macltd
MULTIPLE ACCESS COMMUNICATIONS

The Effect of TDD LTE Signals in the 2.3 to 2.4 GHz band on Bluetooth Equipment Operating in the 2.4 GHz ISM band

Ofcom MC/174

May 2013

MAC-EXFR-27-071-1.0

This report was commissioned by Ofcom.

Multiple Access Communications Ltd
Delta House, Enterprise Road
Southampton Science Park
SOUTHAMPTON
SO16 7NS, UK
Tel: +44 (0)23 8076 7808
Fax: +44 (0)23 8076 0602

Executive Summary

The Effect of TDD LTE Signals in the 2.3 to 2.4 GHz band on Bluetooth Equipment operating in the 2.4 GHz ISM band

Ofcom MC/174

Background

The UK government is planning to release 500 MHz of radio spectrum below 5 GHz by the year 2020. As part of this plan, during 2014, the Ministry of Defence (MoD) intends to bring to market spectrum between 2350 MHz and 2390 MHz, which lies just below the industrial, scientific and medical (ISM) band from 2400 MHz to 2483.5 MHz. It is planned that once released this spectrum will be allocated for cellular mobile radio services using the time division duplex (TDD) mode of the Long Term Evolution (LTE) system. TDD LTE systems have been specified for operation in a range of channel bandwidths, but it is the 10 MHz and 20 MHz bandwidths that are being considered for use between 2350 MHz and 2390 MHz. The two potential band plans are shown in Figure A1, where we have also introduced the LTE terminology Band 40, which refers to the frequency range 2300 MHz and 2400 MHz.

The ISM band is operated on an unlicensed basis and has been adopted for use by several low power, short range systems, including IEEE802.11 (WiFi), Bluetooth and ZigBee. There are concerns that because these systems have an emphasis on low cost and low power they may be vulnerable to out of band interference caused by nearby, high power cellular radio signals with little frequency separation.

Ofcom is assisting the MoD with its plans to release the spectrum and as part of its technical due diligence Ofcom has commissioned measurement studies to investigate the effect of TDD LTE signals on WiFi, Bluetooth and ZigBee and the results of the Bluetooth study are presented in this report. The measurements were carried out by Multiple Access Communications Ltd.

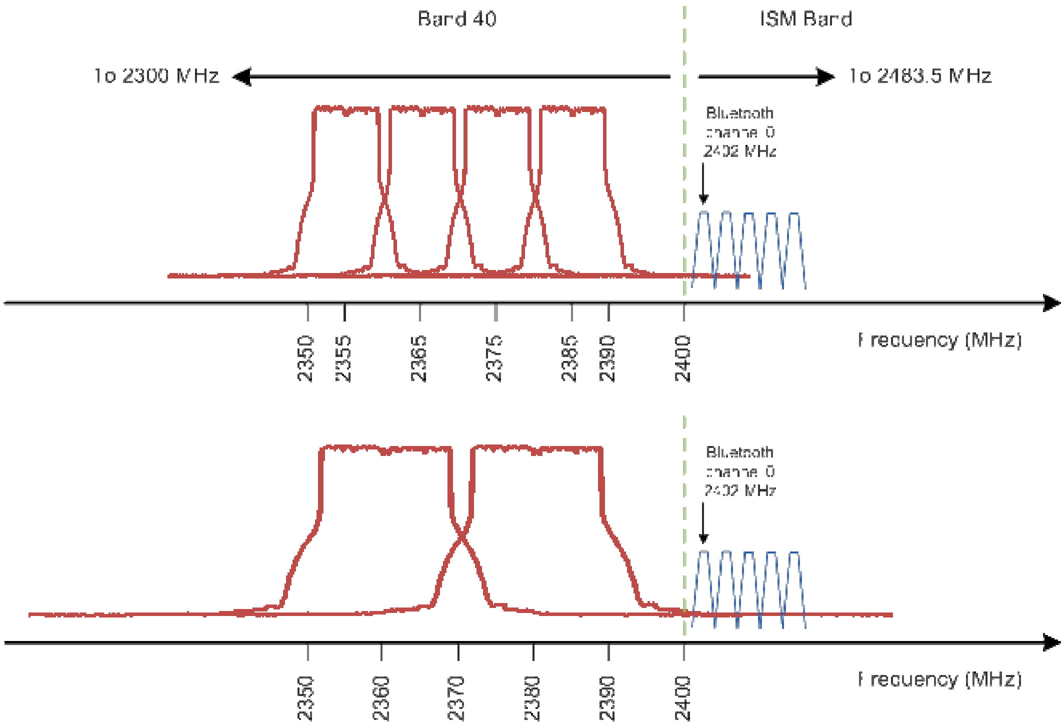


Figure A1 Possible band plans using 10 MHz (top) and 20 MHz (bottom) bandwidth TDD LTE systems.

Since its introduction in 1999 the Bluetooth Standard has undergone several revisions. Beginning with Basic Rate (BR) mode in Version 1, which provided a single physical layer mode operating at 1 Mbps, Version 2 (2004) introduced two extra physical layer modes known collectively as Enhanced Data Rate (EDR), Version 3 (2009) linked Bluetooth to WiFi and, finally, Version 4 has adapted BR mode for low energy (LE) operation. For the purposes of this study Versions 1, 2 and 4 were investigated. Since Version 3 simply uses Bluetooth as a setup channel for a WiFi link it was deemed that the susceptibility of this mode would be covered by the companion WiFi study.

The goal of the measurement study was to establish if Bluetooth devices are likely to be adversely affected by the presence of TDD LTE signals from base stations (BSs) or user equipment (UE) in the adjacent frequency band. To ensure that the tests covered a representative cross section of the Bluetooth devices on the market a survey was conducted using data provided at the www.bluetooth.com website, from which the chart shown in Figure A2 was produced. Figure A2 shows the number of product types that were introduced in 2012 and whilst this is not the same as the number of devices in use, it does provide valuable insight of how Bluetooth is used.

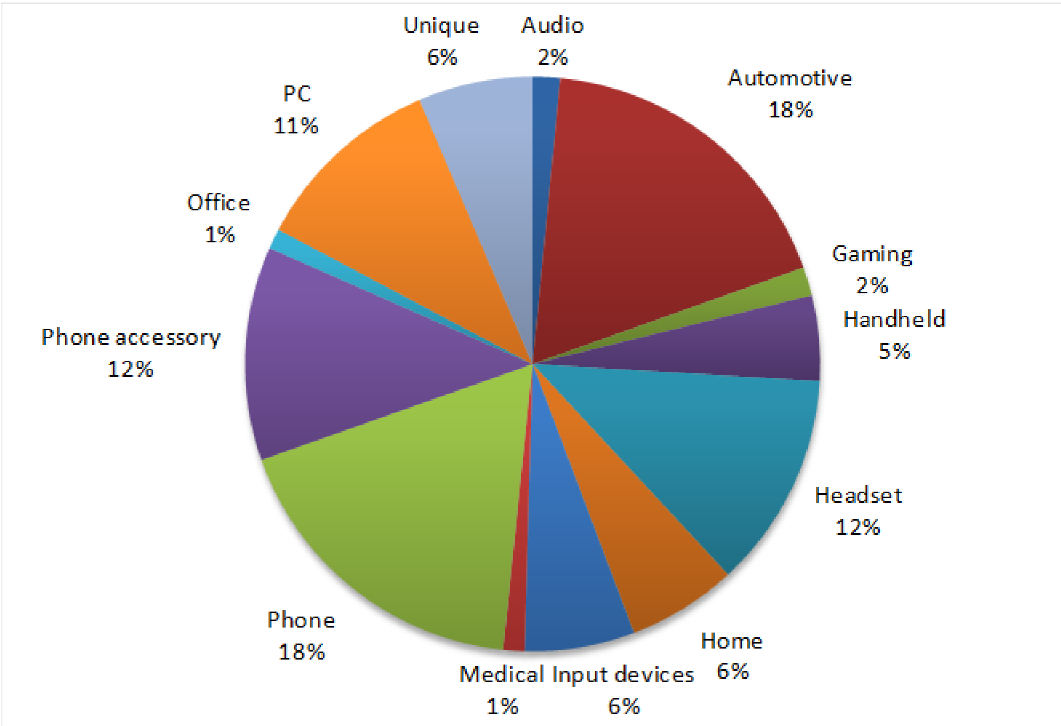


Figure A2 Bluetooth products introduced in 2012.

It is clear from the data in Figure A2 that four categories dominate the market (Phone, Phone accessory, Headset and Automotive) collectively accounting for 60% of the new devices introduced in 2012. Notably these are all audio applications, suggesting that the bulk of Bluetooth devices are still used for the initially envisaged use of Bluetooth as a short range audio link between a mobile phone and a headset. Guided by the survey we chose 14 devices, however, due to practical constraints we were unable to test four of these and so the results presented are based on the ten devices listed in Table A1. Eight of the ten devices were off-the-shelf end products. The two remaining devices were chip set evaluation modules (EVMs) as these provided the necessary test access to evaluate LE mode performance.

Device	Type	BT Version	BT Modes Supported
1	Phone	2.1	BR, EDR
2	Phone	2.0	BR, EDR
3	Chip set evaluation module	4.0	LE
4	Chip set evaluation module	4.0	LE
5	Phone	4.0	BR, EDR, LE
6	SatNav	2.1	BR
7	Keyboard	3.0	BR, EDR
8	Hands-free kit	2.1	BR, EDR
9	Headset	1.2	BR
10	Headphones	2.1	BR, EDR

Table A1 Test devices.

Method

The test methodology was in principle quite simple, but made more complicated by two factors: first that the test devices did not provide an antenna connector; and, second, that the test mode required to enable objective link measurements was not available on half of the devices. The consequences of these factors were: that we were able to determine the relative levels of wanted signal and interference that the test devices could tolerate, but not the absolute levels (except in one case where we modified a chip set evaluation module by adding a connector to provide a direct measurement); and that frequency hopping could not be disabled for measurements on of half of the devices.

Figure A3 shows the test system used. Bluetooth test signals and measurement of BR and EDR error rates were provided by a Rohde and Schwarz CBT test set. Interfering carrier wave (CW) or representative TDD LTE signals were generated using a Rohde and Schwarz SMBV100A signal generator, together with the arbitrary waveform generation software WinIQSIM2. The device under test (DUT) was placed in a screened enclosure to eliminate any interference from local ISM band signals and the whole system was placed under the control of a computer, running scripts written in the scientific computing language MATLAB.

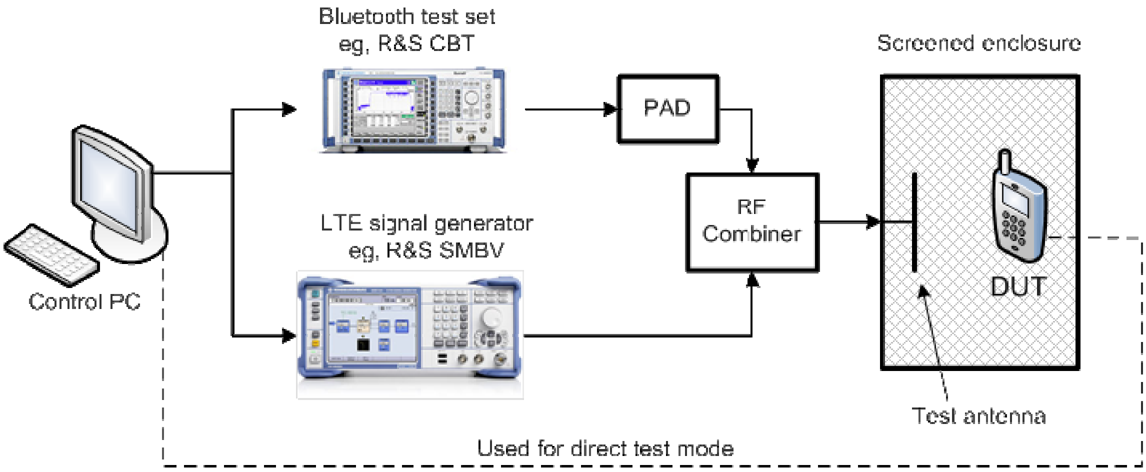


Figure A3 Test system configuration.

For each measurement the scripts running on the control PC conducted the following sequence of actions.

- The DUT's baseline sensitivity was measured; this is the actual sensitivity plus the air gap loss between the test antenna and the DUT.
- The Bluetooth signal level was increased by a margin of between 3 dB and 20 dB above this baseline sensitivity.
- An interfering signal was introduced at a selected frequency offset and, whilst measuring the link error rate, the interference power was raised until it was just sufficient to counteract the Bluetooth signal margin.
- The relative levels of the Bluetooth and interference signals were recorded.
- The process was repeated at a range of frequency offsets and for each interfering signal configuration.

At the time the measurements were taken no information was available about the typical out of band emission (OOBE) profile of a TDD LTE BS. Consequently, the approach was to generate two examples of OOBE profile, which we refer to as 'clean' and 'typical'. Latterly more data about typical BS emissions became available and this enabled a more precise interpretation of the signal profiles. Figure A4 shows the spectrum of an LTE BS[1], overlaid

[1] This measurement was taken from a frequency division duplex (FDD) BS, but we expect it to be representative of a TDD-BS

on the OOBE profiles of the clean and typical signals produced by the SMBV signal generator and compared to the TDD LTE spectrum emission mask.

Comparing the curves in Figure A4 it is clear that the clean signal from the SMBV is a good approximation to the measured BS profile and that the typical SMBV signal is close to the spectrum mask limit. Thus, measurements obtained using these two OOBE profile from the SMBV can be considered as representative of typical and worst case BS emissions. In the main body of the report we also show that the typical SMBV emission profile is representative of measurements made on typical FDD LTE UEs and hence we assume also typical of TDD LTE UEs.

TDD LTE permits a flexible allocation of the transmit-to-receive duty cycle to allow the radio resources to be optimised to meet the uplink and downlink traffic demand. Since transmission time could influence the level of interference experienced by Bluetooth devices the tests were conducted using duty cycles in which the transmissions occupied 85% and 50% of a frame.

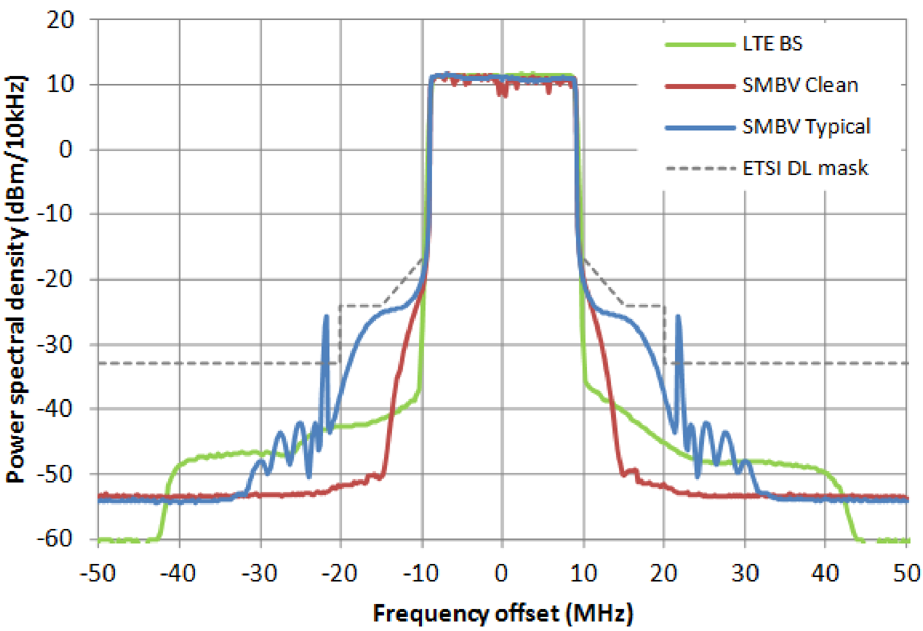
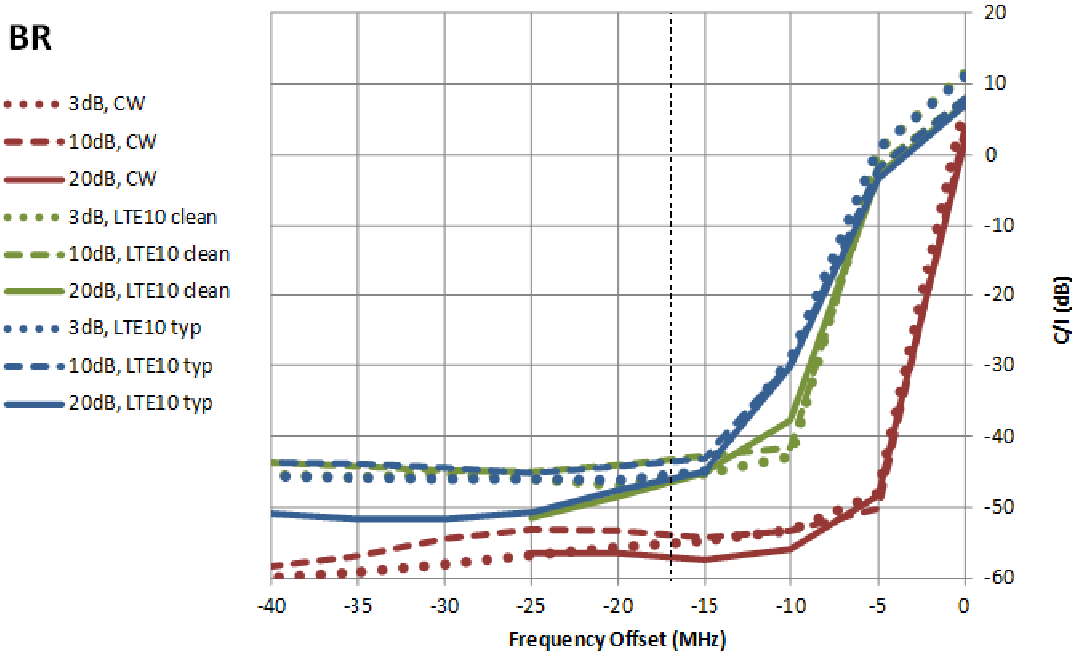


Figure A4 TDD LTE signal spectra.

Results

The complete test results are presented in the main report and we reproduce an example taken from Device 1 in Figure A5. These results are typical of those obtained with most of the devices tested. The red curves shown in Figure A5 are for a CW interference source and hence the impact of the interfering signal diminishes rapidly with increasing frequency offset from the centre of Bluetooth Channel 0. When the 10 MHz wide interfering signal is at an offset of 5 MHz it still causes significant interference as the edge of the signal will be directly adjacent to Bluetooth Channel 0. By 10 MHz offset the interference effect has almost reached its minimum level for typical BS interference (green curves), but the effect of higher OOBE levels from typical UEs (blue curves) can still be seen. However, by the minimum offset that would result from the proposed band plan (17 MHz indicated by the dashed vertical line) there is no apparent difference between the interference caused by a BS or a UE. The same effect is observed with both BR and EDR modes.

One obvious characteristic of the results in Figure A5 is that the curves relating to TDD LTE interference never reach the same level as those for the CW signal, indicating that blocking is not the only interference mechanism. This behaviour was observed for eight of the ten test devices and the conducted measurements we collected using Device 4 (see Figure A5) indicate that the cause is non-linear distortion within the Bluetooth receiver. For the CW (red) curves in Figure A5 we observe that a 10 dB increase in interference level counteracts a 10 dB increase in Bluetooth signal margin. However, when the interfering signal is either a 10 MHz or 20 MHz TDD LTE signal it only takes a 3 dB increase in interference to counteract the 10 dB increase in Bluetooth margin. This result is consistent with the expected behaviour of a third-order non-linearity, which will create odd-order intermodulation products of the interfering signal that appear as co-channel interference to Bluetooth. Because third-order products grow by 3 dB for every 1 dB increase in the fundamental signal level, this explains why a 3 dB increase in out-of-band interference can counteract a 10 dB increase in Bluetooth signal margin.



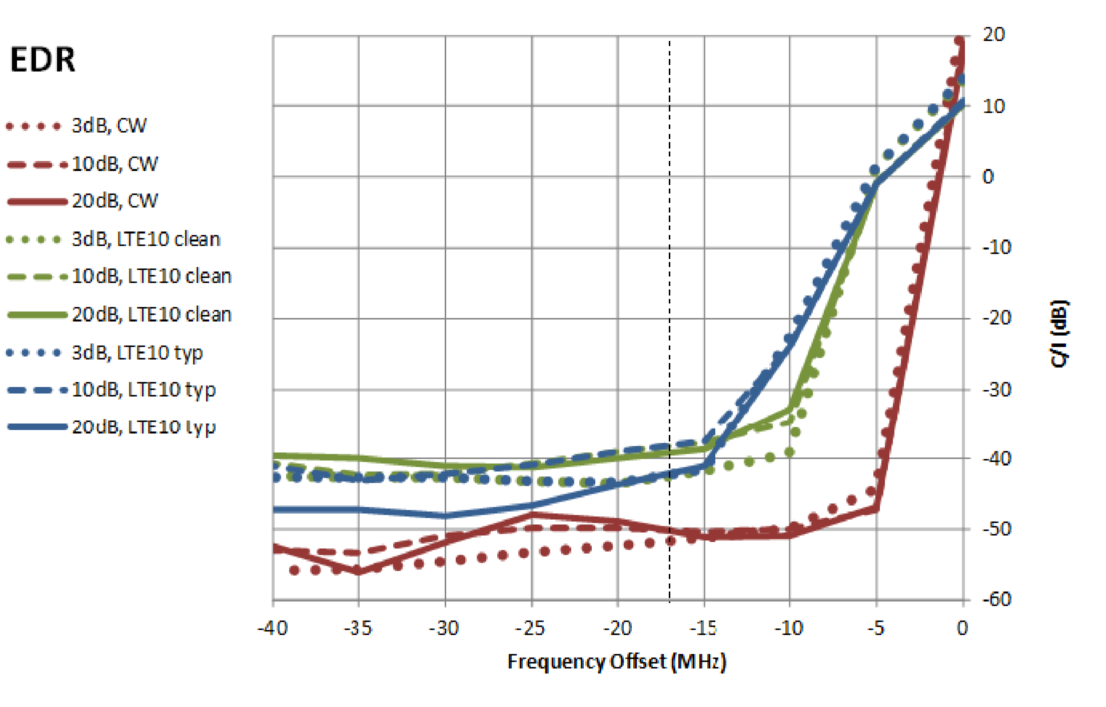


Figure A5 Typical measurement results.

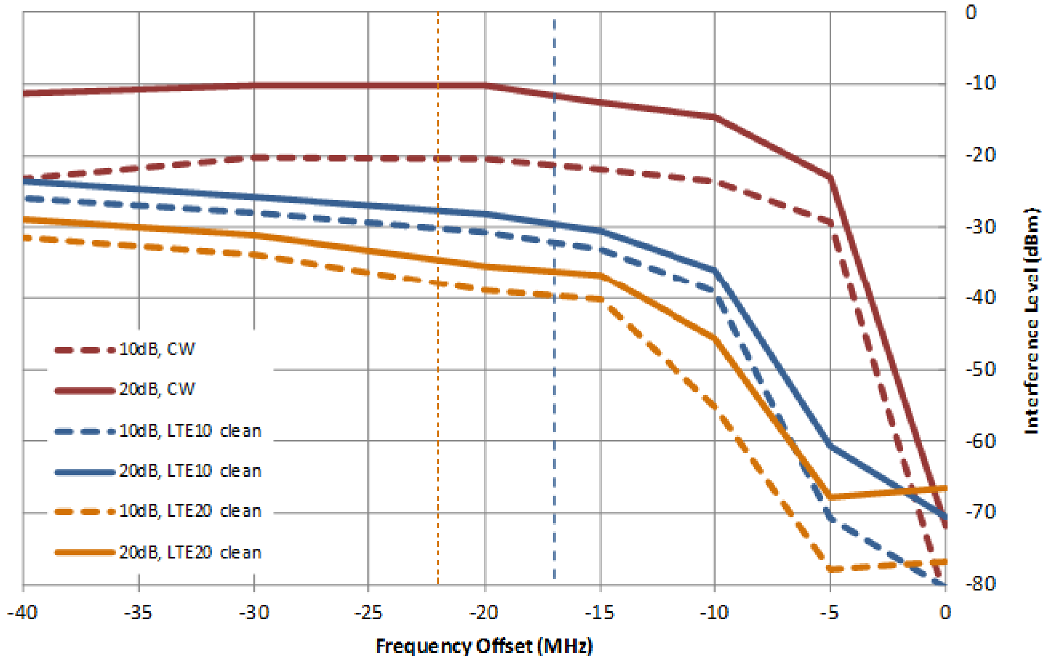


Figure A6 Conducted measurement results on Device 4.

Other findings from the measurements can be summarised as follows.

- TDD LTE transmit-to-receive duty cycle had no noticeable impact on the interference suffered by Bluetooth devices.
- EDR mode is approximately 5 dB more sensitive to interference than BR, because of its use of higher order modulation.
- LE and BR modes show similar performance, though there is some evidence that LE narrowly outperforms BR, possibly by virtue of improved receiver sensitivity.
- There is approximately 10 dB variation in the susceptibility to interference across all devices.
- The adaptive frequency hopping mechanism employed by Bluetooth as a way of mitigating interference is very effective at combating interference on the lower Bluetooth channels.

To draw some objective conclusions about the proximity to TDD LTE equipment that Bluetooth devices could tolerate we used the measurement results to calibrate a simple model of receiver behaviour. The model assumed the following.

- Inverse square law propagation between the Bluetooth devices.
- A breakpoint model for path loss between Bluetooth devices and the TDD LTE interferer, with inverse square law propagation up to 50 m and an inverse fourth order law beyond 50 m.
- A receiver with wideband automatic gain control (AGC) that keeps the blocking level constant once the interference signal exceeds -30 dBm.
- No frequency hopping and Bluetooth operation on Channel 0.

Based on this model we obtain the results shown in Figure A6, which charts the protection distance that is required from a TDD LTE BS as a function of the Bluetooth device separation.

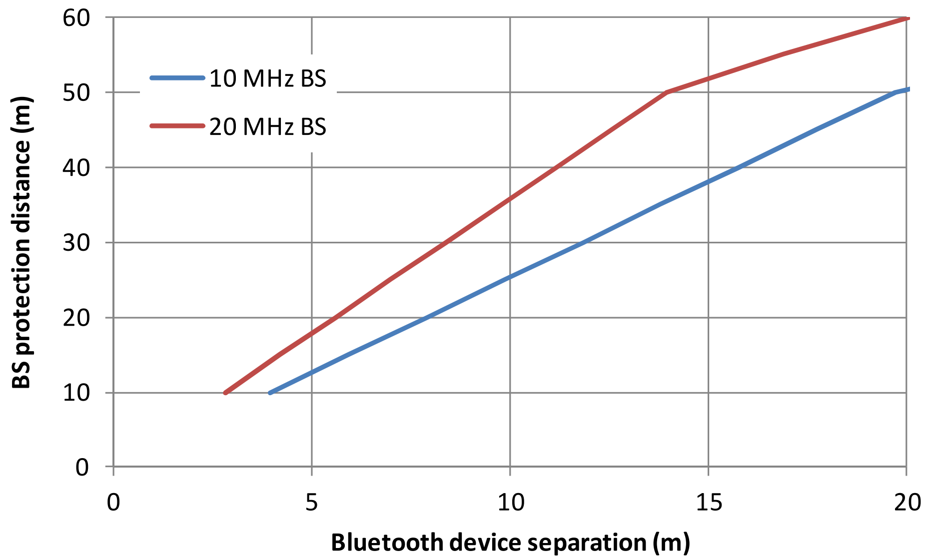


Figure A7 Estimated protection distance required between a Bluetooth device and a TDD LTE BS or UE as a function of Bluetooth device separation.

This model predicts that, without frequency hopping, Bluetooth devices operating on Channel 0 at a typical separation of a few metres could tolerate interference from a 10 MHz BS at less than 10 m or a 20 MHz BS at 15 m. We caution that this model should be taken as a rough guide and real world performance will be heavily influenced by local propagation issues.

The clear conclusion from our tests is that the most significant interference mechanism is Bluetooth receiver blocking. The test results also show that OOBEs from TDD LTE equipment can influence Bluetooth links, but at the smallest proposed frequency offset typical UE emissions and worst case BS emissions would have no impact. We observed that for reasons of cost typical Bluetooth devices operate without a bulk front-end filter and thus rely on linearity and AGC to provide protection against strong out-of-band signals.

All of our quantitative testing was conducted under controlled conditions so that meaningful comparisons could be carried out across the range of test devices. However, the use of specific test modes meant that the test conditions were not truly representative of the typical operating modes employed by applications of Bluetooth. To investigate how a typical audio device would react to interference we undertook qualitative listening tests on three of the test devices. Each headset device was paired with a mobile phone, the devices separated by a few metres and the phone set to stream audio to the headset. Whilst listening to the audio a TDD LTE interfering signal was introduced through a radiated path in close proximity to the headset. With all three devices, only when the interfering signal level reached very high levels (15 dBm into the antenna at a few centimetres separation from the headset) could any distortion of the audio be heard and only in one case could we introduce enough interference to break the Bluetooth link.

Thus, both the quantitative and the qualitative test results provide a clear indication that Bluetooth devices are robust in the presence of interference and support the conclusion that users of Bluetooth devices are unlikely to notice any impact if TDD LTE services are introduced in Band 40.

Prepared by Multiple Access Communications Ltd
May 2013

Table of Contents

List of Abbreviations

ACP	Adjacent channel power
AFH	Adaptive frequency hopping
AGC	Automatic gain control
ALC	Automatic level control
BER	Bit error rate
BR	Basic rate
BT	Bluetooth
CO	Connection oriented
CRC	Cyclic redundancy check
CW	Continuous wave
DQPSK	Differential phase-shift keying
DTM	Direct test mode
DUT	Device under test
EDR	Enhanced data rate
EPL	End product list
eSCO	Extended synchronous connection-oriented
ETSI	European telecommunications standards institute
EVM	Evaluation module
FDD	Frequency division duplex
GFSK	Gaussian frequency-shift keying
GPIB	General purpose interface bus
HS	High speed
IC	Integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, scientific and medical
LE	Low energy

LPB	Loopback
LTE	Long-term evolution
OFDM	Orthogonal frequency-division multiplexing
OOBE	Out of band Emissions
PAD	Matched attenuator
PC	Personal computer
PER	Packet error rate
PRD	Product reference document
QDL	Qualified design list
QPL	Qualified products list
RF	Radio frequency
RFTP	Radio frequency test packet
SAW	Surface acoustic wave
SC-FDMA	Single carrier frequency domain multiple access
SCPI	Standard commands for programmable instruments
SIG	Special interest group
TDD	Time division duplex
UE	User equipment

1 Introduction

By the year 2020 the UK Government plans to have released 500 MHz of radio frequency spectrum below 5 GHz and this spectrum will be reallocated for commercial use. As a part of this plan in 2014 the Ministry of Defence (MoD) intends to take to market spectrum within the band 2310 MHz to 2400 MHz[2]. A likely application of this band will be for mobile radio services using the Time Division Duplex (TDD) mode of the Long Term Evolution (LTE) standard. In LTE nomenclature this frequency range will be referred to as Band 40.

Immediately adjacent to Band 40 is the industrial, scientific and medical (ISM) band between 2400 MHz and 2483.5 MHz, which is an unlicensed spectrum band available to all users on a non-protected basis provided that equipment satisfies restrictions on radiated power, duty cycle and out of band emissions (OOBE). With the explosion in the number of wireless devices over the last 20 years the ISM band has become widely used by many short range radio systems, with IEEE 802.11 (WiFi) and Bluetooth (BT) systems dominating the market.

If TDD LTE is deployed in Band 40 there will be the possibility of interference from systems operating at the high frequency end of Band 40 into systems operating at the low frequency end of the ISM band. Two possible band plans, based on either 10 MHz or 20 MHz TDD LTE channels are illustrated in Figure 1. In both cases the upper edge of the highest frequency channel lies at 2390 MHz, which is just 11 MHz from the lower edge of the lowest frequency Bluetooth channel. Although users of the ISM band have no guarantee that their equipment will be protected, Ofcom wishes to control the introduction of systems in Band 40 to avoid major disruption to ISM band users. In particular, there is concern that Bluetooth devices may be susceptible to interference from TDD LTE because Bluetooth was designed to be a simple and low cost radio link and typically devices have very little front-end filtering to reject adjacent band signals. Furthermore, the possibility exists that the interference avoidance mechanisms within the Bluetooth protocol might automatically restrict the frequencies used, effectively constraining Bluetooth devices to the upper part of the ISM band in affected areas.

---

[2] MoD statement on sharing defence spectrum, published on 12 Dec 2012, available at https://www.gov.uk/sharing-defence-spectrum

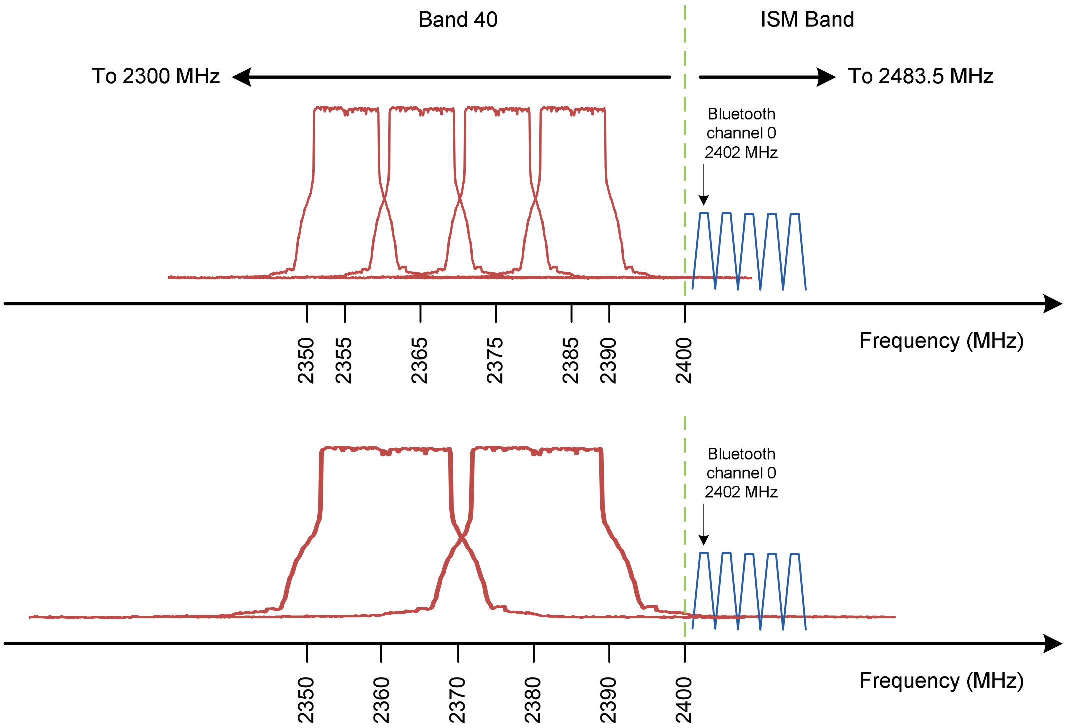


Figure 1 Potential band plans, for 10 MHz and 20 MHz bandwidth TDD LTE systems.

To evaluate the severity of interference from TDD LTE systems operating at the top end of Band 40 into Bluetooth Multiple Access Communications (MAC) Ltd has conducted tests on a range of Bluetooth devices. This report presents the results of these tests followed by an analysis of the results to establish whether or not Bluetooth systems will be affected by the presence of adjacent TDD LTE signals and, if so, to what extent?

This report is divided into four parts: in Section 2 we present a Bluetooth market analysis leading to the selection of our test devices; in Section 3 we describe the measurement system and methodology; in Section 4 we present the raw measurement results taken from a range of Bluetooth test subjects; and in Section 5 we analyse the results to answer the question posed above.

2 Bluetooth Market Analysis

To gain a better appreciation of the relative mix of Bluetooth products in the marketplace we have conducted a survey based on the Bluetooth Special Interest Group (SIG) database of qualified parts [1]. However, whilst that information provides a complete list of Bluetooth products that have been qualified by the Bluetooth SIG, procedural changes introduced throughout the life of the document mean that the data are not stored in a uniform manner. Overall, the database can be viewed as three distinct lists;

1. Qualified Products List (QPL)
2. Qualified Design List (QDL)
3. End Product List (EPL)

The QPL was used up to 2007, and its use coincides with the period during which third party testing of Bluetooth devices was mandated by the SIG in order to achieve qualification. This qualification process was governed by Version 1.0 of the Product Reference Document (PRD). In 2005 Version 2.0 of the PRD was released, which offered device manufacturers the opportunity to self-certify their products, with random checking applied to maintain quality. A two-year transition period gave manufacturers time to make the necessary changes to their procedures. Products qualified under PRD 2.0, and now PRD 2.1, are listed in the QDL. The EPL is an extension of the QDL to accommodate the situation when a single qualified design has been used in several end products. For example, the same hardware design may be used in a range of mobile phones, with the application layer software being the differentiation between the products. In this situation manufacturers may qualify the design once and use it in several end products, so the design is listed in the QDL and the derivative products in the EPL. Inspection of the database revealed that all devices listed in the EPL correspond to one entry in the QDL, but devices listed in the QDL might not appear in the EPL unless they are used in two or more end products. Since it does not unduly affect our analysis we have omitted listings in the EPL from the data used to produce the following charts.

Comparing the numbers of qualified devices listed in the QPL and QDL shown in Figure 2 we see immediately that the there was an upsurge in the number of Bluetooth devices qualified between 2004 and 2007, but since then the number of new devices qualified each year has held steady at around 1300 devices per year. Looking at the cumulative data shown in Figure 3 we see that by the end of the six-year period to 2006 approximately 4000 devices had been qualified, but over the next six years twice that number, 8000, were qualified.

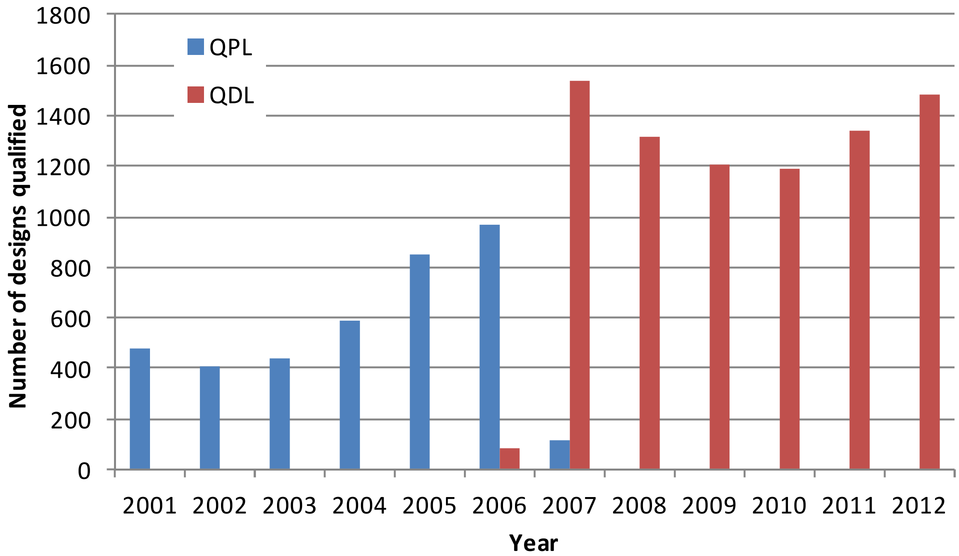


Figure 2 Number of Bluetooth devices added to the QPL and QDL per year.

From these data we might initially conclude that approximately a third of devices in use were qualified under the QDL. However, the QDL contains all devices qualified prior to Version 1.2 of the Bluetooth core specification. During this period of time there were many changes to the specification and products based on V1.0 and V1.1 often suffered compatibly problems, thus it seems likely that many of these devices will have reached the end of their useful life. Nevertheless, one of the earliest market sectors to adopt Bluetooth was automotive and since in general cars have a longer life than portable electronic products some devices based on pre-V1.2 specifications are likely to remain in use. Therefore, we should not overlook pre-V1.2 devices from our test program.

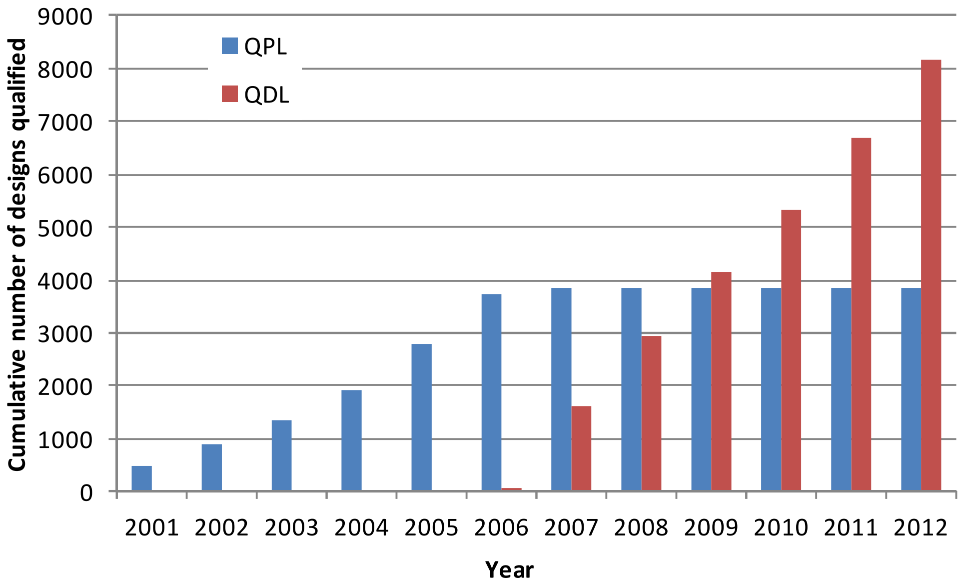


Figure 3 Cumulative number of Bluetooth devices listed in the QPL and QDL.

Figure 4 and Table 1 show the number of products qualified against V1.2 and later versions of the Bluetooth specification. For clarity, and since they do not introduce any features that would influence interference susceptibility, we have rolled up all interim versions, so V2 includes V2.0 and V2.1, etc.

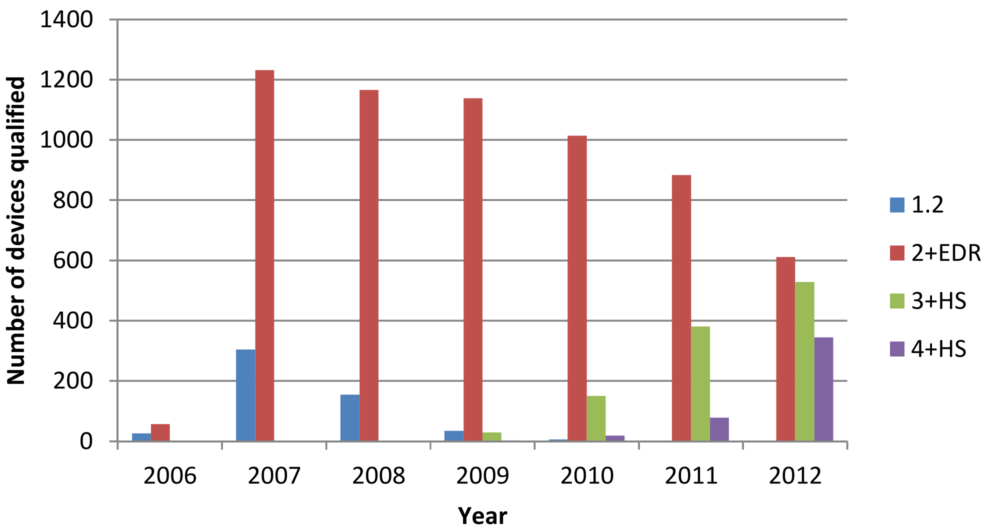


Figure 4 Number of devices qualified against versions 1.2, 2, 3 and 4 of the Bluetooth standard per year.

It is clear from these data that, despite being the first stable release, V1.2 was rapidly overtaken by V2. Furthermore, as V3 does not introduce any physical layer adaptations to

Bluetooth, as far as our test programme is concerned we can consider V2 and V3 to be equivalent.

Revision	Total Devices Qualified
1.2	524
2+EDR	6102
3+HS	1088
4+HS	445

Table 1 Total number of devices qualified against versions 1.2, 2, 3 and 4 of the Bluetooth specification by the end of 2012.

The number of qualified devices based on V4 is showing early growth and we expect that eventually such devices will dominate the market. The V4 specification introduced the low energy (LE) mode of operation whilst retaining the V2/V3 modes of operation. Pertinent to our current investigation the V4 specification permits devices to operate in either single or dual mode. At the time of writing this report we do not have any data from which to estimate the likely division between LE and other modes. Differences between the basic rate (BR) and LE physical layer specifications are in the main confined to the transmitter, for example, limited maximum power, tighter control of modulation index, relaxed frequency stability and a relaxed OOBE mask. On this basis it seems likely that LE and BR modes will exhibit similar susceptibility to interference, but in attempting to reduce the receiver power as much as possible manufacturers may choose to compromise gain compression for power consumption, leading to a greater susceptibility to strong out of band signals. Since this situation is more likely in single mode LE devices our test subjects should, if possible, include such a device.

Data on the mix of Bluetooth product applications are not so freely available. The Bluetooth Products Directory [2] lists all of the devices brought to the market during the last 12 months, grouped into 13 categories. Analysing these data is not entirely straightforward as a single product is often listed under two or more categories. The overlap between Audio and Automotive is particularly significant with 1130 products out of 1207 listed under Automotive also listed under Audio. Similarly there is a large overlap between Headsets and Audio. After using our best judgement to separate the overlaps so that products are counted under the one category that best describes their application we have arrived at the distribution shown by the pie-chart in Figure 5.

Figure 5 shows that Phones, Headsets and Phone Accessories account for 42% of all the new devices launched in the last 12 months, with Automotive accounting for another 18%. As the majority of Automotive products listed are hands-free car kits it is clear that the Bluetooth market is currently dominated by products fulfilling the original concept for Bluetooth - short range audio transmission.

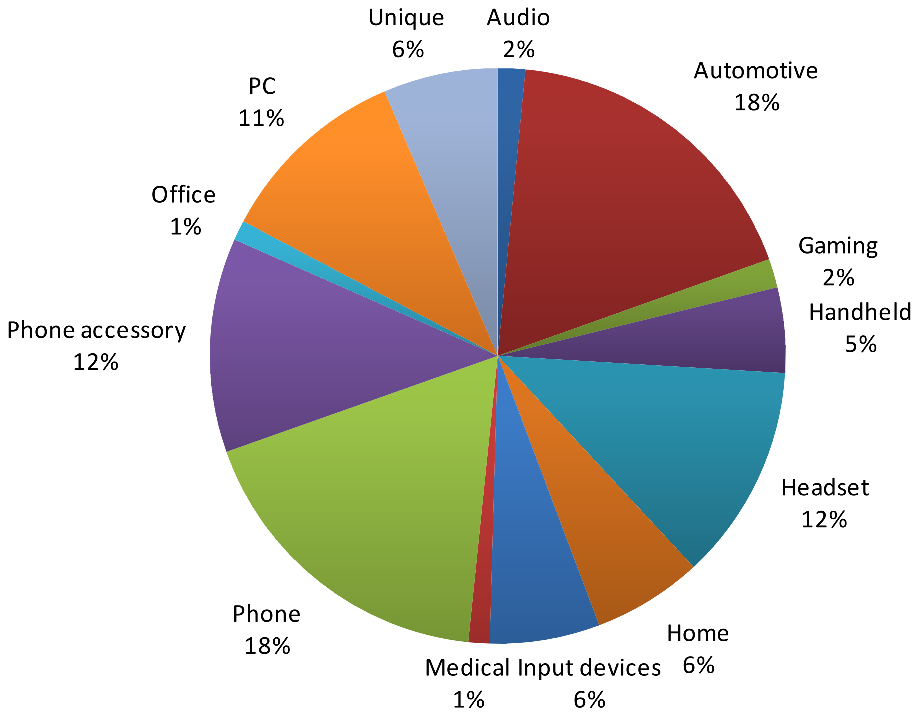


Figure 5 Bluetooth devices launched in 2012 by product category.

A more detailed product breakdown is shown in Figure 6, which shows the product distribution by application. Due to the difficulty in separating devices that fit into two or more categories there are some discrepancies between Figure 5 and Figure 6, but nevertheless the data serve to show the general product distribution trend. When interpreting these figures we must remember that the data relate to the number of different products on the market and not the number of products sold. The latter could, and probably does, have a significantly different distribution. For example, although mobile phones and cars show a similar number of products (18% and 14% respectively) we would expect that many more mobile phones than cars with Bluetooth are actually in use.

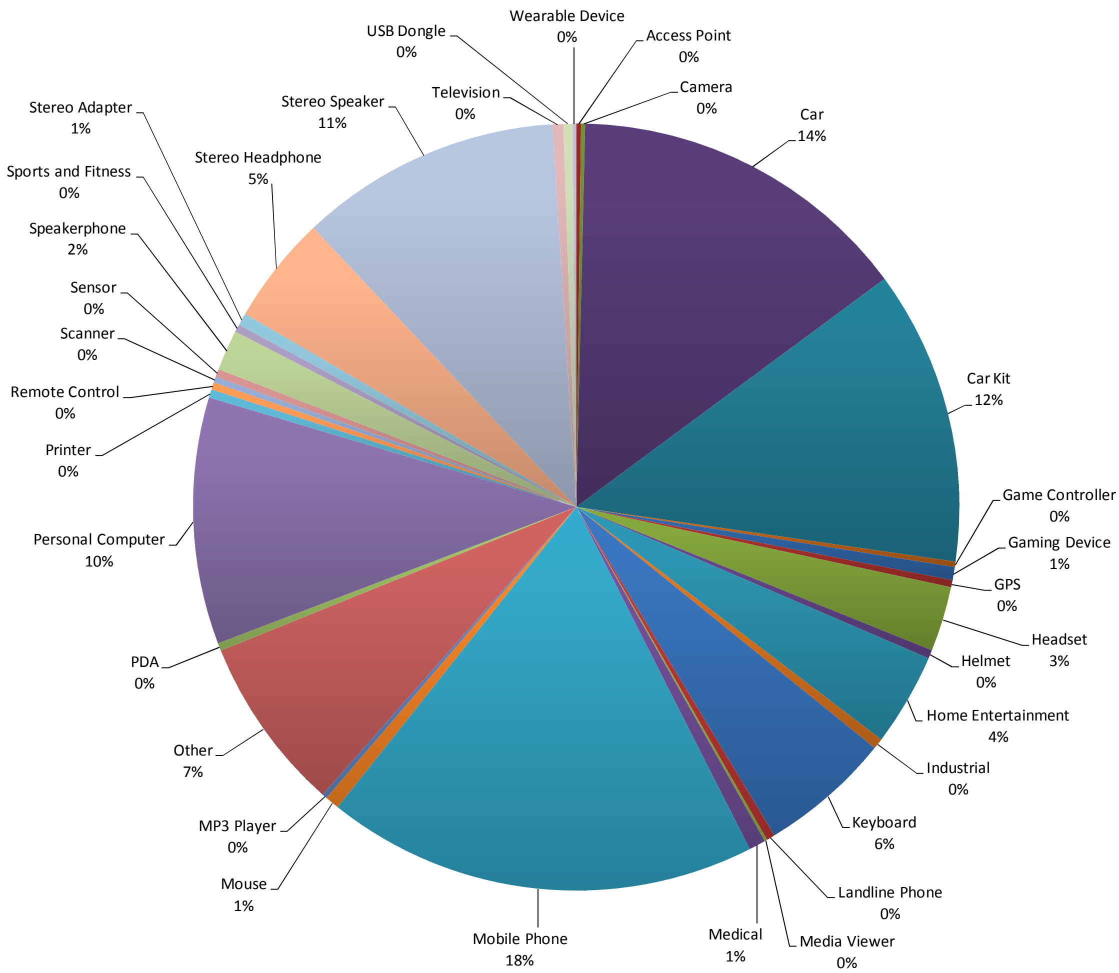


Figure 6 Bluetooth devices launched in 2012 by product application.
Categories listed as 0% should be interpreted as less than 1%.

2.1 Bluetooth Devices

A summary of the ten devices chosen for testing is given in Table 2, which lists the device type, the version of Bluetooth with which it complies, the supported Bluetooth modes and provides the Bluetooth integrated circuit (IC) vendor in anonymous form.

For reference, the evolution of the Bluetooth standard from the initial Version 1 release to the latest Version 4 products is summarised as follows (for further details see the detailed change list in the Bluetooth specification [3]).

1 V1.0 (1999) defines *Basic Rate* (BR) mode which utilises Gaussian frequency shift keying (GFSK) to achieve a data rate of 1 Mbps.

2 V1.2 (2003) introduced the possibility of error detection and limited retransmission of synchronous data packets (as used for voice), providing some error protection for audio signals. This feature is termed extended synchronous connection-oriented (eSCO) packets. Also introduced adaptive frequency hopping (AFH).

3 V2.0 (2004) includes BR and optionally includes *Enhanced Data Rate* (EDR) which utilises either π/4-DQPSK (differential quadrature phase shift keying) to achieve a data rate of 2 Mbps, or 8DPSK (eight phase differential phase shift keying) to achieve a data rate of 3 Mbps.

4 V3.0+HS (2009) primarily extends V2 by adding support for an 802.11 data link. It also adds some other services.

5 V4.0 (2010) is also known as *Low Energy* (LE) and marketed as "Bluetooth Smart". It uses a very similar radio to the original BR mode, but with some restrictions and relaxations to aid power saving. Most of the changes are in the protocol stack, including a low energy link layer and a restriction on network topology to a star.

Device	Type	IC Vendor	BT Version	BT Modes Supported
1	Phone	1	2.1	BR, EDR
2	Phone	1	2.0	BR, EDR
3	EVM	2	4.0	LE
4	EVM	3	4.0	LE
5	Phone	1	4.0	BR, EDR, LE
6	SatNav	4	2.1	BR
7	Keyboard	1	3.0	BR, EDR
8	Hands-free kit	5	2.1	BR, EDR
9	Headset	6	1.2	BR
10	Headphones	5	2.1	BR, EDR

Table 2 Summary of the Bluetooth devices tested.

2.1.1 Adaptive Frequency Hopping

Pertinent to our later analysis of the measurement results is the ability of Bluetooth devices to find and avoid channels that are in use by other ISM band systems and so for background information we provide a brief summary of this capability below.

Bluetooth was designed to share the ISM band with other wireless devices, and one of the ways it manages this is by using AFH. AFH was introduced in v1.2 of the specification and as it plays a significant role in protecting Bluetooth links from interference and is therefore pertinent to this study, we briefly describe its capabilities below.

From the standard ([4] Volume 1, Part A, Section 1.1):

> *"The hopping pattern may be adapted to exclude a portion of the frequencies that are used by interfering devices. The adaptive hopping technique improves Bluetooth co-existence with static (non-hopping) ISM systems when these are co-located."*

Bluetooth's baseband resource manager is responsible for all access to the radio medium, including the management of the six different hopping sequences. Two of the hopping sequences are used for the Paging and Page Responses, another two for the Inquiry and Inquiry Responses and the fifth sequence is the Basic channel hopping sequence, which uses the full 79 carrier frequencies. The sixth sequence, the AFH sequence, is based on the Basic channel hopping sequence, but utilising between 20 and 79 carrier frequencies. The master device in the pico-net maintains a list of available carrier frequencies (the AFH_channel_map), which is a list of up to 79 carriers with the known contended carriers removed. Whilst the standard defines how carriers are defined ("Good", "Bad" and "Unknown"), and where the information may come from (the Master's own measurement or information from a Slave), it does not define how the data are used, leaving that algorithm to the device or chip set designer. Consequently, the interference avoidance behaviour will vary from one Bluetooth device to another.

3 Measurement System and Methodology

Whilst Bluetooth devices are operating in accordance with their intended application it is difficult to make any form of quantitative measurement of the radio performance. To accurately test link performance devices must be placed in a special test mode, which allows access to the raw data flowing across the link and thus permits bit error rate (BER) measurements. Whilst the Bluetooth Standard supports such a mode of operation it also mandates that it must not be possible to enable this mode via the air interface; to prevent this accidentally happening when devices are deployed. Thus, even though it exists in most cases it is not accessible without an intimate knowledge of the product.

During our preliminary tests we identified that objective link performance measurements can be made without entering test mode if the device under test (DUT) will enter and maintain an asynchronous link with a radio test set. We found that this approach worked with some devices, but others simply timed out and dropped the link after a short period, preventing any reliable measurement. For those devices that would hold a link it was possible to measure packet error rate (PER) by sending packets to the device under test and counting the number of missing acknowledgements. A major difference between BER measurements made in test mode and PER measurements using an asynchronous link is that in the latter frequency hopping cannot be disabled and this will tend to mask the effects we are attempting to observe on Bluetooth channel 0. On the other hand this mode is more representative of devices operating normally and so test results obtained this way are indicative of real world performance.

In the remainder of this section we describe the test system configuration, verification and calibration; the TDD LTE signal generation; the Bluetooth devices tested; and the test methodology employed.

3.1 Hardware Configuration

Although it is the absolute levels of the wanted signal and any interferers at the input to the DUT's radio that will determine the severity of any interference problems, the presence of an air gap of unknown attenuation in our test system, which is a consequence of not having access to an antenna connector, means that we cannot determine absolute levels at the antenna of the DUT. Thus, the primary measure used to assess the impact of the interference is the Carrier-to-Interference (C/I) ratio that can be tolerated by the DUT for a range of frequency separations between the wanted Bluetooth signal (C) and the unwanted interference (I).

To measure C/I we used a test environment that could provide known signal levels at the test antenna with the capability to independently adjust both the C and I components whilst measuring the link error rate. On the assumption of a flat frequency response between the test antenna and the DUT the C/I at the test antenna is equal to the C/I at the DUT. From our initial frequency sweeps of the test environment (see Section 3.2) we observed that depending upon the relative positions of the antenna and the DUT this assumption does not always hold, however, the blocking tests conducted on each device provided a good indication that the assumption was valid for most tests.

Due to the presence of a radiated path into the DUT[3] other signals in the ISM band were a potential source of interference to the measurements. To protect against this possibility all of the quantitative tests were performed with the DUT inside a screened enclosure.

Figure 7 shows the test system configuration. The Bluetooth signal was provided by a Rohde and Schwarz CBT Bluetooth test set, the interfering signal by a Rohde and Schwarz SMBV100A signal generator (which we abbreviate to SMBV in the remainder of this document) and the screened enclosure was a TESCOM TC-5916A. During tests these instruments were either configured manually from their front panels or remotely using the control personal computer (PC). When running automated tests the control PC was connected to the instruments via a general purpose interface bus (GPIB) adaptor and ran MATLAB scripts that generated standard commands for programmable instruments (SCPI) commands to control both instruments.

---

[3] One device was physically modified by having an SMA coaxial connector soldered to the end of its PCB antenna track, facilitating a wired link.

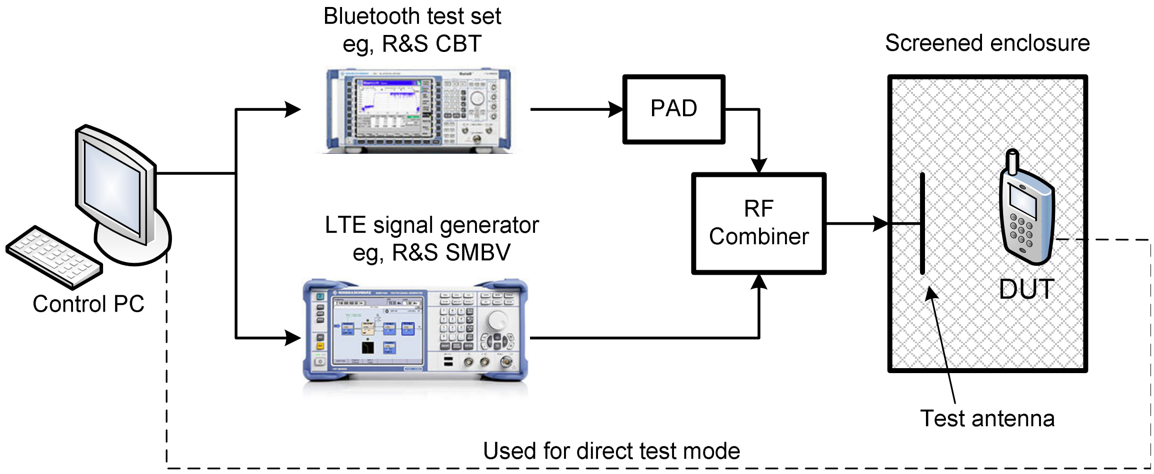


Figure 7 Measurement system configuration.

The matched attenuator (PAD) on the output of the CBT was used to both ensure the CBT's output was well matched to its load and to isolate the CBT from the signal produced by the SMBV. As the interferer's frequency offset increases the power needed to achieve the reference error rate also increases causing high levels of interference to appear at the CBT's receiver input. Thus, to avoid our measurements being influenced by error in the DUT-to-CBT link, the PAD was selected to provide the maximum possible isolation between the CBT and the SMBV whilst still permitting the CBT to generate enough power to provide a Bluetooth signal of the required power at the DUT. Since this was dependent upon the sensitivity of the Bluetooth device we found that it was occasionally necessary to adjust the PAD. For most tests a 20 dB PAD was used, however, for some tests it was necessary to reduce this to 10 dB and in others the system could tolerate 30 dB. The radio frequency (RF) combiner was a simple resistive type, introducing nominally 6 dB of attenuation.

A secondary consequence of using the interfering signal generator at the extremes of its transmit power capabilities is that the fidelity and power control of the generated signal was compromised. When the interferer was within 20 dB of the SMBV's maximum power a warning message stating that the automatic level control (ALC) loop was not within specification was displayed and the OOBEs could be seen to increase.

Figure 8 shows the measurement system, with the screened chamber open and closed.

Figure 8 The measurement system. CBT on top of SMBV, screened chamber open (top) and closed (bottom), and FSW spectrum analyser on the right.

3.2 Test Environment Calibration and Verification

Prior to conducting any tests on Bluetooth devices we conducted a range of tests to verify that the test environment was providing sufficient isolation to external signals, to check the frequency response of the air path between the antenna and the DUT and to calibrate cable and combiner losses.

3.2.1 Screened enclosure isolation

To check the isolation we connected the antenna inside the screened enclosure to a spectrum analyser and the signal generator to another antenna outside the enclosure. With the lid of the enclosure open we adjusted the signal generator power so that the spectrum analyser registered a signal level of -10 dBm. We then closed the lid of the enclosure and noted that the level indicated by the spectrum analyser fell to -63 dBm, indicating 53 dB of isolation.

This is slightly less than the 60 dB claimed for this enclosure in the device data sheet, but sufficient to attenuate any stray Wi-Fi signals to insignificant levels.

3.2.2 Air path frequency response

In order to check the frequency characteristic within the screened test chamber we added a second antenna to detect the radiated signal and connected them to a signal generator and spectrum analyser as shown in Figure 9.

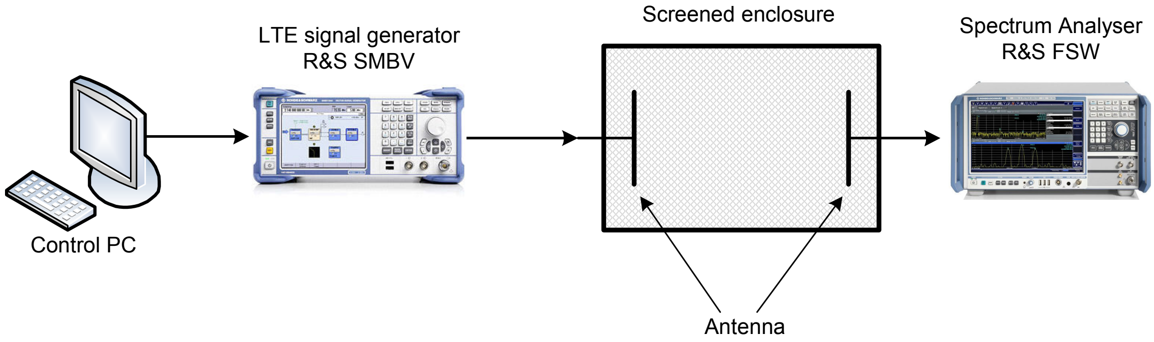


Figure 9 Testing frequency response of test chamber.

The SMBV signal generator was set to transmit a continuous wave (CW) signal at 0 dBm and the FSW spectrum analyser was configured to display the frequency range 2350 MHz to 2450 MHz, with the display trace set to 'Peak Hold'. The SMBV signal frequency was then swept across the same range and the test repeated for several antenna configurations. Figure 10 shows three example antenna configurations and Figure 11 shows the corresponding frequency responses.

Figure 10 Example antenna configurations. Described, from left to right, as "45 degrees", "Parallel" and "Perpendicular".

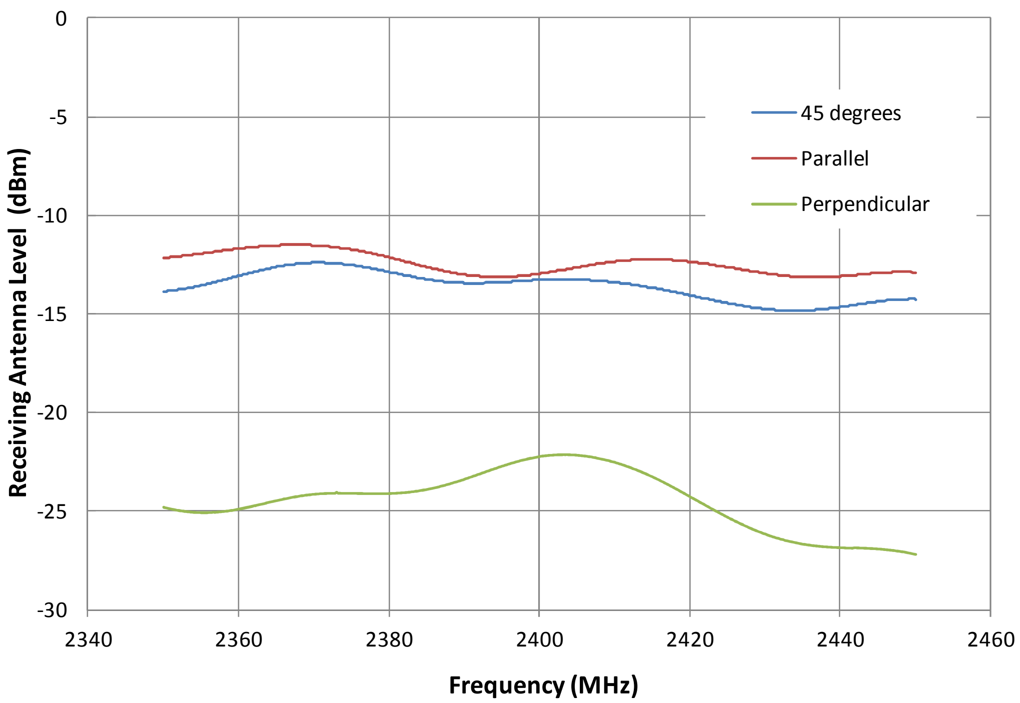


Figure 11 Three frequency responses captured within the test chamber.

Repeating these frequency sweeps after minor adjustment of the antenna positions revealed that the response is quite sensitive to position. The curves in Figure 11 show a representative cross section of the results and, after accounting for cable loss, indicate an air gap loss of 12 dB to 15 dB unless the antennas are cross-polarised when the loss increases to 25 dB. Whilst these responses provide an indication of the signal level variations within the screened enclosure they are not a true measure of what the devices under test may experience, because for eight of the devices we have no knowledge of the orientation of the Bluetooth antenna within the device and the antennas in all devices were electrically small in comparison with our test antennas. From observations of the blocking response characteristics over the same frequency range (see for example Figure 19) we do not observe a significant variation in performance, suggesting that during most tests the air path response between the antenna and the DUT has a characteristic that is close to the 'Parallel' curve.

3.2.3 Cable and combiner loss

The total losses in the paths from the CBT and SMBV to the antenna were measured using the SMBV and a Rohde & Schwarz FSW Spectrum Analyser. The loss of the cables, PAD and splitter from the CBT to the antenna was 26.3 dB with the 20 dB PAD and 16.3 dB with the 10 dB PAD. The loss of the cables and splitter from the SMBV to the radiating element was 6.2 dB. These values were entered into the Excel spreadsheets used to plot the various graphs.

3.3 Methods of Measuring Link Performance

Bluetooth link performance was assessed through a receiver sensitivity test, which required a measurement of the link error rate. Whether BER or PER was used to assess the link depended on the version of Bluetooth and whether or not the device could be placed in test mode. For the ten devices we tested there were three different test conditions.

1. *BR and EDR mode devices with test mode enabled*. For these devices we were able to use loopback to make a BER test on a fixed Bluetooth channel.
2. *LE mode devices with test mode enabled*. For these devices we were able to use direct test mode to measure PER on a fixed Bluetooth channel.
3. *All non-test mode devices*. For these devices a connection-oriented PER measurement was made, but hopping could not be disabled.

These three test methods are described in more detail in the following sections.

3.3.1 Loopback test mode

Loopback test mode is a specified feature of the Bluetooth standard, see reference [4] Volume 3, Part D – Test Support, Section 1.1.3, LoopBack Test. In this mode a DUT receives normal baseband packets from a tester, decodes them and returns the decoded payload to the tester. The tester then compares the data it sent with the data returned by the DUT to determine the BER. To ensure that the test is not influenced by errors on the return path signals from the DUT are transmitted at high power.

Of the ten devices we tested only the three mobile phones could be placed in loopback test mode, which was enabled by entering a 'secret' keyboard code. In the case of one phone (Device 5) we also needed to install a 'rooted' operating system to make the test mode feature available.

For all loopback tests the BERs used to define the baseline sensitivity for BR and EDR were 0.1% and 0.01% respectively. These values were chosen because they are the reference sensitivity levels dictated by the Bluetooth specification, see reference [4] Volume 2, Part A, Section 4. Bluetooth devices are required to meet these maximum BERs when receiving a signal level of -70 dBm. Using these figures established a common baseline between all devices and provided a convenient means of accounting for the unknown path loss between the antenna and the DUT. Hence, whilst variations in sensitivity between devices meant that the target BERs would be achieved at different signal levels, by taking this approach we could be sure that each device was tested at the same point on its sensitivity curve.

Loopback tests were made with DH1 packets for BR and 3-DH5 packets for EDR. These packet types do not contain forward error correction, thus the BER measured was a pure measure of the radio link. The payload lengths used were the maximum available for each mode 27 bytes for BR and 1021 bytes for EDR. The packet payload contained a dynamic pseudo-random data sequence to avoid any systematic error due to worst case bit sequences.

For tests on the three mobile phones using loopback mode we fixed the Bluetooth tester to device link on Channel 0 (the lowest frequency, 2402 MHz) and the return link from the device to the tester on Channel 78 (the highest frequency, 2480 MHz). Arranging the channels in this way placed the wanted signal as close as possible to the TDD LTE interferer whilst keeping the return link at the greatest possible frequency separation.

3.3.2 Direct test mode

As with BR and EDR the Bluetooth standard specifies a method of measuring the error rate of a Bluetooth LE link, however, it chooses to use a PER mechanism that does not require loopback (see reference [4] Volume 6, Part F). Because direct test mode (DTM) does not use loopback an additional control interface to the DUT is required to extract the test results. Such interfaces are usually hidden on final products so that test mode features cannot be accessed. To overcome this limitation our LE mode tests were conducted on two chipset evaluation modules (EVMs), which provided the necessary access to enable DTM.

PER tests in DTM consist of three steps:

1. via the test interface, placing the DUT in a mode that it will receive and decode packets;
2. transmitting a sequence of RF Test Packets (RFTPs) from the tester to the DUT; and
3. requesting the DUT to return (via the test interface) the number of successfully decoded packets.

Determining the PER is then a straightforward calculation using the number of packets transmitted and the number of packets received without error.

Whilst DTM provides a mechanism to measure PER, the LE mode physical layer specification (reference [3] Volume 6, Part A, Section 4.1) states a sensitivity requirement of 0.1% BER at -70 dBm input level, which is the same as BR mode. Consequently we need to relate BER to PER. For the RFTPs used in DTM this can relationship can be calculated as follows.

The RFTP contains 376 bits of which 368 are covered by and include a cyclic redundancy check (CRC); the 8-bit preamble is omitted from the CRC. Thus, a bit error in one or more of these 368 bits will result in a packet error. For a BER of 0.1%, the probability that all of the 368 bits in a test packet are received correctly is $0.999^{368} = 0.692$, so the probability that one or more bits are received in error is 1 – 0.692 = 0.308, or 30.8%. Thus, 0.1% BER equates to 30.8% PER and this is the target error rate used for our tests on LE mode devices.

3.3.3 Connection based testing.

This is applicable to the five devices that we were unable to place in test mode. The CBT was able to measure a PER by transmitting packets to the DUT and monitoring the packet acknowledgement back from the DUT. The DUT has no use for the data it receives (as no link has been established) and so throws away the data from the packets, but not before usefully acknowledging whether it received the packet in error or not. These tests could only be carried out in BR mode, with hopping enabled and for consistency we used a 30.8% PER target for the baseline sensitivity.

3.4 TDD LTE Test Signals

Prior to testing we anticipated that there would be two dominant interference mechanisms caused by the presence of adjacent channel TDD LTE signal; co-channel interference (to Bluetooth) due to out-of-band emissions (OOBEs) and blocking due to saturation of the Bluetooth receiver front-end. Choosing a representative level for the OOBEs was important as basing tests on a signal that just meets the LTE specifications would provide a worst case, but pessimistic result, whereas using a very clean signal would produce an optimistic result. Therefore, in these tests we used a range of interfering TDD LTE signals covering representative as well as limiting cases.

In previous work [5] Ofcom has commissioned measurements of OOBEs from frequency division duplex (FDD) LTE user equipment (UE) devices in the 800 MHz band. In the absence of any measurements from TDD user equipment we have taken these as representative of devices that will operate at 2.4 GHz. Ofcom also provided OOBE measurements from a sample FDD LTE base station (BS) operating in the 2.6 GHz band with a 20 MHz bandwidth. Using these data we modified the SMBV's operation to model these responses as closely as we could within the constraints of the filter characteristics provided by its arbitrary waveform generator. The result was a set of 'clean' and 'typical' spectrum characteristics. The 'clean' signals were produced using the 'Balanced EVM and ACP' mode of the SMBV. The 'typical' signals were created by widening the arbitrary waveform generator's interpolation filters thus allowing more signal leakage adjacent to the intended signal band. As the spectral characteristics of a fully loaded downlink are much the same as a fully loaded uplink, to test a different uplink configuration we created another uplink signal using only a fraction of the available resource blocks. This signal used the same filter as the previously created typical signals, but only allocated one UE in the upper 25% of the 10 MHz channel and was only used with frame configuration 0.

We therefore used five different filter spectrum masks, which from now on we will refer to as follows.

1. 10 MHz clean
2. 10 MHz typical
3. 20 MHz clean
4. 20 MHz typical
5. 10 MHz typical, 25% resource blocks

Figure 12 shows the 20 MHz signals produced by the SMBV compared to the sample BS and the European Telecommunications Standards Institute (ETSI) downlink emission mask [6]. To obtain this figure the SMBV was set to transmit at a power level of 0 dBm and its output captured using a spectrum analyser. The results were then scaled to an in-channel power spectral density equal to that of the sample BS (43 dBm in 20 MHz). We can observe from Figure 12 that the clean SMBV signal is a good approximation of the sample BS; the BS is cleaner immediately adjacent to the channel in use, but above 13 MHz offset the SMBV is between 5 dB and 10 dB better. The typical signal from the SMBV is a close approximation to the ETSI emission mask out to 20 MHz and thus results obtained with this signal will be indicative of the worst case scenario.

The spikes that are visible at approximately 22 MHz from the centre in Figure 12 are artefacts of the signal generation process and could not be removed without significantly reducing the OOBE plateau. However, by careful choice of test frequencies we were able to ensure that in all tests these spikes avoided Bluetooth channel 0 and thus did not unduly influence the results.

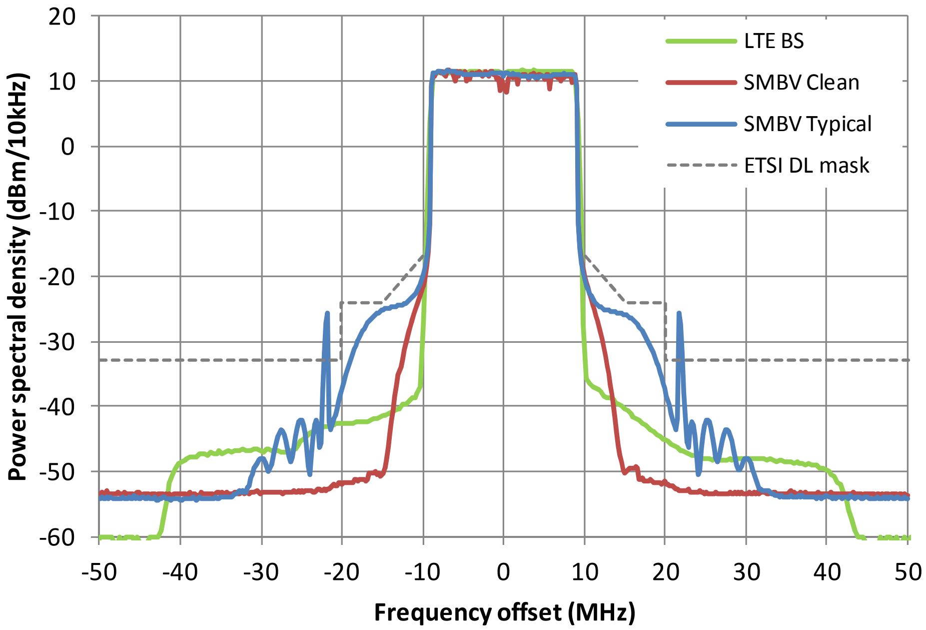


Figure 12 20 MHz TDD LTE signals produced by the Rohde and Schwarz SMBV compared to a sample BS.

Figure 13 shows the 10 MHz bandwidth TDD LTE signals from the SMBV against the ETSI downlink emission mask. In this case we do not have a sample BS for comparison, but we note that the close-in performance of the SMBV is 15 dB better at the channel edge and thus the clean signal is likely to be an even better match for a typical BS than in the 20 MHz case. The typical SMBV signal again approximates the ETSI emission mask limits well out to a 12 MHz offset.

Thus, from the results presented in Figure 12 and Figure 13 we can be confident that our measurements will represent the best and worst case scenarios of interference from downlink TDD LTE signals.

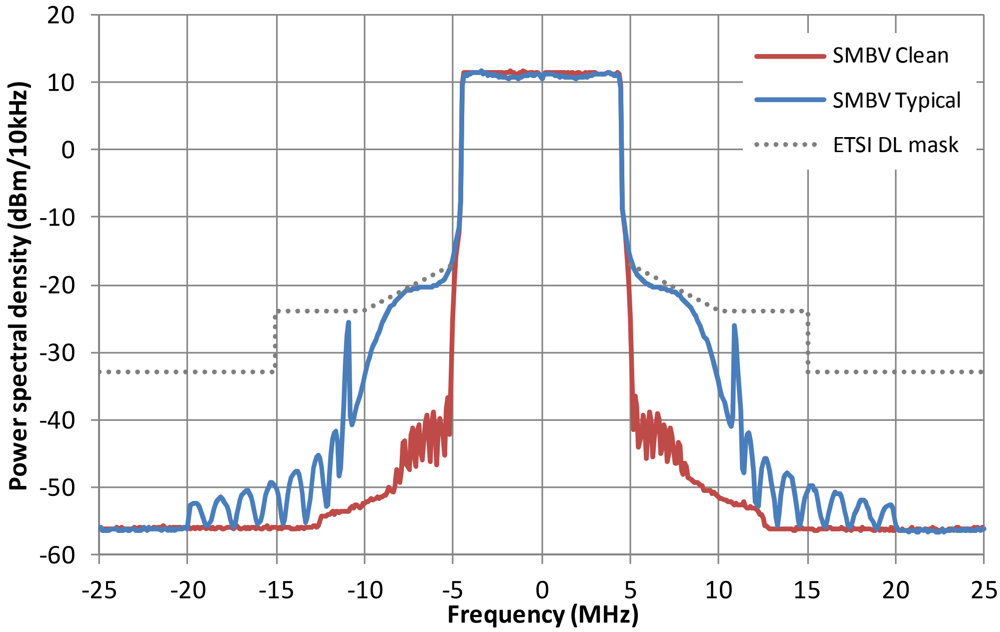


Figure 13 10MHz TDD LTE downlink signals produced by the Rohde and Schwarz SMBV.

For the uplink we have two scenarios to consider: all resource blocks in use by one UE; or a subset of the resource blocks in use by one UE. Since the spectral characteristics of the orthogonal frequency-division multiplexing (OFDM) downlink transmission are very similar to those of the uplink single carrier frequency domain multiple access (SC-FDMA) signal, we can consider the downlink signals already described as a good model of the uplink spectrum when all resource blocks are in use. On this assumption Figure 14 shows the clean and typical 10 MHz signals produced by the SMBV against the ETSI uplink emission mask [7] and a sample UE profile based on the 800 MHz band measurements provided by Ofcom. In this case the SMBV signal has been scaled so that the in-channel power spectral density is -7 dBm/10 kHz, which is equivalent to a UE transmitting at its maximum power of 23 dBm in 10 MHz.

From Figure 14 it is clear that the clean SMBV signal is well within the ETSI emission mask and is likely to be much cleaner than a typical UE. The typical SMBV signal is also well within the emission masks and so does not represent a worst case, but it does correspond well to the sample UE emission profile. In the Ofcom report this particular UE is shown to be a middle case; of the four units tested two were better and one worse.

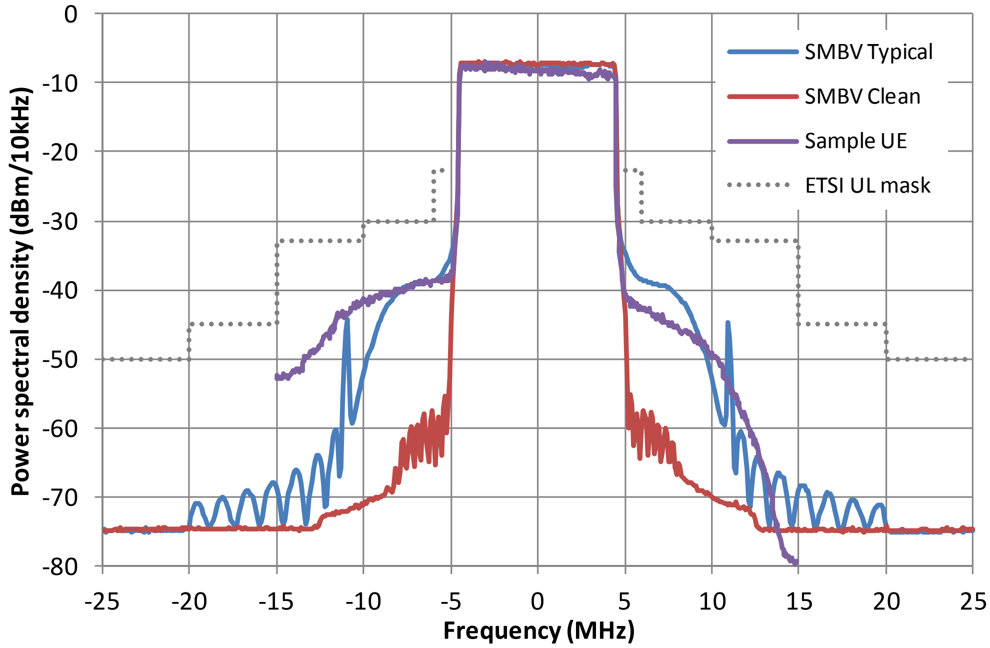


Figure 14 10 MHz TDD LTE signals produced by the SMBV compared to a sample FDD LTE UE.

The sample UE shown in Figure 14 exhibits an asymmetric profile due to the presence of a band filter. The measurements of this UE were made at the upper edge of the band and hence the emissions roll-off faster on the high frequency side due to the attenuation of this filter. The same behaviour can be expected of UEs operating in Band 40 if they also include a band filter, in which case Figure 14 is representative of a UE transmitting on 2395 MHz. Since the typical response from the SMBV is a good match to the high side profile we can consider that our measurements will be representative of a UE with a band filter operating at 2395 MHz, but therefore slightly optimistic compared to a UE operating below 2395 MHz.

An alternative UE transmission that uses just a portion of the available resource blocks and thus concentrates its power in a narrower band was created to check that Bluetooth devices were no more susceptible to signals with this spectral characteristic. In this case the in-channel power spectral density is -1 dBm/10kHz (23 dBm in 2.5 MHz) and the SMBV spectrum compared to the ETSI mask is shown in Figure 15.

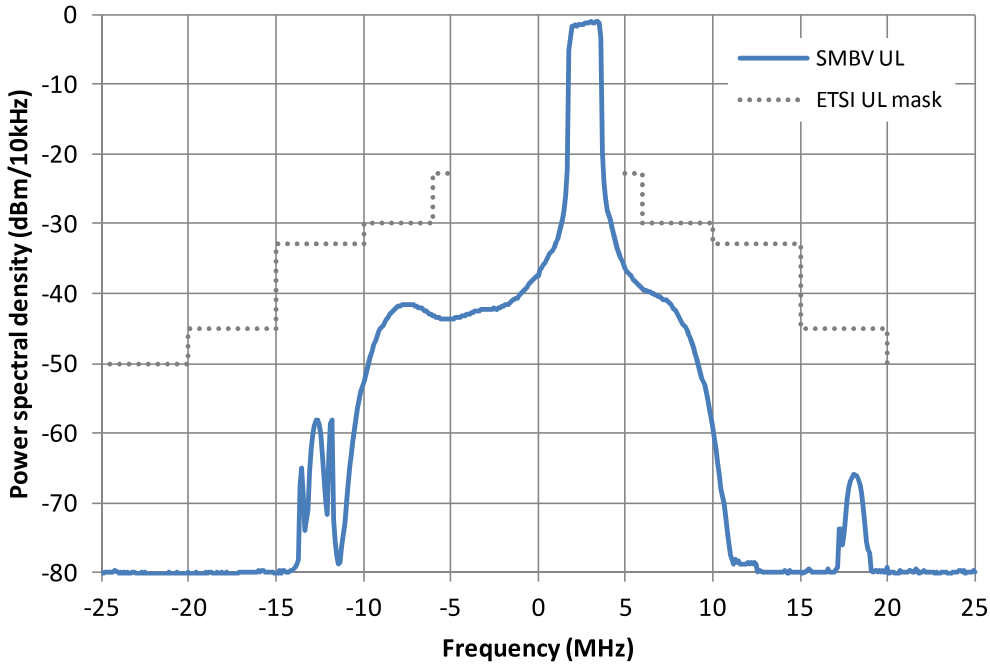


Figure 15 10 MHz TDD LTE uplink signal using the upper 25% of the available resource blocks produced by the SMBV.

The signals described above were used with either LTE frame Configurations 0, 1 or 5. The resource allocations as a function of time for these three modes, generated using the Rohde and Schwarz WinIQSIM2 software, are shown in Figure 16, Figure 17 and Figure 18. In these figures blue and green shading indicates user data. In Configuration 1 the period from 4ms to 5 ms was filled with dummy data as was the period from 3 ms to 5 ms in Configuration 5. As we will explain in more detail later, all devices were tested with Configuration 5, which although populated in the nominally downlink slots, in terms of time occupancy is representative of the worst case uplink or downlink. A subset of devices were also tested with the other configurations so that a comparison could be made.

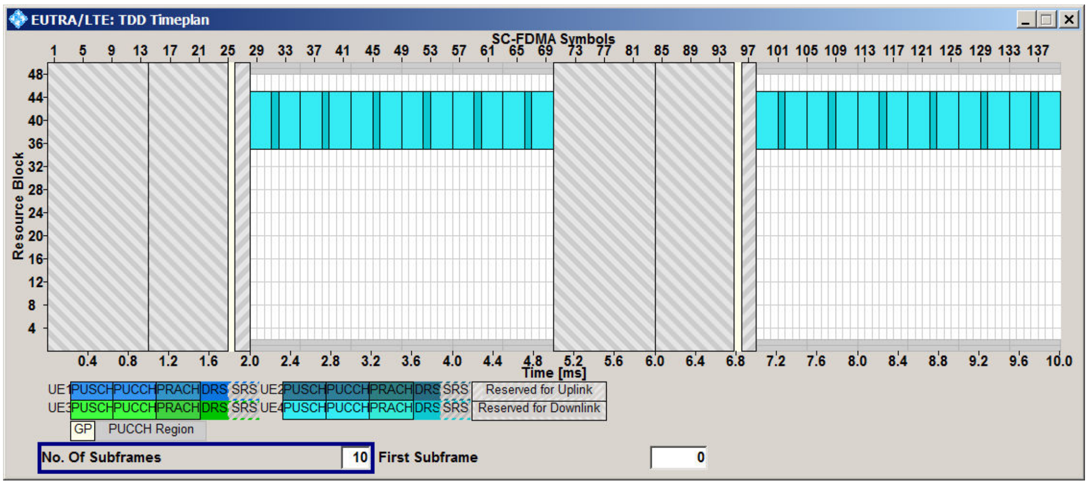


Figure 16 Frame configuration 0, uplink resource allocation.

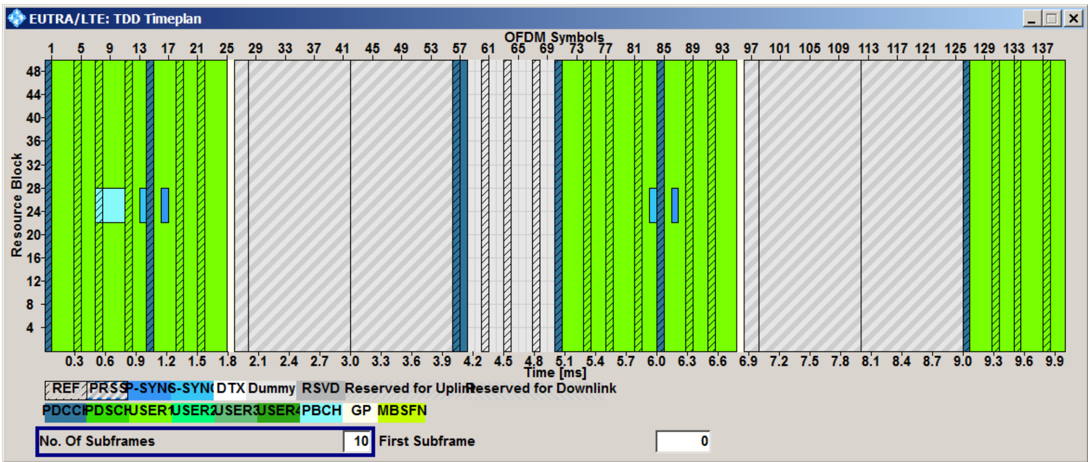


Figure 17 Frame configuration 1, downlink resource allocation.

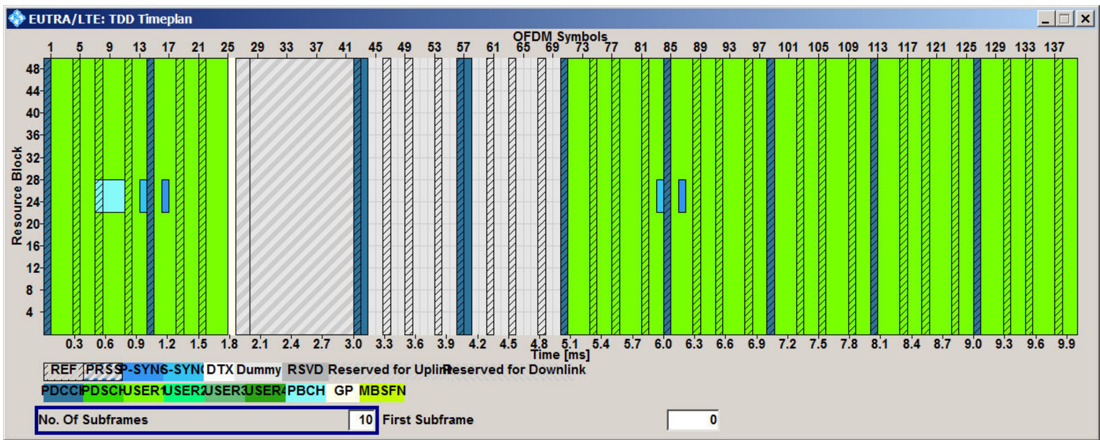


Figure 18 Frame configuration 5, downlink resource allocation.

In summary, the test configurations used and their mapping to TDD LTE equipment are as shown in Table 3.

TDD LTE Frame Configuration	Duty Cycle	10, 20 MHz Clean	10, 20 MHz Typical	10 MHz Typical, 25%
0	70 %			Typical UE
1	50%	Typical BS	Typical UE Worst case BS	
5	85%	Typical BS	Typical UE Worst case BS	

Table 3 Summary of TDD LTE signal configurations.

3.5 Test Configurations

Due to the differing capabilities of the devices and the lack of test mode support in five of the devices it was not possible to test them all in a uniform manner. Table 4 and Table 5 summarise the test methods we were able to employ for each device and the Bluetooth modes that were tested.

Devices 1 and 2 provided the most comprehensive set of results. As test mode could be enabled we were able to measure BER on a fixed Bluetooth channel. Device 4 also allowed test mode to be used but for reasons we were unable to identify did not work reliably in EDR mode and tests were limited to fixed channel, BR mode.

The two EVMs, Devices 3 and 4, operated in LE mode and thus used direct test mode on Channel 0. Direct test mode does not support hopping and so this could not be tested. An additional test was performed on Device 4. The EVM was modified to permit a direct cable connection so that a conducted measurement could be made. In a later section we compare the conducted and radiated results for this device.

Devices 6 to 10 were all tested using the connection-oriented method. This method provided no control over the Bluetooth link and so hopping was always enabled and the mode was fixed to BR. Additionally, Devices 8, 9 and 10 support audio transport and so we were able to perform qualitative listening tests on these.

All devices were tested with carrier wave (CW), typical 10 MHz TDD LTE signals and typical 20 MHz TDD LTE signals, and all but one at 10 dB above the baseline sensitivity level; the one exception was Device 6 (the satellite navigation system), which we found necessary to test at a different PER target and which therefore required interfering powers greater than we could generate with 10 dB uplift. For most devices we also tested at 20 dB uplift and for several also at 3 dB uplift. During early testing we also tried using 30 dB uplift, but dropped this test case because at the power necessary, saturation of the SMBV output resulted in much higher OOBEs than intended thus introducing more severe interference compared to that at lower powers. The 3 dB uplift test cases were introduced to replace the 30 dB cases and 3 dB was chosen because this is the level mandated in the Bluetooth Specification for blocking tests.

The original specification for this work and our initial test plan suggested that measurements would be made with TDD LTE signals at absolute frequencies dictated by the proposed band plans shown in Section 1. However, during early tests we identified that the results would be more instructive by choosing a range of frequency offsets relative to the Bluetooth channel under test and that more points on the curves were required to permit us to analyse the trend. Consequently, the 10 MHz TDD LTE interference was placed at offsets of 0, -5, -10, -15, -20, -30 and -40 MHz, and the 20 MHz interference at offsets of 0, -10, -15, -20, -30, -40, -50 and -60 MHz. Similarly, CW measurements were made in 5 MHz steps from 0 to 60 MHz. In a few cases the C/I at larger offsets could not be measured due to insufficient interference power.

Device	Method	BT Modes Tested	BT Channel	Interference	Frame Config	BT Uplift	Number of Tests
1	LPB	BR, EDR	0	CW	N/A	3, 10, 20	6
			0	LTE10 clean	1, 5	3, 10, 20	12
			0	LTE10 typ	0, 1, 5	3, 10, 20	18
			0	LTE20 clean	5	3, 10, 20	6
			0	LTE20 typ	5	3, 10, 20	6
			Hop	LTE10 clean	5	10, 20	4
			Hop	LTE10 typ	5	10, 20	4
2	LPB	BR, EDR	0	CW	N/A	3, 10, 20	6
			0	LTE10 clean	5	3, 10, 20	6
			0	LTE10 typ	5	3, 10, 20	6
			0	LTE20 clean	5	3, 10, 20	6
			0	LTE20 typ	5	3, 10, 20	6
		BR	Hop	CW	N/A	10	1
			Hop	LTE10 clean	5	10	1
			Hop	LTE10 typ	5	10	1
			Hop	LTE20 typ	5	10	1
3	DTM	LE	0	CW	N/A	3, 10, 20	3
				LTE10 clean	1, 5	10, 20	4
				LTE10 typ	0, 1, 5	10, 20	6
				LTE20 clean	5	10, 20	2
				LTE20 typ	5	10, 20	2
4	DTM	LE	0	CW	N/A	3, 10, 20	3
				LTE10 clean	1, 5	10, 20	4
				LTE10 typ	0, 1, 5	10, 20	6
				LTE20 clean	5	10, 20	2
				LTE20 typ	5	10, 20	2
5	LPB	BR	0	CW	N/A	3, 10, 20	3
				LTE10 clean	1	3, 10, 20	3
				LTE10 clean	5	10	1
				LTE10 typ	0, 1, 5	10	3
				LTE20 clean	5	10	1
				LTE20 typ	5	10	1

Table 4 Summary of test configurations for Devices 1 to 5.
LPB = Loopback,
DTM = Direct test mode,
CW = carrier wave,
LTExx clean = clean xx MHz LTE signal,
LTExx typ = typical xx MHz LTE signal.

Device	Method	BT Modes Tested	BT Channel	Interference	Frame Config	BT Uplift	Number of Tests
6	CO	BR	Hop	CW LTE10 typ LTE20 typ	5 5 5	3 3 3	1 1 1
7	CO	BR	Hop	CW LTE10 typ LTE20 typ	5 5 5	3, 10 3, 10 3, 10	2 2 2
8	CO	BR	Hop	CW LTE10 typ LTE20 typ	5 5 5	10 10 10	1 1 1
9	CO	BR	Hop	CW LTE10 typ LTE20 typ	5 5 5	10 10 10	1 1 1
10	CO	BR	Hop	CW LTE10 typ LTE20 typ	5 5 5	10 10 10	1 1 1

Table 5 Summary of test configurations for Devices 6 to 10.
LPB = Loopback,
DTM = Direct test mode,
CO = connection oriented,
CW = carrier wave,
LTExx clean = clean xx MHz LTE signal,
LTExx typ = typical xx MHz LTE signal..

3.6 Measuring Baseline Sensitivity

To establish a common baseline across all of the test devices each test run (where a test run is a single sweep of frequency offset with one set of test parameters) began with a measurement of *Baseline Sensitivity*. It is important to note that although we used the same target error rate criteria, the Baseline Sensitivity we measured is not the same as the *Bluetooth Reference Sensitivity* defined by the specification. Our Baseline Sensitivity is the signal level into the test antenna within the screened box and hence differs from the reference sensitivity by the air gap loss between the test antenna and the antenna of the DUT. Thus, typically our Baseline Sensitivity figures are 10 dB to 15 dB higher than the specified reference sensitivity limits.

The measurement of Baseline Sensitivity consisted of a BER/PER search to find the signal level at which a target BER/PER was achieved. This search procedure was carried out at the start of every test run and was also used in the search to find the level of interference that returned the link to the same target BER/PER. The procedure to carry out the BER/PER search was automated using MATLAB and followed the steps outlined below.

1. The CBT was set to transmit at -5 dBm, a level high enough that any DUT within specification should receive with no errors.
2. The CBT transmit level was then reduced in 10 dB steps and a BER/PER measurement made at each step until the reference sensitivity was exceeded. At this step only 100 packets were used to measure BER, which was sufficient to identify when the target BER had been exceeded but kept run time to a minimum.
3. The CBT transmit level was then increased to the previous 10 dB step and the search repeated with a 3 dB step size, using 400 packets, until the BER target was again exceeded.
4. The CBT transmit level was then increased to the previous 3 dB step and the search repeated with a 1 dB step size and 1,000 packets to ensure high reliability.
5. Having identified the signal levels that are just above and just below the target point to a 1 dB resolution, linear interpolation is used to obtain the final sensitivity result.

3.7 Test Methodology for Quantitative Tests

The procedure used to determine the C/I ratio for a specified level of link performance under the test conditions defined in Table 4 and Table 5 is described below.

1) The DUT was installed in the RF shielded chamber close to the transmitting antenna for over-the-air tests or connected using coaxial connectors for the wired tests.

2) The Baseline Sensitivity was measured in the absence of interference. By default these reference error rates were either 0.1% for BR tests or 0.01% for EDR tests when the measure was BER, or 30.8% when the measure was PER. For Device 6 we could not achieve a PER as low as 30.8% and therefore had to use a higher value (60% in this case) to get a full C/I characteristic.

3) The CBT transmit level was then increased or ‘uplifted’ by either 3 dB, 10 dB or 20 dB to introduce an operating margin.

4) An interfering signal was then introduced and at each of the frequency offsets of interest, the interferer power was adjusted and the error rate measured using the procedure described in Section 3.6 to find the point at which that the DUT's error rate matched the Baseline Sensitivity error rate. The frequency offset was varied between 0 MHz and 60 MHz relative to Bluetooth channel 0; for example, 20 MHz offset implies that the centre frequency of the interfering signal was 2382 MHz.

5) Steps (2) to (4) were repeated for each test case, ie, each set of BT mode, uplift, interferer type and LTE frame configuration. Thus, for each configuration a C/I *vs* frequency offset characteristic was obtained.

3.8 Test Methodology for Qualitative Tests

For three of the devices whose application is as an audio headset we were able to carry out a subjective listening test in the presence of TDD LTE interference. Although we could not accurately measure the signal levels incident at the DUT this test nevertheless provided a useful indication of how Bluetooth devices will cope with adjacent band interference.

The test was conducted as follows:

1. The audio device was paired with a mobile phone and audio streamed to the device either by making a phone call to a voicemail service or using a music player.
2. The mobile phone was placed away from the device and the interfering signal source, but with an unobstructed path between phone and device.
3. Whilst listening to the audio a TDD LTE signal between 2380 MHz and 2400 MHz was radiated from an antenna in close proximity to the device.
4. The LTE signal power was slowly increased up to +15 dBm and the effect on the audio signal, if any, was noted.
5. The test was repeated with both 10 MHz and 20 MHz bandwidth LTE signals and the frequency separation reduced in 1 MHz steps until it reached 2400 MHz, when the interference overlapped several Bluetooth channels.

4 Measurement Results

The following sections present the raw measurement results for each of the ten sample devices. In all of the charts in this report frequency offset is specified relative to the centre of Bluetooth channel 0, which has a centre frequency of 2402 MHz. Unless stated otherwise the TDD LTE interference used frame configuration 5 and the Bluetooth signal was received by the DUT on Channel 0, ie, hopping was disabled.

For ease of reference the charts in the following sections use the line style conventions described below:

- Line style indicates the level of uplift:
  - dots for 3 dB,
  - dashes for 10 dB,
  - solid line for 20 dB.
- Line colour indicates interfering signal type:
  - Red for CW,
  - Green for LTE 10 Clean,
  - Blue for LTE 10 Typical,
  - Purple for LTE 20 Clean,
  - Orange for LTE20 Typical.
- When comparing results for the same interference type line colour indicates slot configuration:
  - light Blue for Config 0,
  - light Green for Config 1,
  - grey for Config 5.

The charts also have a vertical dashed line frequency marker at 17 MHz when 10 MHz interferers are displayed and at 22 MHz when 20 MHz interferers are displayed. When both 10 MHz and 20 MHz interfering signals are displayed the frequency markers are colour coded according to the lines they correspond to. These dashed lines indicate the frequency of the closest 10 MHz or 20 MHz TDD LTE signal based on the proposed Band 40 channel plan and thus indicate the point on the curve that is of most interest for making deployment decisions.

4.1 Device 1

Device 1 was tested under a wide range of interference conditions for both BR and EDR modes. Figure 19 shows the adjacent channel susceptibility of Device 1 with CW and 10 MHz TDD LTE interferers. Figure 20 show the same CW data alongside the susceptibility data obtained with a 20 MHz TDD LTE interferer. Several of the TDD LTE curves with +20 dB uplift are incomplete due to inadequate interferer power to make a measurement at the specified error rate.

Taken across all 48 measurements made on Device 1 the signal levels corresponding to the baseline sensitivity had a maximum of -58.8 dBm, a minimum of -69.1 dBm and a mean of -65.2 dBm.

At a frequency separation of 5 MHz the effect of the main lobe immediately adjacent to Bluetooth channel zero can be seen with both the clean and typical signals causing the same level of interference. CW interference is strongly rejected by the receiver at 5 MHz offset, indicating good levels of intermediate frequency rejection in the Bluetooth receiver.

At 10 MHz offset the effect of high levels of OOBEs in the typical TDD LTE signal cause the clean and typical curves to diverge, but by 15 MHz offset the OOBEs have reduced to the same level as the clean signal and the curves converge again.

All curves show consistent behaviour as the Bluetooth signal uplift is increased from 3 dB to 20 dB. However, we note that having reached their floor level, the curves relating to TDD LTE interference do not merge with those of the CW signal.

With a 20 MHz TDD LTE interferer the trend of the C/I curves is the same as that with a 10 MHz interferer, but due to the wider signal bandwidth the clean and typical curves do not converge until the frequency offset reaches 30 MHz.

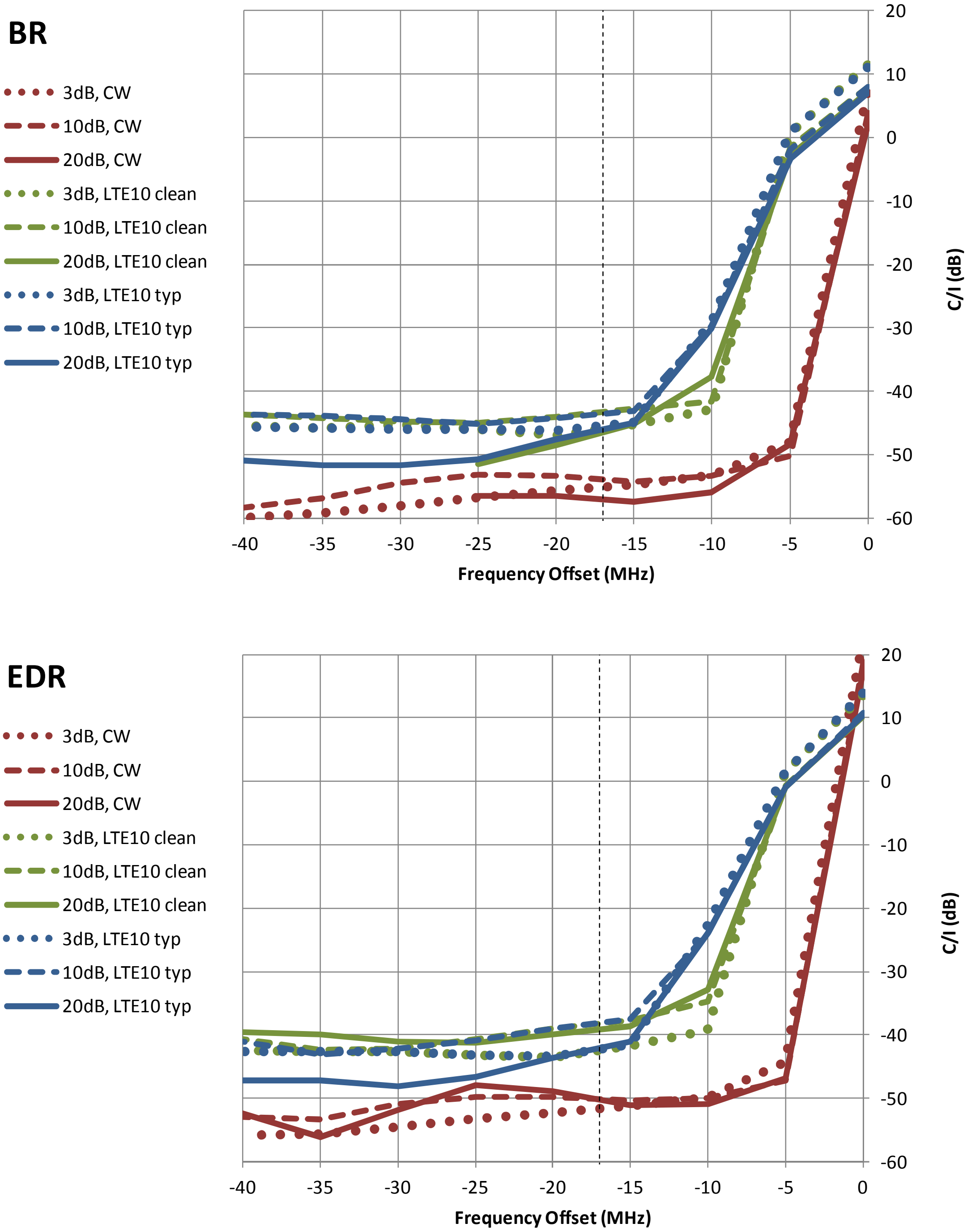


Figure 19 Comparison of Device 1 operation in BR and EDR modes with CW and clean and typical 10 MHz TDD LTE interferers.

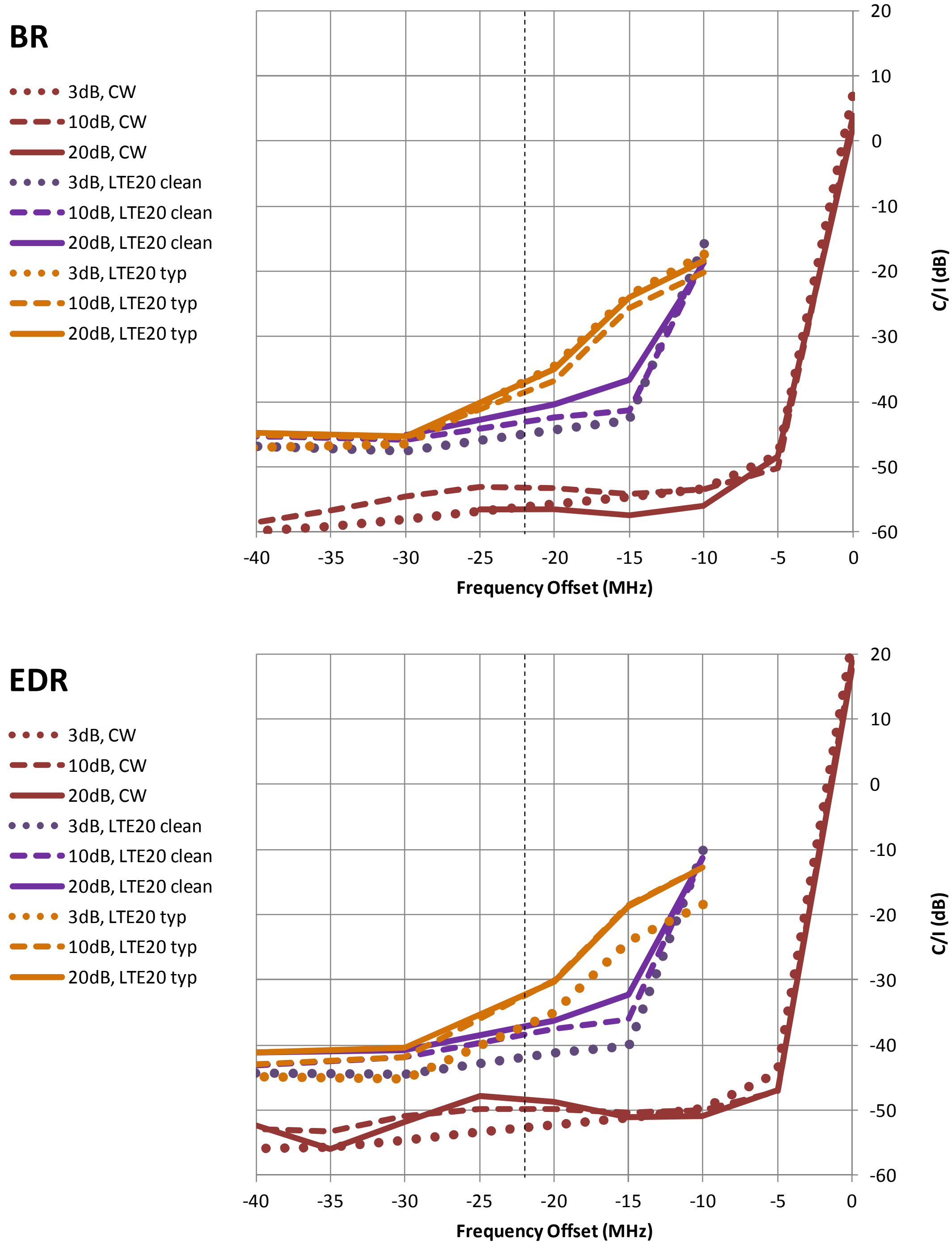


Figure 20 Comparison of Device 1 operation in BR and EDR modes with CW and clean and typical 20 MHz TDD LTE interferers.

4.2 Device 2

Device 2 was tested under most of the same interference conditions as Device 1, but only with frame configuration 5. Both BR and EDR modes were tested. Figure 21 shows the adjacent channel susceptibility of Device 2 with CW and 10 MHz TDD LTE interferers in BR and EDR modes, respectively. Figure 22 shows the same CW data alongside the susceptibility data obtained with a 20 MHz TDD LTE interferer, again for BR and EDR modes.

Taken across all 30 non-hopping measurements made on Device 2 the signal levels corresponding to the baseline sensitivity had a maximum of -54.0 dBm, a minimum of -60.6 dBm and a mean of -56.6 dBm.

As for Device 1 we note that the curves are consistent across the three Bluetooth signal offsets and show the same behaviour that the floor of the TDD LTE and CW signals does not reach the CW floor.

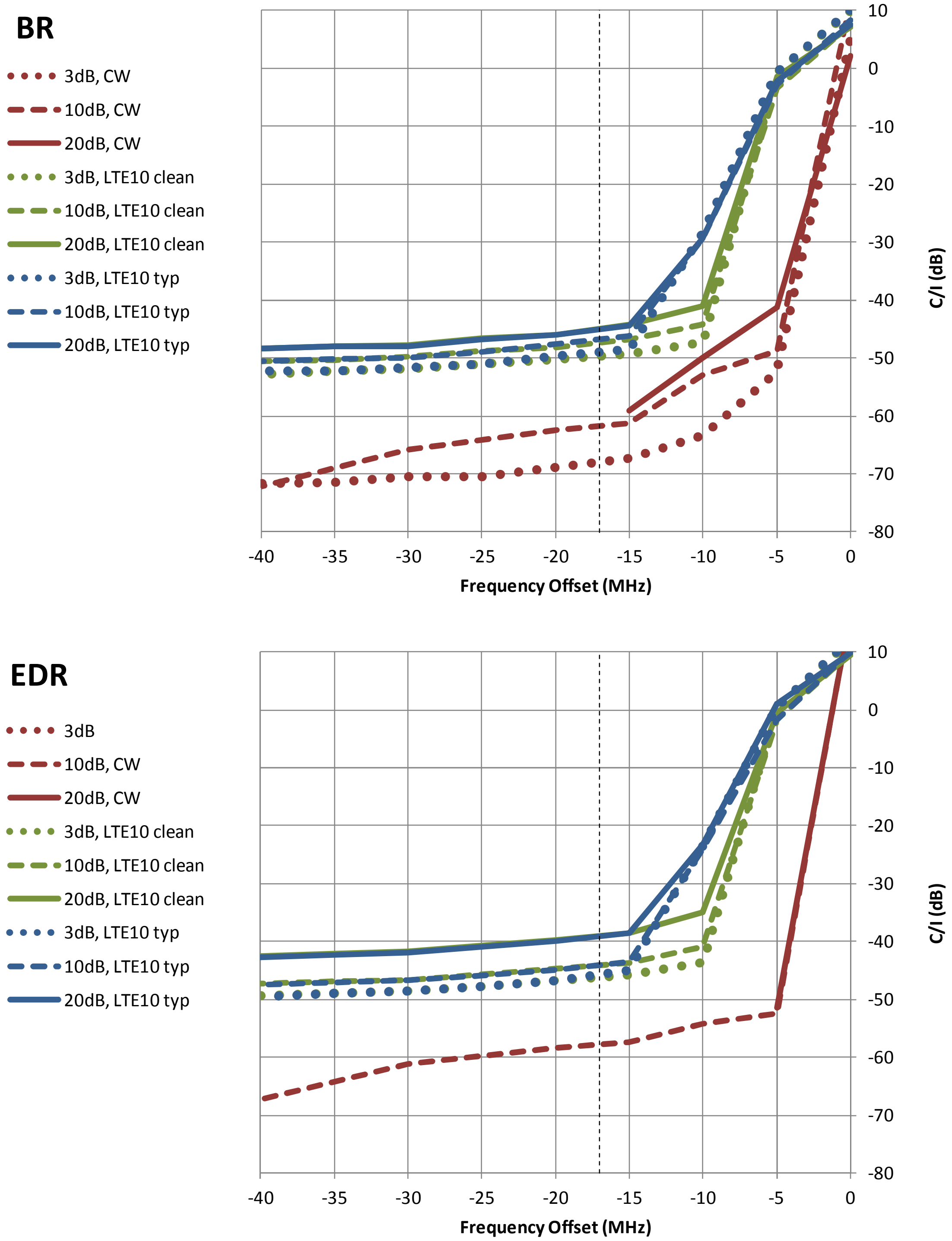


Figure 21 Comparison of Device 2 operation in BR and EDR modes with CW and clean and typical 10 MHz TDD LTE interferers.

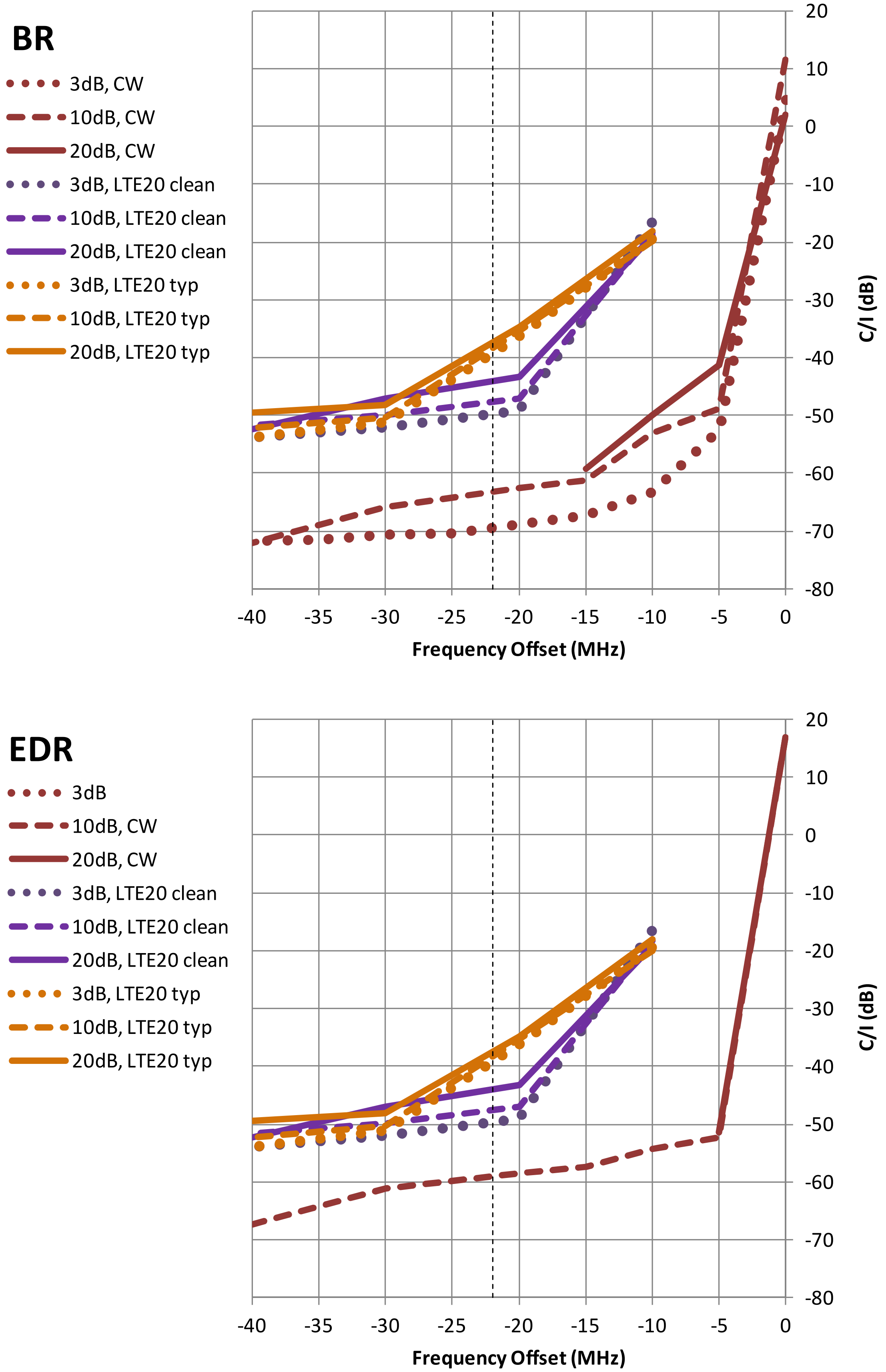


Figure 22 Comparison of Device 2 operation in BR and EDR modes with CW and clean and typical 20 MHz TDD LTE interferers.

4.3 Device 3

Device 3 only supports Bluetooth Low Energy mode, thus there are fewer test cases for this device. It was tested with clean and typical, 10 MHz and 20 MHz TDD LTE interference using frame configurations 0, 1 and 5. Figure 23 and Figure 24 show the results obtained with frame configuration 5, while Figure 25 compares the results across frame configurations 0, 1, and 5.

Taken across all 17 measurements made on Device 3 the signal levels corresponding to the baseline sensitivity had a maximum of -63.1 dBm, a minimum of -67 dBm and a mean of -63.9 dBm.

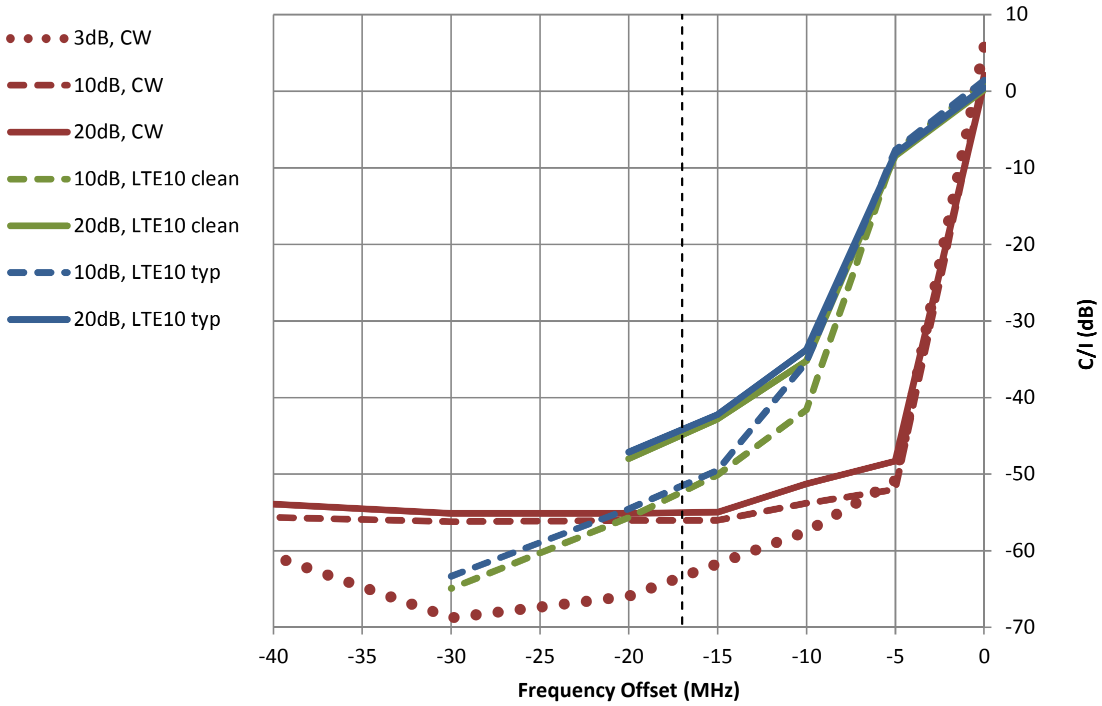


Figure 23 Comparison of Device 3 operation with CW and clean and typical 10 MHz TDD LTE interferers. Frame configuration 5.

Notable differences between the results for Device 3 and Devices 1 and 2 are that the TDD LTE curves have not settled to a floor and that these curves do intersect with the CW curves. The 3 dB CW curve has a different shape to the other CW curves. This is probably explained by the fact that the 3 dB uplift measurements were made at a different time to all other measurements on this device, and even though a new baseline sensitivity was measured and the device was tested using the same configuration and orientation, the DUT would have been moved between measurements. The shape of the 3 dB CW curve in comparison to the other CW curves suggests that the frequency response between the antenna and the DUT was not flat and we are seeing this response reflected in our measurements. This effect may also explain why the TDD LTE results with a 10 MHz interferer do not appear to reach a floor, whereas those for CW and 20 MHz interferers do.

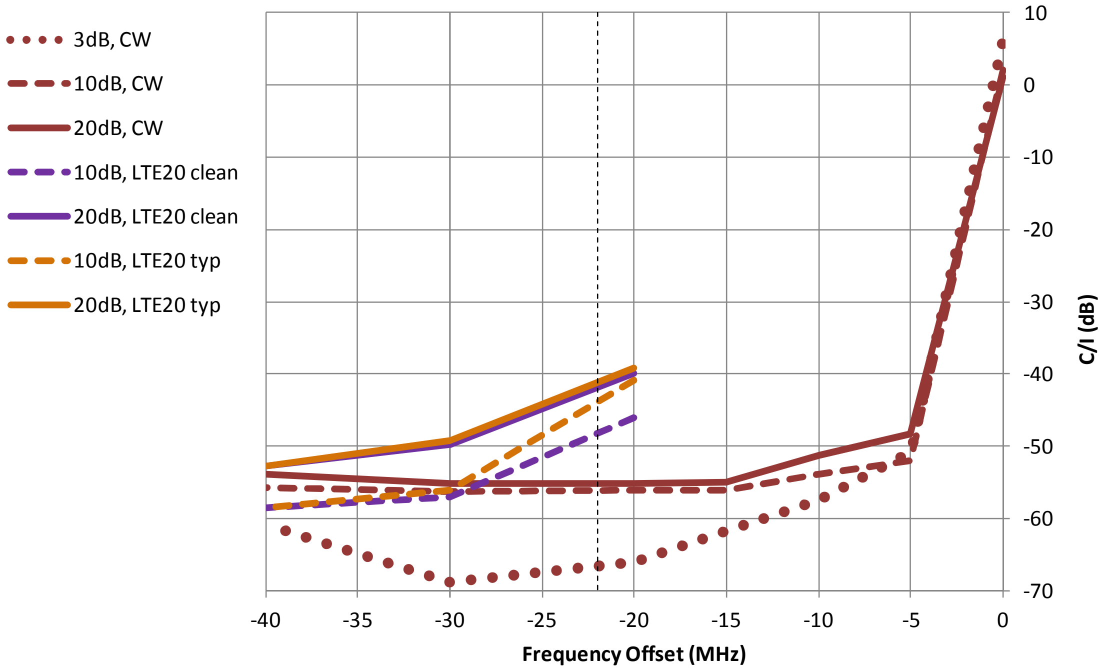


Figure 24 Comparison of Device 3 operation with CW and clean and typical 20 MHz TDD LTE interferers. Frame configuration 5.

The result of varying the frame configuration with Device 3 is shown in Figure 25. The clear indication from this chart is that frame configurations 1 and 5 have an equivalent impact on the Bluetooth link.

The results might also seem to suggest that frame configuration 0 results in less co-channel interference. However, this is not the case and the co-channel performance difference that we can observe in Figure 25 is a result of the chosen spectral characteristics of the TDD LTE uplink signal, which place the signal energy in the upper 25% of the 10 MHz channel. As a result when the uplink TDD LTE signal is co-channel with Bluetooth less energy appears in the Bluetooth channel compared to the case when the downlink signal is co-channel with Bluetooth.

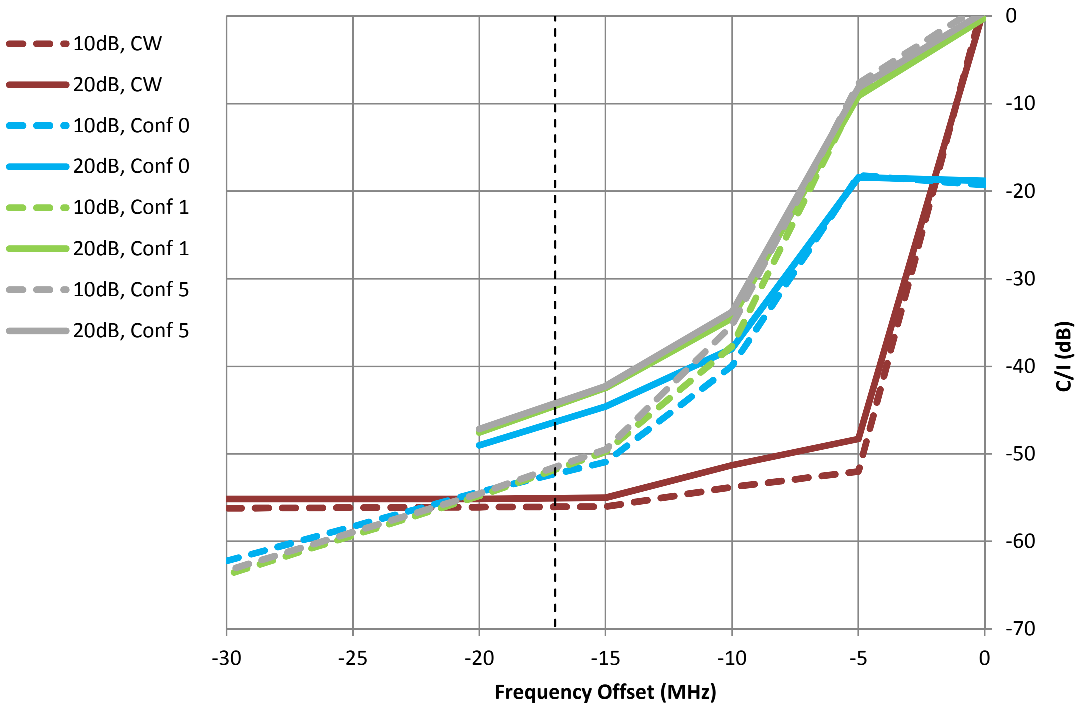


Figure 25 Comparison of Device 3 operation with CW and three slot configurations for a 10 MHz TDD LTE interferer.

4.4 Device 4

This device was tested unmodified 'over the air' using its antenna, and then physically modified to facilitate a wired connection and tested again.

4.4.1 Device 4 over the air results

Like Device 3, Device 4 only supports Bluetooth Low Energy mode. It was tested with clean and typical, 10 MHz and 20 MHz TDD LTE interference using frame configurations 0, 1 and 5. Figure 26 shows the results obtained with frame configuration 5 for both 10 MHz and 20 MHz TDD LTE interferers, while Figure 27 compares the results across frame configurations 0, 1, and 5.

Taken across all 16 measurements made on Device 4 the signal levels corresponding to the baseline sensitivity had a maximum of -66.1 dBm, a minimum of -65.6 dBm and a mean of -65.8 dBm.

The results show a very close match between 10 dB and 20 dB uplift. Baseline sensitivity and blocking performance are very similar to Device 3.

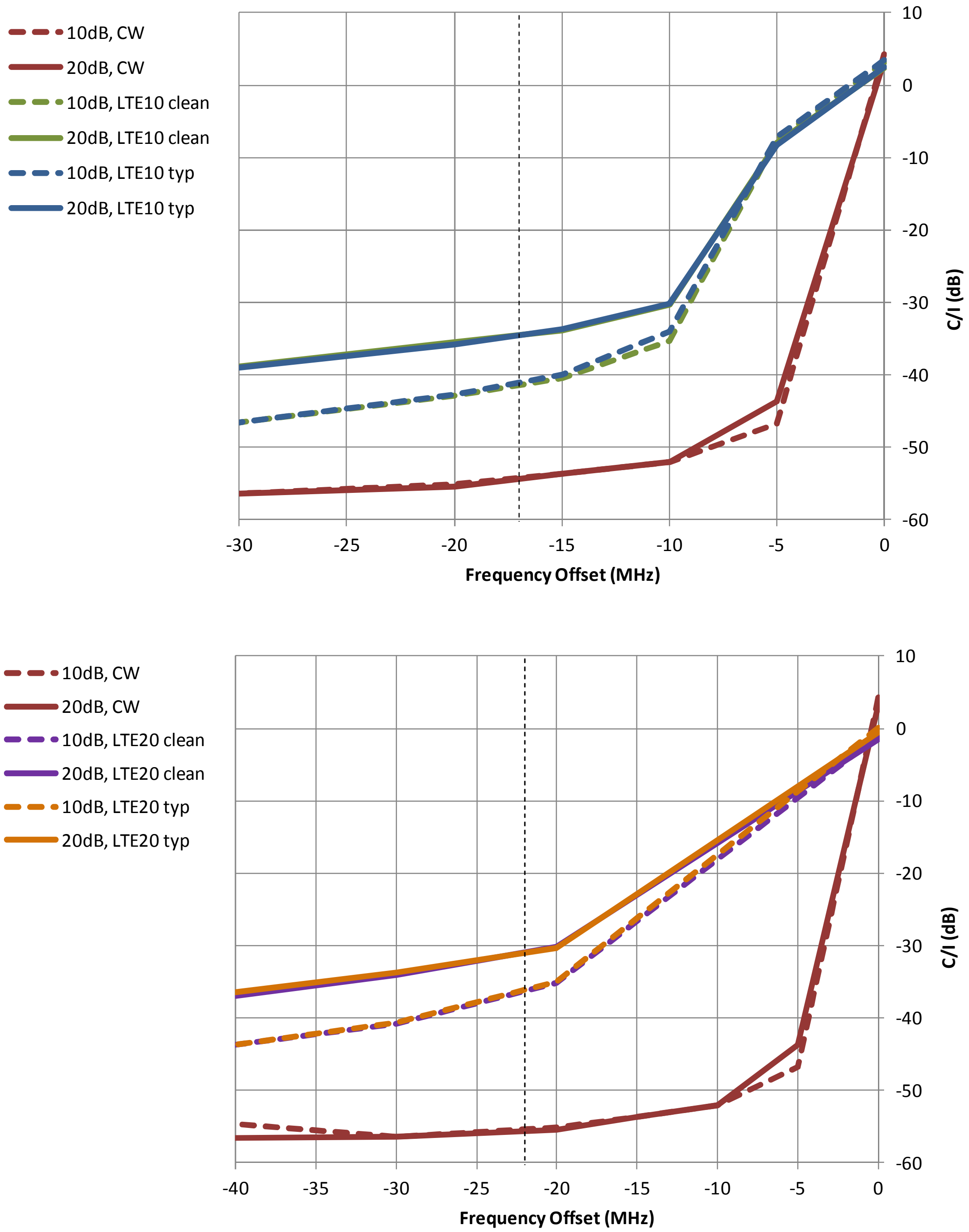


Figure 26 Comparison of Device 4 operation with CW and clean and typical 10 MHz and 20 MHz TDD LTE interferers.

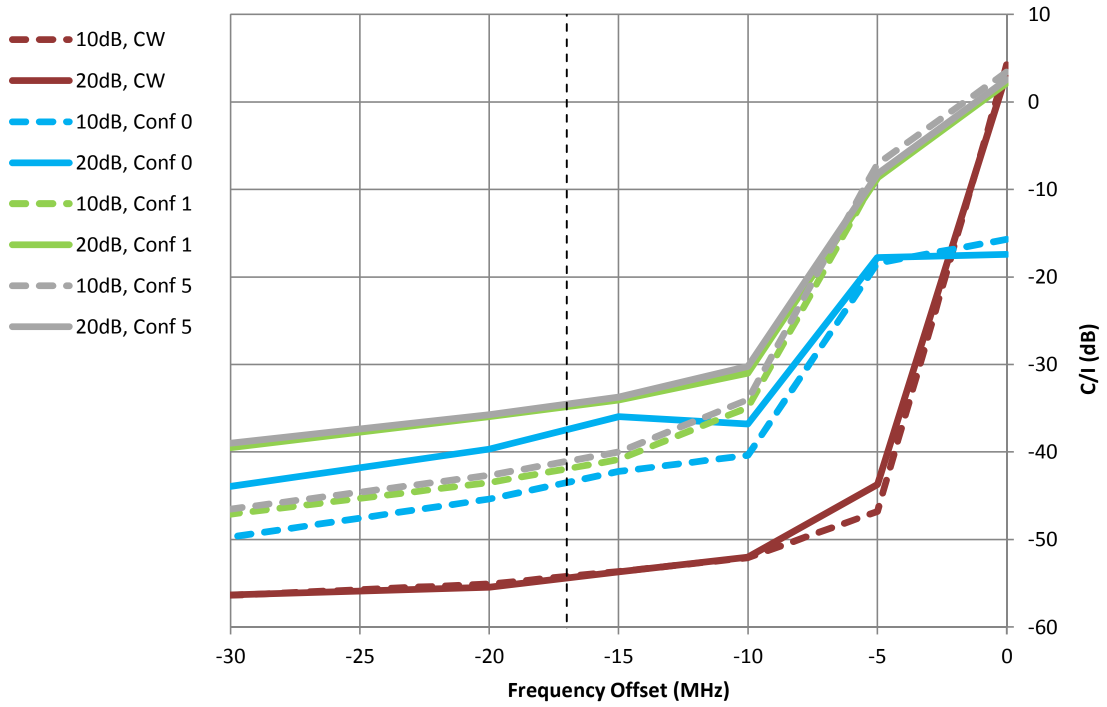


Figure 27 Comparison of Device 4 operation with CW and three slot configurations for a 10 MHz TDD LTE interferer.

4.4.2 Device 4 wired connection results

Figure 28 shows the equivalent results to Figure 26 obtained with a wired configuration and Figure 29 shows a comparison of the results obtained with wired and air gap configurations. Figure 29 demonstrates that there is a close correspondence between the two sets of results, indicating that the presence of the air gap is not unduly affecting our measurements. However, we can see that the results obtained with the air gap are consistently a few dBs more pessimistic than those obtained with a wired connection.

Figure 30 charts the equivalent results to Figure 27 and together with the results for Device 3 indicates that the interference susceptibility is not sensitive to the TDD LTE frame configuration.

Taken across all 24 wired measurements made on Device 4 the signal levels corresponding to the baseline sensitivity had a maximum of -87.9 dBm, a minimum of -88.4 dBm and a mean of -88.2 dBm.

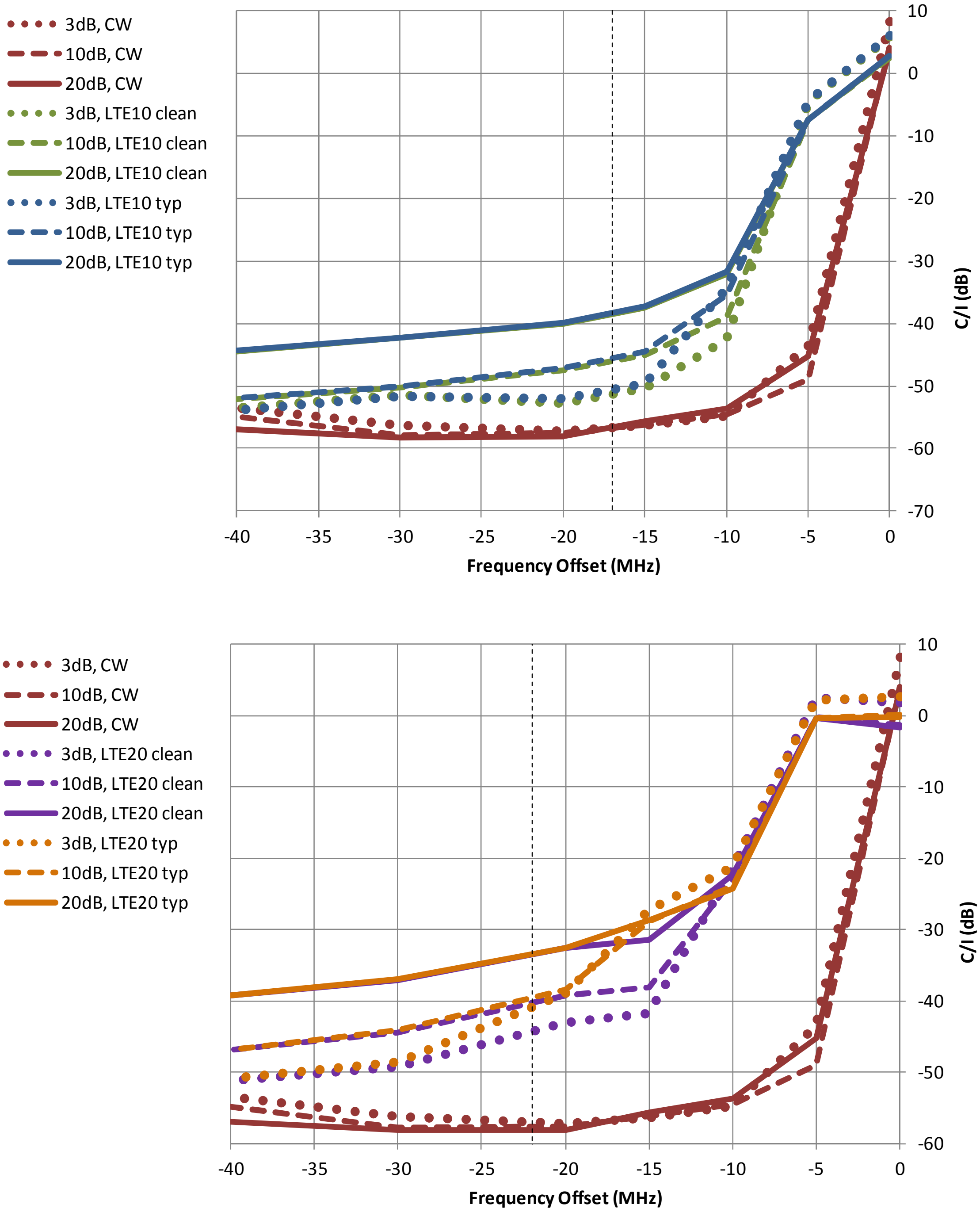
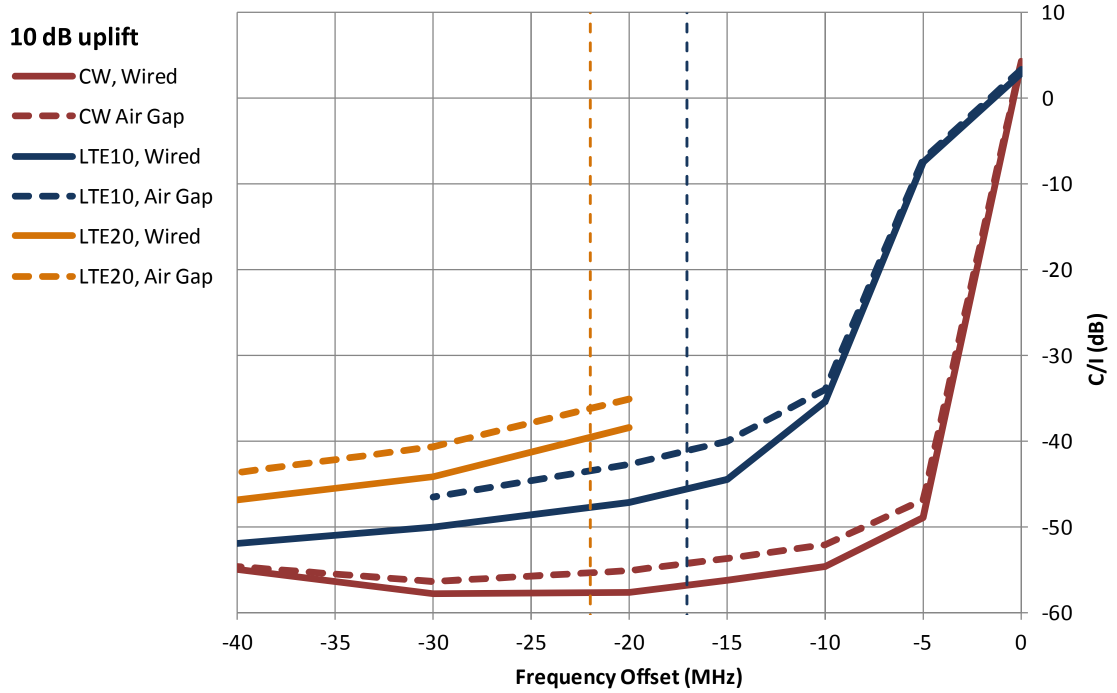


Figure 28 Comparison of wired Device 4 operation with CW and clean and typical 10 MHz and 20 MHz TDD LTE interferers.



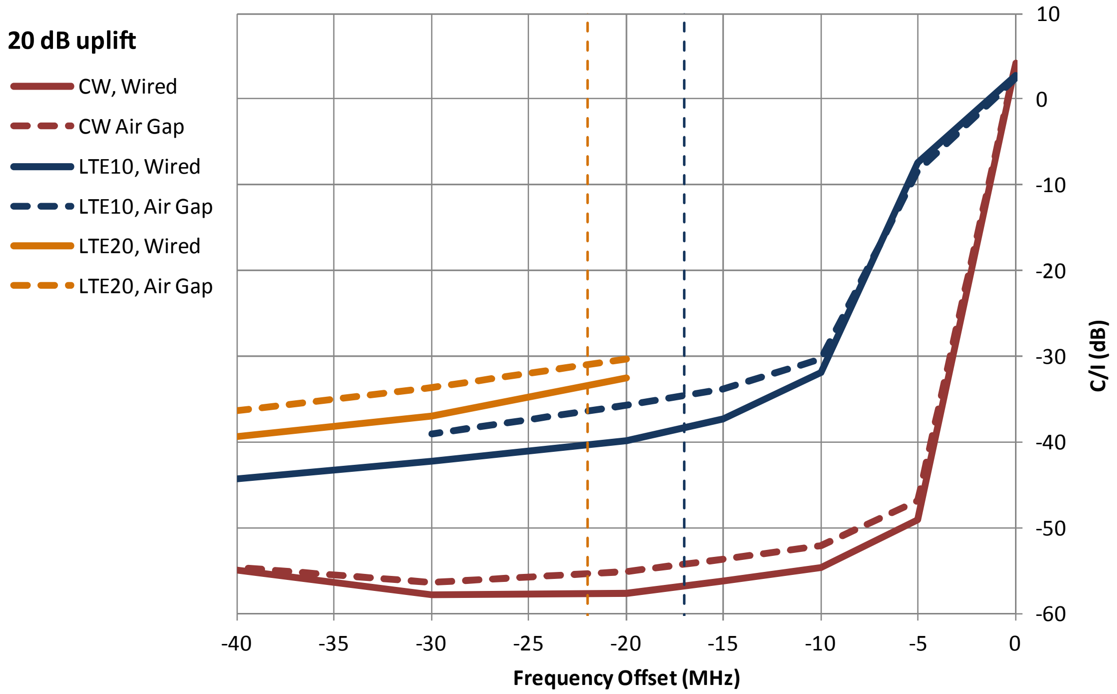


Figure 29 Comparison of Device 4 Air Gap with Wired results for 10 dB and 20 dB uplift.

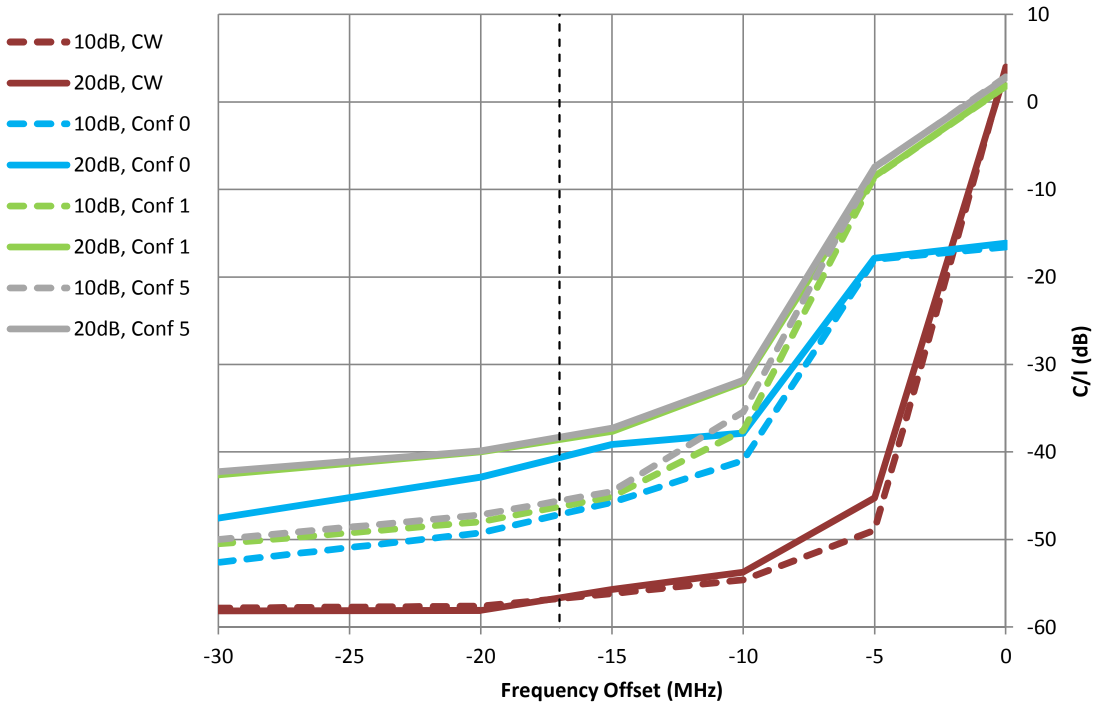


Figure 30 Comparison of wired Device 4 operation with CW and three slot configurations for a 10 MHz TDD LTE interferer.

With the wired configuration we are able to determine the absolute levels of interference that disrupt the Bluetooth link and Figure 31 charts these data. Inspection of these results shows an interesting effect. The CW curves maintain a roughly constant 10 dB separation, which is as expected to yield blocking at a constant C/I ratio, however, the separation between the curves for both 10 MHz and 20 MHz TDD LTE interferers reduces as frequency offset increases, indicating that the impact of blocking by wideband signals is more severe than that of CW signals. We analyse this behaviour in Section 5.6.

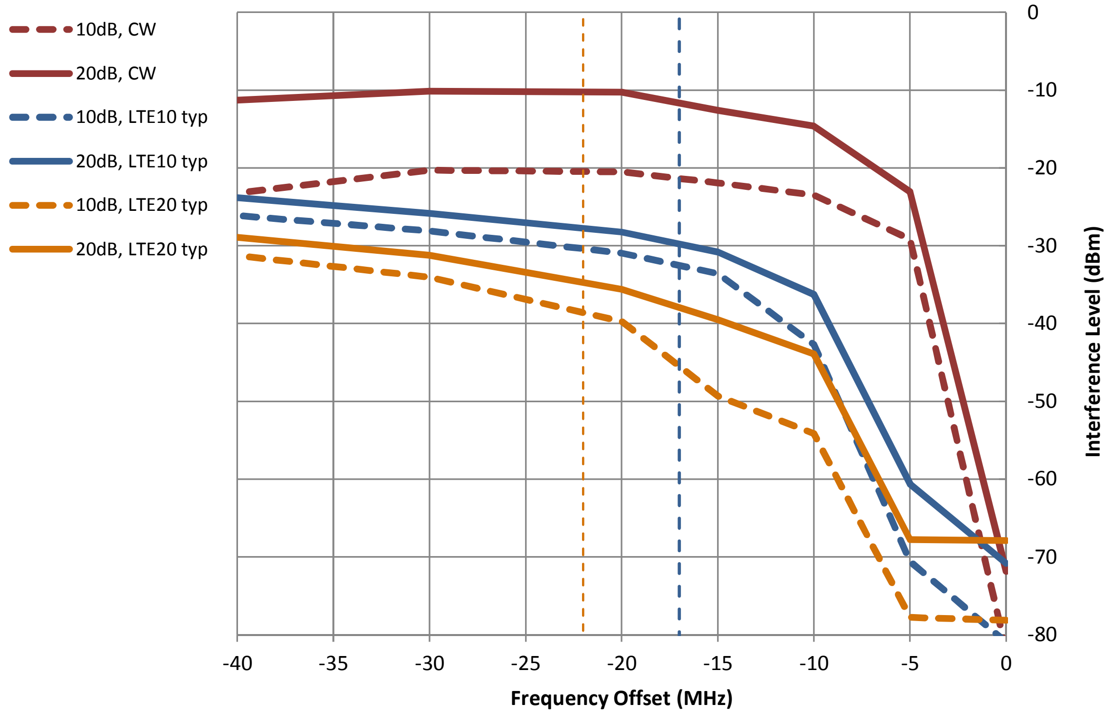


Figure 31 Comparison of wired Device 4 operation with 10 MHz, 20 MHz TDD LTE and CW interferers.

4.5 Device 5

Device 5 was tested in loopback BER mode. Although the device claims to support EDR mode it would not operate in this mode within our test system, therefore, only BR measurements were obtained. These are shown in Figure 32.

The most notable aspect of these results is that the CW and wideband interference curves converge from 20 MHz and is one of only two devices that don't exhibit a 10 dB difference. This could be an indication that this device employs a front-end filter, or simply that it has better linearity.

Taken across all 12 measurements made on Device 5 the signal levels corresponding to the baseline sensitivity had a maximum of -61.5 dBm, a minimum of -64.5 dBm and a mean of -63.0 dBm.

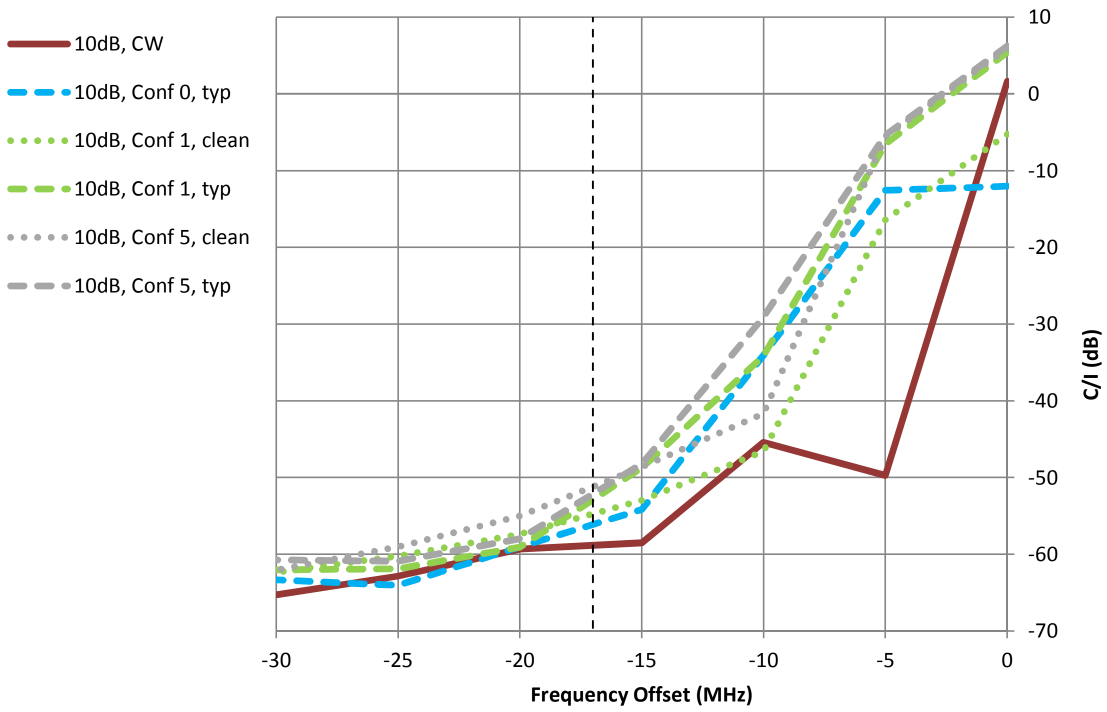


Figure 32 Comparison of Device 5 operation with CW and three slot configurations and with 10 MHz TDD LTE interferers.

4.6 Device 6

Device 6 was tested in connection-oriented mode and in order to make a repeatable measurement we had to choose a different target PER, of 60%, for this device. At this PER the baseline sensitivity was measured at -59.0 dBm. All tests in connection-oriented mode had to be conducted with hopping enabled.

The measurement results are shown in Figure 33, from which we observe that the notable characteristics of the susceptibility of Device 6 to out of band interference are: that there is a much closer correspondence between the CW and TDD LTE interference results (it is one of only two devices to show this behaviour); and that the susceptibility appears to be greater at larger frequency offsets. This latter point may be explained by a non-flat frequency response within the test chamber, or it could be a true measurement caused by the frequency response of the Bluetooth receiver front-end filter. It is quite common for surface acoustic wave (SAW) filters at these frequencies to place a pole just outside the band of interest in order to produce a steep transition. The result of this is a sharp null close to the band edge followed by reduced rejection at greater frequency offsets.

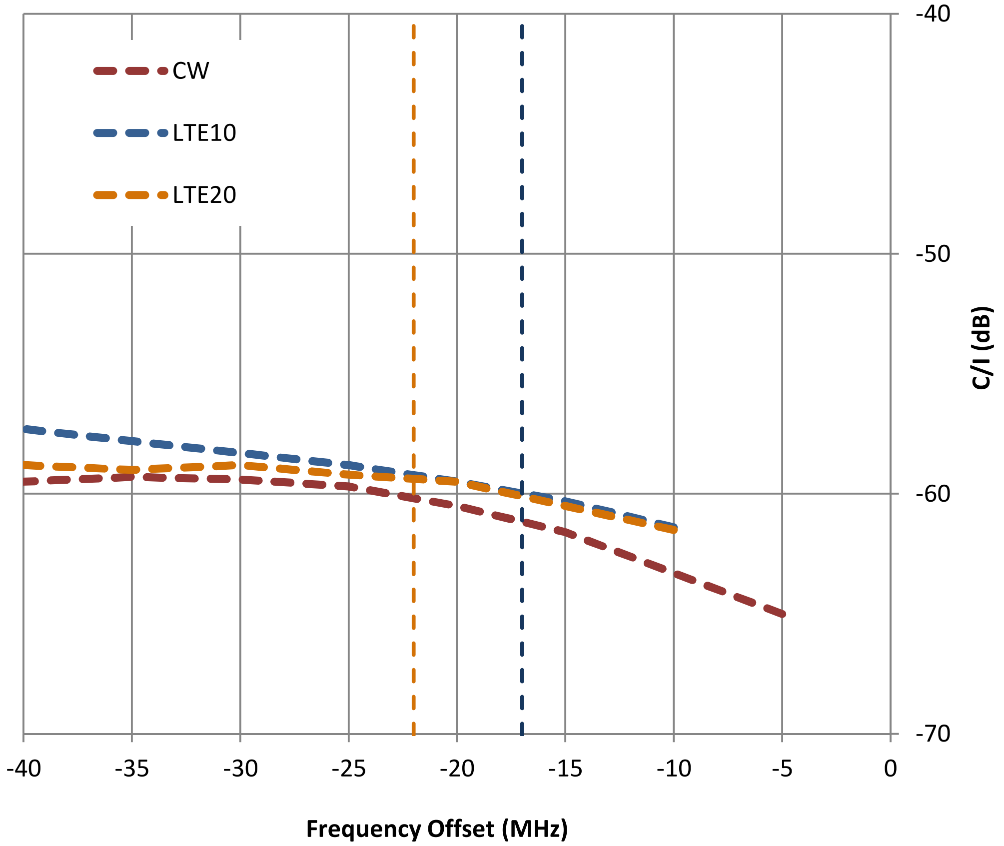


Figure 33 Comparison of Device 6 operation in BR mode with CW and typical 10 MHz and 20 MHz TDD LTE interferers.

4.7 Device 7

Device 7 was tested in connection-oriented mode. The test results are shown in Figure 34 and its baseline sensitivity was measured at -76.0 dBm.

Device 7 shows a large difference between the CW and TDD LTE interference cases, however, the difference is largely due to Device 7 having a greater tolerance to CW.

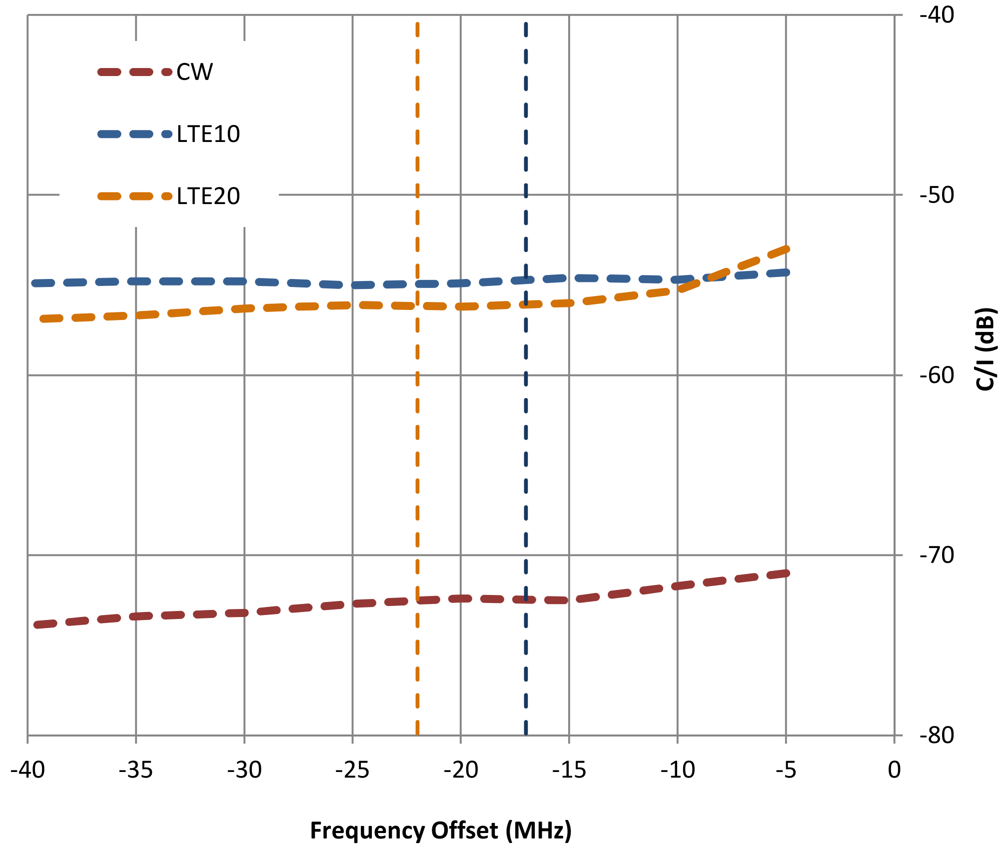


Figure 34 Comparison of Device 7 operation in BR mode with CW and typical 10 MHz and 20 MHz TDD LTE interferers.

4.8 Device 8

Device 8 was tested quantitatively in the test chamber and qualitatively through a listening test.

4.8.1 Test chamber results

Device 8 was tested in connection-oriented mode. The test results are shown in Figure 35 and its baseline sensitivity was measured at -70.3 dBm. These results are typical of those observed with other devices.

4.8.2 Qualitative test results

We made use of the devices ability to stream audio to perform a qualitative test using the test procedure outlined in Section 3.8. Once the link was established the signal source and DUT were separated by approximately 8 m to ensure the DUT was receiving a significantly attenuated signal. At this distance and assuming free space path loss and +10 dBm transmit power the signal received by the hands free kit would be approximately -48 dBm, which is 22 dB above the Bluetooth reference sensitivity specification and therefore we can estimate it to be perhaps 30 dB above the actual sensitivity threshold of the device. An unobstructed path between the signal source and the DUT was maintained.

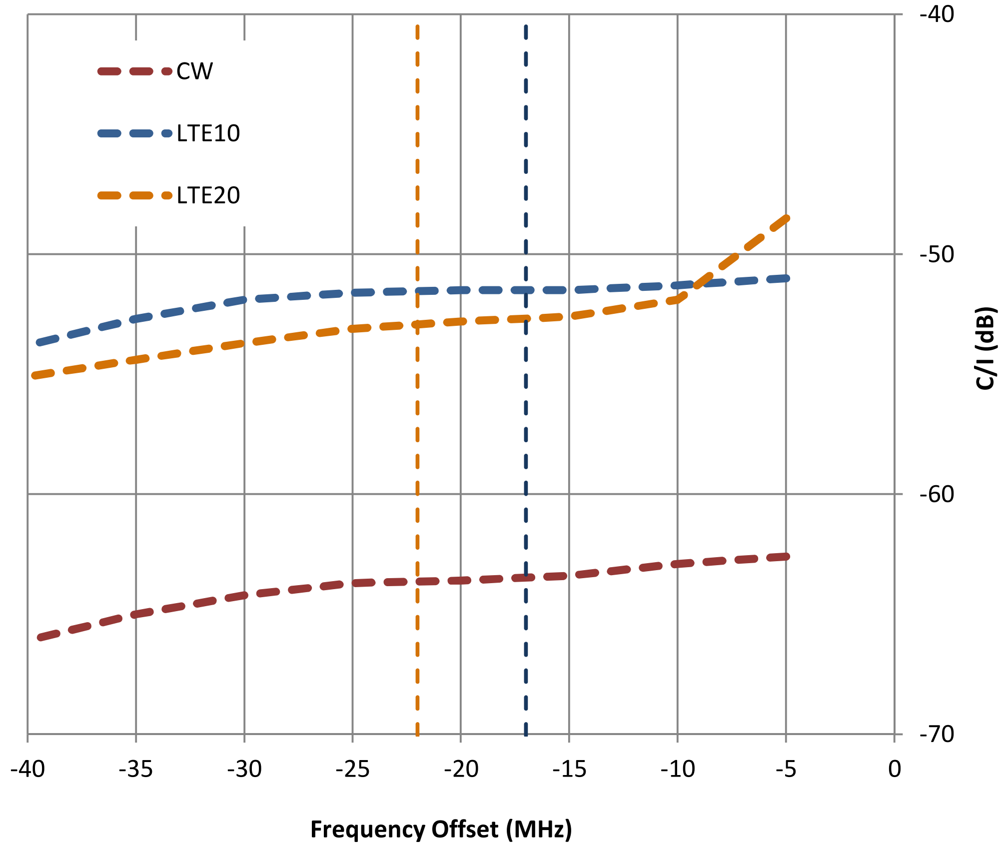


Figure 35 Comparison of Device 8 operation in BR mode with CW and typical 10 MHz and 20 MHz TDD LTE interferers.

The LTE signal generator was connected to an antenna (approximately 10 cm from the DUT) and set to transmit a 10 MHz LTE signal centred on 2395 MHz , i.e. just below ISM band. The level of the LTE interferer was then increased whilst the quality of the audio was subjectively monitored. No audible degradation could be detected even at the SMBV's maximum power of 20 dBm.

The frequency of the interferer was then increased until it was fully within the ISM band. Again, no audible degradation could be detected, so the distance between the interfering antenna and the DUT was reduced. With an air gap of approximately 2 cm the Bluetooth link failed, i.e. the audio muted. Increasing the antenna gap again quickly re-established the link and the audio re-commenced.

Although this was a simple and uncontrolled test it did demonstrate that under normal use scenarios Bluetooth is very tolerant to other signals even when these signals have quite high levels. The test also demonstrated Bluetooth's Adaptive Frequency Hopping very clearly. Observing the ISM band with another antenna connected to the FSW spectrum analyser it was clear to see that the Bluetooth devices were able to detect the channels occupied by the LTE signal and to eliminate them from the hopping list. This also suggests that when the link did fail the cause was blocking of adjacent channels because any channels carrying significant co-channel interference would have been avoided.

4.9 Device 9

Device 9 was tested quantitatively in the test chamber and qualitatively.

4.9.1 Test chamber results

Device 9 was tested in connection-oriented mode. The test results are shown in Figure 36 and its baseline sensitivity was measured at -76.2 dBm. These results are typical of those observed with other devices.

4.9.2 Qualitative test results

The test described in Section 3.8 was conducted using a voicemail service as the audio source. Thus, in this test another wideband, high power RF signal was present, albeit at a greater frequency separation; the mobile phone was a 3G device. A typical Bluetooth separation distance of 1 m was used to simulate a realistic operating scenario. In this case the Bluetooth signal level at the DUT may have been as much as 50 dB above its sensitivity level.

The results observed were as follows.

1. When the headset was placed approximately 5 cm from the antenna radiating a +15 dBm interfering signal at 2380 MHz, some distortion of the audio signal could be heard, but the phone to headset link did not break.

2. Placing the Bluetooth device even closer to the antenna did not break the Bluetooth and although distortion of the audio was apparent it was still possible to understand the recorded message.
3. Increasing the frequency of the interfering signal up to 2400 MHz did not have any additional effect.

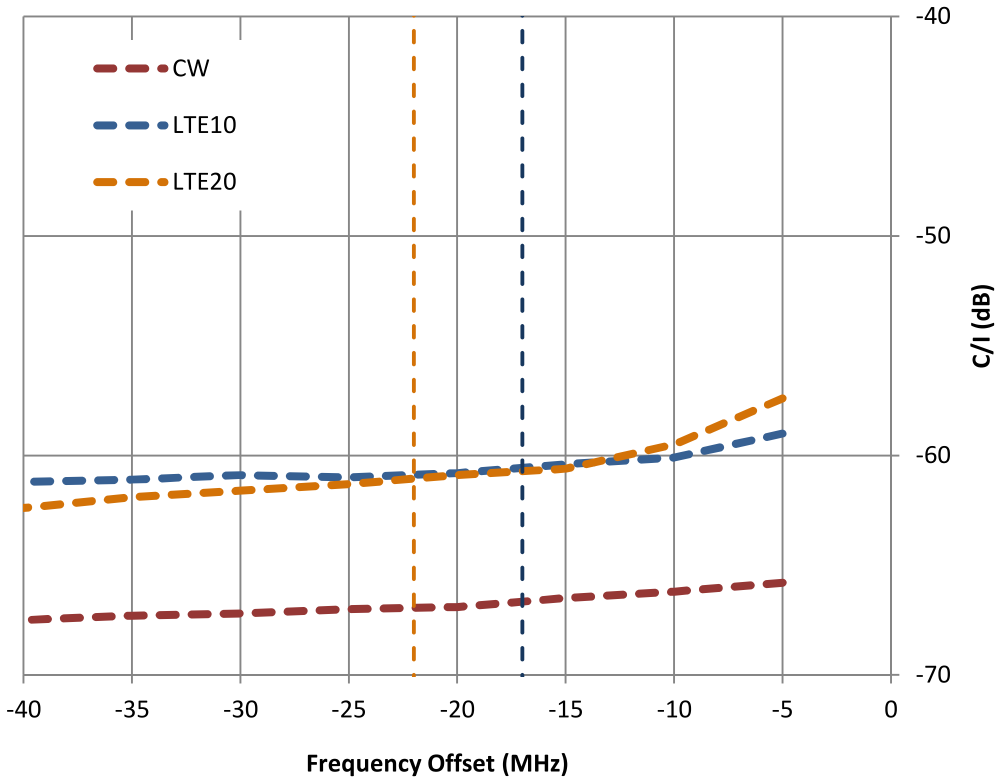


Figure 36 Comparison of Device 9 operation in BR mode with CW and typical 10 MHz and 20 MHz TDD LTE interferers.

4.10 Device 10

Device 10 was tested quantitatively in the test chamber and qualitatively.

4.10.1 Test chamber results

Device 10 was tested in connection-oriented mode. The test results are shown in Figure 37 and its baseline sensitivity was measured at -68.3 dBm.

Like Device 6 this device also exhibits worsening performance as frequency offset increases. However, the difference in performance between 5 MHz and 40 MHz is well within the uncertainty of our measurements and the most likely explanation is a varying frequency response in the air gap.

4.10.2 Qualitative testing

Qualitative testing as described for Device 8 in Section 4.8.2 was performed on this device with similar results.

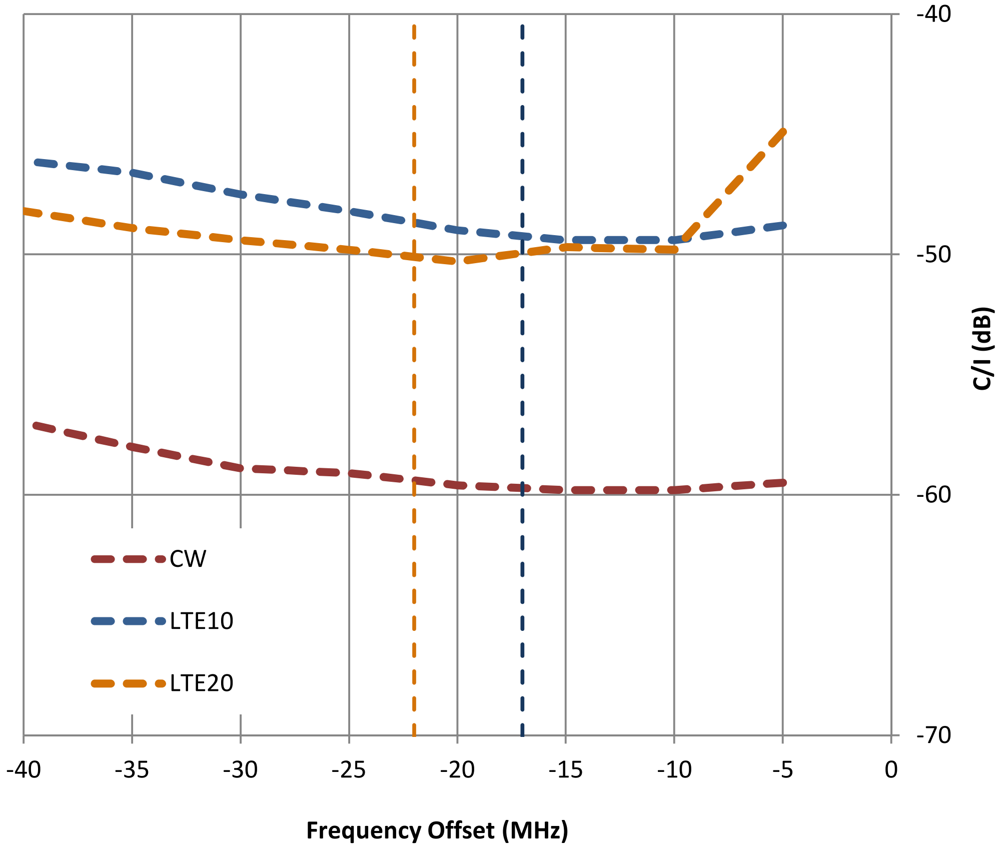


Figure 37 Comparison of Device 10 operation in BR mode with CW and typical 10 MHz and 20 MHz TDD LTE interferers.

5 Analysis

In the following sections we consider what the measurement results reveal about the sensitivity of Bluetooth devices to a range of operating conditions. Unless stated otherwise, all of the results presented in this section are for measurements made with Bluetooth hopping disabled, with the Bluetooth downlink signal fixed on Channel 0 and the uplink on Channel 78.

5.1 Baseline Sensitivity Variation

Table 6 summarises the Baseline Sensitivity measurements for all 10 devices. For Devices 6, 8, 9 and 10 only one measurement was made, hence there are no minimum and maximum figures. The spread in results arises because it was not possible to complete all measurements on one device in a single run, hence there was some variation in the relative positions of the test antenna and the DUT. Leaving aside the Device 4 (wired) case the spread in Baseline Sensitivity is approximately 20 dB (-56.6 dBm to -76.2 dBm), which seems reasonable given the uncertainty in the air gap loss and, perhaps, 5 dB to 10 dB variation in device performance.

Device	Mean Sensitivity (dBm)	Min Sensitivity (dBm)	Max Sensitivity (dBm)	Number of measurements
1	-65.2	-58.8	-69.1	48
2	-56.6	-54.0	-60.6	29
3	-63.9	-63.1	-67.0	17
4 (Air)	-65.8	-65.6	-66.1	16
4 (Wired)	-88.2	-87.9	-88.4	24
5	-63.0	-61.5	-64.5	12
6	-59.0	-	-	1
7	-76.0	-75.6	-76.5	6
8	-70.3	-	-	1
9	-76.2	-	-	1
10	-68.3	-	-	1

Table 6 Comparison of measured baseline sensitivities.
Note, maximum sensitivity corresponds to minimum signal level.

Taking the maximum sensitivity values as representative of the case when the air gap loss was at a minimum of 12 dB, then all devices would be comfortably within the Bluetooth Reference Sensitivity requirements.

5.2 Sensitivity to Out of Band Emission Levels

The obvious mechanism by which LTE signals might interfere with Bluetooth is due to out of band emissions from the LTE signal that overlap the lowest Bluetooth channels and thus appear as co-channel interference to Bluetooth. To analyse if this effect can be observed we compared the results obtained with typical and clean OOBE profiles, for all Bluetooth modes (BR, EDR and LE) and for 10 dB and 20 dB Bluetooth signal uplift. All of the results presented in Figure 38 and Figure 39 were obtained with a TDD LTE signal using frame configuration 5, ie, the maximum transmission time, and with the Bluetooth signal fixed on Channel 0, ie, no frequency hopping. Figure 38 presents the results for a 10 MHz TDD LTE signal and Figure 39 for a 20 MHz signal. For this analysis the important comparison is between the curves of the same style (dashed or solid) and different colour.

Starting with the LE mode results for Devices 3 and 4 the curves in Figure 38 show that there is very little difference in performance when operating in the presence of either a clean or typical LTE signals. Only when operating at 10 dB above baseline sensitivity at a frequency offset of -10 MHz can any significant difference be observed. The clean and typical results with 20 dB uplift for both devices are almost identical, suggesting that it is more tolerant to co-channel interference when there is a greater Bluetooth link margin.

The results for Devices 1 and 2 with a 10 MHz interferer in both BR and EDR modes show very similar characteristics to each other. At 5 MHz frequency offset, the upper edge of the main lobe of the TDD LTE signal will be immediately adjacent to Bluetooth channel zero and so severe interference is to be expected and the results verify that this is the case. At 10 MHz frequency offset, there is a 5 MHz gap between the upper edge of the TDD LTE signal and Bluetooth Channel 0. For the clean TDD LTE signal this separation is sufficient for the OOBEs to have almost reached the noise floor and so the interference level is similarly close to its minimum. However, OOBEs from the typical TDD LTE signal are still 15 dB above the noise floor and so we observe a degradation of the Bluetooth link. By 15 MHz separation the clean and typical curves have converged as the TDD LTE OOBEs are similar for both cases.

In all cases, at the planned frequency offset of the highest frequency TDD LTE carrier (indicated by the marker line at -17 MHz) there is no difference between the clean and typical curves. Thus, a BS with worst case OOBEs would be no more problematic than a clean BS.

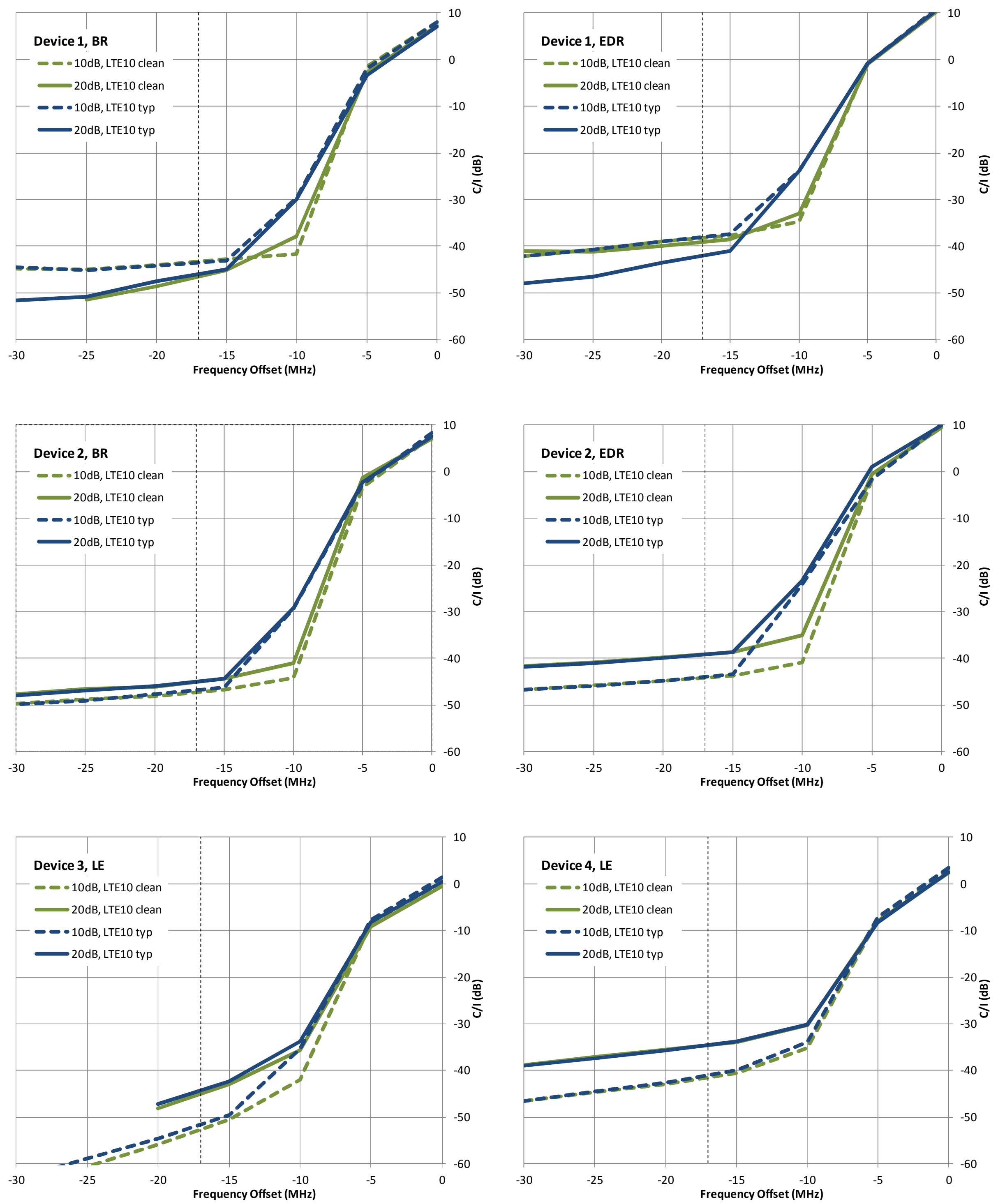


Figure 38 Comparison of response to clean (green) and typical (blue) 10 MHz TDD LTE emissions by Device 1 to 4.

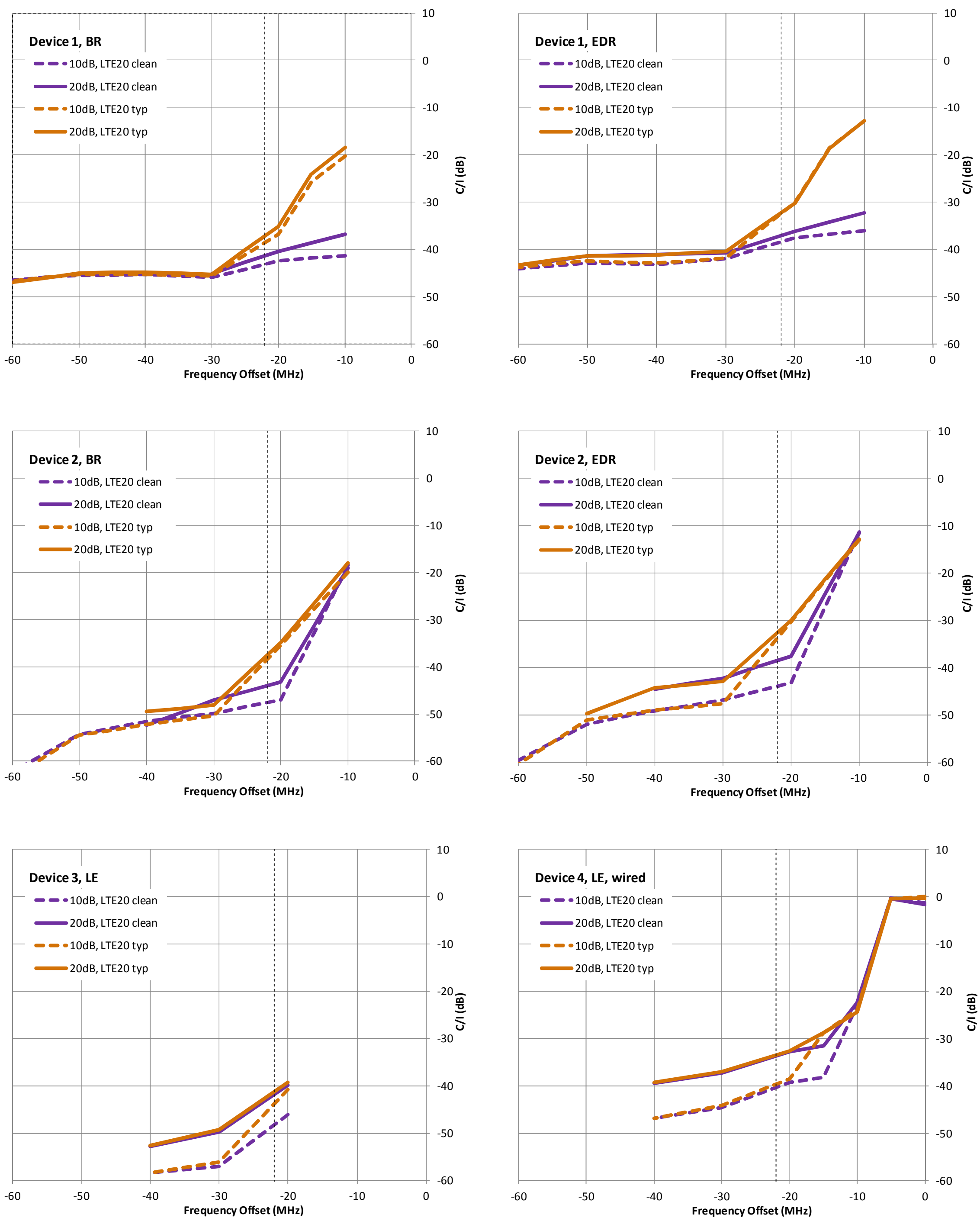


Figure 39 Comparison of response to clean (purple) and typical (brown) 20 MHz TDD LTE emissions by Device 1 to 4[4].

The results obtained with a 20 MHz TDD LTE interferer show the same trends as those with a 10 MHz interferer, but over an expanded frequency range, so that the curves are observed to

[4] In this figure we have substituted the wired results for Device 4 as we have more data points.

merge at 30 MHz instead of 20 MHz. Again both devices show consistent behaviour when operating with 20 dB uplift.

Thus, the observed behaviour is exactly as would be expected. When the LTE signal is offset by half its bandwidth then both the clean and typical LTE signals cause significant disruption to Bluetooth and so we can conclude that operating the systems at this spacing would not be practical. At the frequency separations of the proposed channel plans (indicated by the vertical dashed lines in the figures) the additional OOBEs generated by a typical spectrum profile, which is representative of a UE transmission, will not be a factor for 10 MHz bandwidth systems, but may be slightly more disruptive in the case of 20 MHz bandwidth systems.

5.3 Differences between BR, EDR and LE modes

Figure 40 highlights the performance variation across the three Bluetooth operating modes. The chart includes BR and EDR data from Devices 1 and 2 and LE data from Devices 3 and 4, with all results corresponding to a 10 MHz TDD LTE interferer using frame configuration 5 and with 10 dB uplift above the baseline sensitivity.

With BR and LE modes using an almost identical air interface and EDR mode using higher order modulation, it is natural to expect EDR to be most susceptible to interference. This relative performance is suggested by the results presented in Figure 40, however, the difference is slight. With its emphasis on low power we may also have expected LE mode to be susceptible, however this does not appear to be the case and, indeed, one of the LE mode devices narrowly outperforms the other modes.

The curves in Figure 40 suggest that EDR mode is approximately 5 dB more sensitive to interference than BR mode, which is consistent with the relaxation in the blocking specification for EDR devices.

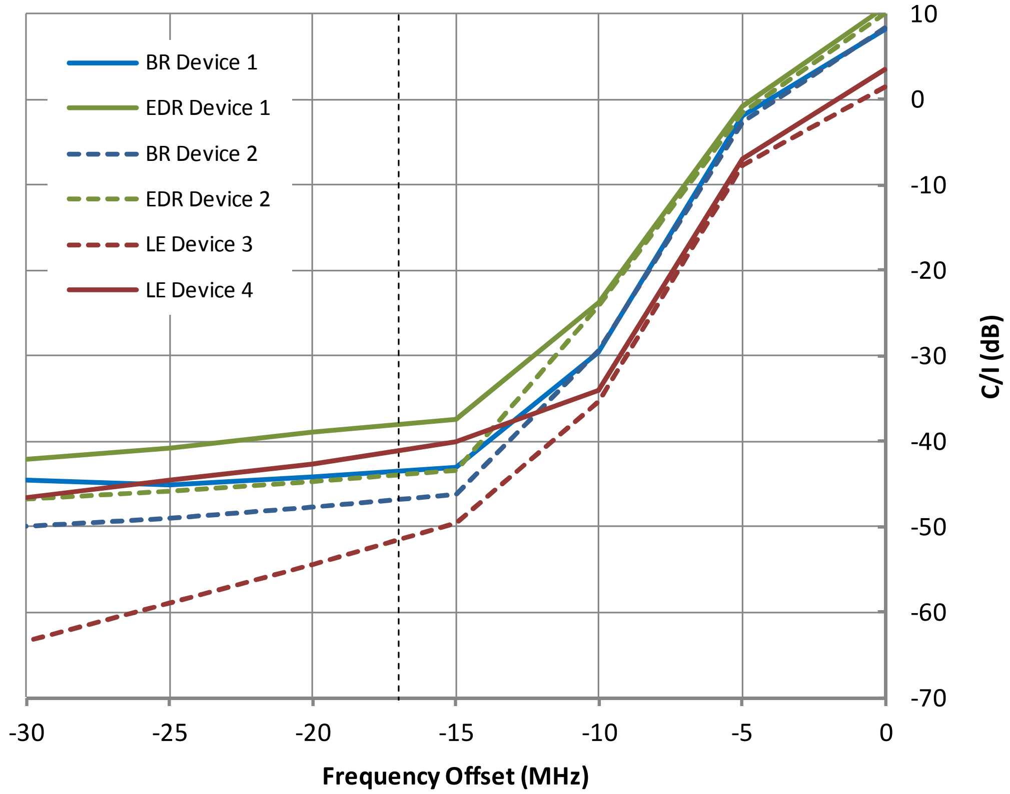


Figure 40 Comparison of the susceptibility of the three Bluetooth operating modes.

5.4 CW *vs.* Wideband Blocking

A major difference between CW and wideband interfering signals is that when a CW signal passes through a compressed amplifier it retains its narrowband characteristic (there is some spreading of phase noise, but this is usually at a very low-level and still relatively narrowband), whereas a wideband signal will spread out due to self-mixing caused by odd-order intermodulation within the amplifier.

Comparing the CW blocking characteristic with those of the TDD LTE signals shown in Figure 41 we can see that even at large frequency separations the TDD LTE signal results in approximately 10 dB poorer performance. The same effect was noted in the conducted tests on Device 4, see Figure 28. At 60 MHz separation OOBEs from the TDD LTE transmitter cannot be the explanation for this behaviour, consequently we conclude that intermodulation is the reason. Even so, we might expect the TDD LTE curves to merge with the CW curves at some suitably large frequency offset; however, this does not happen within the range of our tests. An explanation for this is that the Bluetooth receivers we examined do not use any front-end filtering, choosing to rely on antenna resonance and matching to provide attenuation of out-of-band signals. How much attenuation may be achieved this way is design specific, though it is unlikely to be more than 6 dB over the frequency range of interest. This small attenuation and a sufficiently linear receiver seem to be enough for Bluetooth devices to meet their blocking specifications and thus, for reasons of cost, a bulk filter is omitted.

The Bluetooth specification requires devices to operate in the presence of CW blocking signals at a level of -27 dBm for BR and EDR and -35 dBm for LE when operating with 3 dB uplift. The results comparing BR and EDR presented in Section 5.3 indicate the EDR devices are more sensitive to blocking and so typical devices will make use of this relaxation in the blocking specification.

Our conducted tests on Device 4 suggest that devices narrowly meet the specification, perhaps with 5-6 dB margin. Thus, we might expect devices to tolerate CW interference of -22 dBm to -30 dBm depending on the Bluetooth mode. If EDR devices are 10 dB less tolerant to wideband signals then they will have a similar level of performance when receiving wideband interference at -40 dBm.

By this argument we can conclude that a Bluetooth device operating with just 3 dB of link margin could tolerate a blocking signal of -40 dBm in Band 40, or a Bluetooth link operating with 33 dB of link margin could tolerate a blocking signal of -10 dBm. Since the vast majority of Bluetooth applications are for very short range devices a 33 dB margin is quite realistic for most Bluetooth links, thus we would expect most links to tolerate high levels of interference. We will explore this line of reasoning further in Section 5.6.

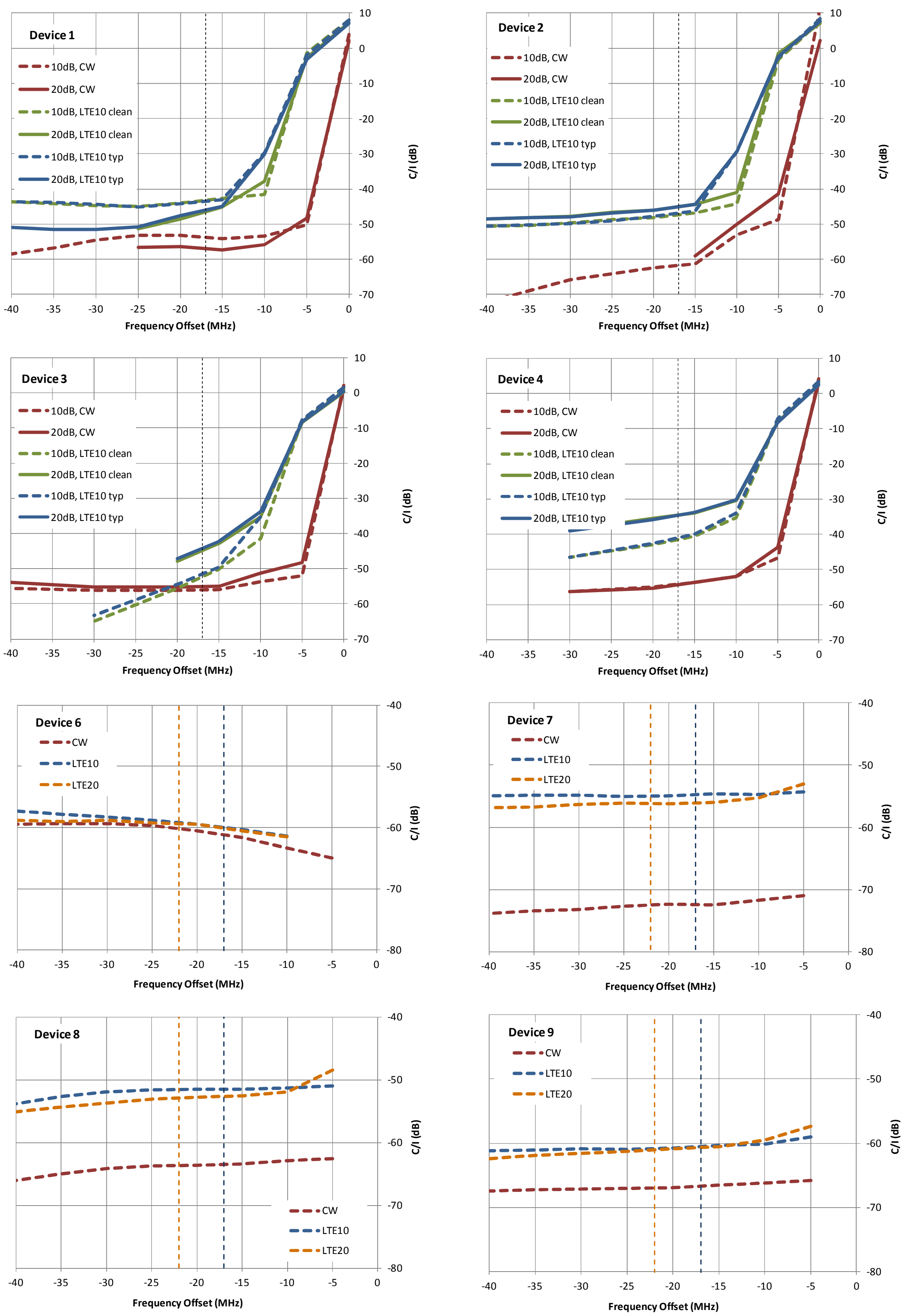


Figure 41 A comparison of CW and TDD LTE interference susceptibility for Devices 1 to 4 and 6 to 9.
[The opposite trend observed for Device 6 is attributed to measurement uncertainty or the presence of a SAW filter in this device.]

5.5 Sensitivity to TDD LTE Frame Configuration

TDD LTE systems may be configured to operate with a variety of frame configurations (see Table 7), permitting a flexible allocation of resources between the up- and down-links. For the majority of our tests we used Configuration 5, which has the maximum number of downlink timeslots and thus when all downlink timeslots are in use (as they were in our tests) it represents a worst case scenario for interference. To test the sensitivity of Bluetooth devices to the LTE frame configuration we also conducted tests on some devices using Configurations 0 and 1 (see Table 4 and Table 5 for a full list of test configurations).

When Configuration 0 was in use it was populated only the uplink slots using an uplink signal spectrum (see Figure 15) and as such it is not directly comparable with the other frame configurations, hence it has been omitted from this analysis. Configurations 1 and 5 were populated in the downlink slots using clean or typical 10 MHz downlink signals (see Figure 13).

To summarise, Configuration 5 represents the worst case scenario of transmissions for approximately 85% of each frame and Configuration 1 is a balanced scenario, approximately 50% occupied.

Frame Configuration	Period (ms)	Subframe									
		0	1	2	3	4	5	6	7	8	9
0	5	D	S	U	U	U	D	S	U	U	U
1		D	S	U	U	D	D	S	U	U	D
2		D	S	U	D	D	D	S	U	U	D
3	10	D	S	U	U	U	D	D	D	D	D
4		D	S	U	U	D	D	D	D	D	D
5		D	S	U	D	D	D	D	D	D	D
6	5	D	S	U	U	U	D	S	U	U	D

Table 7 Permitted TDD LTE frame configurations.
U = uplink
D = downlink
S = special slot (half downlink and half uplink)
Red highlighting indicates the configurations used in our tests.

Figure 42 and Figure 43 show comparison results for Device 1 in BR and EDR modes and for Devices 3 and 4, respectively. In all cases the interfering TDD LTE signal was a typical 10 MHz transmission and either Configuration 1, or 5.

At practical separations of 10 MHz or more we do not observe any significant difference between the three frame configurations and at frequency offsets greater than 5 MHz the curves show that there is little difference between Configurations 1 and 5. Thus, we conclude that frame configuration is not a factor that influences the interference effect of TDD LTE signals into Bluetooth.

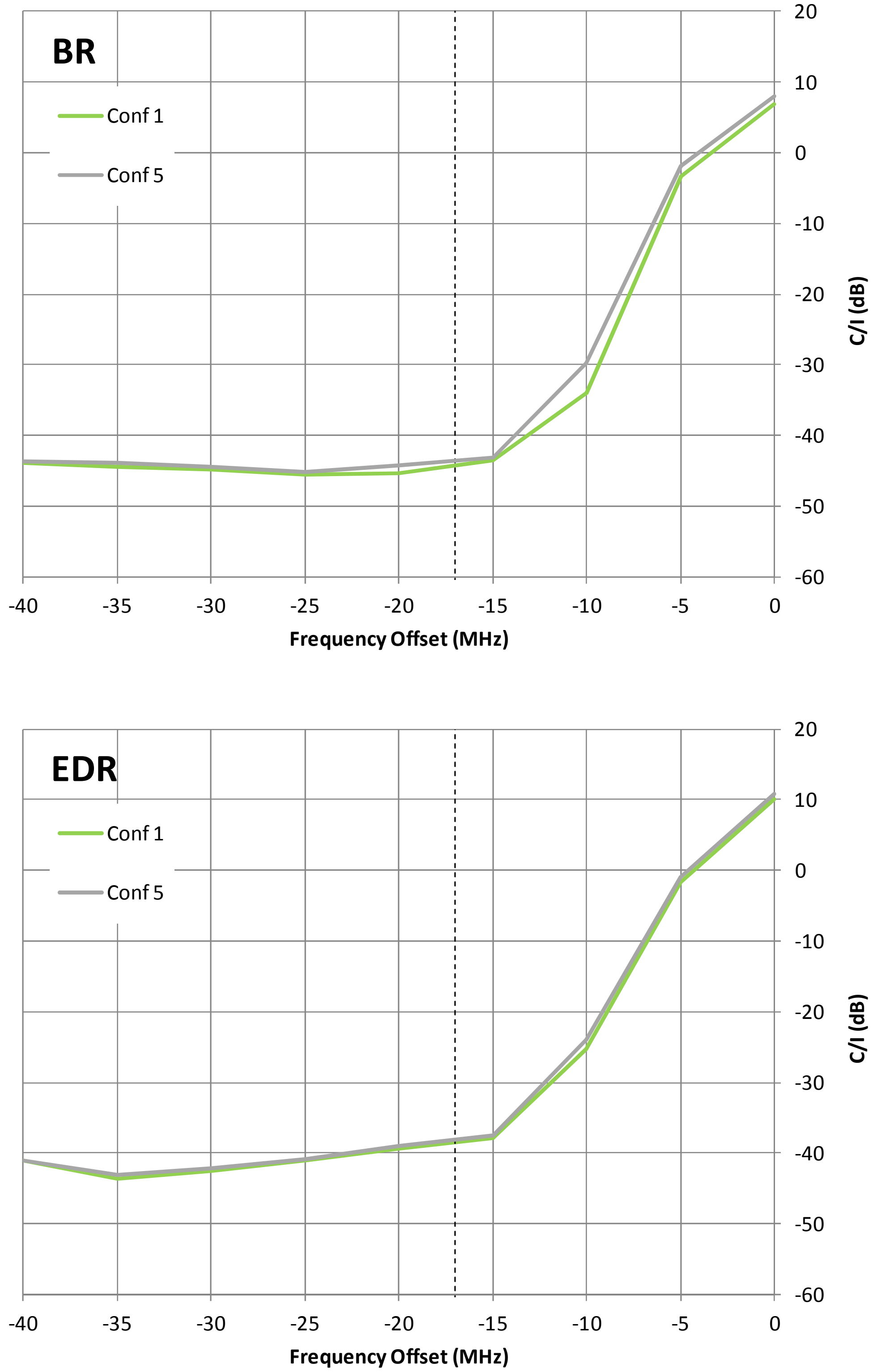
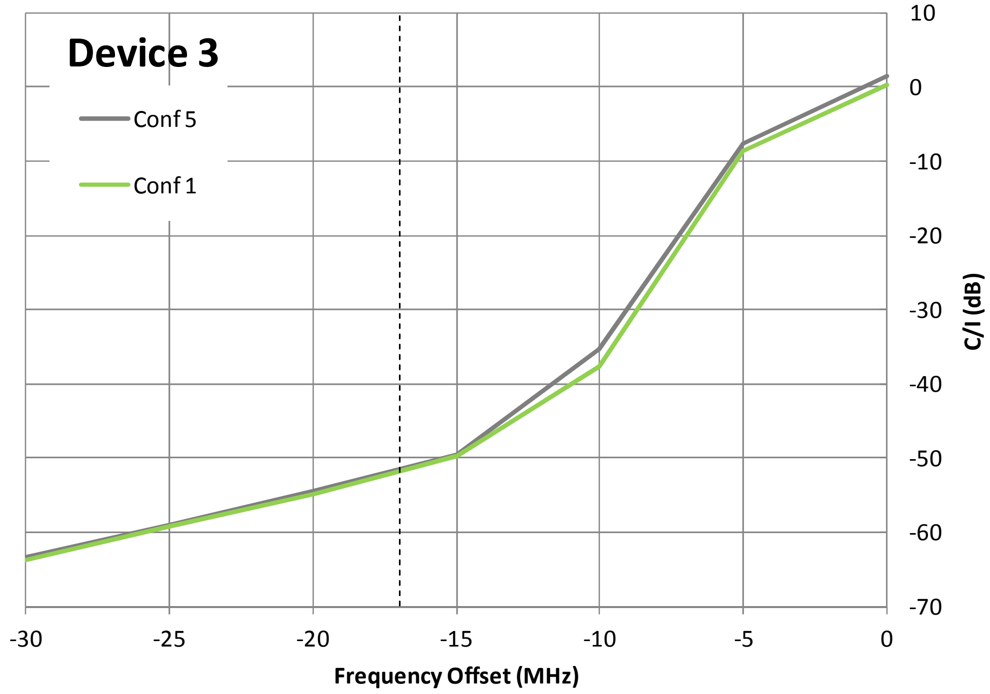


Figure 42 Comparison of Device 1 performance with three TDD LTE frame configurations.



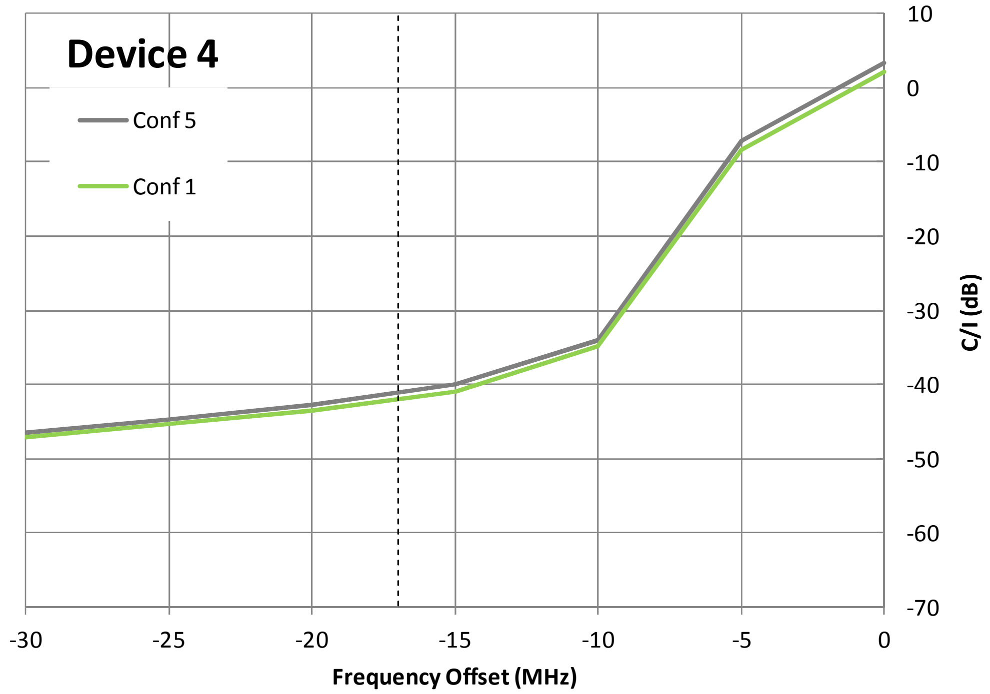


Figure 43 Comparison of Device 3 and Device 4 performance with three TDD LTE frame configurations.

5.6 Absolute Interference Levels

Most of our tests were conducted with an air path of approximately known attenuation between the signal generation equipment and the unit under test. Consequently, except for the case of Device 4, we do not have direct measurements of the absolute levels of interference that disrupt the Bluetooth link. However, knowing the C/I ratios and using the approximated path loss we can estimate the interference levels that were present at the DUT antennas.

The conducted test results for Device 4 using clean TDD LTE transmissions to represent a BS are reproduced in Figure 44. This particular LE device operates well inside the Bluetooth receiver sensitivity specifications, with a data sheet sensitivity for 30.8% PER of -92.5 dBm, and our measurement of -88 dBm suggests that this is realistic with careful design (we note that in modifying the board we made no attempt to match the input impedance to 50 ohms and thus did not expect to achieve the data sheet sensitivity). The specified LE CW blocking performance is -35 dBm when receiving a wanted signal at -67 dBm, which is close to the 20 dB curve in Figure 44, and thus we observe that the specification is exceeded by more than 20 dB at the likely TDD LTE signal offsets.

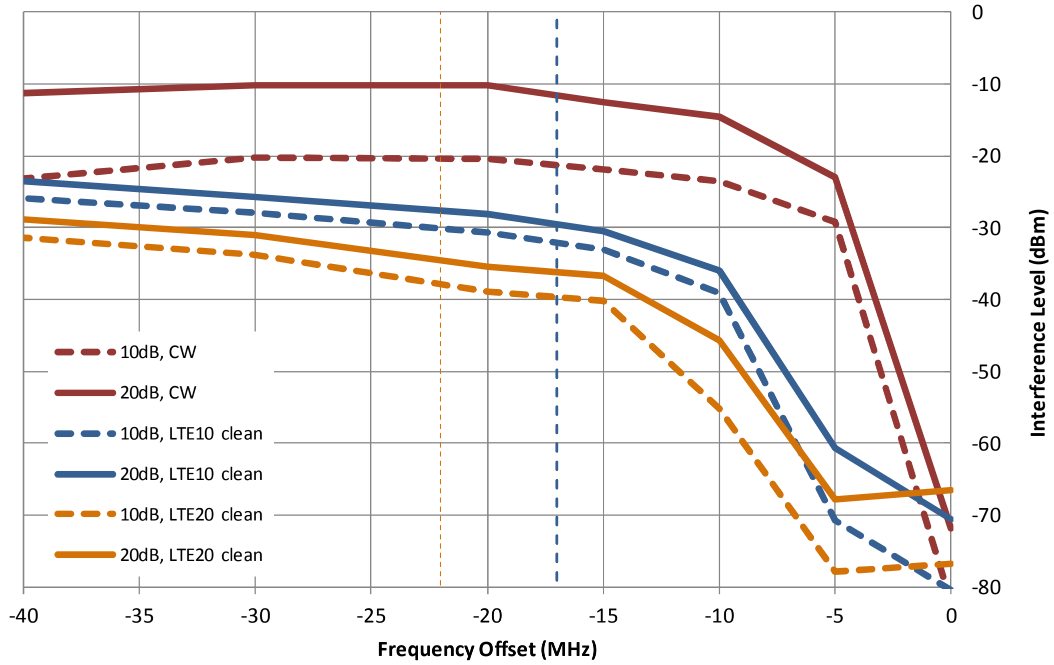


Figure 44 Conducted interference measurements for Device 4.

From Figure 44 we also observe that TDD LTE interference has a much greater impact than CW. At frequency offsets of 17 MHz and 22 MHz, corresponding to the smallest expected offsets of 10 MHz and 20 MHz TDD LTE transmissions, tolerable levels of interference are -32 dBm and -38 dBm, respectively. Examining the two curves for each TDD LTE bandwidth we can observe that although the uplift in wanted signal increases by 10 dB the tolerable level of interference increases by approximately 3 dB. This is precisely the result we would expect to observe for a third-order intermodulation effect, ie, the third-order products increase in power (in dB units) at three times the rate of the fundamental signal. In this case the fundamental signal is the TDD LTE interference and the third order products are OOBEs that overlap Bluetooth Channel 0. Because of the three time multiplication factor a 3.3 dB change in the out of band TDD LTE signal causes a 10 dB change in the power that falls in Bluetooth Channel 0 and hence a 10 dB increase in the wanted Bluetooth signal is counter-balanced by a 3.3 dB increase in interference. Although not quite so obvious the same trend is observed in many of the raw data charts presented in Section 4; see for example Figure 21.

This effect would have serious repercussions for receiver blocking performance in the absence of automatic gain control (AGC), which reduces the receiver gain when receiving strong signals and thus provides additional protection against blocking. The precise relationship between AGC and blocking protection is a function of individual designs and whether or not the power detector is wideband, ie, it reacts to signals outside the Bluetooth band, or narrowband, ie, it looks only at the wanted channel. In either case AGC will increase the receiver tolerance to strong out of band signals at the expense of sensitivity, but as Bluetooth link typically operate at short range this loss of sensitivity is seldom a problem.

5.7 Interference Range

The purpose of the analyses in the preceding sections has been to identify the mechanisms by which Bluetooth devices suffer from interference from TDD LTE signals in the adjacent band. To recap, we have identified that:

1. the major interference mechanism is third order intermodulation distortion within the Bluetooth receiver itself;
2. that typical Bluetooth devices have a margin of approximately 5 dB over the CW blocking specification;
3. that wideband interference is more disruptive than CW; and
4. that EDR mode is approximately 5 dB more sensitive to blocking than BR and LE modes.

Using two simplified receiver models we will now put these results in the context of Bluetooth devices operating in the presence of LTE BSs or UEs.

The first model considers a BR or LE receiver with a narrowband AGC, as depicted in Figure 45. The AGC loop is driven from a signal strength measurement taken after the baseband filter and thus does not respond to out of band power. The second model assumes that signal strength is measured before the baseband filters and hence does respond to out of band power.

In the narrowband AGC model the receiver operates at full gain until a set point of 30 dB above minimum sensitivity is reached and for further increases in wanted signal level maintains the same link margin by reducing the receiver front-end gain. For the wideband AGC case the model assumes operation at full gain until out of band signals exceed -30 dBm and as interfering signals increase further reduces the front-end gain to maintain a constant level into the mixers, which are assumed to be the limiting factor.

Both models simulate a receiver that has continuously variable gain control rather than a more likely implementation in which gain is reduced in fixed steps (eg, 3 dB or 6 dB), but despite this difference the overall conclusions that can be drawn from this model are valid.

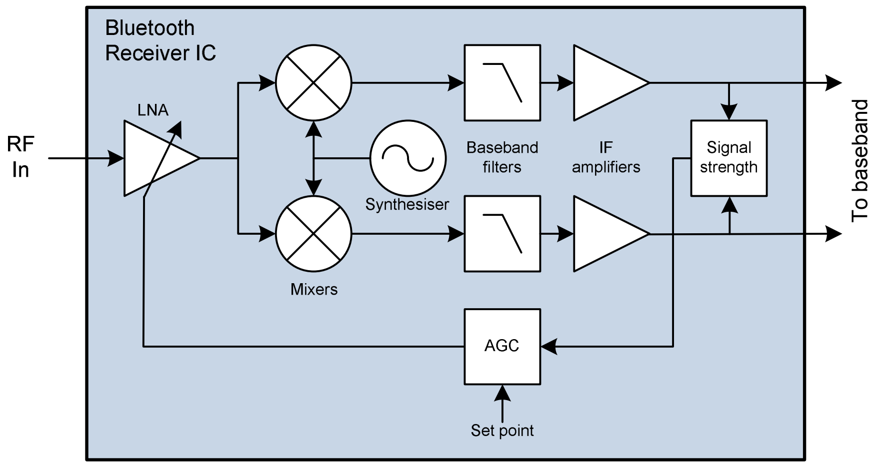


Figure 45 Simplified Bluetooth receiver with narrowband AGC.

For the narrowband AGC case, starting from a calibration point that was taken from the Device 4 figures for 10 dB link margin obtained from Figure 44, ie, -32 dBm for a 10 MHz interferer and -38 dBm for a 20 MHz interferer, the model calculates the blocking level as a function of Bluetooth signal level as follows.

1. For signal levels below the set point the blocking level increases by 0.33 dB for every 1 dB increase in Bluetooth signal level. This simulates the third order distortion behaviour described above.
2. Once the Bluetooth level reaches 30 dB above minimum sensitivity the blocking level increases in line with the Bluetooth signal level, to simulate the effect of reducing gain.

Using the simulated blocking level and assuming BS transmit powers of 64 dBm and 67 dBm for 10 MHz and 20 MHz TDD LTE signals, respectively, the model calculates the tolerable path loss between a BS and the Bluetooth receiver. The calculated path loss is then converted to a protection distance using a dual-slope path loss model; with square law loss below 50 m and fourth order law loss above 50 m as described by Equation 1.

$$\begin{aligned}
&Path\ loss = \begin{cases} K + 20\log_{10}(d/d_0) & d \le d_c \\ K + 20\log_{10}(d_c/d_0) + 40\log_{10}(d/d_c) & d > d_c \end{cases} \\
&K = free\,space\ loss\ at\ d_0 \\
&d_0 = 1m \\
&d_c = 50m
\end{aligned} \tag{1}$$

The same receiver model has also been applied for UE transmissions at a power of 23 dBm, but in this case a purely square law model is assumed, since all distances are well below 50 m.

The results of the model are shown in Figure 46. At low Bluetooth link margins it would appear that a large protection distance is required to a BS. However, we note that for a typical Bluetooth receiver sensitivity of -80 dBm and transmit power of 10 dBm, 10 dB link margin is achieved with 80 dB path loss, which equates to 70 m using the dual slope path loss model. Since typical Bluetooth link ranges are less than 10 m, it is clear that most Bluetooth devices will operate with very large link margins and the typical operating point lies towards the right hand side of Figure 46.

The additional transmit power and increased receiver susceptibility to 20 MHz TDD LTE signals results in larger protection distance being required, but in contrast protection distances from TDD LTE UEs are less than 2 m for most practical purposes.

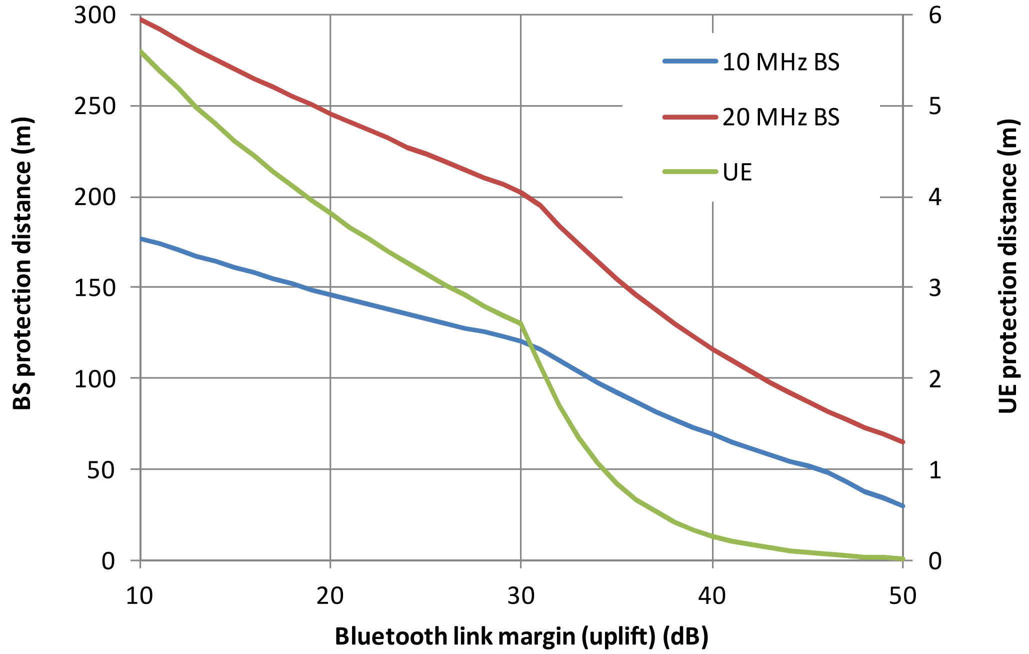


Figure 46 Estimated protection distance required between a Bluetooth device and a TDD LTE BS as a function of Bluetooth link margin.

Using the same transmit power (10 dBm) and receiver sensitivity (-80 dBm) assumptions as above, a 50 dB Bluetooth link margin corresponds to a 40 dB path loss or approximately 1 m separation between Bluetooth devices, which is a typical operating scenario for many Bluetooth links.

Using a square law path loss model for the Bluetooth link we have re-interpreted the x-axis of Figure 46 as Bluetooth device separation distance and plotted, in Figure 47, the protection distance from a TDD LTE transmitter as a function of Bluetooth device separation. From this we can observe that Bluetooth devices separated by 5 m could withstand interference from a UE at less than 1m, a 10 MHz BS at 90 m or a 20 MHz BS at 150 m.

We previously noted that EDR receivers are typically 5 dB more sensitive to interference than BR and LE devices. The effect of this will be to multiply the protection distances by a factor 1.8 for the same Bluetooth device separation. Thus, for the previous example of 5 m Bluetooth device separation the required protection distances are 1.8 m, 162 m and 270 m for a UE, 10 MHz BS and 20 MHz BS respectively.

Finally, we note that the results predicted by this model will be pessimistic in comparison with the behaviour of a real device and should be treated as a worst case scenario for the following reasons.

1. Interference resulting from third order intermodulation has a diminishing impact on Bluetooth channels as they increase in frequency and this model takes no account of Bluetooth's ability to avoid interference through frequency hopping.
2. The model was calibrated using Device 4, which has the worst C/I performance of all the devices we measured. The other nine devices are about 10 dB better and assuming that this results in 10 dB greater tolerance to interference then the previously quoted protection distances will be almost halved.

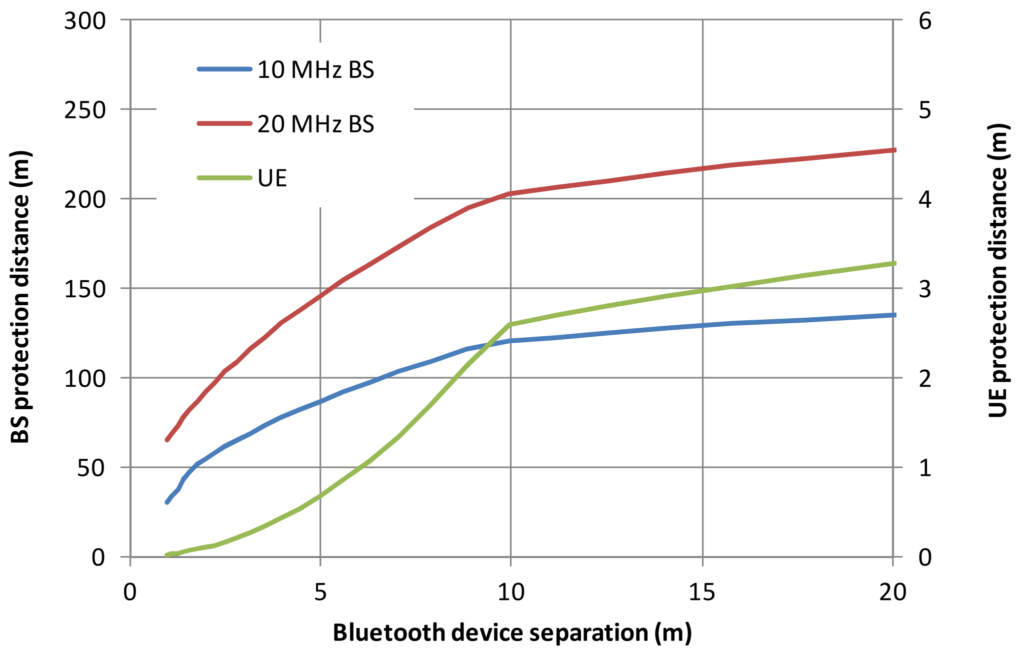


Figure 47 Estimated protection distance required between a Bluetooth device and a TDD LTE BS or UE as a function of Bluetooth device separation.

The wideband AGC model uses the same dual-slope path loss model to determine the blocking signal level as a function of Bluetooth-to-TDD LTE separation distance. For blocking levels exceeding -30 dBm it calculates the loss in gain, and hence the rise in receiver noise floor, to derive the Bluetooth device sensitivity, with a starting assumption that the Bluetooth device reference sensitivity is -75 dBm (assuming a better starting sensitivity would have the effect of decreasing the protection distance). From the Bluetooth sensitivity the model calculates the tolerable Bluetooth path loss and, finally, the Bluetooth separation distance assuming square law propagation. The results are shown in Figure 48 for 10 MHz and 20 MHz BSs with transmit powers as before. No results are shown for a UE interferer because the separation distances are so small that the model cannot be relied upon.

The results from the wideband AGC model are much more optimistic than those of the narrowband model and suggest that Bluetooth devices at 5 m separation could maintain operation to within 20 m of a 20 MHz TDD LTE BS.

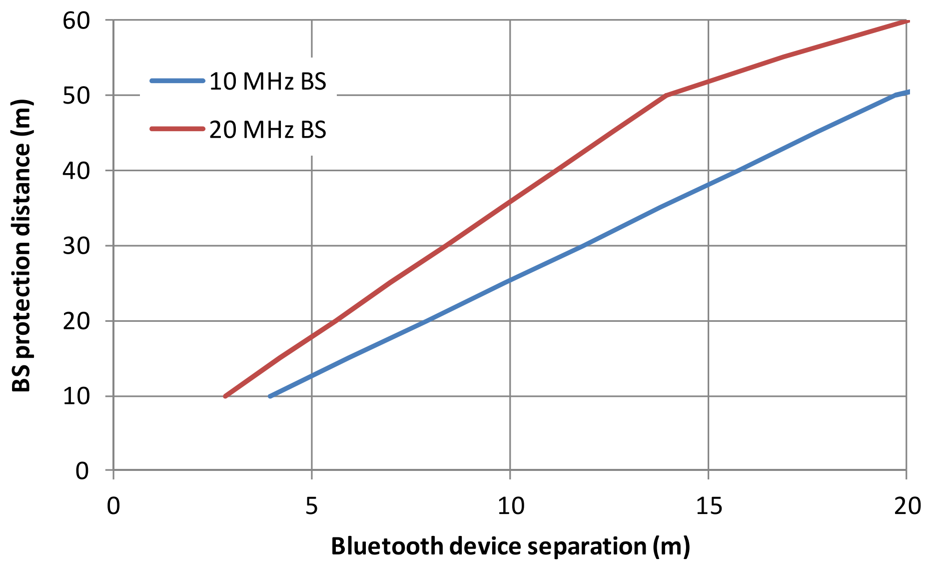


Figure 48 Estimated protection distance required between a Bluetooth device and a TDD LTE BS as a function of Bluetooth device separation assuming wideband AGC at the Bluetooth receiver.

The difference in the predictions between the models occurs because the narrowband model reduces gain in response to the Bluetooth signal level, whereas the wideband model responds to the interference itself. Thus, regardless of the interferer level the narrowband model gains no protection from AGC until the wanted Bluetooth signal level reaches 30 dB above the minimum sensitivity, whereas the wideband model gains an immediate benefit as soon as interference reaches problematic levels. In practice, most Bluetooth links operate well above their minimum sensitivity levels, hence the loss in sensitivity as a result of wideband AGC has little impact on the observed Bluetooth link performance, thus devices using wideband AGC can be expected to be less susceptible to out of band interference.

5.8 Variation Across Bluetooth IC Vendors

The ten devices we tested cover six different Bluetooth integrated circuit (IC) vendors and thus represent a good cross section of the market.

Figure 49 shows the results for Devices 6 to 10 covering four of the Bluetooth IC vendors. All the results correspond to a 10 MHz TDD LTE interferer using frame configuration 5 and with 10 dB uplift above the Bluetooth baseline sensitivity.

With such a small sample it is impossible to draw clear conclusions as to whether the variation observed is a result of differences between the IC vendors technology or simply differences in the designs using these ICs. We note that the best performing device (using a chipset from Vendor 6) is also the oldest one that we tested, whereas those using chipsets from Vendor 5 are recent products, suggesting perhaps that as time has passed cost reduction has taken place and that as a result newer Bluetooth radios operate with less margin compared to the Bluetooth Specification. However, contrary to this suggestion is the performance of Device 4, which operates more than 20 dB inside the receiver sensitivity specification.

The only conclusion that we can draw from this analysis is that variations between devices are to be expected and on the basis of these measurements a spread of approximately 10 dB seems typical.

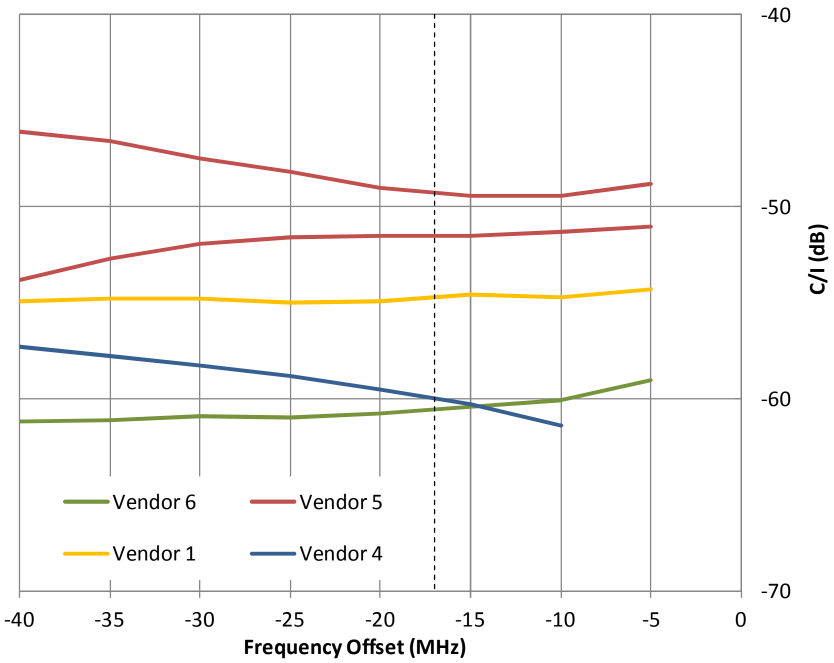


Figure 49 Variation in interference susceptibility as a function of Bluetooth IC vendor.

5.9 Bluetooth Hopping

Tests on Devices 6 to 10 were all conducted with hopping enabled. Test results for all these devices were obtained with frequency offsets up to 60 MHz in 5 MHz steps starting at -5 MHz (or 2397 MHz in absolute frequency). Thus, in the case of a 20 MHz TDD LTE interferer the signal power extended up to 2407 MHz and thus covered the first five Bluetooth channels. Despite this the results show very little performance degradation (5 dB worst case for Device 8) and clearly indicate that frequency hopping significantly reduces the susceptibility of Bluetooth devices to in-band and adjacent band interference.

Further evidence of the benefit of frequency hopping was obtained during our qualitative testing on the three audio devices. By monitoring the Bluetooth transmissions we were able to observe that adaptive frequency hopping was able to remove blocked Bluetooth channels from its hopping list and thus maintain its operation even in the presence of very high levels of in-band interference.

5.10 Device-to-Device Variation

Figure 50 charts the spread of results obtained with Devices 6 to 10. Solid lines show the performance with CW interference and dashed lines with 10 MHz TDD LTE interference using frame configuration 5, in both cases with 10 dB of signal uplift.

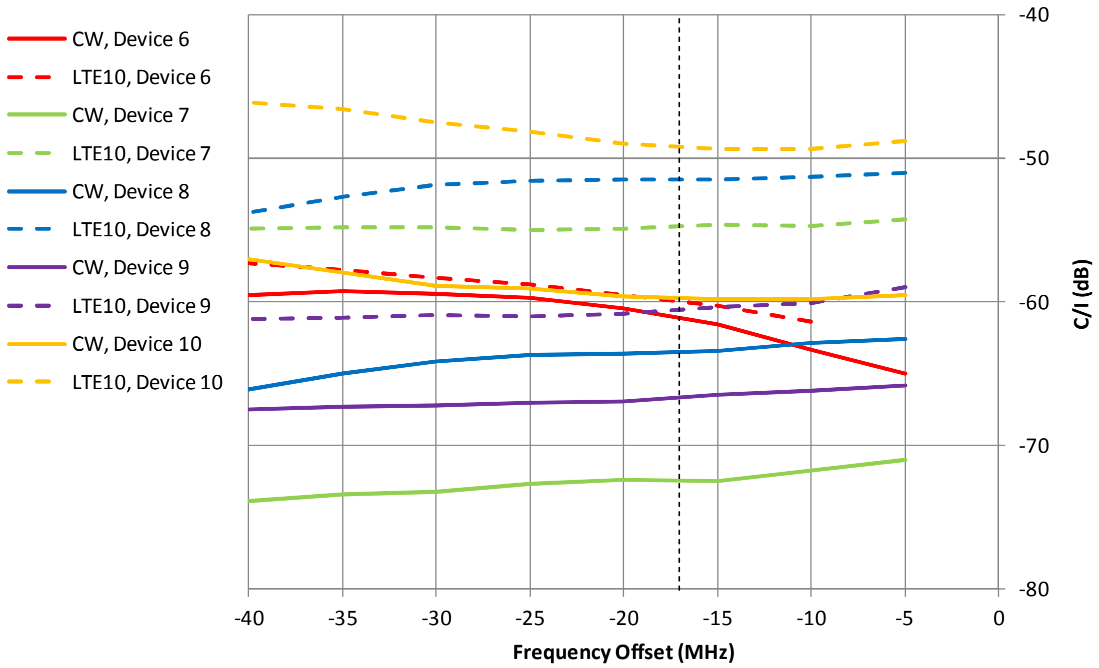


Figure 50 Spread of performance for Devices 6 to 10.

It is apparent from Figure 50 that all devices are more susceptible to wideband interference and that in both cases (CW and LTE10) there is a 10-15 dB performance spread. However, the best performing devices in the presence of CW are not necessarily the best in the presence of TDD LTE interference.

6 Conclusion

In this measurement study we undertook a quantitative evaluation of the tolerance of ten Bluetooth devices to interference in the 2.3 GHz to 2.4 GHz band from TDD LTE user and infrastructure equipment (referred to as UEs and BSs). The ten devices were chosen to be representative of Bluetooth devices on the market, covering all three Bluetooth operating modes (basic rate, BR, enhanced data rate, EDR, and low energy, LE) and spanning a range of applications. For half of the devices we were able to conduct detailed link error rate measurements through built-in test modes, the other half were tested in a mode that more closely reflects their standard operation.

In addition to the quantitative tests, for three devices, we conducted a qualitative assessment of their performance by subjecting them to interference whilst they were operating normally as audio headsets.

In the preceding sections of this report we have presented the raw measurement results followed by an analysis of the data to establish the interference mechanisms and the impact this interference will have on Bluetooth links in the vicinity of TDD LTE equipment.

There are two dominant mechanisms by which out-of-band TDD LTE signals can cause interference to Bluetooth. The first is through out of band emissions from the TDD LTE signal falling into the Bluetooth band and appearing as co-channel interference. Such interference is more likely from TDD LTE user equipment, which for cost and size reasons cannot afford to incorporate high quality filters and oscillators to tightly constrain the modulation spectrum. The second mechanism is through blocking, which is the result of strong out of band signals driving the Bluetooth receiver front-end into compression and thus reducing the gain to the wanted signal. Such interference could be caused by proximity to either TDD LTE UEs or BSs; whilst BS transmit power is much higher than that of UEs, a Bluetooth device is more likely to be very close to a UE.

By taking measurements of link error rate on Bluetooth channel 0 (2402 MHz) in the presence of interference at a range of frequency offsets (from co-channel to -60 MHz) we were able to observe the presence of both interference mechanisms when the interfering signal characteristics modelled the spectrum emissions of a typical UE. But, when the interference modelled a clean BS transmission only the blocking effect could be observed.

TDD LTE systems are able to allocate downlink and uplink resources in a variety of ways leading to a range of transmission duty cycles. To examine whether Bluetooth was affected more or less by any of these profiles we conducted tests using three different duty cycles. The results of these tests indicated that the TDD duty cycle does not significantly alter the level of interference experienced by a Bluetooth device.

The body of evidence we collected provides a clear indication that the most significant interference factor from TDD LTE into Bluetooth is receiver blocking. Furthermore, we identified that most Bluetooth devices operate without a bulk front-end filter and, consequently, Bluetooth receivers may be blocked by signals at large frequency offsets. The measurement data we collected also provided evidence that receiver generated co-channel interference, caused by third order distortion in the front-end, is the dominant interference mechanism and that without automatic gain control (AGC) Bluetooth receivers would perform very poorly in the presence of wideband interferers. Through simple models of the receiver we were able to demonstrate that under typical operating conditions, ie, Bluetooth device separations of less than 5 m, and without taking into account the beneficial effects of adaptive frequency hopping, operation is possible with minimal disruption within 1 m of a UE and within 20 m of a 20 MHz BS. When adaptive frequency hopping is enabled we found that Bluetooth devices were extremely robust in the presence of quite severe levels of interference.

Bluetooth BR and LE mode links use essentially the same physical layer, whereas EDR mode links use a higher order modulation scheme to support higher data rates. By their nature higher order modulation schemes are less tolerant to noise and interference and our measurements of devices operating in EDR mode indicated that these were approximately 5 dB more sensitive to TDD LTE interference. Under the assumption of a square law path loss model 5 dB additional path loss equates to an increase in protection distance by a factor of 1.8.

Device-to-device and vendor-to-vendor variations across the range of samples tested were approximately 12 dB, indicating that some devices will be more susceptible to interference than others. However, comparing the CW and OOBE blocking results also revealed that the CW test specified by the Bluetooth standard is not a good predictor of susceptibility to wideband interference, with the device having greatest susceptibility to CW being one of the most tolerant to wideband blocking. The likely explanation for this behaviour is that this device has a front-end filter but a lower compression point.

The summary conclusion from our objective tests is that the presence of TDD LTE signals in the frequency range 2350 MHz to 2390 MHz causes a measurable but low-level interference effect to Bluetooth channels at the low end of the ISM band. However, when Bluetooth devices operate with frequency hopping enabled there is no observable effect unless the Bluetooth device is subjected to very high levels of interference that are only likely within a few centimetres of a TDD LTE terminal or a few metres from a TDD LTE BS. Therefore, we conclude that TDD LTE services could be permitted according to the proposed band plan without causing any disruption to the vast majority of Bluetooth devices and causing only minor disruption to the most susceptible devices that are operating in close proximity to TDD LTE equipment.

Appendix A – Device Cross Reference Table

Device	Type	Model	Bluetooth IC Vendor	Vendor
1	Phone	Samsung 360	Broadcom	Vendor 1
2	Phone	Nokia C6	Broadcom	Vendor 1
3	EVM	TI EVM	TI CC2540	Vendor 2
4	EVM	Nordic EVM	Nordic	Vendor 3
5	Phone	Samsung Galaxy S3	Broadcom	Vendor 1
6	SatNav	Garmin Satnav	ST Microelectronics	Vendor 4
7	Keyboard	Anker Mini keyboard	Broadcom 553	Vendor 1
8	Hands-free kit	Jabra hands-free kit	CSR6530	Vendor 5
9	Headset	Motorola Headset	Philips 28096	Vendor 6
10	Headphones	CyberBlue Headphones	CSR5370	Vendor 5

References

1. Bluetooth SIG, *Qualified Parts Listing*, Accessible from https://www.bluetooth.org/tpg/listings.cfm, Downloaded 26 January 2013

2. Bluetooth New Products Directory, available at, http://www.bluetooth.com/Pages/Product-Directory.aspx, Accessed January 2013

3. "Specification of the Bluetooth System", Version 4.0. Available from https://www.bluetooth.org/Technical/Specifications/adopted.htm

4. "Specification of the Bluetooth System", Version 2.1 + EDR. Available from https://www.bluetooth.org/Technical/Specifications/adopted.htm

5. Ofcom Research Document, *LTE User Equipment Coexistence with 862 – 870 MHz*, 11 September 2012

6. 3GPP TS 36.104, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception", v11.2.0, September 2012

7. 3GPP TS 36.101, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception", v9.12.0, June 2012