



Award of the 2.3 and 3.4 GHz spectrum bands:

Update on the coexistence of 2.3 GHz LTE with
Wi-Fi in the 2400 to 2483.5 MHz range
and other coexistence issues

Updated analysis

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About this Document

This document sets out a further analysis of potential coexistence issues between new mobile broadband services in the 2.3 GHz band and Wi-Fi and other services in the neighbouring 2.4 GHz band.

This follows a consultation published in February 2014.

The Ministry of Defence is releasing the 2.3 and 3.4 GHz bands to Ofcom for award in late 2015 or early 2016, through an auction, as part of the Public Sector Spectrum Release programme. We expect both award bands to be of interest to mobile network operators wanting to provide extra capacity for mobile broadband.

The 2.4 GHz band is accessed by various services on a licence exempt basis, including Wi-Fi. Our assessment is that there will be very little impact from mobile services in the 2.3 GHz band. If interference does occur, there are some mitigations available, the most effective being use of the alternative 5 GHz Wi-Fi band.

This document also assesses coexistence issues for radar and satellite operating close to the 3.4 GHz band. We set out how interference will be avoided.

Our final decisions on technical coexistence issues will be published alongside our decisions on auction design in 2015.

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Section 1

Executive Summary

- 1.1 This document provides an update on Ofcom's assessment of potential coexistence issues between Wi-Fi in the licence exempt 2.4 GHz band (2400 to 2483.5 MHz) and new mobile broadband services in the neighbouring 2.3 GHz band (2350 to 2390 MHz). It also addresses other coexistence issues for the forthcoming 2.3 and 3.4 GHz award, including issues for medical devices, satellites and radar.

Background and previous assessment

- 1.2 The 2.3 and 3.4 GHz spectrum is being released to Ofcom by the Ministry of Defence (MOD) as part of the Public Sector Spectrum Release (PSSR) programme to release or share 500 MHz of spectrum for civilian use by 2020. We plan to auction the spectrum in late 2015 or early 2016 and it is likely to be of interest to mobile network operators looking to provide extra capacity for high power services such as LTE.
- 1.3 This is the second document we have published addressing LTE coexistence with Wi-Fi. The first, a consultation document published in February 2014¹, identified the potential for Wi-Fi in the 2.4 GHz band to suffer some degradation of service in close proximity to 2.3 GHz LTE transmissions in certain circumstances. It said this degradation may affect both domestic/home Wi-Fi and outdoor or indoor public networks.
- 1.4 However, our technical analysis for the February 2014 consultation suggested the likelihood of interference actually occurring was very low. Even if it did occur, the impact was not likely to be noticed by many consumers. In only a very small number of cases would Wi-Fi become unusable. We said there were, in any case, some relatively straightforward mitigations available, including use of the alternative 5 GHz Wi-Fi band. We therefore proposed that no intervention in the market was necessary or justified to protect Wi-Fi.
- 1.5 Most respondents to the February 2014 consultation did not question the results of our technical analysis, but some challenged particular aspects of our methodology or the proposals we made as a result of our assessment of the risks. A number of respondents said that further technical analysis was needed before we could conclude that the impact of LTE signals was as low as we suggested.
- 1.6 In particular, some respondents suggested we may have underestimated the potential impact on Wi-Fi from LTE small cells (as opposed to the macro-cells on which our work was mainly based) and on the impact from LTE user equipment, such as mobile phones. Some respondents challenged the practicality and effectiveness of some of the mitigations we had identified.

Our further assessment

- 1.7 In light of the consultation responses, and of our own further considerations, we have conducted further technical analysis, including the suggested tests on the impact of 2.3 GHz LTE small cells and LTE mobile user equipment. Some of these

¹ <http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/summary/pssr.pdf>

tests were carried out in conjunction with stakeholders. The results are set out in this further document, which broadly confirms our original findings that the actual risk to Wi-Fi is very low.

- 1.8 In addition to technical tests, we have conducted an intensive programme of engagement with industry stakeholders including mobile network operators, internet service providers and equipment manufacturers. We have also carried out market research to understand better how consumers use Wi-Fi, and how they react when there are connection issues.
- 1.9 Finally, we have given further consideration to the experiences of other countries where 2.3 GHz LTE has been deployed alongside Wi-Fi.
- 1.10 Having taken account of all the new evidence we have gathered we have reviewed the proposals we presented in the February 2014 consultation. We believe the new evidence provides further support for our original conclusions. Accordingly, we do not believe there is any reason or justification for us to revise our proposal to proceed with the 2.3 GHz spectrum award without further intervention to protect Wi-Fi.
- 1.11 In addition to the technical analysis suggesting there is only a small risk of any impact on Wi-Fi we have had regard to the following factors:
 - We have proposed low out-of-band emissions requirements on LTE in the 2.3 GHz band in order to protect licence exempt uses in the 2.4 GHz² band. This is in line with latest proposals from CEPT³;
 - There will be a 10 MHz guard band between LTE in the 2.3 GHz band and Wi-Fi in the 2.4 GHz licence exempt band;
 - If any degradation occurs, the dominant factor will be Wi-Fi 'listening in' to LTE signals from outside its designated licence exempt band rather than LTE causing interference to Wi-Fi bands. Wi-Fi with appropriate filtering is not affected;
 - In reality, it will be virtually impossible to identify 2.3 GHz as a source of any particular degradation, as opposed to any other general spectrum congestion (such as Wi-Fi to Wi-Fi interference);
 - Even in places and circumstances where there is a theoretical risk of Wi-Fi degradation, a number of factors all need to be in place simultaneously for it to actually occur (which reduces the likelihood of it happening even further):
 - **2.3 GHz LTE** would actually need to have been rolled out in that area; there would need to be an LTE source physically nearby; the cell or device would need to be using 2.3 GHz spectrum at the time (and not one of the many alternative LTE bands); transmission would need to be at high power from both base station and/or device;

² <http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

³ European Conference of Postal and Telecommunications Administrators

- **The Wi-Fi device/router** would have to be one that is incapable of using the 5 GHz band as an alternative to the 2.4 GHz band; the Wi-Fi device/router would have to be insufficiently robust to avoid the interference (i.e. unfiltered); the Wi-Fi device/router would need to be in use with a constant throughput and delay sensitive application (such as video streaming or Skype calls);
 - Use of the 5 GHz spectrum band for Wi-Fi is an effective and appropriate mitigation in most cases. We note that virtually all new Wi-Fi enabled equipment on the market has dual band capability (and this has been the case for some time);
 - Most dual band equipment can already switch automatically between the 2.4 and 5 GHz bands to some extent. Natural market developments mean that this capability will become even more widespread;
 - Most remaining issues will apply to legacy equipment unable to access the 5 GHz band. Normal replacement cycles for consumer equipment mean the volume of this old equipment still in use is declining (and will decline further before 2.3 GHz services are rolled out) but some will inevitably remain in use;
 - Other mitigations may be of use for legacy equipment, such as moving affected equipment away from the source of interference (usually by less than 1 metre) or by changing its orientation. In other cases, devices could be wired to a router, although we acknowledge this may not be appropriate in every case;
 - There is no evidence of any noticeable interference issues in other countries where 2.3 GHz LTE has been deployed.
- 1.12 We remain of the opinion that internet service providers (ISPs) are best placed to assess and, if necessary, address most of the very small number of issues that may be faced by their domestic customers. However, there could be exceptional cases where users of certain legacy equipment may need to take action themselves.
- 1.13 We continue to believe that Wi-Fi providers are best placed to address any issues which may affect indoor or outdoor public Wi-Fi networks. These networks already operate in a congested environment and operators already address connection issues as part of their normal upgrade/replacement cycles and through network management.
- 1.14 We have taken steps to ensure ISPs are aware of the implications of the release of the 2.3 GHz spectrum, and that equipment in the 2.4 GHz band will need to operate alongside LTE. We will also encourage manufacturers to take steps to ensure consumers are made aware of potential issues when siting routers and home-based femto-cells (through information in packaging etc.).
- 1.15 Although we are confident the 2.3 GHz award will have very little impact on Wi-Fi in practice, we will continue to monitor the situation as 2.3 GHz LTE rolls out after the auction.

Additional issues

- 1.16 This document also provides an update on the potential impact of new 2.3 GHz LTE services on other licence exempt applications, including assistive listening devices for those who have hearing loss and medical monitoring equipment.
- 1.17 As with Wi-Fi, we believe that no further intervention in the market is necessary because the likely impact is very small and there are appropriate precautions that can be taken.
- 1.18 Finally, the document presents an update on our thinking in respect to coexistence issues for 3.4 GHz LTE close to civilian radar (maritime and aeronautical) and/or satellites.

Next steps

- 1.19 We will set out our final decisions on technical coexistence issues alongside our decisions on auction design next year (2015).

Section 2

Introduction and background

- 2.1 This document updates our assessment of coexistence issues between Wi-Fi operating in the 2.4 GHz licence exempt band (2400 to 2483.5 MHz) and LTE in the 2.3 GHz award band (2350 to 2390 MHz). The document also addresses other coexistence issues for the forthcoming 2.3 and 3.4 GHz award. In doing so, it builds on analysis first set out in a technical consultation document published in February 2014, and takes account of stakeholder responses.
- 2.2 The 2.3 GHz spectrum is being released to Ofcom by the Ministry of Defence (MOD) alongside a further 150 MHz of spectrum in the 3.4 GHz band (between 3410-3480 MHz and 3500-3580 MHz). Both the 2.3 and 3.4 GHz bands form part of the Government's Public Sector Spectrum Release (PSSR) programme which aims to release or share 500 MHz of spectrum for civil use by 2020. We expect both award bands to be of interest to mobile network operators for LTE mobile broadband.
- 2.3 Our February 2014 consultation identified a potential risk of interference to Wi-Fi from new 2.3 GHz LTE services. The risk stems mainly from Wi-Fi equipment (routers, laptops, tablets etc.) picking up signals from outside the designated Wi-Fi operating band, leading to a rise in the noise threshold for Wi-Fi and to signal blocking. It is not caused by LTE itself interfering with Wi-Fi frequencies.
- 2.4 The consultation set out a technical assessment of the likelihood of interference occurring. We said the likelihood was not significant enough to justify regulatory intervention in the market to mitigate the impact to Wi-Fi. We invited responses from stakeholders on this proposal.
- 2.5 Some respondents questioned our interpretation of specific data. Others suggested we should carry out further testing of potential interference from particular sources, especially from small cell LTE deployments and from user equipment such as mobile phones. As a result of these responses, and our own further consideration of the issues involved, we have conducted a range of further tests and analysis. The results are presented in this update.
- 2.6 The update also presents further analysis of coexistence issues for some other applications making use of the licence exempt band, including medical devices (which may use Wi-Fi, Bluetooth or proprietary technology) and assisted listening devices for the those who have hearing loss.
- 2.7 Finally, the document provides an update on our assessment of coexistence issues in respect to civilian radar systems (maritime and aeronautical) and satellites operating close to the 3.4 GHz award bands.

Legal framework

- 2.8 The legal framework within which we must make our decisions was set out in the February 2014 consultation. The full detail is not repeated here. Our principal duties under Section 3 of Communications Act 2003 are:

⁴ <http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/summary/pssr.pdf>

- to further the interests of citizens in relation to communications matters; and
- to further the interests of consumers in relevant markets, where appropriate, by promoting competition.

2.9 In doing so, we have a duty to secure the optimal use of spectrum (Section 3(2)(a)); and a duty to take account of the different needs and interests of all current or potential users of the frequencies (Section 3(4)(f)). In our February 2014 consultation, we said that determining our approach to potential interference issues for licence exempt users needed to take account of balance our requirements for:

- recognising that users of licence exempt spectrum may not cause interference to other spectrum users and may expect no protection themselves from other users; and
- recognising our duty to consider any potentially negative impact on citizens and consumers arising from future use of the award bands for new uses, such as LTE.

The 2.3 GHz spectrum

2.10 The 2.3 GHz frequencies being awarded by Ofcom will be made available for new uses throughout Great Britain (i.e. in England, Scotland and Wales, but not in Northern Ireland). The frequencies will be auctioned cleared of all existing uses⁵.

2.11 The particular characteristics of the 2.3 GHz spectrum, in terms of propagation and the penetration of signals, make it especially suitable for use by mobile broadband applications such as LTE. The band has propagation characteristics very similar to the 2.6 GHz band already used for 4G mobile. It appears particularly suitable for providing additional capacity for LTE networks, rather than for delivering wider coverage.

2.12 We have decided⁶ to award the spectrum with an LTE band plan based on Time Division Duplex (TDD)⁷. However, we propose that any use of the spectrum should be possible if winning bidders have other business plans (subject to compliance with technical parameters and consequent licence conditions).

The 3.4 GHz spectrum

2.13 The 3.4 GHz award band is being awarded throughout the whole of the UK.

2.14 We believe the band may be valuable in providing additional options for mobile network operators facing capacity pressures in other frequencies - either as capacity in itself or as backhaul for small cells using other bands. As with the 2.3 GHz band, we have decided to award the spectrum with a TDD band plan.

⁵ Except for a small number of exclusion zones and some limited coordination requirements. See award consultation: <http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

⁶ The decision was set out in the February 2014 consultation.

⁷ Time division duplex is used to separate the outward and return signals in the same frequency channel by time

Remainder of this document

2.15 The sections which follow this introduction and background are as follows:

Section 3 summarises the proposals on Wi-Fi coexistence we first set out in the February 2014 consultation.

Section 4 outlines the consultation responses we received in respect to Wi-Fi and summarises our own responses to the points made by stakeholders.

Section 5 describes the further technical work we have undertaken as a result of both the consultation responses and our own further consideration of Wi-Fi coexistence issues.

Section 6 then presents other additional evidence we have gathered in respect to the coexistence of 2.3 GHz LTE and Wi-Fi, including further stakeholder engagement and market research. We then set out our overall assessment of the issues.

Section 7 considers the coexistence issues for medical devices making use of the 2.4 GHz licence exempt band.

Section 8 considers the coexistence issues for other licence exempt uses of the 2.4 GHz licence exempt band, including assistive listening devices (ALDs).

Section 9 presents an update on the coexistence issues arising from the 2.3/3.4 GHz award in respect to civilian radar (both naval and aeronautical).

Section 10 presents an update on the coexistence issues for satellites.

2.16 The document as a whole should be considered alongside a number of related Ofcom publications which are of direct relevance to the 2.3 and 3.4 GHz award. These address particular aspects of the award, including some additional issues raised by stakeholders in response to the February 2014 consultation. They are:

- *Public Sector Spectrum Release: Amateur use of 2310 to 2450 and 3400 to 3475 MHz*⁸. This document is a statement on our approach to use of the 2.3 and 3.4 GHz spectrum, and neighbouring spectrum, by amateur radio enthusiasts.
- *Programme Making and Special Events: Strategy for video PMSE applications*⁹. This document addresses issues raised in the February 2014 consultation about the impact of the 2.3 and 3.4 GHz award on the amount of spectrum available for PMSE use, particularly for television coverage of sporting and other events.
- *Public Sector Spectrum Release (PSSR): Award of the 2.3 GHz and 3.4 GHz bands: Consultation on award design*¹⁰. This document is a consultation on the design of the 2.3 and 3.4 GHz award auction. It

⁸ <http://stakeholders.ofcom.org.uk/consultations/public-sector-spectrum-release/statement>

⁹ http://stakeholders.ofcom.org.uk/consultations/pssr-2014/statement?utm_source=updates&utm_medium=email&utm_campaign=pmse-statement-oct14

¹⁰ <http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

includes updated proposals on technical licence conditions applicable in the award bands.

Section 3

Summary of previous proposals on Wi-Fi coexistence

- 3.1 This section of the document summarises our previous assessment of coexistence issues for the 2.3 GHz award band in respect to Wi-Fi uses in the neighbouring 2.4 GHz band (i.e. our February 2014 consultation¹¹).

Technical analysis

- 3.2 The February 2014 consultation set out a detailed technical analysis of the potential impact of the 2.3 GHz award on users of adjacent frequencies based on an assumption that the band will be used for high power LTE. Our primary concern was the potential impact on licence exempt applications in the 2.4 GHz band, particularly Wi-Fi.
- 3.3 We noted that Wi-Fi was deployed in 17.5 million UK households to access the internet via a broadband connection. Wi-Fi also provides coverage to commercial and independent 'hotspots' at a wide range of public locations, both indoors and outdoors. Finally, Wi-Fi is deployed in 'enterprise networks', including in medium and large offices.
- 3.4 Our measurement and analysis work consisted of three broad activities:
- Measurements of devices to quantify their vulnerability to LTE signals;
 - Field trials to validate the effects predicted in real world environments; and,
 - Analysis, using these measurements, to extrapolate the potential scale of interference between LTE networks and Wi-Fi deployments.
- 3.5 Our technical analysis confirmed a risk of interference, in specific circumstances, to both Wi-Fi routers/access points and to client devices (such as smartphones, games consoles or smart TVs). We identified the main risk of interference was from LTE base stations. We said interference was most likely in urban environments where there may be a dense deployment of both LTE base stations and Wi-Fi networks. We said the interference was caused almost entirely by the performance of the Wi-Fi receiver i.e. by Wi-Fi 'listening in' to signals outside its own band rather than by out-of-band emissions from LTE.
- 3.6 We used three different metrics in order to quantify interference into Wi-Fi:
- The onset of degradation i.e. the point at which degradation was reliably measurable in our study, whether or not it was noticeable in practice. This corresponded to a reduction in throughput of 10%;

¹¹ See Section 3 of the February 2014 consultation

- The point at which throughput dropped below 50%. We identified this metric as the most helpful in identifying noticeable impact to client devices; and
 - The point at which throughput drops below 1 Mbps. We identified this as the point at which Wi-Fi suffers severe impact and is no longer usable.
- 3.7 Our analysis showed that the most likely impact for affected consumers would be a slowing of the service, which many would not be able to notice. In only a very few cases would there be a loss of useable Wi-Fi (i.e. a drop in throughput to below 1 Mbps).
- 3.8 We said the scale of potential interference on a nationwide basis was not high (see table 3.1 below). The analysis suggested only around 0.1% of households with Wi-Fi was at any risk of interference (i.e. based on central assumptions and using the onset of degradation as the key metric). This would equate to around 17,400 households if there was a full UK-wide deployment of 2.3 GHz Wi-Fi. However, we considered UK-wide deployment to be highly unlikely in the short-term, because of our expectation that the spectrum will be used initially for providing extra capacity in specific congested areas.
- 3.9 We said the most relevant metric for assessing noticeable impacts to client Wi-Fi devices (such as laptops) was the 50% drop in throughput, rather than the onset of degradation which we used for routers/access points. In doing so, we noted that most devices do not operate at maximum throughput even in normal circumstances – particularly those that are mobile and therefore subject to variable throughput levels depending on location and congestion in the network.
- 3.10 For public Wi-Fi, our testing suggested that interference (onset) may affect around 6.8% of the 4,000 postcode locations where outdoor public networks are established¹², again based on a UK wide roll-out. We said certain parts of the 78,000 indoor public Wi-Fi locations¹³ (around 1.4%) and the 680,000 self-contained enterprise networks in large and medium sized organisations (around 1.2%) may also be affected.

Table 3.1: Number of Wi-Fi networks predicted to be affected by LTE interference

Category	Total no. of networks	Routers		Client devices
		% Locations affected	Total no. of impacts	% Locations affected
1) Domestic	17,500,000	0.1%	17,400	0.0% ¹⁴
2a) Outdoor public (median device)	4,000	6.8%	270	1.4%
2a) Outdoor public (best device)		4.2%	170	N/A
3) Indoor public	78,000	1.4%	1,100	0.1%
4) Enterprise	680,000	1.2%	8,000	0.1%

¹²There may be a number of access points within a single location in some densely populated areas.

¹³ This refers principally to access points located on one side of a building

¹⁴ Figure based on single decimal point

Mitigations

- 3.11 Our February 2014 consultation identified a number of mitigations. By far the most important was the ability of Wi-Fi devices to switch to the alternative 5 GHz band. We noted that almost all new Wi-Fi mobile devices now have dual band capability. However, we acknowledged there were potential issues for legacy mobile devices that were not capable of operating at 5 GHz; and for some smart TVs and games consoles.
- 3.12 Other mitigations we identified included simply moving equipment away from the interference source, such as shifting routers away from a window or changing the position in which a mobile device is held. Alternatively, larger legacy devices – such as smart TVs or games consoles (i.e. generally immobile devices) – could be hard wired via Ethernet cables or power line devices. We noted that users may need to understand how to implement certain mitigations, and that some form of information campaign may be helpful.
- 3.13 We suggested that ISPs would be in the best position to advise consumers on Wi-Fi broadband issues and how to resolve them. If additional action was needed to upgrade routers (or public access points) we said internet service providers would be able to include addressing the impact of 2.3 GHz LTE interference within their existing operational processes. We noted that routers were replaced by ISPs in line with network upgrades or in response to consumer concerns about performance. We said that we expected further market-driven improvements to Wi-Fi reliability to occur before any new LTE services are deployed (which will be from 2016 at the earliest).
- 3.14 We noted that mobile devices (such as mobile phones) are generally replaced by consumers after around 18 or 24 months in line with network contracts. We also noted that many devices (including tablets and smartphones) have both Wi-Fi and mobile broadband capability. We said it was reasonable to assume that chipset manufacturers would ensure future equipment worked properly alongside new 2.3 GHz LTE (as with 2.6 GHz LTE).

Our proposed approach

- 3.15 In light of our technical analysis and our assessment of the available mitigations we proposed that no intervention in the market was necessary to protect Wi-Fi from potential interference.
- 3.16 We said the overall impact of potential interference was small and likely to affect only a very limited number of Wi-Fi users. In most cases, any mitigation that was needed was relatively cheap and straightforward. We said the replacement/upgrade of domestic consumer equipment (including routers and client devices) would occur quite naturally in any case, even without the 2.3 GHz award.
- 3.17 On balance, therefore, we believed mitigation should be left to the market to determine. The ISPs, were in the best position to identify and assess the actual impact of interference on the rare occasions it occurs. They will therefore be in the best position to apply mitigations, and will be incentivised to keep costs to a minimum.

Section 4

Consultation responses on Wi-Fi coexistence

- 4.1 This section summarises the submissions we received from stakeholders in response to the questions we posed in the February 2014 consultation about 2.3 GHz LTE and Wi-Fi coexistence. We asked six questions:

Question 1: Do you have evidence to challenge our methodology and assumptions, which show the number of Wi-Fi routers likely to be affected by LTE interference is low?

Question 2: Do you have evidence to challenge our methodology and assumptions, which show the number of Wi-Fi client devices affected by LTE interference is low?

Question 3: Do you agree with our assessment of the available options for mitigation of interference to home networks?

Question 4: Do you agree with our assessment of the available options for mitigation of interference to public networks (both indoor and outdoor)?

Question 5: Do you agree with our assessment of the available options for mitigation of interference to enterprise networks?

Question 6: Do you agree with our conclusion that the impact to Wi-Fi is not of a significant nature and therefore no regulatory intervention is necessary? If not, can you provide evidence?

- 4.2 Sixteen of the stakeholders who responded to the February 2014 consultation addressed the issue of Wi-Fi coexistence. Four of the responses were submitted in confidence; a further two were submitted with some parts identified as confidential; and two respondents submitted both confidential and non-confidential responses.
- 4.3 A number of stakeholders expressed strong support for both our technical assessment and the proposals we presented in the consultation. However, some respondents questioned our interpretation of some of the data we produced, and others said that further technical tests should be conducted in order to better assess particular issues. Some respondents also queried the effectiveness of the mitigations we proposed.
- 4.4 Overall, a roughly equal number of stakeholders expressed support for the analysis and proposals set out in the February 2014 consultation as expressed caution.
- 4.5 In summarising the responses which challenged certain aspects of our analysis, we have grouped submissions according to identifiable issues, rather than by answers to our consultation questions - because this is clearer and more representative of the way most of the submissions were expressed.
- 4.6 Some of the points raised by stakeholders are addressed below. However, where we have carried out further technical analysis or gathered other evidence to

address the issues raised (such as through stakeholder engagement or market research etc.) our full assessment is set out in sections 5 and 6 of this document. We indicate at relevant points below where this is the case.

Responses related to our methodology and approach to technical analysis

- 4.7 Some respondents questioned our overall approach to assessing potential interference issues, or raised particular issues over aspects of the methodology.
- 4.8 One confidential respondent suggested we had relied too heavily on evidence of less severe potential impacts than those identified in the independent reports we published alongside the consultation document. This view was supported by other respondents, including BT.
- 4.9 A number of specific points about our methodology were raised by these respondents and others. These are addressed in turn below.

Identification of metrics

- 4.10 Sky welcomed the technical work that Ofcom had undertaken but questioned the reliance on using the point at which the throughput drops below 50% as a useful tool in understanding the impact on client devices. Sky accepted there was likely to be a variation among consumers about what constituted 'identifiable' performance degradation – but said that Ofcom should make further results of its modelling available (for example, by presenting the figures for the 'onset of degradation' for client devices).
- 4.11 Virgin Media and a confidential respondent also queried our use of a 50% drop in Wi-Fi throughput as an appropriate base point for defining a harmful impact to domestic Wi-Fi client devices. The confidential respondent argued that Ofcom should always consider harmful impacts as being the onset of degradation, as we did in assessing Wi-Fi access points.
- 4.12 Virgin noted the rationale that throughput is already a variable for consumers, and that they already 'self-mitigate' to achieve better throughput. However, Virgin argued that the 50% benchmark allowed inappropriate levels of interference to be regarded as acceptable to the consumer. The fact that consumers already suffer throughput issues should not be a reason for allowing a further source of interference to disrupt their user experience.
- 4.13 On the contrary, given that user experience is already compromised to a certain degree by factors other than LTE interference, there was a clear argument that 50% allowable degradation from 2.3 GHz LTE would exacerbate an already sub-optimal situation, and the higher benchmark of the onset of degradation would be the better standard to apply.

Ofcom response

- 4.14 In the February 2014 consultation we presented results based on the onset of degradation for both routers and client devices (see Table A7.27 in Annex 7) -

although we acknowledge that our main conclusions for client devices (as opposed to routers/access points) were based on the 50% impact point¹⁵.

- 4.15 As noted, user experience of Wi-Fi is that it can be of variable quality, particularly in outdoor environments, depending on a range of factors. We note Virgin's concerns that introducing 2.3 GHz LTE would be making an existing problem worse. However we don't believe that every instance of interference from LTE will correlate with poor existing performance.
- 4.16 There are complexities involved in linking lab based measurements to user experience in practical deployments. The typical throughputs experienced by users in busy and congested environments will be less than those we measured in the lab and also less than those that we said were at the "onset of degradation". Wi-Fi devices are designed to back off from transmitting if they hear other networks nearby. Other nearby networks will also increase the noise floor. Both of these factors will result in lower instantaneous throughputs. As a result, basing an assessment of degradation for client devices on the onset point is not particularly useful, and assuming a greater degradation would not materially affect our conclusions in any case.
- 4.17 We have now spoken to many stakeholders about this issue, and believe that the likelihood of interference in public congested environments is low because new devices (e.g. laptops, smartphones and tablets) are now beginning to have effective filters or can switch to using the alternative 5 GHz Wi-Fi band (or both). The remaining issues are mainly for domestic legacy devices where we believe the 50% metric is appropriate.
- 4.18 In summary therefore, we judge the onset of degradation to be an appropriate measure for public hotspots, as for other router/access points - and 50% degradation most appropriate for client devices and for more managed environments.

Use of median devices for assessment

- 4.19 BT questioned Ofcom's reliance on a 'median' router in assessing the potential for likely interference. In its consultation response, BT said it had no evidence to dispute Ofcom's assessment of the likely incidence of interference to existing 2.4 GHz Wi-Fi routers as set out in the consultation. However, there will be a wide spread in performance of different Wi-Fi routers, and the impact on devices that may be more vulnerable than the median should also be considered, particularly where these could be deployed in large volumes.

Ofcom response

- 4.20 We note the uncertainty in selecting a median device and the inherent assumption of a uniform market distribution between the tested devices. However we still believe that this is the most appropriate assumption to use, given the available evidence. The tested equipment included a range of prominent and popular devices, but it is not possible to obtain detailed market breakdown figures. We note that we have tested one example of each device, and that it may be misleading to

¹⁵ N.B. The table set out at Fig 6.1 in the February 2014 consultation contains figures for the onset of degradation for client devices, although these figures are incorrectly identified as being for a 50% drop in throughput

infer more detailed statistics of relative performance based on this limited sample size.

- 4.21 We remain of the view that assuming performance based on the median device, whilst certainly not ideal, provides the most balanced assessment of the overall statistical impact of interference based on the evidence we have gathered.

10 dB correction factor

- 4.22 Sky said Ofcom was not justified in applying a 10 dB correction factor in its central case modelling, and took the view that the 'pessimistic case' should be used as the basis for decisions and further testing. Sky said a 10 dB correction should only be used if the assumption is validated through 'real-life' deployments and tests (which would enable the proposed mitigation steps to be evaluated as well). Ofcom should work with operators to ensure that tests are robust and reflective of the current real-life deployment of access points. Unless additional tests provided substantive evidence to validate Ofcom's assumption, the 'pessimistic case' set out in the consultation should be used as the basis for consideration of the award process and mitigating steps.

Ofcom response

- 4.23 We believe the use of this correction factor was justified through independent modelling, using a detailed ray tracing analysis which took into account real world effects. This modelling showed that an offset greater than 10 dB would be required, and so we believe that we have already taken a cautious approach by applying only a 10 dB offset.
- 4.24 We also believe the results from our field testing are relevant here. These did not show a significant impact of interference at short distances from base stations. While there are a number of factors at play - and probability of interference is not solely dependent on propagation - we believe these results support the inclusion of a correction factor in estimating the risk of interference.

Interpretation of standards

- 4.25 BT raised questions about Ofcom's use of international standards in developing policy proposals on LTE/Wi-Fi coexistence. BT said Ofcom had made reference to both the IEEE¹⁶ standard and the ETSI¹⁷ standard in relation to the blocking performance of Wi-Fi devices and had used these to calculate separation distances. BT said neither of the referenced standards were directly applicable to the interference scenario under consideration and hence considered that Ofcom should not rely on these to inform its position. Instead the measured performance of actual devices should be the primary focus.

Ofcom response

- 4.26 The separation distances based on standards were included in the consultation to provide some indicative context, and we note that they are not directly applicable to the interference scenario. We agree with BT's assertion that measurements are an important part of informing our position; however we also acknowledge the practical limitations of testing only a small sample of devices. We therefore think

¹⁶ Institute of Electrical and Electronics Engineers

¹⁷ European Telecommunications Standards Institute

that using both approaches provides a degree of comparison. The impact figures used to inform the policy position in our February 2014 consultation were based on measurements.

Need for further testing

- 4.27 A number of respondents suggested Ofcom needed to carry out more testing before reaching conclusions on likely levels of potential interference. There were some common themes among these respondents. Many identified the potential impact of LTE handsets as an area that needed further testing and consideration. Most of these respondents also suggested further testing should be carried out to assess the impact of in-home femto-cells and other small cell LTE deployments.

Range of devices

- 4.28 A response submitted confidentially noted that Ofcom had looked at a sample of 21 devices to determine whether there was an interference issue. Given the hundreds of devices that are available in the market, and the difference in performance between them, this was unlikely to be fully representative. Accordingly, more devices should be tested. Further testing should include the impact when there are multiple devices involved (both multiple Wi-Fi client devices and multiple 2.3 GHz femto-cells and handsets).
- 4.29 Similar points were expressed by other respondents. BT said it was unable to endorse Ofcom's technical assessment - and the view that no intervention in the market was necessary - based on the analysis set out in the February 2014 consultation. BT said we should conduct a range further tests, including on 802.11n Wi-Fi equipment¹⁸.

LTE mobile devices (user equipment)

- 4.30 BT also suggested interference from LTE mobile devices was likely to be more of a risk than interference from base stations. BT said that potentially harmful Wi-Fi/LTE equipment separations of only a few metres could occur naturally very frequently in residential areas where millions of Wi-Fi networks operate. Virgin and Tech UK also said Ofcom had not considered properly the issue of interference from LTE handsets which may well operate within the home in close proximity to the router.
- 4.31 EE also said the simultaneous use of Wi-Fi client devices and LTE devices may have been overlooked. For example, a user simultaneously using a Wi-Fi client for computer connection and making an LTE call. However, EE believes that within the context of available mitigation options such under estimation is unlikely to prove significantly problematic or is - at worst - a transitory issue in the context of the Wi-Fi client device replacement cycle.
- 4.32 A confidential respondent called for testing of the potential impact to games consoles, particularly where these were likely to be used in close proximity to LTE mobile phones.

¹⁸ 802.11n is newer version of the IEEE Wi-Fi standard which provides faster speeds using wider channels and advanced antenna techniques than the 802.11g version which we focussed on in previous testing

Small cells

- 4.33 The need for further testing to assess the impact of small cells was identified by a number of respondents, including Tech UK, Virgin and BT. BT said it was more likely that the 2.3 GHz spectrum would be used for new capacity sites (including small cells) rather than just additional frequencies on the existing 3G base station sites run by the national network operators.
- 4.34 EE said a hierarchy of deployment was likely to include a macro layer, small cell and femto-cells. The aggregate effects of such a deployment may mean that the number of Wi-Fi routers affected is somewhat under estimated. However, EE said that within the context of available mitigation options such underestimation is not likely to prove significantly problematic.

Ofcom response on further testing

- 4.35 In light of the stakeholder responses outlined above, and as a result of our own further consideration of the issues involved, we have carried out detailed further technical analysis, including engagement with most of the respondents who raised particular concerns. The full details of all our further technical work are set out in the next section of this consultation (section 5), but may be summarised as follows:
- **Small cell deployment** - We have conducted further tests or analysis on the potential impact on Wi-Fi from three categories of small cells:
 1. Outdoor deployments (typically 5 m, <35 dBm EIRP)
 2. Indoor pico-cells (train stations, shopping centres, enterprise environments, typically 30 dBm)
 3. Indoor femto-cells (in-home deployments, <20 dBm)
 - **LTE handsets** - We have conducted tests to identify the potential impact of LTE handsets operating at 2.3 GHz. These use some example user-data profiles that produce transmissions that are more typical than the worst case fully loaded transmissions we previously used. Technical analysis has included examining the impact from other Wi-Fi devices in adjacent channels, and LTE in the 2.6 GHz band in order to provide a fuller context for viewing the 2.3 GHz results.
 - **Real world testing** - In order to understand the impact of interference in a real environment, we conducted a collaborative field trial campaign with Network Rail and Sky (i.e. using Sky hot-spots - The Cloud) at Victoria Station in London. This examined the impact of a simulated LTE base station into The Cloud's Wi-Fi network. We have also received a submission from Telefonica and OptiWi-fi that examines the impact in a number of indoor office scenarios.
- 4.36 Additionally, we have undertaken a programme of further engagement with relevant stakeholders. We have been in contact with 36 organisations across the Wi-Fi supply chain from chipset and device manufacturers to network operators and regulators, including those from countries where 2.3 GHz services have already been rolled out. Further details are set out in section 6.

Market research

- 4.37 A confidential respondent said Ofcom had not produced any evidence to support its assertion that public Wi-Fi does not always provide a high quality user experience. The respondent said this was in contrast to existing consumer research - and pointed to a study by Cisco in 2013 which said that *“consumers using public hotspots are generally quite satisfied with the service. They give high ratings to the ease of use, quality, and overall experience of public Wi-Fi.”*
- 4.38 The respondent said Wi-Fi providers make significant investments in order to provide high quality of service. Customers, in particular those in retail and hospitality establishments, will not accept a degradation in their service compared to what they are receiving today.
- 4.39 Ofcom needed to carry out market research to understand whether or not users will have the knowledge and understanding of interference to know that they should separate mobile devices, LTE femto-cells and Wi-Fi devices. Additionally, Ofcom should consult with femto-cell manufacturers to understand their ‘product roadmaps’ to know whether technological developments are likely to mitigate any issues. Similarly, Ofcom should speak to equipment manufacturers to understand if improved filtering in access points is a reasonable belief.
- 4.40 The Communications Consumer Panel also urged further market and consumer research to understand how users of Wi-Fi react to issues arising from their use of Wi-Fi.

Ofcom response

- 4.41 We have conducted consumer research to understand better the ways in which consumers use Wi-Fi and how they react when there are performance issues. Our findings do not support those of the Cisco study. As noted in the sub-section above, we have also conducted extensive stakeholder engagement. The evidence we have gathered as a result of both the market research and the stakeholder engagement is set out in section 6 of this document.

Cost benefit analysis

- 4.42 The Communications Consumer Panel and one confidential respondent urged Ofcom to undertake a quantified cost-benefit analysis of the value of awarding the 2.3 GHz spectrum band set against the impact to consumers and businesses from a degraded or blocked Wi-Fi service. Another respondent pointed out the high value of Wi-Fi to society.
- 4.43 Sky challenged Ofcom’s suggestion that, in developing a framework for considering interference issues, it must strike a balance between the principle that licence exempt spectrum may not cause interference to other spectrum users and may expect no protection themselves from other users; and the duty to consider any potentially negative impact on citizens and consumers arising from the future use of the award bands for services such as LTE. Sky said Ofcom had misconstrued its duties in this regard. There is not a balance to be struck between the two – rather, one is a subset of the other. It is incumbent on Ofcom to further the interests of citizens and consumers in respect of communications markets. The principle relating to licence exempt use may be one way to achieve this, but adherence to this principle is not to be ‘balanced’ against any negative impact on consumers.

- 4.44 Sky also said Ofcom had failed to undertake work which estimates the benefit currently delivered by Wi-Fi (and indeed other uses which may be impacted by coexistence). Without an indication as to the value that current uses deliver, Ofcom cannot sufficiently assess the scale of the impact of the 2.3 GHz award and make a fully informed decision as to what mitigation steps are necessary. Ofcom had chosen not to quantify either the costs of the anticipated interference or the benefits associated with the release of spectrum at this time.
- 4.45 Virgin pointed out that Ofcom's cost benefit analysis suggested that the mitigations are "*relatively cheap and straightforward*"¹⁹, and the cost of alternative remediation schemes would outweigh its benefit. However, Virgin said this proposition appears to be made on the basis of little evidence of the costs themselves, and little thought has been given to remediation schemes, which can come in various forms. Schemes could range from those involving extensive support and cost from government to those administered and funded by the mobile industry. There appeared to be little discussion of these potential issues.

Ofcom response

- 4.46 An impact assessment is always carried out when Ofcom takes a decision about a change of spectrum use. Part of that assessment may include quantified elements, but many impact assessments are based around qualitative factors. Both the February 2014 consultation and this further document represent an impact assessment.
- 4.47 In this case, we do not believe it would be of value to attempt a *quantified* cost/benefit analysis. We accept that Wi-Fi is a very valuable technology of immense benefit to the UK economy and to citizens and consumers. However, by any measure, the potential adverse impact of the 2.3 GHz award to Wi-Fi (i.e. cost) will be relatively very small because LTE will only affect a tiny number of people negatively. It will not impact on Wi-Fi services as a whole. Therefore quantifying the reduction in that benefit would be of little value in assessing the impact of interference from 2.3 GHz LTE.
- 4.48 In any case, many of the potential costs involved (such as time lost due to slow connections, inconvenience etc.) are impossible to quantify. Other costs (such as implementing mitigations) cannot be assessed in any meaningful way when we don't know the scale of 2.3 GHz roll-out; the timescales involved; the number of resulting impacts; the pace of technological improvements which will happen anyway; or the cost and volume of any replacement equipment (e.g. for enterprise networks) etc.
- 4.49 Nevertheless, we believe it is clear from the technical evidence we have about the very limited level of noticeable impact that those costs (e.g. a limited replacement of some Wi-Fi routers, provision of information etc.) will be relatively very low. In contrast, the benefits of 2.3 GHz LTE – though unknown at present – will be very significantly greater based on the value of additional spectrum to meet the increasing demand for mobile data.
- 4.50 We have continued to build on the impact assessment contained in the February 2014 consultation in our further overall assessment of the coexistence issues for Wi-Fi contained in this document. We agree that our primary duty is to further the interests of citizens and consumers in respect of communications markets. In

¹⁹ Paragraph 6.76

doing so we need to take account of a range of factors. This includes taking into account the fact that users of licence exempt may not cause interference to other spectrum users and may expect no protection themselves from other users.

Consumer support

- 4.51 Some confidential and some non-confidential respondents argued that Ofcom should give further consideration to offering support for consumers over potential interference issues.
- 4.52 One confidential respondent said that the February 2014 consultation had suggested at various points that there was a need to inform consumers about the issues involved. However, there were no firm proposals in the document. There was a need for a labelling scheme so that users will know whether the Wi-Fi access point or client device that they buy will be susceptible to interference from 2.3 GHz users.
- 4.53 The Communications Consumer Panel made comparisons with the TV digital switchover (which it said was well managed, especially for older and disabled people) and with the planning and execution of work to mitigate potential TV interference at 800 MHz. Although the panel recognised that both of these projects were large scale, it hoped they would be used to inform how best to provide support to consumers following any re-allocation of 2.3 (and 3.4) GHz spectrum.

Ofcom response

- 4.54 We consider it important that the very small number of Wi-Fi users potentially affected by 2.3 GHz Wi-Fi are in the best position to be able to mitigate any issues. This will include making helpful information available to ISPs and consumers through our website. We will also encourage manufacturers to include relevant information about siting equipment such as femto-cells away from Wi-Fi routers.
- 4.55 We note there are some practical difficulties in providing a formal support scheme – not least the fact that it will be virtually impossible to determine that 2.3 GHz LTE is the cause of any degradation of Wi-Fi. Our assessment of the options for consumer support is set out in section 6 of this document.

International comparisons

- 4.56 A confidential respondent drew Ofcom's attention to a paper on LTE spectrum issues published last year (2013) by the Global TD-LTE Initiative (GTI). It said tests by China Mobile showed that there is a severe risk of interference to Wi-Fi from base stations and mobiles even when LTE is only operated below 2370 MHz (i.e. a 30 MHz guard band compared to the 10 MHz that is presently proposed in the UK)²⁰.
- 4.57 The Communications Consumer Panel also raised issues about our reference to international comparisons, and the fact that no issues had so far been recorded in other countries. The panel urged caution about presuming that there had not been any consumer detriment.

²⁰ See Annex 4 of <http://www.lte-tdd.org/d/file/Resources/pub/2013-11-22/180e4fbd9e544d019d42bc6d67913bf2.pdf>

- 4.58 Sky questioned the international pace of roll-out and usage of future mobile services operating in the 2.3 GHz band. It said the implication that significant and widespread international adoption of these services is to be expected needed to be questioned. Extensive deployment of LTE services in these bands (i.e. 2.3 and 3.4 GHz) across other global regions is infrequent at best, and certainly limited within the rest of the EU. Only four countries have launched commercial LTE services using 2.3 GHz (often at the bottom of the band), and while trials are ongoing in several other territories, many major consumer markets - such as the USA - are not amongst them.
- 4.59 Ofcom should take the relatively low usage of these frequencies for mobile use into account when assessing the likely benefit of releasing the spectrum. Given the limited international roll-out, it may be that the consumer value which is anticipated to arise does so only after a delay, as devices are released in line with wider adoption.

Ofcom response

- 4.60 We have had further engagement with overseas regulatory bodies in those territories where 2.3 GHz LTE has been rolled out. A summary of the information and insights we have gained is included in section 6 of this document.
- 4.61 In response to the point raised by Sky regarding the low deployment of 2.3 GHz in the EU and globally, we note the ongoing European harmonisation process which is due to complete in mid-2015. We expect uptake to increase in Europe after this point (as in the UK). We also note that 10 countries have existing commercial 2.3 GHz deployments, including major markets such as China, India and Australia.

Responses about proposed mitigations

- 4.62 The greatest volume of responses on Wi-Fi to the February 2014 consultation concerned the mitigations we said could be applied if any interference issues arose in practice. For example, in expressing concern that the risks of interference to Wi-Fi may have been under-estimated by Ofcom, BT said the proposed mitigation measures may have been over played. Many mitigations were costly and unrealistic or unsuitable, BT said. Other respondents also questioned the effectiveness or practicality of mitigations, as set out below.

Use of the 5 GHz Wi-Fi band

- 4.63 Almost all respondents agreed that use of the 5 GHz band provided mitigation for equipment capable of accessing those frequencies, but a few had some reservations as outlined below.
- 4.64 Sky agreed that use of the 5 GHz band provided an effective mitigation, but pointed to resulting increased levels of congestion in the band. This could still represent a negative impact on UK citizens and consumers. As a result, Ofcom should prioritise offsetting any loss through interference by securing additional Wi-Fi spectrum. Sky highlighted the importance of extending the 5 GHz spectrum availability to licence free use by adding frequencies between 5350 and 5470 MHz (120 MHz) and 5850 to 5925 MHz (75 MHz) at the earliest opportunity.
- 4.65 Tech UK said 5 GHz Wi-Fi coverage does not match that at 2.4 GHz and some devices do not have 5 GHz Wi-Fi capability. Thus a move to 5 GHz is not universally feasible and could also represent a reduction in overall spectrum

capacity for Wi-Fi. However the availability of 5 GHz Wi-Fi equipment will increase in the time between now and implementation of LTE networks at 2.3 GHz in 2016.

4.66 A confidential respondent pointed out some limitations of the 5 GHz band:

- Currently both the 2.4 GHz and the 5 GHz band are available to deliver Wi-Fi services and both are being used. Only using the 5 GHz band reduces the overall capacity from what is available today so it does not seem appropriate to describe it as a mitigation;
- Not all devices are capable of accessing 5 GHz. The band is not standard in all the Wi-Fi enabled devices and Wi-Fi access points that are being supplied new into the market;
- Even if devices support both the 2.4 GHz and the 5 GHz bands they may not automatically switch to 5 GHz to mitigate against LTE interference. The reality is that the 2.4 GHz service would be degraded and users would suffer this even with a 5 GHz option being available. While some Wi-Fi products may support band steering to 5 GHz many do not;
- The propagation characteristics of 5 GHz mean that in some situations 2.4 GHz is the only option available, and relying on 5 GHz only would mean that homes would need to be served by additional Wi-Fi access points with the additional cost that would incur (as well as the practical limitations of households being able to do that).

4.67 BT said that in some cases it is feasible to use 5 GHz instead of 2.4 GHz, but in many cases this is not reasonable due to the costs; the coverage limitations of 5 GHz; and life expectancy of existing equipment (e.g. games consoles).

Ofcom response

4.68 Whilst noting the reservations about 5 GHz expressed by some respondents (as outlined above) we also note that the majority of respondents agreed that use of this alternative band was in fact an appropriate and effective mitigation. Our views on the effectiveness of using 5 GHz have been reinforced in subsequent stakeholder engagement, although we recognise it may not be possible in all cases.

4.69 Virtually all new equipment on the market now has 5 GHz capability. As a result, there will be an ever-declining volume of legacy equipment unable to access the band. We note that the 5 GHz band is not currently congested, but acknowledge that increasing use of the band may generate pressure for more 5 GHz frequencies to be made available for Wi-Fi. Ofcom has identified the need for additional spectrum in 5 GHz as part of our mobile data strategy²¹, and we are working in relevant international groups to explore potential options²².

²¹ See 4.17 and Table 5 of our Mobile Data Strategy Statement from May 2014:

<http://stakeholders.ofcom.org.uk/binaries/consultations/mobile-data-strategy/statement/statement.pdf>

²² See section 3 of our Spectrum sharing consultation from April 2014:

http://stakeholders.ofcom.org.uk/binaries/consultations/spectrum-sharing/statement/spectrum_sharing.pdf

- 4.70 A fuller consideration of available mitigations in the context of our overall assessment of the coexistence issues for Wi-Fi is included in section 6.

Other consumer mitigations

- 4.71 Our February 2014 consultation said mitigations other than use of the 5 GHz were available and may be helpful in particular circumstances. However, they were of less overall importance. Some respondents disputed the usefulness of alternative mitigations, as set out under separate headings below. Our assessment of stakeholder submissions about all of the alternative mitigations is set as a single Ofcom response below.

Moving affected equipment

- 4.72 Whilst noting that moving affected equipment away from a source of interference may well be an effective mitigation, a number of stakeholders questioned whether it was realistic to expect domestic consumers to identify the source of any interference and to know how to react.
- 4.73 EE strongly supported Ofcom's proposals in general, but said it would be difficult in any case for either consumers or professionals to understand the sources of interference affecting Wi-Fi performance e.g. whether the source is a neighbour's Wi-Fi router or LTE. In such a scenario the solution of moving the device may not entirely resolve the issue from the user's perspective.
- 4.74 Tech UK said some of its members believe that the separation needed to avoid interference between 2.3 GHz LTE and 2.4 GHz Wi-Fi devices could extend to 10 metres or more, and in such cases, the feasibility of increasing separation between devices is questionable. These implications should be covered in additional studies.
- 4.75 The Communications Consumer Panel said it was not appropriate to include consumers having to move equipment to another location in their homes as a planned mitigation activity. Such mitigation assumed a number of factors:
- That the consumer identifies a degradation to their service;
 - That the consumer correctly identifies the degradation to their service as being a result of interference;
 - That the consumer is able to move their equipment/device to another location (for example that it is possible to move a router sufficiently far from the original wired point and that a room is sufficiently large for this to be done);
 - That they are physically able, or confident to do so;
 - That the consumer is happy with equipment being situated in another part of his or her home.
- 4.76 These factors argue for mitigation that has less impact and less reactive reliance on the consumer. At the very least, a proactive and focussed programme with a well-defined support scheme and communication campaign that is appropriately funded was needed.

- 4.77 Virgin said that to base the effective use of Wi-Fi on a need to position a router in a 'safe' environment away from walls/windows risks creating an overly prescriptive and inappropriate siting requirement through the back door.
- 4.78 Some respondents, including BT, expressed concern about the ability of consumers to reposition their devices in public Wi-Fi environments. A confidential respondent said both femto-cells and Wi-Fi access points require access to the broadband backhaul. Therefore the ability to separate them will be limited in many cases. It will be impossible to know the source of any interference.
- 4.79 Even when it is clear that interference is coming from a 2.3 GHz LTE device (such as a mobile phone), the person experiencing Wi-Fi interference is unlikely to know the phone user. It is unrealistic to expect someone to ask a stranger to stop using their phone to avoid interference.

Use of power-line technology

- 4.80 The Communications Consumer Panel expressed concern that, in a wireless age, customers may find themselves having to use a cable to restore their device to its previous level of efficiency. As well as involving a cost, this may be inconvenient or restrictive for consumers.
- 4.81 A confidential respondent also noted that wired technology is available already as an alternative to Wi-Fi, but consumers were making the choice to use Wi-Fi over power-line. Therefore to consider this a mitigation was wrong. It also seems inconsistent of Ofcom to suggest that consumers should move from a widely used and highly valued wireless technology (i.e. Wi-Fi at 2.4 GHz) to a wired technology (i.e. power-line) in order to enable an incremental increase to an existing wireless technology (i.e. LTE).
- 4.82 On the other hand, one confidential respondent noted that the use of power-line technology as an alternative mechanism was already fairly common because end-users already need to use such equipment to mitigate Wi-Fi having insufficient coverage within the home.

Ofcom response on alternative consumer mitigations

- 4.83 The February 2014 consultation identified a number of mitigations that may be applied to Wi-Fi equipment that does not have sufficiently good filters to block out unwanted signals from nearby spectrum bands. However, as noted, by far the most important of these is the ability of routers and devices to switch to the alternative 5 GHz Wi-Fi band. We do not consider the alternative mitigations to be of equivalent importance.
- 4.84 In assessing the usefulness of the alternative mitigations we have identified, it is particularly important to bear in mind the nature and context of potential degradation to Wi-Fi. This is discussed more fully in section 6 but, in summary, we believe noticeable interference to Wi-Fi equipment unable to access the 5 GHz band – and any consequent need for mitigations to be applied in the first place – will occur in only a very small number of locations.
- 4.85 We consider the mitigations identified in the February 2014 consultation are all possible, and could solve interference problems in some circumstances. However, we now accept that we cannot necessarily rely on consumers to take appropriate action in the absence of relevant information.

Market developments and equipment replacement cycles

- 4.86 Sky noted Ofcom's assertion that many devices (including tablets and smartphones) have both Wi-Fi and mobile broadband capability, and that chipset manufacturers will ensure future equipment is developed to take account of both Wi-Fi and 2.3 GHz LTE. However, Sky again noted that large-scale deployment of LTE services in the 2.3 GHz band has not yet occurred in major markets around the world. It was therefore reasonable to assume a delay in the widespread introduction of more robust equipment, beyond the 18-24 month replacement cycles which Ofcom suggests.
- 4.87 Sky added that some equipment – in particular Wi-Fi routers – will in any case have longer replacement cycles than the 18 to 24 month projection identified by Ofcom, with timescales in the region of 3 to 5 years being normal. The projected timetable will therefore result in additional expense for business and consumers.
- 4.88 BT said it did not consider it acceptable that affected users should be required to upgrade their Wi-Fi devices, especially where these are in expensive items such as PCs, games consoles and tablets that consumers would expect to have a life span of many years.
- 4.89 On the other hand, one confidential respondent stated that, if anything, Ofcom's estimates of the scale of impact are likely to be high, as the normal replacement cycles of equipment means that many poorly performing devices will have been replaced with better designed equipment before the 2.3 GHz band is introduced. This is particularly the case given the UK is not unique in utilising 2.3 GHz for LTE services, and the fact that mobile phones will inherently be engineered to support both LTE at 2.3 GHz and Wi-Fi.
- 4.90 The same respondent said it was relatively unusual for consumers to purchase their own Wi-Fi routers, with every major ISP providing this as part of their broadband package, and replacing them regularly. Where an ISP does not have a regular replacement strategy, the respondent said it was an issue to be addressed by that ISP rather than a regulatory concern. Those consumers that do buy their own router tend to be technically savvy, generally having the latest equipment. The respondent said it was therefore reasonable to conclude that the predominant interference model will be that of poorly-engineered end-user equipment in close proximity to either base stations or mobile handsets.
- 4.91 In respect to public networks, the respondent said that operators have a commercial incentive to deliver the best service experience, hence it is in their interests to use the most up to date equipment, including effective filtering. The response concluded that no action is required for this category of user.
- 4.92 EE also said public Wi-Fi was generally installed and managed by professionals who would be well placed to understand any causes of interference and how to deal with them.
- 4.93 However, Virgin expressed concern about the idea that equipment should be replaced in public access points. There has now been considerable investment in outdoor Wi-Fi networks, and the lifespan of an access point can be lengthy, and considerably longer than the period suggested in the consultation. Access points which were high performing at the time of installation may not be so high performing at the time of this consultation, or indeed 2.3 GHz LTE roll out. It would

be inappropriate to penalise early investment in outdoor Wi-Fi networks by assessing acceptable interference by reference to more recent technologies.

- 4.94 The Communications Consumer Panel said it would welcome further detail on replacement cycles for both domestic and public Wi-Fi equipment. It also sought information about the extent to which relevant consumer support - and costs related to refreshing routers - had been incorporated into ISP's planning.

Ofcom response

- 4.95 As with the comments about use of the 5 GHz Wi-Fi band, we have discussed industry developments with a wide range of stakeholders since the February 2014 consultation was published. We believe industry is increasingly aware of the need for equipment to operate in a congested environment alongside other technologies, both licensed and unlicensed. This awareness is likely to lead to a quicker adoption of more robust technology in Wi-Fi devices.
- 4.96 A full assessment of the issues – together with further discussion of our stakeholder engagement – is set out in section 6 of this document.

Funding of mitigations

- 4.97 A number of respondents – most of them from the Wi-Fi industry – said the cost of implementing mitigations should not fall on Wi-Fi operators. A confidential respondent said it was unreasonable for Ofcom to expect the 'victims' of harmful interference to pay the costs of any mitigation as they are using equipment that fully complies with Ofcom's authorisation, and as they are not the cause of the interference.
- 4.98 Another confidential respondent said the costs of any mitigation should fall to the beneficiaries of the 2.3 GHz release. This viewpoint was also expressed by the Communications Consumer Panel.
- 4.99 A confidential respondent said Wi-Fi access points will need to have higher specifications than would otherwise be required, and this will mean they are more expensive than access points that would not require protection from interference from 2.3 GHz LTE. Similarly Wi-Fi operators may need to accelerate the normal replacement cycle for equipment, which carries an additional cost. Ofcom and the Government should provide funding to cover these costs.
- 4.100 BT said it was not at present sufficiently confident that Wi-Fi interference problems will be of low enough probability and readily mitigated to agree that regulatory intervention is not needed. BT argued that the main mitigation in the case of public Wi-Fi networks was to replace Wi-Fi access points or install filters where feasible. However, this will introduce new costs to Wi-Fi operators, and in this case financial compensation should be provided. The cost of fixing such problems should anyway be estimated and compared with the opportunity cost of implementing a larger guard band (i.e. awarding less than 40 MHz of spectrum or a slightly different 40 MHz of spectrum).
- 4.101 An alternative view was expressed by another confidential respondent who expressed strong support for Ofcom's proposals. The respondent recognised that there could be a very small minority of end-users who need to replace or upgrade their equipment. Whilst being sympathetic, the respondent said there was a need to recognise that mobile usage of the 2.3 GHz band will be subject to relatively

stringent technical constraints and that a guard-band has already been provided - meaning that the main interference mechanism is one of Wi-Fi equipment performing poorly to reject signals that are in the 2.3 GHz band (as opposed to mobile usage of 2.3 GHz band impinging into the 2.4 GHz Wi-Fi band).

- 4.102 Further, Wi-Fi operates in a licence exempt band with no guarantees of ongoing access. As such, it would be totally inappropriate for there to be a compensation scheme, as to do so would set a dangerous precedent, according to this respondent.

Ofcom response

- 4.103 We recognise that consumers are using equipment that is compliant with current standards and that, up until now, the environment in neighbouring bands has been benign. We note this and have been in discussion with relevant standardisation bodies to explore how they should take account of higher power signals in neighbouring bands in future standards.
- 4.104 As with other points raised by some stakeholders, there are some practical and contextual issues to take into account in considering the question of funding for mitigations.
- 4.105 Firstly, it is important to note the difficulty there will be in establishing that any interference to Wi-Fi in the 2.4 GHz band – if it actually occurs – will be due to LTE in the 2.3 GHz band, and not some other source. Secondly, the likelihood of interference remains extremely low. A generally funded scheme to replace equipment that may – or may not – be affected by interference due to the performance of Wi-Fi equipment in this new interference environment may be disproportionate. The issues involved are explored further in section 6.
- 4.106 In response to the suggestion that a different 40 MHz of 2.3 GHz spectrum could be awarded, we note that the particular frequencies being made available are those the MOD has determined to be suitable, given their own operational requirements i.e. they could be freed of alternative military uses. We have discussed with MOD whether changes to the release band could be made to move it lower by 10 MHz. However it has confirmed that this is impractical due to constraints within certain types of defence equipment.

Section 5

Further technical assessment of coexistence issues for Wi-Fi

- 5.1 In this section we outline the additional technical analysis and measurements we have undertaken in order to supplement the assessment of coexistence issues outlined in the February 2014 consultation.
- 5.2 As noted in the previous section, a number of respondents to the consultation suggested we had not conducted enough technical analysis before setting out our proposals that no market intervention was justified to protect Wi-Fi in the 2.4 GHz band. In particular, some respondents suggested:
- The impact from LTE small cells might be worse than for the national macro-cell deployment on which we based our assessment;
 - We may have underestimated the impact from LTE user equipment, such as mobile handsets;
 - More real world testing was required to gain a better understanding of the impact of 2.3 GHz LTE.

Additional technical analysis

- 5.3 Taking the consultation responses into account, we have conducted further technical analysis to assess the impact of interference from small cells and from mobile devices. This includes theoretical analysis as well as measurements and field trials. Our analysis is set out below as follows:
- First, we describe the additional lab measurements we have carried out to help us assess the potential impact of 2.3 GHz LTE, including in particular the impact from mobile devices;
 - We then describe the field trials that have been conducted to help us gain a better understanding of the 'real-life' impact of 2.3 GHz LTE (both mobile devices and small cells).
 - We then set out our overall assessment of the impact of mobile devices;
 - Finally, we set out our overall assessment of the impact from small cells.

Lab measurements

- 5.4 Our further analysis has included a programme of lab measurements to address the issue of interference from mobile devices. We have also tested a small number of additional devices including 802.11n capable equipment²³, and video streaming, in order to address the points raised in responses about higher throughputs and

²³ 802.11n is newer version of the IEEE Wi-Fi standard which provides faster speeds using wider channels and advanced antenna techniques than the 802.11g version which we focussed on in previous testing.

newer applications. The full details and results of this test program can be found in annex 1. We make reference to relevant results in the sub-sections below.

- 5.5 We have not conducted tests on a significantly larger range of devices than before. This is because we believe that the devices already tested exhibit a spread of performance and we expect other devices to also fall within that range. We believe our original testing covered the main chipsets available. As explained in section 4, we have insufficient information to consider any form of weighted performance by device market share. We therefore considered that an extensive programme of additional device measurements was unlikely to deliver any greater benefit to our analysis.
- 5.6 Nevertheless, we acknowledge there may be devices that are either more or less susceptible to interference than those we have tested as part of our February 2014 consultation or in this additional work.
- 5.7 In addition to our own further work, the Wi-Fi Alliance has recently published a report of its own campaign of measurements²⁴. This includes testing on five common devices including two access points, two smartphones and one tablet. The interference metric is based on de-sensitisation rather than throughput degradation, but the results support our own testing i.e. performance varies widely across different devices, and interference appears to be dominated by 'blocking'. One smartphone device is shown to be resilient to interference, suggesting that it includes an appropriate coexistence filter.

Comparison with previous results

- 5.8 Our further testing uses a slightly different measurement set-up which we believe provides more reliable results than the previous tests. It is noted that with the new set-up the onset of degradation is generally at the same level of interference, but some devices show more resilience to interference at the 50% and 1Mbps throughput levels.

Investigation of the impact of time domain effects

- 5.9 The main focus of our further measurements has been to investigate in more detail the impact of interference from mobile devices. We previously noted our belief that the time domain effects²⁵ of uplink signals mean the impact of interference will be low, as Wi-Fi users will be able to use gaps between LTE transmissions.
- 5.10 In order to better understand the time domain effects of LTE uplink signals we have collaborated with stakeholders in conjunction with the Wireless TIC group²⁶ to record signals from a live 2.3 GHz LTE network. A range of recordings were taken looking at different usage profiles. We focussed on the following cases for use in further measurements:

²⁴ LTE band 40 desensitization of Wi-Fi® devices - Technical note, Steve Shearer, Wi-Fi Alliance, October 2014: <https://www.wi-fi.org/file/lte-band-40-desensitization-of-wi-fi-devices>

²⁵ Time domain effects refers to the gaps in transmission of LTE signals within which Wi-Fi can operate

²⁶ The Wireless TIC group is a collaborative test and measurement forum as part of the techUK Future Technologies Network

1. Light loading based on a user downloading data and only sending acknowledgements on the uplink. We believe this represents the most typical usage case for mobile devices;
 2. Heavy loading based on a user uploading a large file for a long duration. This represents the assumed worst case in terms of interference, but is not likely to represent typical user behaviour for long periods of time;
 3. Continuous video streaming based on a Skype call. We believe this represents a typical case of persistent uplink usage.
- 5.11 The recorded signals were then used to replace the previous simulated LTE uplink signals in lab measurements for seven devices. The detailed process is outlined in annex 1.
- 5.12 We have compared the difference in interference impacts of these recorded signals with a simulated profile using LTE 'configuration 2' as this is consistent with our proposed technical licence conditions²⁷. It should be noted that uplink signals with a configuration 2 profile generally show a significant improvement (i.e. more resilience to interference) compared to the downlink 'configuration 5' signals which were used in the main impact figures for the February 2014 consultation, so the results should be viewed in this context.
- 5.13 The results for some devices showed improvement in resilience to interference for all recorded uplink signals. In some cases we could not generate sufficiently high interference power levels to cause degradation over the 3 metre test distance. As the generated levels were based on the recorded levels, we believe this is representative of a real-world scenario, and shows that resilience to interference can be expected in practice for these devices at close range to an interfering mobile device.
- 5.14 For other devices there was no noticeable improvement in resilience to interference when compared with the simulated uplink 'configuration 2' signal.
- 5.15 These results are explored in more detail in Annex 1.

Interference from other sources

- 5.16 We also undertook the following tests to compare the impact of 2.3 GHz LTE handsets with other potential interference scenarios:
1. Interference from 2.6 GHz uplink from user terminals;
 2. Interference from other Wi-Fi networks.
- 5.17 These tests were undertaken to provide some context for our theoretical 2.3 GHz results based on both adjacent and in-band systems with which existing Wi-Fi networks have to coexist.
- 5.18 The 2.6 GHz tests were undertaken with the interfering 2.3 GHz signal replaced with a 2.6 GHz FDD uplink signal – i.e. above the 2.4 GHz Wi-Fi band rather than

²⁷ There are six possible configurations of TDD for LTE with varying uplink/downlink ratios. Our previous use of configuration 5 reflected a 'worst-case scenario' in the downlink.

below it. This 2.6 GHz signal was simulated based on different levels of loading on the uplink rather than based on recorded signals.

- 5.19 We note there is a slightly larger frequency separation between the Wi-Fi band and the 2.6 GHz band²⁸, but believe that the scenarios are otherwise equivalent when compared to 2.3 GHz simulated uplink signals. The results show that the impact from a 2.6 GHz uplink signal is generally similar to that from a 2.3 GHz uplink signal, and in some cases is slightly worse. This is because Wi-Fi access protocols allow some data to be transmitted during the 'off' part of the TDD signal with some devices. 2.6 GHz signals are FDD and therefore there are no 'off' periods to be used.
- 5.20 This provides some useful context; our test results show that the risk of interference from 2.3 GHz LTE user equipment is no more significant than from existing devices using the 2.6 GHz band. No specific considerations were made as part of the 2.6 GHz award with regard to coexistence with Wi-Fi and we are not aware of any interference cases from actual 2.6 GHz network deployments, either in the UK or internationally²⁹.
- 5.21 Additionally, further testing was undertaken with the interfering LTE signal replaced with another Wi-Fi signal – both co-channel and adjacent channel Wi-Fi were tested separately.
- 5.22 The impact from an adjacent channel Wi-Fi signal results in an onset of degradation that happens with less interference power, although the drop in throughput is found to be more gradual than with the 2.3 GHz LTE signals. This is as expected, as the polite protocols in Wi-Fi cause both the interferer and the wanted signal to 'back off' if it senses the other network (even on an adjacent channel it can be expected to pick up the energy of a nearby network and back off accordingly). A co-channel Wi-Fi network is found to cause interference at lower levels than a 2.3 GHz LTE network which is adjacent
- 5.23 These tests also provide some useful context on the typical environment in which existing Wi-Fi networks have to operate. As Wi-Fi and LTE are both providing data connections, 2.3 GHz could be seen as an alternative to Wi-Fi in some cases. Therefore we can assume a 2.3 GHz mobile device in a home environment will not cause significantly higher interference than if that same user was using Wi-Fi to upload data instead. In more congested hotspot locations, the complexities of the Wi-Fi resource sharing means that although an 'interfering' Wi-Fi user would cause degradation, it might not be directly comparable with the degradation caused if the same user was using 2.3 GHz TD-LTE instead.

Other measurements

- 5.24 In addition to the measurements on interference from mobile devices described above, we have also looked at a few additional devices for specific reasons:
- We have tested an 802.11n Wi-Fi link in direct response to the concern raised by BT that the non-interfered throughputs achieved in previous

²⁸ There is 17 MHz separation between the upper edge of the highest Wi-Fi channel (2483 MHz) and the lower edge of the 2.6 GHz uplink (2500 MHz), as compared with 11 MHz between the edge of the lowest Wi-Fi channel (2401 MHz) and the top of the release band (2390 MHz)

²⁹ We considered this issue as part of our stakeholder engagement campaign outlined in section 6. We note that in-device coexistence with 2.6 GHz is recognised as an issue, but have not found any evidence of interference between devices

testing (based on 802.11g) were lower than can typically be achieved in practice with current 802.11n technology. The results of these tests show slightly less resilience to interference for two devices, and one device has no noticeable difference.

- One ISP provided us with home routers that are currently widely used models within its domestic customer base. We therefore included the testing of these as additional results. The performance of these routers was found to be within the performance range of other devices tested;
- In response to points raised regarding new Wi-Fi applications which require high throughput, we looked subjectively at how robust one device designed to receive streaming video signals was in practice. The tests showed the device was more resilient to interference than most of the other devices previously tested.

Field trials

- 5.25 We have also received additional submissions from two stakeholders with regard to testing that has been conducted in real environments.
- 5.26 Telefonica, in conjunction with OptiWi-fi, conducted some indoor testing independently of Ofcom. A range of tests was performed looking at the impact from both a base station configured to represent an indoor LTE pico-cell type base station or typical levels that would be seen indoors as a result of a nearby macro-cell; and mobile devices to Wi-Fi access points and clients in a busy indoor office environment
- 5.27 The results showed only minimal impact to Wi-Fi at close ranges to the LTE device:
- With an indoor LTE base station at a distance of 5 metres from the Wi-Fi access point, throughput was reduced by 10% on average. At 0.5 metres from the base station the reduction was 50%, but the connection was still usable;
 - With an LTE mobile device at a distance of 0.5 metres from a Wi-Fi client device, throughput was reduced by less than 10% on average. With no physical separation between the devices, the reduction was less than 20%;
 - The impact from LTE mobile devices to Wi-Fi access points varied between devices. In the worst case there was a 50% reduction in throughput at 1 metre separation;
 - The impact from LTE mobile devices varied significantly with traffic profile – the impact was more pronounced when the mobile device was uploading than when it was downloading.
- 5.28 The findings of this trial support the results of our own measurements, particularly with regards to the impact from mobile devices. It additionally supports the latest results which show that higher levels of interference are required to cause a reduction in throughput to 50% than those found in our previous tests. Further

details and full results from the Telefonica trial are available in a separate report published alongside this document.³⁰

- 5.29 We also undertook a field trial in conjunction with Sky and 7Signal, whereby we provided a base station simulator based on a high traffic loading simulated signal in a busy train station environment (Victoria Station in London). During the tests some passive Wi-Fi monitors were deployed across the station to observe throughput and other metrics, such as re-transmissions from live usage on the network.
- 5.30 Tests were conducted during different times of the day to ensure all typical usage patterns (particularly the busier morning and evening rush hours as well as quieter lunchtime periods) were captured. The tests were conducted on four days over two weeks to ensure repeatability. Measurements were also taken on days with no LTE transmitting, for purposes of comparison.
- 5.31 A range of LTE transmit powers was used for different tests, ranging from typical indoor pico-cell powers to higher powers more representative of an outdoor deployment. The results showed that LTE did not cause noticeable disruption to the network. This was the case even with the base station transmitting at higher powers than would normally be typical for cellular deployments in this type of environment.
- 5.32 7Signal noted that the limiting factor on throughput and user experience was likely to be the ADSL back-haul connection to the internet. However, we note that 5 GHz networks were found to give better performance than 2.4 GHz. A slightly higher number of users was generally seen on the 5 GHz network. We also note that there appeared to be significant congestion on the 2.4 GHz network at all times of day - and there was no significant reduction in throughput when the interference source was active. This makes it difficult to draw wide ranging conclusions.
- 5.33 Further details and full results from the Sky trial are available in a separate report published alongside this document.³¹ The results from both trials are discussed further in the sub-sections below.

Overall assessment of interference from small cells

- 5.34 Our original analysis in the February 2014 consultation focussed on the impact of interference from a nationwide network of macro-cells. We believed this was the worst case scenario due to the high transmit power and extent of roll-out. Additional analysis has focussed on the impact of small cells. We have considered outdoor small cells, indoor pico-cells in public buildings, and in-home femto-cells as separate scenarios.
- 5.35 The results from the field trial conducted in Victoria Station are also relevant here, in both the outdoor and indoor pico-cell scenarios.

Outdoor small cells

- 5.36 We have conducted some additional analysis to determine the relative impact from an outdoor deployment of small cells as compared with the impact from macro-cells.

³⁰ See Annex 2 for details of associated documents

³¹ See annex 2 for details of associated documents

5.37 It is difficult to predict specific details of a wide area small cell deployment as these will vary based on an operators' business model. We have therefore focussed our analysis on a single area in central London³². In order to compare the impacts, we considered the existing coverage from a single 2.1 GHz macro-cell along a street and determined the number of small cell sites required to match this coverage.

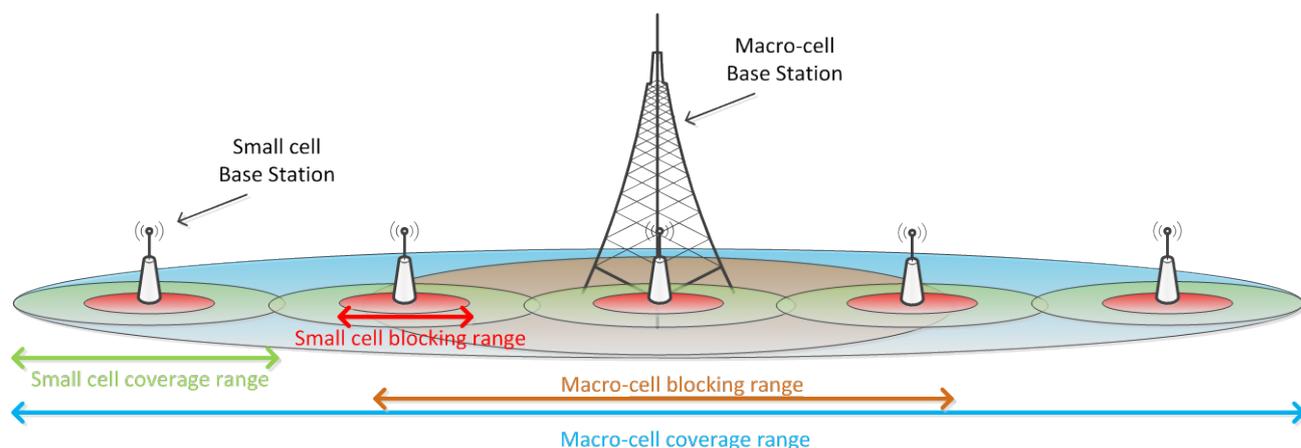
5.38 We used the central London ray tracing analysis results used in the February 2014 consultation to determine the total linear distance along the street where signal strength from the existing macro-cell was above a threshold that caused an onset of degradation to the throughput. This is calculated as 62 metres. Assuming a small cell height of 5 metres and an EIRP of 35 dBm, the interference radius in free space is calculated as 8 metres, which is doubled to give a 16 metre linear distance along the street.

5.39 The number of small cells within the macro-cell coverage can be estimated in two different ways:

1. By counting the existing 2.1 GHz small cell sites providing coverage within the area of interest: Five relevant sites from the same network as the macro-cell are found. This means the impact from small cells is 1.3 times worse than from the macro-cell³³
2. By assuming a new network is planned, and calculating the required number of small cell sites needed to provide coverage. This results in 8 sites³⁴, which implies the impact would be twice that of the macro-cell.

5.40 This is illustrated in the diagram below.

Figure 5.1: Illustration of small cell and macro-cell coverage areas



5.41 Based on this simplified analysis we can assume that in a dense urban environment the risk from small cells may be approximately 1.3 to 2 times worse than the risk from a macro-cell. Even though the interference range from an

³² We have assumed that small cell deployments are mainly used to provide coverage from lamp-posts along streets, and interference issues will mainly be caused to outdoor Wi-Fi networks on the same street. We are therefore not considering the full coverage region of the macro-cell.

³³ i.e. the total affected linear range from the 5 small cells is $5 \times 16 = 80$ m. This is 1.3 times higher than the 62 m range from the macro-cell

³⁴ Based on the average radius of existing small cell sites in the area of 62 m

individual site is lower than from a high power macro-cell, the higher density of small cells deployed in urban areas results in a higher total risk.

- 5.42 However this will not necessarily translate to higher risk nationally, as we don't believe operators are likely to match existing national macro-cell coverage with 2.3 GHz small cells – i.e. small cells would primarily be used for capacity in-fill in urban areas. We also note that, as the interference range is lower (typically 8 metres from a small cell site and up to 220 metres³⁵ from a macro-cell site), interference could be avoidable through careful deployment of 2.3 GHz with respect to existing nearby Wi-Fi access points. We recognise this would require cooperation between Wi-Fi and LTE operators and it would be up to these operators to choose to cooperate if they felt it was of mutual benefit.
- 5.43 The Victoria Station field trial is relevant in this scenario. While this was conducted in an indoor environment, we believe the scenario could also be representative of an outdoor deployment. We ran some of our additional tests at a higher power than would be applicable to an outdoor small cell in practice.
- 5.44 Additionally, due to the size of the testing area, there was a line of sight link from the interfering base station to certain access points, as may be the case in an open outdoor environment. The higher power and line of sight links did not cause any noticeable additional degradation to user experience, which was already relatively low for the 2.4 GHz layer.

Indoor pico-cells

- 5.45 The scenario for indoor pico-cells covers 2.3 GHz deployments in public buildings, such as train stations and shopping centres, as well as in enterprise environments (large office buildings). The results from the Telefonica and Sky trials are particularly relevant here as the test environments were representative of typical pico-cell deployments in busy indoor office and commercial environments respectively.
- 5.46 Based on the evidence from the trials, we believe the impact of interference from pico-cells is low, unless they are located at very short distances from Wi-Fi. As with outdoor small cells, careful siting between operators may play a role here. This is a viable option in an enterprise environment with one IT provider, but potentially more difficult in a shopping centre or train station with multiple independent Wi-Fi operators.

In-home femto-cells

- 5.47 In the February 2014 consultation we assumed the impact from femto-cells would be low on the basis that femto-cells implement power control to avoid causing interference to the wider network. In fact, we have proposed in our auction design consultation that femto-cells must employ power control³⁶. This is in line with ECC decision 14(02).

³⁵ Based on the calculations set out in Table A7.21 in Annex 7 of the previous consultation from February 2014 using Suburban Hata propagation. It is noted that this range is found to be lower in dense urban environments.

³⁶ See section 9 of our consultation on award design

<http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

- 5.48 We also note that existing femto-cells in other bands are primarily used for extending voice coverage within the home. We believe that 2.3 GHz will predominantly be used for data coverage, and we have not found any evidence to suggest that 2.3 GHz would be used specifically for in-home femto-cells.
- 5.49 The assumption that data will dominate over voice is based on the fact that 2.3 GHz equipment and coverage is not expected to be as prevalent as other bands - such as 2.6 GHz, which has been available for longer and has more spectrum available. Furthermore, FDD is generally more suitable for voice transmission due to the requirement for symmetry (as opposed to the TDD we specify for the 2.3 GHz band).
- 5.50 As noted above, femto-cells are required to transmit at low power. Therefore the impact is likely to be similar to that from mobile devices (see assessment below). Much of the analysis and conclusions for mobile devices can therefore also be applied to femto-cells.

Overall assessment of interference from mobile devices

- 5.51 Our previous analysis indicated that the impact of 2.3 GHz mobile devices would not be significant, based on the intermittent nature of mobile transmission and because transmit powers are typically low enough that the risk of interference is minimal. Specifically, we calculated a maximum interference range of less than 1 metre, based on a typical transmit power of 3 dBm.
- 5.52 We have outlined above our further lab measurements which focussed on this issue. The following conclusions have been drawn from these results:
- The use of frame 'configuration 2', as is proposed in our technical licence conditions, shows there is an improvement in interference levels from uplink transmission compared to the levels used in the previous consultation. Those previous levels were derived from the measurement results based on worst case high duty cycle downlink assumptions³⁷. This is because Wi-Fi is able to exploit the gaps in transmission when using frame 'configuration 2', and the impact of interference is not as severe as when using other higher duty cycle frame configurations. However this ability does vary by Wi-Fi device suggesting it is related in part to the algorithms within the Wi-Fi device;
 - When additional time domain effects based on typical uplink traffic profiles are considered, the impact is further reduced from the previous analysis, resulting in better resilience to interference.
 - The impact of interference from other Wi-Fi networks, and from 2.6 GHz FDD uplink signals, is found to be similar to the impact from 2.3 GHz uplink signals. As these are existing coexistence scenarios, the results suggest the impact of 2.3 GHz uplink may be no worse in reality than existing congestion.
- 5.53 We have also considered further the transmit power of mobile devices, in response to concerns that our previous assumption of an average transmit power³⁸ of 3

³⁷ In the previous analysis, the interference levels were derived based on a heavily loaded downlink signal with frame configuration 5.

³⁸ We assume an antenna gain of 0 dBi so this is equivalent to an EIRP value

dBm was too low. In order to address this point we have conducted a series of walk tests in urban and suburban areas recording the transmit power of a mobile device on different existing mobile networks. The results show a range of powers in different areas, depending on the position of the mobile in the cell, as may be expected. As with other tests, the full results are presented in annex 1.

- 5.54 We use the 50th percentile results from each test, as we believe these are the most relevant for a mobile system, while noting that higher powers are possible in extreme cases. The distribution of transmit power varied depending on the environment and LTE frequency band. As a result the 50th percentile value varied from -2 dBm in areas of good coverage to 19 dBm in more cell edge locations. The median of all the results is 9 dBm which we think is an appropriate value to use in our statistical modelling.
- 5.55 We understand from informal discussions with a stakeholder that they have seen similar results in walk test campaigns but we have not seen detailed results.
- 5.56 We note that in a small cell coverage area (including outdoor and indoor pico-cell and in-home femto-cell scenarios described above) mobile devices are more likely to undergo power control, thus reducing the risk of interference from the LTE user equipment (although there may be a risk of interference from the small cell base station to Wi-Fi).
- 5.57 Therefore, while our measurements show that typical transmit powers may be 5 dB higher than our previous assumption of 3 dBm, we note that the measurements for use of 'configuration 2', and for recorded signals can result in a significant improvement in resilience to interference compared to previous results, and therefore the effect of an increase in transmit power is largely offset by this.
- 5.58 Therefore we believe that assuming a 3 dBm transmit power against interference thresholds calculated from worst case 'configuration 5' scenarios (as in previous analysis) is broadly equivalent to a 9 dBm assumption of power with a more typical traffic profile. Therefore we believe the 1 metre separation is still applicable.

Summary

- 5.59 Our additional work outlined above suggests that the risk of interference is no higher than in the results set out in the February 2014 consultation.
- 5.60 Based on the results of our further measurements and from field trials, we believe that while the onset of degradation occurs at a similar level to the previous analysis, the 50% throughput and 1Mbps failure points occur at higher interference levels than previously predicted, meaning that users are unlikely to suffer significant or noticeable degradation in practice.
- 5.61 Therefore we don't believe that the impact of interference from small cells will be significantly worse than that from macro-cells. We also believe that our previous assessment that the impact of interference from mobile devices is minimal in typical usage scenarios is reasonable.
- 5.62 Additional field testing shows that, in a real world scenario, interference from 2.3 GHz LTE is unlikely to cause noticeable impact to a user's experience. We are not therefore proposing to change the impact figures set out in the February 2014 consultation.

Section 6

Other considerations and overall assessment of Wi-Fi coexistence

- 6.1 In this section we build on the analysis set out in the previous sections to review our overall approach to the coexistence of 2.3 GHz LTE and Wi-Fi operating in the 2.4 GHz licence exempt band.
- 6.2 Before doing so, we discuss the extensive stakeholder engagement we have conducted since publication of the February 2014 consultation and also note the evidence we have gathered from other countries where 2.3 GHz LTE has already been rolled out. In addition, we outline some additional market research we have conducted into consumer use of Wi-Fi and into users' understanding of connection issues. We also set out some further thinking about the context in which an individual Wi-Fi user might experience interference issues in 'real-life' scenarios (as opposed to the theoretical possibility).
- 6.3 Finally, we consider again the proposals set out in the February 2014 consultation to assess whether they remain valid.

Industry stakeholder engagement

- 6.4 Since the publication of the February 2014 consultation, we have engaged extensively with industry and other stakeholders involved in the mobile/Wi-Fi markets. This has helped us to better understand the issues raised in consultation responses and has further informed our policy development.
- 6.5 Industry stakeholders have been closely involved in some of the further technical work we have undertaken in conjunction with the techUK FTN and Wireless TIC groups. As noted in section 4 we have engaged with a total of 36 organisations across the mobile and Wi-Fi supply chains including equipment makers, mobile operators and ISPs. Although the conversations were held in confidence, our further thinking on coexistence issues has been developed taking account of this engagement.
- 6.6 Of particular importance has been our greater understanding of a number of key issues including the pace of technological development and its impact on device design; and the normal replacement cycles for equipment.

Technology roadmaps and device design

- 6.7 We have discussed with stakeholders the market forces currently influencing the future development of LTE and 2.4 GHz technologies. Market forces help determine the nature and pace of technological development, including the type and quality of equipment which will be available.
- 6.8 As a result of our discussions, we know that manufacturers are now well aware of the potential for degradation of 2.4 GHz devices from signals in adjacent mobile bands (2.6 GHz as well as 2.3 GHz) - if they were not already. They have indicated that new devices are already being designed and manufactured in the light of this awareness.

- 6.9 Stakeholders told us we should expect some divergence in the quality of devices coming onto the market in future and, consequently, their tolerance to interference. They confirmed our own belief that it was reasonable to expect that mainstream consumer devices will improve their tolerance to interference. On the other hand, devices targeting the 'Internet of Things' (IoT) market face strong cost pressures, and may end up being less tolerant to interference in the future than they are now. However, these devices can often mitigate this risk by using short packets and retransmissions to 'get in the gaps' between interfering transmission signals.
- 6.10 We consider that these new devices are coming onto the market in the full knowledge of the release of 2.3 GHz for TD-LTE services. It is therefore a matter for manufacturers and operators to determine the appropriate level of robustness required for particular applications.

In-device coexistence

- 6.11 According to stakeholders, techniques have already been developed to manage in-device coexistence for devices which use both LTE and Wi-Fi. This includes many of the most recent and popular smartphones and tablets, such as the iPhone 6 and some variants of iPhone 5.
- 6.12 Filters are one such mechanism – although their effectiveness in allowing maximum use of the available frequencies depends on the size and cost of the filter. Most LTE devices will not be able to use both the full 2.3 GHz band and the full 2.4 GHz Wi-Fi band³⁹. Other techniques available include frequency switching and in-device scheduling. Devices may well use a combination of techniques.

Routers/access points

- 6.13 Routers and access points can make use of filtering alone, although there may be some drawbacks in terms of cost and power consumption. It is our understanding from stakeholder engagement that the cost of appropriate filters is less than one dollar, depending on volume.
- 6.14 Enterprise Wi-Fi access points are typically higher cost devices, and users have high expectations of performance, making filtering a sensible design precaution (and which some already adopt).

Band switching

- 6.15 Filtering and other technical mitigations are in addition to the ability of Wi-Fi enabled devices to switch to 5 GHz spectrum. The effectiveness of 5 GHz spectrum as a mitigation can be judged through two related questions: does a device have 5 GHz capability; and does the device switch *automatically* between the 2.4 and 5 GHz bands?
- 6.16 A device using a 2.4 GHz Wi-Fi connection might only attempt to automatically connect to a 5 GHz network once the 2.4 GHz Wi-Fi connection has failed (i.e. so-called 'break before make'). As a result, the current consumer experience of switching between 2.4 and 5 GHz bands can sometimes be 'clunky' because seamless transition and network self-organisation is not possible in all devices.

³⁹ Current spectrum allocations in the US and Chinese markets mean that current generation filters are often optimised to remove the impact of LTE signals below about 2370 MHz although other cut offs are possible.

However, most Wi-Fi devices will allow a user to choose what network they wish to connect to – although our market research (see below) suggests not all consumers know how to do this. Stakeholders indicate that newer products are more likely to select better connections seamlessly if they are available.

- 6.17 Many equipment manufacturers express confidence that the 5 GHz band will eventually be dominated by streaming audio and video applications, whilst 2.4 GHz is used for lower throughput applications such as web browsing. There is more spectrum available at 5 GHz, and it is currently less congested than the 2.4 GHz band, making it more suitable for the higher bandwidth applications.

Replacement cycles for equipment

- 6.18 We have discussed with stakeholders the normal lifetimes of Wi-Fi-enabled devices and the consequent upgrade/replacement timetables.
- 6.19 In general, the stakeholders we have engaged with accept our assumption that smartphones are generally replaced every 18 months or two years – but said that we may have under-estimated the importance of ‘hand-down’ i.e. devices being passed on to others, such as from parents to children.
- 6.20 Some stakeholders suggested that we had under-estimated normal replacement cycles for Wi-Fi access points, including domestic routers. We now believe that replacement cycles of perhaps three to five years may be normal instead of around two years. Current access points in some outdoor hotspot locations are even older than this. Stakeholders agreed with our assessment that TVs and games consoles might be expected to have longer life-cycles.

Overall lessons from stakeholder engagement

- 6.21 We noted from our meetings that manufacturers’ development cycles were short - usually six months to one year – but that they tended only to address coexistence issues as they arise. However, our discussions show they do understand the issues for 2.3 LTE and Wi-Fi coexistence and, already have a broad suite of options available for mitigating interference (although the options vary across devices).
- 6.22 As a result of our stakeholder engagement we continue to believe that manufacturers are best placed to understand the trade-offs they need to make between cost and quality in their future design decisions, and are starting to take account of this in developing products.
- 6.23 The development of in-device coexistence techniques alongside dual-band capability suggests that interference to mobile Wi-Fi enabled equipment will not be of particular concern. We are also satisfied that industry developments will ensure that any issues for public hotspots and enterprise networks will also be resolved by operators and equipment manufacturers.
- 6.24 Since we believe manufacturers are best placed to implement any changes, we believe they should also be best placed to choose *when* to react to the risk of interference. If such changes were instead to be mandated through regulatory intervention, there is a real risk of imposing unnecessary costs to address a perceived problem that that may not even materialise (or which will affect only a very small number of consumers).

- 6.25 Overall, the evidence on market developments confirms the position set out in the February 2014 consultation that the main concern for policymaking is the potential impact to legacy routers/devices which only use 2.4 GHz Wi-Fi.

International comparisons

- 6.26 Our February 2014 consultation noted that no significant interference between LTE and Wi-Fi has been reported in those countries where services have already been rolled out in the 2.3 GHz band – although we noted that not all overseas deployments used the higher channels in the 2.3 GHz band, and that deployment densities are still relatively low. Nevertheless, there are deployments in a number of countries outside Europe, including Australia, China, India, Nigeria, and South Africa.
- 6.27 We have used the time since publication of the consultation to undertake further research into the international experience of both international 2.3 GHz releases and those at 2.6 GHz (if issues were likely to arise from 2.3 GHz handsets we would also expect them to arise from 2.6 GHz).
- 6.28 There is still little reported evidence of interference between LTE and Wi-Fi internationally, but this may change as deployment densities increase in future and the intensity of use of the higher 2.3 GHz band frequencies develops. Additionally, we are not aware of any reports of serious interference from 2.6 GHz TDD or FDD LTE into Wi-Fi. We note that the 2.6 GHz FDD and TDD bands are more widely used worldwide than the 2.3 GHz band.
- 6.29 In **China**, the 2.6 GHz TDD band (Band 41) is allocated from 2555 to 2655 MHz for LTE. There has been no evidence of significant interference into Wi-Fi from deployed systems. The 2.3 GHz band is allocated to three operators: 2300 to 2320 MHz China Unicom; 2320 to 2370 MHz China Mobile and 2370 to 2390 MHz China Telecom. Services have begun to be rolled out by China Unicom and China Mobile but China Telecom is still planning its network.
- 6.30 Deployments are indoor only, in order to avoid interference to radars. Consequently, deployments are almost entirely small cells including femto-cells and pico-cells in environments such as homes, offices, cafés, shopping malls, train stations and conference centres. There are no reports of significant interference, although we are aware that a precautionary approach has been adopted to the siting of equipment.
- 6.31 In addition to considering the situation in China, we have approached regulators and operators in other countries where LTE has already been deployed in the 2.3 GHz band⁴⁰. Since Wi-Fi is used in the 2.4 GHz band globally, the experience from these countries may be relevant. There are also some deployments of WiMAX in 2.3 GHz in certain countries, which is likely to create a similar risk of interference.
- 6.32 Specific deployment scenarios vary between countries – in some cases frequencies up to 2400 MHz are allocated (i.e. no guard band between LTE and

⁴⁰ According to the Global mobile Suppliers Association (GSA), 10 countries have commercially launched LTE TDD networks in 2.3 GHz, and networks are in the process of being deployed or planned in a further 8 countries: http://www.gsacom.com/downloads/pdf/gsa_status_of_the_global_lte_tdd_market_120913.php4

Wi-Fi) and in other cases only the lower part of the 2.3 GHz band is used. Additionally the scale of deployments varies widely. Although we are clear there are no examples of overseas deployments which are directly comparable to the likely UK scenario, we believe that relevant concerns should have surfaced if there were significant general issues for LTE/Wi-Fi coexistence. To date, we have not become aware of any such evidence.

- 6.33 We have been provided in confidence with details of a particular deployment in Australia of 2.3 GHz TDD WiMAX. There are no reported coexistence issues between these deployments and 2.4 GHz Wi-Fi. Our international engagement with mobile operators and regulators has also found no evidence of interference issues between 2.3 GHz mobile systems and Wi-Fi in **South Korea, USA, Saudi Arabia, Finland or Portugal**. In **France**, there is no reported evidence of coexistence issues arising between 2.6 GHz LTE and 2.4 GHz Wi-Fi.
- 6.34 Overall, we see manufacturers adjusting to new LTE deployments by developing filters and improving in-device technology. This suggests coexistence issues are being addressed as part of normal international market developments, as suggested in our February consultation.

Market research

- 6.35 Through a market research omnibus conducted on our behalf by Kantar Media, we asked consumers about their use of Wi-Fi and how they react if they experience performance issues⁴¹.
- 6.36 The survey found that three quarters of people who use Wi-Fi outside the home (76%) have experienced connection problems (slow or broken connections). Nearly all of those affected by such issues outside the home (94%) say they have taken action to remedy any issues when they occur – with 34% saying they opt to use mobile data (3G/4G) instead.
- 6.37 Nearly half (48%) of domestic Wi-Fi users say they have experienced connection problems in the home. When asked what initial action they take to remedy these issues 45% of domestic users said they simply restart their router; 32% said they tried again later; 14% said they contacted their ISP for help in addressing the issues.
- 6.38 In a separate research omnibus⁴² we asked consumers about their knowledge of dual band Wi-Fi and use of the 5 GHz band as an alternative to the 2.4 GHz band. Nearly a third of consumers questioned (29%) said they had heard of dual band Wi-Fi. 71% said they had not.
- 6.39 We then asked those consumers who were aware of dual-band Wi-Fi if they knew how to switch between the 2.4 and 5 GHz spectrum bands when using a smartphone or tablet at home. Nearly half (46%) said they knew how to switch between the bands manually (although we note that many devices switch automatically). Slightly more than half (56%) said they did not know how to switch bands themselves.

⁴¹ http://stakeholders.ofcom.org.uk/binaries/research/telecoms-research/Wifi_and_cellular_data_omnibus_2014.pdf

⁴² http://stakeholders.ofcom.org.uk/binaries/research/statistics/2014Nov/Consumer_issues_survey_experience_of_nuisance_calls_Nov_2014.pdf

- 6.40 We have taken these findings into account in our further overall review of coexistence issues for Wi-Fi which is set out below. Ofcom has public guidance on its website setting out the factors which may affect broadband speed, and how these might be addressed⁴³. This information includes giving advice to consumers to contact their ISPs if there are issues with performance.

Further consideration of the context in which degradation of Wi-Fi may occur

- 6.41 Since the publication of the February 2014 consultation document we have engaged in further consideration of the conditions which would need to be in place in order for degradation to Wi-Fi to actually occur in practice. This further consideration focuses on individual consumers and devices rather than just locations. We have done this to provide a 'real-life' context for assessing the issue, as opposed to the theoretical framework used in our original testing.

- 6.42 In 'real-life', interference to an individual Wi-Fi router/device will only occur if all of the following conditions apply simultaneously:

- The Wi-Fi would need to be in one of the areas where 2.3 GHz services had been rolled out by a mobile network operator. The extent and pace of roll-out will depend on which company acquires the spectrum, and the amount of extra LTE capacity needed in a particular location;
- There would need to be an LTE source (i.e. a base station, small-cell, or user equipment, such as a mobile phone) that was enabled for the use of 2.3 GHz close to the location of the Wi-Fi device or router;
- The LTE source would actually need to be using the 2.3 GHz spectrum band at the time, rather than any of the other spectrum bands available (e.g. 800, 900, 1800, and 2100 MHz spectrum, or frequencies at 2.6 GHz). In that context, we note that the 2.3 GHz band is unlikely to be the 'first choice' spectrum for most mobile operators in normal operation. This is a particularly relevant consideration for assessing potential interference from user equipment (such as mobile phones);
- Any actual LTE transmission would need to be of sufficiently high power to cause a problem (e.g. a smartphone operating at full power uploading a video stream)⁴⁴;
- The Wi-Fi router/device would need to be in use at the same time;
- The router/device would need to be a one which could not use 5 GHz Wi-Fi spectrum as an alternative to the licence exempt 2.4 GHz band;
- The affected router/device would need to be insufficiently robust to avoid the interference (i.e. did not have effective filters or other methods to avoid 'blocking').

- 6.43 Noting the likelihood of all these circumstances needing to be in place at the same time, we have considered some specific scenarios, which are set out in the figures

⁴³ <http://consumers.ofcom.org.uk/internet/broadband-speeds/broadband-speeds-2/>

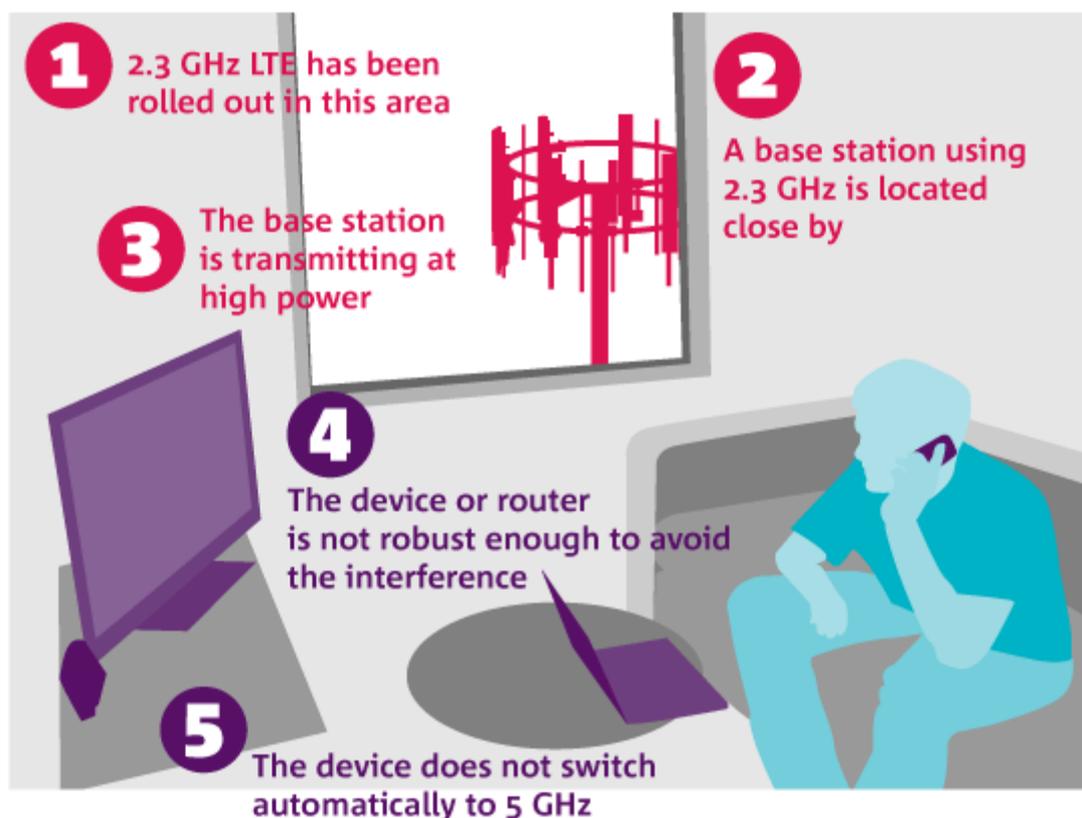
⁴⁴ See section 5 for further analysis of potential interference

below. In all these scenarios, the potential for interference would depend on the particular Wi-Fi use at the time. Interference is unlikely in any case for low data rate activity (such as simple web browsing or email).

Scenario 1:

Interference to in-home Wi-Fi from a base station

All five conditions need to be in place before interference can occur:



Available consumer mitigations:

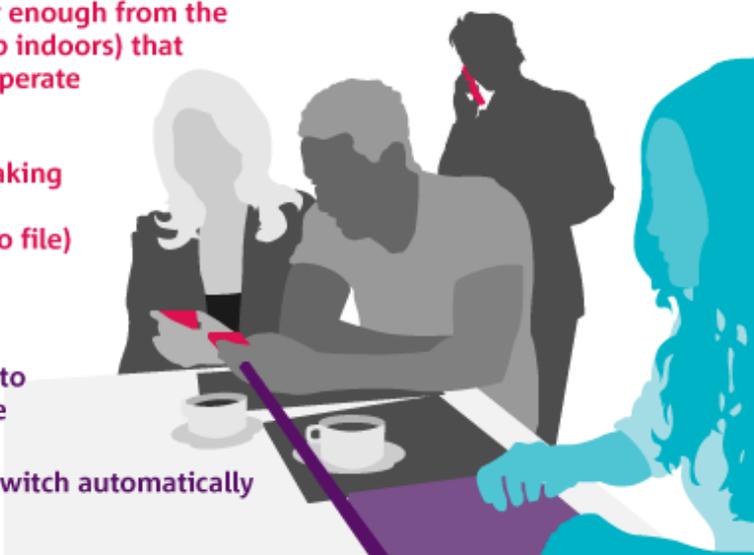
- The router could be moved to a more resistant location inside the building – e.g. away from windows. A move of around 1 metre should be sufficient
- The affected device (e.g. smart TV or games console) could be ‘hard-wired’ to the router
- The affected device could be manually switched to 5 GHz (if this is possible)

Scenario 2:

Interference to Wi-Fi from a LTE mobile device in a crowded environment (eg. a cafe)

All six conditions need to be in place before interference can occur:

- 1** The mobile user's network operator holds 2.3 GHz spectrum
- 2** The mobile is actually using 2.3 GHz at the time rather than any alternative frequencies its operator may hold
- 3** The mobile user is far enough from the base station (eg. deep indoors) that the device needs to operate at high power
- 4** The mobile user is making heavy use of data (eg. uploading a video file)
- 5** The affected device is not robust enough to avoid the interference
- 6** The device does not switch automatically to 5 GHz



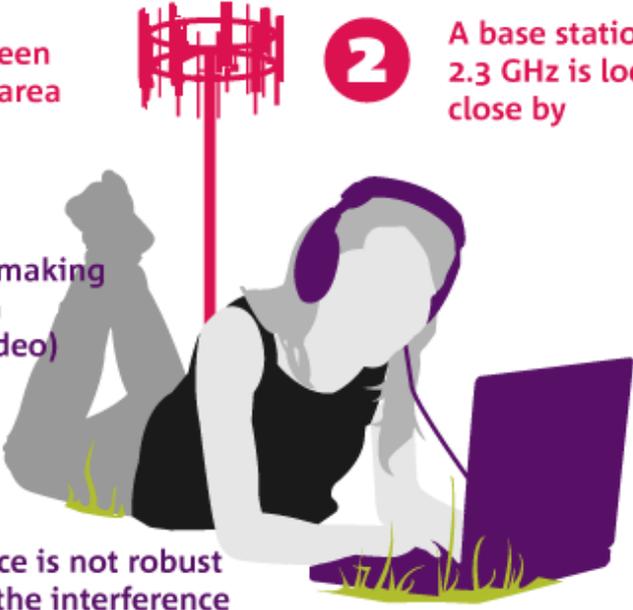
Available consumer mitigations:

- The Wi-Fi user moves to another location - a move of around 1 metre should be sufficient - or re-orientates the affected device in relation to the nearby interfering mobile
- The interfering mobile device moves away or ceases transmission
- The affected device could be manually switched to 5 GHz (if this is possible)

Scenario 3

Interference to Wi-Fi devices outdoors from an LTE base station

All five conditions need to be in place before interference can occur:

- 1** 2.3 GHz LTE has been rolled out in this area
 - 2** A base station using 2.3 GHz is located close by
 - 3** The Wi-Fi user is making heavy use of data (eg. streaming video)
 - 4** The affected device is not robust enough to avoid the interference
 - 5** The device does not switch automatically to 5 GHz
- 
- An illustration showing a person sitting on the grass, wearing headphones and using a laptop. In the background, there is a tall tower with a red antenna array at the top, representing an LTE base station. The person is shown in a grey silhouette, while the laptop and headphones are in a dark purple color. The tower is also in a dark purple color.

Available consumer mitigation:

- The Wi-Fi user moves to a different location in relation to the 2.3 GHz base station and access point
- The Wi-Fi user changes orientation of the device (i.e. moves position)
- The affected device could be manually switched to 5 GHz (if this is possible)

Overall assessment of coexistence issues

- 6.44 Taking note of all the evidence set out in this document, we turn now to our further overall review of the coexistence issues for Wi-Fi and 2.3 GHz LTE, and the decisions we need to take in respect to the 2.3 GHz award. The assessment is set out below in terms of a) the risk of interference and b) the appropriateness of mitigations.

Risk of interference

- 6.45 We have carried out all the further testing suggested by industry stakeholders in responses to the February 2014 consultation - particularly in respect to assessing interference from small cells and from LTE mobile equipment. This is in addition to a re-examination of our own earlier work.
- 6.46 The further technical assessment, as set out in section 5 of this document, confirms there is a theoretical risk of interference from 2.3 GHz LTE to Wi-Fi in the neighbouring 2.4 GHz band. Importantly, it also confirms that our original assessment of the level and scale of that risk was correct. Additionally, our new location testing has shown real-life impacts to be as predicted - or even less severe in some cases. The findings suggest the possibility of interference in all scenarios is very low.
- 6.47 As noted at the time of the February consultation, the risk stems not from 2.3 GHz LTE causing interference into 2.4 GHz but from Wi-Fi routers/devices 'listening in' to LTE transmissions outside their own operating bands. To that extent, the LTE cannot be considered as a 'polluter', nor can Wi-Fi be considered as a 'victim'.
- 6.48 We note that appropriately filtered 2.4 GHz Wi-Fi devices are not at risk of degradation - and that new equipment is much less likely to be affected by interference because of market developments already well underway (5 GHz dual-band capability; in-device filtering etc.). The longer it takes for 2.3 GHz deployment to spread, the less the impact will be for consumers because of the normal replacement of older equipment.
- 6.49 Our further technical work confirms that the impact of 2.3 GHz LTE is far more likely to result in some degradation of Wi-Fi services than in a complete loss of service. In only a tiny number of cases is there a risk of Wi-Fi becoming unusable. The new results suggest there may be even less chance of Wi-Fi actually failing than we originally believed. We note that degradation will not even be noticed by consumers in many cases.
- 6.50 We have noted that Wi-Fi already operates in a congested environment and that degradation of service is unlikely to be any worse than if a number of people in a particular area are all using Wi-Fi at the same time.
- 6.51 The actual number of people who will be affected after the 2.3 GHz award is difficult to determine since it depends on a number of variables, including the extent of LTE roll-out; the timing of LTE roll-out; and the type of Wi-Fi equipment being used.
- 6.52 We note that degradation is, of course, only a possibility in areas where 2.3 GHz LTE is actually deployed. We continue to believe that a UK wide roll-out is highly unlikely in the short term, because we expect the spectrum to be used initially for the provision of additional capacity in areas of particular congestion. This means it

is likely to be deployed initially in dense urban areas where usage is high, and not necessarily areas that are predominantly residential (such as suburbs).

- 6.53 We have also noted the large number of other factors that all need to come together simultaneously for interference to occur. All of these factors point to the scale of the issue for Wi-Fi being even less than we originally anticipated – although we do not expect it to be zero.

Mitigations

- 6.54 Noting the very small likelihood of noticeable interference occurring in the first place, we have nevertheless reconsidered the effectiveness of available mitigations for the small number of Wi-Fi users affected. In doing so, we need to also acknowledge that in almost all cases it will be impossible to determine that degradation of 2.4 GHz Wi-Fi services is due to the proximity of 2.3 GHz LTE base stations or user equipment.
- 6.55 As noted throughout this document, the most important and effective mitigation is for the Wi-Fi router/device to use the alternative 5 GHz Wi-Fi band. Almost all new Wi-Fi equipment has this capability. If the equipment is able to switch automatically then consumers will not even notice this has occurred. However, some older equipment which is able to operate at 5 GHz may need to be switched manually.
- 6.56 Remaining issues are mainly limited to legacy equipment that can operate only at 2.4 GHz and which has inefficient filtering (noting that a small volume of newer equipment may also be 2.4 GHz only). We note that other mitigations may be appropriate in these circumstances.
- 6.57 Where a router or device is not able to use the 5 GHz band, then simply relocating the equipment within a building may well resolve any issues. This is particularly the case where routers are located close to windows and therefore more susceptible to receiving LTE signals from base stations. Our further analysis suggests that moving a device by around 1 metre should make a significant improvement.
- 6.58 We note that the Communications Consumer Panel has expressed doubt about the ability of domestic Wi-Fi users to identify and react to performance issues, let alone understand what needs to be done. The published Ofcom advice, which we noted above, suggests that anyone experiencing problems with their Wi-Fi should contact their ISP for advice or assistance.
- 6.59 If an ISP supplied router/device is not able to switch (or be switched) to the alternative 5 GHz band, and if relocation is not possible or effective, the equipment may need to be replaced. In our February 2014 consultation, we suggested that this was in line with existing ISP practice when performance issues were identified for ISP-supplied equipment.
- 6.60 Whilst accepting that routers may have a slightly longer lifespan than we originally suggested, we still believe that replacement of equipment is an appropriate response for ISPs. It may represent an acceleration of normal replacement cycles in the very small number of affected homes, but is not a significant additional burden.
- 6.61 In some cases consumers (particularly early-adopters of new technology) may possess self-purchased legacy Wi-Fi equipment which cannot be switched to the 5 GHz band and which cannot be easily relocated. In our February 2014 consultation

we said this was most likely to be large non-mobile equipment such as smart TVs and games consoles. The consumers who purchased this equipment did so in good faith at the time, and have a reasonable expectation that it will continue to work as intended.

- 6.62 We said it could be appropriate to hard wire these devices instead. We further note that some instruction manuals also make this suggestion as an alternative to Wi-Fi use in order to ensure the best connection.
- 6.63 However, having given regard to the views of Communications Consumer Panel, we accept that this mitigation – whilst probably effective – is not always practical because it relies on some degree of technical awareness and a willingness to forego use of a preferred technology. We also accept that the range of legacy equipment may be wider than we originally thought, noting that older equipment (such as mobile phones, tablets and Kindles) is often passed on to other family members or friends.
- 6.64 Nevertheless, we again note the very small likelihood of interference occurring in the first place. We can understand that for a very few people with particular pieces of equipment and in very specific circumstances it is possible (but unlikely) that there may be a negative impact. However, we do not believe it is practical or proportionate to intervene in the market to address this issue.

Public and enterprise Wi-Fi

- 6.65 Although the main thrust of our concerns about potential impact to Wi-Fi has been focussed on consumers, we have also given some further consideration to mitigations available to operators of public and enterprise Wi-Fi networks.
- 6.66 In our February 2014 consultation we said the wireless operators are in the best position to assess for themselves the quality of the service they provide. In that regard, we noted that such Wi-Fi systems already operate in a congested environment and that the addition of 2.3 GHz LTE was no different in essence to other forms of interference that are routinely addressed. Our market research suggests a large majority of Wi-Fi consumers have experienced connection problems in public areas outside their homes, and that the majority take no action to address these issues.
- 6.67 We note that both public and enterprise networks are operated by dedicated suppliers or by IT professionals. Wider use of the 5 GHz spectrum band, coupled with better filtering and the replacement of equipment where necessary, represent appropriate mitigations to address any issues.
- 6.68 We have noted the comments of Wi-Fi operators, received both through the consultation process and in subsequent meetings, that any additional costs they might face should be met by the 'beneficiaries' of the 2.3 GHz award, or by the taxpayer. We do not accept these arguments. The main issues arise from Wi-Fi being insufficiently robust to prevent interference by 2.3 LTE rather than from LTE generating out-of-band emissions. In any case, as with domestic Wi-Fi, it would always be difficult to identify 2.3 GHz as the cause of any interference.
- 6.69 Having reconsidered the arguments, we remain of the view that the introduction of 2.3 GHz LTE into a band close to licence exempt Wi-Fi is essentially no different from any other legitimate use of the spectrum which must be taken into account by

licence exempt operators. We do not consider additional costs to be either excessive or unreasonable to bear.

Consumer support

- 6.70 Although we have assessed the impact of 2.3 GHz LTE on domestic Wi-Fi as not significant, we have considered afresh whether it would be appropriate to offer some form of support for the very small number of consumers who may be affected. We note that the Communications Consumer Panel expressed strong support for such an approach.
- 6.71 In considering the options available, we note that we are already proposing to limit out-of-band emissions from LTE in the 2.3 GHz band above 2403 MHz. Additionally, we have taken steps to ensure ISPs are aware of the implications of the release of the 2.3 GHz spectrum, and that equipment in the 2.4 GHz band will need to operate alongside LTE.
- 6.72 We considered four possible options:
- Option 1: Establish a general help scheme. This would provide a central contact point for consumers to call if they had issues with Wi-Fi as a result of 2.3 GHz roll-out. Appropriate mitigations, such as replacement of equipment, could be funded centrally.
 - Option 2: A targeted provision of publicity/information for consumers in those areas where 2.3 GHz LTE had been rolled out. It would advise consumers on mitigation options, and steer them towards contacting their ISPs who would be responsible for resolution.
 - Option 3: A funded support scheme targeted at ISPs rather than consumers. This would recognise that ISPs are in the best position to identify and address issues and could respond effectively to consumer inquiries.
 - Option 4: No active intervention. This was the position set out in our February 2014 consultation. As with Option 3, it recognises that ISPs are best placed to enact mitigations but leaves customers and ISPs to resolve issues between them, without additional funding.
- 6.73 In considering the most appropriate option to adopt we have had to take into account a number of practicalities.
- 6.74 We do not consider it is appropriate for any funding to be extracted from the mobile operators who might acquire the spectrum, because the interference that may occur is not caused by LTE out-of-band emissions. Any funding would therefore need to come from taxpayers, either directly or from the proceeds of the 2.3 GHz auction.
- 6.75 In light of the very small number of people impacted, it seems wholly disproportionate to establish a general help scheme (Option 1), with its attendant costs of administration, offices, staff etc. in addition to covering the costs of any funded mitigations. The mere existence of such a scheme is likely to prompt consumers with any Wi-Fi issue – regardless of cause – to turn to the central contact point for resolution. In only a very small number of cases will 2.3 GHz LTE be responsible.

- 6.76 Even a targeted publicity/information scheme for consumers (Option 2) would risk raising similar expectations, albeit with the burden of dealing with issues falling on ISPs.
- 6.77 We remain of the view that ISPs themselves are in the best position to support and address most issues experienced by their customers – noting that manufacturers are already addressing equipment issues. Even if ISPs did not possess detailed LTE roll-out information (which mobile operators may be reluctant to provide for commercial reasons) ISPs could make a judgement on whether to replace/upgrade equipment or try alternative mitigations. This leaves us to consider Options 3 and 4.
- 6.78 The essential difference between these two options is whether mitigations proposed by ISPs should be funded in some way. We believe such funding carries the risk of excessive expenditure.
- 6.79 Although it will not usually be possible to identify the source of interference to Wi-Fi, the existence of funding would provide ISPs with a financial incentive to blame 2.3 GHz LTE for any issues that arise, in the hope/expectation of having the costs of replacement/upgrade covered. Funding could also act as a disincentive to continue with normal upgrade/replacement programmes.
- 6.80 We have considered whether such a situation could be avoided. It could, for example, be partly addressed if a fixed level of funding were determined in advance and then divided amongst the ISPs, based on their market share.
- 6.81 After careful consideration, we continue to believe it is not unreasonable to expect ISPs to carry the marginal cost of addressing the very small number of anticipated impacts to their Wi-Fi customers.
- 6.82 If it proves necessary, we will assist ISPs in gathering information about LTE roll-out, subject to respecting commercial confidentiality. We will continue to ensure Wi-Fi equipment manufacturers (in addition to ISPs) understand that their devices should be able to coexist alongside LTE in the 2.3 GHz band. For higher cost devices (smartphones, tablets) this might involve them incorporating suitable filters.
- 6.83 Finally, we will work with industry to ensure precautions are taken to limit the possibility of interference occurring in the first place. We will provide guidance to manufacturers/retailers recommending that suitable information should be provided in installation guides and on packaging. As a specific example, we will encourage manufacturers to place stickers on 2.3 GHz femto equipment to advise about suitable separation distances from Wi-Fi routers.

Summary

- 6.84 In summary, we believe the proposals set out at paragraphs 6.79 and 6.80 of the February 2014 consultation remain proportionate and appropriate. In particular, we believe:
- There is no justification for further intervention in the market to protect Wi-Fi in the 2.4 GHz band from issues caused by coexistence with 2.3 GHz LTE;

- That a funded consumer help scheme is not justified or practical and that we will instead provide information to ISPs and work with industry to ensure consumers and businesses using Wi-Fi are provided with appropriate advice.

Section 7

Coexistence of LTE and medical devices

- 7.1 This section considers coexistence between LTE in the 2.3 GHz spectrum band and medical devices. These devices are used primarily for monitoring within hospitals, but may also be deployed to transmit information from patients being monitored from home⁴⁵.
- 7.2 In our February 2014 consultation, we noted that our analysis had suggested a very low likelihood of interference problems occurring in practice. We therefore considered that regulatory-led intervention in the market would be disproportionate. Our analysis was not challenged in the consultation responses, but we have decided to reassess the issues for medical devices in light of our further testing of general Wi-Fi devices.

Nature of medical devices

- 7.3 Medical monitoring devices operate in a number of frequency bands and are not restricted to the licence exempt 2.4 GHz band. Our Licence-Exemption Framework Review⁴⁶ states that users of licence exempt spectrum bands can expect no protection from interference from licensed spectrum users. Accordingly, licence exempt bands are not appropriate for safety-critical equipment.
- 7.4 Our engagement with stakeholders suggests that most medical equipment operating in the licence exempt band uses Wi-Fi technology, although there may be a small amount of equipment using Bluetooth or proprietary technology. We would expect any potential impact on proprietary equipment to replicate that for Wi-Fi because technologies are likely to be based on similar radio chipsets. They would typically incorporate spread spectrum or frequency hopping technologies for avoiding interference.
- 7.5 A number of devices for medical applications which do not have safety implications make use of the 2.4 GHz licence exempt band. This can be beneficial because these devices can inter-connect with existing Wi-Fi networks. The most common kind of devices in this category are for medical telemetry (including heart rate recorders and electrocardiograms) and for monitoring (including for blood pressure, temperature, carbon dioxide concentration and/or oxygen saturation in the bloodstream).

Previous assessment

- 7.6 Our previous analysis focussed mainly on hospitals because we considered these to be the most important uses to evaluate. We established contact with the Department of Health; Public Health England⁴⁷; the Medicines and Healthcare

⁴⁵ Home monitor devices transmit to an in-home receiver which then sends data to the hospital via broadband

⁴⁶ http://stakeholders.ofcom.org.uk/binaries/consultations/lefr/statement/lefr_statement.pdf

⁴⁷“Public Health England's mission is to protect and improve the nation's health and to address inequalities through working with national and local government, the NHS, industry and the voluntary and community sector. PHE is an operationally autonomous executive agency of the Department of Health.”

products Regulatory Agency (MHRA)⁴⁸; a large London acute care hospital trust and several device manufactures.

- 7.7 Our research suggested that the UK market for licence exempt medical equipment using the 2.4 GHz band is relatively small i.e. only around 1,000 or so devices were available. We carried out representative market analysis to determine how much wireless medical equipment was actually deployed in hospitals. This included an audit of all monitoring equipment used in the London hospital mentioned above. The audit suggested there was very little wireless equipment actually in use, with most monitoring being carried out via wired devices. However, the hospital trust said the level of use of such equipment was expected to grow in the future.
- 7.8 Our technical analysis suggested some licence exempt medical devices may be vulnerable to interference in certain circumstances. We determined that this was most likely to be from base stations but could, to a lesser degree, be from mobile devices e.g. mobile handsets and tablets. In setting out our proposals for consultation, we said that interference was not likely to be of significance, and that no intervention in the market was justified.
- 7.9 We noted that it was already standard practice for many hospitals to require mobile devices to be switched off in areas where licence exempt medical equipment was being used. We noted, however, that there remained a small risk of interference from LTE base stations.
- 7.10 Our analysis suggested around 2.5% of the 850 hospitals in the UK could be close to 2.3 GHz base stations (based on existing UK-wide 3G deployments). We noted that some transmitters are actually located within hospital sites. Even so, the analysis suggested that only small areas of any particular hospital site may actually be impacted by LTE (i.e. part of a ward in around 20 hospitals). We said impacts were likely to be much reduced deeper within buildings.
- 7.11 As a precaution, we recommended that hospitals should work with relevant LTE licensees to satisfy themselves that any proposed 2.3 GHz base station deployments on hospital premises did not cause unacceptable interference to hospital systems operating in the 2.4 GHz licence exempt band. We also noted that future licensees should be conscious of the potential risks associated with placing base stations too close to hospital perimeters.

Consultation responses

- 7.12 The February 2014 consultation asked the following question:

Do you agree with our technical analysis in relation to medical devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

- 7.13 We received very few responses from stakeholders addressing the issue of medical devices. However, two confidential respondents indicated their agreement with our analysis and proposal, with one of those suggesting that those

⁴⁸ Government agency with responsibility for regulating all medicines and medical devices by ensuring they work and are acceptably safe.

responsible for hospital procurement should consider band pass filtering for medical equipment⁴⁹.

- 7.14 The Communications Consumer Panel noted “*the critical nature of these systems*” and said there should be a more proactive approach than simply recommending that hospitals work with licensees. The panel suggested a coordinated outreach campaign.
- 7.15 The Bluetooth Special Interest Group said our analysis had not focussed sufficiently on Bluetooth medical devices. The group said this was a major growth segment. Bluetooth low energy products were particularly vulnerable to interference and the deployment of LTE in the 2.3 GHz band could limit the potential market size of this technology.

Ofcom response

- 7.16 We have noted the small number of consultation responses we received on the question of 2.3 GHz coexistence with medical devices. We have also noted the small volume of such devices currently in use in hospitals. However, we acknowledge the potential importance of these products in assisting health care professionals to monitor and treat patients - even though they are not safety-critical.
- 7.17 For that reason, we have conducted further assessment of the potential impact of LTE to existing equipment through stakeholder engagement and technical analysis.

Stakeholder engagement

- 7.18 We have engaged with three of the main manufacturers of medical devices. We note that they are relatively unconcerned about the impact of interference from LTE to equipment in the 2.4 GHz band, although one of them expressed a few particular reservations (see below). Our engagement has given us further understanding of how medical equipment actually functions in practice.
- 7.19 Equipment used in hospital scenarios transmits data wirelessly to a central display or a mobile monitoring station. Bedside monitors and central displays both have visual and audible alarm mechanisms in the event of a lost connection. Generally, the screen changes colour, there is a text display, and an audible alert. Body worn devices do not tend to have alarm mechanisms because this is viewed as intrusive.
- 7.20 In most cases, the information being transmitted is not latency critical and can, in many circumstances, be retransmitted if interference occurs (however, body worn devices have a 250 ms latency requirement as there is no acknowledgment mechanism). Re-transmission delays in the order of seconds are generally considered tolerable (approximately 10 seconds to one minute).
- 7.21 Crucially, the data being transmitted is of low data rate, meaning it is likely to still operate even in a significantly degraded Wi-Fi environment. This means that LTE transmission would need to be of high strength to impact on devices. Much of this kind of medical equipment is capable of accessing both the 2.4 and 5 GHz

⁴⁹ The viability of band pass filtering for Wi-Fi equipment is explored in more detail in section 6 under stakeholder engagement

frequency bands, but many hospitals are equipped only with 2.4 GHz access points. Device lifecycles are typically 7 to 10 years.

- 7.22 One manufacturer suggested the data transmitted by its monitoring devices was, in some cases, “critical” - and loss due to interference would be unacceptable (notwithstanding our clear guidance that licence exempt spectrum is not suitable for safety-critical applications).
- 7.23 However, the manufacturer said it was not aware of any issues associated with the earlier 2.6 GHz mobile spectrum award, which might be considered to have similar characteristics to 2.3 GHz LTE. Nevertheless, the company had some concerns about the potential interference from 2.3 GHz mobile devices because it believed they could be used within close proximity (within 1 metre) of a receiver e.g. by a doctor, nurse, patient or visitors. Interference from a base station would be easier to diagnose and resolve than interference from mobile devices.
- 7.24 The company said it would like to see a co-ordination scheme being introduced, because this had proved effective in other coexistence scenarios. It suggested that a 2.3 GHz LTE operator could be required to notify (via a third party) all healthcare bodies within a certain radius of new deployments. This should ensure issues were mitigated.
- 7.25 We have attempted to engage further with companies developing Bluetooth medical devices to assess the volume of such equipment on the market. Our own audit suggested very little – if any – was actually in current use. Manufacturers have not supplied any information to suggest this assessment is incorrect.
- 7.26 We note that manufacturers who are developing new medical monitoring equipment need to take account of 2.3 GHz LTE in their design processes if their devices are to operate in the 2.4 GHz licence exempt band.

Further technical analysis

- 7.27 In line with our previous findings, our further technical analysis suggests the potential impact to medical equipment using the licence exempt 2.4 GHz band is broadly consistent with that for more general Wi-Fi equipment. In fact, much of the equipment in question is likely to be deployed using a hospital’s own Wi-Fi system.
- 7.28 The further analysis (as for Wi-Fi in general) has included a greater emphasis on the impacts from mobile LTE devices. In the Wi-Fi analysis (discussed in section 5) we noted in particular the time domain effects of LTE TDD uplink signals, which minimise the risk of interference in practice. We concluded that with a minimum separation distance of 1 metre there would be no risk of impact based on the onset of degradation.
- 7.29 We understand from our conversations with manufacturers that the required application layer throughput for medical applications is typically of the order of 150 kb/s. A 5.5 Mbit/s physical layer rate is recommended in order to guarantee this. Our onset of degradation was measured in the lab with a physical layer rate of 54 Mbit/s, with an achieved application layer rate of typically 20 Mbit/s. As the required data rate for medical applications is much less than this, the risk of interference is also significantly reduced.

- 7.30 Impacts from mobile devices can only therefore be expected at very short ranges (i.e. no separation between the devices), and only while the mobile device is continuously uploading data.
- 7.31 Further analysis of the risk of interference from outdoor base stations based on this lower data rate suggests the required separation distance is 16 metres. This is assuming the access point is located near an external wall or window. Additional protection can be assumed if it is located deeper within the hospital. Therefore we believe the risk of interference from base stations is negligible.
- 7.32 If a hospital installs a 2.3 GHz LTE indoor pico-cell, there may be a risk of interference to access points within a few metres, in line with the analysis in section 5. However this could easily be mitigated through careful siting of equipment, which would be in line with best installation practice.
- 7.33 We note that manufacturers themselves increasingly prefer to use the 5 GHz Wi-Fi band, rather than the 2.4 GHz. We also note that we have no evidence of currently available licence exempt medical equipment using Bluetooth low energy technology

Existing practice in hospitals

- 7.34 In reaching conclusions on the ‘real-life’ impact of LTE on medical systems we have given regard to existing practice in hospitals. Our analysis suggests a very low likelihood of interference problems occurring in practice.
- 7.35 As already noted, hospitals already need to protect their systems from potential interference. Most hospitals already have policies on the use of mobile phones. Those restrictions on use are not only in respect to potential interference: there is general discouragement of mobile phone use to take and send photographs, because of medical confidentiality issues.
- 7.36 In January 2009, the Department of Health issued guidance for NHS trusts on the use of mobile phones in NHS hospital. The guidance recognises that communication with family and friends is important when someone is in hospital, and says that that the use of mobile phones should be allowed, as long it does not affect:
- the safety of patients or other people
 - patients’ privacy and dignity;
 - the operation of medical equipment
- 7.37 There is specific information in the guidance on medical equipment. It says that *“interference from mobile phones can stop medical equipment from working properly. This includes:*
- *dialysis machines*
 - *defibrillators*
 - *ventilators*
 - *monitors*

- *pumps*”

- 7.38 The guidance goes on to advise that hospitals display signs to show where mobile phones can normally be used, including in hospital entrances; communal areas; day rooms; and non-clinical areas of wards. It also suggests areas where using mobile phones could be forbidden or restricted. This includes in critical or intensive care wards and units; special care baby units and neonatal wards; and any area where specialist medical equipment is being used to treat a patient.
- 7.39 The guidance is clear that mobile phones should be switched off and not just placed on silent or vibrate settings because, in the Department of Health’s view, this can still affect medical equipment. It is important to note that these guidelines are in place even before the deployment of 2.3 GHz LTE and would not need to be introduced simply for the new award.

Summary

- 7.40 We have noted that there is a small volume of medical equipment currently deployed in the 2.4 GHz licence exempt band. We note that this equipment uses mainly Wi-Fi or related technologies and that the impact of LTE is likely to be broadly similar to that for other types of Wi-Fi devices. We note that safety critical equipment is not suitable for deployment in licence exempt bands, and that equipment using the 2.4 GHz band is therefore of a less critical order.
- 7.41 We note the results of our further technical assessment which suggests, when typical medical data rates are considered, the required separation distances are low. In conclusion, our technical analysis suggests the risk of interference is extremely low.
- 7.42 Finally, we note that hospitals are already a controlled environment. Mobile phones are already restricted in key areas because of the potential impact on medical equipment, even without 2.3 GHz deployment. Hospitals also have the ability to work with mobile network operators to ensure that base stations on their sites do not risk causing interference.
- 7.43 In respect to home deployments of medical monitoring, the risk of interference from base stations is extremely low, in line with that for general Wi-Fi. There may be some risk of interference from LTE handsets if they are used in extremely close proximity to medical equipment, although lower throughput requirements are likely to mean that any interference is not noticeable in a domestic scenario. Any interference is easily mitigated by moving the mobile away from the equipment, as outlined earlier in this document in respect to 2.4 GHz Wi-Fi in general.
- 7.44 In summary, we are of the view that we should not change our proposal set out in paragraphs 7.75 and 7.76 of the February 2014 consultation that regulatory intervention in the market is not justified. However, as discussed in the February 2014 consultation, we recommend that hospitals work with any mobile network licensee seeking to site a 2.3 GHz base station on hospital premises to ensure it does not risk interference to critical hospital systems operating in the 2.4 GHz licence exempt band. This could take the form of a simple RF test under controlled conditions prior to deployment for example.
- 7.45 We also note the views of the Communications Consumer Panel that some form of proactive approach may be worthwhile, such as a targeted information campaign. We will write to hospital trusts to alert them of the need to ensure there are no

interference issues for medical equipment, and to advise on how best to address any problems that arise.

Section 8

Coexistence issues for other licence exempt technologies

- 8.1 In this section we consider outstanding issues in respect to the coexistence of LTE in the 2.3 GHz spectrum band and licence exempt use of the neighbouring 2.4 GHz band by technologies other than Wi-Fi. In light of a large volume of responses to our February 2014 consultation, we pay particular attention to issues for assisted listening devices used by those who have hearing loss. These devices are considered separately below.

Our previous assessment

- 8.2 Our February 2014 consultation considered the potential for interference to a range of licence exempt equipment.
- 8.3 All applications operating in this band are required to coexist with other users through the use of polite protocols (typically listen before talk, low duty cycles or frequency hopping). Systems are therefore designed to tolerate interference from other low power users, e.g. through multiple transmissions and retries. However, our analysis showed that - in certain circumstances - there was a potential risk of interference from high power users in the adjacent 2.3 GHz award band which do not have the same requirements for polite operations, and whose presence may not have been considered in the design of some existing licence exempt devices.
- 8.4 We identified the following technologies/applications for analysis:
- **Bluetooth** (including both regular Bluetooth and Bluetooth low energy or Bluetooth 'Smart' devices): these are typically used for short-range communications, with the most popular and widely recognised use being hands-free cordless headsets for mobile phones. Bluetooth low energy is a new variant targeting the emerging machine-to-machine (m2m) market.
 - **ZigBee**: another m2m technology, where low power devices are intended to operate for several years off a single battery to provide low data rate communications. Applications include the provision of an in-home communications link for smart meters, as well as other monitoring and control tasks such as agriculture, traffic and street light control.
 - **Video Devices**: including in-home video senders, door entry monitors and baby monitors. Although many new devices are digital, we recognised there were some analogue products still on the market or in use.
 - **Audio Devices**: we used radio microphones as representative of a broad range of audio devices in order to assess susceptibility to interference. We recognised there was also a growing market for assistive listening devices (ALDs) operating in this band (considered separately below).

- **Short Range Devices (SRDs):** a generic classification representing a large diversity of devices. We were unable to identify any particularly common equipment types. We assessed the risk of interference from a theoretical standpoint based on ETSI standards.

8.5 For each technology we considered the likelihood and impact of interference from new services using LTE technology in the adjacent 2.3 GHz award band in typical scenarios. This included assessing the separation distances that may be required from an LTE base station or mobile device.

8.6 Our assessment showed that interference is possible in certain circumstances. However, in setting out our proposals we said the applications and protocols were robust to interference in almost all circumstances. We therefore proposed that mitigations in the very few cases where interference remained a possibility were more appropriately left to natural market developments.

8.7 Our February 2014 consultation asked the following questions:

Do you agree with our technical analysis in relation to Bluetooth devices operating in the 2.4 GHz band, and that no additional restrictions are required in order to protect these applications?

Do you agree with our technical analysis in relation to ZigBee devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

Do you agree with our technical analysis in relation to video sender devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

Do you agree with our technical analysis in relation to radio microphone devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

Do you agree with our technical analysis in relation to short range devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

Consultation responses

8.8 Excluding responses which addressed issues for assistive listening devices and medical devices (which are dealt with separately, in this section and in section 7 respectively) we received 11 responses which addressed one or more of our consultation questions on the coexistence of LTE and licence exempt applications other than Wi-Fi. Most were broadly supportive of our proposed approach, but four of the responses raised particular concerns.

8.9 The Bluetooth Special Interest Group said that any increase in the risk of interference for devices using the bottom part of the 2.4 GHz band was particularly problematic for Bluetooth technologies. At present, the lower bands are used by Bluetooth because they are the channels least used by Wi-Fi and are currently the least congested.

8.10 The Special Interest Group also said that the Bluetooth low energy variant of the technology uses static advertising channels in its operation, and is unable to self-

mitigate by adopting adaptive frequency hopping to make use of parts of the band less susceptible to interference.

- 8.11 The group believes that standard Bluetooth devices may be more vulnerable to interference when setting up a new connection than when one is already established. The response suggested the interference risk increased when considering a large deployment of Bluetooth devices and said our measurements of individual devices might therefore be unrepresentative of 'real world' scenarios where a number of devices are expected to interact.
- 8.12 Energy UK and a respondent who wished to remain confidential noted concerns about the potential impact of new 2.3 GHz LTE services on the Government's smart metering programme. Energy UK acknowledged that the actual risk of interference was low, but requested that mobile network operators share information about the location of their 2.3 GHz base stations with energy companies. Energy UK said this would help to reduce investigation and site visit costs. It said the information could be 'anonymised' to protect the commercial interests of individual mobile operators.
- 8.13 EE said that video senders had caused interference to its 3G systems in the past. As a result, EE requested further information about the potential for 2.4 GHz licence exempt devices to cause interference to 2.3 GHz LTE systems.

Further assessment of issues

- 8.14 We note that the lower channels used by Bluetooth are currently the clearest in the 2.4 GHz licence exempt band, which is shared with a growing number of Wi-Fi devices. Our measurements have shown that the close proximity of new LTE systems in the 2.3 GHz band may increase the risk of interference on these and other channels.
- 8.15 However, as for Wi-Fi itself, it is important to note that our measurements showed that the dominant interference was a wideband blocking effect caused by Bluetooth devices 'listening' outside the 2.4 GHz band – rather than LTE out-of-band emissions.
- 8.16 We have spoken to a number of manufacturers who have told us that receiver filtering would be an effective solution where use of the lower channels was essential for future devices. Where costs are a limiting constraint, the use of short 'packets' can allow Bluetooth signals to operate in the gaps between TD-LTE transmissions. We have no evidence to suggest the risk will increase significantly when setting up a new connection or when there are a large number of connections.
- 8.17 We have engaged with the energy industry through EnergyUK to discuss the potential risk of interference to the Smart Meter Home Area Network (HAN). We have no evidence to suggest that a requirement for mobile operators to share 2.3 GHz LTE base station locations with energy companies would significantly reduce investigation and site visit costs. We anticipate that 2.3 GHz LTE signals might cause degradation to the smart meter HAN in only a very small proportion of households, reducing coverage by 0.25%. This is within the margin of error already associated with coverage assumptions understood to be achieved by smart meter HAN rollout at 2.4 GHz. A HAN solution at 868 MHz is also being developed by industry.

- 8.18 We believe there are a number of technical and procedural issues which are likely to reduce the usefulness of sharing information on 2.3 GHz LTE base stations further. Mobile networks are dynamic and growing so any information shared about sites is likely to lag behind actual installations. This means that if a home's smart meter home area network fails due to a new 2.3 GHz base station installation, then this would not be necessarily immediately apparent from a simple search of a site database.
- 8.19 As with potential degradation to Wi-Fi, it will be virtually impossible to identify 2.3 GHz LTE as the cause of any interference. Mobile operators have told us in the past that base station locations can be commercially sensitive and that there is also a cost involved in collating and distributing this information. In the absence of evidence of significant benefit, we believe it would be disproportionate to require mobile operators to share this information.
- 8.20 In response to EE's concern about Wi-Fi to LTE interference, we believe there is only a very small risk and only in very particular circumstances. In any case, our stakeholder engagement leads us to believe that device manufacturers will design new equipment taking any current spectrum environment into account. We spoke to one major LTE chipset manufacturer who had conducted its own investigation into this risk. The analysis showed that LTE was a robust technology, and that the risk of interference to LTE devices from licence exempt devices was very small in realistic scenarios.

Assistive Listening Devices (ALDs)

- 8.21 Our February 2014 consultation also addressed the coexistence of 2.3 GHz LTE with assistive listening devices (ALDs). At the time, we spoke to manufacturers of ALDs (including those recommended to us by Public Health England and Action on Hearing Loss⁵⁰) because we understood that several ALDs currently on the market use the 2.4 GHz band. Uses for such devices include:
- Streaming audio to hearing aids from a central presenter (e.g. a teacher in a classroom has a device which transmits and is picked up by the devices worn by pupils);
 - In home media streaming to a body worn device or directly to a hearing aid;
 - Streaming between in-ear devices in the left and right ears;
 - Remote controls to allow settings to be changed on a hearing aid to suit different scenarios.
- 8.22 In the particular circumstance where radio assisted hearing aids and ALDs are being used (i.e. in classroom and in home scenarios) our February 2014 consultation said it was reasonable for users be made aware of the slight risk of interference from LTE mobile devices (e.g. smartphones). We said most issues can be resolved by careful positioning of the LTE devices, or by switching off mobile phones in the classroom.
- 8.23 We noted that it was important there was no transmission delay, in order to maintain user experience, and that there are uncertainties about the form

⁵⁰Action on Hearing Loss was formerly known as Royal National Institute for Deaf People (RNID)

interference might take and the impact on a hearing impaired user (i.e. loss of service or noise). Since this may impact a potentially vulnerable group of users, we said we were planning a test programme during the consultation period where manufactures could self-assess their devices in the presence of a simulated base station signal.

8.24 We asked the following consultation question:

Do you agree with our technical analysis in relation to hearing aids and assisted listening devices operating in the 2.4 GHz band and that no additional restrictions are required in order to protect these applications?

Consultation responses

8.25 We received a very large number of responses to the consultation. Virtually all of them (in excess of 160 responses) contained almost identical wording which appeared to be pre-prepared text as part of a campaign.

8.26 The essence of the response was that, in the case of the various forms of ALD, there had been insufficient testing and that any interference into an ALD would be “significant” and “frightening”. ALD equipment used for TV-hearing aid links was produced relatively cheaply and so LTE equipment passing by or in adjacent premises was liable to cause interference. This was an infringement of The UN Human Rights Convention 1976, The European Rights of The Child 1989, and The Disability Act 2010, as it failed to address the needs of individuals, both adults and children, who use hearing aids and radio amplification.

8.27 There appeared to be confusion in some of these responses over Ofcom’s release plans. Many respondents appeared to be under the impression that the award covered the same frequencies as those used for ALD equipment, where in fact the award frequencies (2350 to 2390 MHz) are in an adjacent band to the licence exempt band used by ALDs (2400 to 2483.5 MHz), with a 10 MHz guard band in between. This is an important distinction to note when assessing the potential impact of interference.

8.28 Some of the multiple responses said that the “*English government*” had introduced The Newborn Hearing Screening Programme nationally in 2006 to ensure deaf infants were identified very early and provided with appropriate amplification. Such intervention was linked with improved linguistic outcomes. Any interference with the quality of the auditory signal would compromise this already vulnerable group.

8.29 We note, in fact, that the impact of interference – if it were to occur – affects only the radio aspects of assistive listening - for example, wireless connections to televisions and mobile phones; connections to external microphones; or use of remote controls to change settings on certain high end devices. Therefore the proposed release will not affect the quality of audio signals received and amplified by hearing aids.

8.30 We also received a response from GN Resound, a manufacturer of ALD equipment. The company said it was content for us to reveal that it had submitted a response, but that the content should remain confidential. We have taken account of the points made in the response in our further assessment.

Further assessment of issues for assistive listening devices

- 8.31 Our technical and policy assessment has focussed primarily on the audio-streaming link typically used in classrooms or similar environments. We believe this is both the most common usage of 2.4 GHz for ALDs and the most important in terms of potential impact to users. However our analysis will also be applicable for users of ALDs in domestic environments.
- 8.32 We note the comments of respondents to the February consultation. As indicated at the time, we invited equipment manufacturers to participate in testing their devices in the presence of a simulated LTE signal.
- 8.33 A total of 12 ALD systems from 4 manufacturers were tested as part of this programme. The impact of interference from both base stations and mobile devices was investigated. The methodology used and the test results are outlined in a separate report published alongside this document⁵¹. The results showed there was a risk to some systems if operated in close proximity to an interfering base station or mobile device operating at high power:
- Base stations could cause a reduction in maximum operating range, if there is no wall between a close-by base station and the ALD receiver;
 - A mobile device operating at maximum power (23 dBm) with a continuous heavy upload could cause interference within 1 to 4 metres (depending on equipment) of an ALD unit. However as we showed in section 5, the median LTE terminal power is lower than 23 dBm. We would therefore expect these distances to reduce to less than 1 metre for a power of 8 dBm;
 - Newer devices (mainly development models) using the newer Bluetooth low energy standard are more susceptible to interference than existing systems which use proprietary protocols. This is in line with our previous tests on other types of Bluetooth and Bluetooth low energy equipment;
 - In some limited circumstances the Bluetooth link/device pairing was broken by a full power LTE handset in very close proximity to the ALD. Manual intervention was required to reestablish this link.
- 8.34 A further more recent test campaign investigated the impact using time domain signals, and some other types of ALD equipment. The time domain signals were tested with one manufacturer's equipment only. Unlike our testing with Wi-Fi (detailed in section 5), there was no improvement compared to the worst case data transmissions from an LTE handset that were used in the earlier study.
- 8.35 This testing also confirmed that there was no interference caused to cochlear implants, and results for those implants with additional ALD capability were in line with the results from the first phase of testing. While these results show interference is a possibility to certain devices in certain scenarios, we note that the overall likelihood of these scenarios occurring in practice is very low, for the following reasons:
- The vast majority of systems will be used indoors which will provide protection from any nearby base stations;

⁵¹ See annex 2 for a full list of associated documents

- For the mobile device scenario, we note that the probability of persistently transmitting at maximum power is low, as explored in detail in section 5;
- Interference will only occur when both the mobile device (e.g. phone) and the ALD are in close proximity within the same room. If ALD users are able to determine that the interference happens when they use their phones, we believe interference could be mitigated by them moving or disabling the device (e.g. by switching the phone off). Since the majority of usage is in the controlled environment of a classroom (or the same room in a domestic environment) we believe this is a viable assumption. We believe that manufacturers and user groups are best placed to provide any advice and we will seek to work with the European Hearing Instrument Manufacturers Association (EHIMA).

- 8.36 Therefore, we believe the likelihood of impacts to ALDs is very low and there are some mitigations to avoid this if necessary (such as small changes in position relative to the LTE handset). As a result, we do not believe there are any reasons to change to our release proposals for the 2.3 GHz band.
- 8.37 With regards to the susceptibility of Bluetooth low energy devices to interference, we note that this is a new technology. We note there are some products available on the market, but that this functionality is not expected to be standardised until 2016. Manufacturers have confirmed that usage is currently low. In line with our policy for Wi-Fi (outlined in section 6) we believe the Bluetooth Special Interest Group should encourage manufacturers to improve coexistence capabilities in new equipment using Bluetooth low energy. This should be taken into account in the upcoming standardisation of audio profiles.
- 8.38 We will continue to engage with the ALD industry and where appropriate will support further test programmes to assist manufacturers in mitigating the risk of interference to new equipment and communicating these risks to users. Although we are confident the 2.3 GHz award will have very little impact on assistive listening devices, we will continue to monitor the situation as 2.3 GHz LTE rolls out after the auction.
- 8.39 We note that that in addition to the main ALD audio link, there are other links in ALD systems where 2.4 GHz is often used (including control links and ear to ear links). We believe our assessment is also applicable to these scenarios.

Section 9

Update on civilian radar systems

- 9.1 This section of the document presents an update on our assessment of issues for civilian radar. The coexistence of these services with LTE in the 3.4 GHz award band was first addressed in our February 2014 technical consultation. That consultation addressed potential issues for both maritime and civilian radar.
- 9.2 Our ongoing discussions regarding Navy systems suggest that the MOD is likely to direct us to put in place some coordination around a small number of coastal locations, including but not limited to Portsmouth. The exact number of sites and the extent of any coordination are still being evaluated and we will provide an update prior to the award of the spectrum.

Maritime radar

- 9.3 S-band maritime radars are mandatory on ships with a gross tonnage greater than 3,000 tonnes. These radars operate in the frequency range 2900-3100 MHz. The lowest communications frequency in the 3.4 GHz award band is located 310 MHz higher in frequency than the top frequency of the maritime radar band.
- 9.4 The February 2014 consultation identified several possible ways in which radar performance could be degraded by the presence of 3.4 GHz LTE transmissions nearby:
- Communications out-of-band/noise/spurious emissions entering into the radar band;
 - Compression of the radar dynamic range caused by communications signals power entering the radar receiver - due to poor radar selectivity and resulting in inter-modulation effects in the radar;
 - Mixer and other inter-modulation product effects causing communication signals to appear in the radar band.
- 9.5 However, our technical analysis found low ranges of potential interference to S-band maritime radars in 'real-life' testing. In view of the results of these tests, we agreed with the Maritime and Coastguard Agency that it was not necessary to propose any additional mitigations (such as coordination) to address interference from 3.4 GHz LTE. However, we recommend that radar manufacturers should consider these and future systems when developing the receivers for new radar systems.

Consultation responses

- 9.6 We received four responses to our consultation proposal that no formal mitigations were necessary to protect maritime radar from 3.4 GHz LTE (EE, UK Broadband and two from respondents who wished their submissions to remain confidential).
- 9.7 All of the respondents agreed with our proposed position. However, EE noted that we had considered the potential interference only for 3.4 GHz LTE and not for 2.3 GHz.

- 9.8 We did not put in place any specific protections for maritime radar as part of the 2.6 GHz award and are not aware of any issues in relation to the use of 2.6 GHz either in the UK or overseas. 2.3 GHz LTE is further away from the usual 2.9–3.1 GHz maritime radar deployment band (at least 500 MHz) and we therefore expect a lower impact than for 2.6 GHz. In light of this we have done no additional testing for maritime radar and have not considered the impact further.

Aeronautical radar

- 9.9 In the frequency band 2700-3100 MHz there are both air traffic control (ATC) and air traffic management (ATM) radars, both civil and military, used for aviation radio navigation purposes.
- 9.10 In total there are approximately 92 S-band ATC/ATM radars distributed around the UK. These radars are primary sensors, and their effective operation is integral to the air traffic management of UK airspace. The target detection range is from 40 to 80 nautical miles. They are generally located at airports, military bases or other positions that allow the air traffic management function to be achieved. There are a number of radars located to allow the detrimental effects of wind farms to be mitigated.
- 9.11 In our February 2014 consultation, we said the use of the 2.6 GHz band for 4G communications services had raised concerns associated with radar performance vulnerability. We said there was potential for similar issues to arise as a result of the proposed award of the 3.4 GHz spectrum if the band was used for high power applications, such as LTE. As a result of that award, the affected radars were upgraded to cope with LTE transmissions within the 2.6 GHz and 3.4 GHz bands. There were two possible sources of vulnerability:
- Insufficient selectivity within the radar to enable signals from outside the radar band to be rejected. The vulnerability may be in the front end of the receiver chain or further down the receiver chain and results in receiver compression or the mixing of the communications signals into the radar bandwidth; and
 - The reception of radio frequency noise emissions from sources in other bands into the radar band
- 9.12 However, the radar manufacturers in a number of studies suggested the risk of harmful interference to ATC/ATM from communications transmissions operating at 3.4 GHz was less than the risk of interference from similar systems at 2.6 GHz. Nevertheless the risk was not negligible and remediation was required.
- 9.13 We therefore proposed to follow the same approach we put in place for the earlier 2.6 GHz release. This required a coordination procedure to be implemented alongside existing radar remediation filtering, as agreed with the Civil Aviation Authority. We said in the 3.4 GHz band this was justified to retain the integrity of the ATC/ATM radio navigation services in the 2.7-3.1 GHz band. A coordination procedure should be implemented in addition to the already improved radar selectivity performance associated with different manufacturers' filter designs.
- 9.14 We said there should be a coordination procedure to specify power flux density (pfd) limits for both signal and noise that must not be exceeded at the defined radar locations. The use of the radar remediation filter and the limited coordination

conditions as supported by the CAA is expected to provide a good level of resilience for the ATC/ATM radar to the potential 3.4 GHz deployments.

Consultation responses

- 9.15 We received six consultation responses (EE, Global TD-LTE Initiative, Huawei, UK Broadband and two respondents who wished their submissions to remain confidential).
- 9.16 All agreed with our overall approach in aligning coordination procedures with those applying to the 2.6 GHz award. However, Global TD-LTE Initiative and Huawei said in identical responses that there was no need to apply the same pfd levels across the whole of the 3.4 GHz award band, and that for frequencies above 3500 MHz it was “a necessity” for us to consider applying a “more reasonable” pdf level.
- 9.17 We believe the impact of the procedures will be small. Whilst filter responses implemented as part of the remediation will improve at higher frequencies, the contractual requirement was a fixed limit across the whole band. We therefore have no evidence or certainty to determine by how much the requirement may be exceeded. Therefore we remain of the opinion that we should we apply a constant value for pfd across the whole band.
- 9.18 EE supported our proposal in full, but pointed out that we had not stated the required out-of-band noise limit that would be applied to the 3.4 GHz spectrum licences. EE also said we had not addressed the issue of potential interference with respect to the 2.3 GHz award.
- 9.19 We note that the noise spectral power flux density threshold in the band 2720 – 3100 MHz was specified in the proposed radar coordination procedure (table A13.6 of the February 2014 consultation) with reference to the protected radar locations rather than as a general licence condition. We do not consider that there is a material risk from TD-LTE deployments at 2.3 GHz.

Section 10

Update on satellites

10.1 This section of the document presents an update on our assessment of issues for satellite services operating above 3.6 GHz. The coexistence of these services with LTE in the 3.4 GHz award band was first addressed in our February 2014 technical consultation.

Our previous assessment

10.2 The February 2014 consultation included discussion of a range of satellite services operating close to both the 2.3 and the 3.4 GHz bands. These services include, but are not limited to, television programme transfer; data downloads for meteorological services; financial systems; and embassy communications. Users take these services from the different international satellite operators, including those licensed by Ofcom and operators who hold grants of Recognised Spectrum Access (RSA)⁵².

10.3 We specifically addressed:

- MSS 2 GHz - mobile satellite and integrated Complementary Ground Component (CGC) mobile receivers (2170-2200 MHz);
- MSS 2.4 GHz - mobile satellite services (MSS) (2483.5-2500 MHz);
- SR and SO - space research and space operations (2200-2290 MHz);
- AmSat - amateur satellite services (2400-2450 MHz); and
- C-band PES - permanent Earth stations (3600-4200 MHz)

10.4 Our technical analysis suggested there would be no significant interference to satellite operations close to the award bands. However, we said we expected all licensees to cooperate in reaching a resolution in the unlikely event that interference was to occur. We said we believed this would address any issues and we proposed that no additional regulatory intervention was necessary.

10.5 In respect to permanent Earth stations (PES) above 3.6 GHz we considered the technical licence conditions of the existing licensee directly below 3600 MHz (UK Broadband) and the risk of interference to PES and receive only Earth stations (ROES). The risk was considered under both the current technical licence conditions and new more permissive technical conditions proposed by CEPT. (N.B. the CEPT proposed conditions have since been adopted in a European Commission (EC) decision 2014/276/EU and we intend to grant access to the 3.4 GHz band under these new conditions).

10.6 Our analysis showed that interference may occur within around 8 km of each of the two worst affected PES sites when the antennas of a full power LTE base station and PES site were aligned. We also showed that 10dB of additional loss between the LTE base station and the PES would reduce this to around 1 to 3 km, making

⁵²Among others, RSA is available to receive only earth stations which, as they do not transmit, do not need a licence.

the likelihood of interference very low. Additional coupling losses in the order of 10dB are likely with practical deployment scenarios.

- 10.7 In our February 2014 consultation we proposed 3 options in respect to UK Broadband's spectrum holding in the 3.4 GHz band:
- Maintain the existing UK Broadband mask (at the 3600 MHz boundary);
 - Adopt our proposed mask with informal cooperation on a case-by-case basis if required;
 - Adopt our proposed mask with mandatory coordination procedures
- 10.8 Our preference was for the second option. This option is in practice an ex-post cooperation between the new licensee and the PES operator should interference have occurred. Under the licence condition not to cause harmful interference, they would be expected to share information and re-engineer or remediate their own sites - where this is proportionate - to ensure harmful interference is not caused.
- 10.9 In some cases this may require the fitting of filters by the PES operator; in other cases it might be small changes in power or antenna orientation by the LTE licensee to increase the coupling loss between the two sites.

Consultation responses

- 10.10 We received a total of seven responses addressing satellite issues. There was no disagreement with our position in respect to coexistence issues close to the 2.3 GHz award band. However, two responses disagreed with our position in respect to PES above 3.6 GHz (responses from the European Satellite Operators Association and one respondent who wished its submission to remain confidential).
- 10.11 The European Satellite Operators Association (ESOA) felt that risk to UK PES would be significantly higher if the new block edge masks were adopted and said it could not support option 2. In its submissions, it said: "*we support that the licensee of any new terrestrial stations should be required to ensure protection to existing permanent earth stations. This requirement should be clearly defined and explicitly stated in the licence conditions*". ESOA also felt that it would be fair if the new LTE base stations were subject to the more relaxed mask, that any negative impact should fall on those operators and not the PES. They disagreed with us that a formal coordination would be onerous and disproportionate.
- 10.12 ESOA also suggested that "*a mandatory coordination requirement would not prevent local solutions to be developed between the relevant parties but would provide some legal certainty and clear responsibility that should ensure that interference is not caused.*" This position was supported to some extent by another (confidential) respondent who recommended that mandatory procedures are drawn up as a backstop regulation for the scenario where agreements cannot be reached.
- 10.13 Another confidential respondent was also concerned about the ability of a PES operator to enter a discussion with the new licensees prior to site deployment and preferred to have regulatory certainty for future deployments in the 3.4GHz band.

Summary of assessment

- 10.14 There are currently 34 C band PES sites in the UK within 600 MHz between 3.6 GHz and 4.2 GHz; this includes five with Recognised Spectrum Access (RSA). Of these only seven receive signals that extend below 3660 MHz and only two extend below 3625 MHz and will be most affected by any change in block-edge masks (see our consultation on design of the award and technical licence conditions⁵³).
- 10.15 We remain of the opinion that the likelihood of interference from new services in the 3.4 GHz band to PES operators in the 3.6 GHz band is low with practical deployment scenarios. Therefore consistent with our usual policy to only consider adjacent channel coordination in exceptional circumstances we do not consider it is necessary for us to put in place any formal coordination procedures between UK Broadband or any new licensee in the top part of the band and C- band PES operators. Additionally, there should be no expectation that UK Broadband or any new licensees operating in the top part of the 3.4 GHz band with our proposed licence conditions should have any additional responsibility to protect the PES sites other than the general licence clause not to cause harmful interference⁵⁴. Nor should they have any requirement to pay for remediation of the PES sites should that prove necessary.
- 10.16 This approach is consistent with our general approach to spectrum management in the vast majority of cases.
- 10.17 In summary, we do not believe there is any reason for us to change the proposals set out in Section 12 of the February 2014 consultation in respect to coexistence with satellite services. However, we reserve the right to intervene ex-post should interference be experienced in practice. Any resulting assessment will take into account whether any of the actions that may be required by either party are reasonable to expect.

⁵³ <http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

⁵⁴ We note that our auction design proposals may allow for a licensee other than UK Broadband to end up with the 3580–3600 MHz allocation after the award.

Annex 1

Measurements and analysis of Wi-Fi coexistence

Introduction

- A1.1 In this annex we set out the detailed results of our further measurement campaigns on the impact of interference from 2.3 GHz LTE into Wi-Fi, and supplementary analysis.
- A1.2 This includes the results of a short set of testing to determine typical LTE mobile device transmit power levels in existing LTE networks in other bands. These results are used to provide some context to the results from lab tests and to determine the likelihood of interference from LTE mobile devices to Wi-Fi in practice.
- A1.3 We also set out in detail the methodology and results of further lab measurements on Wi-Fi coexistence, which supplement earlier tests performed by MASS Consultants Ltd which we published as part of our February 2014 consultation⁵⁵. We provide the following results:
- Limited repeated tests to ensure consistency with the test setup compared to the previous work undertaken by MASS;
 - Interference impact when the interfering signal is a recorded signal from a 2.3 GHz mobile device to determine if these show any difference from the simulated worst case signals. The recordings were taken in collaboration with industry stakeholders as part of the Wireless TIC group⁵⁶;
 - Impact when filters – which are designed to mitigate the impact of interference from LTE into Wi-Fi – are fitted onto some devices;
 - We provide some context for the likely interference by showing the impact on throughput when a Wi-Fi device is in the presence of another Wi-Fi network or 2.6 GHz mobile device transmissions (2.6 GHz mobiles transmit close to the upper end of the 2.4 GHz Wi-Fi band);
 - Some limited Wi-Fi 802.11n devices, to understand if this higher throughput technology is more susceptible to interference;
 - Interference impact on some additional devices that were made available, including some subjective video tests, to understand the impact on user experience for this example high throughput streaming application.
- A1.4 Our results focus on the relative downlink/uplink ratio of LTE frame configuration 2. This is in line with our proposed technical licence conditions, presented in the auction design consultation⁵⁷ for the 2.3 GHz release band. The previous tests

⁵⁵ The MASS report and annexes is published at <http://stakeholders.ofcom.org.uk/consultations/pssr-2014/>

⁵⁶ The Wireless TIC is an industry collaboration as part of the techUK Future Technologies Network

⁵⁷ <http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz-auction-design/>

mainly focussed on configurations 0 and 5 as being representative of the worst case uplink and downlink signals respectively. However following stakeholder feedback and our further considerations around synchronisation (discussed in the auction design consultation) we now think that these worst cases are unlikely. We include results for these configurations for comparison with previous results, but it should be noted that the results based on frame configuration 2 are those which are proposed will be applicable to the release band.

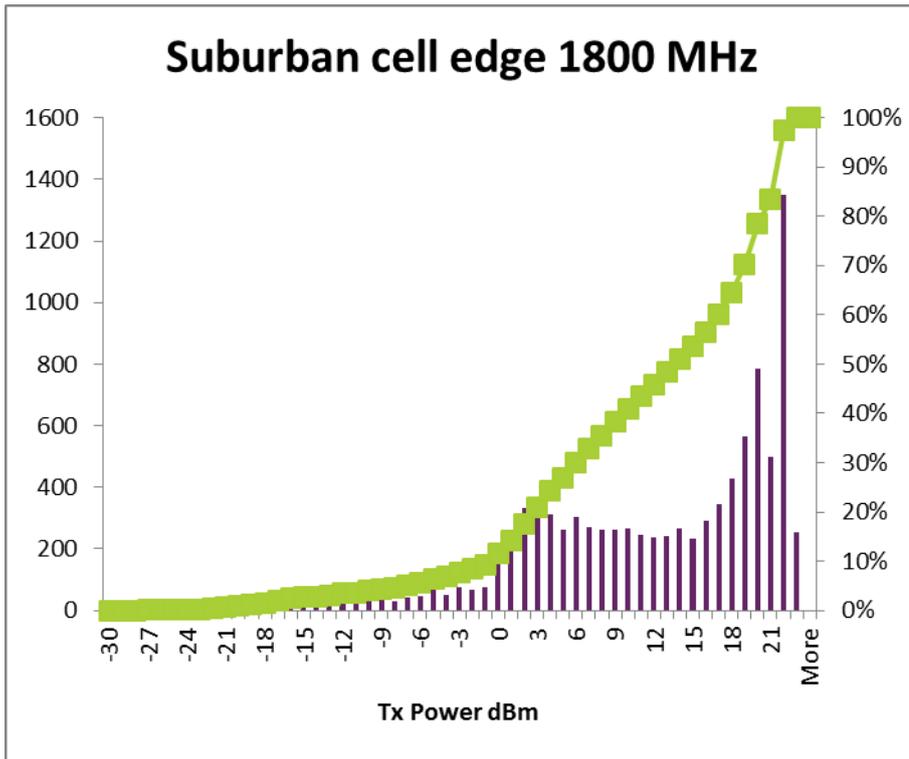
- A1.5 In this annex we present a comparison of the measurement results with the previous tests. We then explore the results in the context of the issues raised in responses to the February 2014 consultation (as outlined in section 4).
- A1.6 We then outline some conclusions on how the results of both the lab measurements and walk tests would affect the results of the existing analysis from the February consultation.
- A1.7 The full lab results are presented in a final separate section for completeness.

Measurements of LTE mobile device transmit power

- A1.8 In order to understand the potential impact of interference from 2.3 GHz mobile devices on Wi-Fi, we have undertaken a short set of measurements to record transmit powers⁵⁸ from LTE mobile devices in other bands (800 MHz and 1800 MHz) in typical environments.
- A1.9 Using a Rohde and Schwarz FreeRider system, we carried out a series of walk test in a dense urban and two suburban scenarios. The suburban areas consisted of both good (cell centre) and poor (cell edge) coverage areas that were identified using mobile operators' coverage checkers and field measurements of signal strength and signal quality.
- A1.10 During the walk test, our methodology was to successively run a testing pattern consisting of: an HTTP download; Ping; HTTP browsing; and FTP upload, with 5 seconds pause in between each data task.
- A1.11 Measurements were taken on two networks in different bands – one in 800 MHz and one in 1800 MHz.
- A1.12 The resulting distributions of the transmit power as reported by the handset are presented in Figure A1.1.1 and summarised in Figure A1.2 and Table A1.1.

⁵⁸ We assume a 0 dBi antenna gain so all values are equivalent to EIRP

Figure A1.1: Suburban cell edge 1800 MHz mobile device transmit power distribution



A1.13
A1.14

Figure A1.2: Suburban cell edge 1800 MHz mobile device transmit power distribution

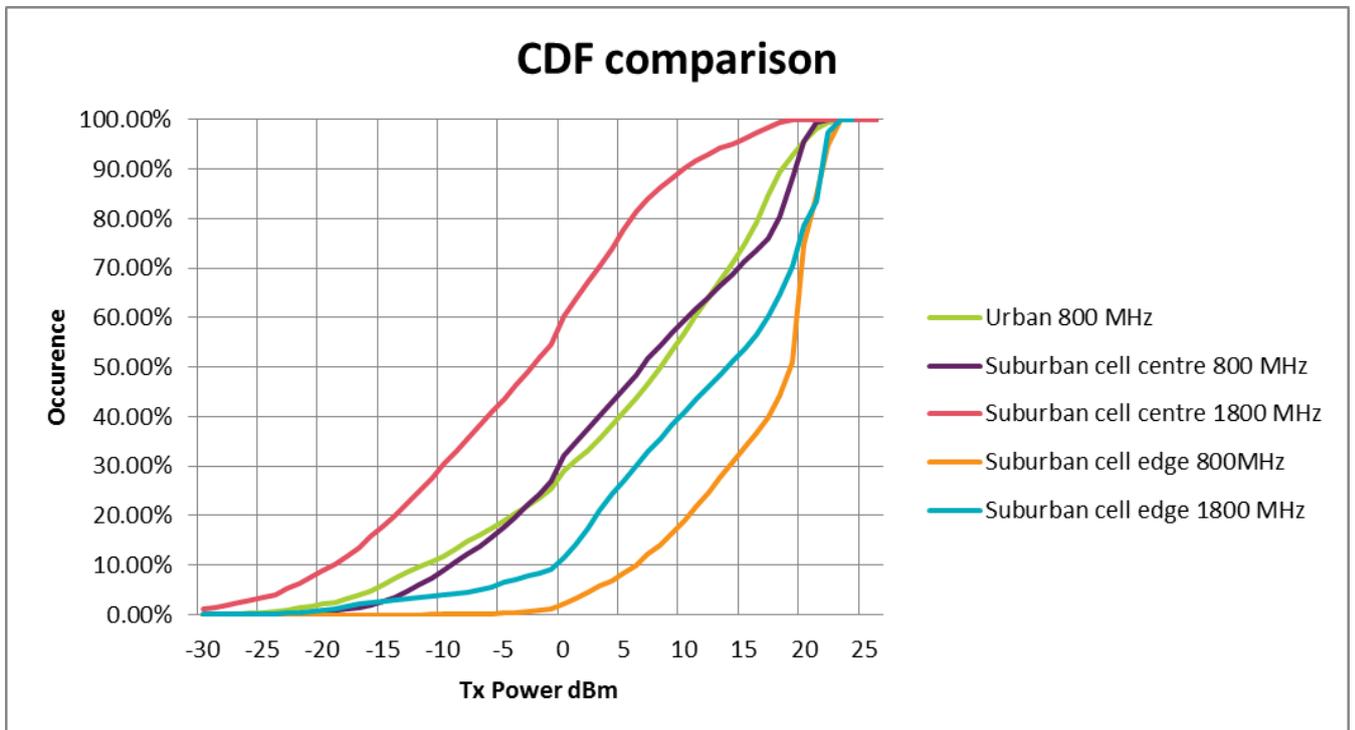


Table A1.1: Summary of walk test results

Area	Band	UE Tx power (dBm)		
		Average	50th percentile	90th percentile
Urban	800 MHz	6	9	18
Suburban cell centre	800 MHz	7	7	19
	1800 MHz	-3	-2	10
Suburban cell edge	800 MHz	16	19	21
	1800 MHz	12	14	22

- A1.15 A wide range of transmit powers can be seen in all cases. Transmitting at the maximum value of 23 dBm is shown to be unlikely in all cases.
- A1.16 As may be expected, power control causes a significant reduction in transmit power in urban and suburban cell centre coverage areas. Higher powers closer to the maximum can be seen in cell edge scenarios. We believe the cell edge scenario is also representative of indoor scenarios.
- A1.17 We have found no relationship between transmit power level and frequency band, although it is difficult to draw any firm conclusions on this as there are a number of unknown factors to consider, such as possible different network deployment configurations in these areas.
- A1.18 As these results show a wide range of distributions in different scenarios, it is difficult to derive one transmit power figure to use in further analysis. However we have taken a simple approximation of 50th percentile results across both bands and all scenarios. This gives a figure of 9 dBm. These figures can then be used as a reasonable representation of typical transmit power, while noting in practice it is heavily dependent on the usage scenario.

Further lab measurements

Tested devices

- A1.19 The following devices covering a range of types (routers, smartphones, laptops and tablets) were tested in this measurement campaign. Where devices under test (DUT) are the same as those used in the previous measurements published in February 2014, we have kept the same numbering.

Table A1.2: Tested devices

Device	Type	Tested previously?
DUT1	Laptop	Yes
DUT3	Laptop	Yes
DUT4	Smartphone	Yes
DUT5	Tablet	Yes
DUT9	Router	Yes
DUT14	Router	Yes
DUT15	Tablet	Yes
DUT26	Router	No
DUT27	Router	No
DUT28	Router	No

Methodology

Main tests

A1.20 The test setup for the main set of testing is shown in Figure A1.3 below. This is similar to the setup used by MASS in their original measurement campaign for our February 2014 consultation. A semi-anechoic chamber was used for the tests. The equipment was located outside the chamber with separate antennas used to feed the wanted and unwanted signals to the device under test (DUT) as this minimised the equipment inside, leading to more repeatable results. The key elements are as follows:

1. A wanted Wi-Fi link was set-up between the device under test (DUT) and a reference router.
2. The data throughput of this link was measured using IPerf⁵⁹ in the absence of the unwanted LTE signal.
3. The wanted power level at the DUT location was measured using a spectrum analyser connected to a reference port by the access point. Measured losses from this point to the DUT were then taken into account and the result checked using a reference antenna placed inside the chamber. The DUT was orientated to provide maximum throughput for a given level of wanted signal, suggesting that the DUT antenna gain was at a maximum towards the signal source.
4. The minimum usable signal (MUS) value was determined by reducing the wanted signal power at the DUT using an attenuator until the data throughput reduced to 1 Mbps⁶⁰. This was recorded for each of the devices.
5. For all tests the wanted signal was set to MUS + 20dB.
6. An Unwanted LTE signal was setup using either a Signal Generator (Rohde and Schwarz SMBV100A) as the source, or 10 second long recordings of

⁵⁹ Iperf is a network testing tool which creates TCP packets to measure application layer throughput

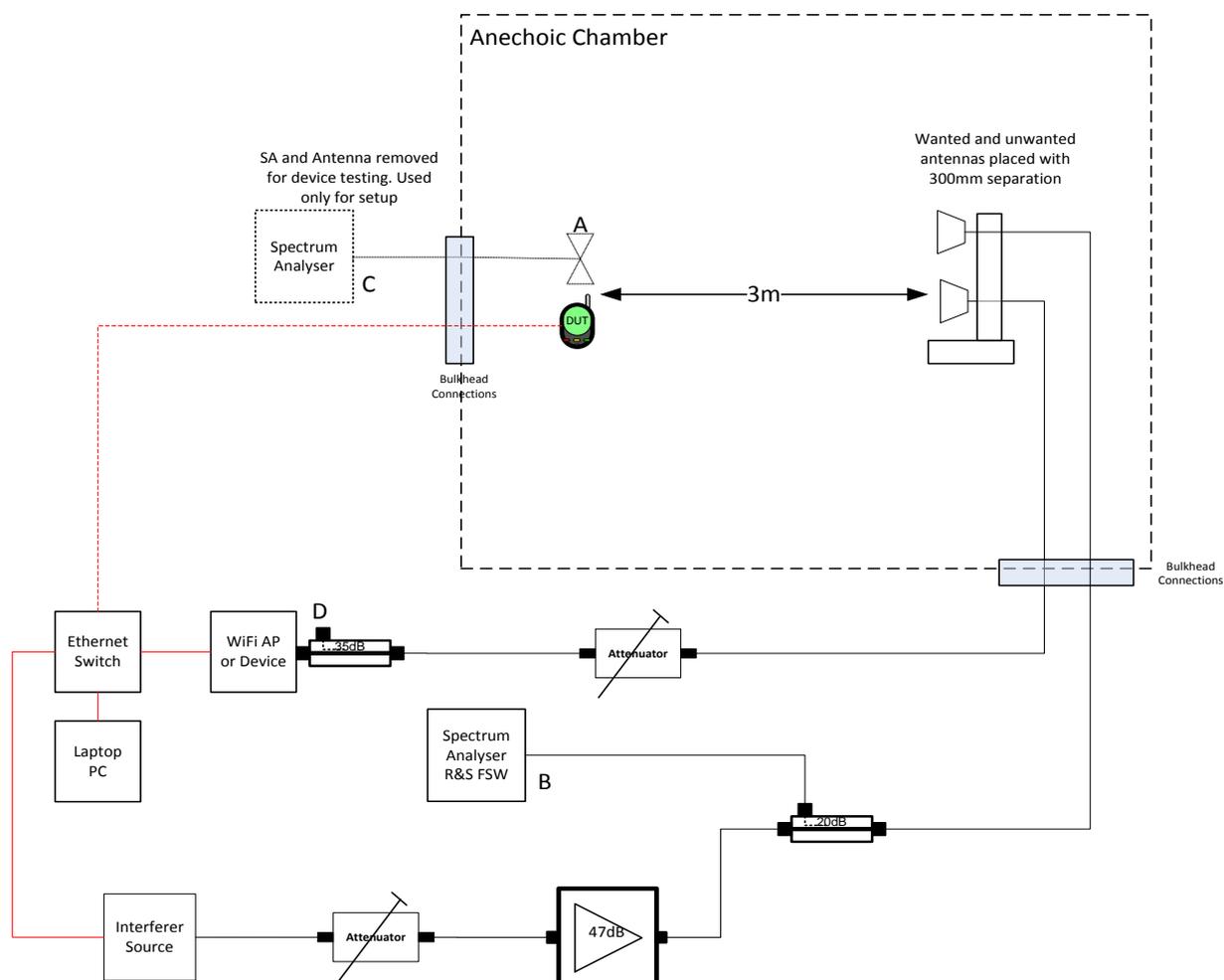
⁶⁰ This was a slightly different to the MUS values for the previous MASS testing where MUS was determined as the point the throughput dropped to almost zero

transmissions from a 2.3 GHz mobile in a test network (recordings were made – in conjunction with members from the Wireless TIC – of transmissions in a number of different network and throughput configurations).

7. The throughput values were then measured for different LTE power levels incident at the DUT. Wherever possible the interference signal strength was increased until the throughput of the Wi-Fi link reduced to below 40 to 50%⁶¹ of the starting point with no interference. This element of the testing was automated using software to ensure consistent and reliable results in a time efficient manner.
8. The tests were repeated for different LTE data profiles, configurations and frequencies. When testing with 2.3 GHz a 20 MHz LTE signal centred on 2380 MHz was used and the impact to Wi-Fi channel 1 was (2412 MHz) investigated. The 2.6 GHz test used a 20 MHz signal centred on 2510 MHz and the impact to Wi-Fi channel 13 (2472 MHz) was investigated.

⁶¹ Stakeholders suggested in their responses to our February consultation that the 50% throughput reduction and complete failure modes of Wi-Fi were not representative of real networks. Unlike the MASS testing, we therefore terminated the automated testing at around 40 to 50% of the throughput for speed of testing

Figure A1.3: Main test set-up



A1.21 The recordings of 2.3 GHz LTE signals were conducted in collaboration with industry stakeholders using a real 2.3 GHz base station and two mobile devices. A range of uplink and downlink traffic profiles were recorded using a National Instruments Record and Playback System. We focus on three different traffic profiles⁶² here:

- Light loading based on a user downloading data and recording only the acknowledgements sent on the uplink. We believe this represents the most typical usage case for mobile devices;
- Heavy loading based on a user uploading a large file for a long duration. This represents the assumed worst case in terms of interference, but is not likely to represent typical user behaviour for long periods of time;

⁶² For reference for members of the Wireless TIC, the relevant file numbers from the recording campaign are: Light loading (acknowledgements) - File 1; Heaving loading - File 3; and Skype call - File 43.

- Continuous video streaming based on a Skype call. We believe this represents a more typical case of persistent uplink usage.

A1.22 Three different resource loading configurations were used for the 2.6 GHz LTE simulated signals, with 10 and 50 resource blocks respectively. This provides a range of values which may have a different effect on Wi-Fi interference, and provided a comparison with the different TDD frame configurations, C0, C2 and C5.

A1.23 Care must be taken when measuring the power of a TDD or power varying signal. Standard power meters and spectrum analysers provide a time averaged value for power, whereas the power specified in an LTE base station or mobile device is related to the 'on' part of the waveform only. We therefore calculated a correction factor⁶³ that accounts for the difference between the maximum power in the signal and the mean power of the signal over the duration of the simulated waveform or recorded signal. This correction varied depending on the frame structure of the signal and in the case of the recorded signals, the way LTE resources are scheduled.

A1.24 The correction factors for the simulated signals and recorded signals of interest are shown in the following table:

Table A1.3: Correction factors for simulated and recorded signals

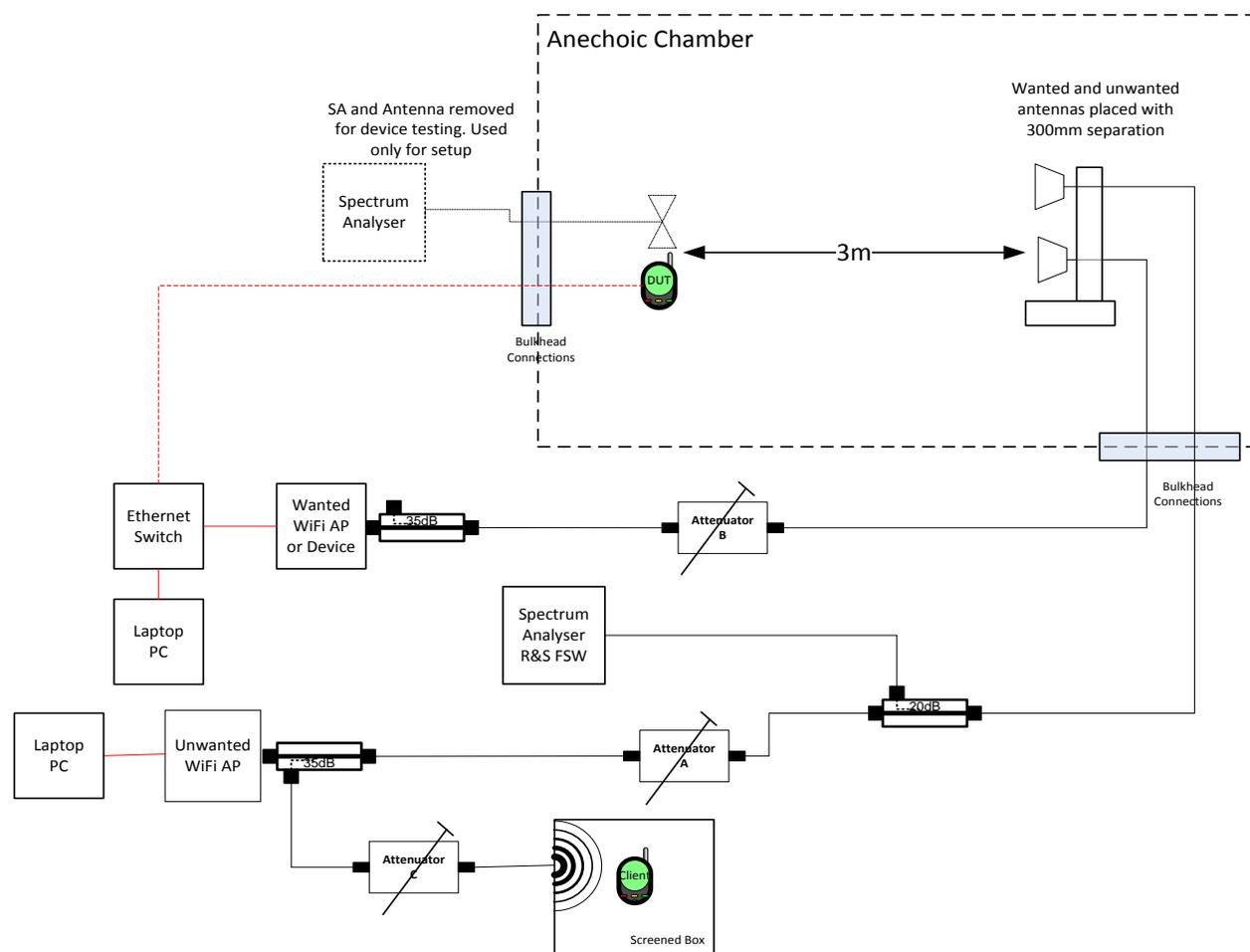
Interfering signal	Correction factor (dB)
Simulated C0 DL	4.0
Simulated C0 UL	2.2
Simulated C2 DL	1.0
Simulated C2 UL	7.0
Simulated C5 DL	0.5
Simulated C5 UL	10.0
Recorded File: Acknowledgements	15.3
Recorded File: Heavy upload	10.1
Recorded File: Skype call	16.6
Simulated 2.6 GHz mobile transmissions	0

Wi-Fi to Wi-Fi interference test method

A1.25 For tests on the impact of interference from other Wi-Fi networks, the test method was similar to the main tests with some changes to the interference source outlined in the diagram below. A Wi-Fi Access point and client device replaced the signal generator in order to provide the unwanted signal link. The second client device was isolated within a screened box so that only the second access point could cause interference in this controlled test.

⁶³ The correction factor is derived by generating a zero-span trace of the RMS power of the recorded file using a real-time spectrum analyser. The maximum value P_{max} and average power P_{avg} over the 10 second file are calculated, and the correction factor is the difference between the two. In the case of the simulated signals, the mean power only varies as a consequence of the frame structure and the correction factor can therefore be directly calculated from the duty cycle within this frame structure.

Figure A1.4: Wi-Fi to Wi-Fi test setup



802.11n test method

- A1.26 The 802.11n tests used the same setup as the main tests (A1.18), but with an additional antenna placed behind the DUT radiating an attenuated version of the wanted signal, to simulate a multi-path effect.
- A1.27 We initially attempted to setup 802.11n tests in a real multipath environment in our offices, however we were unable to achieve higher initial throughputs (in the absence of interference) than were achieved for equivalent 802.11g tests in the anechoic chamber, and therefore results would not be comparable. Therefore the above method using the simulated multi-path environment is believed to give more comparable and repeatable results.
- A1.28 The lower throughput achieved in the office test is believed to be due to the presence of other Wi-Fi networks in the location. We believe that this demonstrates that whilst 802.11n at 2.4 GHz may give faster throughputs in some environments this was not achievable in a heavily congested location where the performance was similar to 802.11g.

Subjective video test method

A1.29 For the subjective video tests a high definition test video pattern was streamed to the video streaming DUT and monitored while varying the LTE power level, as follows:

1. The DUT was connected to a TV and placed in the anechoic chamber.
2. A test pattern video was streamed over the wanted Wi-Fi link.
3. The wanted MUS was determined as the lowest value of Wi-Fi signal where the picture is present without breakup and there was no buffering.
4. The test was run with the wanted signal 10 and 20dB above MUS.
5. The LTE interfering signal was increased until the TV picture started to breakup and the video stalls whilst buffering takes place.

Coexistence filters test method

A1.30 The effect of filtering was investigated by performing a conducted test on devices that had an external antenna. This allowed us to insert a production model LTE/Wi-Fi coexistence filter mounted on an evaluation board between the antenna port of the DUT and its antenna. The main 2.3 GHz tests above were then repeated with the device in this configuration.

Comparison with previous results

A1.31 The results for the main tests are presented below. Equivalent results from the previous testing performed by MASS are included for the purposes of comparison.

A1.32 Results are presented in terms of throughput versus absolute interference level.

A1.33 Some differences were found in the MUS values and initial throughput. Thus the wanted signal levels were generally different. There were some differences in some devices in our MUS values and throughputs compared to those determined by MASS previously. This is believed to be due to our different thresholds and the fact that the devices were tested in different orientations⁶⁴.

A1.34 The resulting differences in MUS value are shown in the following table.

⁶⁴ MASS orientated devices for maximum throughput in the one plane only. In this measurement campaign the orientation was changed in both vertical and horizontal planes.

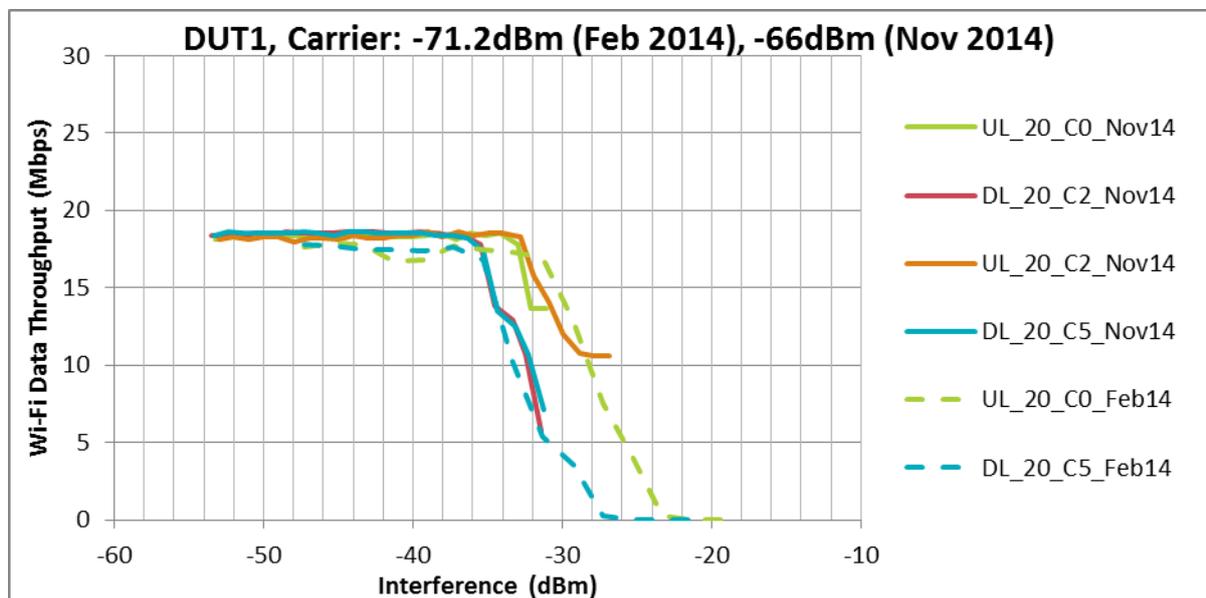
Table A1.3: Differences in MUS values

Device	Device Type	MUS (dBm)		Delta (dB)
		MASS values (Feb 2014)	Our values (Nov 2014)	
DUT 1	Laptop	-91.2	-86	-5.2
DUT 3	Laptop	-90.8	-79	-11.8
DUT 4	Smartphone	-89.5	-84	-5.5
DUT 5	Tablet	-95.3	-87	-8.3
DUT 9	Router	-93.0	-94	1.0
DUT 14	Router	-91.8	-92	0.2
DUT 15	Tablet	-90.6	-78	-12.6

A1.35 There were a few other differences in the setup which could give rise to differences in results⁶⁵. Despite the difference in wanted signal and throughput, results for absolute interference levels are generally found to be consistent

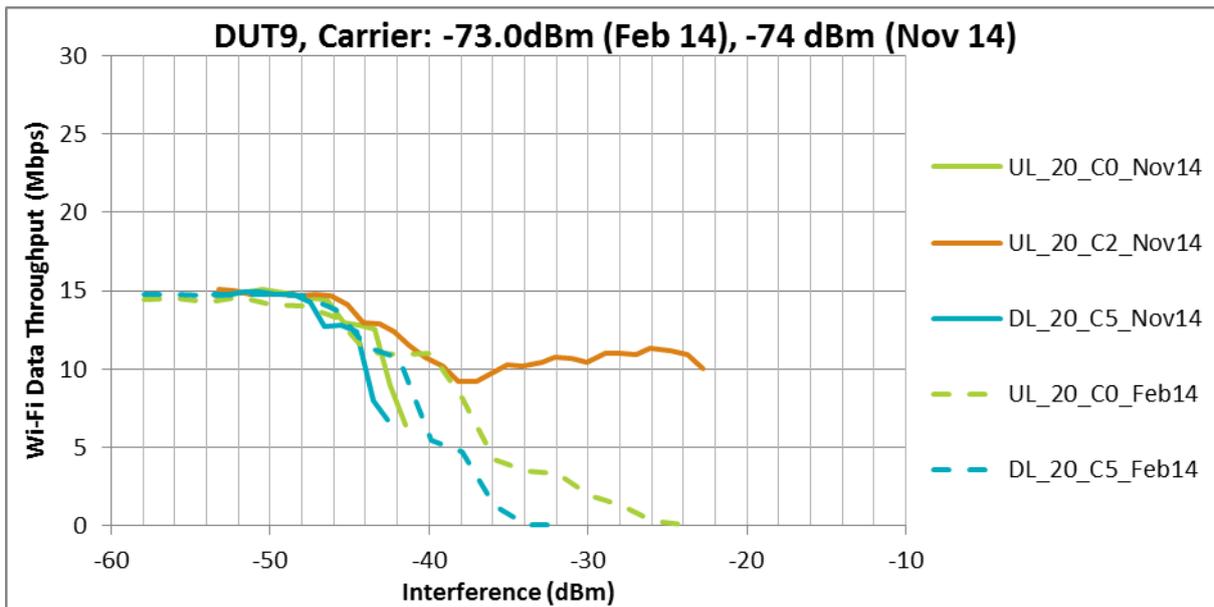
A1.36 For DUT 1 and 9 it is observed that the results are similar to the previous results conducted by MASS in terms of achieved throughput and MUS value. This is illustrated in the following plots. We note that these devices are both routers with external antennas, and are therefore likely to be less sensitive to the orientation issues identified above. Thus it is logical that reasonable correlation is achieved here.

Figure A1.5: Comparison with previous test results for DUT 1.



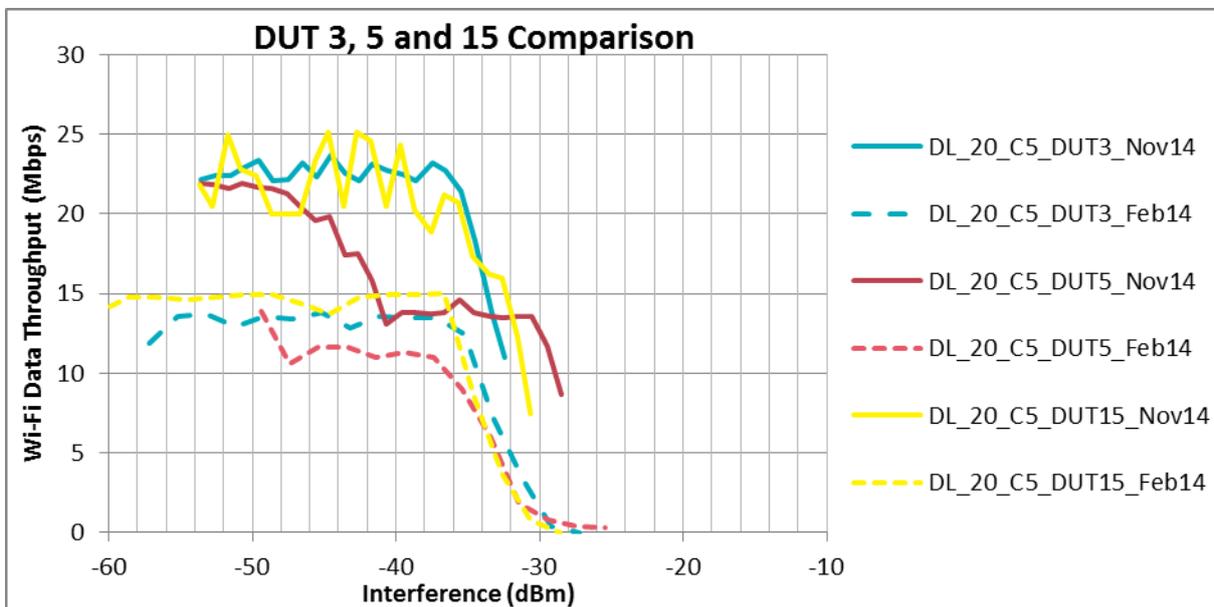
⁶⁵ In particular, the unwanted signal power levels measured by MASS did not use a correction factor for signals of different frame configurations, however as we based our previous analysis on the downlink parts of frame configuration 5 this should have negligible effect on our previous analysis.

Figure A1.6: Comparison with previous test results for DUT 9.



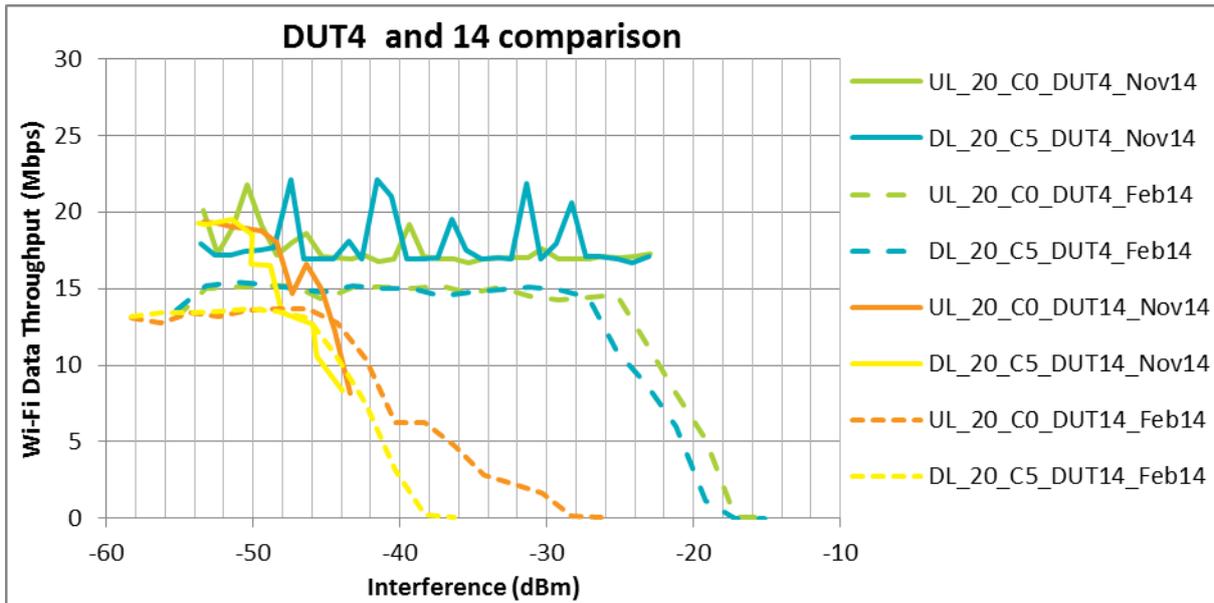
A1.37 DUTs 3, 5 and 15 have a higher MUS than in the previous tests, and consequently the wanted signal is set higher (see Figure A1.7). This results in higher initial throughputs than were previously seen. In absolute throughput terms, our recent test show slightly higher interference levels can be tolerated and in most cases the relative onset of degradation and 50% reduction points occur at slightly higher interference levels for the new results.

Figure A1.7: Comparison with previous results DUT 3, 5 and 15



A1.38 DUTs 4 and 14 have more similar MUS values but higher starting throughputs in our more recent tests (Figure A1.8). We did not have enough interference power to cause DUT4 to have a reduction in throughput (the variability in throughput seems to be a function of the power management or scheduling employed by the device). However both devices show a broadly similar trend in terms of the reduction in throughput.

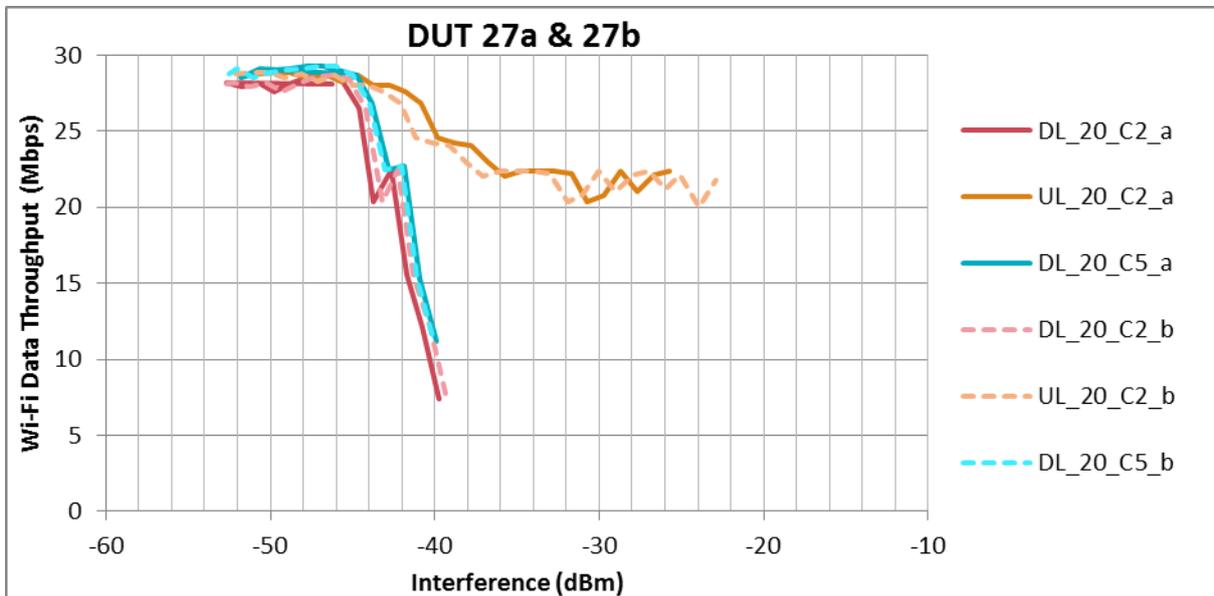
Figure A1.8: Comparison with previous results DUT 4 and 14



Repeatability between devices

A1.39 In order to confirm the repeatability of results between different devices, we performed some tests on two different devices of the same model. Reasonable correlation is found between the two sets of results, as shown in the following figure.

Figure A1.9: DUT 27 repeatability results



Comparison of different frame configurations

A1.40 The three sub frame configurations used for the LTE TDD testing in both the uplink and the downlink are: C0, C2 and C5. These can be seen in Table A1.4.

Table A1.4: TDD LTE frame configuration

DL/UL Configuration	DL/UL ratio	Downlink-to-Uplink Switch-point periodicity (ms)	Subframe number									
			0	1	2	3	4	5	6	7	8	9
0	1:3	5	D	S	U	U	U	D	S	U	U	U
1	1:1	5	D	S	U	U	D	D	S	U	U	D
2	3:1	5	D	S	U	D	D	D	S	U	D	D
3	2:1	10	D	S	U	U	U	D	D	D	D	D
4	7:2	10	D	S	U	U	D	D	D	D	D	D
5	8:1	10	D	S	U	D	D	D	D	D	D	D
6	3:5	5	D	S	U	U	U	D	S	U	U	D

A1.41 The table shows the supported uplink-downlink frame configurations where:

1.41.1 "D" denotes a subframe reserved for downlink transmission.

1.41.2 "U" denotes a subframe reserved for uplink transmission.

1.41.3 "S" denotes a special subframe used for guard time to separate the uplink and downlink transmissions. The special subframe also contains some uplink and downlink traffic⁶⁶.

A1.42 The downlink configuration 2 and configuration 5 profiles show similar results (Figure A1.10 to Figure A1.12). This implies that the results from the February 2014 consultation, which were mainly based on downlink configuration 5, should be representative of a configuration 2 base station scenario in practice.

A1.43 For uplink configuration 2 most DUTs show some improvement when compared with the downlink signals. This is likely due to Wi-Fi managing to schedule packets in the gaps of the TD-LTE frame structure when the LTE mobile devices is not transmitting. The onset of degradation typically occurs at a similar level, however, the slope of roll-off is not as sharp, meaning that the 50% throughput level occurs at a much higher level of LTE interference. This supports our view that the impact of interference from mobile handsets will not be significant in practice.

⁶⁶ The ratios in Table 4 ignore the special subframe. In practice the amount of downlink and uplink traffic within the special subframe is determined by the guard period which can vary by implementation.

Figure A1.10: Frame configurations comparison DUT 3

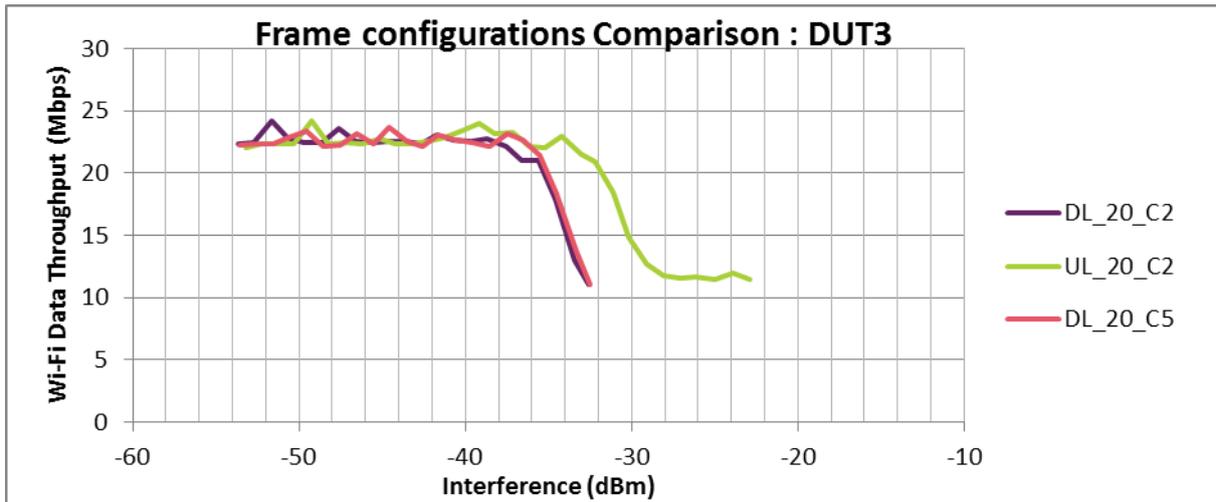


Figure A1.11: Frame configuration comparison DUT 1, 4 and 5

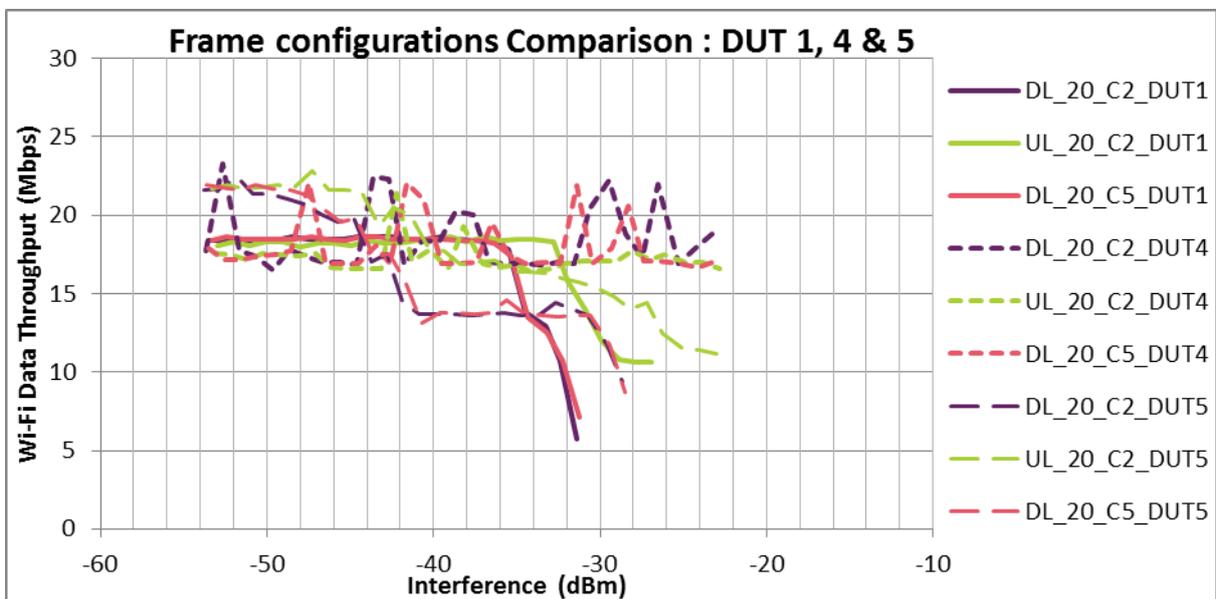
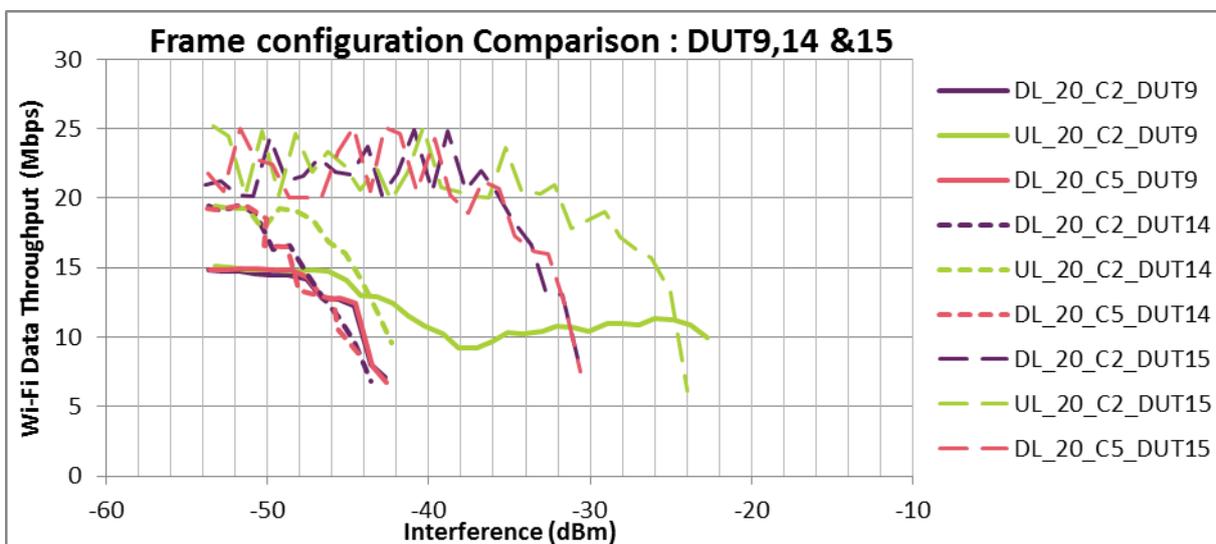


Figure A1.12: Frame configuration comparison DUT 9, 14 and 15



Recorded LTE signal results

A1.44 As described above, we used some recorded LTE signals from mobile devices in order to replicate a more realistic scenario than the heavy upload simulated results. The results with the recorded signals in general show less effect on the Wi-Fi throughput and most of the profiles show more resilience for the same interfering power. An example can be seen in Figure A1.13 and further results are in Figure A1.31 to Figure A1.35.

A1.45 We also include time domain results in Figure A1.14 showing the effect on throughput over a 5 minute variant of the Skype video profile. It should be noted there is a large power increase in the middle of the file for approximately 10 seconds which may be an anomaly specific to this file. Whilst we do not believe this power spike is representative of normal behaviour it can be clearly seen that when the power increases, throughput drops but recovers afterwards showing the device to be able to cope with these situations. Similar results were seen for other devices when using the same file but are not presented here.

Figure A1.13: Recorded LTE to Wi-Fi, DUT 14

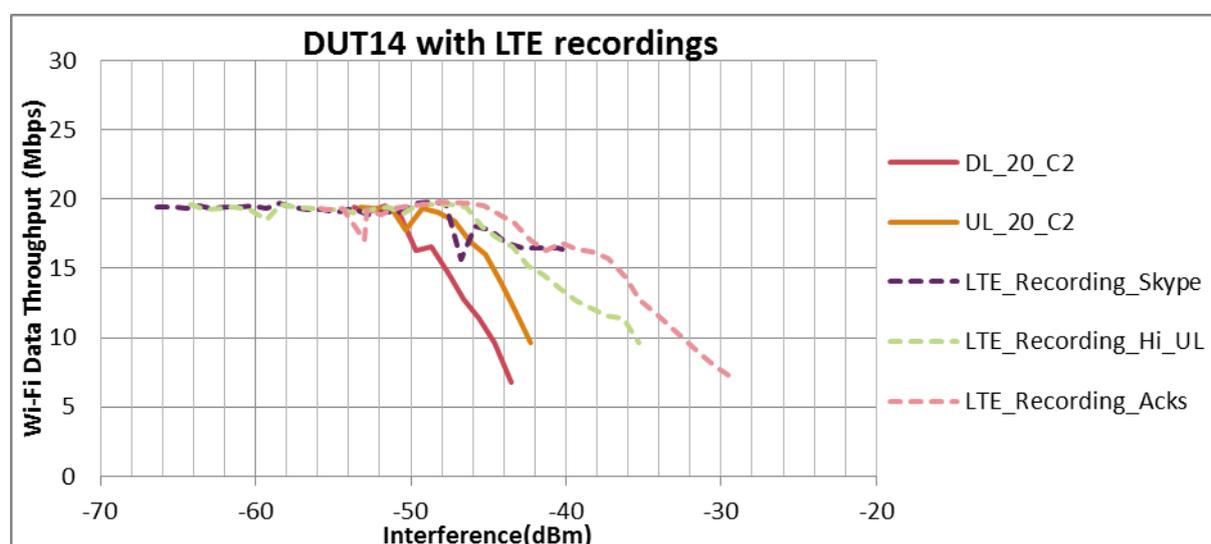
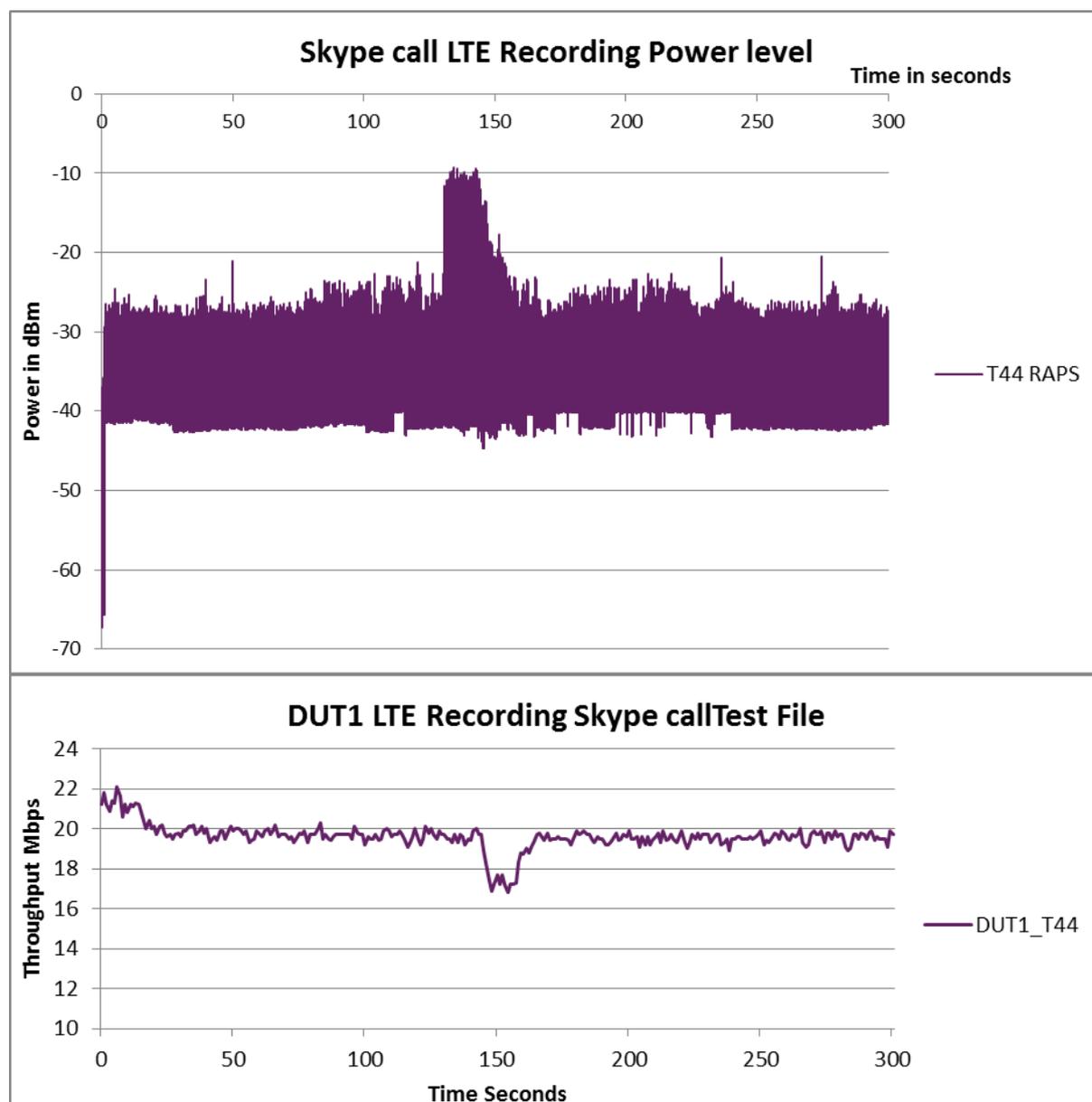


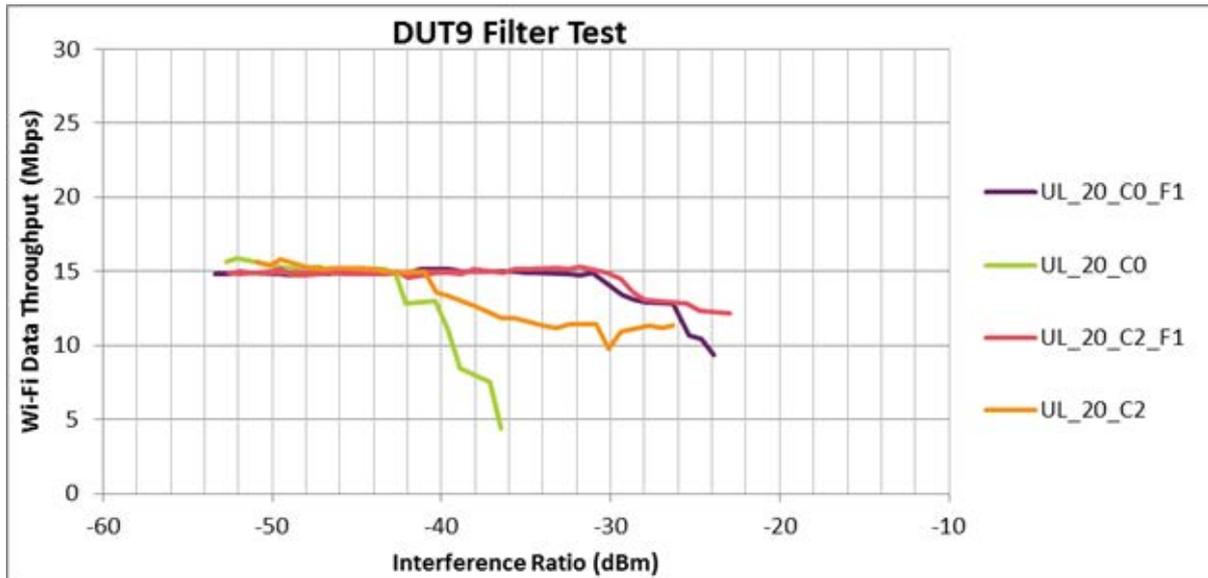
Figure A1.14: Time domain plot of recorded LTE power level and throughput



Results showing the effect of additional filtering

- A1.45 Adding a band-pass filter which is specifically designed to protect Wi-Fi from 2.3 GHz LTE signals is shown to completely resolve the impact of interference (See Figure A1.15)
- A1.46 The viability and timeframe for introducing these filters to Wi-Fi equipment is explored in section 6.

Figure A1.15: Filter test Results on DUT 9

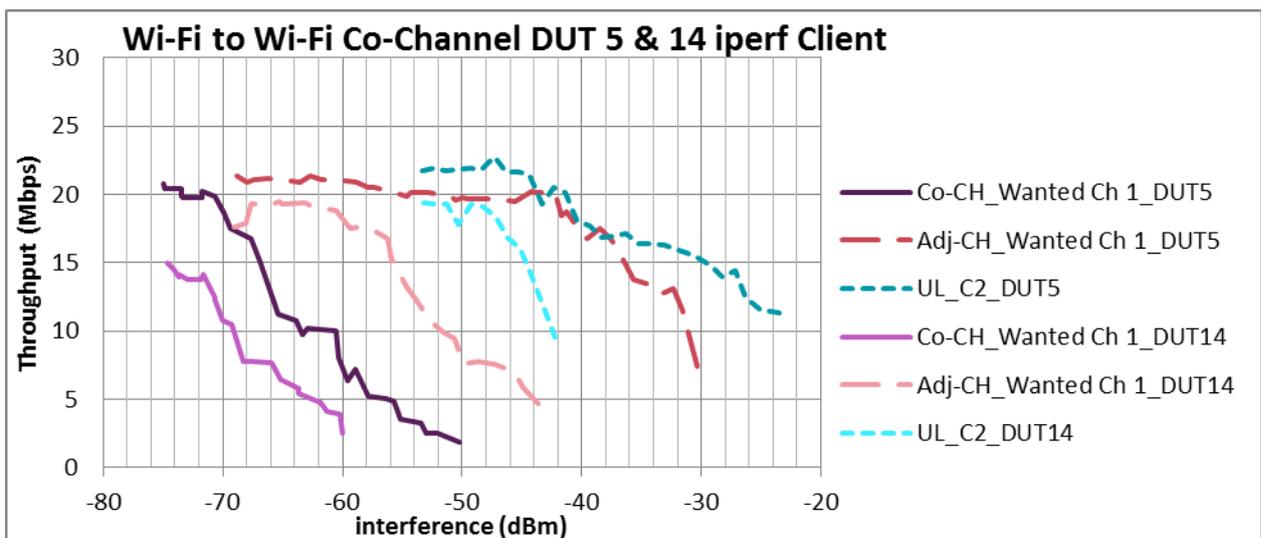


Wi-Fi to Wi-Fi interference results

A1.47 Figure A1.16 shows the effect of W-Fi as an interferer (i.e. another Wi-Fi device on a different network). Wi-Fi signals on adjacent channels affect Wi-Fi throughputs at slightly lower interference levels to 2.3 GHz LTE signals, although we note in this case that the interfering Wi-Fi could not ‘hear’ the wanted Wi-Fi signal due to our setup and so in practice the unwanted might also reduce its throughput as a result of the wanted signal (particularly in the co-channel example) and more equitable sharing may occur below about 10 Mbps.

A1.48 In the co-channel case the Wi-Fi is much less tolerant to interference as there is no frequency separation between the two signals.

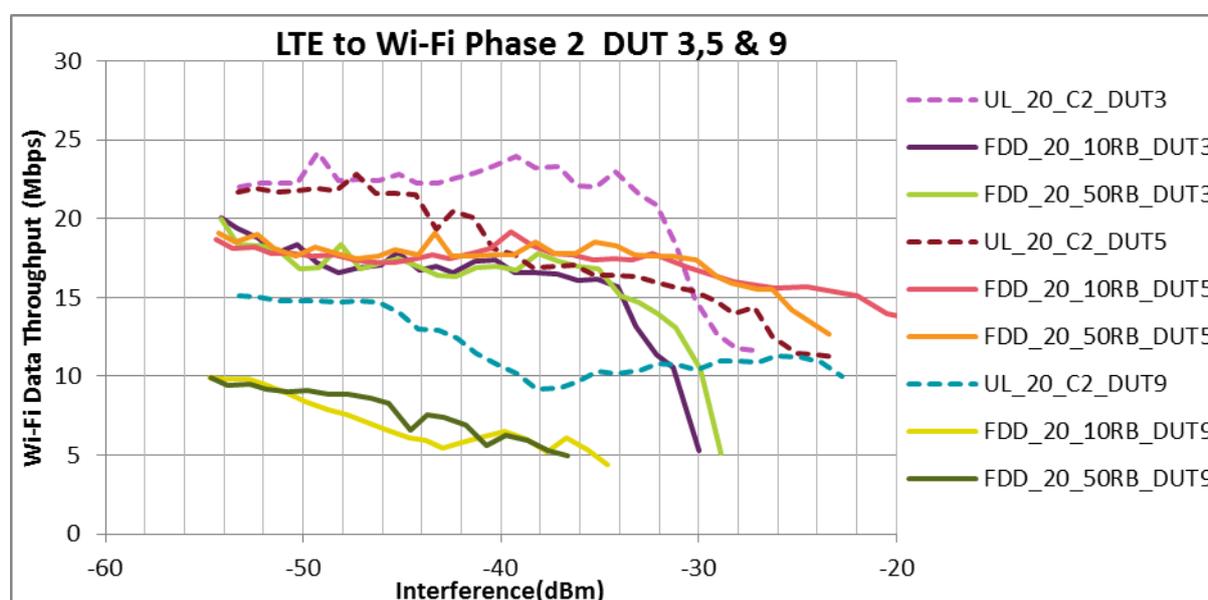
Figure A1.16: Wi-Fi to Wi-Fi, DUT 5 & 14



2.6 GHz FDD uplink interference results

- A1.49 The results for 2.6 GHz FDD uplink signals (Figure A1.17) show that the impact of interference has a similar profile compared to that from 2.3 GHz, with interference occurring at broadly similar levels. However we note that in general the throughput is lower than with the 2.3 GHz interferer. This may be due in part to the lack of gaps in the FDD waveform but also that measurements were made on Wi-Fi channel 13 which may have a slightly different receiver performance than that at channel 1⁶⁷.
- A1.50 The tests were run with 2.6 GHz FDD signals using 10 and 50 resource blocks, to show two extremes of traffic loading. There is no significant difference seen between these profiles suggesting that the bandwidth of the interferer makes little difference.

Figure A1.17: FDD LTE to Wi-Fi, DUT 3, 5 & 9



802.11n results

- A1.51 The onset of degradation for 802.11n occurs at similar levels to the equivalent 802.11g results (see Figure A1.18 to Figure A1.20), but there is typically a sharper roll off for 802.11n. It is noted that in practice the link would revert to an 802.11g mode if degradation occurred.
- A1.52 As noted in the methodology section, when attempting to perform 802.11n tests in a real office environment the initial throughputs were lower than for 802.11g devices tested in the anechoic chamber. This is believed to be due to the presence of other Wi-Fi networks in the location. We believe that this demonstrates that whilst 802.11n at 2.4 GHz may give faster throughputs in some environments this was not achievable in a heavily congested location where the performance was similar to 802.11g.

⁶⁷ We have noted from previous tests, and from our engagement with manufacturers, that band-pass filters and antennas on Wi-Fi devices are generally optimised for channels in the middle of the 2.4 GHz band, and therefore there is usually some additional loss in link budget at the edges of the band (channels 1 and 13).

Figure A1.18: 802.11n DUT 14

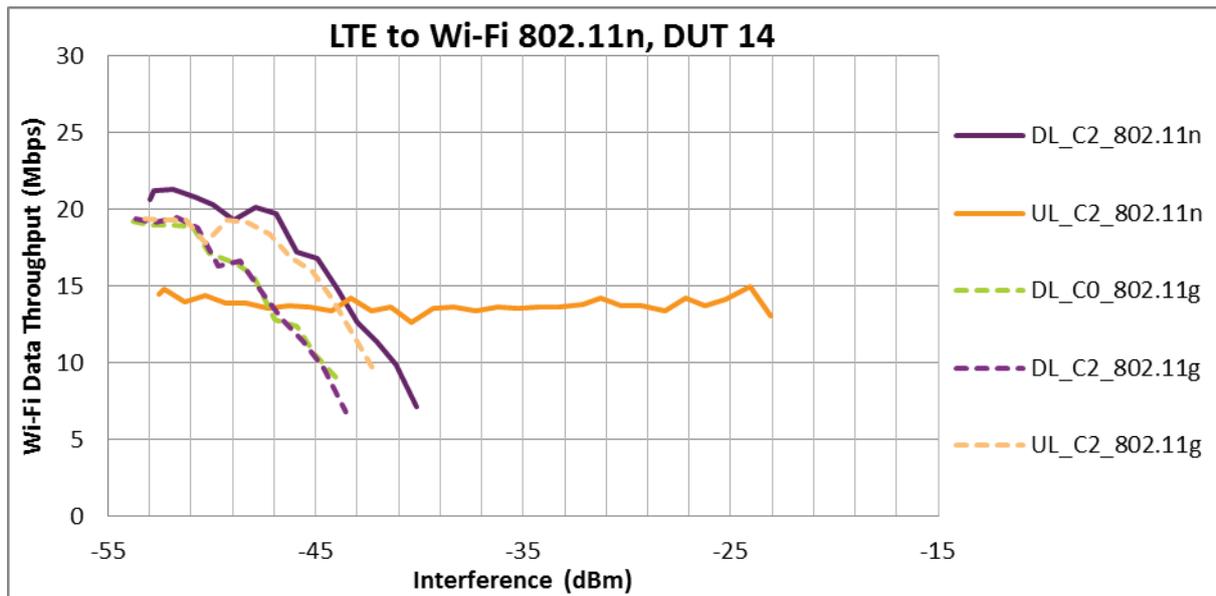


Figure A1.19: 802.11n DUT 27b

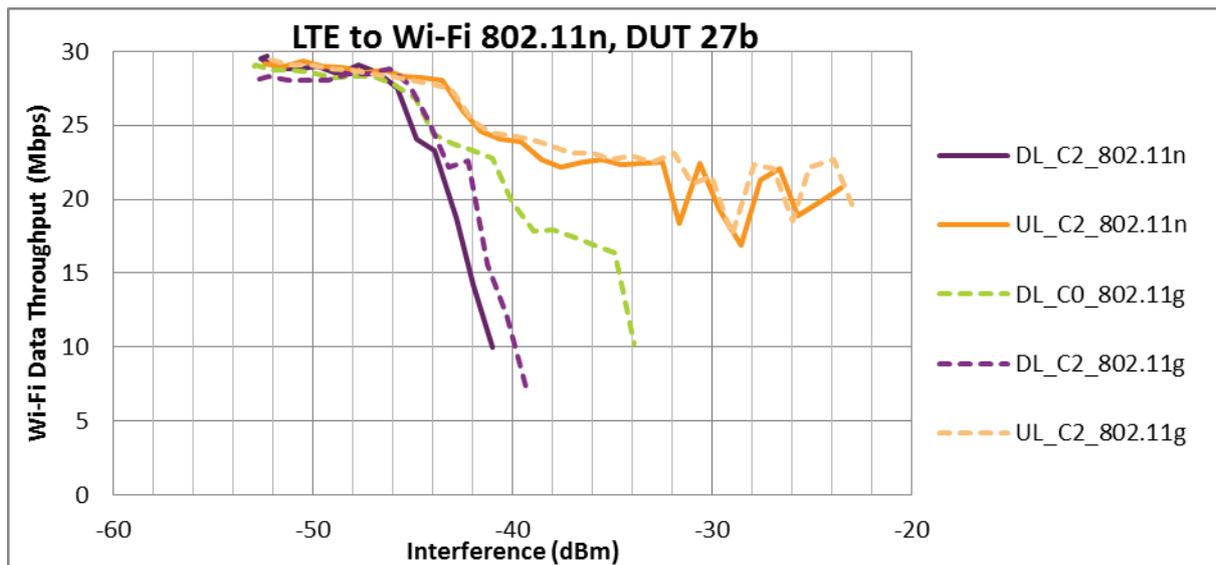
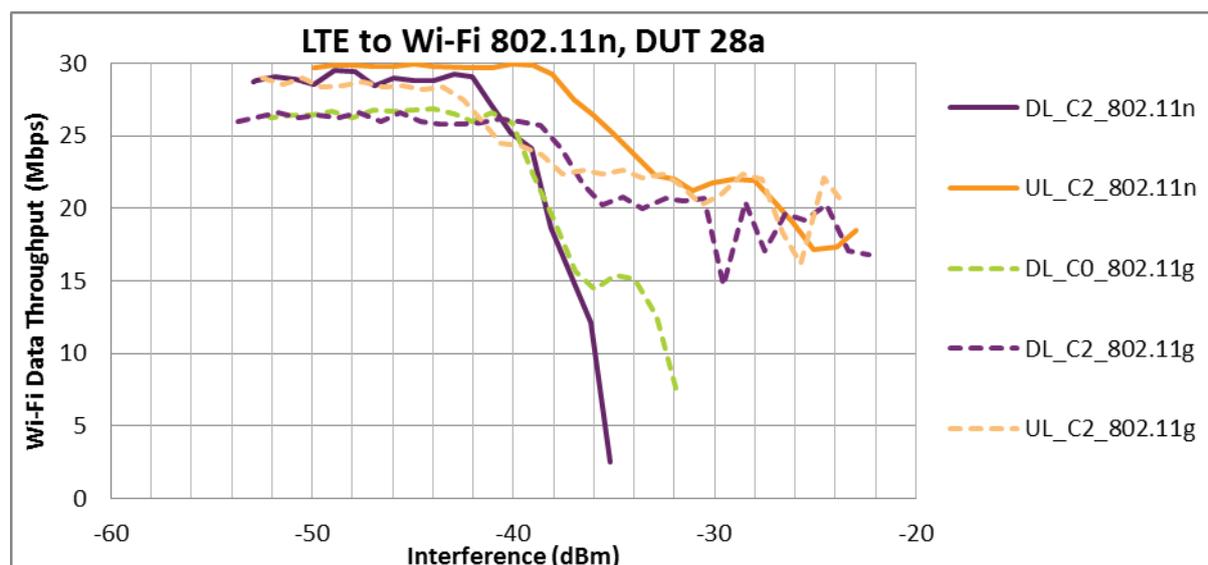


Figure A1.20: 802.11n DUT 28a



Subjective video test results

- A1.53 The results from our subjective testing of a video streaming device showed there was no noticeable degradation to the video stream with the Wi-Fi signal 20 dB above MUS and an unwanted signal level of -28 dBm.
- A1.54 At a lower signal level of 10 dB above MUS, and an unwanted signal level of -28 dBm, the video ran at a lower resolution with some minor breakup, but improved after approximately 60 seconds.
- A1.55 To conclude, this DUT was deemed to be fairly robust to interference.

Additional devices results

- A1.56 As explained above, a few additional devices were made available to us for testing by stakeholders. As expected, the results are within the same range as other devices. The devices are more resilient to the lighter LTE uplink profiles than our other devices but the other profiles show similar trends. We expect that this is a result of different Wi-Fi retry algorithms that work particularly well with the spaces in the TD-LTE frames structure for an uplink configuration 2.

Figure A1.21: Additional Device 1 Result

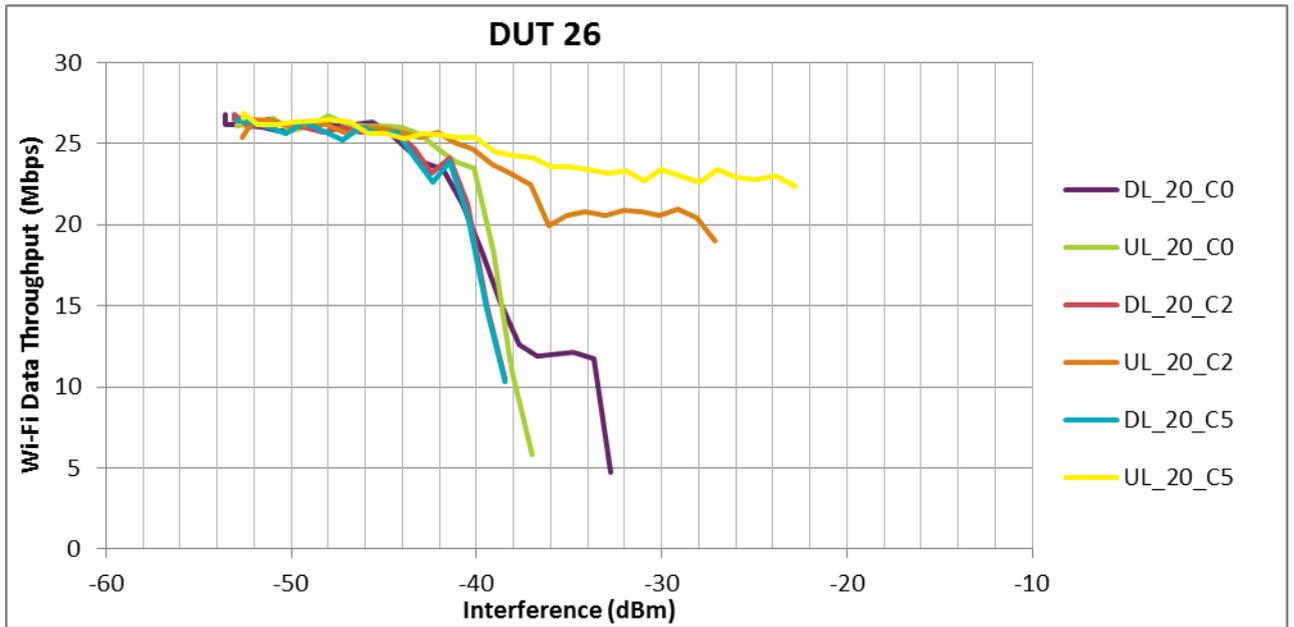


Figure A1.22: Additional Device 2 Result

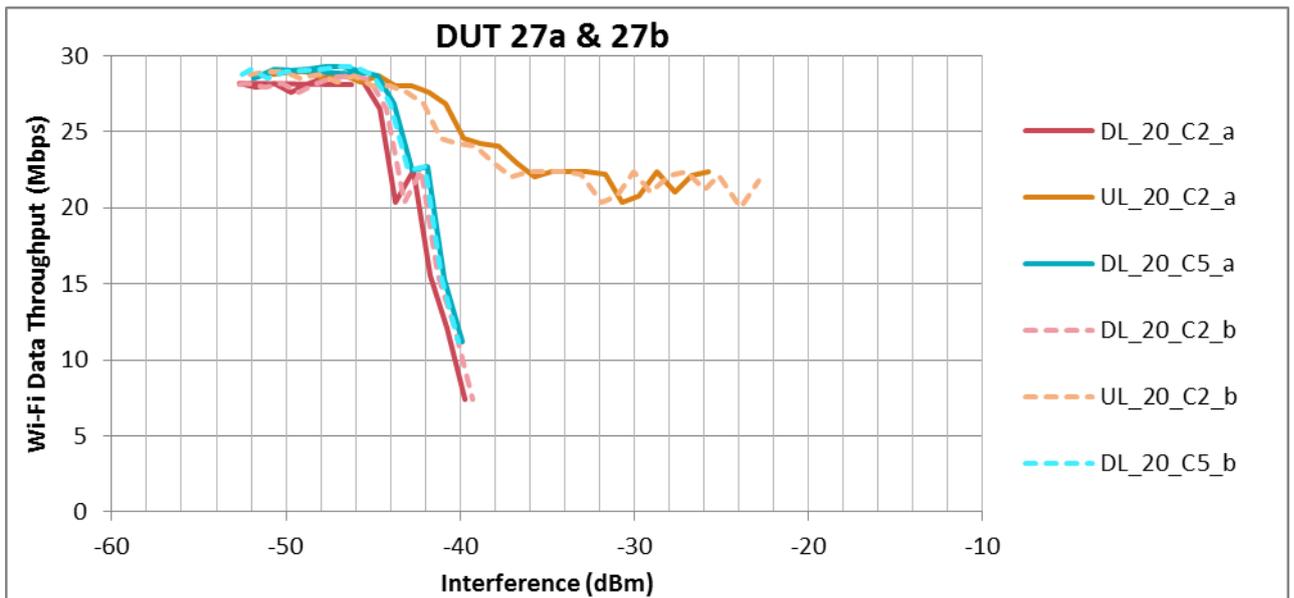
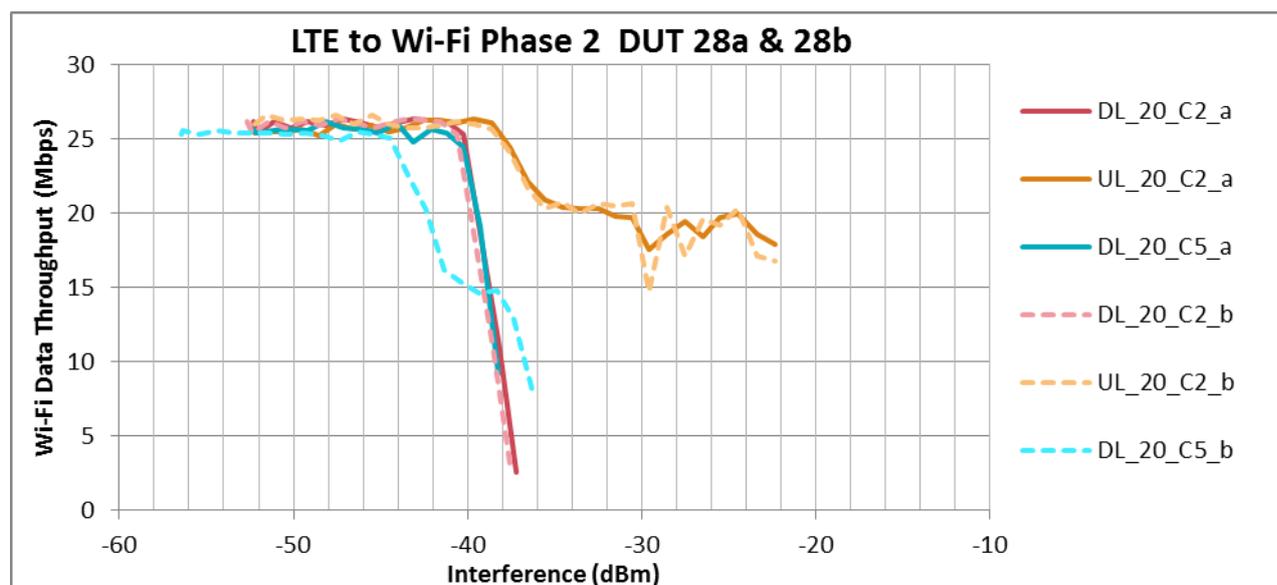


Figure A1.23: Additional Device 3 Result



Conclusions from further lab measurements and walk tests

- A1.57 Based on the results and analysis presented in this annex, we believe our original statistical analysis in the February 2014 consultation is still applicable.
- A1.58 The combined effect of the use of frame configuration 2 and more realistic data profiles suggests that while the onset of degradation is found to occur at a similar level as to the previous analysis, the 50% throughput reduction point generally occurs at higher interference levels. By extension we assume this is also the case for the 1Mbps failure point. Therefore the impact on user experience in practice may not be as pronounced as assumed previously.
- A1.59 We note that based on the results of our walk test campaign UE transmit powers may be up to 6 dB higher than we previously assumed. However, this increase is largely offset by the measurement results for UEs which show that interference levels for UEs are higher than assumed in the previous analysis
- A1.60 Therefore, based on the evidence outlined above we believe that the previous separation distances are still applicable, and we do not believe that the impact of interference from mobile devices will be worse than we previously suggested in our February 2014 consultation.
- A1.61 These issues are explored in more detail in section 5 of this document.

Full results from further lab tests

A1.62 The full results for all DUTs tested in this measurement campaign are presented in the following figures.

Simulated signal tests

Figure A1.24: DUT 1 results

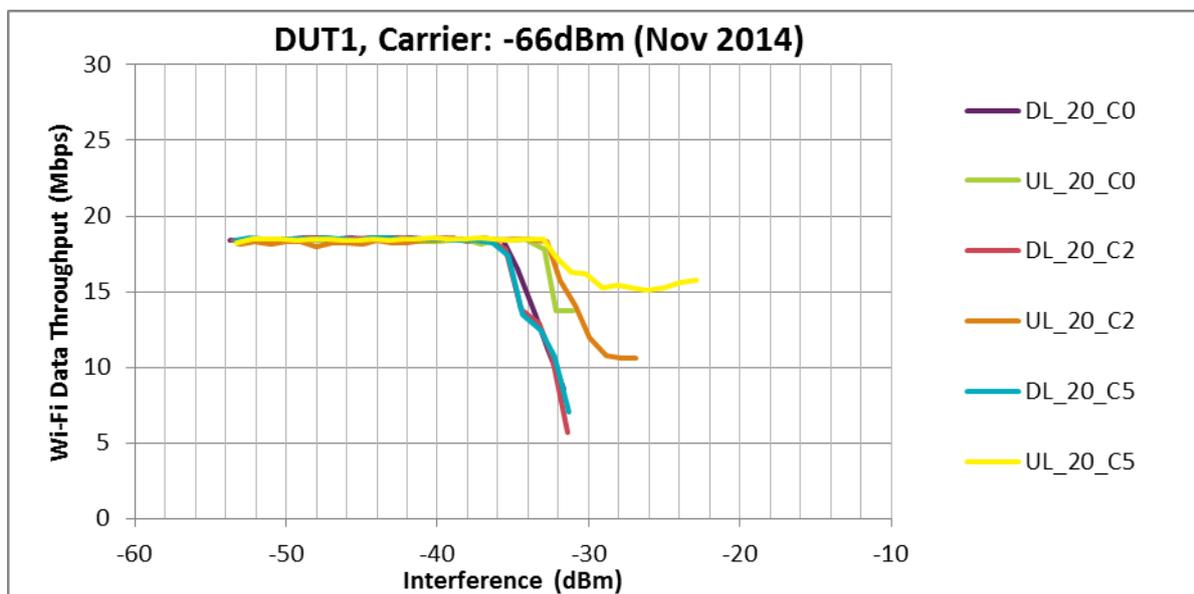


Figure A1.25: DUT 3 results

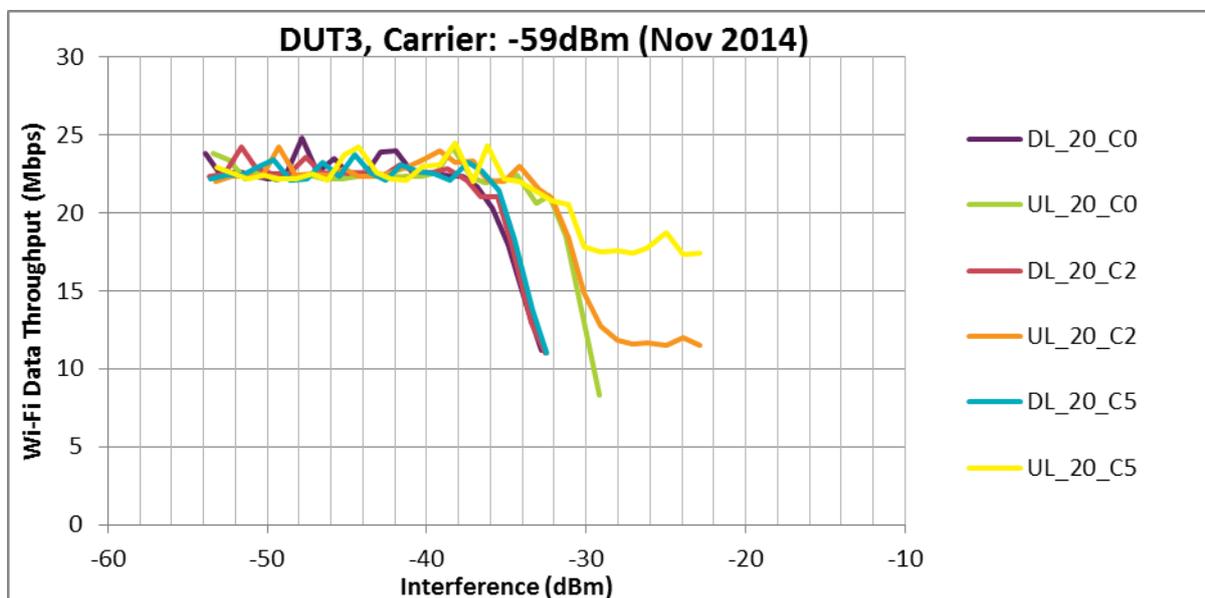


Figure A1.26: DUT 4 Results

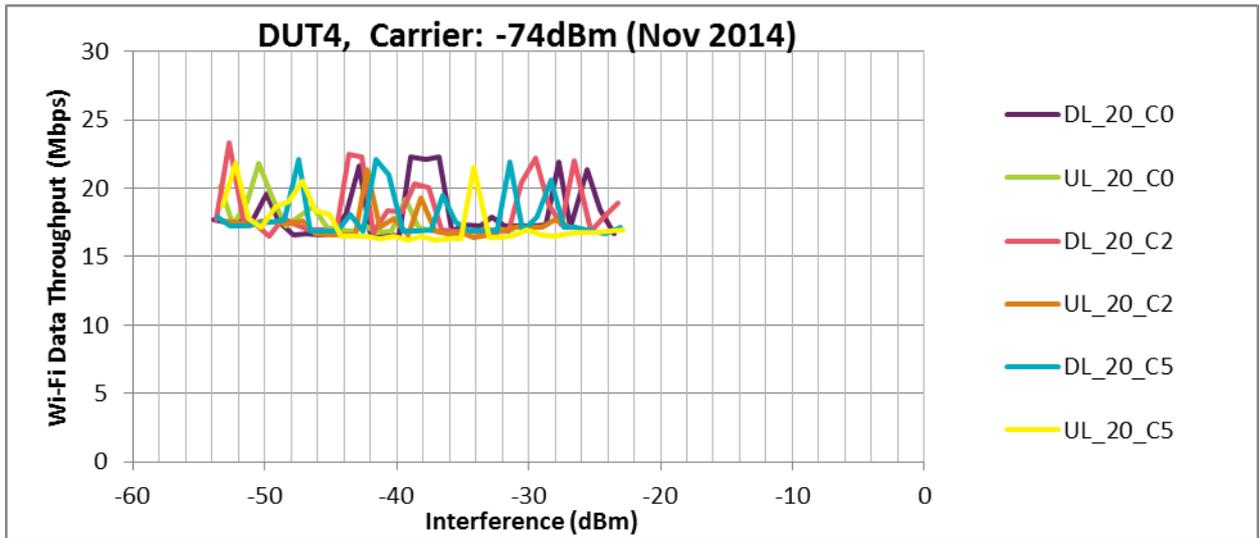


Figure A1.27: DUT 5 Results

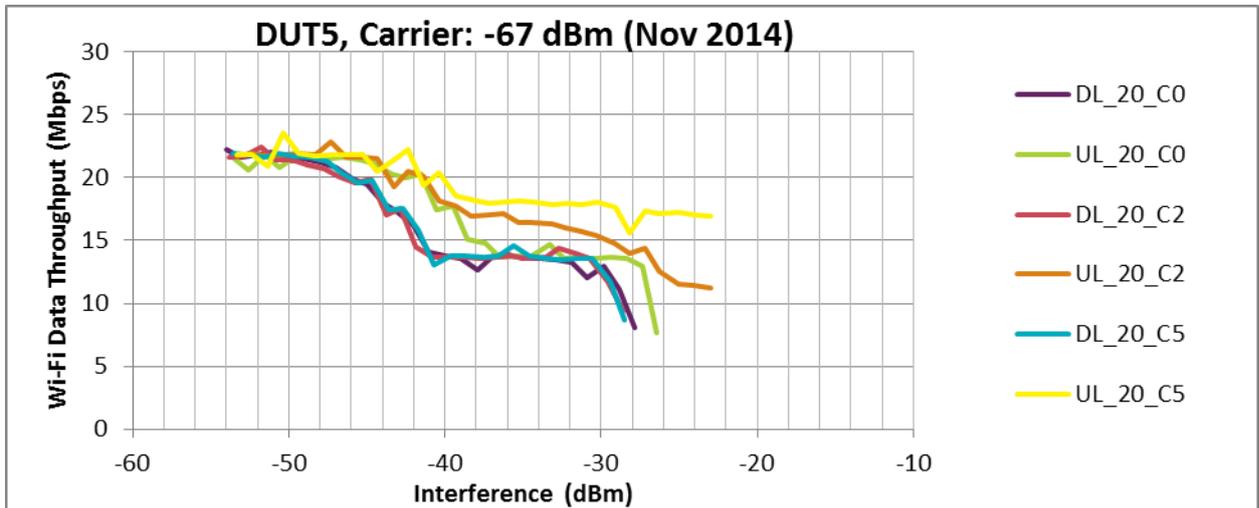


Figure A1.28: DUT 9 Results

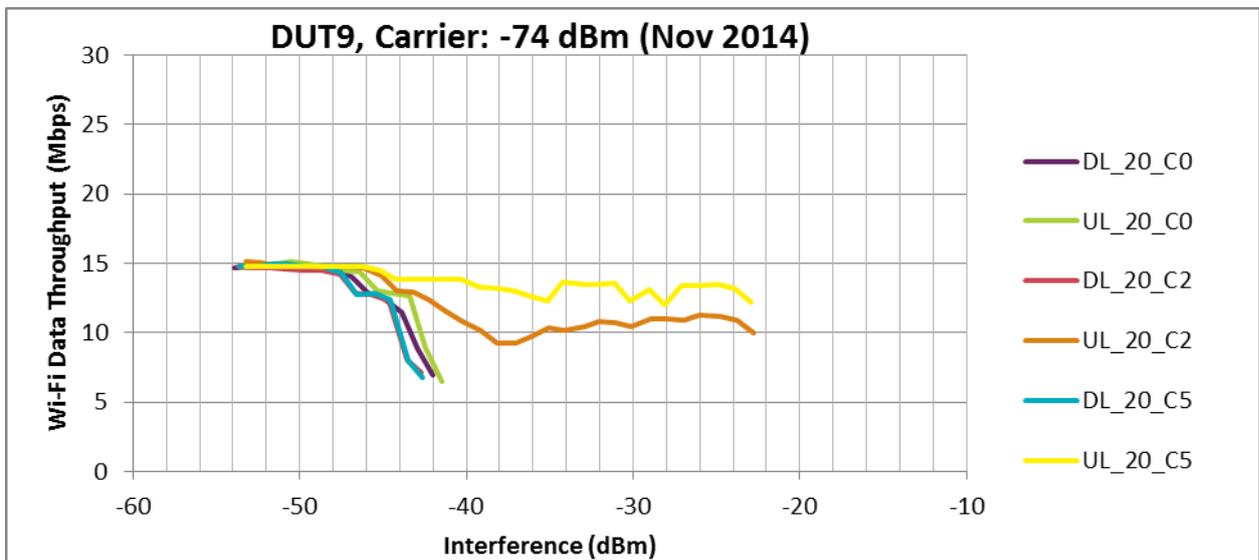


Figure A1.29: DUT 14 Results

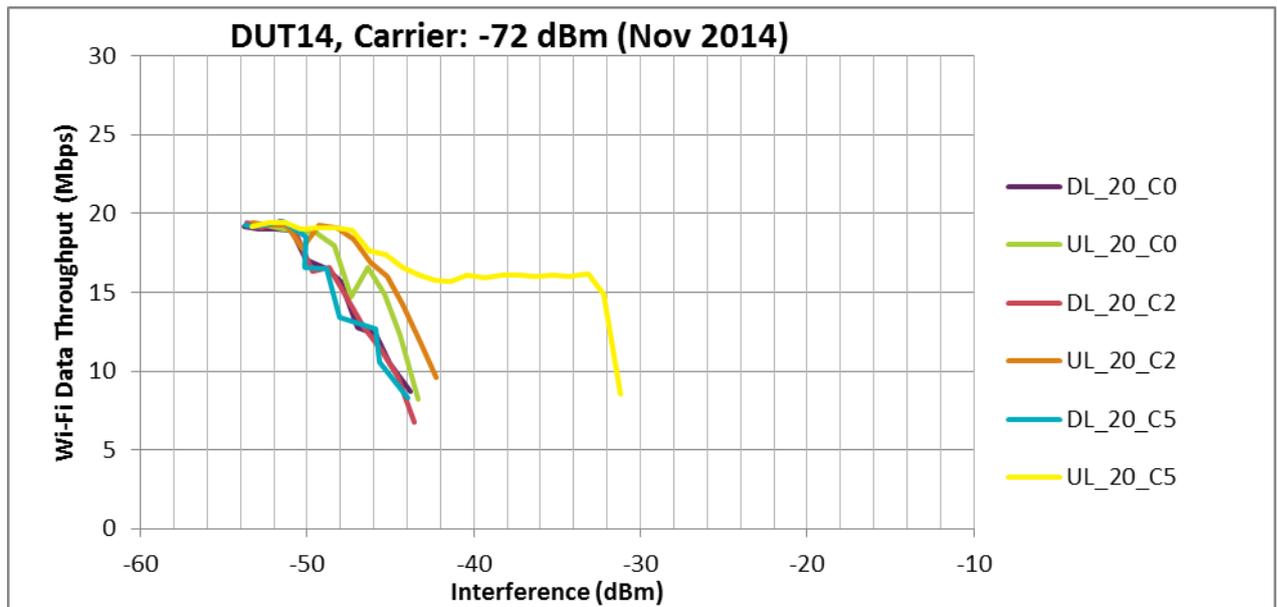
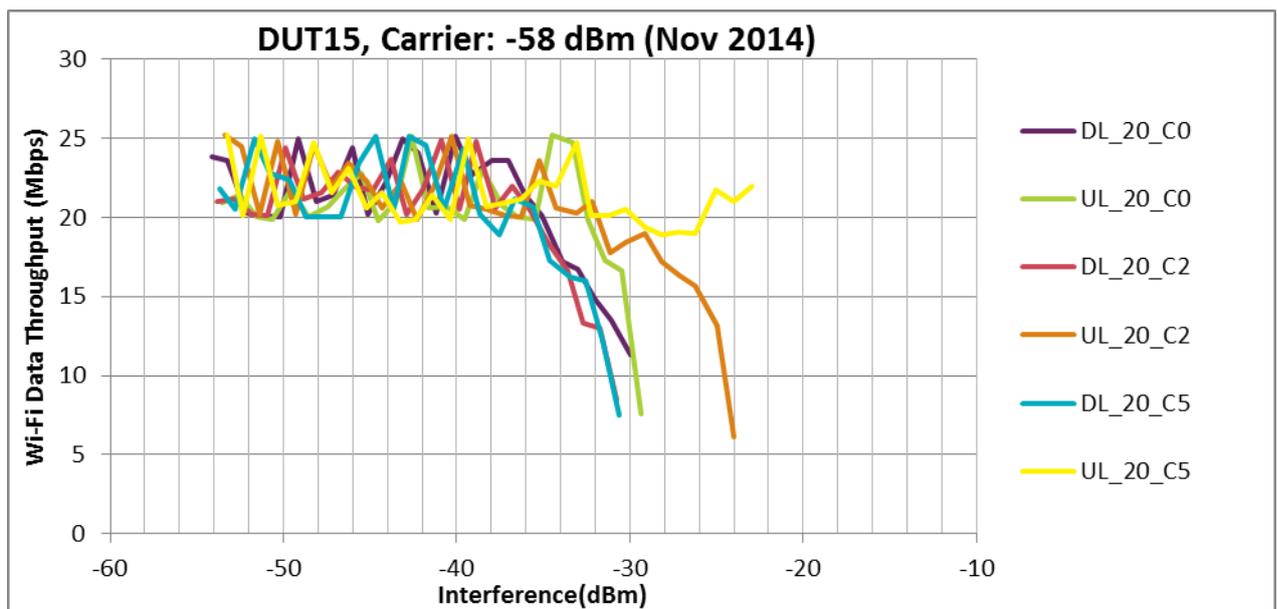


Figure A1.30: DUT 15 Results



Recorded signal tests

Figure A1.31: Recorded LTE to Wi-Fi, DUT 1

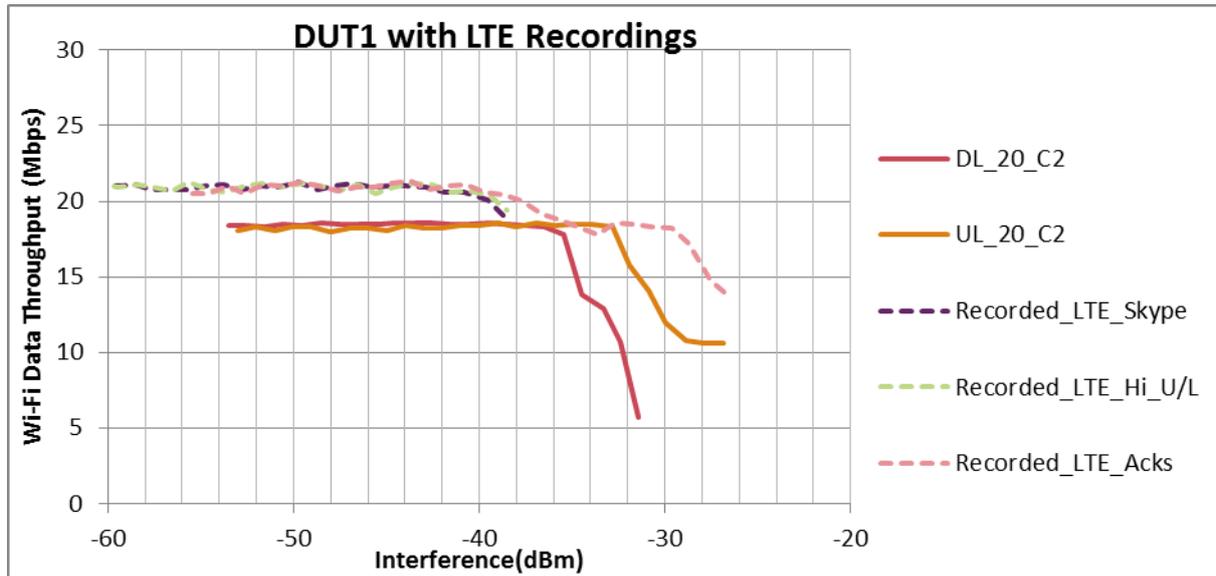


Figure A1.32: Recorded LTE to Wi-Fi, DUT 3

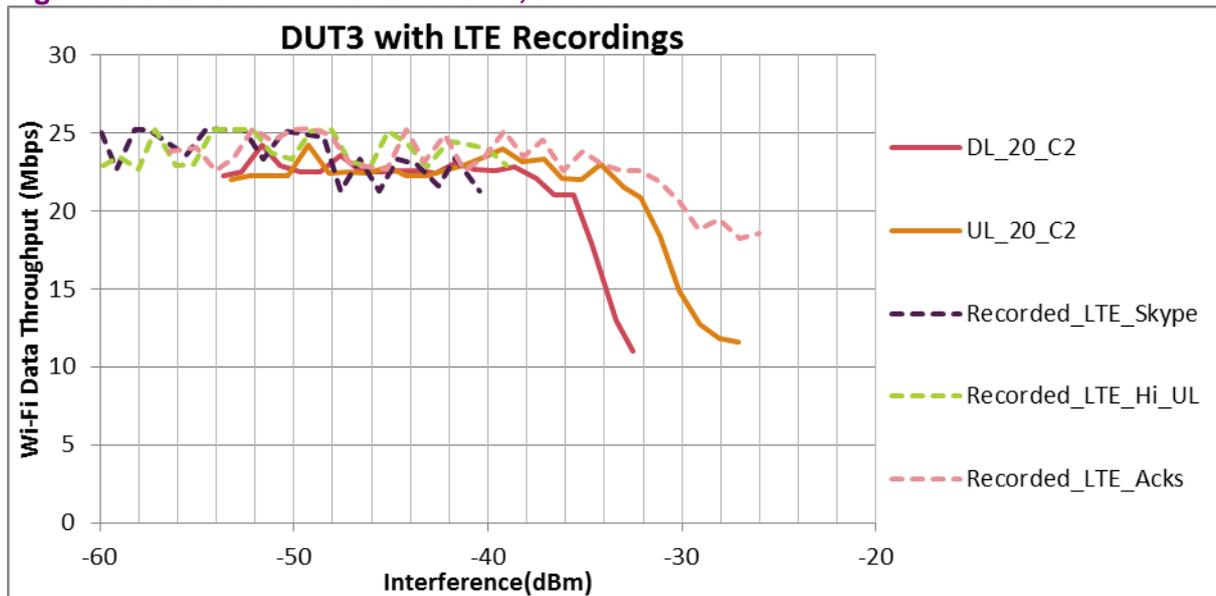


Figure A1.33: Recorded LTE to Wi-Fi, DUT 5

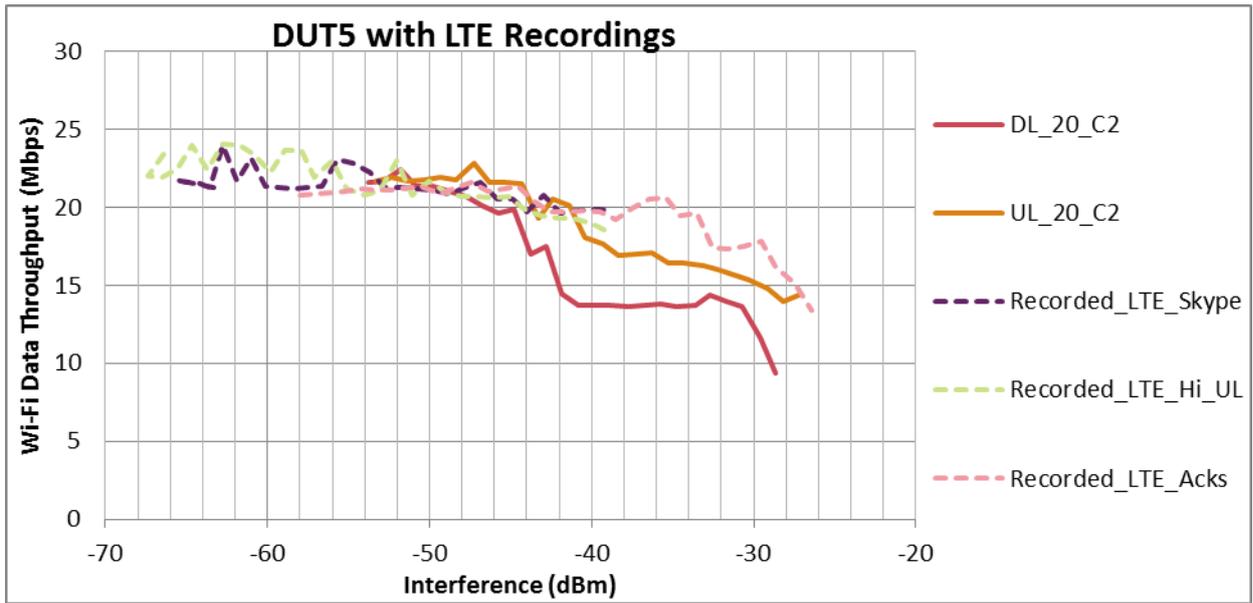


Figure A1.34: Recorded LTE to Wi-Fi, DUT 9

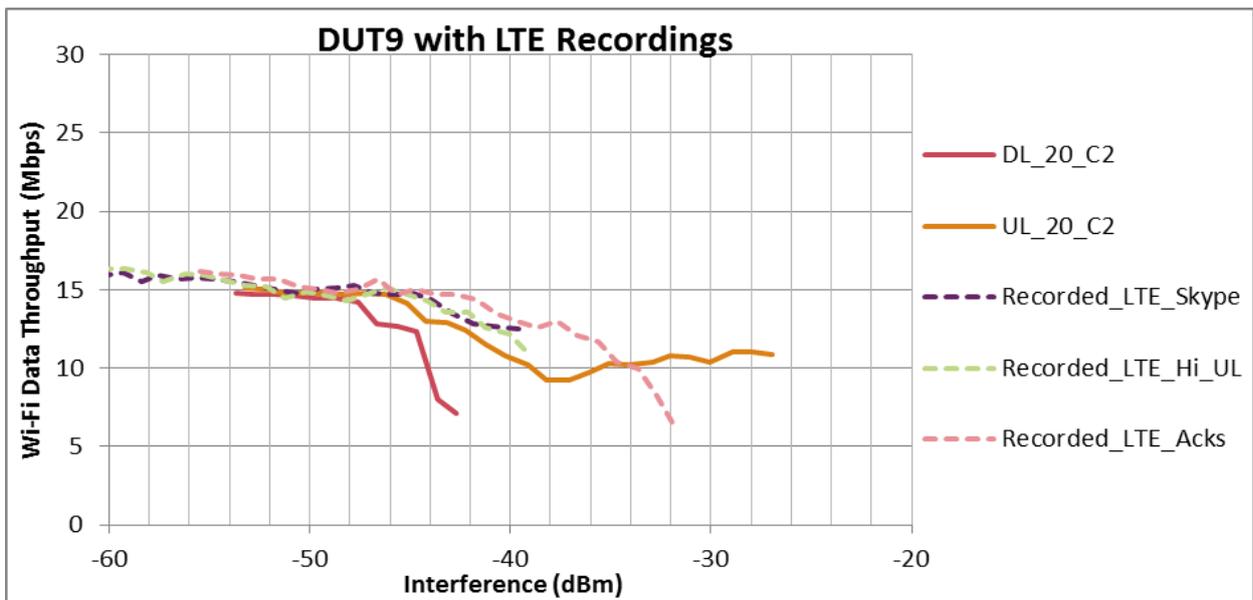
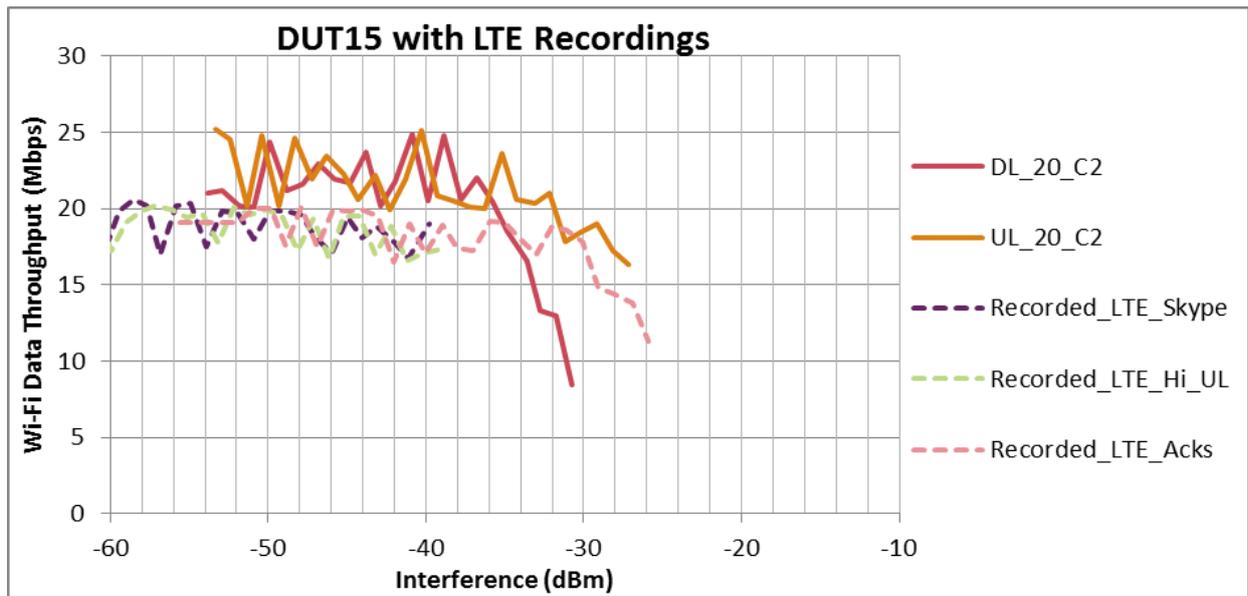


Figure A1.35: Recorded LTE to Wi-Fi, DUT 15



Annex 2

Directory of related documents

A2.1 We list below a number of documents that are published alongside our own further analysis of coexistence issues for the 2.3 and 3.4 GHz award. These documents have been produced independently of Ofcom.

1. 7Signal Wi-Fi testing reports (x3):
 - Executive summary
[\(\[http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_Exec_Summary.pdf\]\(http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_Exec_Summary.pdf\)\)](http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_Exec_Summary.pdf)
 - Wi-Fi and LTE 2.3 GHz co-location field testing
[\(\[http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_co-location.pdf\]\(http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_co-location.pdf\)\)](http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_co-location.pdf)
 - Wi-Fi and LTE co-location, general performance trending addendum
[\(\[http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_general_trending.pdf\]\(http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_general_trending.pdf\)\)](http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Ofcom_and_Sky_Final_report_v10_general_trending.pdf)
2. OptiWi-fi Report 2.3 & 2.4 GHz Coexistence
 - [\(\[http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/OptiWi-fi_Report_2_3_and_2_4_Ghz_Coexistence.pdf\]\(http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/OptiWi-fi_Report_2_3_and_2_4_Ghz_Coexistence.pdf\)\)](http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/OptiWi-fi_Report_2_3_and_2_4_Ghz_Coexistence.pdf)
3. ALD compatibility testing against 2.3GHz LTE TDD signals at UK Ofcom Baldock June 2014
 - [\(\[http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Summary_of_Results_ALD_Testing.pdf\]\(http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Summary_of_Results_ALD_Testing.pdf\)\)](http://stakeholders.ofcom.org.uk/binaries/consultations/pssr-2014/Summary_of_Results_ALD_Testing.pdf)

A2.2 This document also refers to the following technical reports:

- LTE band 40 desensitization of Wi-Fi® devices - Technical note, Steve Shearer, Wi-Fi Alliance, October 2014:
[\(<https://www.wi-fi.org/file/lte-band-40-desensitization-of-wi-fi-devices>\)](https://www.wi-fi.org/file/lte-band-40-desensitization-of-wi-fi-devices)
- TDD Spectrum White Paper, Global TD-LTE Initiative, July 2013:
[\(<http://www.lte-tdd.org/d/file/Resources/pub/2013-11-22/180e4fbd9e544d019d42bc6d67913bf2.pdf>\)](http://www.lte-tdd.org/d/file/Resources/pub/2013-11-22/180e4fbd9e544d019d42bc6d67913bf2.pdf)

Annex 3

Glossary

3GPP	The 3rd Generation Partnership Project - Collaboration between groups of telecommunications associations, to make a globally applicable third-generation (3G) mobile phone system specification within the scope of the International Mobile Telecommunications-2000 project of the International Telecommunication Union (ITU).
4G	Fourth generation mobile phone standards and technology
802.11g / n	802.11 is the IEEE standard applicable to Wi-Fi. 802.11g refers to a variant of Wi-Fi operating in the 2.4 GHz band and 802.11n is a newer variant for Wi-Fi, which uses wider channels and additional transmission techniques to allow faster data throughput
ACIR	The Adjacent Channel Interference Ratio is a useful method for determining the interference between two systems in adjacent bands. It takes into account both the out-of-band leakage (ACLR) of the transmitter (interferer) and the receive filtering (ACS) of the receiver (victim).
ACLR	The Adjacent Channel leakage ratio (ACLR) of a radio transmitter is the ratio of in band transmitted power to out-of-band power in the adjacent channel (or for a specified frequency offset).
ACS	Adjacent channel selectivity. A measure of how susceptible a receiver is to unwanted signals in adjacent spectrum.
ADSL	A digital technology that allows the local loop to send a large quantity of data in one direction and a lesser quantity in the other.
ALD	Assistive Listening Device – equipment used by those who have hearing loss to listen to sound transmitted from a particular source (such as a teacher in a classroom)
BEM	Block Edge Masks
Block-edge-mask	A transmitter spectrum mask that applies at the edge of a licensed block of spectrum and is designed to offer sufficient protection from interference to any anticipated receiving system in an adjacent frequency block. The emissions of all transmitters operating within a licensed block must comply with this block edge mask, regardless of the bandwidth of such transmitters.
Bluetooth	Wireless standard for short-range radio communications between a variety of devices such as PCs, headsets, printers, mobile phones, and PDAs.
BS	Base Station

CEPT	The European Conference of Postal and Telecommunications Administrations
Communications Act	The Communications Act 2003
dB/dBm	Decibel. A notation for dealing with ratios that vary over several orders of magnitude by using logarithms / The power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW).
Downlink	The downlink part of a network connection on a mobile device is used to receive, or download, data to the mobile device from the base station. The uplink connection is used to send data from the mobile device back to the base station.
EC	European Commission
ECC	Electronic Communications Committee – One of the three business committees of the European conference of Postal and Telecommunications.
EE	Everything Everywhere Ltd – An MNO.
EIA	Equality Impact Assessment
EIRP	Equivalent Isotropically Radiated Power. This is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain).
ETSI	European Telecommunications Standards Institute; a European standards body
EU	European Union
FDD	Frequency Division Duplex – a technology that deals with traffic asymmetry between uplink and downlink where separate frequency bands are used for send and receive operations
Femto-cell	A small base station of low power (typically up to around 20 to 24dBm) and often used to provide mobile coverage in a domestic environment.
GHz	Gigahertz. 1,000,000,000 (or 10^9) oscillations per second.
GPS	Global Positioning System
GSA	Global Suppliers Association
GTI	Global TD-LTE Initiative – industry body to promote the interests of TDD operators

IEEE	Institute of Electrical and Electronic Engineers; a standards body responsible for technical standards for communications systems such as Bluetooth, Wi-Fi and Zigbee
ISP	Internet Service Provider
ITU	International Telecommunications Union - Part of the United Nations with a membership of 193 countries and over 700 private-sector entities and academic institutions. ITU's headquarters are in Geneva, Switzerland.
LTE	Long Term Evolution. Part of the development of 4G mobile systems that started with 2G and 3G networks. Aims to achieve an upgraded version of 3G services having up to 100 Mbps downlink speeds and 50 Mbps uplink speeds.
Mbps	Megabytes per second (internet speed)
MHz	Megahertz. A unit of frequency of one million cycles per second.
MNO	Mobile network operator
MOD	The Ministry of Defence
MVNO	Mobile virtual network operator
NAO	National Audit Office
NGR	National Grid Reference
NRA	National Regulatory Authority. The relevant communications regulatory body for each country in the EU. Ofcom is the NRA for the United Kingdom.
Ofcom	The Office of Communications
Pico-cell	A small base station of slightly higher power than a femto-cell; often used to provide mobile coverage in indoor environments or low height outdoor scenarios (such as on lampposts or other street furniture).
PMSE	Programme-making and special events. A class of radio application that support a wide range of activities in entertainment, broadcasting, news gathering and community events.
PSSR	Public Sector Spectrum Release
TDD	Time Division Duplex – a technology that deals with traffic asymmetry where the uplink is separated from the downlink by the allocation of different time slots in the same frequency band.
TD-LTE	Time Division Long Term Evolution. Sometimes referred to as Long Term Evolution Time-Division Duplex.

Time domain effect	Time domain effect refers to the effect on interference caused by LTE transmissions in a real-life network that vary significantly in power as a consequence of the user throughput and resource scheduling on the network.
TRP	Total Radiated Power. The TRP is defined as the integral of the power transmitted in different directions over the entire radiation sphere.
UE	User Equipment
UL/DL	Uplink/Downlink
Uplink	The uplink part of a network connection is used to send, or upload, data from a mobile device to a base station. The downlink connection on a mobile device is used receive data from the base station.
WiFi	Commonly used to refer to wireless local area network (WLAN) technology, specifically that conforming to the IEEE 802.11 family of standards. Such systems typically use one or more access points connected to wired Ethernet networks which communicate with wireless network adapters in end devices such as PCs. It was originally developed to allow wireless extension of private LANs but is now also used as a general public access technology via access points known as 'hotspots'.
WiMAX	Worldwide Interoperability for Microwave Access is a wireless communications standard designed to provide 30 to 40 megabit-per-second data rates.
WTA	Wireless Telegraphy Act 2006