussed for use in WSDs. As of yet, the technology is not being considered for PMSE devices.

- *"Safe harbour" spectrum* – this is spectrum which WSDs would voluntarily not transmit, leaving the space free from WSD interference for wireless microphone and talkback use. Google has suggested that channels 36-38 could be used for as the safe harbour allowance, but wireless microphone lobby groups say that the spectrum is insufficient. Channel 37 is already in use for medical telemetry and radio astronomy, and channels 36 and 38 are used by DTV in some market (including New York and LA).

Which proposals the FCC will eventually adopt remain unclear. The FCC's decision on white space, and hence the fate of current wireless microphone and talkback spectrum usage, is expected to be made in 2008. However, since the DTV transition date is set as the 17th of February, 2009, it will be important for the FCC to meet this white space decision making timeframe in order that infrastructure and devices can be designed, tested and deployed to meet the usage guidelines.

3.2 France

Across the world, PMSE is known by a number of interchangeable terms. In France, as well as a number of other markets, PMSE is known as Services Ancillary to Broadcasting and Programme Making (SAB/SAP). ARCEP, the French regulator for electronic communications and post, is currently preparing a new decision on audio SAB/SAP.

Traditionally, audio SAB/SAP has used the 470-830MHz band on a secondary basis for many years. Wireless microphone and talkback equipment can operate in this band under a general authorisation regime, without the need for an individual licence per operator. The spectrum immediately above this band, 830-862MHz, is reserved for military use and so is unavailable to SAB/SAP applications.

France has begun its digital television switchover process, and is using a simulcast scheme to ease consumer transition problems. The additional spectrum consumed by parallel broadcast of analogue and digital TV signals has meant that SAB/SAP users already have to contend with significantly reduced spectrum. As DTV switchover progresses, these problems will only become more pronounced as less and less spectrum is available for SAB/SAP usage.

In particular, the intensive use of the band 470-862 MHz by digital television – including new applications such as mobile TV, HDTV or new local TV – will diminish the amount of white space spectrum in UHF bands IV and V that is available for audio SAB/SAP. Moreover, ARCEP, the National Assembly's Digital Dividend Commission and others have all called on the French government to allocate the 790-862 MHz band to new mobile-broadband services, which would also reduce the amount of spectrum available for radio microphones.

In this context, ARCEP has decided to make two additional frequency bands available for audio SAB/SAP users with secondary status, in accordance with Annex 10 of ECC Recommendation TR 70-03. These are the VHF band (174-223 MHz) and the 1.8 GHz band (1785-1800 MHz). ARCEP intends to apply a general authorisation regime with no individual licence required.

As some PMSE users move to the new designated frequencies, there are likely to be PMSE equipment implications due to the majority of devices being built to operate in UHF bands IV and V.

3.3 Germany

Germany started its analogue TV switch-off process in the Berlin area in November 2002. Since then, switchover has been completed in areas such as Berlin, Hamburg and Bremen but the country as a whole is not expected to switch off its last analogue transmission until the end of 2008.

In some parts of the country, analogue and digital transmissions are being broadcast in parallel, known as "simulcast". This simulcasting is intended to ease the TV transition process for consumers, but also has the consequence that spectrum usage goes up significantly in the short-term, leaving little space for PMSE applications to operate in.

Germany has traditionally used 7 MHz channels for analogue TV transmission within defined 8 MHz bands, with the remaining 1 MHz per band used by PMSE applications. The DTV standard defines 8 MHz channels for television, which removes the gaps that allowed radio microphones and other devices to operate as a secondary application within the analogue TV spectrum.

As a result, wireless microphone and talkback manufacturers are in the process of lobbying the government and the regulator to guarantee the safety of radio microphone usage. The German equipment manufacturer Sennheiser has expressed concerns that when transmission power of DTV is significantly increased upon final DTV switch-over, it will interfere with the neighbouring channels that PMSE applications could be moved into.

3.4 Sweden

Sweden was one of the first countries in the world to complete the switchover from analogue to digital TV transmission. The last analogue transmissions were switched off in October, 2007, ending a two-year phased switchover process. The large variation in DTV switchover scheduling between European nations is highlighted by the fact that the UK DTV transition process started two days after the Swedish process was complete.

The Swedish government decided in December 2007 that it would clear DTV allocations from the 790-862 MHz band to create a digital dividend for new mobile-broadband services. Regulator PTS is considering how to implement this decision. This leaves PMSE users in the same position as they face in many other markets.

3.5 ETSI

The European Telecommunications Standards Institute (ETSI) produces globally-applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, broadcast and internet technologies.

ETSI is comprised of manufacturers, industry experts and user groups. Standards bodies such as ETSI are an important forum for developing new products and technology.

ETSI has published a technical report (TR 102 546) with its findings and proposals for dealing with digital switchover and, therefore, less spectrum available for PWMS use:

- ETSI concluded that “the combination of antenna size, equipment size and propagation characteristics mean that UHF spectrum is the only solution for practical PWMS applications in the vast majority of scenarios …”
- The report also noted the problems with use of VHF band for PWMS because it is “… too noisy for fulfilling the high audio quality requirements.”

Before Ofcom and other national authorities made any decisions on the nature of their digital dividends, ETSI proposed new bands for PMSE use (in addition to current ones) for some usage scenarios:

Frequency band	**Channel spacing***	**Comments**
470 MHz to 790 MHz	200 kHz	
790 MHz to 862 MHz	200 kHz	
1452 MHz to 1492 MHz	Up to 600 kHz	New
1492 MHz to 1530 MHz / 1533 MHz to 1559 MHz	Up to 600 kHz	New – for indoor installations only
1785 MHz to 1800 MHz	Up to 400 kHz	Currently for digital use only. Analogue use proposed. Small frequency range. Could be used as PMWS band for ENG

* PWMS channel is always at least a distance of channel spacing/2 from the respective band edge.

It is important to note that ETSI has proposed higher channel spacing in the bands above 1452 MHz. This will allow for sufficient capacity for digital SD and HD transmission within a channel. However, further research is needed to understand implications of using this spectrum under different usage scenarios.

3.6 ITU

In November 2007, the World Radio Conference (WRC, part of the ITU) agreed a co-primary allocation for advanced / 3G mobile services (IMT) in the 790-862 MHz band, to apply across Region 1 (including Europe) by 2015. Manufacturers are assuming that this band will no longer be available for even secondary use by the PMSE sector.

3.7 EU/CEPT

The European Commission’s second digital-dividend mandate to the European Conference of Postal and Telecommunications Administrations (CEPT) asks for consideration of the best approach to ensuring the continuation of existing services for PMSE operating in the 470-862 MHz band. This report is due to be delivered in summer 2009.

3.8 Summary and Implications for the UK

Many countries around the world are facing the same issues as the UK relating to increasing demand for finite spectrum, and the uncertainty caused by the complexity of shifting national TV broadcasting from analogue to digital transmission.

Regulators around the world are considering the possibility of shifting wireless applications that have traditionally been allocated access to a significant portion of UHF bands IV and V into alternative spectrum and/or making greater use of interleaved spectrum.

Alternative technologies such as digital and UWB transmission have alleviated some problems for a subset of general wireless audio users, but not the whole market. Some applications such as corporate conferencing, which value ease of configuration and operation over sound quality, have adopted new technology but many other users prefer to continue using existing analogue equipment.

In the long term, technologies such as software-defined or cognitive radio may also provide the flexibility to solve the needs of other small market segments. They are still generally at the research and development stage and subject to the same physical properties of radio propagation as other wireless technologies.

To summarise the findings from international markets as they relate to PMSE spectrum allocation in the UK:

- Analogue PMSE equipment is still widely favoured
- PMSE operation outside UHF bands IV and V is currently limited, and therefore most equipment caters to this spectrum
- Digital PMSE equipment is used in the US, but on a limited basis. It is important to note that digital in this case is not compressed to avoid latency issues. This, in turn, has implications for bandwidth / spectrum requirements. The US allows up to 800 kHz bandwidth (compared with 200 kHz analogue PMSE channel spacing in Europe) for digital wireless microphones (but at lower power)
- ETSI has proposed PMSE use of some spectrum in the ranges of 1452 – 1559 MHz and 1785 – 1800 MHz spectrum. ETSI has also proposed higher channel spacing in these bands, which will provide capacity for digital SD and HD transmission. However, this spectrum will be appropriate for only certain usage scenarios
- New technologies such as ultra wideband (UWB) are in development, but international benchmarks do not provide a clear indication of new technologies that will enable PMSE use of spectrum to be more efficient or to enable use of non-UHF spectrum

4. PMSE new technology and spectrum: identification and assessment

4.1 Assessment of new technology / equipment

The purpose of this section is to assess the potential for technology/equipment – current or new – to access post-DSO interleaved spectrum or, alternatively, spectrum outside UHF bands IV and V. In order to ensure a breadth of possibilities were considered, we relied on the following framework.

Ⓑ **New Equipment / Technologies**	***"New Equipment" approach*** • Digital transmission (SD) • Digital transmission (HD) • Hybrid digital-analogue technology • Cognitive radio – Spectrum sensing (Listen before talk) • Software defined radio (SDR) • Femtocells	***"Blue Sky" approach*** • Digital transmission (SD) – Frequency Hopping Spread Spectrum (FHSS) • Digital transmission (HD) • Cognitive radio – Spectrum sensing (Listen before talk) • Software defined radio (SDR) • Ultra wideband • Bluetooth • Wi-Fi • WiMAX • CDMA
Ⓐ **Current Equipment**	***"Re-tune" approach*** • Digital interleaved spectrum • Leased / spectrum from auction winner • Guard band	***"Re-engineer" approach***
	Current Spectrum Used (Post-DSO)	**Other Spectrum**

Framework for identifying new technologies for wireless microphones

Inputs and validation were provided by industry stakeholders, international developments, research and manufacturers. These options were evaluated against a range of criteria including the potential to use spectrum more efficiently than current technology and considerations such as cost, latency, audio quality and reliability important to PMSE users.

The framework is based on the ability of both current and new equipment to access spectrum available both in UHF bands IV and V after DSO and in other bands.

A. Current Equipment

Current equipment could access spectrum under two models:

- **"Re-Tune" Approach:** this model is based on re-tuning current equipment to make use of post-DSO spectrum in UHF bands IV and V
- **"Re-Engineer" Approach:** Re-engineering in this sense refers to the replacement of some or all of the electronic components within current equipment with new components to enable operation in alternative spectrum. Thus the same

modulation scheme would be employed but at different operating frequencies depending on the location of the new spectrum band. Equipment antennae are almost always tuned to specific frequencies, albeit sometimes with a wide bandwidth, and are usually matched to the transmitter. Large changes in operating frequency could entail a re-design, re-fit, of the antenna. This option would require the replacement of components such as inductors and this may not be physically possible due to a lack of space in the microphone transmitter housing. Furthermore, any re-engineered equipment would require re-certification before it can be used, adding to the costs of pursuing this option. This approach is not seen as viable given costs and complexity

For the "re-tune" approach, the following options are possible:

- Option 1 – Potential to use interleaved spectrum (specific channels vary by location) (user dependent)
- Option 2 – Possibility of accessing cleared digital-dividend spectrum held by successful bidders (equipment geographically dependent)
- Option 3 – Guard bands between future uses of UHF bands IV and V (equipment tuneability)

4.1.1 Option 1 – Interleaved spectrum

This option is a continuation of the current use of interleaved spectrum. It would be useful depending on two factors:

1) Extent of national availability – the greater this is, the easier it will be to use the same equipment across the country

2) Tuneability of current equipment – the further the tuning range of existing equipment can be extended the more of these channels can be covered to facilitate multi-channel operation. In practice some equipment may not be able to tune over a much wider frequency range

What is required are details regarding the pattern of interleaving, which will have a significant impact, particularly in relation to migrating existing users to new frequencies. These include the ability of their equipment to tune into these frequencies and the cost of acquiring new, tuneable equipment.

4.1.2 Option 2 – Accessing cleared digital-dividend spectrum from successful bidders

This could be implemented in three ways:

1. The successful spectrum bidders could lease (through a concurrent trade) entire channels or sub-channels as stand-alone businesses for PMSE use.

2. Successful spectrum bidders would allow temporary PMSE use – with a notice period – until their own services were ready to be deployed, although this would only be a transient option.

3. The successful spectrum bidders could lease (again through a concurrent trade) the white space in their own spectrum. This will amount to additional interleaved spectrum for any new DTT multiplexes, while mobile operators are likely to build their networks on a cellular repeat pattern, which may leave ‘pockets’ that could be utilised by lower power applications, such as PMSE.

This model would be consistent with Ofcom’s award of most of the spectrum allocated to PMSE to a band manager, with obligations to meet reasonable demand on fair, reasonable and non-discriminatory terms. The band manager could negotiate access to spectrum with primary rights holders on behalf of its customers.

4.1.3 Option 3 – Guard bands between future uses of UHF bands IV and V

It may be possible to use guard bands between future uses of UHF bands IV and V (i.e. between the existing DTT multiplexes and new uses, and between new uses themselves) for PMSE use. If these are frequency-division duplex mobile systems with the transmission in one sub-band and reception in another sub-band, the guard band between them (also known as the duplex split) could also be useful for PMSE applications. This would be low capacity use, however, with only a few channels available depending on the size of the guard band. However, concerns have been raised about the effect using these guard bands would have on wireless microphone receivers. Depending on the use of the mobile band, either band adjacent to the guard band may contain base station transmitters which could saturate a wireless microphone receiver, resulting in blocking problems.

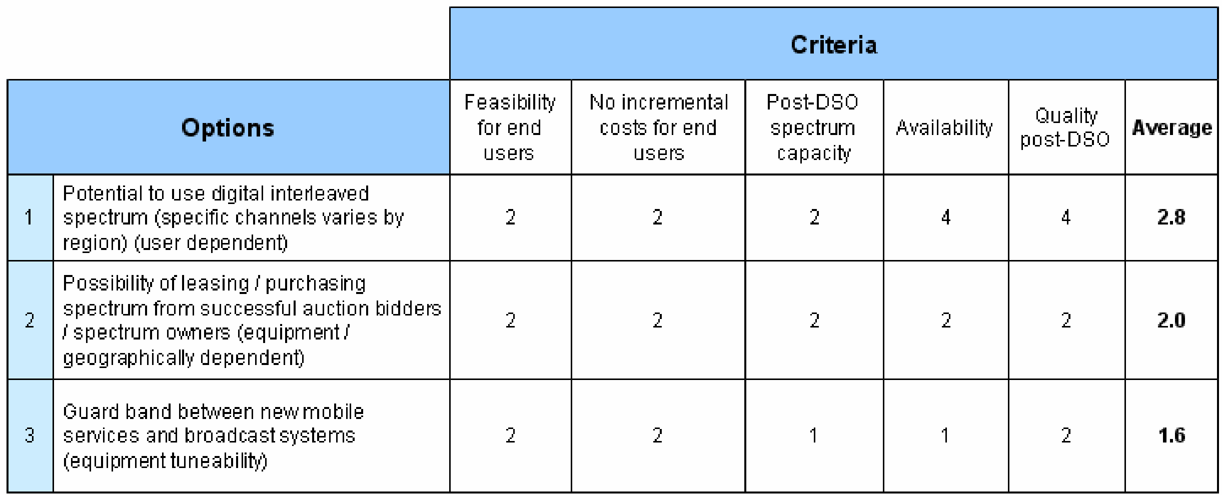
Additionally, the ownership of these guard bands – whether awarded to the adjacent licensees or retained by the regulator – may affect the possibility of PMSE usage.

4.1.4 Summary

Each model contains a number of options which are assessed against a range of criteria and scored relative to each other. The scoring for each criteria ranges from 0-4, with 0 being the lowest and least favourable in terms of benefits to the end user. The different options are also scored relative to each other.

The “re-engineer” approach is fraught with difficulties, including feasibility and costs. It is difficult to predict the amount of hardware which would need to be disposed of as part of the system upgrade. If the vast majority of the hardware needs to be discarded, then there is little benefit to be gained from “re-engineering” in relation to a migration to new equipment which could access alternative spectrum. Our interview feedback was that re-engineering is unlikely to be a feasible option.

The ability to re-tune some current equipment, particularly high-end systems, to enable them to use post-DSO interleaved spectrum is significant because it will prevent premature equipment obsolescence and preserve the financial investment made in them. However, it is understood that re-tuning to a broad-range of interleaved spectrum post-DSO will be a challenge for most PMSE equipment.



		Criteria					
Options		Feasibility for end users	No incremental costs for end users	Post-DSO spectrum capacity	Availability	Quality post-DSO	**Average**
1	Potential to use digital interleaved spectrum (specific channels varies by region) (user dependent)	2	2	2	4	4	**2.8**
2	Possibility of leasing / purchasing spectrum from successful auction bidders / spectrum owners (equipment / geographically dependent)	2	2	2	2	2	**2.0**
3	Guard band between new mobile services and broadcast systems (equipment tuneability)	2	2	1	1	2	**1.6**

Assessment of options for re-tuning current PMSE equipment to use post-DSO spectrum (scored relatively against each other)

B. New technology / equipment

This section describes the assessment of equipment / technology for accessing new spectrum. The following new technology and equipment were evaluated against a range of criteria including the potential to use spectrum more efficiently than current analogue technology and critical PMSE performance requirements such as audio quality and latency.

- Option 1 – Digital transmission (SD)
- Option 1a – Frequency Hopping Spread Spectrum (FHSS)
- Option 2 – Digital Transmission (HD)
- Option 3 – Cognitive radio
- Option 3a – Spectrum Sensing (Listen Before Talk)
- Option 4 – Software Defined Radio (SDR)
- Option 5 – Ultra Wideband (UWB)
- Other options assessed include Bluetooth; Wi-Fi; WiMAX; Femtocells; and CDMA

4.1.5 Option 1 – Digital transmission (standard definition – SD)

Digital transmission has been described in chapter 2. Please consult section 2.1 for further details.

4.1.5a Option 1a – Frequency Hopping Spread Spectrum (FHSS)

This technology operates on a licence exempt basis, satisfying the critical need to avoid causing interference to, and suffering interference from, other services.

In relation to wireless microphones, frequency hopping spread spectrum systems will not only be expensive but it is unlikely they will be viable until the medium or even long term. This assumes the technology would be capable of satisfying fundamental performance criteria such as audio quality, latency and reliability for many PMSE users.

4.1.6 Option 2 – Digital transmission (high definition – HD)

High definition (HD) digital wireless microphones have been considered because of the move to HD content creation across the world. Production companies, studios and broadcasters are either moving or have stated their intention to move to HD for video, and it is anticipated that this trend will result in a move to HD audio for improved sound quality.

Although technically feasible, HD quality digital wireless microphones have substantially increased bandwidth requirements. They require between 3-6 times the channel spacing of current analogue systems (200 kHz). Thus, as an alternative to analogue systems, they are much less spectrally efficient, and they will also cost more. Compressing the signal will compromise audio quality, which would be unacceptable for the majority of PMSE applications as they tend to be live. Significant bandwidth requirements render the congested spectrum bands below UHF unsuitable for high definition digital wireless microphone applications. In the L-band (1492-1599 MHz; 1785-1800 MHz), some suitable spectrum is available and the 600 kHz bandwidth required by HD digital wireless microphones is feasible.

HD digital wireless microphones should benefit from the same technology improvements anticipated for SD digital wireless microphones.

4.1.7 Option 3 – Cognitive Radio

The issues concerning cognitive radio have been described in chapter 2. Please consult section 2.2 for further details.

4.1.7a Option 3a – Spectrum Sensing (Listen before Talk)

Spectrum Sensing is a specific implementation of cognitive radio in which only the RF spectrum is monitored, thus the comments about cognitive radio in section 2.2 are applicable. Improvements in processing power will be important to the viability of this option as it depends on the ability to detect the presence of other channels in order to avoid causing interference to established users of the channel.

4.1.8 Option 4 – Software Defined Radio (SDR)

The issues concerning software defined radio have been described in chapter 2. Please consult section 2.2 for further details.

4.1.9 Option 5 – Ultra Wideband (UWB)

The issues concerning UWB radio have been described in chapter 2. Please consult section 2.2 for further details.

Option 6 – Bluetooth

Although Bluetooth was designed at the outset to carry audio signals, its poor latency (40 to 50 ms)[13] renders it unsuitable for PMSE use. It is a technology designed to optimise data through-put, not latency or audio quality.

4.1.10 Option 7 – Wi-Fi

The major problem with this option is latency (100 ms or more)[14] and the reliance on packet-based transmission. The relatively long delays would be unacceptable in PMSE applications, and the loss or reversal of packets could lead to uncertain situations where the option would be either to delay the transmission of the audio – unacceptable – or leave a gap in the transmitted data. The latter would degrade the quality of the audio output, in addition to interference from other wireless devices. Additionally, the spectrum assigned to Wi-Fi systems is used by microwave ovens, cordless phones, lighting systems and several other low power applications. Due to the likelihood of inference, professional users are highly unlikely to use equipment designed to operate in this spectrum because reliable operation is not guaranteed.

4.1.11 Option 8 – WiMAX

The issues identified above for Wi-Fi are also applicable to WiMAX, but it is important to note that WiMAX does not operate in licence-exempt spectrum.

4.1.12 Option 9 – Femtocells

These are small mobile network base stations typically designed for use in residential or small business environments. Quality of service might be a problem because it is likely packet-based technology would be used for the connection between the femtocell and the audio receiver. Using 3G mobile handsets, for instance, to deliver professional audio quality would be impracticable due to their poor audio quality, large latency (100 – 150 ms) and poor frequency response (300 Hz – 3 kHz). Furthermore, although dropped calls and echoes are acceptable in mobile communications despite their unsettling effects, they would be completely unacceptable in most wireless microphone applications.

4.1.14 Option 10 – CDMA

Code Division Multiple Access (CDMA) technology is used in mobile telephony and mobile radio systems as a form of multiplexing which allows a large number of signals to occupy a single transmission channel. It uses spreading algorithms to distribute the RF energy over a wide bandwidth and encryption codes to uniquely identify a given transmitter. The resulting emission is noise-like and can only be decoded by a receiver which possesses the matching code. Without the code, the

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[13],[14] Electronic Times, Wireless scheme tuned to high-end audio, May 30, 2005

emission will appear as random noise to the receiver. In this way, many transmitters could operate in the same spectrum.

CDMA is not practical as a wireless microphone technology for a number of reasons:

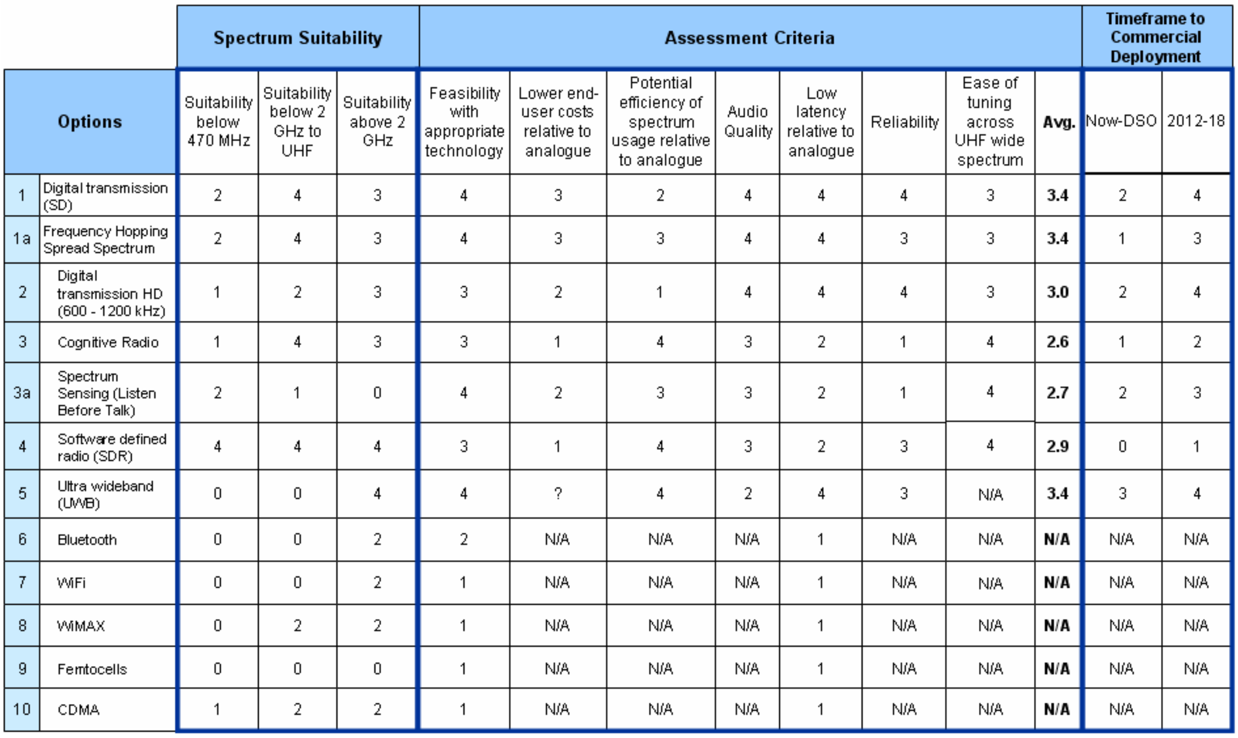
- The delays inherent in CDMA systems would be unacceptable to most wireless microphone users. In mobile telephone systems, such delays are acceptable because two people talking tend not to be in the same place when they are speaking. However, in a theatre production, for instance, an audience would notice the time delay between a performer speaking/singing and the audio output becoming audible over the loudspeakers. Delay in CDMA systems is complex and depends on trading-off a number of factors such as forward error correction and the length of the code sequence used to spread the frequencies of the transmitted signals.

- For PMSE use, CDMA technology would likely be challenged by the fact that the nose floor increases with the number of transmitters used, with the limit depending on interactions between technology and spectrum.

- CDMA systems are bidirectional and need control channels to enable the receiver to co-ordinate the operating parameters – such as output power – of the transmitters. This might not necessarily be an efficient use of spectrum

- CDMA technology is an unknown factor in the PMSE world and would require thorough research to determine its suitability

4.1.15 Summary



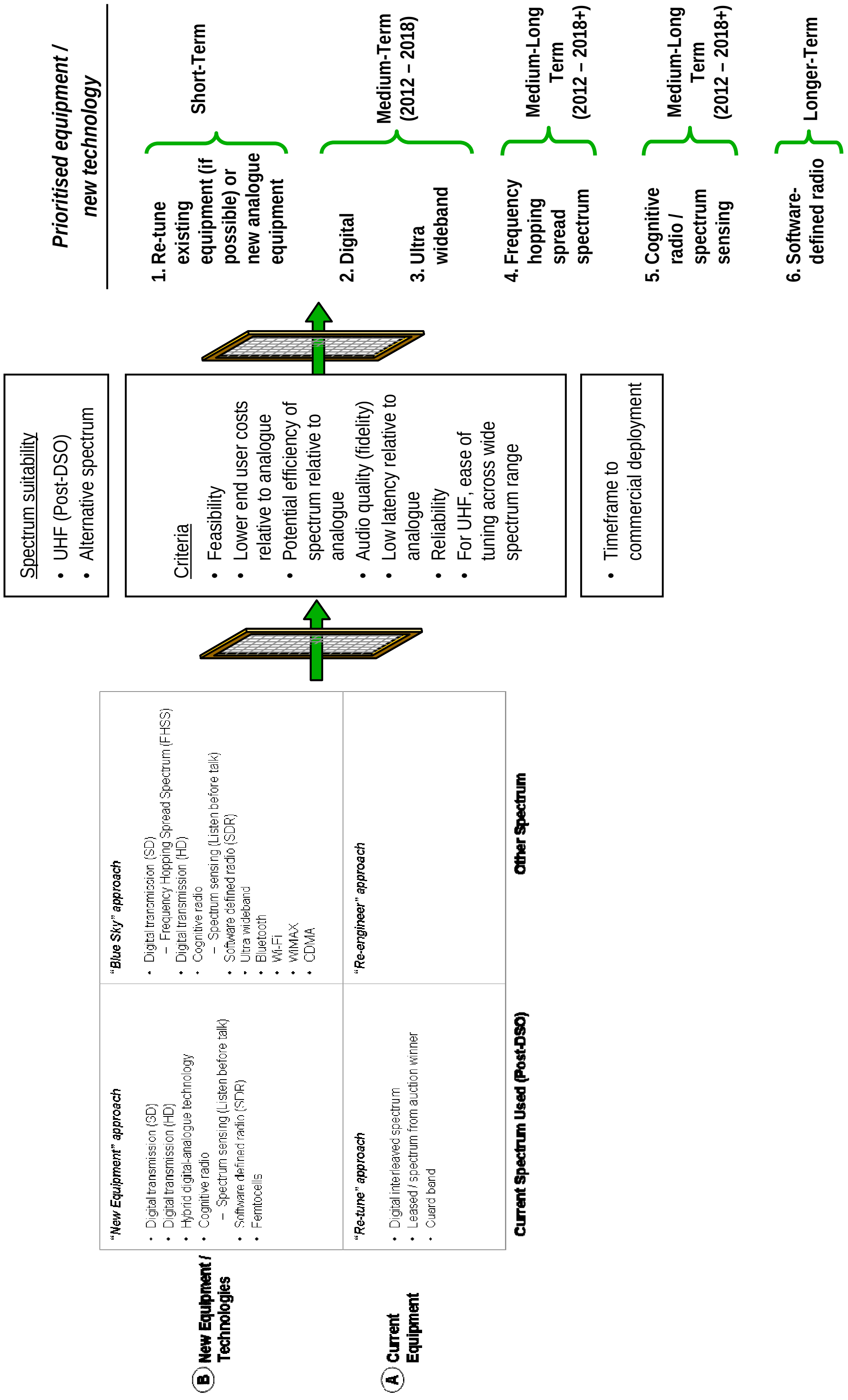
		Spectrum Suitability			**Assessment Criteria**								**Timeframe to Commercial Deployment**	
Options		Suitability below 470 MHz	Suitability below 2 GHz to UHF	Suitability above 2 GHz	Feasibility with appropriate technology	Lower end-user costs relative to analogue	Potential efficiency of spectrum usage relative to analogue	Audio Quality	Low latency relative to analogue	Reliability	Ease of tuning across UHF wide spectrum	**Avg.**	Now-DSO	2012-18
1	Digital transmission (SD)	2	4	3	4	3	2	4	4	4	3	**3.4**	2	4
1a	Frequency Hopping Spread Spectrum	2	4	3	4	3	3	4	4	3	3	**3.4**	1	3
2	Digital transmission HD (600 - 1200 kHz)	1	2	3	3	2	1	4	4	4	3	**3.0**	2	4
3	Cognitive Radio	1	4	3	3	1	4	3	2	1	4	**2.6**	1	2
3a	Spectrum Sensing (Listen Before Talk)	2	1	0	4	2	3	3	2	1	4	**2.7**	2	3
4	Software defined radio (SDR)	4	4	4	3	1	4	3	2	3	4	**2.9**	0	1
5	Ultra wideband (UWB)	0	0	4	4	?	4	2	4	3	N/A	**3.4**	3	4
6	Bluetooth	0	0	2	2	N/A	N/A	N/A	1	N/A	N/A	**N/A**	N/A	N/A
7	WiFi	0	0	2	1	N/A	N/A	N/A	1	N/A	N/A	**N/A**	N/A	N/A
8	WiMAX	0	2	2	1	N/A	N/A	N/A	1	N/A	N/A	**N/A**	N/A	N/A
9	Femtocells	0	0	0	1	N/A	N/A	N/A	1	N/A	N/A	**N/A**	N/A	N/A
10	CDMA	1	2	2	1	N/A	N/A	N/A	1	N/A	N/A	**N/A**	N/A	N/A

Assessment of technologies which could be used for PMSE equipment (Scored relatively against each other)

It is expected that improvements in technology will be such that ultra wideband could meet PMSE requirements within the medium term (2012-2018), whereas in all likelihood frequency hopping spread spectrum and cognitive radio are medium to long-term options, while software defined radio is a long-term option. The cost of these technologies would have to decrease significantly before they can be used in PMSE equipment.

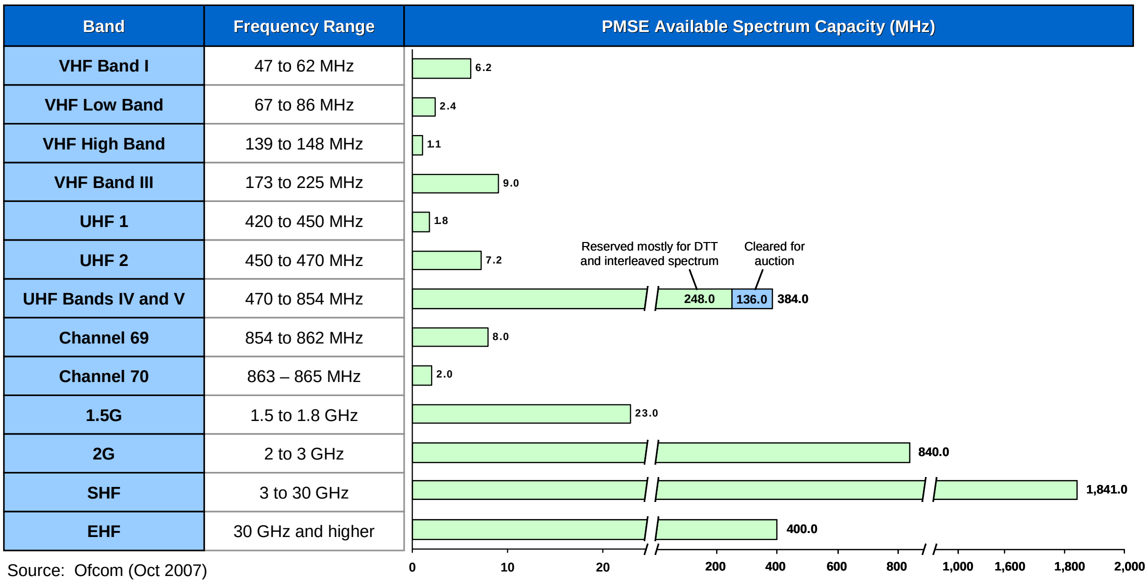
The diagram below summaries the process by which the equipment/new technology options were filtered to assess their potential for using spectrum more efficiently while satisfying the needs of PMSE users. Use of new equipment/technology will vary by end-user and this is described in section 5.

Identification of PMSE equipment/new technology and potential timeframe for commercial availability



4.2 Assessment of new spectrum

This section assesses the potential for use of spectrum outside UHF bands IV and V. The following chart shows capacity available for PMSE use as of October 2007:



Band	Frequency Range	PMSE Available Spectrum Capacity (MHz)
VHF Band I	47 to 62 MHz	6.2
VHF Low Band	67 to 86 MHz	2.4
VHF High Band	139 to 148 MHz	1.1
VHF Band III	173 to 225 MHz	9.0
UHF 1	420 to 450 MHz	1.8
UHF 2	450 to 470 MHz	7.2
UHF Bands IV and V	470 to 854 MHz	248.0 136.0 384.0
Channel 69	854 to 862 MHz	8.0
Channel 70	863 – 865 MHz	2.0
1.5G	1.5 to 1.8 GHz	23.0
2G	2 to 3 GHz	840.0
SHF	3 to 30 GHz	1,841.0
EHF	30 GHz and higher	400.0

Source: Ofcom (Oct 2007)

PMSE Available Spectrum Capacity (October 2007)

Given the above capacity constraints, UHF Bands IV and V spectrum and spectrum above 1.5G are key options for providing necessary capacity since existing PMSE allocations below UHF Bands IV and V do not provide sufficient capacity.

Given the above, spectrum that could be considered for use by wireless microphones includes:

- Post-DSO Interleaved Spectrum: 470 – 550 MHz (channels 21-30) and 630 – 790 MHz (channels 41-60)
    - In addition to channel 69, part of channel 70 as well as channel 38
- 1.5 GHz:
    - 1452 – 1559 MHz
    - 1785 – 1800 MHz
- 2 – 3 GHz
- Above 3 GHz (SHF and EHF)

Each of the above spectrum bands has varying degrees of practicality of use given suitability of PMSE usage scenarios, availability and capacity, alignment with international developments and manufacturer strategic intent as well as impact of new technology. These considerations are discussed below.

4.2.1 Post-DSO Interleaved Spectrum

This band meets PMSE end user requirements for audio quality and range. Analogue equipment does operate in these frequencies. However, only high-end analogue equipment can operate across this entire band.

4.2.2 1.5 GHz Band

- 1452 – 1559 MHz. Spectrum within this band has been proposed by ETSI for indoor use. Further research is needed to understand the possibilities of using this band for PMSE. It is a band that manufacturers are closely following developments for current and new technologies. However, it is in alternative use outside the UK (e.g. for digital radio in Germany), and usage rights for part of this band (1452 – 1492 MHz) have already been awarded in the UK and many other countries. Availability is further limited by the usage of just under half of the band by satellite services. ETSI has proposed greater channel spacing than analogue for this band in 1452 – 1559 MHz, which facilitates digital SD and HD transmission.

- 1785 – 1800 MHz. At a European level, CEPT allocated this band to fixed and mobile services applications on a primary basis, and also identified for potential use by digital wireless microphones. Neither the former nor the latter are binding on Member States, and digital wireless microphones capable of operating in this band have been slow to emerge. The band also has alternative uses (e.g. air-to-ground communications for the pan-European Terrestrial Flight Telephone Systems (TFTS)). In co-ordinated awards, Ofcom (in respect of Northern Ireland) and ComReg (in respect of the Republic of Ireland) have granted rights to use the band for wireless broadband systems.

4.2.3 2 – 3 GHz Band

- Broadcast-quality cameras typically use 2 – 3 GHz for video transmission. Where audio is embedded with the video transmission, there could be some usage scenarios where cameras can act as a receiver for audio

- Equipment manufacturer Sabine uses 2.4 GHz spectrum for its equipment. This spectrum is an industrial, scientific and medical (ISM) band and is restricted to low power applications operating on a licence-exempt basis, therefore it inherently minimises the chances of high power interference. However, this band is used by Wi-Fi, microwave ovens, cordless phones, lighting systems and several other low power applications. Due to the likelihood of inference, professional users are highly unlikely to use equipment designed to operate in this spectrum because reliable operation is not guaranteed.

4.2.4 Above 3 GHz

- Currently, spectrum at this level is used for point-to-point links. Ultra wideband could make this spectrum accessible to PMSE end users. Broadcast-quality cameras can also make use of SHF spectrum (at 6 – 10 GHz) and EHF spectrum (at 60 GHz) for video transmission. Where audio is embedded with the video transmission, there could be some usage scenarios where cameras can act as a receiver for audio

There are also other issues to consider when examining new spectrum for the PMSE sector above UHF:

- Portability needed for many PMSE users means that line of sight becomes a problem. Propagation of radio waves means that line of sight becomes more of an issue above 1-2 GHz due to multi-path interference and absorption
- At higher frequencies, antenna size becomes so small that they are generally less efficient at collecting radiated energy
    - New technology such as adaptive or smart antenna technology could overcome the above issues

4.2.5 Summary

The following chart summarises potential use of new spectrum:

	Key Considerations				
Alternative PMSE Spectrum	Suitability for PMSE end user with current technology		Alignment with international developments / manufacturer strategic intent	Requirement for new equipment / technology	Potential new equipment / technology
Post-DSO UHF Interleaved Spectrum	◕	Tuning capabilities of current equipment an issue	●	Moderate / High	Analogue Digital
1452 - 1559 MHz	◑	Proposed by ETSI for indoor use	◕	High	Analogue Digital
1785 - 1800 MHz	◑	Proposed by ETSI for ENG use	◕	High	Analogue Digital
2 – 3 GHz	◔	2.4 GHz used in some cases	◑	High	Analogue Digital
Above 3 GHz	◔	Currently used for point-to-point links	◑	High	UWB

○ = does not meet key consideration
● = fully meets key consideration

Overall, the spectrum just above UHF bands IV and V provides capacity, although signal propagation is an issue. To utilise spectrum above these bands, new technology will be required. Because of requirements for wireless microphone technology, use of new spectrum will therefore be limited to certain usage scenarios. Details follow on usage scenarios and applicability of straw-man models.

5. PMSE new technology and spectrum: straw-man models

There are possibilities for use of new spectrum for the PMSE sector, as assessed in the previous section. Given that the PMSE sector consists of a diverse group of users, the potential to use spectrum more efficiently or new spectrum (as well as necessary new equipment / technology) will vary. Taking into account where usage scenarios have similarities for key requirements, we have identified four potential straw-man models:

Straw-man model 1: High-end entertainment and media audio
Straw-man model 2: Short-range audio
Straw-man model 3: Short-range camera audio
Straw-man model 4: Talkback

Details on each of these straw-man models follow:

Straw-man model 1: High-end entertainment and media audio

PMSE segments:

- Fixed-venue performances, concerts and events: Professional theatre, fixed-venue concerts, sporting events, major indoor events and corporate events
- Touring performances, concerts and events
- Studio-based programme making (TV broadcasters, TV products, radio)
- Complex electronic news gathering (ENG) and outside broadcasts (OB) of major events: multiple presenters, participants, and / or interviewees
- On-site TV / film production
- Community users

Context: High-end entertainment and media audio users typically have the most demanding requirements for wireless microphones. These users typically need portable transmitters (non line of sight operation is typical as well as need for long battery life), low latency, multi-channel operation and appropriate transmission range

Short-term possibilities (to 2012)

- Potential post-DSO / new spectrum: Given requirements of these users, UHF Bands IV and V will remain critical. Therefore, interleaved spectrum will be critical in the short-term and into the medium-term
- New equipment / technology required: Many users may need new equipment to access post-DSO frequencies in interleaved spectrum

Medium-term possibilities (2012-2018)

- Potential post-DSO / new spectrum: *Use of new spectrum is uncertain – will depend on technology evolution.* Potential new spectrum (in addition to interleaved) could be just above UHF bands IV and V
- New equipment / technology required: To address line of sight issues in order to use bands above UHF bands IV and V, improvements are needed for antenna technology.

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** Although digital equipment is available, it is not yet widely deployed in the UK. Because of this we did not find evidence that it is able to deliver robust performance across a range of PMSE usage scenarios

- **Commercial adoption:** Currently, the relatively high costs of digital technology, coupled with the relatively long equipment replacement cycle, suggest that adoption of digital equipment will be limited in this timeframe

Medium-term (2012-2018):

- **Technological readiness:** We expect the issues concerning the robustness of digital equipment across a range of usage scenarios to be mostly resolved
- **Commercial adoption:** By the end of this timeframe, we anticipate moderate adoption of digital equipment supported by the market entry of leading equipment manufacturers, which should lead to greater competition and reduction in equipment prices

Straw-man model 2: Short-range audio

PMSE segments:

- Boardroom conferencing
- *Some* community users (with short-range audio requirements and little multi-channel)

Context: These users tend to have relatively less stringent requirements for transmission range and quality. Newer technologies and spectrum could meet requirements in the short and medium term.

Short-term possibilities (to 2012)

- Potential post-DSO / new spectrum: Potential to use higher spectrum bands at 1.5 GHz, 2.4 GHz and above 3 GHz.
- New equipment / technology required: Will require digital or UWB equipment. UWB equipment for boardroom conferencing already exists and is in use, although mostly in the US and Japan.

Medium-term possibilities (2012-2018)

- Potential post-DSO / new spectrum: Continued take-up of above
- New equipment / technology required: Continued take-up of above

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** UHF-based analogue and digital equipment are currently available for these end-users, in addition to licence-exempt equipment, although the latter needs to be proven for some community users
- **Commercial adoption:** We expect limited adoption over this timeframe due to the current relatively high costs of UWB equipment targeted at boardroom conferencing applications

Medium-term (2012-2018):

- **Technological readiness:** Improvements are expected to improve the performance of current UWB audio products by leveraging advances in the technology for other areas of the communications industry
- **Commercial adoption:** We expect UHF spectrum scarcity to drive broad adoption of licence-exempt, alternative technologies such as UWB

Straw-man model 3: Short-range camera audio

PMSE segments:

- Short-range ENG / OB audio: narrator / presenter to camera

Context: Camera situations where there is a presenter in front of a camera (or a narrator) have less stringent requirements for wireless microphones for portability, latency (although the audio needs to be synched with video), multi-channel operation and audio / transmission range. These ENG and OB users could leverage new spectrum and equipment. 1785 – 1800 MHz is being considered for ENG audio by ETSI. Broadcast cameras already use 2-3 GHz. With embedded audio and/or UWB, spectrum above 3 GHz could also be used.

Also, the short range in this model means that, in the medium to long term, emerging technology such as low-rate wireless Personal Area Network (PAN) may be possible to link a presenter microphone to camera.

Short-term possibilities (to 2012)

- Potential post-DSO / new spectrum: Potential to use higher spectrum bands at 1785 – 1800 MHz and 2-3 GHz
- New equipment / technology required: Will require digital equipment, which already exists for ENG usage.

Medium-term possibilities (2012-2018)

- Potential post-DSO / new spectrum: Continued take-up of above as well as potential to use spectrum above 3 GHz
- New equipment / technology required: Continued take-up of above as well as potential to leverage new technologies (depending on evolution), possibly UWB and /or Wireless PAN

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** Digital equipment currently available for ENG usage and there is potential to use higher bands such as 1785 – 1800 MHz , which is being considered for ENG audio, as well as 2 – 3 GHz
- **Commercial adoption:** Continued take-up of existing digital equipment for ENG

Medium-term (2012-2018):

- **Technological readiness:** We expect continued take-up of the above as well as the potential to use spectrum above 3 GHz by utilising digital equipment (embedded audio) and, possibly UWB and Personal Area Network (PAN)
- **Commercial adoption:** Further adoption of the above is expected, assuming current digital equipment improves in performance while decreasing in price. If UWB and other emerging technologies such as (PAN) prove to be robust, they could enjoy limited adoption

Straw-man model 4: Talkback

PMSE segments:

- Talkback (across many usage scenarios)

Context: Requirements for Talkback, which is typically used for coordinating production and shows, vary, especially for latency and audio quality. Some users have moderate requirements. However, in some cases such as studio-based programme making, users are migrating to IEM due to the discomfort of listening to lower quality talkback for extended periods of time. The move to IEM by some users only increases demand for spectrum in UHF Bands IV and V. For less demanding users that can utilise new technology and move to higher spectrum bands, there will be limited impact on use of UHF Bands IV and V since talkback use is mostly in UHF 1 and 2.

Short-term possibilities (to 2012)

- Potential post-DSO / new spectrum: Talkback users requiring high quality audio would need interleaved spectrum for IEMs. For less demanding users, potential to use higher spectrum bands (such as 1.5 GHz or 2.4 GHz)
- New equipment / technology required: Will require new analogue equipment or digital equipment

Medium-term possibilities (2012-2018)

- Potential post-DSO / new spectrum: Continued take-up of above
- New equipment / technology required: Continued take-up of above

Potential for more efficient use of spectrum / use of new spectrum (including timeframe for broad adoption of necessary new technology):

Short-term (to 2012):

- **Technological readiness:** Depending on the transition to IEMs, we expect developments in talkback systems to be broadly in line with those of wireless microphone equipment (UHF-based analogue and digital) due to similarities in the underlying technologies. Current R&D efforts are focused on equipment operating in non-UHF spectrum (1.5 GHz and 2.4 GHz)
- **Commercial adoption:** Depends on the transition to IEMs, but the potential exists for broad adoption of UHF-based analogue equipment and, to a lesser degree, digital, depending on price

Medium-term (2012-2018):

- **Technological readiness:** Depending on the transition to IEMs, we expect developments in talkback systems to continue leveraging advances in wireless microphone equipment (UHF-based analogue and digital). Equipment operating in non-UFH spectrum (1.5 GHz and 2.4 GHz) may be available
- **Commercial adoption:** This depends on the transition to IEMs, but there is the potential for talkback equipment to be adopted widely, although the price of digital systems would be a significant factor

As discussed above, in addition to general requirements such as audio quality, there are some variations in requirements by end user usage scenario. Similarities among these requirements determine potential straw-man models for using new spectrum:

Straw-man models according to PMSE end-user scenarios and equipment requirements

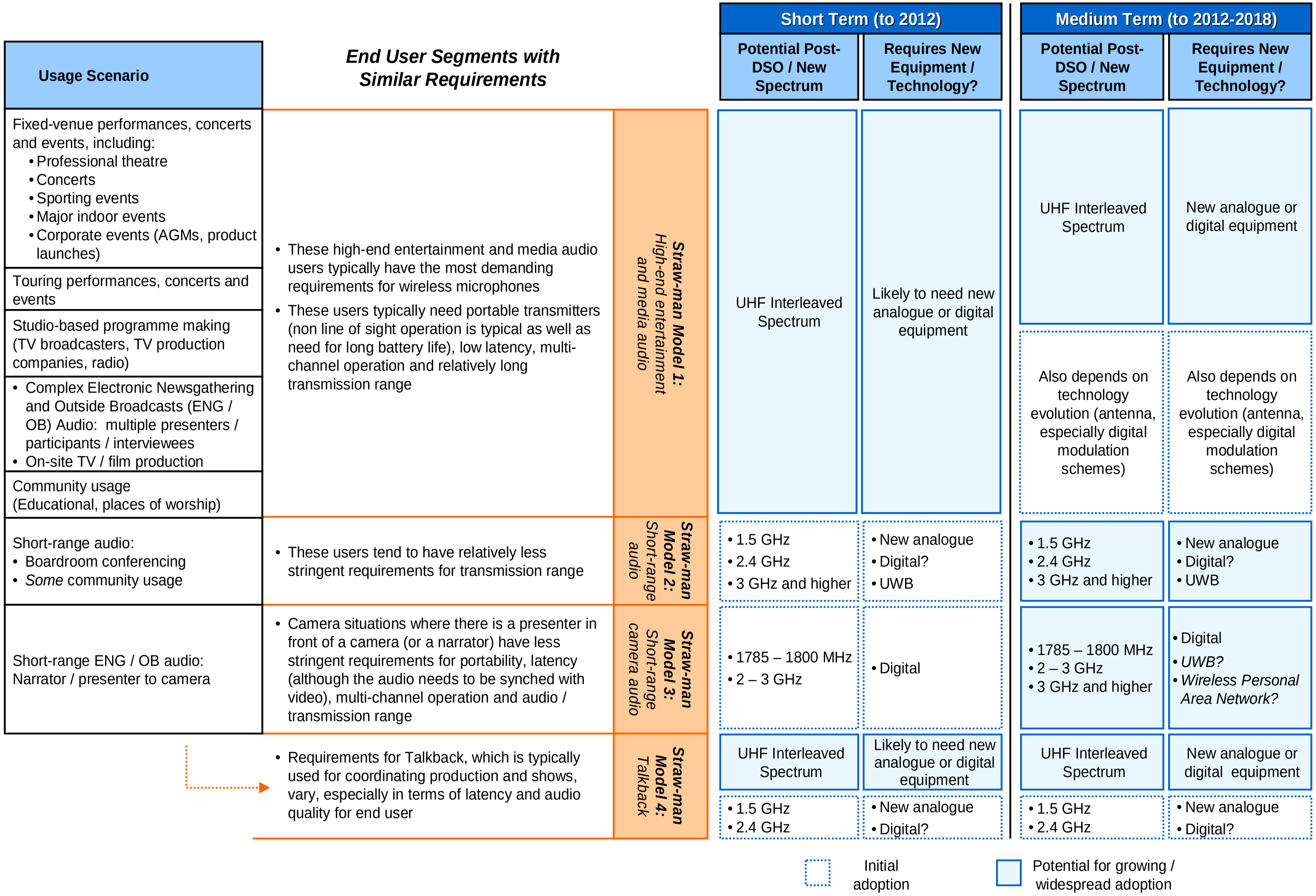
	Equipment Used			Relative Requirements					
Usage Scenario	**Wireless Mics**	**IEM**	**Talkback**	**For Portability**	**For Low Latency**	**For Multi-Channel** (Simultaneous)	**Typical RF Transmission Range** (Transmitter to receiver)	***End User Segments with Similar Requirements***	
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches)	🟩	🟩	🟩	High	Important	High	Up to 200m	• These high-end entertainment and media audio users typically have the most demanding requirements for wireless microphones • These users typically need portable transmitters (non line of sight operation is typical as well as need for long battery life), low latency, multi-channel operation and relatively long transmission range	***Straw-man Model 1:*** *High-end entertainment and media audio*
Touring performances, concerts and events	🟩	🟩	🟩	High	Important	High	Up to 200m		
Studio-based programme making (TV broadcasters, TV production companies, radio)	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	High (depending on event)	Important (for live events)	High	Up to 200m		
• Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Moderate / High (depending on event)	Moderate / High (depending on event)	Moderate / High (depending on event)	Up to 200m		
Community usage (Educational, places of worship)	🟩	🟨	🟨	Varies	Important	Low / moderate (depending on user)	Up to 200m		
Short-range audio: • Boardroom conferencing • *Some* community usage	🟩	🟩	🟨	Typically low	Moderate (depending on event)	Typically Low	Up to 20-30m	• These users tend to have relatively less stringent requirements for transmission range	***Straw-man Model 2:*** *Short-range audio*
Short-range ENG / OB audio: Narrator / presenter to camera	🟩	🟩 *Increasing use due to quality vs talkback*	🟩	Low / Moderate (depending on event)	Low / Moderate (depending on event)	Low	1.5-10m	• Camera situations where there is a presenter in front of a camera (or a narrator) have less stringent requirements for portability, latency (although the audio needs to be synched with video), multi-channel operation and audio / transmission range	***Straw-man Model 3:*** *Short-range camera audio*
								• Requirements for Talkback, which is typically used for coordinating production and shows, vary, especially in terms of latency and audio quality for end user	***Straw-man Model 4:*** *Talkback*

Sources: Quotient, Sagentia, CSMG analysis

🟩 = Typically used
🟨 = Occasionally used

For each of these straw-man models, the following spectrum bands could potentially be used. To do this, new equipment or technology would likely be needed in the short and medium term:

Potential spectrum bands and technology for PMSE straw-man models



			Short Term (to 2012)		**Medium Term (to 2012-2018)**	
Usage Scenario	***End User Segments with Similar Requirements***		**Potential Post-DSO / New Spectrum**	**Requires New Equipment / Technology?**	**Potential Post-DSO / New Spectrum**	**Requires New Equipment / Technology?**
Fixed-venue performances, concerts and events, including: • Professional theatre • Concerts • Sporting events • Major indoor events • Corporate events (AGMs, product launches) Touring performances, concerts and events Studio-based programme making (TV broadcasters, TV production companies, radio) • Complex Electronic Newsgathering and Outside Broadcasts (ENG / OB) Audio: multiple presenters / participants / interviewees • On-site TV / film production Community usage (Educational, places of worship)	• These high-end entertainment and media audio users typically have the most demanding requirements for wireless microphones • These users typically need portable transmitters (non line of sight operation is typical as well as need for long battery life), low latency, multi-channel operation and relatively long transmission range	***Straw-man Model 1:*** *High-end entertainment and media audio*	UHF Interleaved Spectrum	Likely to need new analogue or digital equipment	UHF Interleaved Spectrum Also depends on technology evolution (antenna, especially digital modulation schemes)	New analogue or digital equipment Also depends on technology evolution (antenna, especially digital modulation schemes)
Short-range audio: • Boardroom conferencing • *Some* community usage	• These users tend to have relatively less stringent requirements for transmission range	***Straw-man Model 2:*** *Short-range audio*	• 1.5 GHz • 2.4 GHz • 3 GHz and higher	• New analogue • Digital? • UWB	• 1.5 GHz • 2.4 GHz • 3 GHz and higher	• New analogue • Digital? • UWB
Short-range ENG / OB audio: Narrator / presenter to camera	• Camera situations where there is a presenter in front of a camera (or a narrator) have less stringent requirements for portability, latency (although the audio needs to be synched with video), multi-channel operation and audio / transmission range	***Straw-man Model 3:*** *Short-range camera audio*	• 1785 – 1800 MHz • 2 – 3 GHz	• Digital	• 1785 – 1800 MHz • 2 – 3 GHz • 3 GHz and higher	• Digital • *UWB?* • *Wireless Personal Area Network?*
	• Requirements for Talkback, which is typically used for coordinating production and shows, vary, especially in terms of latency and audio quality for end user	***Straw-man Model 4:*** *Talkback*	UHF Interleaved Spectrum • 1.5 GHz • 2.4 GHz	Likely to need new analogue or digital equipment • New analogue • Digital?	UHF Interleaved Spectrum • 1.5 GHz • 2.4 GHz	New analogue or digital equipment • New analogue • Digital?

⬚ Initial adoption

▢ Potential for growing / widespread adoption

6. Implications

The key implication of this analysis is that UHF Bands IV and V spectrum will remain critical to many PMSE users (fixed-venue and touring performances, concerts and events, studio-based programme making, complex ENG / OB use, on-site TV / film production and many community users) through to the medium term (2012 – 2018) Over this time frame, it is also understood that analogue technology will remain the preferred choice of many PMSE users because of its cost advantages and the long replacement cycles for wireless microphone equipment.

There is significant capacity available for PMSE use above UHF Bands IV and V. However, signal propagation is an issue in most usage scenarios where portability is critical. Therefore, the most useful spectrum, in addition to UHF Bands IV and V, is just above these bands. Improvements in antenna technology may help, but require significant R&D efforts. However, for some users, spectrum above UHF Bands IV and V could start to be used in the short term (by 2012). In some cases, especially with shorter range requirements and line of sight, UWB could enable use of spectrum above 3 GHz for specific usage scenarios.

It is important to note that the transition to a new technology (such as UWB) is likely to take approximately 5-10 years, once a technology is viable, due to the timeframes needed for initial take-up, widespread adoption and then sufficient time to recoup investment.

Other countries undergoing DSO are also grappling with how to accommodate the spectrum demands of the PMSE industry. International benchmarks indicate use of new spectrum or technology only in certain or limited cases. ETSI has proposed PMSE use, in addition to UHF, of some spectrum in the ranges of 1452 – 1559 MHz and 1785 – 1800 MHz spectrum. However, ETSI expects this spectrum will be appropriate for only certain usage scenarios.

There is a practical implication for PMSE end users with equipment that cannot tune across a wide frequency range (previous analysis conducted for Ofcom found that most equipment in use was designed to operate in channels 67, 68 and 69). For these users, there is a risk that they will need to buy high-end equipment with a broader tuning range to access interleaved spectrum in the short term (to 2012). Then, assuming protection for PMSE spectrum ends in 2018, end users may need to purchase new technology such as digital or UWB to access other spectrum. Yet this timeframe would be within the lifetime for use of new equipment purchased to access interleaved spectrum. This means that many end users may need to re-tool twice by the end of the medium term, which has significant cost implications.

During this analysis, PMSE manufacturers and users expressed their concerns about security of tenure for spectrum. A greater degree of certainty (within suitable bands) would, in turn, help to support technology developments by manufacturers and investment decisions for new equipment / technology by end users. We note that

Ofcom recognised this in its consultation on the detailed design of the DDR band-manager award[15] and stated that the band manager would be able to request a variation to increase the notice period for variation or revocation of its licence where this would facilitate the use of its spectrum by a third party. Also, providers of touring performances, concerts and events are concerned about access to sufficient interleaved spectrum.

It has been questioned as to why the PMSE industry cannot match or even leverage the capabilities of other wireless audio (and video) equipment; such as TV cameras, TVs and mobile phones, which are also examples of equipment where digital technology has made a significant difference in spectrum efficiency:

- TV cameras operate at higher frequencies (above 2 GHz), so why cannot wireless microphones? TV cameras do not have stringent low delay requirements since the signal is being broadcast or saved. Furthermore, TV cameras are mobile, even portable, but do not need to move to the degree a performer must, so line of sight is less of an issue.
- In the case of mobile phones, delay and audio quality requirements are not as stringent as they are for most PMSE users. Audio delay is less of a problem because return echoes are suppressed, so the user is much less aware of the effects of delay. This is demonstrated by the occasional situation where the suppression fails and a return echo of many hundreds of milliseconds can be heard, making conversation very difficult.

The impact of the new technology and spectrum straw-man models on use of UHF Bands IV and V is modest in the short-term. While moving Talkback to new spectrum and/or technology is feasible in the short-term, the impact on UHF Bands IV and V will be limited since most use takes place in the 450-470 MHz range. However, for short-range audio (boardroom conferencing and some community users) and short-range camera audio (electronic newsgathering / outside broadcasting) applications, there is the potential to use new spectrum in the short term (to 2012).

Nonetheless, overall, there are opportunities for improvements in wireless microphone technology to improve spectrum efficiency or enable use of spectrum not traditionally utilised. The consensus of our interviews is that digital is the most promising of the technologies identified. The timescales for the mainstream adoption of digital technology are expected to be in the 7 – 10 year range.

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[15] http://www.ofcom.org.uk/consult/condocs/bandmngr/condoc.pdf. Paragraph 6.18.

Acknowledgements

We would like to think the following people and organisations for their contribution to this report:

- Pete Myring, Myrcomm

- AMPS (Association of Motion Picture Sound)
- Autograph Sound Recording
- BEIRG (British Entertainment Industry Radio Group)
- Brian Copsey, ASP (Association of Service Providers)
- BBC
- IBS (Institute of Broadcast Sound)
- JFMG Ltd.
- Orbital Sound
- Paul Johnson, EARS Media (Production company)
- PSA (Production Services Association)
- J. Adrian Pickering, School of Electronics and Computer Science, University of Southampton and Sound Supervisor, Highfield Church
- Mike Martindell, Plextek (Radio design consultants)
- Simon Pike, Vodafone
- PLASA (Professional Lighting And Sound Association)
- Richmond Film Services
- SECC (Scottish Exhibition and Conference Centre)

PMSE equipment manufacturers:

- PMSE EU Manufacturer Group
- AKG
- Audio Ltd
- Audio-Technica
- Beyerdynamic
- Lectrosonics
- Sabine
- Sennheiser
- Shure
- Trantec

- Zaxcom

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Glossary of abbreviations

ADPCM – Adaptive Differential Pulse Code Modulation
AIP – Administrative Incentive Pricing

BBC – British Broadcasting Corporation
BER – Bit Error Rate

CD – Compact Disc
CDMA – Code Division Multiple Access
CR – Cognitive Radio

dB – Decibels
DDR – Digital Dividend Review
DECT – Digital Enhanced Cordless Telecommunications
DSO – Digital Switch Over
DSP – Digital Signal Processing / Processor
DTT – Digital Terrestrial Television
DTV – Digital Television

ECC – Electronic Communication Committee
EFP – Electronic Field Production
EHF – Extremely High Frequency
EMF – Electromagnetic Field
ENG – Electronic News Gathering
ERM – Electromagnetic Compatibility and Radio Spectrum Matters
ETSI – European Telecommunications Standards Institute
EU – European Union

FHSS – Frequency Hopping Spread Spectrum
FCC – Federal Communications Commission
FEC – Forward Error Correction

FM – Frequency Modulation

GHz – Gigahertz
GMSK – Gaussian Minimum Shift Keying
GMS – General System for Mobile

HD – High Definition
HDAP – High Definition Audio Performance
HDTV – High Definition Television

ICT – Information, Communication and Technology
IEM – In Ear Monitor
IF – Intermediate Frequency
IMD – Intermodulation Distortion
IMT – International Mobile Telecommunications
ISM – Industrial, Scientific and Medical
ITU – International Telecommunications Union
ITV – Independent Television

JFMG – Joint Frequency Management Group

MIMO – Multiple Input Multiple Output
MHz – Megahertz
mW – Milliwatt

NAB – National Association of Broadcasters

OB – Outside Broadcast

PAN – Personal Area Network
PCM – Pulse Code Modulation
PLL – Phase Locked Loop
PMR – Professional Mobile Radio

PMSE – Programme Making and Special Events
PSK – Phase Shift Keying
PWMS – Professional Wireless Microphone System

QPSK – Quadrature Phase Shift Keying
QAM – Quadrature Amplitude Modulation

R&D – Research & Development
RF – Radio Frequency

SAB – Services Ancillary to Broadcasting
SAP – Services Ancillary to Programme Making
SD – Standard Definition
SDR – Software Defined Radio
SHF – Super High Frequency
S/N – Signal-to-Noise
SRD – System Reference Document

TETRA – TErrestrial Trunked RAdio
TR – Technical Report
UHF – Ultra High Frequency
UWB – Ultra Wideband

VCO – Voltage Controlled Oscillator
VHF – Very High Frequency
VoIP – Voice Over Internet Protocol

WLAN – Wireless Local Area Network
WRC – World Radio Conference
WSD – White Space Devices

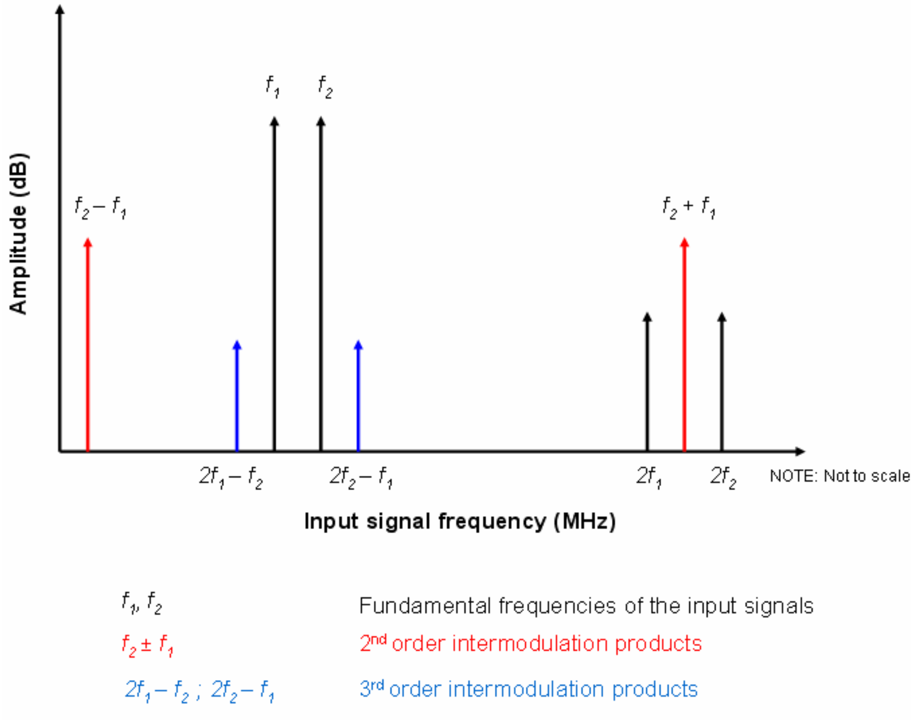
Appendix A: Effects of Intermodulation Products

The design of a standard analogue wireless microphone receiver typically consists of a front-end circuit with narrowband (narrow bandwidth) filters to select only the wanted signals bound within a range of a few MHz. For instance, a wireless microphone transmitter operating at a frequency f_1 of 300 MHz has a second harmonic at 600 MHz which is far removed from the receiver's bandwidth, assuming a receiver with a typical bandwidth of 24 MHz is being used between 290 M – 314 MHz, for example. If another wireless microphone is used at a carrier frequency f_2 of 302 MHz (second harmonic at 604 MHz) the sum and difference frequencies become:

- Sum: $f_1 + f_2 = 300 + 302 = 602$ MHz
- Difference: $f_2 – f_1 = 302 – 300 = 2$ MHz

Both of these signals are far outside of the receiver's bandwidth. The third order harmonics, however, present a problem, as shown below.

- $2f_1 – f_2 = 2×300 – 302 = 298$ MHz
- $2f_2 – f_1 = 2×302 – 300 = 304$ MHz

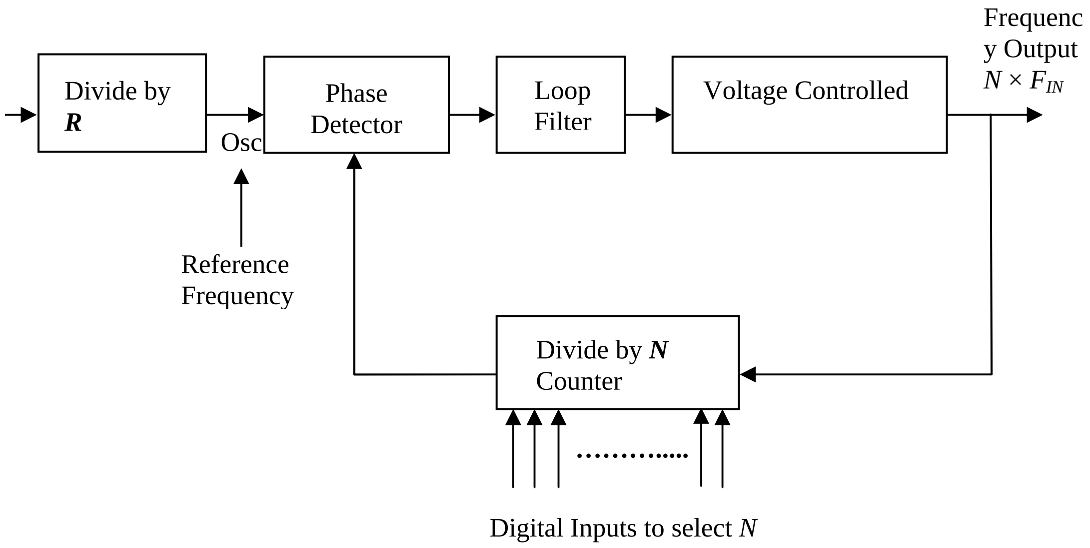


Intermodulation spectrum with 2^{nd} and 3^{rd} order intermodulation products

Both of these new signals ($2f_1 – f_2$ and $2f_2 – f_1$) are well within the bandwidth of the receiver and could cause interference to any systems operating at these frequencies. Assuming the wireless transmitters are deployed on useable frequencies spaced 500 kHz apart, e.g transmitter 1 is on 300 MHz, transmitter 2 is on 300.500 MHz, transmitter 3 is on 301 MHz, transmitter 4 is on 301.500 MHz, transmitter 5 is on 302 MHz etc, transmitter 9 on 304 MHz will be subject to interference from the intermodulation products of transmitters 5 and 1. Therefore the frequency of 304 MHz must be avoided to ensure transmitter 9 operates reliably.

The above example indicates that there is a limit to the number of wireless transmitters which can be used in a bank of spectrum once the effects of intermodulation products have been accounted for. Intermodulation products serve to reduce the number of useable frequencies within a given block of spectrum. It is the fundamental reason why the channel spacing of analogue wireless microphones cannot be adjacent to each other simply by dividing the spectrum into equally spaced channels. As a result, reducing the transmission bandwidth of analogue wireless microphones by a few kHz will not lead to significant improvements in spectrum efficiency.

Appendix B: Frequency agile technology



A Phase Locked Loop (PLL) frequency synthesiser

The input signal, F_{IN}, is derived from a crystal oscillator which provides a very stable reference signal. This is then divided down to a frequency, F_R, equal to the desired synthesiser channel spacing. The output of the voltage controlled oscillator (VCO), $N \times F_{IN}$, is also divided down to the desired channel spacing by feeding it to the divide by *N* programmable frequency counter. This signal and that from the reference divider are then applied to the phase detector circuit. Normally the frequencies of both signals will be nearly the same. The phase detector compares the two inputs and produces a control signal (a voltage) proportional to the phase difference between them. This output signal is filtered by the loop filter to remove noise (undesirable signals) and then used to drive the VCO, whose output, as well as being synthesiser output signal, is also fed back to the phase detector circuit to repeat the process. Therefore the VCO output is *locked* to the frequency of the reference signal. It must be noted that, before *locking* is achieved, the VCO will normally be operating at its default or free-running frequency.

The key to the frequency synthesising ability of the circuit above is the divide by N counter placed in a feedback loop between the VCO output and the input of the phase detector. It is typically implemented as a digital counter clocked by the VCO output, with the count value *N* determined by digital inputs from another digital component such as a microprocessor, making it relatively easy to control the overall output of the circuit. The counter is preset to an initial count value, counting down on each cycle of the clock pulse until it reaches zero, whereby the counter output changes state and the count value N is re-loaded.

For instance, let us assume the desired radio microphone channels are to be spaced at 125 kHz intervals. The control signal produced by the phase detector will be zero only if both the reference input and the feedback signal from the VCO are divided down to125 kHz. For this happen, the VCO must operate at a frequency which is 125 kHz × *N*, the count value. Therefore it will produce an output of 700 MHz for a count of 5,600 (700 MHz ÷ 5600 = 125 kHz). For a count of 5,601, the output will be 700.125 MHz, and a count of 5,602 yields an output of 700.250 MHz, and so forth. Theoretically, the output frequency range is limited only by the range of the VCO and the count value *N* of the programmable counter. In this way, a number of operating frequencies can be obtained for radio microphones.

Appendix C: Example PMSE manufacturer products, features, and pricing

Manufacturer	Product	Device Type	Analogue / Digital	Global Product Line Frequency Range*	Price
AKG	HT 40 FLEXX	Wireless microphone	Analogue		£ 85
AKG	HT 40 PRO	Wireless microphone	Analogue		
AKG	HT 4000	Wireless microphone	Analogue	650-862	£ 275
AKG	HT 450	Wireless microphone	Analogue	650-865	£ 188
AKG	PT 40 FLEXX	Bodypack transmitter	Analogue		£ 85
AKG	PT 40 PRO	Bodypack transmitter	Analogue		
AKG	PT 4000	Bodypack transmitter	Analogue	650-862	£ 275
AKG	PT 450	Bodypack transmitter	Analogue	650-865	£ 179
AKG	SR 40 DUAL	Receiver unit	Analogue		
AKG	SR 40 FLEXX	Receiver unit	Analogue		£ 110
AKG	SR 40 SINGLE	Receiver unit	Analogue		
AKG	SR 4000	Receiver unit	Analogue	650-862	£ 350
AKG	SR 450	Receiver unit	Analogue	650-865	£ 256
Sennheiser	EK 100	Bodypack transmitter	Analogue	518-866	£ 415
Sennheiser	EK 300 IEM	IEM receiver	Analogue	518-866	£ 890
Sennheiser	EK 3052-U	IEM receiver	Analogue	450-960	£ 1,100
Sennheiser	EK 3053-U	IEM receiver	Analogue	450-960	£ 1,100
Sennheiser	EK 3241	Slot in Receiver	Analogue	450-960	£ 1,807
Sennheiser	EK 500	Bodypack camera receiver	Analogue	518-866	£ 558
Sennheiser	EK-3253	IEM transmitter	Analogue	450-960	£ 641
Sennheiser	EM 100	Receiver Unit	Analogue	518-866	£ 415
Sennheiser	EM 300	Receiver Unit	Analogue	518-866	£ 400
Sennheiser	EM 3031-U	Receiver unit	Analogue	450-960	£ 1,666
Sennheiser	EM 3532-U	Receiver unit	Analogue	450-960	£ 4,399
Sennheiser	EM 3731	Receiver unit	Analogue	450-960	£ 3,872
Sennheiser	EM 3732	Receiver unit	Analogue	450-960	£ 5,164
Sennheiser	EM 3732 COM	Receiver unit	Analogue	450-960	£ 5,869
Sennheiser	EM 500	Receiver unit	Analogue	518-866	£ 558
Sennheiser	EM 550	Receiver Unit	Analogue	518-866	£ 2,516
Sennheiser	SK 100	Bodypack transmitter	Analogue	518-866	£ 306
Sennheiser	SK 250-UHF	Bodypack transmitter	Analogue	450-960	£ 4,020
Sennheiser	SK 300	Bodypack transmitter	Analogue	518-866	£ 699
Sennheiser	SK 3063-U	Bodypack transmitter	Analogue	450-960	£ 1,579
Sennheiser	SK 500	Bodypack transmitter	Analogue	518-866	£ 374
Sennheiser	SK 50-UHF-a	Bodypack transmitter	Analogue	450-960	£ 2,671
Sennheiser	SK 5212	Bodypack transmitter	Analogue	450-960	£ 2,849
Sennheiser	SKM 135	Wireless Microphone	Analogue	518-866	£ 306
Sennheiser	SKM 135	Wireless Microphone	Analogue	518-866	£ 306
Sennheiser	SKM 145	Wireless Microphone	Analogue	518-866	£ 333
Sennheiser	SKM 165	Wireless Microphone	Analogue	518-866	£ 401
Sennheiser	SKM 3072-U	Wireless Microphone	Analogue	450-960	£ 1,430
Sennheiser	SKM 335	Wireless Microphone	Analogue	518-866	£ 699
Sennheiser	SKM 345	Wireless Microphone	Analogue	518-866	£ 330
Sennheiser	SKM 365	Wireless Microphone	Analogue	518-866	£ 763
Sennheiser	SKM 500	Wireless Microphone	Analogue	518-866	£ 558
Sennheiser	SKM 5200-UHF	Wireless Microphone	Analogue	450-960	£ 1,663
Sennheiser	SKM 535	Wireless Microphone	Analogue	518-866	£ 374
Sennheiser	SKM 545	Wireless Microphone	Analogue	518-866	£ 401
Sennheiser	SKM 565	Wireless Microphone	Analogue	518-866	£ 503
Sennheiser	SKM 935	Wireless Microphone	Analogue	518-866	£ 469
Sennheiser	SKP 100	Plug-on transmitter	Analogue	518-866	£ 306
Sennheiser	SKP 3000	Plug-on transmitter	Analogue	450-960	£ 983
Sennheiser	SKP 500	Plug-on transmitter	Analogue	518-866	£ 374
Sennheiser	SR 3054-U	IEM transmitter	Analogue	450-960	£ 1,728
Sennheiser	SR 3056-U	IEM transmitter	Analogue	450-960	£ 2,985
Sennheiser	SR-3254	IEM transmitter	Analogue	450-960	£ 1,937
Sennheiser	SR-3256	IEM transmitter	Analogue	450-960	£ 3,232
Shure	P2R	Bodypack receiver	Analogue		£ 212
Shure	P2T	Transmitter unit	Analogue		£ 227
Shure	P4R	Bodypack receiver	Analogue		£ 319
Shure	P4T	Transmitter unit	Analogue		£ 306
Shure	P6R	Bodypack receiver	Analogue	626-862	£ 523

*Note: Overall RF frequency range – actual tuning range of each product is less (see section 1.4)

Manufacturer	Product	Device Type	Analogue / Digital	Global Product Line Frequency Range*	Price
Shure	P6T	Transmitter unit	Analogue	626-862	£ 623
Shure	P7R	Bodypack receiver	Analogue	722-865	£ 919
Shure	P7T	Transmitter unit	Analogue	722-865	£ 998
Shure	PG1	Bodypack transmitter	Analogue		£ 81
Shure	PG2	Wireless Microphone	Analogue		£ 81
Shure	PG4	Receiver Unit	Analogue		£ 98
Shure	PGX1	Bodypack transmitter	Analogue	572-590 or 644-662	£ 145
Shure	PGX2	Wireless Microphone	Analogue	572-590 or 644-662	
Shure	PGX4	Receiver Unit	Analogue	572-590 or 644-662	£ 225
Shure	SLX1	Bodypack transmitter	Analogue	518-865	£ 142
Shure	SLX2	Wireless Microphone	Analogue	518-865	£ 231
Shure	SLX4	Receiver Unit	Analogue	518-865	£ 268
Shure	ULX1	Bodypack transmitter	Analogue	554-865	£ 200
Shure	ULX2	Wireless Microphone	Analogue	554-865	£ 229
Shure	ULXP4	Receiver Unit	Analogue	554-865	£ 534
Shure	UR1	Bodypack transmitter	Analogue	470-952	£ 607
Shure	UR2	Wireless Microphone	Analogue	470-952	£ 694
Shure	UR4D	Receiver Unit	Analogue	470-952	£ 2,179
Shure	UR4S	Receiver Unit	Analogue	470-952	£ 1,441
Sony	DWR-S01D	Receiver unit	Digital	798-862MHz	£ 2,344
Sony	DWT-B01	Bodypack transmitter	Digital	798-862MHz	£ 1,996
Sony	UTX-P1/62	Plug-on transmitter	Analogue	798-822MHz	
Sony	UTX-P1/67	Plug-on transmitter	Analogue	838-862MHz	
Sony	UWP-C1/67	Bodypack transmitter	Analogue	838-862MHz	
Sony	WRT-807B/62	Wireless Microphone	Analogue	798-822MHz	
Sony	WRT-807B/67	Wireless Microphone	Analogue	838-862MHz	
Sony	WRT-822B/62	Bodypack transmitter	Analogue	798-822MHz	
Sony	WRT-822B/67	Bodypack transmitter	Analogue	838-862MHz	
Sony	WRT-8B/62	Bodypack transmitter	Analogue	798-822MHz	
Sony	WRT-8B/67	Bodypack transmitter	Analogue	838-862MHz	
Sony	WRU-806B/62	Receiver unit	Analogue	798-822MHz	
Sony	WRU-806B/67	Receiver unit	Analogue	838-862MHz	
Trantec	S4.16LTX	Bodypack transmitter	Analogue	854-865	£ 121
Trantec	S4.16MTX	Wireless microphone	Analogue	854-865	£ 121
Trantec	S4.16RX	Receiver unit	Analogue	854-865	£ 158
Trantec	S4.4LTX	Bodypack transmitter	Analogue	863-865	£ 104
Trantec	S4.4MTX	Wireless microphone	Analogue	863-865	£ 104
Trantec	S4.4RX	Receiver unit	Analogue	863-865	£ 122
Trantec	S4000IEM-RX	IEM Receiver	Analogue	790-865MHz	£ 148
Trantec	S4000IEM-TX	IEM Transmitter	Analogue	790-865MHz	£ 197
Trantec	S5.3HTX	Wireless microphone	Analogue	854-865	£ 240
Trantec	S5.3LTX	Bodypack transmitter	Analogue	854-865	£ 240
Trantec	S5.3RX	Receiver unit	Analogue	854-865	£ 219
Trantec	S5.5HTX	Wireless microphone	Analogue	692-865	£ 323
Trantec	S5.5LTX	Bodypack transmitter	Analogue	692-865	£ 323
Trantec	S5.5RX	Receiver unit	Analogue	692-865	£ 302
Trantec	S6000CTX	Wireless microphone	Analogue	590-865	£ 900
Trantec	S6000LTX	Bodypack transmitter	Analogue	590-865	£ 900
Trantec	S6000RX-Mod	Receiver unit	Analogue	590-865	
Trantec	SD7200/10	Wireless microphone	Digital		£ 1,660
Trantec	SD7300	Bodypack transmitter	Digital		£ 1,624
Trantec	SD7802	Receiver Unit	Digital		£ 3,168
Zaxcom	RX4900	Receiver unit	Digital	518-870	£ 3,750
Zaxcom	RX900M	Receiver unit	Digital	518-870	£ 934
Zaxcom	RX900S	Receiver unit	Digital	518-870	£ 1,010
Zaxcom	TRX700	Plug-on transmitter	digital	518-870	
Zaxcom	TRX800	Wireless Microphone	Digital	518-870	
Zaxcom	TRX900	Bodypack transmitter	Digital	518-870	£ 934
Zaxcom	TRX900AA	Bodypack transmitter	Digital	518-870	£ 934
Zaxcom	TRX990	Bodypack transmitter	Digital	518-870	

*Note: Overall RF frequency range – actual tuning range of each product is less (see section 1.4)

Appendix D: End user demand validation

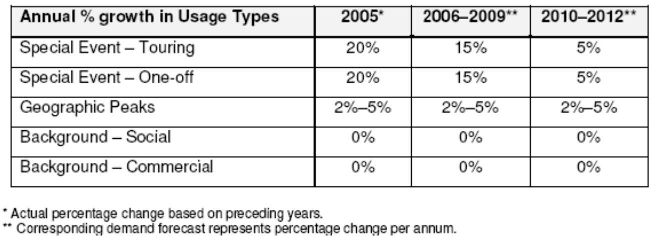
The latest available PMSE usage forecast was conducted as part of a report entitled, "Use of UHF Spectrum for Programme Making & Special Events in the UK", produced for Ofcom by Sagentia in December, 2006.

The forecast takes two major factors as inputs; number of organizations or entities which require PMSE licenses, and the level of PMSE equipment usage that those organizations require. These factors are split across five usage types, as described at the start of the PMSE End User section of the document:

- Special Event – Touring: PMSE use over multiple sites by a touring company
  - 12% annual growth in organizations and 20% growth in equipment usage from 2006-09
- Special Event – One-off: Short-term, large events such as concerts
  - 20% annual growth in organizations and 30% growth in equipment usage from 2006-09
- Geographic Peaks: Long-term use at fixed sites where more than one TV channel is required
  - 15% annual growth in organizations and 10% growth in equipment usage from 2006-09
- Background Social: Small scale social use such as schools, churches and village fetes
  - 30% annual growth in organizations and 25% growth in equipment usage from 2006-09
- Background Commercial: Small scale commercial use such as local theatres and AGM sites
  - 12% annual growth in organizations and 25% growth in equipment usage from 2006-09

For each usage type, the forecast provided year-on-year growth rates for both number of organizations and level of equipment take-up growth. By combining these growth factor inputs, the forecast produced a spectrum demand forecast. The spectrum demand forecast itself takes the two input factors in combination with spectral efficiency of the usage over time and spectrum management policies in order to establish the total spectrum requirements of PMSE users. It is important to note that the drop in demand in 2010-2012 is due to assumptions regarding lack of spectrum, not a fall in underlying demand. The data is given in the table below:

Spectrum Demand Forecast



Annual % growth in Usage Types	2005*	2006–2009**	2010–2012**
Special Event – Touring	20%	15%	5%
Special Event – One-off	20%	15%	5%
Geographic Peaks	2%–5%	2%–5%	2%–5%
Background – Social	0%	0%	0%
Background – Commercial	0%	0%	0%

* Actual percentage change based on preceding years.
** Corresponding demand forecast represents percentage change per annum.

Source: Use of UHF Spectrum for Programme Making & Special Events in the UK (Sagentia)

In its report, Sagentia noted that the data sources used in the derivation of the demand forecast were primarily:

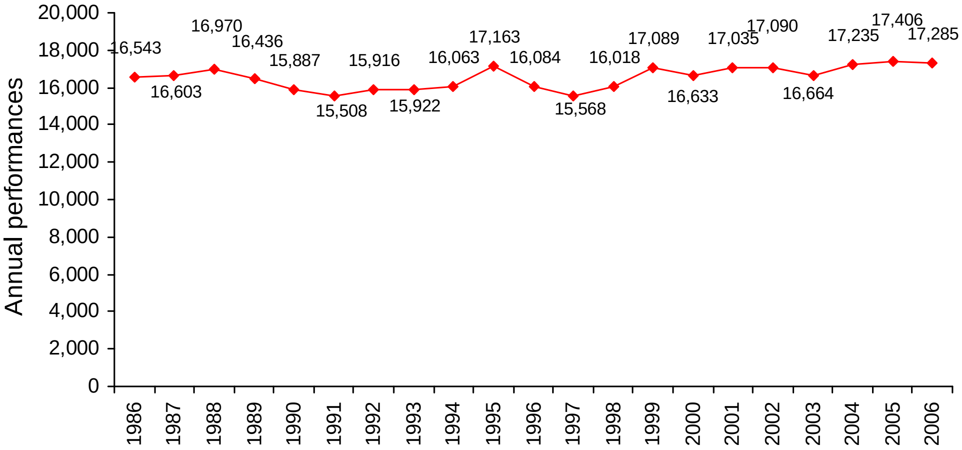
- Licence data from the JFMG database
- A market model and background documentation supplied by Quotient Associates
- Anecdotal evidence provided in stakeholder interviews carried out by Sagentia

Without access to these sources, a full validation of the spectrum demand forecast is not possible. However, by revisiting the input assumptions of the forecast, the validity of the forecast output can be sense-checked.

In the remainder of this section, growth trends in theatre performances, live music and film production will be examined in turn and compared to the growth rates used as inputs to the existing spectrum demand forecast.

The chart below shows that theatre performances in London's West End have remained largely flat since 1986. However, this does not provide information on the level of PMSE equipment usage involved in those performances.

Additionally, this data is for the mature theatrical market of London's West End. More recently established theatre districts in other UK regions could be experiencing growth in number of performances.



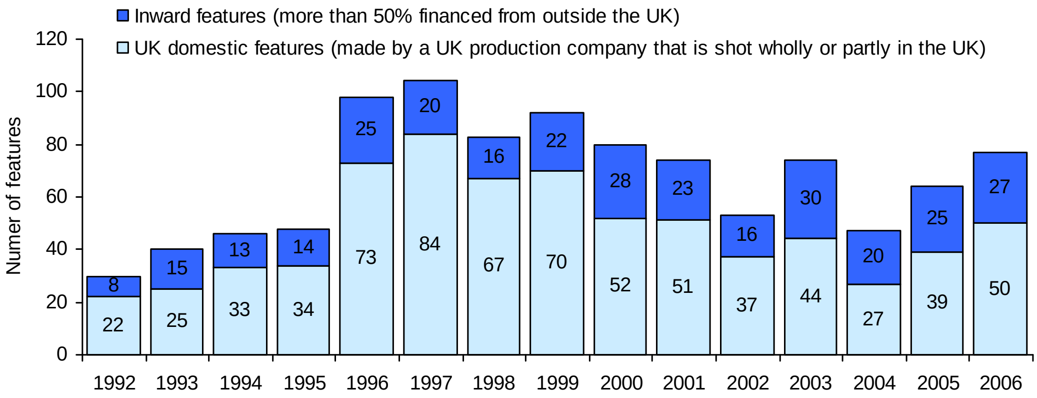
Theatre Performances in London's West End

Source: SOLT Box Office Data Report 2006

Live music is another important category of PMSE usage since it relies heavily on wireless microphones and talkback systems. While the overall music industry battles against decline, the live music sub-segment has flourished and grew 8% to £743m in 2007, which is equal to 57% of the recorded music market (source: Department of Culture, Media and Sport).

Film production in the UK could be considered either Special Event or Geographic peak usage. The chart below shows the number of features produced or part-produced in the UK since 1992.

Films produced in the UK



Source: UK Film Council Statistical Yearbook

In aggregate, the theatre, music and film data suggests modest growth market for these media in the UK. However, the PMSE equipment usage within these disciplines is much more difficult to gauge. Trends for growth in equipment use within the PMSE segment include the rising complexity of productions in general, and the rise of specific applications such as reality TV. Illegal use in the licensed bands also consumes spectrum, but by its nature is not tracked in the allocations database. Equally, there is little evidence that illegal use has had a significant detrimental effect on licensed spectrum users.

As a result, the Sagentia forecast seems reasonable based on the benchmark data above. Establishing usage in detail is very difficult without a major in-depth interview process of end users. The growth levels used as inputs for the spectrum demand process may slightly overestimate the market demand for PMSE applications, but any overestimation is healthy in the context of a demand model intended to assist in spectrum allocation.

One additional point to note is that any significant movement towards HD audio from studio-based producers would increase future spectrum demand considerably, and may render the existing demand forecast inaccurate over the longer-term. However, HD audio is a nascent market and its widespread adoption by the market, and therefore the additional spectrum required by it, is far from certain.

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