Technology Evolution in the PMSE Sector - Appendices

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Appendix A Methodology

Our methodology for assessing technology evolution in the PMSE sector is described below. We begin with an overview of the objective of this study, and describe the engagement strategy (interview programme) employed.

A.1 Objective of this study

Our study set out to answer the key question from Ofcom:

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

We addressed this key question though four subsidiary areas of investigation:

1. Evaluation of how the demand for spectrum may rise per use due to an increase in production quality;
2. Identification of future drivers likely to lead to an increasing quantity of demand for spectrum by the PMSE sector.

In each case we identified each driver of demand, justifying why it is included, and estimating by how much will it increase demand in transmission capacity ('bits per second'). Therefore, remaining areas of investigation were:

3. How future technological innovations could reduce this demand by using available spectrum more efficiently;
4. How future working methods or different approaches – which could be separate from the technology – could reduce this spectral demand.

Again, in each case we identified how the technology or method satisfied the expected PMSE requirement and mitigated the forecasted increase in demand for spectral bandwidth ('Hertz').

A.2 Engagement strategy

Our engagement strategy identified industry demand- and supply-side stakeholders for interview derived from key activities such as co-participants in industry interest groups and attendance at relevant conferences which Cambridge Consultants attended during the course of the study. A list of stakeholders interviewed is provided in Table 1, below. An interviewee introductory email was sent to stakeholders, which outlined the purpose of the study and the nature of the interview (see Section 2.3). An interview guide was developed in order to streamline the interview process; this guide is shown in Section 2.2.

A.3 List of PMSE demand- and supply-side stakeholders interviewed

Table 1, below, sets out details of stakeholders interviewed, including name, title and organisation, and identification of whether the stakeholder represents part of the demand (D), part of the mitigation possibilities (B) or both (B).

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-006	Commissioning Editor, TV LE	ITV	Demand	ITV is a producer broadcaster and the largest commercial TV network in the UK. Commissioning Editor, Light Entertainment
INT-007	Camera manufacturer	Arri Cine Technik Ltd	Demand	Global manufacturer and distributor of motion picture cameras, digital systems and lighting equipment. Senior Company Director level
INT-008	Radio mic manufacturer	Sennheiser UK Ltd	Both	Radio Microphone Manufacturer. UK Sales and Application Specialist
INT-009	Radio camera supplier	Videosys Ltd	Mitigation	Design and manufactures products for TV, Film and A/V industries. Senior Company Director
INT-010	Communications equipment supplier	The Wireless Works	Demand	Technical Consultancy for wired and wireless communications. Senior Company Director level
INT-011	UAV manufacturer	Cambridge UAV	Mitigation	Cambridge Unmanned Aerial Vehicles design and manufacture range of aircraft for aerial video and surveillance. Senior Company Director level
INT-012	Radio camera link equipment manufacturer	Gigawave	Mitigation	Supplier of technology for TV broadcasting and live streams. Senior Company Director level
INT-013	Radio camera supplier	Videosys Ltd	Mitigation	Design and manufactures products for TV, Film and A/V industries. Sales Manager
INT-015	Technical head, TV news organisation	Independent Television News	Demand	British based news and content provider. Senior Management level for news gathering operations
INT-016	Independent TV producer	TwoFour Productions	Demand	TwoFour is a factual, features and entertainment television production company. Senior company officer level

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-017	Camera Manufacturer	Sony Europe Ltd	Both	TV camera, video link and radio microphone manufacturer. Product Specialist Cameras
INT-018	Radio microphone manufacturer	Shure Inc.	Mitigation	Global manufacturer of microphones and audio electronics. Product Manager, radio products; spectrum specialist
INT-019	Radio microphone designer	Wisycom Srl, Italy	Mitigation	Manufacturer of quality wireless audio systems. Senior Company Director
INT-020	Radio microphone manufacturer	Sennheiser	Mitigation	Radio Microphone Manufacturer. UK Sales and Spectrum Specialist
INT-021	TV technical futurologist	SRI International	Demand	Non-profit independent research and innovation centre based in US for government and industry. Senior Principal Scientist in vision technologies
INT-022	Head of Entertainment, UK broadcaster	Channel 4	Demand	British television broadcaster. Senior Management level for Entertainment
INT-023	Radio camera supplier	Broadband RF	Mitigation	Hire company broadcast quality digital, analogue and HD microwave links, radio cameras and accessories. Senior Company Director
INT-024	Digital radio microphone manufacturer	Sony Europe Ltd	Mitigation	TV camera, video link and radio microphone manufacturer. Senior Management level, Technology
INT-025	BBC R&D, HD video specialist	BBC Research & Development	Demand	British public service broadcasting corporation. Senior Research Engineer
INT-026	UAV manufacturer	Horizon AP	Mitigation	Provides remote aerial services including aerial video, stills and data capture. Senior Company Director level
INT-027	Radio mic hire/supply company	Autograph Sound Recording	Demand	Sound designer and supplier to theatre. Senior Management level and Radio microphone expert
INT-028	Outside broadcast sound supervisor	NEP Vision Ltd	Demand	A leading outside broadcast provider.- Management level, sound

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-029	Commissioning Editor, TV LE	ITV	Demand	ITV is a producer broadcaster and the largest commercial TV network in the UK. Commissioning Editor, Light Entertainment
INT-030	TV technical futurologist	National Association of Broadcasters	Demand	Trade Association for broadcasters in the US. Senior Company Director level in Technology
INT-031	Radio mic manufacturer	Shure Distribution UK.	Mitigation	Global manufacturer of microphones and audio electronics. Management level in Pro Audio Group
INT-032	Sound Supervisor, TV light entertainment	Video Sound Services Ltd	Demand	Audio services provider to broadcasting community (worldwide) for all types of programming. Senior Company Director level in Sound
INT-034	Radio microphone manufacturer	Sennheiser Electronic GmbH & Co KG	Mitigation	Radio Microphone Manufacturer. Senior Company Management, Engineering
INT-035	Spectrum policy manager, TV broadcaster	BBC	Demand	British public service broadcasting corporation. Senior Management level for Spectrum
INT-036	Sound supervisor / designer	Sound Supervisor and PA designer	Demand	Freelance
INT-037	Spectrum planning consultant	Spectrum Matters Ltd	Demand	Radio Frequency and Broadcast engineering consultancy. Consultant Radio Engineer
INT-038	Radio microphone designer	Lectrosonics Inc.	Mitigation	Manufacturer of wireless microphone systems and audio processing products to broadcasting industry. VP Engineering
INT-039	BBC R&D, audio specialist	BBC Research & Development	Demand	British public service broadcasting corporation. Senior Audio Technologist
INT-040	CEO, TV sport producer	IMG	Demand	IMG is an international Management Group operating a sports and media business. Senior Management Level, Sport Production Worldwide
INT-041	BBC R&D, RF projects	BBC Research & Development	Mitigation	British public service broadcasting corporation. Management level for Distribution Core Technologies

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-042	Film production mixer	Film production mixer (sound recordist)	Demand	Freelance
INT-043	Radio camera link equipment manufacturer	Cobham Communications	Mitigation	A global leader in design and manufacture of antenna systems. Senior Company Director Level for Broadcast Systems
INT-044	Film production mixer	Film production mixer (sound recordist)	Demand	Freelance
INT-045	MIMO on-camera link equipment manufacturer	Boxx TV	Mitigation	A supplier of digital microwave solutions to the broadcast industry. Senior Management level
INT-046	Film production mixer	Film production mixer (sound recordist)	Demand	Freelance
INT-047	Digital radio microphone manufacturer	Zaxcom	Mitigation	Radio microphone manufacturer. Founder and CEO.
INT-048	Sound designer, large outside events	Auditoria Pty Ltd	Demand	Technical design and management of audio, communications, audio visual and infrastructure for major events. Company Director
INT-049	Film production mixer	Film production mixer (sound recordist)	Demand	Freelance
INT-050	Technical head, sports broadcaster	BBC TV	Demand	British public service broadcasting corporation. Management level Outdoor Broadcasting & Special Events, Sport
INT-051	Formula One	Formula One Management Ltd	Demand	A subsidiary of Formula One World Championship Limited, FOM designs and operates technical systems for broadcasting global motor racing events. Senior Technical Expert.
INT-052	Director of Sport, TV broadcaster	BBC Sport	Demand	British public service broadcasting corporation. Director and directorate Chief Engineer

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-053	Theatre head of sound and broadcast	The Royal Opera House	Demand	Royal Opera House, London home to the Royal Opera and the Royal Ballet companies and guest events. Dept. Manager, sound and broadcasting
INT-054	Technical head, TV news organisation	London Live News	Demand	A new 24/7 entertainment channel owned by London Evening Standard, for television, online, tablets, mobile, taxis and outdoor media exclusively for the London area. Chief Engineering Manager
INT-055	Technical head, sports broadcaster	ESPN Disney, Sport	Demand	A US-based global sports broadcasting company operating cable, satellite networks and radio, internet and wireless platforms. Senior director level, Engineering
INT-056	Technical head, TV news organisation	Sky News	Demand	Sky News is a dedicated news channel providing 24 hour news coverage via TV, mobile, online, radio and iPad platforms. Senior Management, operations
INT-057	RF designers' panel	Cambridge Consultants	Mitigation	Product development and technology consultancy. RF design experts
INT-058	Technical head, sports broadcaster	IMG	Demand	IMG is an international Management Group operating a sports and media business. Senior Director level, Sport
INT-059	Sports Technical manager, UK broadcaster	Sky Sports	Demand	UK home entertainment and communications company, provides television content including six sports channels, online live streaming and iPad sport apps. Senior Management, operations.
INT-060	Technical director, film studio	Pinewood Studios	Demand	Part of the Pinewood Studios Group, Pinewood Studios is a major British film and television studio. Senior Operations level
INT-061	Glastonbury organiser	APL Event	Demand	Events management organisation. Specialist for Glastonbury.
INT-062	West End producer	Cameron Mackintosh	Demand	For over 45 years Cameron Mackintosh has been producing musicals, including *Les Misérables, The Phantom of the Opera* and *Cats*. Chief Executive Officer.

Ref	Brief role	Stakeholder Organisation	Demand / Mitigation	Details of stake(s) and of person interviewed
INT-063	West End producer	David Ian Productions	Demand	David Ian Productions is a leading entertainment company, formed in 2006, and specialising in presenting large-scale theatrical productions in the UK, the US and internationally.
INTM-001	Mobile network operator	Telefonica	Mitigation	Provides mobile and fixed communication services in Europe and Latin America. Senior Management level for Spectrum Policy
INTM-002	Spectrum specialist, mobile industry	GSMA	Mitigation	Industry body. Spectrum specialist
INTM-003	Mobile network operator	Orange Group	Mitigation	Provides mobile and fixed communications, internet, data and multimedia services worldwide. Senior Company Management level, Management of Spectrum
INTM-004	Mobile Virtual Network Operator	Stream Communications	Mitigation	Wireless network service for connected devices worldwide over GSM and Satellite. Technical management level

Table 1 List of PMSE demand- and supply-side stakeholders interviewed

A.4 Stakeholder interview guide

The following interview guide was used to derive quantitative and qualitative responses to demand- and supply-side PMSE considerations.

Interviewee name and details

Interviewee	
Position	
Company	
Address	
Telephone	
Email	
Interview date/time	
Interviewer	

Introduction

We are currently undertaking a study on behalf of Ofcom to evaluate the future demand for radio spectrum to support Programme Making and Special Events (PMSE) wireless communication – which includes radio microphones and in-ear monitors, wireless video links (including wireless cameras) and intercom systems – with the aim of:

- *Gauging the demand for radio spectrum over the next five to ten years, especially as production quality increases,*
- *Finding and assessing innovations in technologies and working practices, to use spectrum more efficiently.*

This study will support Ofcom's strategic view on the spectrum requirements for PMSE and how they can best be met.

Demand interviewees: industry demand; market drivers and capacity

In your view what are the quantities of the wireless devices that you are involved with today, and what do you predict them to be over the next 5 and 10 years?

Device Prompts: radio microphones, personal ('in-ear') monitors, wireless cameras, longer range audio/video links, wireless talkback/ intercom

What are the key drivers that are affecting both the *quantity* and *quality* of wireless devices – needed for your activities now and in the next 5 years? And why?

Driver Prompts: increased production quality (picture resolution etc.), number of productions, size of productions, fragmentation of rights

What are the problems that you face when you use wireless devices for your activity (activities)?

Prompts: Administrative stumbling blocks, technical performance issues, production demands

Do you see in the future any impact technically, or from other industry uses, affecting your use of wireless devices?

What do you see as the next big thing in your industry area and how will this affect spectrum demand for wireless devices?

Demand interviewees: Estimation of Future PMSE Demand

[Interviewees are asked beforehand to provide this information via email – use questions in this section if not answered in email]

A key part of this study is to estimate the future demand for wireless devices for PMSE.

Could you estimate the number of events your company/organisation will be involved in this year?

In your view has the number increased over recent years? Do you see anything coming up in the future that will affect this rate?

Prompt e.g. sporting events, film productions

For each event what is the main UK location? [where it isn't obvious]

Please estimate the number and types of wireless devices that are expected to be used for the largest events that you are involved with, within one location?

In your view how will the number and types of wireless devices change over the next 5 years? Would you like to see different ways of licensing spectrum for your activities?

Prompts: Licence-exempt; some halfway house where you get spectrum cheaper if you have to perform some other activity like checking before use; lower quality spectrum at lower cost.

In your view what will be the next generation of innovations specifically for:
[use questions/areas relevant to interviewee]

- Sport coverage

  Prompts: following developments of cameras on accompanying vehicles and on competitors themselves in the next 5 years?

  Are there any additional sports are likely to have TV coverage in the next 5 years?

- Live performance
- Television and film production
- News events

Demand interviewees: Trends in enhancing audiences' experiences

In your view what are the current trends that are focused on enhancing the experience for live audiences?

General prompts: personal screens, local audience participation

Sport provider prompts: use of personal screens, smartphones running event apps, streamed video feed

Major production and equipment hire companies prompts: trends in the West End /major theatres: video screens, interactivity with audience

In your view what are the future trends for enhancing experience for home audiences, and how do you think this will affect how much content you need to capture?

Prompts: 'red button' options, second screens in the home (viewing on iPads etc.), possibility of second main screen, viewpoint/perspective choice, iPlayer feeds

Demand interviewees: Effect of Licensed Shared Access with other services [technical respondents only]

What are your views on the concept of Licensed Shared Access with other services? For example in a new band 550-606 MHz?

We would like to get your views on a possible 3 level Licensed Shared Access structure where you have, for example:

Full exemption e.g. like the 'channel 70' allocation 863-865 MHz

Fully licensed by Arquiva PMSE or similar i.e. fully protected

Intermediate 'lower quality' licensing in which a lesser level of enforcement against interference might be appropriate, at a lower cost, and where criticality of the service is lower.

Do you think this type of LSA structure is *fit for purpose*?

What are the advantages and disadvantages of this type of structure?

Have you had any experience of automated / cognitive / sensing techniques for PMSE?

Demand interviewees: Final questions

In your view what will be the next generation of innovations in wireless devices specifically for your area of interest?

What innovations would you like to see?

Are there any additional comments that you would like to make that you think would be beneficial for our research?

Is there anybody else that you could recommend that we could speak to in this field for our study?

Thank you for participating in the interview

Supplier interviewees: Technology Innovation in the PMSE sector

What products do you make [if not already known] and what volumes do you ship annually, and what growth do you forecast?

In your view what are the major technology and demand drivers in the PMSE space that are affecting the demand for spectrum? What are the major drivers in the PMSE space?

In your view what will be the next generation of innovation specifically for:

- Sport coverage
- Live performance
- Television and film production
- News gathering?
- Any other area that you know you [do or might] sell to?

What more spectrally efficient solutions are you selling now than in the past?

<u>Prompts/examples of past solutions</u>: analogue radio microphones, single carrier / single path video links, improved codec/compression

What future technology innovations could reduce the demand by using spectrum more efficiently?

> *Prompts: More/better digital transmission, time division multiple access (TDMA), data compression, system integration (closer coupling to the rest of the system). These interviews will have RF and signal processing system designers present to prompt and develop further technical discussion.*

What is on your R&D roadmap to improve spectral efficiency and resilience to interference within a more spectrum constrained environment?

> *Prompt: consider influence(s) from other, non-PMSE sources?*

Do you feel that there is pressure on radio spectrum that is affecting R&D practices?

What do you consider the maximum carrier frequency feasible for your product(s)?

> *Prompts: propagation distance decreases with frequency for given power; antenna efficiency can increase with frequency for small antennas; antenna Q might be an issue?*

In your view what specific future developments do you expect in:
[relevant to interviewee]

- Handheld and flying cameras?
- Single and multichannel audio devices?
- Any other devices in your market area?

For each technology mentioned, on a scale of 1 to 5 (1 very unlikely and 5 almost certain) how likely do you think this new technology will be commercially available to the PMSE industry

- within 5 years?
- over 10 years?

What risks do you see with these technologies?

In your view what are the advantages (if any) of implementing polite assess technologies e.g. listen-before-talk, ask-before-talk or cognitive techniques for PMSE applications?

Are you involved in cognitive techniques?

> *Prompt example: the C-PMSE project in Germany [ministry for economics and technology] and ETSI*

Future working practices/methods and approaches

In your view what future working methods or different approaches could be employed to reduce spectral demand?

> *Prompts: Closer coupling to rest of programme chain [to use radio resource only when needed], local frequency re-use/co-ordination, use of services like mobile/PMR*

What do you see as the barriers to employing these different approaches?

For each new work practice,

- On a scale of 1 to 5 (1 very unlikely and 5 almost certain) how likely do you think this new work practice will be adopted by the PMSE users over the next 5 years?
- How many years do you think it will take before the practice will be routinely used/ adopted by the industry?

Final questions for 'Supply' side only

Are there any additional comments that you would like to make that you think would be beneficial for our research?

Is there anybody else that you could recommend that we could speak to in this field for our study?

Thank you for participating in the interview

A.5 Stakeholder interviewee introductory email template

This following sets out a draft of the email that was sent following initial contact to the stakeholders identified in the PMSE study work. For some special cases – including for example Arqiva PMSE and some mobile operators – a different email or other form of contact was used.

Dear **XXX**,

Cambridge Consultants is a leading technology innovation consulting company, based in Cambridge, UK.

We are currently undertaking a study on behalf of Ofcom to support their strategic view on the spectrum requirements for Programme Making and Special Events (PMSE) and how these can be best met. The study will build on Ofcom's evaluation of the future demand for radio spectrum to support PMSE wireless communication – which includes radio microphones and in-ear monitors, wireless video links (including wireless cameras) and intercom systems. Our main aims are to

- gauge the demand for radio spectrum over the next five to ten years, especially as production quality increases,
- find and assess innovations in technologies and working practices, that have the potential to improve spectrum efficiency.

As part of this research we are keen to engage technical experts within broadcasters, large event, theatre and film producers, who have experience and knowledge of using radio devices in their activities and are able to provide a view on these services and the future direction of their requirements. We are also keen to solicit the views of the corresponding equipment manufacturers in the PMSE industry who can provide a view on current and future technological innovations.

As **the XXX [broadcaster etc]** at **XXX,** I would be very grateful if you could help us with your perspective on the current and future trends in **XXX [Sport coverage / live performance / TV / film production / radio mic design / video link design / etc]** and on emerging technological developments that enhance the experience of different audiences, and that will impact on the type of content originated and transmitted.

For this we ask you to participate in a 30 minute telephone interview. Your participation will allow us to gather the best possible information to inform future regulation, ensuring sustainable access to appropriate spectrum.

Please let me know if you would be available for such an interview and, if possible, a date and time when it would be best for us to phone you. We are aiming to schedule interviews between **24th February and XX March 2014.**

I look forward to hearing from you,

Best regards
XXX

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Appendix B Straw-man reference for a co-ordinated wireless audio system

B.1 Introduction

This is a straw-man proposition for a possible radio microphone or in-ear monitor system with a 5-10 year time-scale, for discussion with manufacturers of radio systems. It is not a complete design as significant factors[1] are not yet determined, and it is possible that we may need to appeal to Moore's law concerning power consumption and cost of digital elements over the 5-10 year time being considered.

The layout aims to borrow techniques from the current-day, or near-future, LTE physical layer. A base station unit provides a common downlink and co-ordinates all connected 'client' units (which will usually be transceivers) in time and frequency, including the allocation of bit-rate per user application. There could be more than one application per client unit (e.g. microphone and personal monitor).

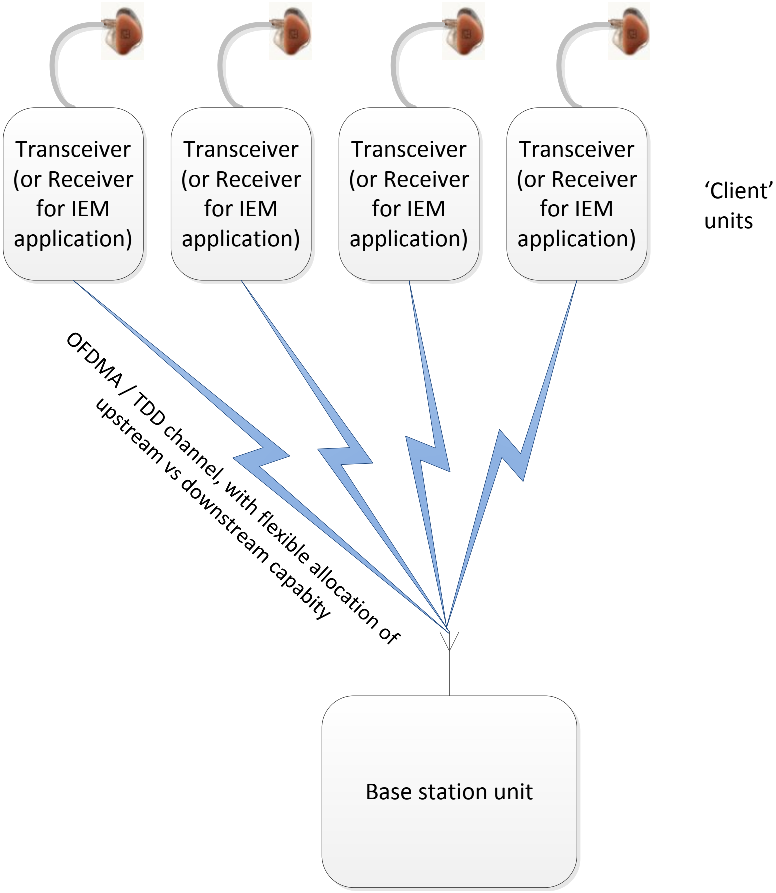

Figure 1 – Example of proposed future in-ear monitor system using LTE-like technology

The carrier system would be OFDMA from base station to client, and could be the similar from client to base station. The multiplex would be designed to fit within an 8MHz TV channel, and a modified form would be offered for regions that use 6MHz TV channel width.

[1] See section B.3 of this document

B.2 Possible parameters.

Table 2 gives possible design figures for an OFDM system for multi-channel audio transmission which, based on LTE technology, uses techniques that should become readily available to designers within the course of a few years. Two configurations are offered within a 7.5MHz wide channel, depending on the signal to noise ratio available in the channel.

Item	Configuration 1	Configuration 2
Constellation	QPSK (2 bits/symb)	16QAM (4 bits/symb)
E_b/N_0 required for BER=10^{-7}	11.7dB	16.1dB
Signal : (noise + interference) ratio in 8MHz channel	14dB	20dB
Bandwidth available	7.5MHz	
Transmission system	OFDMA, TDD	
Number of OFDM subcarriers	500	
Symbol period (including 1/32 cyclic prefix)	69µs	
Symbol rate	14.6kHz	
Bit rate per subcarrier	29.1kbit/s	58.2kbit/s
Symbols available after overheads (see Figure 2), and allowance for occasional block in opposite direction	~80%	
Code rate for FEC etc.	4/5	4/5
Gross bit rate	9.4Mbit/s	18.8Mbit/s
Audio payload per channel (16 bit, sample rate 48kHz)	768kbit/s (programme quality: less for comms.)	
Total number of programme quality channels	12	24

Table 2 – Parameters for two possible OFDM configurations

The assumption is that the audio channel will be uncompressed 16-bit, 48kHz sample rate; greater sample depths being accommodated by some sort of range data (similar to the original NICAM approach). Forward error correction is allowed for.

No proposal is made for the allocation of audio data to subcarriers and symbols, but a high degree of robustness could be achieved by an appropriate diverse allocation.

The period of the data block sent is proposed to be 7 symbols = 480µs to give acceptable latency in all applications – there being only small further delay due to codecs etc., as uncompressed 16-bit audio data is being sent.

B.3 Straw-man OFDM implementation

The figure shows a proposed carrier and symbol configuration:

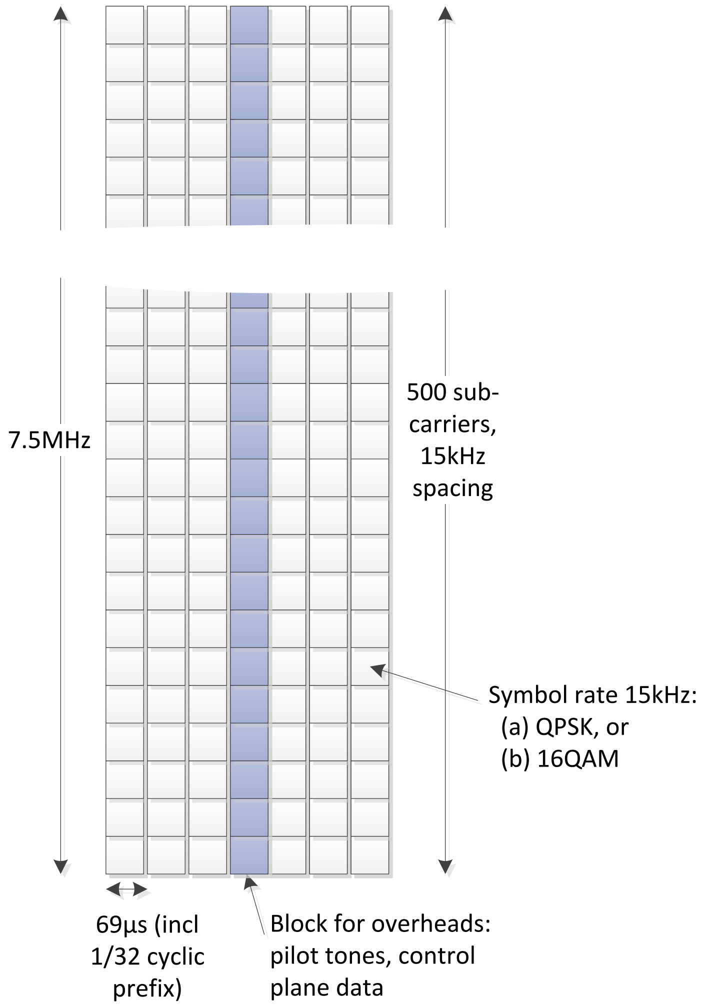

Figure 2 – Straw-man OFDM configuration showing signal in one direction only

Figure 2 shows a possible resource block, without showing how payload is multiplexed into the block.

A central co-ordination function is needed – the base station as shown in Figure 1.

Microphones and intercoms are transceivers, and a downstream resource block is sent occasionally to provide synchronisation and co-ordination.

Client devices with in-ear monitor application only could be receive-only.

Various mitigation techniques can be used in upstream transmission to manage RF signal peak-to-mean ratio.

The system could be configurable for constellation, transmit power, to provide optimal solution per application.

Channel filtering is required only to remain within the 8MHz TV channel

At the proposed constellations, and with the required linear RF power amplifier, this proposed system should be deployable without the need for intermodulation planning.

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Appendix C Link budget calculations for a ground-to-air video link at 2.5 and 7.1GHz

This Appendix contains calculations for the case of an up-link from a motorcycle or other small vehicle, to an aircraft circling at 3000m height, of a video signal at about 20Mbit/s in a 10MHz bandwidth, as described in Section 3.2.5 of the main report. This calculation is done at 2.5GHz and 7GHz, and is done on the assumption that a somewhat more efficient antenna can be fitted within the same space at 7GHz, with, if necessary, a slightly more accurate positioning system. The antenna figures used are shown in Table 7. In both cases a 1W transmitter power is assumed.

The following losses are compared, all assumed to be simultaneous for a worst case of a sporting event which passes through landscaped urban topography where trees and tall buildings might be simultaneously present:

- Free space propagation
- Atmospheric, including water vapour (ITU-R P.676-6)
- Rain (ITU-R P.618-8)
- Polarisation errors and misalignment – estimated about twice as large at 7.1GHz as at 2.5GHz.
- Cloud (ITU-R P. 840-3)
- Tall buildings – see Table 5
- Trees – see Table 6

In this hypothetical case the link margin at 2.5GHz is 10.9dB, but at 7.1GHz it falls to 1.3dB. A further increase in antenna gain would make their deployment and control much more difficult, so the main remedy would be to increase the transmitted power by 10dB (i.e. to 10W).

2.5 GHz				
Frequency of Operation	f1	2.5	GHz	
Wavelength	λ1	0.12	m	
Transmit Power	P_t	1	W	
Gain of the transmitting motorcycle antenna	G_mo	3	dBi	From [14]
Gain in log scale		1.9952623	W	
Implementation Loss in the transmitter	IL_mo	0.5	dB	Includes cables loss and noise figure
Duty Cycle Gain + Coding Gain	G_du	10	dB	32 ms average in 100 ms window
EIRP	EIRP	1.9952623	W	
EIRP in log scale		3	dBW	dBm = dBW+30
EIRP		22.5	dBm	Up to +30 dBm transmit power (1W)
Gain of the receiving aircraft antenna	G_pl	18	dBi	From [11]
= (linear)		63.095734		
Implementation Loss in the receiver	IL_pl	1	dB	Includes cables loss and circuit loss
Distance between transmitter and receiver	D	3	km	
		3000	m	
Propagation Losses				
Free Space Path Loss	L_f	109.95123	dB	d in km and f in MHz
Attenuation due to atmosphere (dry air + water vapour)	L_at	0.007	dB	ITU-R P.676-6 and [7]
Attenuation due to rain	L_r	0.12	dB	ITU-R P.618-8 and [7]
Attenuation due to polarization	L_pol	0.25		
Attenuation due to misalignment	L_al	1.5		
Attenuation due to clouds	L_cl	0.08	dB	ITU-R P. 840-3 and [8]
Attenuation due to trees	L_tr	8.9431796	dB	
Attenuation due to Buildings	L_bl	3.7135433	dB	
Bandwidth of the signal	B	10	MHz	Channel bandwidth
Boltzmann's Constant	k	-228.56985	dBW/Hz/K	Boltzmann's constant in dB
Noise Bandwidth	B_N	70	dBHz	
System Noise temperature in dB	T_S	24.602211	dBK	NF = 3dB
Noise power	P_N	-133.96764	dBW	
Received Power	P_R	-105.06495	dBW	
Data Rate	Rb	20	Mbps	Raw data rate
Data Rate in log scale		73.0103	dB	
Energy per bit	E_bit	-178.07525	dB	From [21]
C/N ratio		28.902693	dB	10^-4 BER requires SNR=18 dB SNR for 16 QAM
Remaining link margin		**10.9027**	dB	

Table 3 Link calculations at 2.5GHz

7.1 GHz				
Frequency of Operation	f2	7.1	GHz	
Wavelength	λ2	0.0422535	m	
Transmit Power	P_t	1	W	
Gain of the transmitting motorcycle antenna	G_mo	8	dBi	
Gain in log scale		6.3095734	W	
Implementation Loss in the transmitter	IL_mo	1.5	dB	Includes cables loss and noise figure
Duty Cycle Gain + Coding Gain	G_du	10	dB	32 ms average in 100 ms window
EIRP	EIRP	6.3095734	W	
EIRP in log scale		6.5	dBW	
EIRP		25	dBm	Up to +30 dBm transmit power (1W)
Gain of the receiving aircraft antenna	G_pl	35	dBi	[15]
= (linear)		3162.2777		
Implementation Loss in the receiver	IL_pl	2	dB	Cable and circuit loss
Distance between transmitter and receiver	D	3	km	
		3000	m	
Propagation Losses				
Free Space Path Loss (FSPL)	L_f	119.01759	dB	d in km and f in MHz
Attenuation due to atmosphere (dry air + water vapour)	L_at	0.02	dB	ITU-R P.676-6 and [7]
Attenuation due to rain	L_r	0.8	dB	ITU-R P.618-8 and [7]
Attenuation due to polarization	L_pol	0.5		
Attenuation due to misalignment	L_al	3		
Attenuation due to clouds	L_cl	0.75	dB	ITU-R P. 840-3 and [8]
Attenuation due to trees	L_tr	17.035627	dB	
Attenuation due to Buildings	L_bl	8.2216592	dB	
Bandwidth of the signal		10	MHz	Channel bandwidth
k=Boltzmann's Constant	B	-228.56985	dBW/Hz/K	Boltzmann's constant in dB
Noise Bandwidth	k	70	dBHz	
System Noise temperature in dB	B_N	27.973095	dBK	NF = 5dB
Noise power	T_S	-130.59676	dBW	
	P_N			
Received Power		-111.34488	dBW	
Data Rate	Rb	20	Mbps	Raw data rate
Data Rate in log scale		73.0103	dB	
Energy per bit	E_bit	-184.35518	dB	From [21]
C/N ratio	P_R	19.25188	dB	10^-4 BER requires SNR=18 dB SNR for 16 QAM
Remaining link margin		**1.25188**	dB	

Table 4 Link calculations at 7.1GHz

BUILDINGS: Walfisch-Ikegami NLOS Model [22]			
2.5 GHz			
Distance in meters	d	5	m
Distance between buildings	w	100	m
Center to Center distance between buildings	b	200	m
Aircraft antenna height over street level	hb	3000	m
Mobile station antenna height	hm	1.5	m
Nominal height of building roofs	hB	175	m
Height of aircraft antenna above rooftops	Δhb	2825	m
Height of mobile antenna below rooftops	Δhm	173.5	m
Angle of incident wave with respect to street	φ	90	deg
Path Loss Term 1	Lrts	41.86539	dB
Path Loss Term 2	Lori	0.01	dB
	Lbsh	-62.1211	dB
	Ka	54	
	Kd	18	
	Kf	2.554054	
Path Loss Term 3	Lmsd	-38.1518	dB
L_bl = Lrts+Lmsd		**3.71354**	dB
7.1 GHz			
Distance in meters	d	5	m
Distance between buildings	w	100	m
Center to Center distance between buildings	b	200	m
Aircraft antenna height over street level	hb	3000	m
Mobile station antenna height	hm	2	m
Nominal height of building roofs	hB	175	m
Height of aircraft antenna above rooftops	Δhb	2825	m
Height of mobile antenna below rooftops	Δhm	173	m
Angle of incident wave with respect to street	φ	90	deg
Path Loss Term 1	Lrts	46.37351	dB
Path Loss Term 2	Lori	0.01	dB
	Lbsh	-62.1211	dB
	Ka	54	
	Kd	18	
	Kf	2.554054	
Path Loss Term 3	Lmsd	-38.1518	dB
L_bl = Lrts+Lmsd		**8.22166**	**dB**

Table 5 Attenuation due to buildings at 2.5 and 7.1GHz

TREES: Extended Empirical Roadside Model				
Using the procedure outlined in page 3-8 of [1], Section 3.3				
Using values in Table 3.1 for 1.5 GHz and P=5%				
θ (deg)	**θ (rad)**	**M(θ)**	**N(θ)**	**Comments**
60	1.047197551	2.09	8.36	Picked the 60 degree angle of elevation asuming aircraft is 3 km high and the radius of the area of coverage is 1.5 km
55	0.959931089	2.7525	10.56	
50	0.872664626	3.315	12.76	
45	0.785398163	3.7775	14.96	
40	0.698131701	4.14	17.16	
35	0.610865238	4.4025	19.36	
30	0.523598776	4.565	21.56	
25	0.436332313	4.6275	23.76	
20	0.34906585	4.59	25.96	
P(%)	**A(P,30°,1.5GHz) (dB)**	**A(P,30°,2.5GHz) (dB)**	**A(P,30°,7.1GHz) (dB)**	Comment
20	9.820847309	12.94317958	25.03562656	Picked 20% P value because this is for slow moving runners (and not for F1 cars)
15	10.08196927	13.28731979	25.54175601	
10	10.45	13.77235816	26.25510541	
5	11.07915269	14.60153675	27.47458427	
1	12.54	16.5268298	30.3061265	
Reduction due to single row of trees		4	8	dB - Ref [1] figs 3-7 and 3-8, interpolating between the two frequencies plotted
	L_tr =	8.943179579	17.03562656	

Table 6 Attenuation due to trees at 2.5 and 7.1GHz

ANTENNA CALCULATIONS						
Location	**Type**	**Polarization**		**Frequency (GHz)**		**Units**
				2.5	**7.1**	
Motorcycle	Yagi or Cylindrical helix	Linear, or circularly polarised with axial ratio ~4 dB	G_mo	**3**	**8**	dBi
			θHPBW_mo	360	360	deg
			φHPBW_mo	76	56	deg
Aircraft wing	Patch Array or dish	Circularly polarised with axial ratio ~2 dB	G_pl	**18**	**35**	dBi
			φHPBW_pl	27	15	deg
			θHPBW_pl	35	2	deg

Table 7 Antenna figures assumed

#	REFERENCES
[1]	Handbook of Propagation Effects for Vehicular and Personal Mobile Satellite Systems, EERL-98-12A (EERL), December 1998
[2]	http://www.radiowavesinc.com/pdf/7_GHz_(7.125-7.750)_High-Performance.pdf
[3]	http://www.tessco.com/products/displayProducts.do?groupId=90197&subgroupId=91178

#	REFERENCES
[4]	S. CAKAJ, Rain Attenuation Impact on Performance of Satellite Ground Stations for Low Earth Orbiting (LEO) Satellites in Europe, Int. J. Communications, Network and System Sciences, 2009, 6, 480-485
[5]	Aderemi A. Atayero, Matthew K. Luka and Adeyemi A. Alatishe, Satellite Link Design: A Tutorial, International Journal of Electrical & Computer Sciences IJECS-IJENS Vol: 11 No: 04
[6]	http://rf-video.com/pdf/mx3000b.pdf
[7]	http://descanso.jpl.nasa.gov/Propagation/Ka_Band/JPL_D27879.pdf
[8]	Investigation of the Effects of Cloud Attenuation on Satellite Communication Systems
[9]	Parsons, The Mobile Radio Propagation Channel, Pentech Press, 1992
[10]	http://www.prosoft-technology.com/Products/Industrial-Wireless/Accessories/2.4-GHz-Directional-Antennas/2.4-GHz-Yagi-Antennas
[11]	http://www.fab-corp.com/pdf/pa24.pdf
[12]	http://luxul.com/wp-content/documents/SPEC/LUX-SPEC-XW-24O-FP14.pdf
[13]	http://www.pulseelectronics.com/download/3279/r380500218pdf/pdf
[14]	http://www.l-com.com/wireless-antenna-24-ghz-9-dbi-radome-enclosed-high-gain-yagi-antenna
[15]	http://ultratelecom.kiev.ua/catalog/(7GHz,1.2m)20041227154950251901-HAA0712_00-PA3.pdf
[16]	http://live-gear.com/products/newstream/
[17]	http://broadcastrf.com/wp-content/uploads/delightful-downloads/2013/09/02-Gigawave-HD-Rate-Card-NEW-ADDRESS1.pdf
[18]	http://www.broadcast-services.co.uk/images/pdfs/Gigawave.pdf
[19]	http://www.presteignecharter.com/en/hire/ratecard
[20]	Hadaschik et al, ACHIEVABLE DATA RATE OF WIDEBAND OFDM WITH DATA-AIDED CHANNEL ESTIMATION, 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'06)
[21]	Ahmed et al, Performance Evaluation of DVB-T Based OFDM over Wireless Communication Channels, IMECS 2012, 14-16 March 2012
[22]	Walter Debus, Axonn, LLC, RF Path Loss & Transmission Distance Calculations, Page 3 et seq.

Table 8 References for Appendix C

Appendix D Modelling of highest carrier frequency feasible for a body-worn radio microphone

This Appendix contains a series of calculations for a hypothetical body-worn radio microphone transmitter, at a series of frequencies between 1GHz and 5GHz. The propagation loss from the transmitter to receiver is modelled in four parts:

- Model of FM radio microphone transmitter and receiver system, with the losses included as listed below. 50mW output power was modelled, and unity gain (0dBi) antennas.
- Short-range propagation losses estimated for outdoor and indoor deployments using ITU-R models.
- Shadowing loss from an adjacent person, taken from published work on shading by human bodies for the outdoor model, and allowances for Rayleigh fading for the indoor model.
- Measured total antenna efficiency of a short wire antenna mounted on to a radio microphone case which was worn by a person. The antenna performances measured are shown in Table 11.

The results are shown in Table 9 and Table 10 below. At frequencies higher than 2GHz or so, some improvement is likely to be achieved with a patch antenna in place of a wire antenna, as shown by the measurements at 2225 and 2475MHz.

Antenna efficiencies are seen to fall above around 1.5GHz, and the polar characteristic (in plan view) becomes very uneven when shadowed by the wearer. However, above 3GHz, both the efficiency and the polar characteristic show some improvement, and at 4850MHz, a fairly uniform plot is shown.

These results show that, within the range investigated, there is no fundamental limit to the frequency at which radio microphones can be deployed. To achieve the same range above 1GHz as for UHF TV bands will require higher gain antennas, which can readily be designed within an envelope considerably smaller than their UHF counterparts, but at the cost of greater directivity. In order to cover a wide physical space, more antennas would need to be deployed, each with its own diversity channel in the receiving system.

Higher transmitted power is another possibility, but there is already a penalty in power consumption for all RF circuitry at a higher frequency, so there may be a limit set by the acceptable size for a battery.

Ultimately, we expect that shadowing by other bodies (than that of the wearer) is likely to be a significant contributor to some higher limit in frequency, as cost will limit the number of receive antennas that can reasonably be deployed, especially outdoors where multipath propagation may be relatively low.

D.1 Radio microphone range estimated for a number of frequencies

FM 45kHz dev, 200kHz channel, outdoor model without multipath										
Frequency	1170	1400	1700	2225	2475	2900	3550	4850	MHz	
Antenna type tested (on body)	wire	wire	wire	wire	patch	wire	wire	wire		
Tx power	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	dBm	The mean transmitter power
Tx measured total antenna efficiency on body	-4.1	-8.0	-4.4	-4.7	-1.9	-3.2	-1.9	-6.4	dB	as measured
Polar worst over at least 30deg	-14.0	-19.0	-16.0	-20.0	-17.0	-16.0	-10.0	-10.0	dBi	
EIRP	-1.1	-10.0	-3.4	-7.7	-1.9	-2.2	5.1	0.6	dBm	
Range	**111**	**60**	**87**	**76**	**80**	**70**	**80**	**34**	**m**	Adjusted tp give range at which the Remaining Margin ~=0
Fixed path loss	-91.8	-81.1	-87.5	-85.2	-86.1	-83.7	-86.1	-75.4	dB	Basic transmission loss ITU-R P.1411 page 8, upper bound (but omitting fading margin as shadowing by person added below)
Receiver Antenna Gain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	dB	Assumed omnidirectional
Standard deviation of shadowing by other persons	-3.0	-4.0	-4.0	-5.0	-5.0	-6.0	-8.0	-11.0	dB	Kara: "Human body shadowing in short-range radio links ..."
Number of standard deviations used in calc	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		
The total log normal shadowing allowance	-6.0	-8.0	-8.0	-10.0	-10.0	-12.0	-16.0	-22.0	dB	
No fast fading <100m outdoor										
Antenna diversity gain [applies only to multipath]										
Received signal level	-98.8	-99.0	-99.0	-102.9	-98.0	-97.9	-97.0	-96.8	dBm	
NPSD	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	dBm/Hz	= kT
Receiver noise bandwidth	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	dBHz	The receiver is using 200kHz noise bandwidth
Receiver noise figure	3.0	3.0	3.0	4.0	4.0	4.0	5.0	5.0	dB	An estimate of what is possible
Receiver noise power	-117.9	-117.9	-117.9	-116.9	-116.9	-116.9	-115.9	-115.9	dBm	
Required CNR	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	dBm	Estimate for reasonable level quieting
Receiver sensitivity	-98.9	-98.9	-98.9	-97.9	-97.9	-97.9	-96.9	-96.9	dBm	Approximate receiver sensitivity
Achieved CNR	19.1	18.9	19.0	14.1	18.9	19.0	18.9	19.1	dB	
Remaining margin	0.1	-0.1	0.0	-4.9	-0.1	0.0	-0.1	0.1	dB	At maximum range this equals 0dB

Thermal Noise Parameters		
k =	1.38E-23	J / K
T =	20	C
kT =	-173.93	dBm/Hz
Receiver Noise Bandwidth		
B =	200,000	Hz
Rx, Tx heights		
h1	1.00	meters
h2	1.00	meters

Table 9 Outdoor radio microphone range estimates for frequencies between 1GHz and 5GHz

Deployment will be very near line-of-sight, and potential shading by other performers is added to the fixed path propagation loss. Higher antenna gains are easier to implement at higher frequencies, but fairly low receive antenna gain may be mandated where performers move around a lot. At least two-antenna diversity is assumed, in order to fill ‘gaps’ in the polar characteristic of the transmit antenna. No multipath propagation is modelled.

FM 45kHz dev, 200kHz channel, indoor model with multipath										
Frequency	1170	1400	1700	2225	2475	2900	3550	4850	MHz	
Antenna type tested (on body)	wire	wire	wire	wire	patch	wire	wire	wire		
Tx power	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	dBm	The mean transmitter power
Tx measured total antenna efficiency on body	-4.1	-8.0	-4.4	-4.7	-1.9	-3.2	-1.9	-6.4	dB	as measured
Polar worst over at least 30deg	-14.0	-19.0	-16.0	-20.0	-17.0	-16.0	-10.0	-10.0	dBi	
EIRP	-1.1	-10.0	-3.4	-7.7	-1.9	-2.2	5.1	0.6	dBm	
Range	**105**	**35**	**58**	**26**	**44**	**37**	**59**	**28**	**m**	The range at which the margin ~=0
Path loss exponent	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0		'Commercial' (= large room) - from ITU-R P.1238
Fixed path loss	-77.8	-68.9	-75.4	-70.1	-76.0	-75.7	-82.0	-77.6	dB	Path loss due to the path loss exponent used
Receiver Antenna Gain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	dB	Assumed omnidirectional
Standard deviation of shadowing by other persons	-5.0	-5.0	-5.0	-5.0	-5.0	-6.0	-8.0	-11.0	dB	(this row not used)
Number of standard deviations used in calc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		Assume body shadowing is mitigated by multipath
The total log normal shadowing allowance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	dB	
Fast fading indoor	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	dB	0.1% probability of event
Antenna diversity gain [mitigation of multipath]	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	dB	for diversity decision made on signal level
Received signal level	-98.9	-98.9	-98.8	-97.8	-98.0	-97.9	-96.9	-96.9	dBm	
NPSD	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	-173.9	dBm/Hz	= kT
Receiver noise bandwidth	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	dBHz	The receiver is using 200kHz noise bandwidth
Receiver noise figure	3.0	3.0	3.0	4.0	4.0	4.0	5.0	5.0	dB	An estimate of what is possible
Receiver noise power	-117.9	-117.9	-117.9	-116.9	-116.9	-116.9	-115.9	-115.9	dBm	
Required CNR	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	dBm	Estimate for reasonable level quieting
Receiver sensitivity	-98.9	-98.9	-98.9	-97.9	-97.9	-97.9	-96.9	-96.9	dBm	Approximate receiver sensitivity
Achieved CNR	19.0	19.1	19.1	19.2	19.0	19.0	19.0	19.0	dB	
Remaining margin	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0	dB	At maximum range this equals 0dB

Thermal Noise Parameters		
k =	1.38E-23	J / K
T =	20	C
kT =	-173.93	dBm/Hz
Receiver Noise Bandwidth		
B =	200,000	Hz

Table 10 Indoor radio microphone range estimates for frequencies between 1GHz and 5GHz

Deployment is indoor, assuming ‘commercial space’ for propagation loss and 30dB-deep nulls due to Rayleigh fading, with some mitigation from dual-antenna diversity. Shadowing by other bodies is not modelled, as it is assumed that indoors, multipath propagation will mitigate this. Higher antenna gains could be implemented more easily at higher frequencies to improve range, assuming that the range of performers’ movement is limited. If not, then multiple receiving antennas, each with its own receiver channel (making a multiple-antenna diversity system) could be deployed, at higher cost.

D.2 Propagation loss models

D.2.1 Outdoor

Outdoors, the ITU-R P.1411 [23] propagation model upper bound is used, but omitting the 20dB shading margin in formula (3), due to the short ranges being considered, and also that shading from individual bodies is accounted for separately:

An approximate upper bound $L_{LoS,u}$ is given by:

$$L_{LoS,u} = L_{bp} + \cancel{20} + \begin{cases} 25 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d \le R_{bp} \\ 40 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d > R_{bp} \end{cases} \qquad (3)$$

L_{bp} is a value for the basic transmission loss at the break point, defined as:

$$L_{bp} = \left| 20 \log_{10}\left(\frac{\lambda^2}{8\pi h_1 h_2}\right) \right| \qquad (4)$$

where R_{bp} is the breakpoint distance in m and is given by:

$$R_{bp} \approx \frac{4 h_1 h_2}{\lambda}$$

D.2.2 Indoor

Indoors, ITU-R P.1238 [24] propagation model is used, with coefficient N = 22, the figure given in P.1238 for commercial buildings, from 1.2GHz to 4GHz. The term $L_f(n)$ refers to loss between floors and is not used; it is assumed that everything is on the same floor in a radio microphone deployment.

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_f(n) - 28 \quad \text{dB} \qquad (1)$$

where:

- N: distance power loss coefficient;
- f: frequency (MHz);
- d: separation distance (m) between the base station and portable terminal (where $d > 1$ m);

D.3 Shadowing loss from adjacent person

References [25], [26] study the effect of a human body passing between transmit and receive antennas at various frequencies, in various scenarios including outdoor. Figure 3 shows the analysed results from a large number of measurements at a number of frequencies, as standard deviations for a log-normal (Gaussian) fading characteristic. A worst-case loss of twice the standard deviation is used in the model.

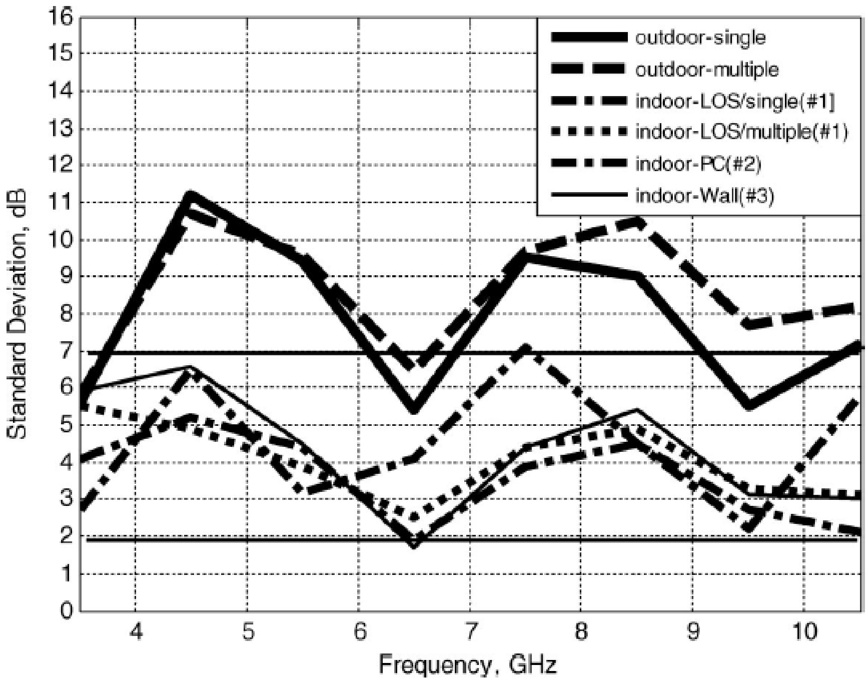


Figure 3 Standard deviation of human body shadowing (from [3])

For lower frequencies, data is given in [26] for 2.4GHz, and standard deviations for lower frequencies are extrapolated from the available data.

D.4 Measurement of antenna efficiency

Total antenna efficiencies with a mocked-up radio microphone transmitter case and short wire antennas were measured using an all-round receiving antenna array (type Satimo SG-64), with the radio microphone case clipped to a canvas belt worn in the small of the user's back – as a typical example of deployment by performers. In addition, one 2.4GHz patch antenna was measured for comparison.

The measured efficiencies are in Table 11.

Polar plots were also recorded (both plan-view 2D and 3D plots are shown in Figure 4 to Figure 11 below) and the 'worst-case over 30 degrees or more' dBi value was recorded by inspection, on the presumption that space diversity should resolve any sharper dips in radiation pattern. Indoors, multipath effects would also tend to 'fill in' any sharper nulls than this.

The measurements on antennas were done with a cable feeding from a signal generator together with a simple air-cored coaxial cable choke to minimise radiation from the cable, so were not fully realistic (as a radio microphone is self-contained without external connections) and this may have caused some anomalies in efficiency or polar pattern. A sanity check was carried out between the polar plot made at 1700MHz (Figure 6) and one made of a stand-alone Sennheiser 1800MHz belt-pack transmitter [27] and whilst there are detailed differences in the shape of the plot, the maximum EIRPs of +2.4 and -2dBi respectively, and minimum EIRPs of -25dBi in both cases, suggest that the anomalies are not great.

A full series of experiments could be carried out with a wide-range miniature signal generator fed from batteries, or using optical transmission of the RF signal to the antenna, to be certain that the arrangement is fully modelled.

Antenna type	Frequency MHz	Efficiency free space %	Efficiency on body %	Polar best dBi	Polar worst over >30deg dBi
wire	1170	76%	39%	2	-14
wire	1400	65%	16%	-1	-19
wire	1700	73%	36%	3	-16
wire	2225	52%	34%	3	-20
patch	2475	87%	64%	2	-17
wire	2900	53%	48%	5	-16
wire	3550	80%	64%	5	-10
wire	4850	29%	23%	-2	-10

Table 11 Measured antenna performance results over range 1GHz to 5GHz

In all cases, the radio microphone user faced in the +y, or 90º, direction and the radio transmitter and antenna were in small of the user's back (i.e. in the –y or 270º direction). The 2D polar plots are all plan view (i.e. looking down on the user's head).

The efficiency of the transmitting antenna (Terminal Efficiency on the plots) is the vector sum of the total radiated power, divided by the input power to the transmitting antenna. The radiated power is received by two sets of receiving antennas with different polarisations 90º apart: the plots show their measurements as Theta Efficiency and Phi Efficiency respectively.

$$TRP = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left(EIRP_\theta(\theta,\phi) + EIRP_\phi(\theta,\phi)\right)\sin\theta\, d\theta\, d\phi$$

and

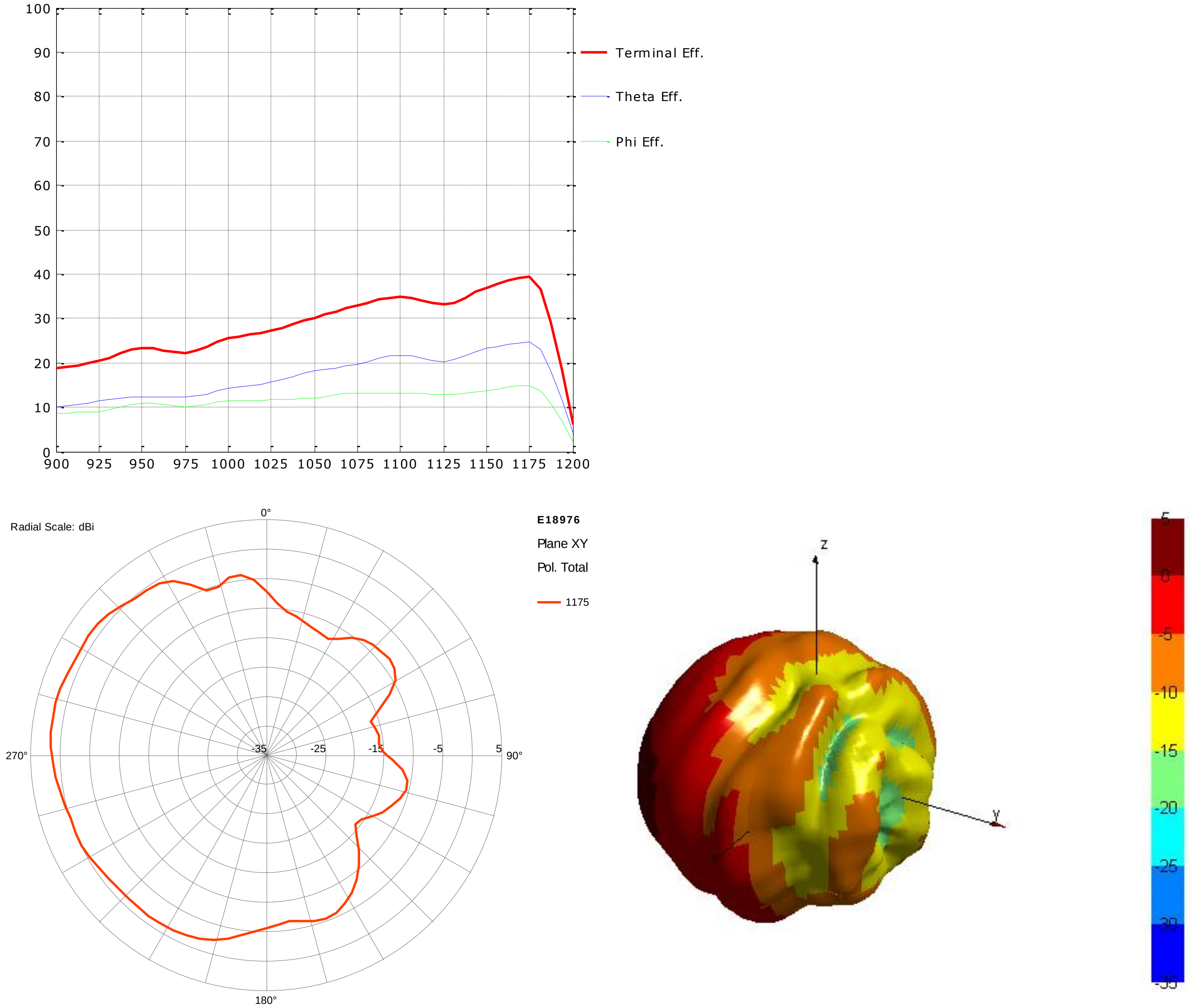
$$Efficiency = \frac{TRP}{Input\ power\ to\ Tx\ antenna}$$

where $EIRP_\theta$ and $EIRP_\varphi$ are derived from the received signals at the two sets of receiving antennas.

The Satimo measuring rig approximates the TRP integral by a series of samples:

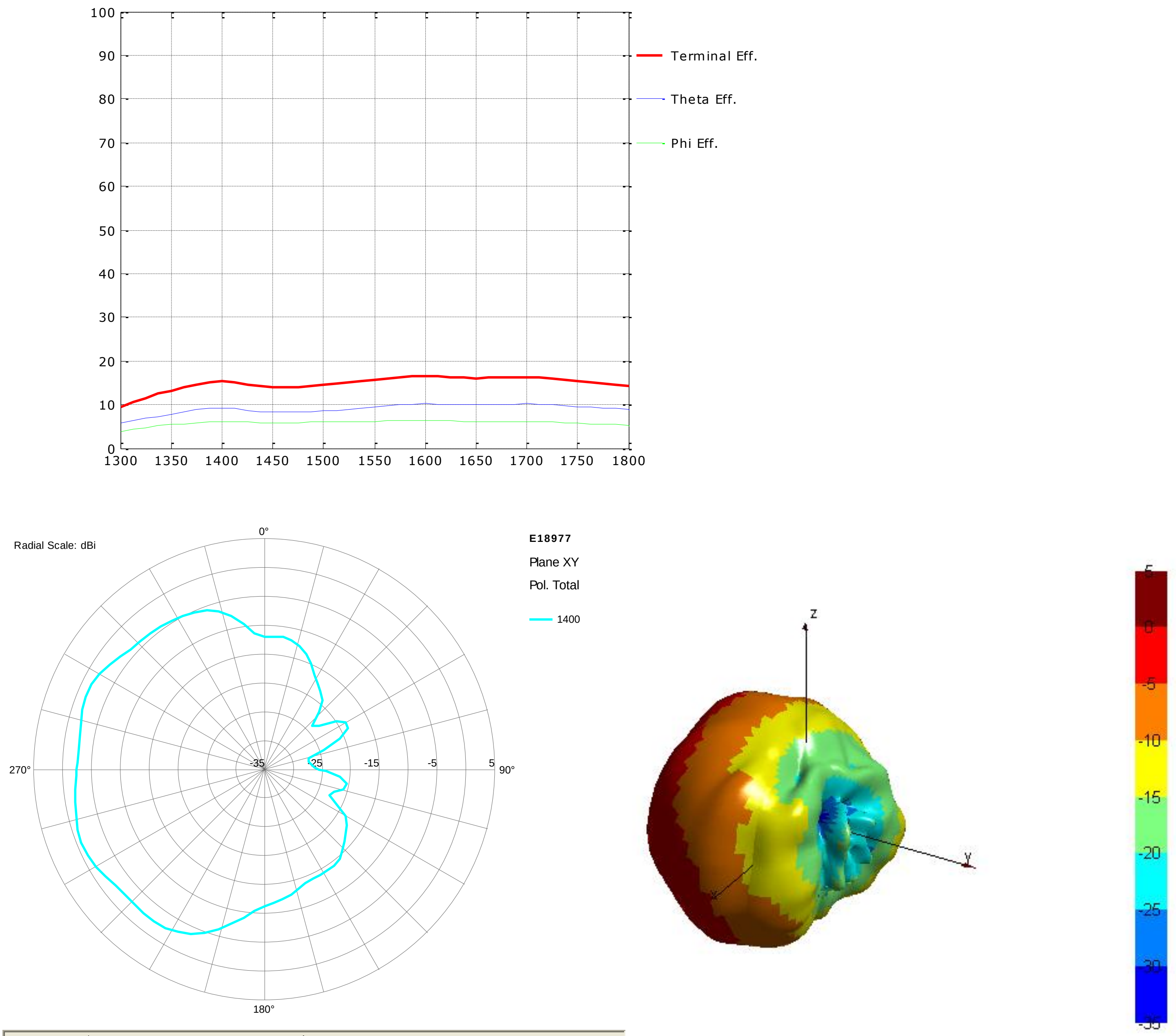
$$TRP \approx \frac{\pi}{2NM}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1}\left(EIRP_\theta(\theta_n,\phi_m) + EIRP_\phi(\theta_n,\phi_m)\right)\sin\theta_n$$

and for these tests, M = 64 and N = 32.



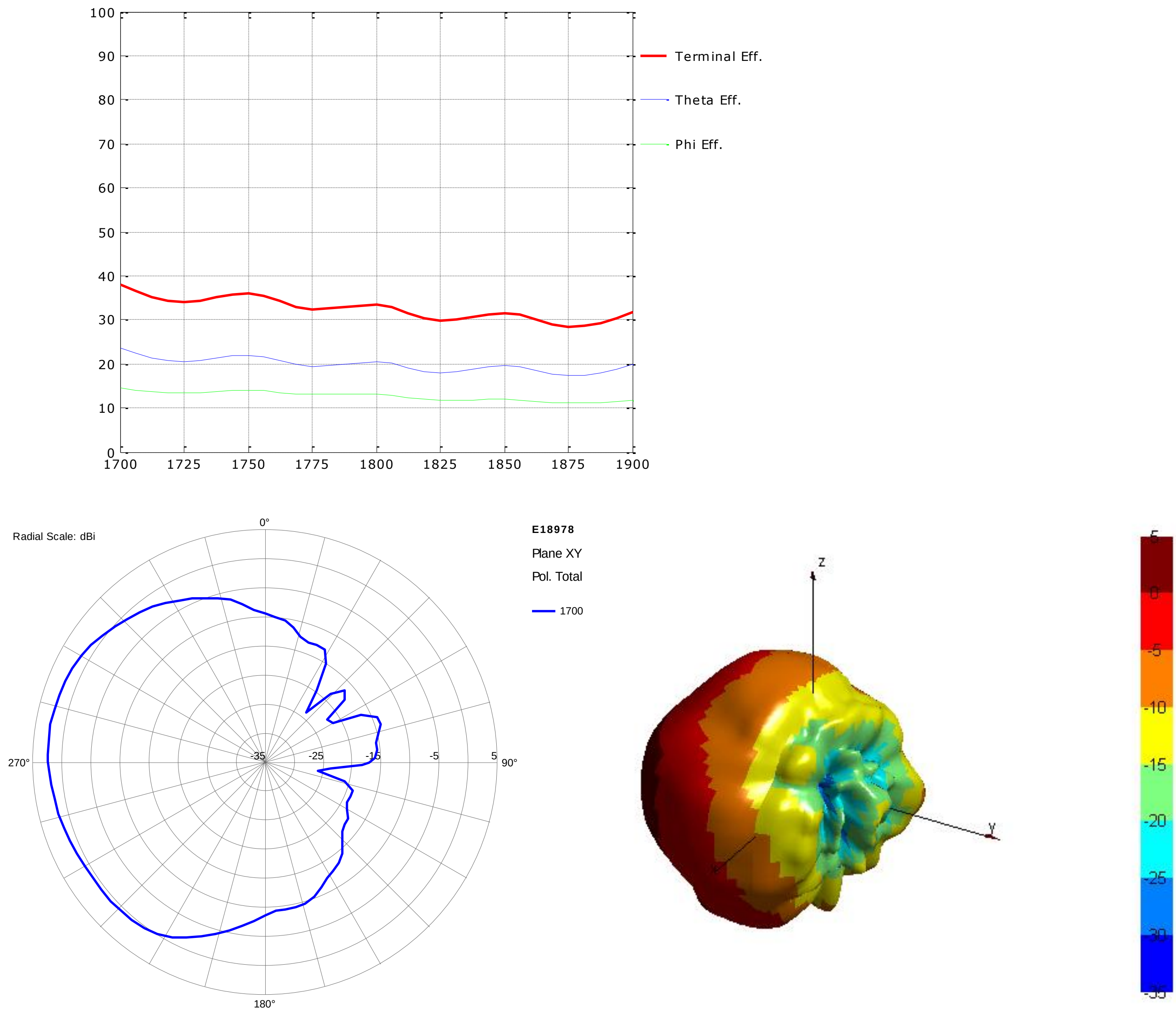
Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
> E18976: P1867 - jwj - 20-May-2014			
> Body800MHz			
> Plane: XY - Polarization: Total			
1175	1.8	-3.1	-2.5
Mean:	1.8	-3.1	-2.5

Figure 4 On-body antenna results: 1175MHz



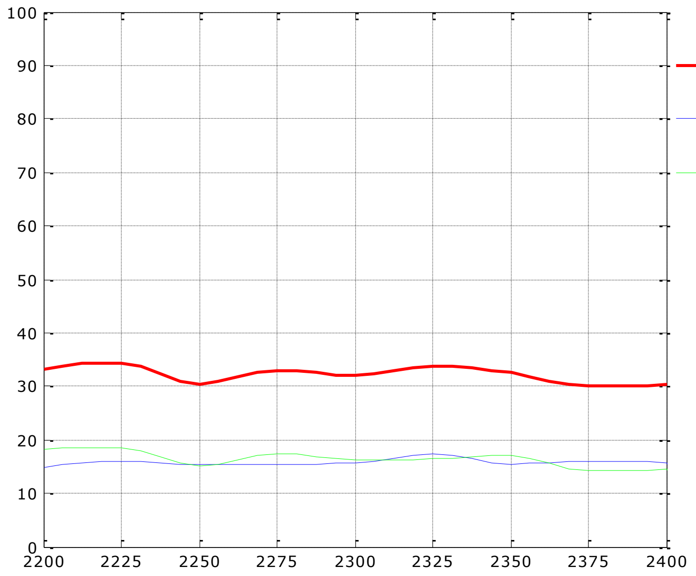

```
Freq.    Peak          Linear          Spheric
[MHz]    Gain          Average         Average
> E18977: P1867 - jwj - 20-May-2014
> Body1400MHz
> Plane: XY  -  Polarization: Total
1400     -0.8          -6.1            -5.4
Mean:    -0.8          -6.1            -5.4
```

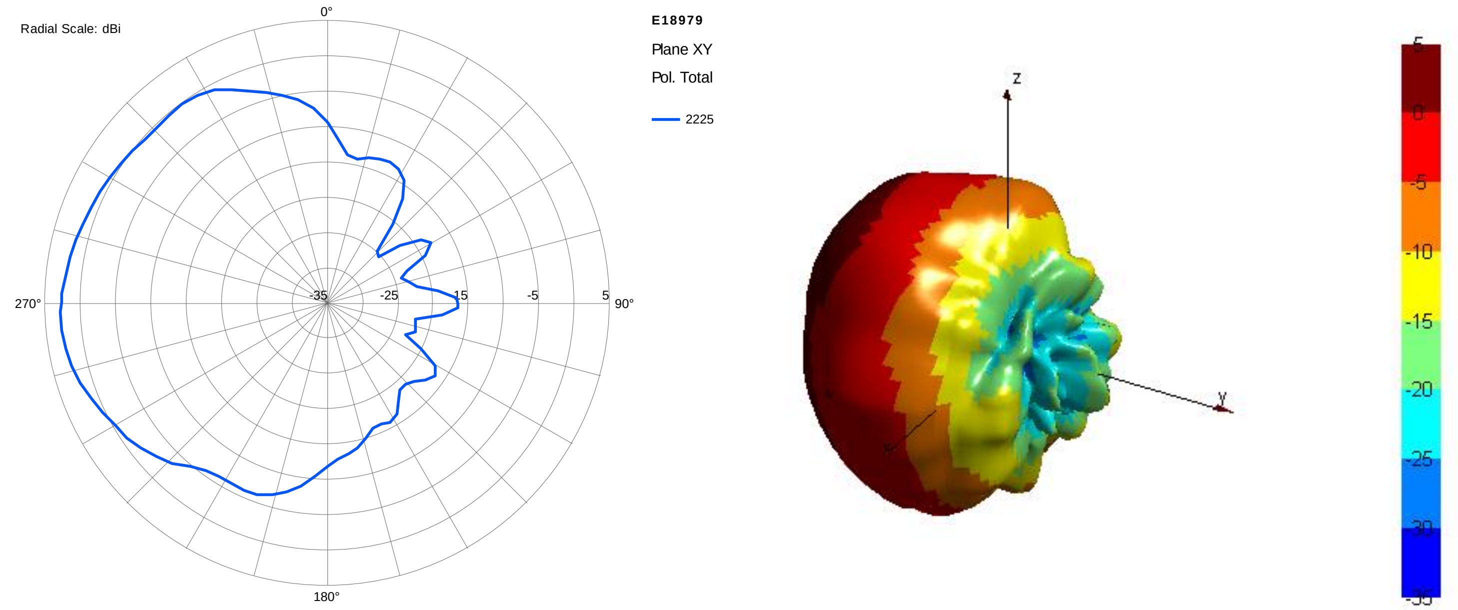
Figure 5 On-body wire antenna results: 1400MHz



Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
> E18978: P1867 - jwj - 20-May-2014			
> Body1800MHz			
> Plane: XY - Polarization: Total			
1700	2.4	-3.0	-2.1
Mean:	2.4	-3.0	-2.1

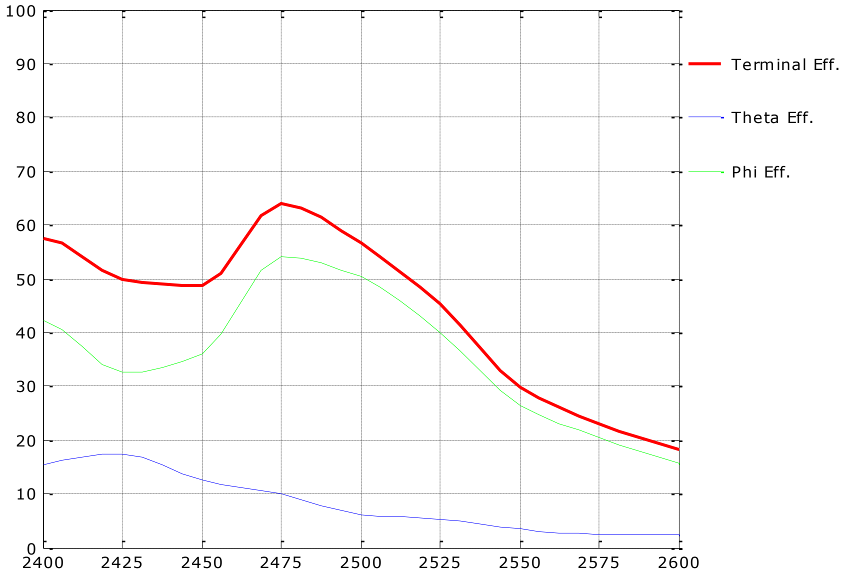
Figure 6 On-body wire antenna results: 1700MHz

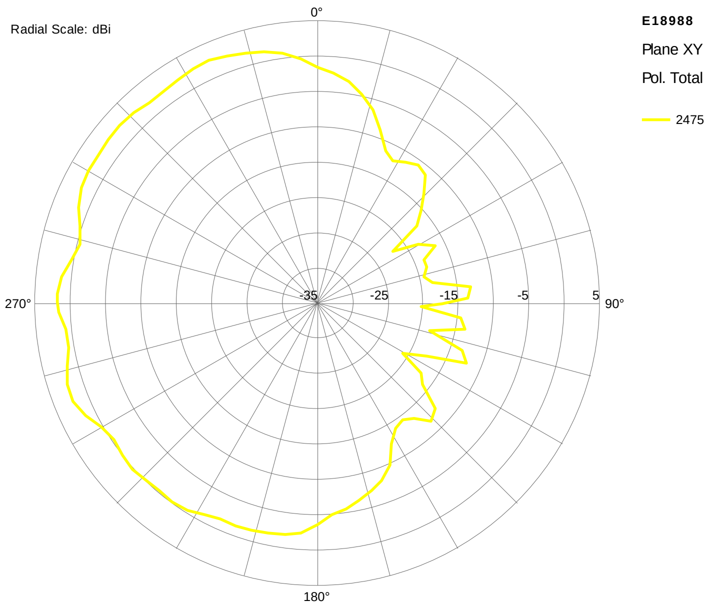


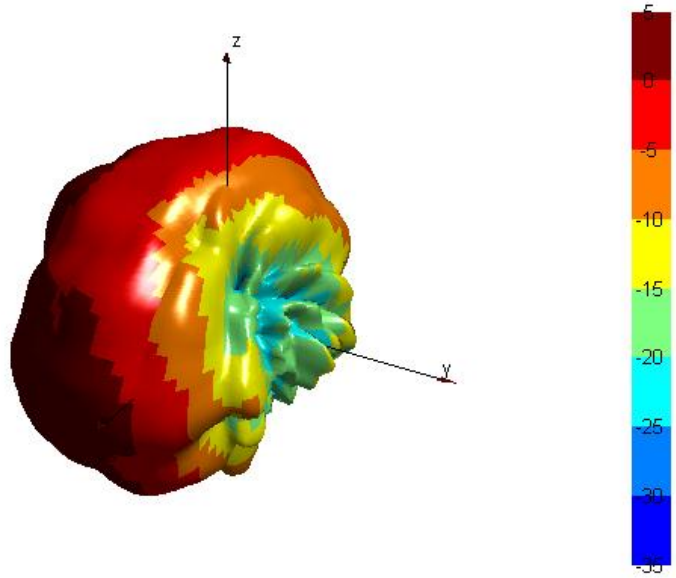



```
Freq.   Peak         Linear       Spheric
[MHz]   Gain         Average      Average
> E18979: P1867 - jwj - 20-May-2014
> Body2300MHz
> Plane: XY  -  Polarization: Total
2225    2.8          -3.6         -2.6
Mean:   2.8          -3.6         -2.6
```

Figure 7 On-body wire antenna results: 2225MHz



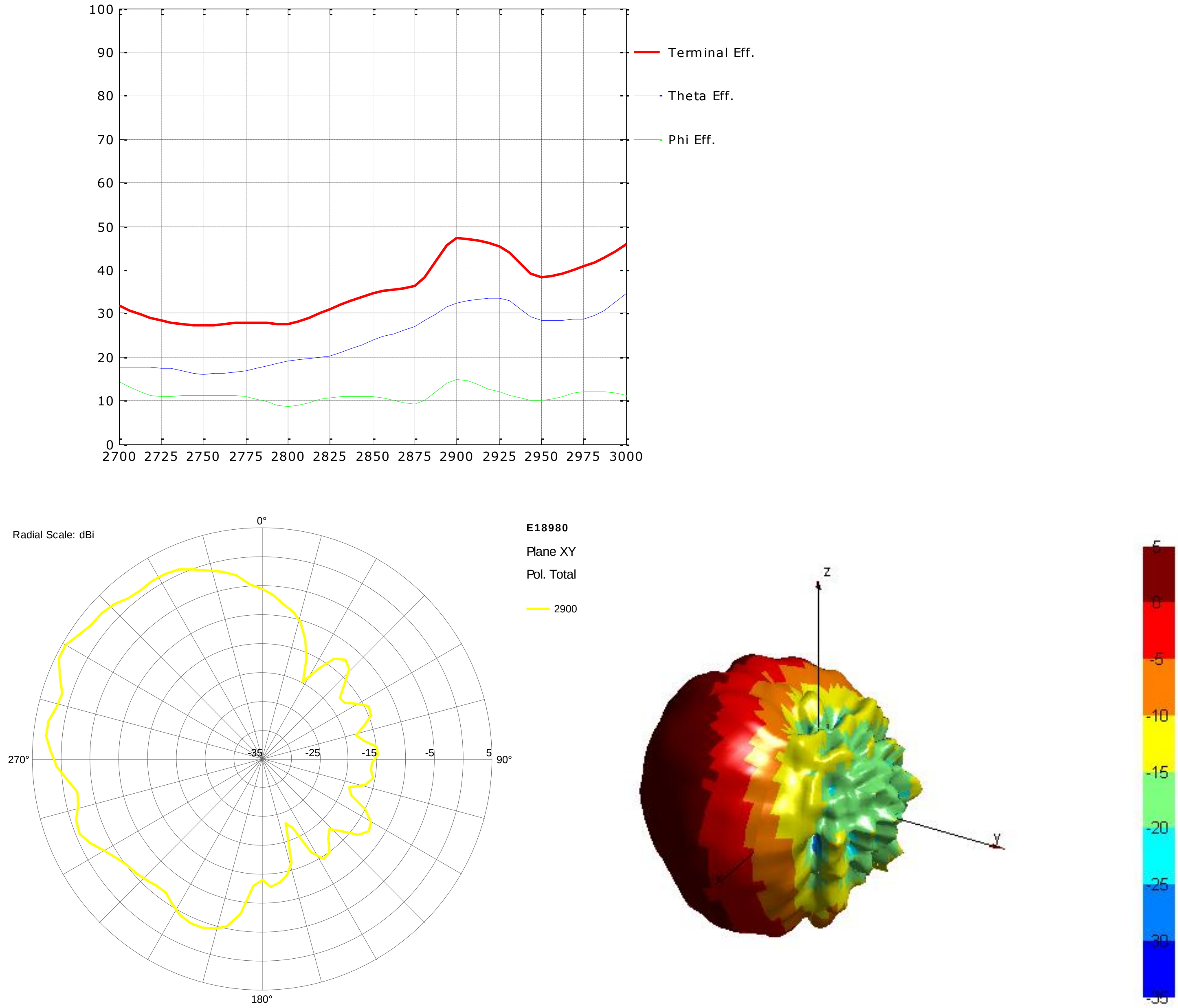




Freq. [MHz] Peak Gain Linear Average Spheric Average
> E18988: P1867 - jwj - 21-May-2014
> Body2400MHz - patch antenna shortened lead
> Plane: XY - Polarization: Total

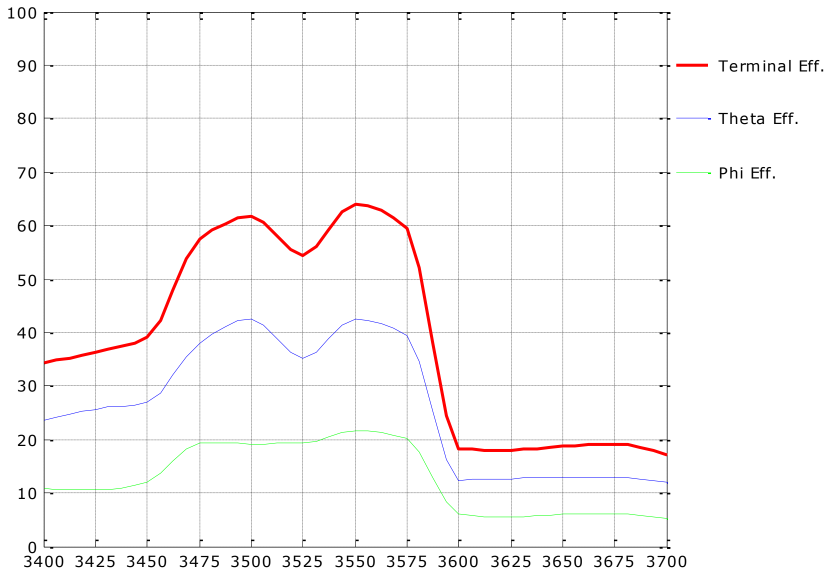
Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
2475	2.6	-1.7	-1.7
Mean:	2.6	-1.7	-1.7

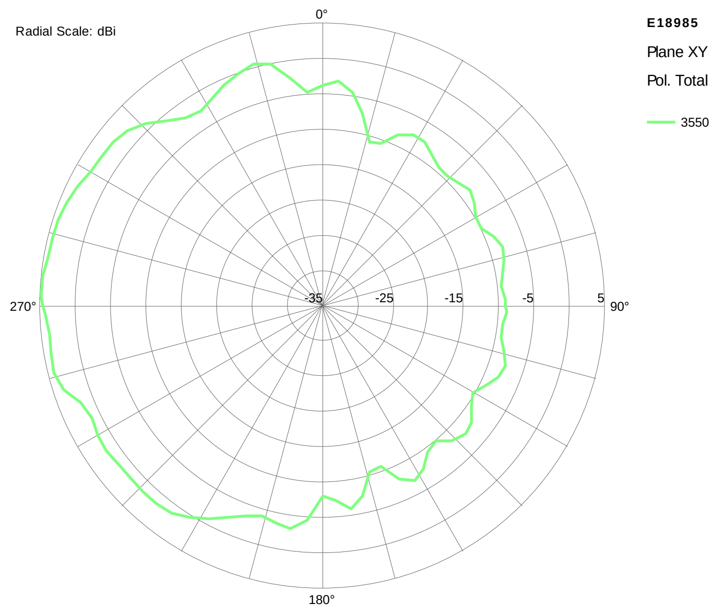
Figure 8 On-body patch antenna results: 2475MHz

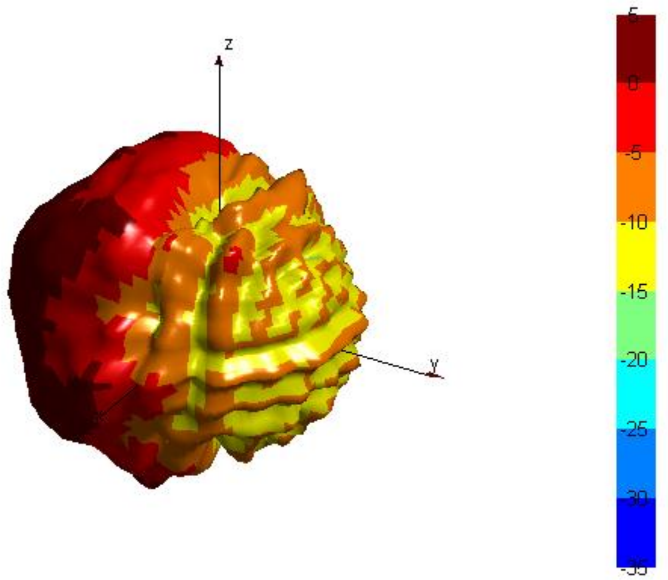


Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
> E18980: P1867 - jwj - 20-May-2014			
> Body28400MHz			
> Plane: XY - Polarization: Total			
2900	4.4	-3.0	-2.4
Mean:	4.4	-3.0	-2.4

Figure 9 On-body wire antenna results: 2900MHz

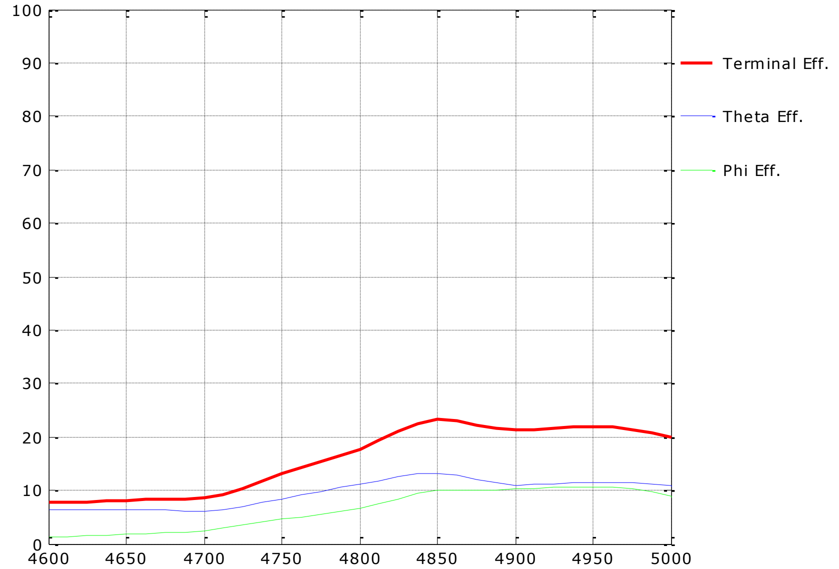


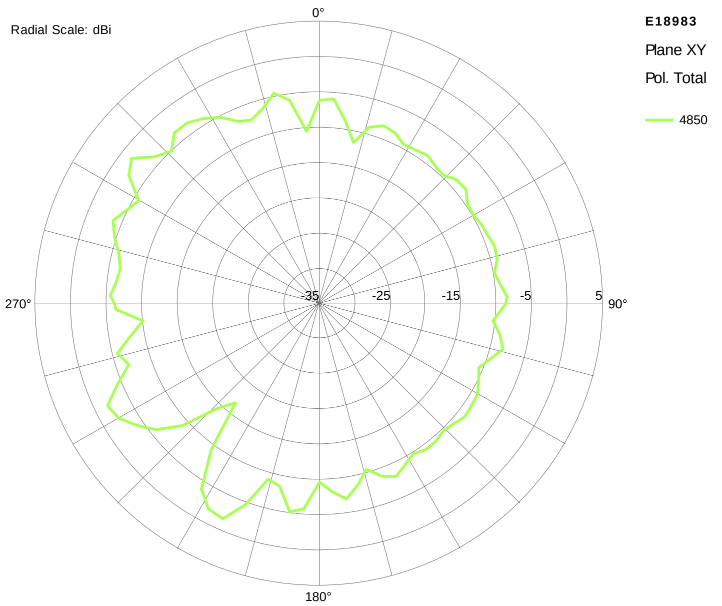


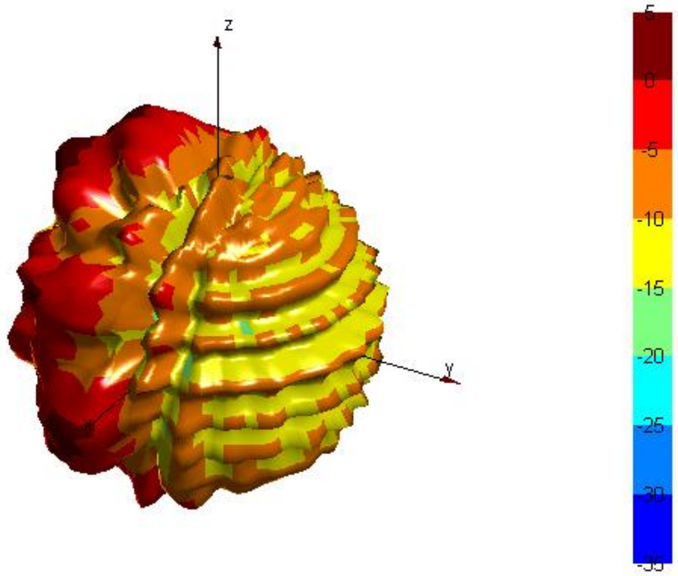


Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
> E18985: P1867 - jwj - 21-May-2014			
> Body3300MHz - Tim's belt removed 21/05/14			
> Plane: XY - Polarization: Total			
3550	4.8	-1.0	-0.2
Mean:	4.8	-1.0	-0.2

Figure 10 On-body wire antenna results: 3300MHz







Freq. [MHz]	Peak Gain	Linear Average	Spheric Average
> E18983: P1867 - jwj - 20-May-2014			
> Body 4800MHz			
> Plane: XY - Polarization: Total			
4850	-1.6	-6.7	-6.7
Mean:	-1.6	-6.7	-6.7

Figure 11 On-body wire antenna results: 4850MHz

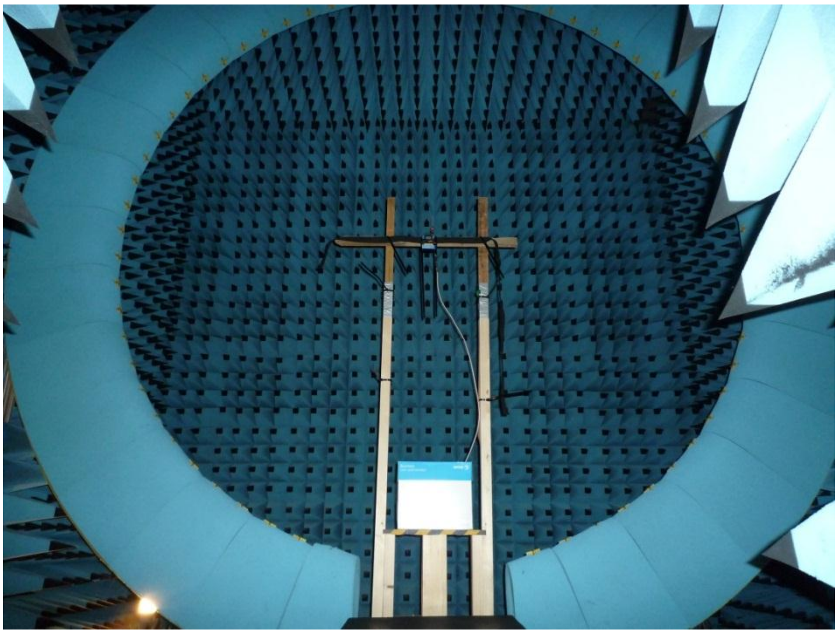


Figure 12 Free-space antenna measurement in Satimo SG-64 antenna test chamber

Figure 13 Test antenna in radio microphone case

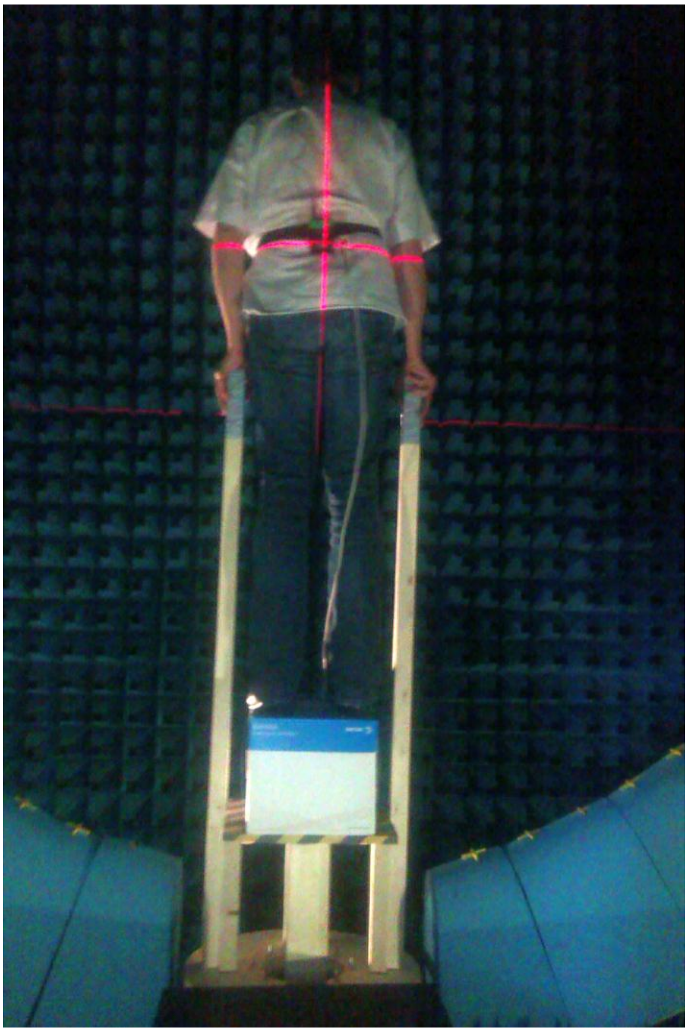


Figure 14 Test antenna and radio microphone mock-up on body (also showing laser alignment tool for chamber)

#	REFERENCES
[23]	Recommendation ITU-R P.1411-7 Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz
[24]	Recommendation ITU-R P.1238-7 Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz
[25]	Ali Kara: Human body shadowing variability in short-range indoor radio links at 3–11 GHz band. *International Journal of Electronics Vol. 96, No. 2, February 2009, 205–211*
[26]	Ali Kara and Henry L. Bertoni: Effect of People Moving near Short-Range Indoor Propagation Links at 2.45 GHz. *Journal Of Communications and Networks, Vol. 8, No. 3, September 2006*
[27]	Measurement of the radiated power of 0.8 / 1.8 GHz hand held PMSE: http://www.apwpt.org/downloads/dke_pmse_822mhz_1800mhz.pdf