Coexistence of 2.3 GHz LTE with 2.4 GHz Wi-Fi

Measurements of Blocking Level and LTE UE Power to Estimate Separation Distances

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Executive summary

Arqiva have undertaken a range of co-existence studies to investigate the impact of LTE User Equipment operating at 2.3GHz on victim Wi-Fi devices operating at 2.4GHz.

This study was commissioned to investigate the following areas:

- Blocking measurements of LTE user devices into Wi-Fi devices, including a range of LTE traffic profiles and LTE TDD duty cycles
- An assessment of LTE user terminal output peak power levels in a number of operational environments using a range of traffic profiles
- An evaluation of the separation distances necessary to limit interference, based on the measured blocking levels and LTE terminal powers

Measured blocking levels for LTE user devices were found to be less damaging than LTE base station signals because of their lower duty cycle.

The LTE user device output powers measured varied significantly depending on the user application. An FTP heavy upload from the user device used the highest powers resulting in a median power of +18dBm. This is significantly higher than the +3dBm assumed in earlier Ofcom studies.

A range of separation distances from less than 1 metre to 3.7 metres are seen to cause a reduction in throughput of the Wi-Fi session depending on the Wi-Fi Access Point and the type of traffic that the LTE UE is handling. In normal installation scenarios Wi-Fi Access Points and LTE UEs will be within these distances causing a reduction in the performance of Wi-Fi networks.

1 - Introduction

Ofcom are preparing to auction 40MHz of the 2.3GHz band in 2015 for LTE services[1], presently used by the UK MoD. Prior to the auction process, the UK MoD frequency allocation in the 2.3GHz band is from 2.310GHz to 2.4GHz. The auction process will release the upper 50MHz of the band which will allow a number of LTE TDD carriers into the band. Figure [1] shows one outcome with two 20 MHz TDD carriers. In this example they will have center frequencies of 2.360 and 2.380GHz respectively leaving a 10MHz guard band between the LTE service and licence exempt ISM 2.4GHz band. New LTE services operating in the 2.3GHz band will be required to operate in a TDD configuration, as standardised in ETSI TS_136101[2].

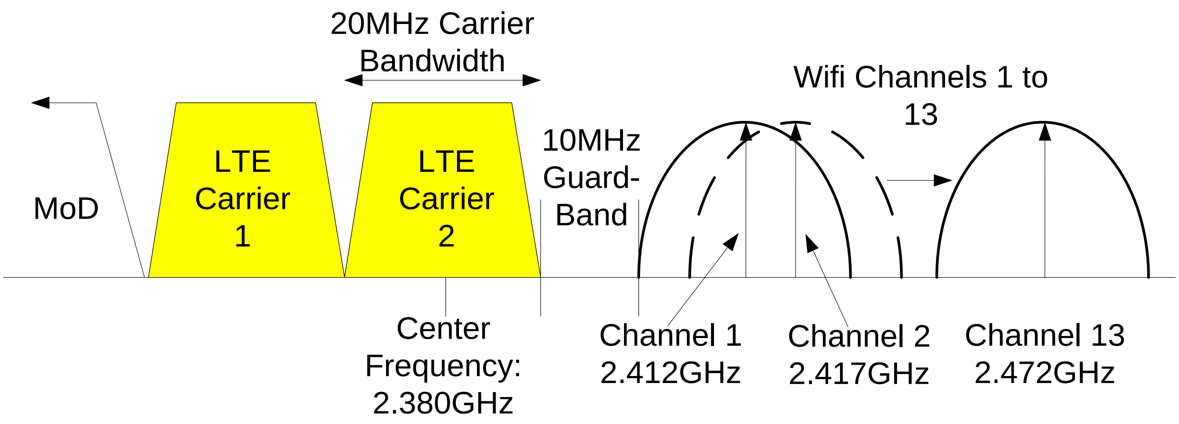

Figure 1: An example of LTE and Wi-Fi services in the 2.3 and 2.4GHz bands

Ofcom published a co-existence consultation in February 2014[3] which outlined the potential impact of LTE services located in the 2.3GHz band with Wi-Fi services located in the licence exempt 2.4GHz band. The consultation concluded that the impact for the deployment of LTE services into Wi-Fi services would be low. In addition to the low likelihood of interference the consultation proposes that a range of interference mitigation techniques could be employed. These mitigation techniques included physically moving the location of the Wi-Fi device, input filtering for the Wi-Fi devices and forcing the Wi-Fi service to operate in the 5GHz band. The necessity to use these mitigation techniques and the viability of physically moving the Wi-Fi device depends on the separation distance needed between the Wi-Fi device and LTE interferer. The purpose of this study is to estimate practical separation requirements by measuring Wi-Fi blocking levels and LTE peak operating powers.

Previous Ofcom Findings for Wi-Fi Receiver Blocking and Separation Distances

Earlier Ofcom studies showed that the primary failure mechanism for victim Wi-Fi devices was receiver blocking. It also concluded the LTE base-station signals are more destructive than UE terminal waveform characteristics because they have a longer active on period due to their duty-

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[1] http://stakeholders.ofcom.org.uk/consultations/2.3-3.4-ghz/summary; 2.3 and 3.4 GHz spectrum award: Consultation on a 3.4 GHz band plan, varying UK Broadband Limited's license and a call for inputs on other aspects of the award

[2] ETSI TS 136 101, LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception – section 5.5, operating bands

[3] http://stakeholders.ofcom.org.uk/consultations/pssr-2014/ ; Technical coexistence issues for the 2.3 and 3.4 GHz award – Annexes 7 -13

cycle. Ofcom studies also concluded that a safe separation distance between LTE UE to Wi-Fi device separation is typically less than 1m. This distance was based on earlier UMTS terminal device operating powers using a median power of +3dBm EIRP. Finally no blocking measurements were undertaken when a Wi-Fi AP supported multiple clients.

Blocking Level Measurements

Arqiva have undertaken Wi-Fi receiver blocking measurements using LTE TDD waveforms captured from equipment operating on a representative test 2.3GHz TDD network. This was in contrast to tests earlier undertaken by Ofcom where test equipment using a PRBS configuration was used. The requirement was to test a range of Wi-Fi devices using these RF recordings and establish if there was any significant difference between the test signals created by Ofcom and waveforms captured from a live network. Test waveforms included base station and UE terminal equipment.

Impact of LTE UE Terminals on Wi-Fi Devices

ETSI standards stipulate that the peak power for LTE UE is +23dBm EIRP during the active or "on" period of the TDD frame. In practice the UE power is often lower than this because power control and scheduling are applied depending on propagation conditions and other network factors. Therefore co-existence studies may use a lower peak power figure than +23dBm to represent realistic interference. Earlier ITU studies[4] based on UMTS terminal equipment operating on existing networks concluded that the median power for UE terminals is +3dBm. Arqiva believes that +3dBm is too low an assumption and the aim of this measurement campaign was to establish realistic LTE UE operating powers in live networks.

Separation Distances

Establishing median operating powers for LTE UE terminals in a range of live operating conditions in combination with median blocking levels can be used to establish the required separation distance between LTE UE terminals and representative victim Wi-Fi devices.

[4] ITU-R; Radiocommunication Study Groups; Anne 14 to document 5-6/88-E; 3rd June 2009

2 – LTE UE Terminal Blocking Measurements

Overview

Receiver blocking occurs due to a combination of poor Wi-Fi receiver ACS (Adjacent Channel Selectivity), non-linearity of the Wi-Fi amplifier and high LTE signal levels due to the RF coupling from LTE to Wi-Fi devices.

Receiver blocking measurements were undertaken using pre-recorded LTE TDD waveforms coupled into example victim Wi-Fi devices. The power of the LTE waveforms was varied to evaluate the impact on Wi-Fi data throughput so that a receiver blocking level could be established.

RF Test Signals

RF recordings were taken from a test LTE TDD network operated by BT Research. This network consisted of a network grade (commercially available) E-Node B and two LTE UE terminal devices. The network (for each test) was configured for a TDD profile in accordance with ETSI TS 136 211[5] and a number of recordings were taken for a range of user traffic profiles. The LTE signal consisted of a single 20MHz carrier with a center frequency of 2.380GHz.

The recordings were made by Ofcom, BBC Research, BT and Arqiva using a National Instruments PXI RF recorder. The waveforms were subsequently post-processed by Sony in order to configure them for use on Rohde and Schwarz arbitrary waveform generators[6]. The out-of-block of the recorded waveforms was significantly better that the LTE UE terminal equipment used in the test LTE network. Therefore the receiver blocking measurements using the processed waveforms were solely due to Wi-Fi receiver blocking and not the out-of-block performance of the R&S test equipment.

The TDD network configuration and traffic profile can be seen in table [1] below.

TDD Configuration	BS / UE Recording	Waveform (File)
60 (BS) / 30 (UE)	UE	UE Uplink AKS
60 (BS) / 30 (UE)	UE	UE Heavy Upload
60 (BS) / 20 (UE)	UE	Skype Call
60 (BS) / 30 (UE)	BS	Base-station Heavy Download

Table 1: LTE TDD waveform characteristics

Wi-Fi devices and Wi-Fi Link calibration

Four Wi-Fi devices were tested, one was a client device and the other three were APs. The client and one of the APs were low-grade consumer devices. Two of the APs were higher grade designs used in public networks by Arqiva. One of the high-grade devices had integrated LTE 2.3GHz rejection filters. The Wi-Fi devices under test are referenced in this report as follows:

- Wi-Fi client – **Client**
- Wi-Fi AP consumer grade – **AP A**
- Wi-Fi AP high grade – **AP B**

[5] ETSI TS 136 211 V12.3.0 (2014-10); LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 12.3.0 Release 12)
[6] Plots of Ofcom/BT LTE TDD Recordings, Version 7, 23 October 2014, John Wilson, Sony Corporation

- Wi-Fi AP high grade with integrated LTE rejection filters – **AP C**

All devices had integrated SMA connectors which enabled direct coaxial tests. All devices were configured to be fixed to 802.11g, channel 1 (2.412GHz). MIMO was disabled for all devices and a single RF connection was used from each device.

In order to measure the degradation of the Wi-Fi link, an IPERF[7] session was established between the AP and client using TCP. The RF path was initially configured so that the Wi-Fi signal was 5dB stronger than the level needed for maximum IP throughput. This ensures that any measured degradation in the tests is due to receiver blocking caused by the introduction of the LTE signal and not poor Wi-Fi signal. Typical 802.11g IP throughput for a non-interfered link was approximately 24Mbit/s. The operating level was approximately 30dB above the minimum Wi-Fi operating level.

Calibration of the Wi-Fi device without the presence of the interfering LTE Signal

The test equipment set-up for this calibration can be seen in Figure [2]. Attenuation was applied to the Wi-Fi link from approximately 30dB above link failure until the IP throughput of the Wi-Fi link was less than 1Mbit/s.

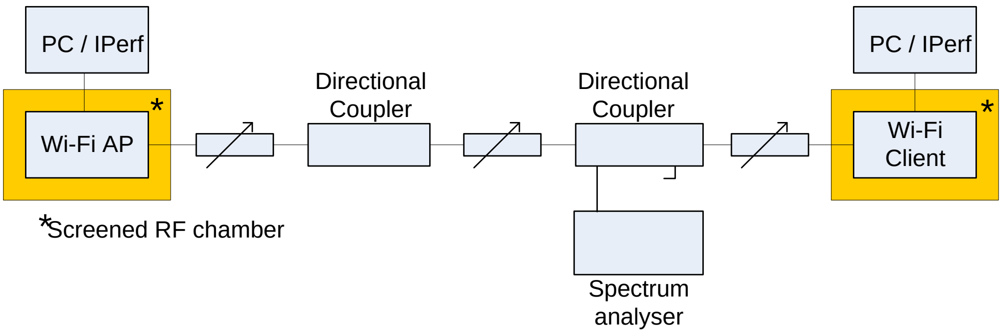

Figure 2: Calibration of the Wi-Fi devices

Figure [3] below shows the IP throughput of the Wi-Fi link for each device under test from full modulation conditions to Wi-Fi link failure. The light blue line (Figure [3]) shows the Wi-Fi signal strength that was used for all subsequent testing. This value was -67dBm.

[7] IPERF is an IP network testing tool that can be configured to create TCP data streams and measure the throughput of a network

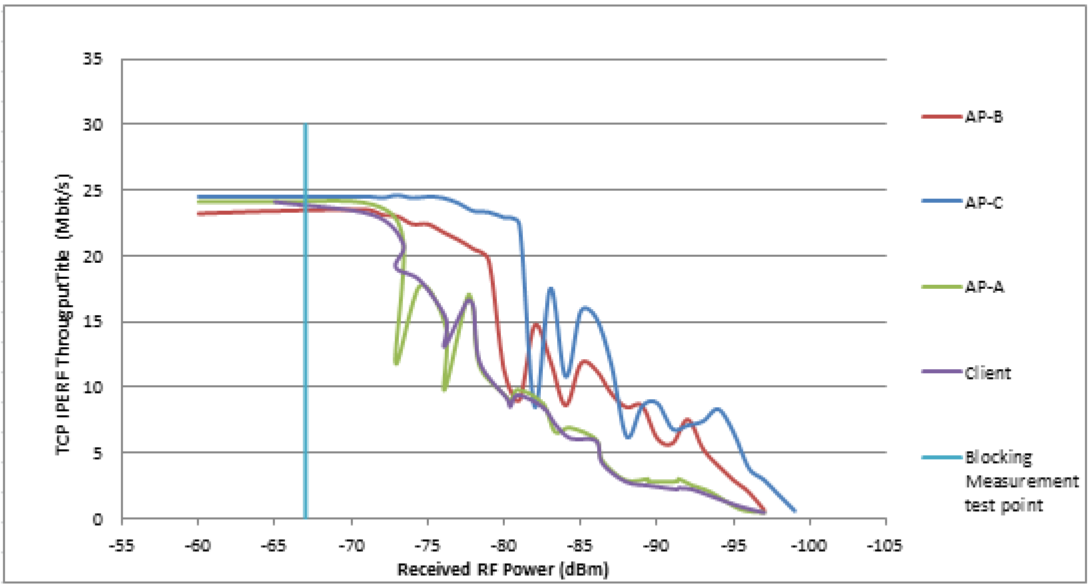

Figure 3: Wi-Fi device calibration results

Blocking Level Measurements

Blocking level measurements were conducted by coupling LTE recorded signals from an R&S SFU with an arbitrary waveform generator (ARB) into the Wi-Fi RF link as shown in Figure [4] below, with the Wi-Fi link configured to operate at its maximum IP throughput. The LTE signal was increased in 2dB steps from a low to high power interfering signal level. The IPERF session was measured over a period of 60 seconds. At the end of each measurement, the average throughput of the IPERF session was recorded. A linear amplifier was required to increase the LTE signal level on the output of the ARB. The amplifier was operated at input power levels well below its 1dB compression points and therefore the measurement results were not affected by second order non-linear effects.

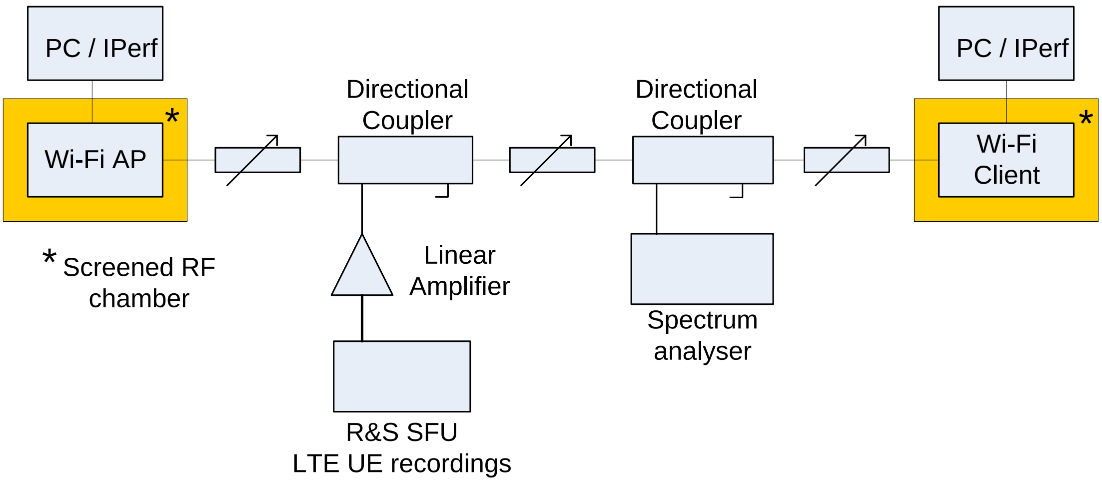

Figure 4: Test equipment setup for Wi-Fi receiver blocking measurements

Blocking Level Results

The results for each Wi-Fi device can be seen in Figures [5],[6],[7], and[8]. A table of results for each of the impairment metrics can be seen in Table [2].

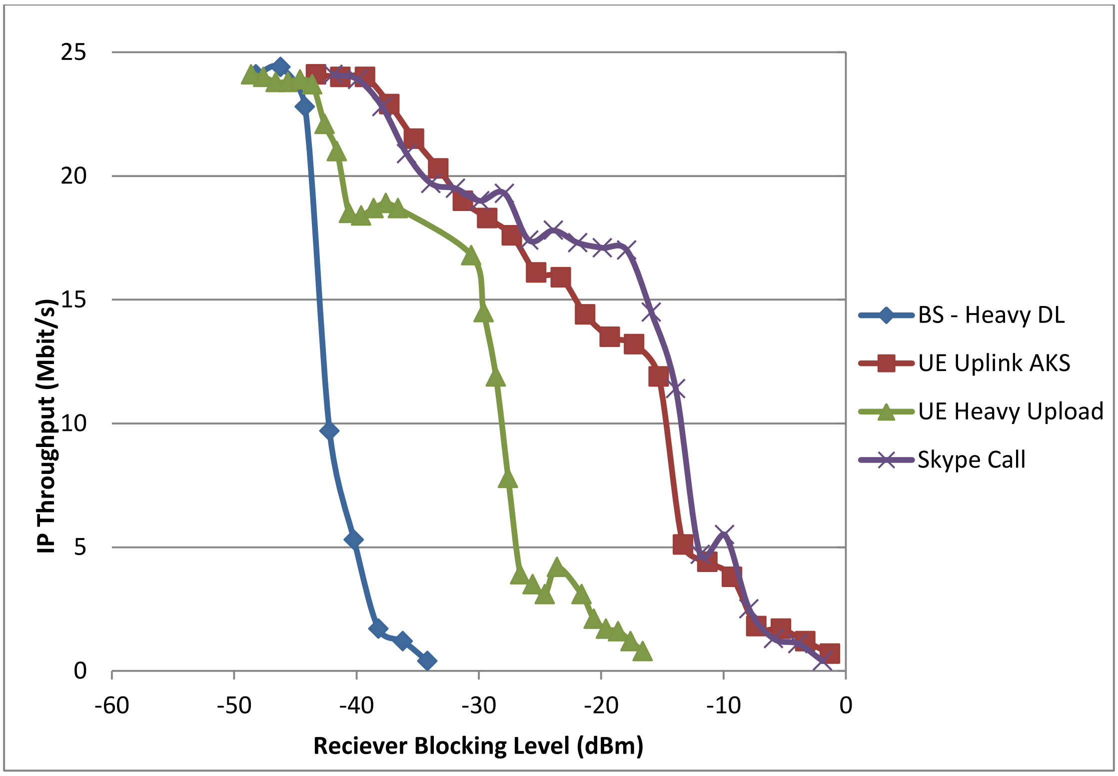

Figure 5: Blocking level measurements for Client

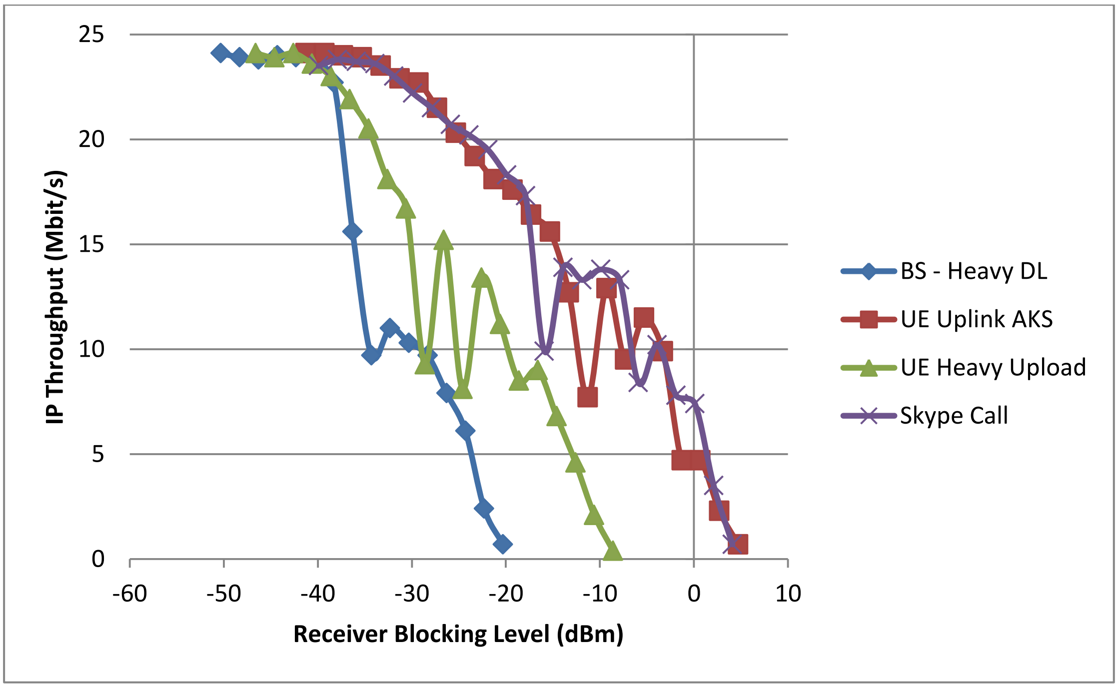

Figure 6: Blocking level measurements for AP1

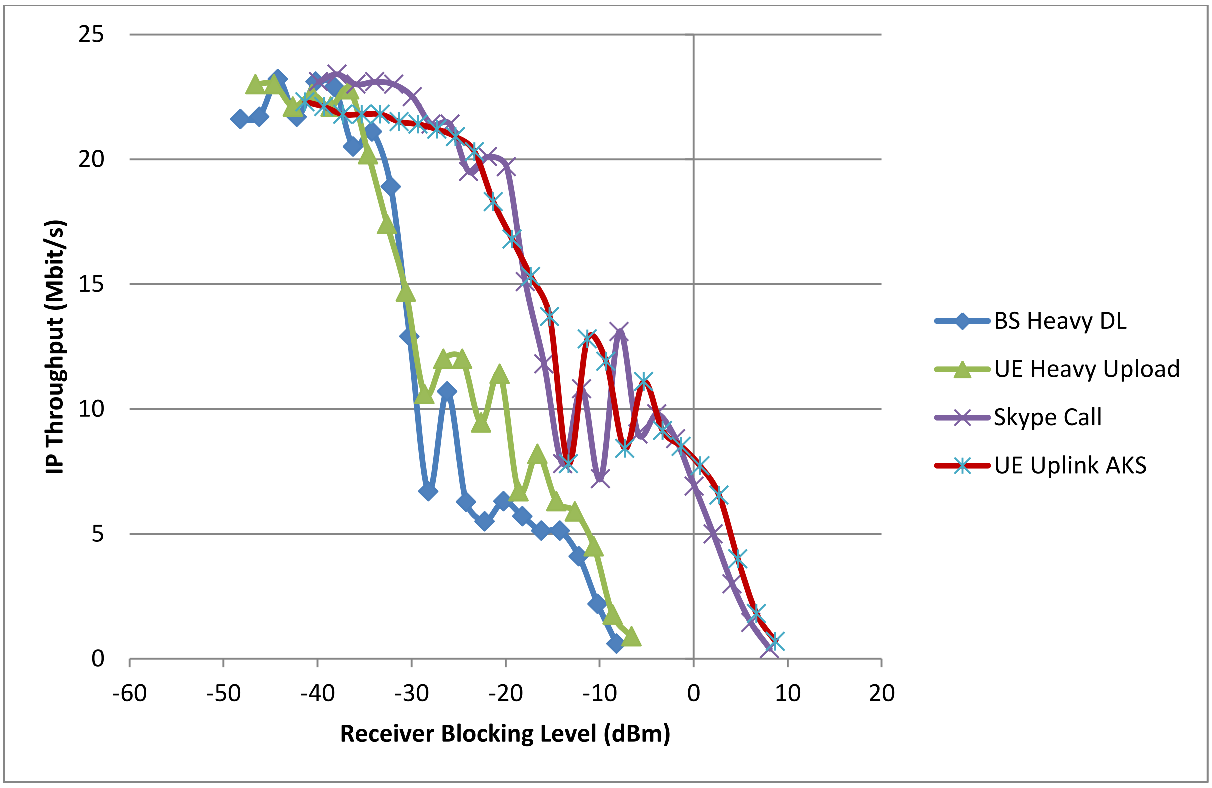

Figure 7: Blocking level measurements for AP2

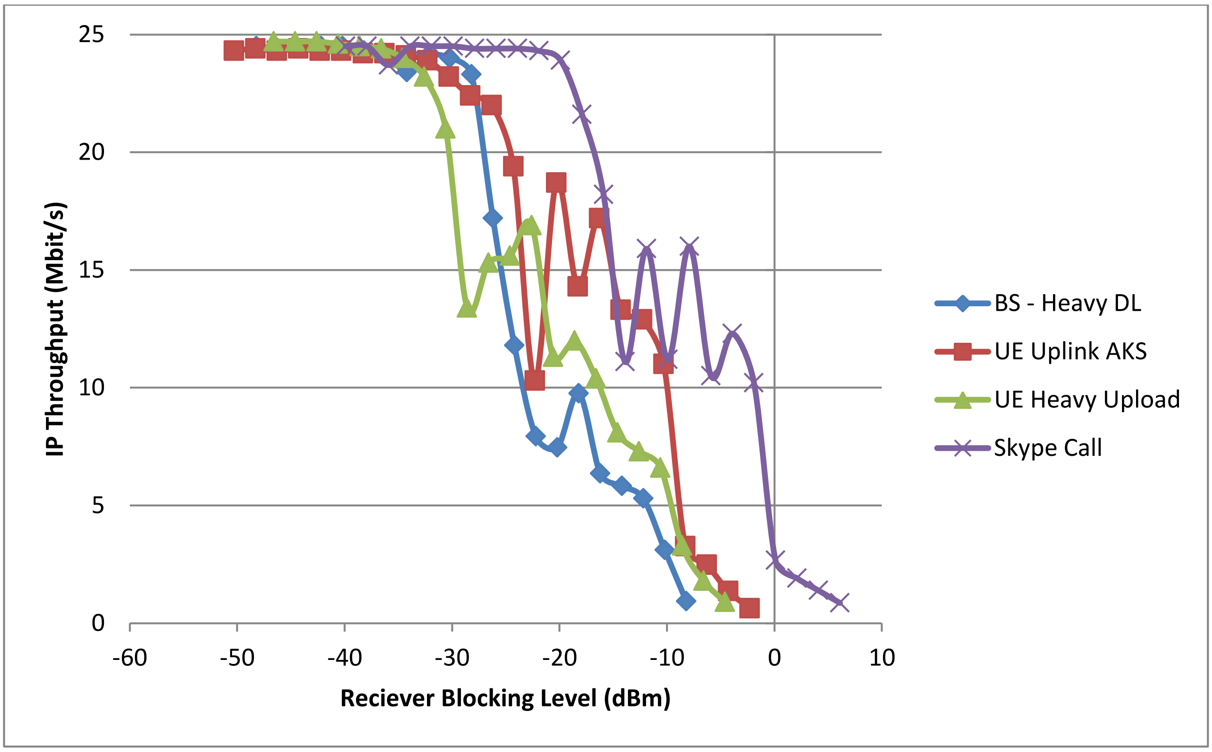

Figure 8: Blocking level measurements for AP3

Blocking level measurements were categorised into three impairment metrics which were used to identify the level of degradation of the Wi-Fi link. These were:

[1] A reduction to the IP throughput of the Wi-Fi link by 1Mbit/s when compared to normal operation due to the introduction of the interfering signal – This is classed as "onset of failure"
[2] A 50% reduction in Wi-Fi link throughput
[3] <1Mbit/s throughput of the Wi-Fi link due to the interfering signal

Device	**File**	**Onset of Failure (dBm)**	**50% Failure (dBm)**	**<1Mbit/s throughput (dBm)**
Client	UE uplink AKS	-37.3	-15.3	-1.3
	UE heavy upload	-42.6	-28.6	-16.6
	UE Skype call	-37.9	-13.9	-1.9
	Base-station heavy download	-44.2	-40.2	-34.2
AP1	UE uplink AKS	-29.3	-17.3	4.7
	UE heavy upload	-34.6	-24.6	-8.6
	UE Skype call	-29.9	-15.9	4.1
	Base-station heavy download	-38.2	-34.2	-18.2
AP2	UE uplink AKS	-25.3	-13.3	8.7
	UE heavy upload	-34.6	-28.6	6.6
	UE Skype call	-27.9	-15.9	8.1
	Base-station heavy download	-36.2	-30	-16.1
AP3	UE uplink AKS	-23.2	-11.3	6.7
	UE heavy upload	-32.6	-20.6	-4.6
	UE Skype call	-17.9	-13.9	6.1
	Base-station heavy download	-34.2	-24.2	-8.2

Table 2: Blocking level measurements

The overall statistics of the blocking level tests are includes in Table [3] below.

	All LTE Waveforms / All Wi-Fi Devices	LTE UE Waveforms Only / All Wi-Fi Devices	LTE UE Waveforms Only / Non-filtered Wi-Fi Device Only
Median Blocking Level (dBm)	-32.8	-31.1	-33.2

Table 3: Median blocking levels for the Wi-Fi devices under test

Multiple Clients

The above measurements refer to scenarios with a single client. In practice there will be multiple client devices connected to a single AP. To investigate this tests have been carried out with three client devices connected to a single AP. These measurements used a configuration similar to Figure [4] with the "Heavy base-station download" file which was found to be the most disruptive file for all Wi-Fi devices under test. For the first test, all clients were configured to receive the same RF conditions from the AP (each RF path received the same path attenuation). In the second test, the clients had different signal levels to represent variations in propagation losses between the client and AP found in a typical deployment. Client one had a received signal level of -62dBm, client two had a received signal level of -67dBm, and client three had a received signal level of -72dBm.

In all of these tests the performance was no worse that the single client tests.

The throughput reduction was similar for all clients under test when the LTE signal was introduced. The exception to this was when one of the clients was configured to operate with a link budget below full IP throughput prior to the introduction of the LTE signal (-72dBm). In this condition the client IP throughput reduced to <1Mbit/s earlier than the other clients under test, which was expected.

These initial tests show that in general the impact on multiple clients is not significantly different to the single client case so further testing has not been carried out at this time. However the above testing for multiple clients is simple and does not cover the full range of client scenarios. Further investigation is required in live operating conditions where there may be many client devices with a range of link budgets.

Key findings from results

In all cases, the Base-station heavy download waveform was found to be the most destructive

The LTE UE terminal Heavy upload file was found to be the second most destructive; in most cases it was found to have an onset of failure within 2.5dB of the base-station signal

The Skype and "AKS" waveforms showed to be the least aggressive

AP3 with integrated LTE filtering was found to improve the rejection of the LTE signal and reduced receiver blocking levels.

There is approximately a 10dB spread of receiver blocking performance between the high quality Wi-Fi devices and the low grade consumer types, with the client device being the worst performing equipment under test.

3 - Walk tests

Description of the tests

The licenced power for LTE FDD and TDD terminal devices is +23dBm EIRP. It is the peak power of the device which is regulated which applies for FDD and all TDD modes of operation. In practice the operational power varies and is subject to network conditions. This series of walk tests were designed to establish typical peak operating powers of the LTE terminal on live networks. The operation of the LTE terminal device was subject mobile network conditions. A single Samsung LTE S3 production device was used to record peak operating power on the Everything Everywhere 1800MHz network. This network is FDD in design, with a 20MHz carrier bandwidth; however the power characteristics obtained from this series of tests should be directly representative of a TDD network as the peak power should be similar.

Measurements were undertaken in a number of test locations in South East England, representing a range of cellular coverage areas, outdoor, indoor, building penetration types and height. The locations are:

- A hotel in a dense urban environment at Kings Cross train station, London.
- A hotel located at Heathrow airport
- A hotel located in a sub-urban environment located on the edge of Milton Keynes
- Concourse area outside of Kings Cross railway station
- Concourse area inside of Kings Cross railway station
- Tottenham Court Road
- Commercial offices in Hemel Hempstead

In the hotels and commercial offices separate measurements were taken on the ground floor and second floor.

There were three individual tests carried out at each location with the same duration and route. The three user profiles were:

- Heavy FTP upload
- Skye Call to a local 3G enabled handset
- Heavy download (a “YouTube” session from a popular BBC children’s programme)

Test Equipment Configuration

A Samsung Galaxy S3 LTE “Smart-Phone” was directly connected to a Rhode and Schwarz TMSE LTE analyser to capture peak transmit power from the LTE terminal device. The Samsung device reported its peak power to the R&S TMSE every second. Peak powers are reported as EIRP, with a manufacturer measured antenna gain of 0dBi. The smart phone was locked to “4G”, which meant that it was not possible for the device to transfer any data via another bearer through the period of the walk tests.

Walk Test Results

In this section there are charts showing the distribution of LTE peak power for each user profile. These are shown in Figures [9], [10] and [11]. Each chart combines the measurements from all of the surveyed locations. In all cases the 50th percentile is chosen to represent a typical operating power for the LTE UE for that specific user profile.

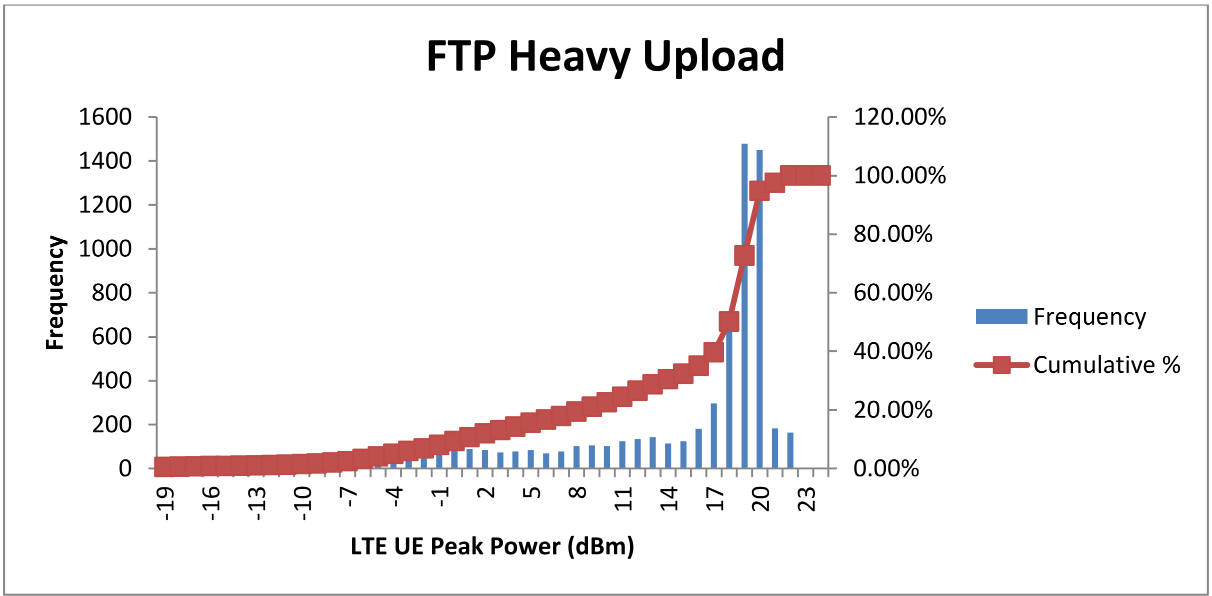

Figure 9: FTP Heavy Upload walk tests

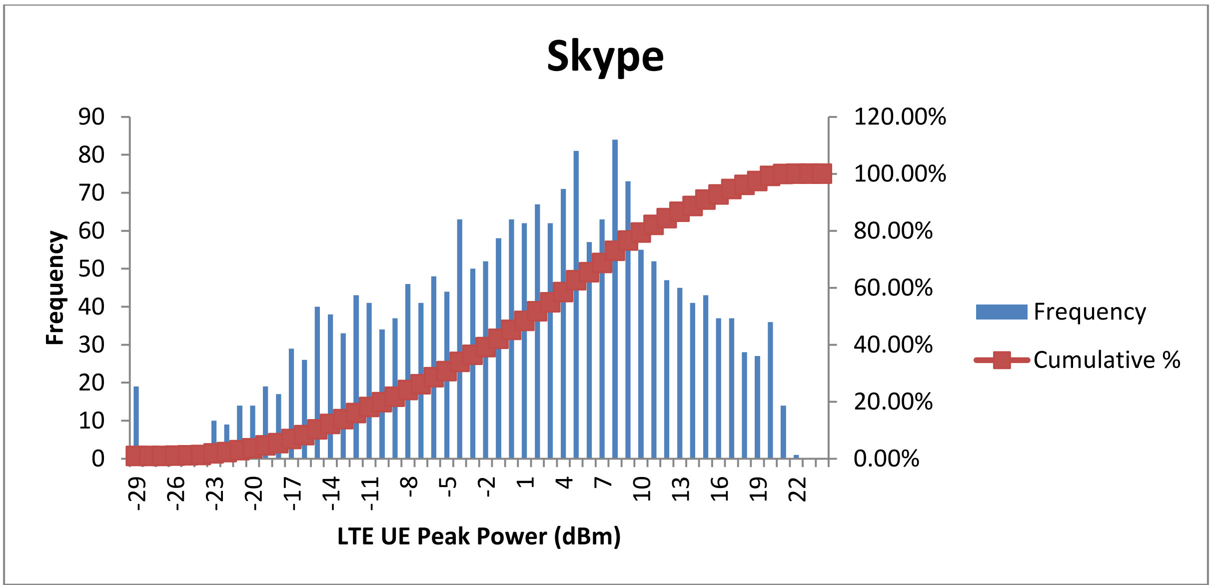

Figure 10: Skype walk tests

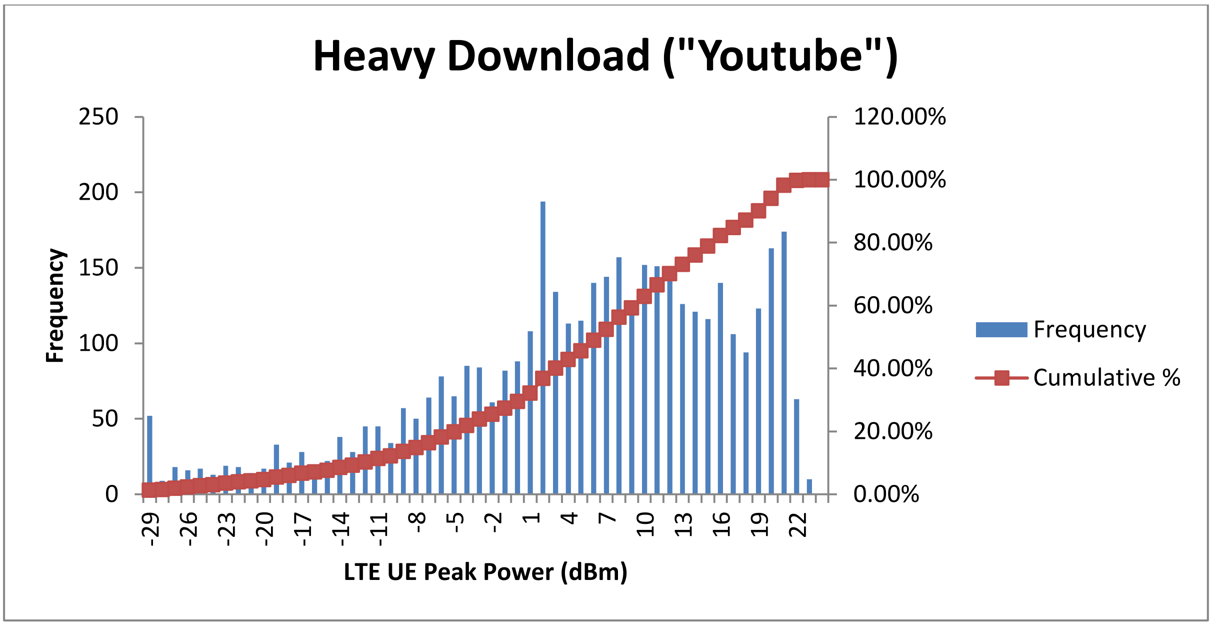

Figure 11: Heavy Download ("YouTube") walk tests

In all cases the 50th percentile is chosen to represent a typical operating power for the LTE UE terminal device for each specific user profile. Table [4] below shows the 50% percentile for each user case.

	User Traffic Profile		
	Heavy Upload	Skype	Heavy Download
50th Percentile (Peak Power - dBm)	+18	+1.5	+6.5

Table 4: 50th percentile for each user case showing peak power for the LTE UE

4 - Impact Analysis – Minimum Separation Distances between LTE UE Terminals and Wi-Fi Devices

Minimum separation distances between LTE UE devices and Wi-Fi devices can be calculated using the peak power 50th percentile values (recorded in Table [4]) and Wi-Fi receiver blocking levels recorded in table [3].

Separation distances assume the following coupling gain parameters:

- Free-space-loss between the two devices
- 0dBi receive antenna on the victim Wi-Fi device
- Antenna co-polarisation between the LTE UE and Wi-Fi devices

The separation distances for the three scenarios have been calculated, and are listed in Table [5].

			Heavy Upload	Skype	Heavy Download
		dBm	+18	+1.5	+6.5
Blocking Level	UE Waveforms / All Wi-Fi Devices	-31.1	2.8m	0.4m	0.8m
	All LTE Waveforms / All Wi-Fi Devices	-32.8	3.5m	0.5m	0.9m
	UE Waveforms Only / Non-filtered Wi-Fi Device Only	-33.2	3.7m	0.5m	1m

Table 5: Minimum separation distances in metres

Table [5] shows that for a heavy upload LTE UE user profile, the minimum separation distances are approximately 3m or greater for all LTE waveforms.

Table [5] also shows that for both Skype and Heavy Download user profiles the resulting separation distance is less than 1m, which is in-line with earlier Ofcom results.

5 - Conclusions

Blocking Level Measurements

Blocking level measurements were conducted in laboratory conditions using pre-recorded base-station and UE terminal waveforms from representative test LTE TDD networks. TDD configurations of the waveforms were representative of LTE TDD network deployments and in-line with 3GPP standards.

Combining the results for all types of LTE waveforms (base-station and LTE UE) and all Wi-Fi devices under test, a median blocking level for Wi-Fi devices was found to be -32.8dBm.

Separating out measurements undertaken using the LTE UE terminal waveforms only, blocking levels reduced to -31.1dBm.

One of the high-quality test Wi-Fi APs had integrated LTE rejection filters. Removing the Wi-Fi device with integrated LTE filters and using LTE UE waveforms only, the blocking level increased to -33.2dBm.

It is observed from this measurement campaign that the addition of LTE filters on Wi-Fi devices can improve the performance of Wi-Fi devices in the presence of interfering LTE signals.

No additional effect was found for multiple victim Wi-Fi clients when connected to a single Wi-Fi AP in the presence of LTE interference signals. The reduction in IP traffic throughput of the link affected all clients equally, with no single device being more affected than any other. Further real-world tests are required to fully explore scenarios with more complex networks.

LTE UE Output Powers

LTE walk tests were conducted in a range of locations in the UK. These locations included dense urban, sub-urban and rural locations and included major commercial and transport hubs. The measurement locations represented a range of RF operating conditions for the UE within the serving base-station coverage area. This resulted in a wide range of RF link budgets between the UE and the base-station site.

Measurements were undertaken using 3 LTE UE terminal traffic profiles; Heavy (FTP) upload, Heavy ("YouTube") download and a local Skype call between the UE device and a UMTS UE.

The Median peak power measured in the walk tests was:

- Heavy Upload: +18dBm
- Skype: +1.5dBm
- Heavy Download ("YouTube"): +6.5dBm

Separation Distances

For the heavy upload LTE UE user profile, with a median peak power of +18dBm, the minimum separation distances between the LTE UE and Wi-Fi device are approximately 3 metres or greater for all LTE waveforms.

For both Skype and Heavy Download user profiles the resulting separation distance is less than 1 metre, which is in-line with earlier Ofcom results.