MC/193

Study to Determine the Potential Interference from TDD LTE into WiFi

Final Report

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1 INTRODUCTION

This is the final report for Ofcom research project MC/193, *A Study to Determine the Potential for Interference from TDD LTE into WiFi*.

1.1 Why was this research necessary?

WiFi equipment, based around the IEEE 802.11 series of standards, operates within the unlicensed Industrial, Scientific and Medical (ISM) frequency band in the UK from 2401 to 2483 MHz, which is commonly referred to as the 2.4 GHz band. The adjacent frequency band, from 2300 to 2400 MHz, has been identified as a candidate band for Time Division Duplex (TDD) Long Term Evolution (LTE) services, which raises concerns about the risk of future interference between TDD LTE transmissions and WiFi receivers.

In addition to widespread use in both business and home wireless networks, WiFi devices are now in use in a range of consumer applications including digital multimedia (televisions, games consoles, Blu-ray and streaming music players), mobile computing (laptops, tablets and computer peripherals), mobile phones, printers and healthcare. There is hence the potential for a broad cross-section of consumers to be affected should the performance of WiFi receivers be degraded by interference from an adjacent band.

1.2 Research objectives

MASS's understanding of Ofcom's requirement for the proposed study was initially based on the information provided in the Invitation to Tender and clarification letters (Ofcom, 2013a-c). This understanding was refined subsequently in a series of formal and informal meetings with Ofcom staff.

The research was targeted to answer the following research questions:

1. What different WiFi devices are available in the UK market?
2. What is the effect of TDD LTE interference on WiFi receivers?
3. How does domestic WiFi equipment perform when compared to professional equipment installed in office networks or as commercial hot-spots?

1.3 Scenarios

The measurements made during the study have been interpreted in terms of five scenarios identified by Ofcom.

The following sections define a generic interference model which allows the measurements made in the RF chamber to be interpreted as a Minimum Separation Distance (MSD) for each scenario.

Ofcom are interested in the following types of installation:

1. Domestic installations in the home;
2. Outdoor public access points, e.g. BT Openzone access points on lamp posts and phone boxes;
3. Indoor public access points (managed), e.g. cafés, shopping centres and pubs managed by large network providers (Sky, O2, BT);

4. Indoor public access points (independent). As above but installed and maintained by independent business owners;

5. Enterprise networks.

It is assumed that categories 1 and 4 above will generally use the same kind of equipment, whereas categories 2, 3 and 5 will use corporate grade equipment.

The table below identifies the typical heights and ranges assumed for the WiFi Access Points (AP) and clients in each scenario.

The last column assigns new scenario numbers as the results of this study strongly suggested that it would be more appropriate to assess scenarios in a different way. See section 4.5 for more details.

Scenario	AP type	AP-Client distance	AP height	Client height	New scenario
1	Domestic AP	1 m – 5 m	1.5 m	1.5 m	A
2	Outdoor public AP	2 m – 50 m	Phonebox: 2 m Lampost: 5 m	1.5 m	C
3	Indoor public AP – managed	1 m – 10 m	1.5 m	1.5 m	B
4	Indoor public AP – independent	1 m – 10 m	1.5 m	1.5 m	B
5	Enterprise AP	1 m – 10 m	1.5 m	1.5 m	B

Table 1 : Scenarios of interest

1.4 Approach

Preliminary market research to establish the types and relative quantities of WiFi devices was carried out using a combination of literature search and speaking to vendors on an informal basis. The results of this activity are documented in section 2.

The majority of the study concentrated on obtaining measurements on representative WiFi devices with a view to providing evidence to support Ofcom's policy decision process. A series of tests was carried out to investigate the effect TDD LTE transmissions have on WiFi devices.

Using representative equipment in a suitable anechoic chamber a WiFi link was established using the DUT. The TDD LTE power was then ramped up until the WiFi throughput dropped. This was repeated several times using different TDD LTE waveforms and frequencies so that statistics could be built up to describe the interference cases to be expected in the real world. Additionally an enterprise test was carried out to see whether TDD LTE would impact the WiFi access points used in a typical business network. The test methods are described in section 3.

The results are given in section 4 and the overall conclusions of the study are in section 5.

2 MARKET RESEARCH

2.1 Growth of WiFi

The growth of WiFi services and devices has been clear to see and is well documented. Williamson *et al* (2013, p.7) described the "virtuous circle" between the availability of WiFi access, device availability and a shift in behaviour that has stimulated demand for more WiFi provision. They go on to identify a number of market drivers that will continue to stimulate this demand, including the rise in the number of portable computing devices, improving WiFi technology and a move towards mobile offload onto WiFi.

In 2010 the market research company In-Stat predicted that the number of WiFi devices would grow from over 500 million in 2009 to nearly 2 billion in 2014 (Market Wired, 2010). This is commensurate with Williamson *et al* (2013, p.9) who show the number of WiFi chipsets globally rising dramatically to over 1 billion in 2011.

In 2011 a survey of 1,000 UK adults showed that households had an average of 4.6 devices connected to a home WiFi network at any given time (Sawers, 2011). This demonstrates the extent to which UK households have become dependent on this technology. Businesses also rely increasingly on their WiFi networks, which is why testing of an enterprise network has been included in this study.

There are a wide variety of different types of WiFi device available in the UK. The categories of particular interest to this study are mobile computing devices, home routers, public hotspots and medical devices. The current state of the market and market trends in these market sectors are explored in the sections below.

2.2 Number of devices

There is no single source of data that gives a clear and accurate view of the number of WiFi devices currently in use in the UK. Figure 1 uses data from a number of sources to give an approximate indication of the numbers of devices. (Note that enterprise routers have been excluded as there is insufficient data to produce reliable estimates.)

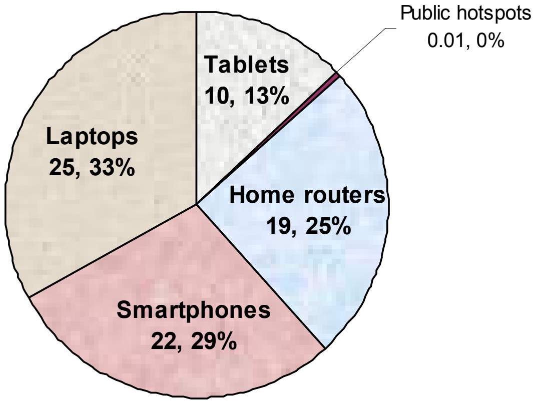


Figure 1 : Number of WiFi devices in the UK (millions, 2012)

It is clear that this picture is continually changing. The available evidence indicates that laptop sales have levelled off and that smartphone and tablet sales are continuing to increase.

2.3 Internet Service Providers (ISP)

Many of the main UK ISPs provide home routers to their subscribers. Although after-market routers are available, it is a reasonable deduction that ISP-supplied routers constitute the majority of home routers in the UK.

According to ISPreview (2013), the top ten UK ISPs by subscriber size are as follows:

ISP	Subscriber Size
BT (PlusNet)	6,704,000
Virgin Media	4,490,500
Sky Broadband (BSkyB)	4,387,000
TalkTalk (AOL, Tiscali, Pipex)	4,063,000
EE (Orange)	694,000
O2 (BE Broadband)	519,400
Kingston Comms (Eclipse, KC)	178,200
Zen Internet	94,000
THUS Group (Demon Internet)	87,000
Entanet	70,000 (estimated)

2.4 Dominant manufacturers

The following table shows the dominant providers of WiFi networking products in 2011 (TP-LINK, 2011).

Vendor	Market Share
TP-LINK	26.13%
NETGEAR	16.11%
D-Link	15.32%
Linksys	8.03%
Technicolor	7.01%

Apple currently dominates the UK tablet market. By August 2013, YouGov predicts that Apple will have a 67% share, equating to 6.8 million tablets, with Samsung increasing its market share to 10% (1.02 million tablets), (YouGov, 2012).

Canalys reports that the global mobile phone market, which currently stands at 438.1 million units per quarter, was flat year-on-year, while the worldwide smartphone market grew 37%. Android smartphones accounted for 34% of all phone shipments and iOS phones 11%. Smartphones now represent almost 50% of all the phones that shipped in Q4 2012. The two leading smart phone OEMs are Samsung (29.0% market share) and Apple (22.1%). The Chinese vendors, Huawei, ZTE, Lenovo and Yulong, are all gaining market share rapidly, while other vendors such as Blackberry, Microsoft and Nokia have strategies in place to increase their presence (Canalys, 2013).

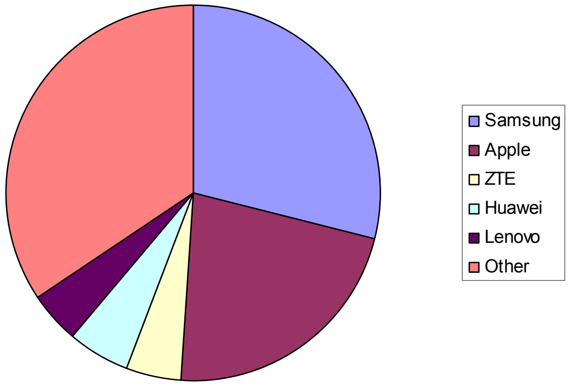


Figure 2 : Global smartphone market, Q4 2012

Broadcom is currently reported to dominate the WiFi chip market with a 62% share but this is predicted to drop to 51% by 2016 because of increased competition from Qualcomm, Mediatek and Samsung (Clarke, 2013).

2.5 Medical devices

The use of WiFi in medical applications is of particular interest to Ofcom and the study looked at including suitable devices that would be representative of this area. Wireless technologies have been used in healthcare for many years, but the rise of smartphones and tablets means the opportunities to do more wirelessly are proliferating (Malim, 2012).

However, there are relatively few WiFi devices targeted solely at the healthcare market. Examples of healthcare devices currently on the market include voice-over WiFi communication systems such as the Ascom 162 (Ascom, 2013), which is also marketed as a GE Healthcare product (GE, 2013a), and the Vocera hands-free communication system (Vocera, 2013).

GE Healthcare also offers an ECG device (GE, 2013b) which supports WiFi transmission of the ECG data to analysis software.

GE Healthcare is planning to market wireless patient-worn devices for use within hospitals to monitor serious complaints in a non-intrusive manner (Malim, 2012).

With relatively few medical WiFi devices identified, it was decided to concentrate on other types of WiFi device.

3 TEST METHOD

This section provides a summary of the test programme. Full details of the test methodology are provided in the Measurement Plan and Test Specification produced for the study (Pryor, 2013).

There are two main types of testing:

- **RF chamber tests** – in which the test conditions can be precisely controlled and measurements of receiver performance can be made with confidence in the absence of other signals that might otherwise affect the results.

- **Enterprise network tests** – in which the behaviour of WiFi receivers can be examined in a real world setting. The main question to be investigated is whether the presence of TDD LTE signals in the 2.3 GHz band could cause the Access Points (AP) in an enterprise network to automatically switch to other WiFi channels.

3.1 WiFi devices tested in this study

The scope of this study included selection of a minimum of 15 WiFi devices for testing which satisfy the following parameters:

- Devices under test (DUTs) should be representative of the current market deployment and application scenarios;
- DUTs should include examples of home routers, mobile phones, mobile computing applications, a medical device and outdoor / public hotspots;
- DUTs should cover all of the major chipset manufacturers.

Our choice of device was informed by Ofcom's Communications Market Report (Ofcom, 2012b), which provides statistics on the percentage of the UK population owning various types of WiFi device. This information was used to infer the number of each type of device that should be included in the study, as shown in the table below.

Device Type	Proportion of population owning device type	Normalised number of devices	Number of DUTs
Home Router (HR)	85%	4.8	4
Laptop (LP)	61%	3.4	2
Tablet (TB)	11%	0.6	2
Mobile Phone (MP)	39%	2.2	3
Multimedia Dongle (MD)	No data	1	1
Outdoor Hotspot (OH)	N/A	5	3
Medical[1]	N/A	0	0
Total		**17**	**17**

[1] Very few WiFi devices were found after searching the internet and speaking to suppliers of medical equipment. The medical category was removed after discussion with Ofcom. Many devices used in a medical context will share similar characteristics to those listed here and the results of the study will be applicable.

Where multiple devices of a specific type were selected for test (e.g. home routers and outdoor hotspots), the selected devices cover a broad range of pricing options and different WiFi chipset manufacturers.

3.2 Chamber testing

The tests were conducted using Ofcom's test facilities at the Baldock radio monitoring station (Figure 5) with the DUT inside the chamber and the majority of the test equipment outside.

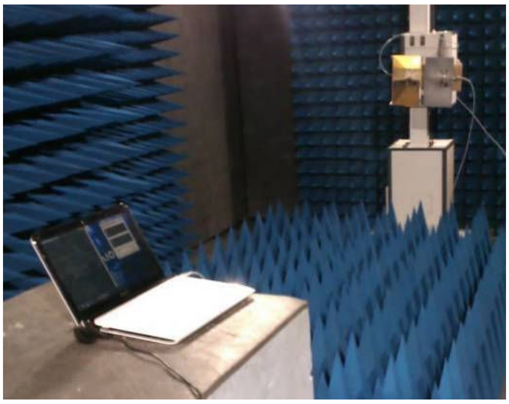


Figure 3: DUT in Ofcom's anechoic chamber

A series of tests were conducted to characterise the selected devices in terms of receiver selectivity and blocking in the presence of out-of-band CW emissions and the potential reduction in the performance of the device's WiFi receiver due to out-of-band LTE emissions.

In summary, this was achieved by establishing WiFi traffic with the device under test and then measuring the WiFi data throughput as the level of the CW or TDD LTE interference (on a different frequency) was varied. The reduction in the performance of the device's WiFi receiver is seen as a drop in the data throughput. A typical result is shown in Figure 4, which shows the WiFi throughput dropping as the C/I protection ratio dropped from -25 dB to -40dB.

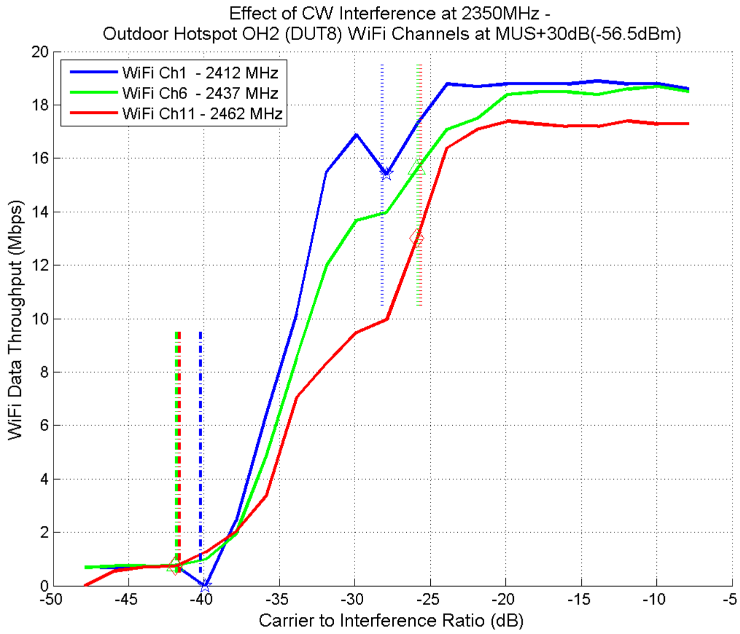


Figure 4 : Effect of CW interference on WiFi data throughput. The graph shows the WiFi throughput at different values of C/I protection ratio, which is the ratio of WiFi carrier power to interference power. Dot-dashed lines indicate 1 Mbps interference point and dotted lines indicate 90% interference points.

3.2.1 Test Configurations

Figure 5 shows the test configuration used for the RF chamber tests.

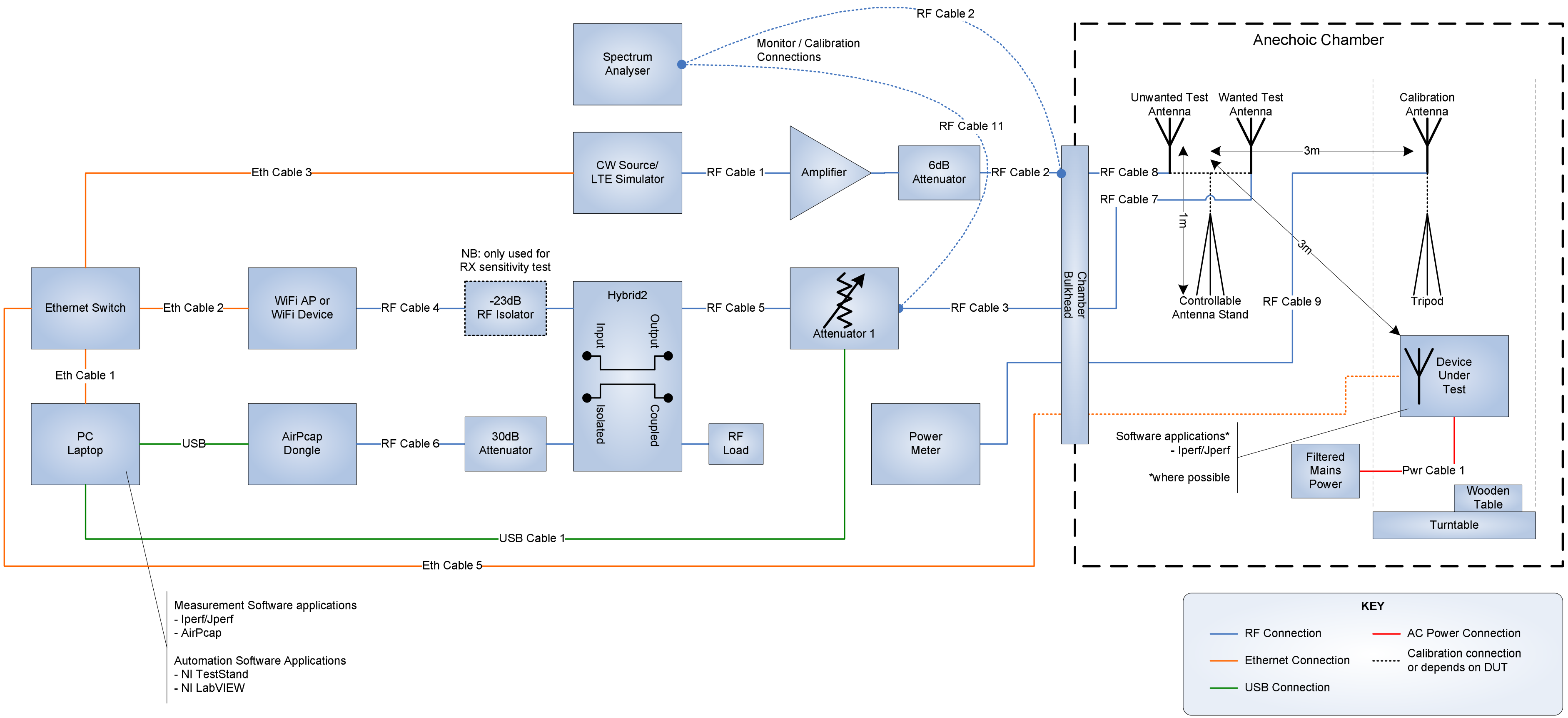


Figure 5 : Test configuration for RF chamber tests

3.2.2 Test Parameters

3.2.2.1 RF level at the DUT

The RF level at the DUT was defined as the power that would be received by an isotropic antenna at DUT location.

3.2.2.2 Wanted WiFi Signal

The term Minimum Usable Signal (MUS) is defined as the minimum magnitude of wanted WiFi signal required to produce a response in the DUT. In order to be able to identify the 1 Mbps throughput point the testing only terminated when the throughput went below 500 kbps.

Measurements on the DUT were conducted with the WiFi signal set to MUS+10dB, MUS+20dB and MUS+30dB. After testing several DUTs it was found that the MUS+10dB level was too low in most cases, so these results were discarded.

The analysis of the results aggregated the MUS+20dB and MUS+30dB results on the basis that these would form a sound basis on which to consider the effects of TDD LTE at the edge of a WiFi network and this is the viewpoint that is needed for network planning purposes.

3.2.2.3 CW Test Settings

The WiFi and CW settings for the blocking and selectivity tests are shown in Table 2:

WiFi Receiver Sensitivity	WiFi Channels	CW Frequencies
MUS +30dB	1, 6, 11	2350MHz, 2380MHz

Table 2 : LTE downlink frame structures used for testing

A block diagram of the test setup and the test parameters is shown in Figure 6.

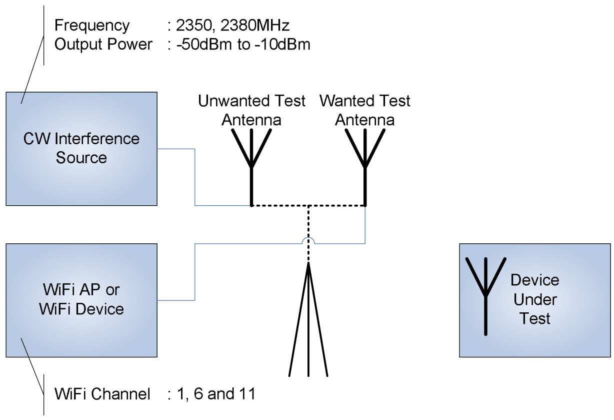


Figure 6 : Blocking and selectivity test setup

3.2.2.4 LTE Frame Structure

Figure 7 defines the frame structure for LTE TDD, where one radio frame is 10ms in duration and is divided into 10 standard or special sub-frames each of 1ms. Standard sub-frames consist of uplink or download data while special sub-frames consist of the three fields:

- DwPTS – Downlink Pilot Time Slot
- GP – Guard Period
- UpPTS – Uplink Pilot Time Slot

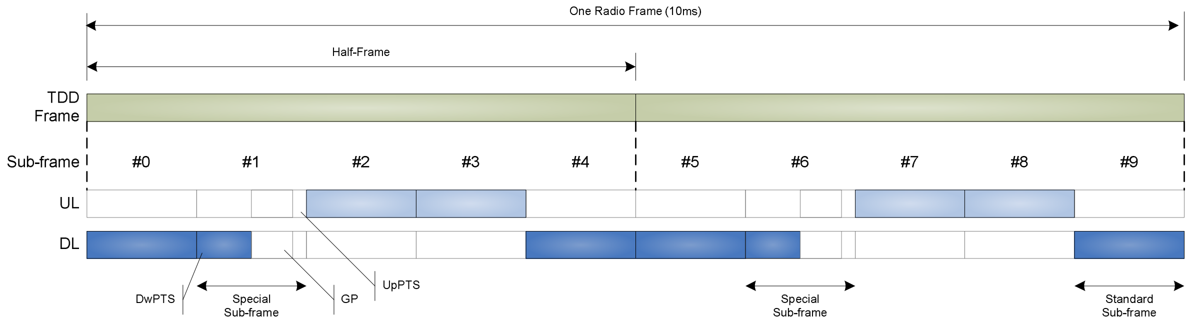


Figure 7 : LTE TDD frame structure

LTE TDD defines a finite number of uplink and downlink configurations these are given in Table 3 where:

- D – a sub-frame used for downlink transmission
- S – is a special sub-frame used for guard time to separate uplink and downlink transmissions
- U – is a sub-frame for uplink transmission

UL/DL Configuration	DL/UL Switch Periodicity	Sub-frame Number									
		0	1	2	3	4	5	6	7	8	9
0	5ms	D	S	U	U	U	D	S	U	U	U
1	5ms	D	S	U	U	D	D	S	U	U	D
2	5ms	D	S	U	D	D	D	S	U	D	D
3	10ms	D	S	U	U	U	D	D	D	D	D
4	10ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5ms	D	S	U	U	U	D	S	U	U	D

Table 3 : LTE sub-frame allocations

Each sub-frame divides into two slots. The smallest modulation structure in LTE is the Resource Element. A Resource Element is one 15 kHz sub-carrier by one symbol. Resource Elements aggregate into Resource Blocks. A Resource Block has dimensions of sub-carriers by symbols. Twelve consecutive sub-carriers in the frequency domain and six or seven symbols in the time domain form each Resource Block. This relationship between LTE slot, symbol and resource block is given in Figure 8.

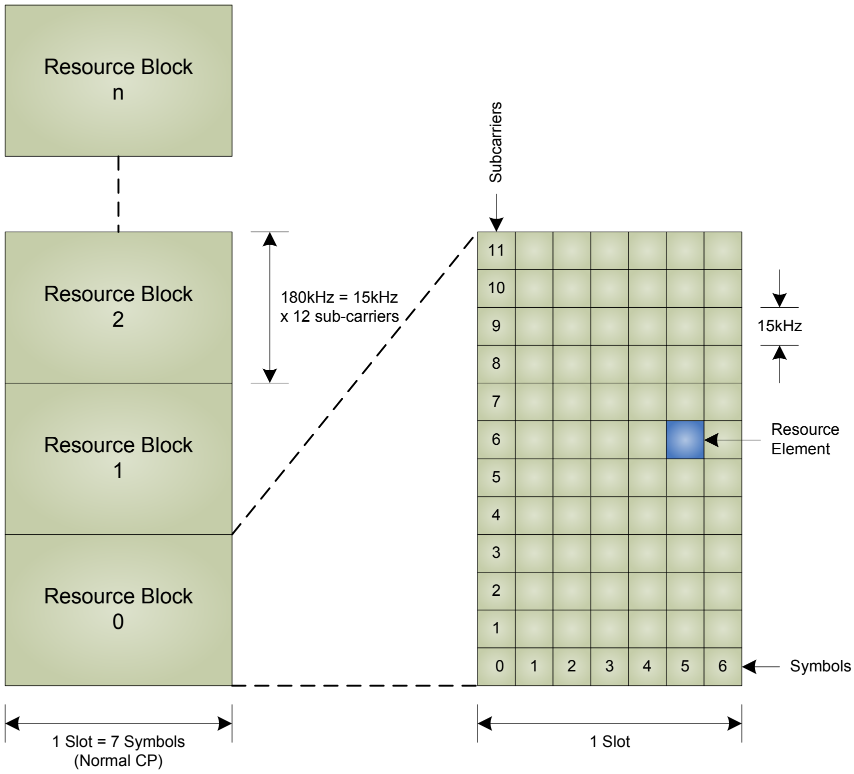


Figure 8 : Relationship between LTE slot, symbols and resource blocks for a DL

3.2.2.5 LTE Frame Structures Used for Testing

Four frame structures were used for testing, two for uplink and two for downlink frames, as shown in Table 4.

The uplink and downlink sets include both a minimum and a maximum loaded frame for a single User Equipment (UE).

The rightmost columns give the duty cycle of each waveform estimated in two different ways. Further work is needed to determine which estimate of duty cycle correlates most accurately with the impact on WiFi receivers.

- Duty cycle A - These duty cycles were calculated from the measured average power level reductions compared to the CW reference. This is the estimate used in the remainder of this report.

- Duty cycle B – This is ratio of the number of time slots used to the total number of time slots in the frame.

ID	Waveform File	B/W	DL/UL	Frame Information	DL/UL Configuration	Payload	Special Subframe Configuration	Duty cycle A	Duty cycle B
UL#1	UL20MHz_c0_v1	20MHz	UL	One UE with PRBS, 6 loaded UL slots, RB allocations including PUSCH, PUCCH	0 (DSUUUDSUUU) Maximum UL loading	PN23 Scrambled QPSK Modulation	0	59%	80%
UL#2	UL20MHz_c5_v1	20MHz	UL	One UE with PRBS, 1 loaded UL slots, RB allocations including PUSCH, PUCCH	5 (DSUDDDDDDD) Minimum UL loading	PN23 Scrambled QPSK Modulation	0	10%	20%
DL#1	DL20MHz_c5_v1	20MHz	DL	One UE with PRBS, 8 loaded DL slots, RB allocations including PBCH, PDCCH, PDSCH	5 (DSUDDDDDDD) Maximum DL loading	PN23 Scrambled QPSK Modulation	0	95%	90%
DL#2	DL20MHz_c0_v1	20MHz	DL	One UE with PRBS, 2 loaded DL slots, RB allocations including PBCH, PDCCH, PDSCH	0 (DSUUUDSUUU) Minimum DL loading	PN23 Scrambled QPSK Modulation	0	26%	40%

Table 4 : LTE frame structures used for testing

3.2.2.6 LTE Test Settings

The WiFi and LTE settings for the LTE out-of-band (OOB) tests are shown below:

WiFi Receiver Sensitivity	WiFi Channels	LTE Channel Bandwidth	LTE Frequency Offsets	LTE Frame Structure
MUS +20dB	1	20MHz	2412MHz (co-channel)	UL_C0, UL_C5, DL_C0, DL_C5
MUS +10dB, +20dB, +30dB	1	20MHz	2380MHz	UL_C0, UL_C5, DL_C0, DL_C5

Table 5 : LTE Test Settings

A block diagram of the test setup and the test parameters is shown in Figure 9.

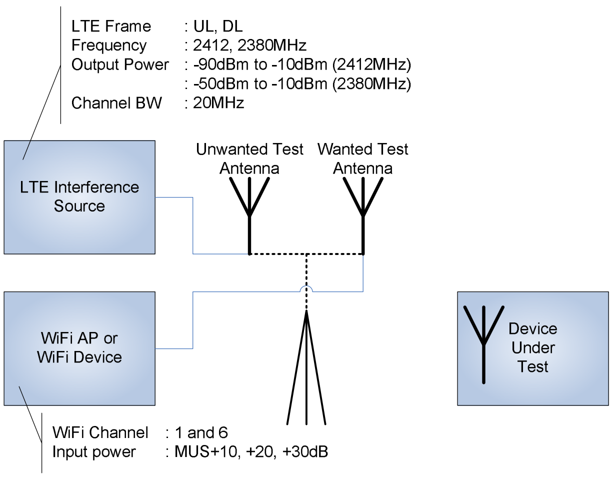


Figure 9 : LTE OOB test setup

3.2.3 Test Procedure

The general test procedure was as follows:

1. General configuration set-up;
2. Measure unwanted power at DUT location;
3. Measure wanted power at DUT location;
4. Measure WiFi output level at 100% with isolator in place. The isolator was used for the MUS measurement to ensure that the power levels at the DUT were sufficiently low;
5. Establish polarisation characteristics (horizontal / vertical) of DUT;
6. Orient the DUT in the chamber by rotating until the highest emitted WiFi level is achieved;
7. Measure WiFi DUT receiver sensitivity by running the automated test script. Check that the measured value is within acceptable bounds;
8. Calculate MUS, interference loss and carrier loss and record attenuator settings;
9. Conduct LTE out-of-band tests by running the automated test script. Check that the plateau data throughput is within acceptable bounds;
10. Conduct CW blocking and selectivity tests by running the automated test script.

Tests were conducted on a device-by-device basis, so the full range of tests was completed on a device before moving onto the next device.

3.2.4 Test Automation and Control

3.2.4.1 Measurement of WiFi Data Throughput

Iperf was used for measuring TCP/IP throughput for all devices. Various means were used to create TCP data streams to the DUT with Iperf used to measure the data throughput.

As a check on Iperf, the tests also included AirpCap monitoring of the throughput at the MAC layer. In the case of DUT 16 it was not possible to run Iperf so AirPcap was used instead.

3.2.4.2 Automation Software

Since the tests require variation of a large number of parameters, it was decided to automate the tests to optimise the test speed, accuracy and repeatability.

Three test sequences were produced to automate the test programme:

- WiFi receiver sensitivity: determines the minimum usable sensitivity for the DUT. The output of the test sequence is the maximum attenuation to the wanted signal that can be applied before data throughput falls to zero;
- CW blocking and selectivity test: measures the DUT’s sensitivity to CW interference. The test is conducted on multiple WiFi channels with various interference signal frequencies and power levels;
- LTE out-of-band test: measures the DUT’s sensitivity to LTE signal interference. The test is conducted on multiple WiFi channels with various interference signal frequencies, LTE waveforms and power levels.

3.3 Enterprise test

A series of tests were performed at a corporate head office on Thursday July 4th 2013 between 6pm and 10pm.

A specific victim access point was illuminated with a simulated LTE BS transmission using a horn antenna located approximately 3 m distant (Figure 10). The victim access point was set to WiFi channel 1 (2,412 MHz) as part of a planned deployment.

The test equipment was located approximately 5 m away in a shielded position.

Figure 10 : WiFi AP tested (circled) showing arrangement of test antennas

The power density at the victim access point was measured with an additional horn antenna and power meter for calibration purposes.

An obstructed path existed for the wanted WiFi connection to test the WiFi device. The precise level could not be measured but it was representative of typical WiFi levels.

The interference frequencies were 2,350 MHz and 2,380 MHz with a modulation corresponding to a 20 MHz downlink C5, which has a high duty cycle.

Iperf was used to measure the WiFi throughput from client laptop to server PC.

It was observed that the expected reduction in throughput with applied interference was present.

The results of the enterprise test are given in section 4.6.

4 RESULTS

This section explains the results obtained from the testing. The detailed results are available in a separate document (MacDonald, 2013).

Measurements were made at WiFi levels of MUS+10dB, MUS+20dB and MUS+30dB. The MUS+10dB results have not been included in this analysis as the WiFi devices did not generally show repeatable, reliable performance and were therefore deemed to be outside their normal usable operating parameters.

The first step in evaluating the results was to define the points at which interference from TDD LTE affects WiFi. These 'interference points' are described in section 4.1. There are two points of interest to Ofcom, which are the point at which interference just starts to have a noticeable impact (90% throughput) and the point at which the WiFi throughput is reduced to 1 Mbps.

An understanding of the performance characteristics of WiFi receivers helps to explain the behaviour of WiFi links in the presence of interference. Section 4.2 explains that this behaviour is not a simple one, but that blocking is a suitable first order model.

In section 4.3 the interference points are shown to be affected by the difference in centre frequencies of the two signals and by the TDD LTE frame structure.

Given that the WiFi receiver performance is not simple but may be approximated by a blocking model, section 4.4 gives summaries of the results in terms of the TDD LTE power levels required to disrupt the WiFi to both of the two interference points.

Section 4.4 presents the overall results in the form of a series of boxplots. These show the statistics of the TDD LTE power required to produce interference in a WiFi link.

The boxplots from section 4.4 are interpreted in section 4.5 as Minimum Separation Distances (MSD) and related to the scenarios of interest to Ofcom.

4.1 Interference points

The results of the testing have been considered in terms of two interference points which are defined as:

- 90% - The level of interference from the TDD LTE at which there is starting to be a noticeable impact on the WiFi link is defined as the point at which the WiFi link throughput falls below 90% of that observed in a non-interfered state[2].

- 1 Mbps – The level of interference from TDD LTE at which the WiFi link is no longer usable is defined as the point at which the WiFi throughput falls below 1 Mbps.

These two points are shown on Figure 11 which shows four tests on a single DUT. Here the C/I protection ratio has been varied in 2 dB steps and the corresponding steady-state WiFi throughput has been plotted.

[2] The 90% point was determined in each case by finding the C/I protection ratio at which there have been two successive throughput measurements below the maximum throughput in the given test. In some cases the 90% points were determined by eye, as the data was too noisy for the automatic algorithm to handle

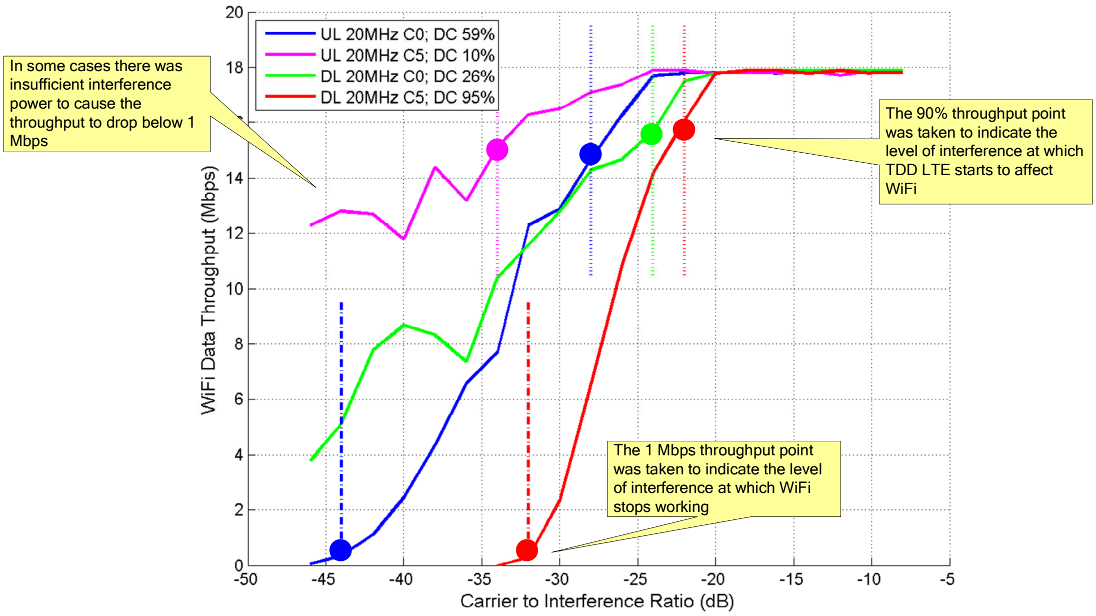


Figure 11 : WiFi throughput versus C/I ratio showing the 1 Mbps and 90% points that were taken as the key indicators of interference for this study (DUT 7)

Observations from looking at the interference points include the following:

1. Both interference points occur across a range of C/I ratios. In some cases these ranges are wide enough to cause an overlap between the 90% and 1 Mbps points. This means that for some DUTs a change in the TDD LTE signal structure, without any change in the power relationships, can be sufficient to make the difference between a working WiFi link and one that doesn't work at all;

2. The interference points are affected by the difference in centre frequencies of the TDD LTE and WiFi. This relationship cannot be seen in Figure 11, but is examined further in section 4.3 using a different set of graphs.

4.2 Receiver behaviour in the presence of interference

The WiFi receivers studied did not behave in a simple, linear manner, a fact that is readily seen by considering the example shown in Figure 12. This shows the carrier and interference levels at the 1 Mbps point for one of the DUTs.

Dashed lines have been drawn on the graph to show the slope that would be seen if the receiver were behaving in an idealised linear way or purely blocking way. If the receiver were linear then a 1 dB rise in the WiFi carrier power level would require a corresponding 1 dB rise in the TDD LTE power level to see the same WiFi performance. If the receiver were behaving in a purely blocking manner then only the TDD LTE power level would matter and the WiFi throughput would not be changed by an increase or decrease in the WiFi power level.

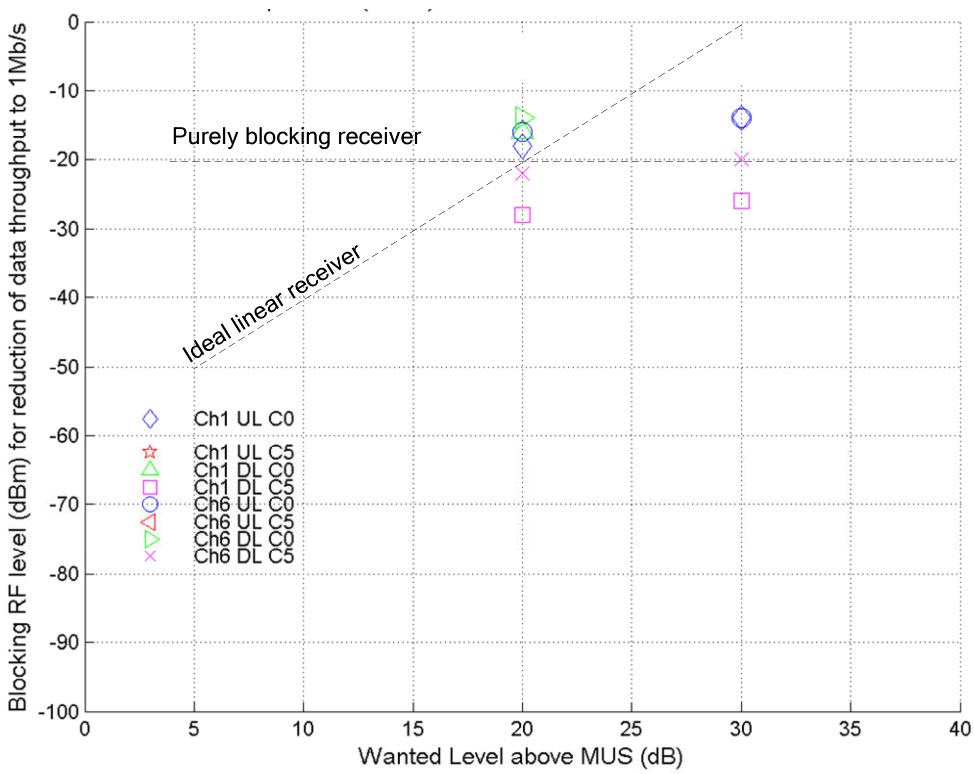


Figure 12 : Example of relationship between interference and carrier levels showing that the relationship is neither ideally linear nor purely blocking at the 1 Mbps point (DUT 7)

In the example here it is clear that the receiver is neither purely linear nor purely blocking, rather it is somewhere between the two. This was generally the case, although there were examples where the slope went above one or below zero. To expand on this argument, Figure 13 shows the line slope data as a histogram. Looking across all the DUTs it was found that the DUT receiver performance was about half way between the two behaviours with a median slope on the graph of 0.4. Blocking is the simpler of the two models so is preferred for first order modelling purely on the grounds of simplicity.

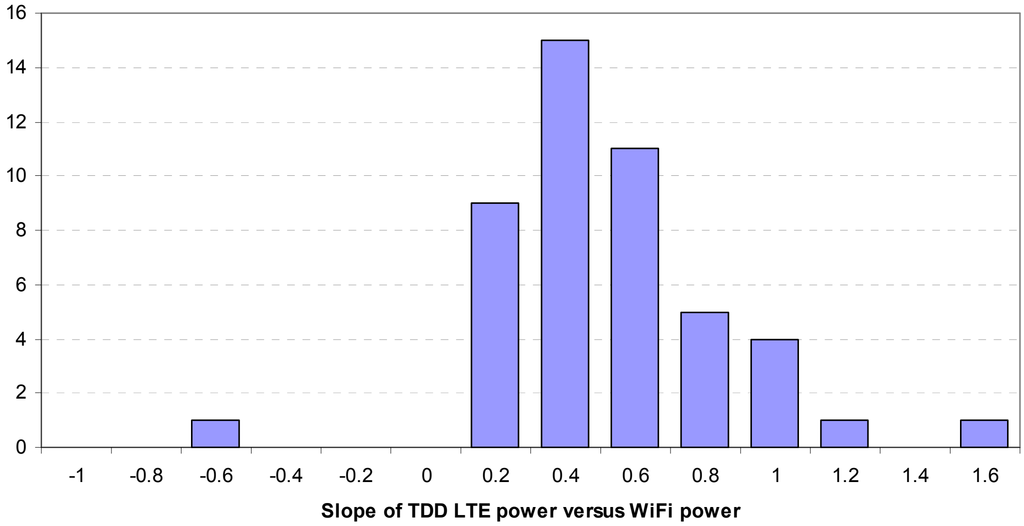


Figure 13 Histogram of line slopes showing that the median slope is 0.4, indicating WiFi receiver tending towards blocking rather than linear behaviour

As a first order model, then, a blocking model was used to gauge the effects of TDD LTE on WiFi. This is a first order model and it is expected that there will be scenarios in which the WiFi signal strength should also be accounted for by using a model that combines the two types of behaviour.

4.3 Effect of frequency offset and frame structure

The impact of TDD LTE on WiFi is partly dependent on the difference in frequencies between the two signals and partly on the frame structure of the interfering TDD LTE. To investigate these effects and having established that blocking is a reasonable first order model, attention is now focussed on the level of the interference signal, with the level of the WiFi signal put to one side for now.

For each DUT the level of the TDD LTE signal has been plotted in Figure 14 against the difference in centre frequency between the TD LTE and WiFi signals. This has been done for both interference points. In Figure 14 all the results for a single DUT operating on WiFi channels 1 and 6 have been combined.

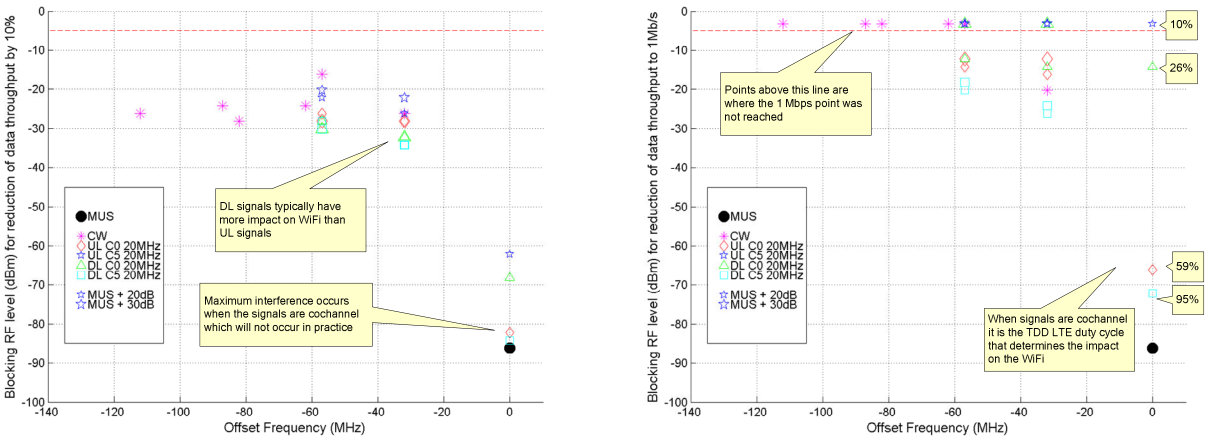


Figure 14 : Interference level versus offset frequency at 90% and 1 Mbps points (DUT 7)

A number of observations can be made from examining these plots:

1. The co-channel case is only given for reference as TDD LTE will not operate co-channel with WiFi in practice;

2. In general the DL signals have more effect on the WiFi than the UL signals. We attribute this mainly to the higher duty cycles of the DL signals compared to the UL signals. At lower duty cycles it will be possible for WiFi frames to be passed successfully. The detailed mechanisms will be more complex than this and are outside the scope of the current study and we have not investigated the detailed behaviour of the WiFi Medium Access Control (MAC) protocol in the presence of TDD LTE.

3. When the two are co-channel then there will be the maximum impact of TDD LTE on WiFi. This can be seen in Figure 14 where the TDD LTE power level needed to disrupt WiFi is usually relatively low and typically less than 20dB above the WiFi MUS;

4. For frequency offsets greater than 50 MHz it is reasonable to assume that the results will be similar to the 57 MHz offset. The frequency response beyond this is relatively flat, as indicated by the CW test points.

5. The transition to the co-channel frequency case is a gradual one and starts to set in when the separation in centre frequencies is less than 40 MHz. The slope of the curve is due to a combination of the OOB characteristics of the TDD LTE as seen by the WiFi receiver and the selectivity of the WiFi receiver. Figure 14 does not reveal which effect is the more significant of the two;

6. Another observation about the co-channel case is that the duty cycle of the TDD LTE determines the amount of impact on the WiFi. On the right hand graph in Figure 14 the four rightmost points show the duty cycle varying from 10% to 95%. The most likely explanation for this effect is that the WiFi link can ‘see through’ the TDD LTE when the duty cycle is low and thereby carry on delivering user traffic.

4.4 Interference power statistics

In this section we consider the statistics of the TDD LTE power levels that cause disruption to WiFi. It is assumed that the WiFi receiver is exhibiting predominantly blocking behaviour, as discussed in section 4.2. The amount of interfering power required varies from device to device and depends on the TDD LTE frame structure, so the results of the tests are given as boxplots to indicate the statistical distributions that may be encountered in the real environment.

4.4.1 All DUTs

Figure 15 summarises the results by showing the distribution of the TDD LTE power levels for all the DUTs at two frequency offsets. The horizontal axis shows the TDD LTE power required to cause the given level of interference.

Figure 15 shows the results at the 90% throughput point and also the 1 Mbps point.

The results are shown as boxplots which indicate the minimum, maximum, median and the quartiles.

The following important points should be noted:

1. All the measurement data from WiFi levels of both MUS+20dB and MUS+30dB have been aggregated in the DL boxplots and all the TDD LTE waveform results have been included.

2. All the measurement data from WiFi levels of both MUS+20dB and MUS+30dB have been aggregated in the UL boxplots, but only the low duty cycle measurements have been used. The reason for this is that individual TDD LTE User Equipment (UE) devices are expected to be occupying a single uplink channel and it is the device nearest to the WiFi receiver that is important for interference assessment purposes.

3. Measurements at MUS+10dB have not been used as these did not represent stable operating conditions for a WiFi network. The data used in Figure 15 should therefore be interpreted as our best estimate for how the outer edge of a WiFi Access Point (AP) coverage area will be affected by TDD LTE.

Also shown in the figures are Minimum Separation Distance (MSD) axes. These are estimates of the separation required to prevent interference at the given interference point. They are based on the assumptions of a TDD LTE BS with +60dBm EIRP for the DL boxplots and a TDD LTE UE with +23dBm EIRP for the UL boxplots. Ofcom understands that TDD LTE BS EIRPs may be as high as +67dBm, so there may be cases where the MSDs will be longer than indicated here.

Three scales are given with path loss exponents of 2 and 3.3, which are described in section 4.5. A path loss exponent of 2 corresponds to line of sight and 3.3 is for open office environments.

Observations on Figure 15 include:

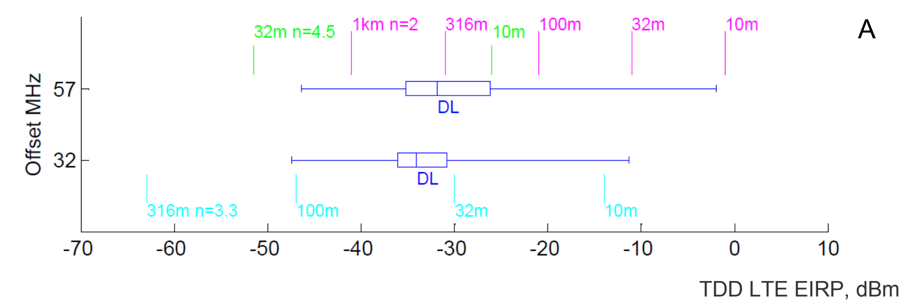
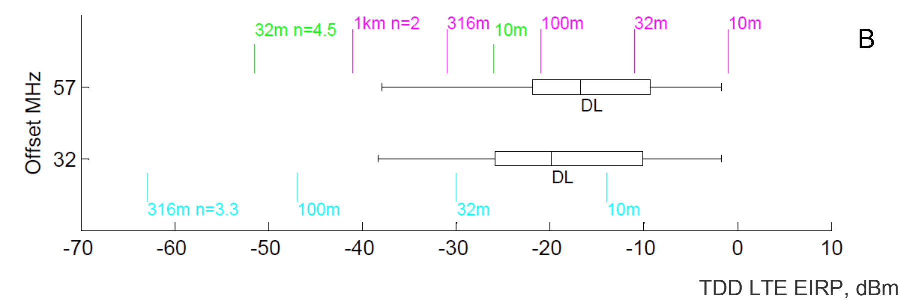
1. As expected the median TDD LTE power level needed to cause complete disruption of the WiFi link (i.e. 1 Mbps) is higher than the level at which the WiFi throughput is reduced to 90%. This difference is about 15 dB for the DL results and about 25 dB for the UL results;

2. There is over 30 dB variation between the minimum and maximum TDD LTE power levels in all of the boxplots. The interquartile ranges are much smaller, typically less than 20 dB;

3. The TDD LTE powers range down to below -60 dBm and up to nearly 10 dBm. In general it is the lower ends of the ranges that are of interest as these give the minimum power needed to cause interference. We recommend concentrating on the lower quartile points which indicate where 75% of WiFi devices will be protected at the estimated range. (As an aside, a value such as 90% would be a more commonly accepted statistic, but there are insufficient measurements to estimate this reliably.)

4. In the line of sight case (n=2) the MSD ranges from less than 10 m to more than 1 km. With this very wide range of MSDs it is worth understanding the scenarios in greater detail.

<table>
<tr><th>TDD LTE link</th><th>Interference Point</th><th>TDD LTE power required to give rise to WiFi interference</th></tr>
<tr><td rowspan="2">Downlink

(+60 dBm)</td><td>90% Throughput</td><td>
</td></tr>
<tr><td>1 Mbps</td><td>
</td></tr>
<tr><td rowspan="2">Uplink

(+23 dBm)

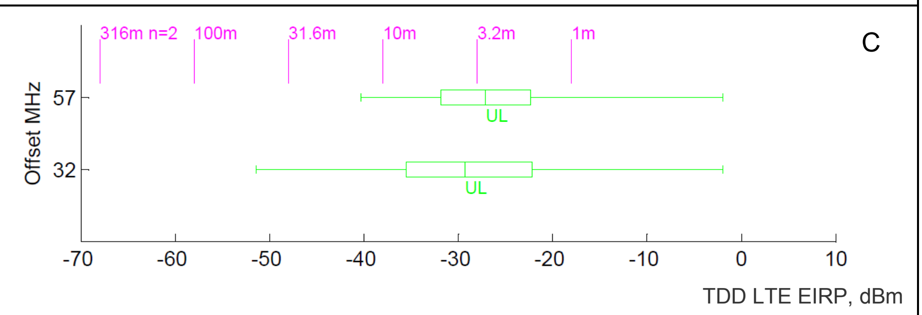
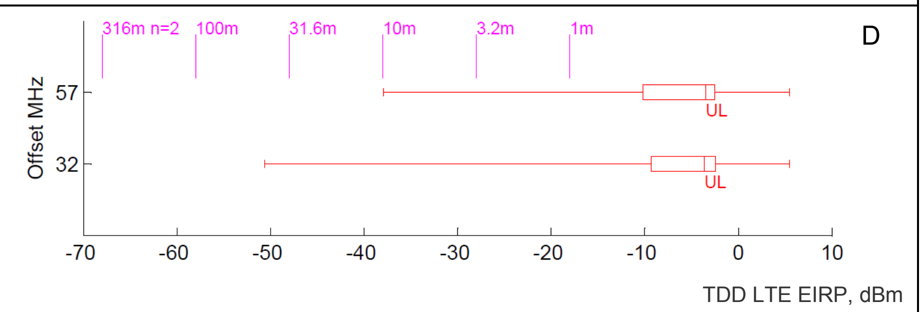
(Low duty cycle only)</td><td>90% Throughput</td><td>
</td></tr>
<tr><td>1 Mbps</td><td>
</td></tr>
</table>

Figure 15 : TDD LTE power levels causing disruption to WiFi (all DUTs)

4.4.2 Types of DUT

The measurements from all of the DUTs have been grouped by type (home router, laptop, tablet, mobile phone, multimedia dongle and outdoor hotspot) and analysed using a similar process to that in section 4.4.1. No significant differences in interference performance were found between the different types of WiFi device.

There was a specific research question (section 1.2) that asked how domestic WiFi equipment performs when compared to professional equipment installed in office networks or as commercial hot-spots. The evidence from the measurements did not support the hypothesis that there would be a difference in performance between these devices. The power distributions given in Figure 15 apply to both types of device as well as to the other types of WiFi device investigated in this study.

4.5 Interpretation of scenarios

Five scenarios of interest to Ofcom were outlined in section 1.3. These can now be examined in terms of the evidence gleaned from the chamber measurements.

We concentrate here on the lower quartiles of the boxplots in Figure 15 as these give the probability that interference will occur in no more than 25% of cases, which is a reasonable criterion given the amount of measurement data available.

Figure 15 shows MSD scales for two different values of the path loss exponent, n. These have been taken from the following table which has been compiled from a variety of references including Rubicon (2004), Cisco (2013) and Cebula III *et al* (2013).

Path loss exponent	Environment
1.6 to 1.8	In-building line of sight (<10m)
2	**Free space, outdoor**
2 to 3	Obstructed in factories
2.7 to 3.5	Urban area cellular radio
3 to 5	Shadowed urban cellular radio
3.3	**Open office**
3.5	Indoor office
3.7 to 4.0	Dense commercial or industrial
4 to 6	Obstructed in building
4.5	**Home environment (>10m)**

Table 6 : Path loss exponents for WiFi operating in different environments

Initial major assumptions are that:

(a) The TDD LTE transmitter and WiFi receiver are copolarised;

(b) There is no pointing loss due to the transmit and receive antennas being misaligned.

(c) The aggregation of MUS+20dB and MUS+30dB within the Figure 15 boxplots is an appropriate representation of the outer edge of a WiFi AP coverage area. This is believed reasonable as the MUS+10dB points were not included, these being seen as being outside the area where users would get adequate performance to perform their tasks.

With these assumptions and using the boxplots in Figure 15 the scenarios are now analysed to determine the MSD values that are predicted to apply at both interference points.

1. Domestic installations in the home

   At the relatively short WiFi ranges of below 5 m of interest to Ofcom WiFi links should be regarded as line of sight, so a path loss exponent of 2 (or less) should be used when interpreting Figure 15. At longer ranges (>10m) the higher path loss exponent of 4.5 should be used to account for additional losses due to obstructions in indoor environments.

   Figure 15 assumes that a TDD LTE UE will only be transmitting on the lowest duty cycle. Whilst other time slots may be occupied by other devices it is reasonable to assume that the nearest UE will dominate the interference scenario.

   If a TDD LTE UE is brought into the house it may be trying to communicate to a distant BS through the walls of the house, in which case it may reasonably be assumed that it will sometimes be transmitting at its maximum EIRP of +23dBm.

   Using boxplot C (57 MHz) in Figure 15 if the TDD LTE power is less than -36 dBm then this will be sufficient to prevent this UE interfering with a WiFi device in the house in more than 75% of cases. This would require approximately 5 m separation between the UE and the WiFi device.

   Achieving 5 m separation will not always be realistic in the domestic environment, so it is expected that there is the potential for significant interference in this scenario. Looking at boxplot D (57 MHz) in Figure 15 then the UE would have to be much less than 1 m from the WiFi receiver to actually stop the WiFi link and would probably never do so.

   Decreasing the frequency separation from 57 MHz to 32 MHz would increase the MSD from about 5 m to about 7 m at the 90% throughput point but would make virtually no difference at the 1 Mbps point.

   Holding a TDD LTE UE very close to a WiFi device may reduce the WiFi throughput significantly but will not normally stop it completely.

   Another scenario that may be of interest here is that of a TDD LTE BS radiating into the home. Here we assume a propagation index of 4.5 to allow for the additional losses due to obstacles. The corresponding MSDs would then be in the order of 15 m for the 90% point (boxplot A) and 8 m at 1 Mbps (boxplot B).

2. Outdoor public access points, e.g. hotspot operator access points on lamp posts and phone boxes

   It is assumed that a WiFi user is in the street and connecting to a public AP within line of sight. With ranges of 2 to 50 m in outdoor scenarios, a path loss exponent of 2 should be used. At greater ranges this should be increased to 3.

   It is further assumed that the main interferer is likely to be a public TDD LTE BS operating at an EIRP of +60 dBm.

   At typical ranges considered here the height of the BR antenna will have a negligible effect on the interference scenario, so has not been included in the calculations.

   Using boxplot A (57 MHz) in Figure 15 the TDD LTE power needs to be below -36 dBm to prevent the BS interfering with a WiFi device in more than 75% of cases.

This would require approximately 500 m separation between the UE and the WiFi device.

Achieving 500 m separation will not always be realistic in an urban environment. Looking at boxplot B (57 MHz) in Figure 15 the MSD needs to be in the order of 120 m to avoid completely stopping a WiFi link.

Decreasing the frequency separation from 57 MHz to 32 MHz would have no significant effect on the MSD at the 90% interference point, so the MSD would still have to be in the order of 500 m. At the 1 Mbps point the MSD would increase from about 120 m to about 200 m.

A WiFi user accessing an outdoor public AP in the street is therefore likely to experience noticeable reduction in throughput if they come within 500 m of a TDD LTE BS.

3. Indoor public access points (managed), e.g. cafés, shopping centres and pubs managed by large network providers

It is assumed that the WiFi user is using a managed public AP and that there are two potential interference scenarios. The first is from TDD LTE UEs operating in the same area, the second is from a TDD LTE BS with coverage into the public space.

Scenario 3.1 – UE UL

This a short range scenario and a path loss exponent of 2 has been used.

The interpretation of the boxplots is the same as scenario 1, and the MSD is taken to be 5m at the 90% point and 1m at the 1 Mbps using an exactly similar analysis.

Scenario 3.2 – BS DL

Here the operating ranges are likely to be further in a public space so we have used the path loss exponent of 3.3.

Using boxplot A (57 MHz) in Figure 15 the TDD LTE power needs to be below -36 dBm to prevent the BS interfering with a WiFi device in more than 75% of cases at the 90% interference point. This would require approximately 50 m separation between the BS and the WiFi device.

Referring to the lower quartile of boxplot B (57 MHz) gives an MSD of less than 20 m for the 1 Mbps interference point.

The implication is that there would be a radius of 50 m around a TDD LTE BS within which WiFi users may experience difficulty with using a public hotspot and if they come to less than 20 m it is likely that the WiFi service will not be usable.

4. Indoor public access points (independent). As above but installed and maintained by independent business owners

As explained in section 4.4.2 the results of the measurements made in this study do not support the hypothesis that there is a significant difference in interference resistance between access points manufactured for different purposes.

We therefore assert that scenarios 3.1 and 3.2 are equally representative of scenario 4.

5. Enterprise networks

As explained in section 4.4.2 the results of the measurements made in this study do not support the hypothesis that there is a significant difference in interference resistance between access points manufactured for different purposes.

We therefore assert that scenarios 3.1 and 3.2 are equally representative of scenario 5.

To summarise the above discussions the table of scenarios is given below with the MSDs. Scenarios 1, 3, 4 and 5 have been replaced by indoor DL and UL scenarios, A and B, which better match the evidence from our measurements. Scenario 2 has been renamed C.

Scenario	WiFi network / TDD LTE	AP-Client distance	AP height	Client height	MSD 90%	MSD 1 Mbps
A (1)	Indoor WiFi / UE UL	1 m – 5 m	1.5 m	1.5 m	5 m	1 m
B (3,4,5)	Indoor WiFi / BS DL	1 m – 10 m	1.5 m	1.5 m	50 m	20 m
C (2)	Outdoor WiFi / BS DL	2 m – 50 m	Phonebox: 2 m Lampost: 5 m	1.5 m	500 m	120 m

Table 7 : Summary of scenarios with results

These results are supported by the evidence of the measurements made in the chamber as part of this study. They are, however, somewhat pessimistic because of assumptions (a) and (b) above. The measurement results could be adjusted to deal with both of these issues.

Polarisation mismatch

Mismatch of linearly polarised antennas can be modelled using the Polarisation Loss Factor, L_P, as a function of the misalignment angle, θ.

$$L_P = 20 \log_{10}(| \cos(\theta) |)$$

Taking the median of this function over the range 0º to 90º gives a value of 3 dB. This could be subtracted from the link budget to allow for the case where it is not known what orientation the two antennas will be at.

Similarly the boxplots could be stretched to allow for the extra uncertainty in polarisation mismatch.

Antenna misalignment

The TDD LTE antenna is unlikely to be facing the maximum gain of the WiFi receive antenna, so again the measurement results are expected to be erring on the pessimistic side.

It would be possible to put all the DUTs through the chamber again and measure their receive antenna patterns. This would produce another factor to be subtracted from the link budget. WiFi devices do not generally have high gains, so the benefits of such an exercise are not expected to merit the cost of doing so.

As with the polarisation mismatch the boxplots could be stretched to allow for the extra uncertainty in receive antenna gain in the direction of the TDD LTE transmitter. The variation is not expected to be high enough to merit carrying out the tests.

Increasing WiFi level

The case has been made above that the blocking model is a reasonable first order model for the WiFi receivers considered in this study. It is however also true that there will be scenarios in which it will be practical to move a WiFi client closer to its AP to increase the WiFi signal strength at each receiver. Where this is possible there will be some advantage to be gained.

At shorter WiFi ranges a simple rule would be that an increase in WiFi level of 20 dB would increase the blocking level by approximately 10 dB. This would lead to a corresponding decrease in the MSD.

4.6 Results of enterprise test

The test equipment setup is given in section 3.3.

General interfering power check

The WiFi AP was subjected to varying levels of simulated TDD LTE downlink traffic in a configuration that was as close to a replication of the chamber tests as possible.

The required interference levels obtained corresponded approximately to those measured in the chamber, but there were large variations across the tests. These large variations were attributed to the difficulties of maintaining stable levels of both WiFi and TDD LTE in an open uncontrolled radio environment where there were other signals out of the control of the test team.

It was therefore concluded that the test setup was sufficiently representative of a real environment to proceed with the main objective of the test, which was to determine the channel selection of the WiFi AP in the presence of TDD LTE.

WiFi AP configured for fixed channel operation

In the above tests the WiFi AP was configured to use channel 1. During the tests none of the devices moved to a different WiFi channel, even when the TDD LTE signals were strong enough to completely stop the WiFi link. In this respect, the WiFi AP functioned as expected.

WiFi AP configured for automatic channel selection

By setting the victim WiFi AP to automatic channel selection mode and applying TDD LTE interference during the initialisation process it was possible to cause the AP to change channel.

The following observations relate to this particular WiFi Access Point only. Other units may behave differently:

1. It was necessary to configure the unit to ‘Automatic’ channel mode to allow the AP to change channels;
2. Automatic channel selection occurred only on power up initialisation;
3. The AP’s channel changes were not consistent with the victim AP moving to three different channels during the tests;
4. Data throughput after switching channels was greatly reduced from the non-interference state and so the change of channel provided no significant benefit.

> This result is commensurate with the observation in the chamber that blocking behaviour is the predominant mode seen in WiFi receivers.
>
> Linear performance is a secondary effect so moving to a different WiFi channel will have limited effect in alleviating the effects of interference from TDD LTE.

5. The WiFi AP was not equipped for 5 GHz operation, and so was unable to migrate to the 5 GHz band.

5 CONCLUSIONS AND FURTHER WORK

The following conclusions have been drawn from this study of the effects of TDD LTE in the 2.3 GHz band on WiFi in the 2.4 GHz band.

1. The MSD estimates in Table 7 are high enough to be a cause for concern.

    - In all three scenarios it is conceivable that a TDD LTE BS or UE could cause noticeable interference to a WiFi network.
    - In scenarios B and C it is also conceivable that the TDD LTE BS could completely stop a WiFi link.
    - It is recognised that there are a number of factors that will cause these risks to reduce and some of these could be estimated to a reasonable degree of accuracy. In particular, the polarisation mismatch and antenna misalignment could be estimated with a small amount of additional testing in the chamber, so have been included in the recommendations for further work.
    - TDD LTE uplinks are of least concern. Keeping a TDD LTE UE at least 5 m from a WiFi receiver should be sufficient to prevent most interference risks. The TDD LTE BS is more of a concern with (90% throughput) MSDs of 50 m in the indoor case and 500 m in the outdoor case.

2. All WiFi receivers showed a mixture of blocking and linear performance.

    - Blocking is a suitable first order model for high level assessment of the risks of impact of TDD LTE on WiFi;
    - Another way of putting this is to say that the TDD LTE power is the most important factor in determining whether an interference problem exists;
    - An important ramification of this result is that increasing the received WiFi power will relieve an interference situation but not as much as might be expected from thinking about the C/I ratio alone.

3. The duty cycle of the TDD LTE is a significant factor in the impact of TDD LTE on WiFi.

    - When the duty cycle is low then the WiFi link can ‘see through’ the TDD LTE signal and continue to deliver traffic. As the duty cycle increases the opportunities to transmit and receive WiFi packets reduces, so the interference from the TDD LTE worsens.
    - The results presented here are an aggregate of the highest and lowest possible duty cycles of the TDD LTE waveform. When the TDD LTE network is not being used heavily then there will be a considerably reduced risk of interference.
    - It is expected that the risks to WiFi will be at their highest when the TDD LTE network is at its busiest. It is further expected that these period will coincide with the busy hours of the WiFi networks.

4. In general DL signals are more of a threat to WiFi than UL signals.

    - DL signals will come from TDD LTE base stations which have a higher transmit power;
    - DL signals have greater amplitude variation which will create a greater blocking effect in the WiFi receiver;
    - DL signals have higher duty cycles than UL signals so there is less time available in which WiFi links can transfer packets.

5. In a test with a WiFi AP in a corporate network it was found that moving to a different WiFi channel did not help avoid TDD LTE.

    - The corporate WiFi AP was normally configured to use a fixed WiFi channel so would not normally try to move away from interference;
    - When configured to move to another channel automatically, the corporate WiFi AP would only do this once when started up. Subsequent changes in the radio environment would not cause it to move channel;
    - When the corporate WiFi AP did move channel in response to detecting the TDD LTE interference, this did not improve the throughput. This result was commensurate with the earlier conclusion from the chamber tests that WiFi receivers exhibit a response to interference which is closer to a blocking performance than a linear performance. Hence it is concluded that moving to a different channel will have at best only a small benefit.

5.1 Further work

The following recommendations are made for further work in this area:

1. During the analysis of the results it became clear that the measurements could be corrected by a relatively simple offset to account for misalignment of the TDD LTE and WiFi antennas. It would be a straightforward exercise to measure the receive antenna patterns of the WiFi DUTs in the chamber to a degree of fidelity sufficient to estimate a suitable correction factor.

2. With 17 WiFi devices in total the overall statistics are reasonably indicative of the effects of TDD LTE on WiFi in general. Within each class of device (e.g. home router, tablet) there were not many devices so the statistical relevance cannot be relied on to the same extent. It is therefore proposed that, should there be time, funds and facilities available, then any further testing should concentrate on the categories of laptop, tablet and multimedia dongle where there were the fewest DUTs in this study.

3. A more complete multivariate analysis of the test results is expected to reveal more understanding of the relative significance of different factors. The timescales of the study prevented such an analysis, but it is felt that there is more to be gleaned by analysing the data further.

4. The simple blocking receiver model gives a reasonable approach for first order deductions about the possible effects of TDD LTE on WiFi. It was clear, however, that a better description of the WiFi receivers would be obtained by producing a model that combines blocking and linear behaviour. An initial investigation during the study confirmed that such a model could be

developed based on the data obtained in the chamber. If a generic model of a WiFi receiver could be developed then it would be possible to use this to reduce the number of tests required in future coexistence work.

6 GLOSSARY OF TERMS

AGC	Automatic Gain Control
AP	Access Point
BS	Base Station
C/I	Carrier to Interference ratio
CW	Continuous Wave
DL	Down Link
DUT	Device Under Test
ECG	Electrocardiogram
FSL	Free Space Loss
IP	Internet Protocol
ISP	Internet Service Provider
LTE	Long Term Evolution
MAC	Medium Access Control
MPL	Minimum Path Loss
MSD	Minimum Separation Distance
MUS	Minimum Usable Signal
OOB	Out Of Band
PC	Personal Computer
RF	Radio Frequency
TDD	Time Division Duplexing
UE	User Equipment
UL	Up Link

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