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Bluetooth Performance with 2.3 GHz LTE Interference

Report

Issue 5

Document History

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4	16 JAN 15	First public distribution of this document
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Tables, Figures and Equations

1. Introduction

Increasing allocation of spectrum worldwide to mobile networks is reducing the frequency separation between low power devices in the 2.4GHz ISM band and higher power devices operating in close physical proximity.

In the UK there are currently proposals being consulted upon to allocate further LTE spectrum between 2.3 and 2.4GHz (see *2.3 and 3.4 GHz spectrum award: Consultation on a 3.4 GHz band plan, varying UK Broadband Limited's licence and a call for inputs on other aspects of the award*). Auctions for this spectrum are currently scheduled for late 2016. This band has already been allocated in a number of European countries with roll out starting in 2016. Within the UK a 10MHz guard band above 2390MHz will be in place, this would not be the case in Europe.

In principle this means that providing on-board attenuation to protect a Bluetooth or Wi-Fi device from high level signals in adjacent LTE Bands at small frequency offsets is non-trivial and adds significant cost.

This report considers the measured performance of some products on the market using CSR Bluetooth devices when exposed to LTE interference at anticipated signal levels. Where possible the assessment of Bluetooth link performance is made in both qualitative and quantitative terms.

2. Interference Mechanisms

There are two mechanisms that are of concern as a cause of interference from LTE devices:

1. Receiver blocking due to high level out-of-ISM-band signals.
2. Co-channel interference due to low level ISM in-band noise.

There can be no mitigation for the second mechanism, when energy is present within the ISM band it cannot be filtered out in the Bluetooth receiver. This means that a sufficiently low level of spectral regrowth in the LTE transmitter must be achieved by design and regulatory specification, allowing for the anticipated proximity of the devices in use.

2.1. Coexistence

2.1.1. Synchronised Case

For a device that contains both the LTE and Bluetooth transceivers, coexistence between them must be achieved by mitigating the most sensitive interference case. This requires the Bluetooth link to be receive-disabled while the local LTE transmitter is active, additionally some RF filtering may be needed.

2.1.2. Unsynchronised Case

Where enforced synchronisation is not possible, such as when an LTE interference is in close proximity to an active Bluetooth link and the two are in separate devices, then the only options available are RF filtering or reducing the LTE transmitter power. If neither of these is a possibility then the interference must be accepted and allowed for in the design of the Bluetooth device.

2.2. Physical Environmental Factors

2.2.1. Introduction

Previous work on the likely effects of 2.3 GHz LTE on ISM band devices at CSR has identified that there are two possible scenarios where the physical proximity of LTE transmitters allows the RF field strength around the ISM band device to reach a level at which interference to normal operation becomes noticeable to the user.

The *LTE/Bluetooth Coexistence – Where the Shadows Lie* document describes the calculations together with the assumptions made that allow the expected signal levels to be determined.

2.2.2. LTE Node Effects

LTE/Bluetooth Coexistence – Where the Shadows Lie indicates that the transmitter of a high power LTE node is able to cause a maximum signal level of -17.5 dBm at the RF input of a Bluetooth device, in general such a node is planned and sited so that it is not possible for a member of the public to be within the main beam from a panel antenna with a typical gain of +18d Bi and so the radiated power level in an area that a Bluetooth device is likely to be used is reduced due to a combination of distance and the antenna radiation pattern in the vertical plane.

2.2.3. LTE UE Effects

An LTE capable mobile phone, known as a UE (User Equipment), has a much lower transmit power than an LTE node but in contrast it can be placed very close to ISM band devices using Bluetooth or Bluetooth Smart, see *LTE/Bluetooth Coexistence – Where the Shadows Lie*.

From calculation a UE at a 1 m range can cause a maximum signal level of -15 dBm and this can increase if the range is reduced. As this is greater than the maximum signal from a node it is clear that the UE produces the more taxing interference case.

In addition, the PAPR on a UE is potentially lower because of the simpler SC-FDMA modulation scheme used on the uplink; this means that the average signal power in use is higher for the UE case relative to its peak power.

3. Testing

3.1. Test Environment

Testing has been carried out at Ofcom's radio monitoring station which is remote from local RF signal sources but has significant ISM band traffic from on-site wireless networking equipment together with an RF anechoic chamber to allow measurements in a quiet environment.

Tests have been made using both heuristic analysis of the audio quality of streamed Bluetooth audio and a Bit Error Rate (BER) analysis of devices in DUT mode where the received data frame is looped back to the test equipment allowing various parameters to be measured and monitored.

The main testing has been carried out in a standard conference room to simulate an office environment. This room has a ceiling-mounted Wi-Fi Access Point (AP) which provides in-building network access. There are a significant number of APs in the entire building so there are 3 or 4 APs on each of the non-overlapping Wi-Fi channels 1, 6 and 11.

This means that there is a significant background level of RF traffic in the ISM band. While this is useful for performance assessment under real-world conditions it is not easy to determine the precise effect, therefore a comparison has been made where possible without these background signals using the screened property of the anechoic chamber.

3.2. Test Descriptions

Testing involved the use of 4 devices:

1. A CSR8510 (BlueCore7 architecture) development evaluation board
2. A small Bluetooth portable speaker
3. A mid-range in-ear Bluetooth headset
4. An android smartphone (streaming data source)

3.2.1. In-building ISM RF Measurement

The RF signal level from the in-building Wi-Fi APs was measured using a horn antenna with a gain of 10 dBi. The signal level from the R&S FSW spectrum analyser was ~ –20 dBm with the horn facing the in-room AP, pointed horizontally.

Approximate range from the AP was 2.5 m. The signal level across the ISM band was quite constant, suggesting that either the AP was operating on multiple frequencies simultaneously or that the more distant APs were operating at a higher RF power.

3.2.2. Test Matrix

Table 3.1 shows the device combinations used in the testing performed.

Device Tested	Notes	Loopback Test	Heuristic Test
CSR8510 development evaluation board	Unable to perform heuristic test due to lack of streaming connection. Use to establish performance of raw Bluetooth chip without external filtering.	Tested	Not tested
Mid-range in-ear Bluetooth headset	-	Tested	Tested
Small Bluetooth portable speaker	Loopback test not carried out as device did not enter DUT mode on command.	Not tested	Tested

Table 3.1: Test Matrix

Note:

It was not possible to enable DUT loopback mode on the Bluetooth portable speaker.

3.2.3. Heuristic Streaming Audio Tests

3.2.3.1. Small Bluetooth Portable Speaker

A streamed audio connection was set up using the smartphone as a streamed audio source using a UMTS HSPA connection. Audio bit rate used was 64 kbps variable AAC encoded.

The speaker was placed on the conference table and the smartphone was placed flat on the same table with 1 m between the two devices.

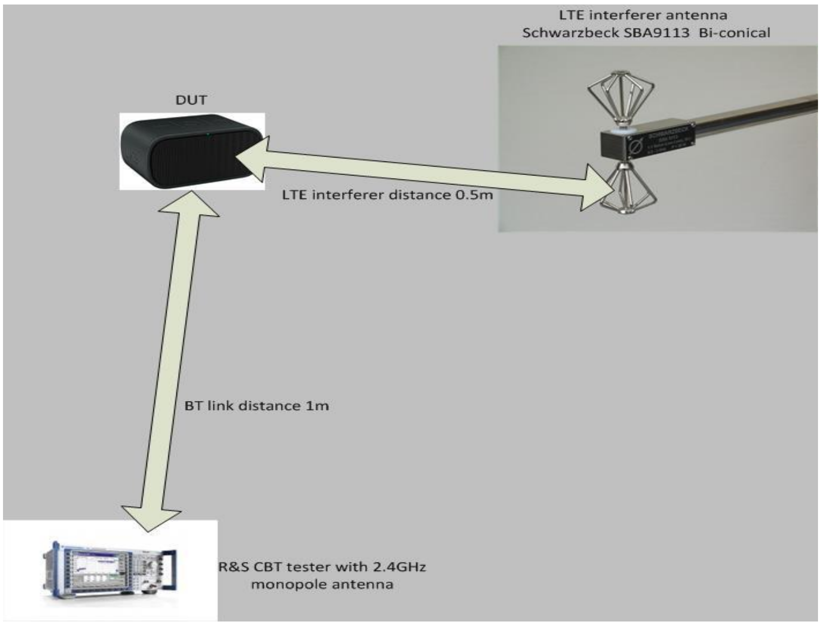

Figure 3.1: Test Geometry

A 2.38GHz LTE SC-FDMA transmission generated from an off-air recording was radiated from a biconical antenna placed 0.5 m from the Bluetooth speaker. The RF power level was reduced by means of a stepped attenuator, set to 0 dB this produced a maximum of +23 dBm EIRP.

Reducing the attenuation from >30 dB to 0 dB did not produce any noticeable change in the streaming audio quality the range was then reduced to 0.1 m. Under this condition the Bluetooth speaker muted completely at +21 dBm EIRP horizontally polarised.

Repeating the test using the stepped attenuator found that the streaming audio quality began to reduce with the attenuator set to 10 dB degrading slowly until the mute occurred when set to 0 dB.

3.2.3.2. Mid-range In-ear Bluetooth Headset

A streamed audio connection was set up in the conference room using the smartphone as a streamed audio source using a UMTS HSPA connection. The audio bit rate used was 64 kbps variable AAC encoded.

The headset was placed in-ear and the smartphone was placed flat upon the same table with a separation of ~1 m between the devices.

A 2.38 GHz LTE SC-FDMA transmission generated from an off-air recording was radiated from a biconical antenna placed 0.5 m from the Bluetooth headset.

With the LTE RF level at its maximum of +23 dBm EIRP no effect on the streaming audio was noticeable.

After some experimentation it was found that the streaming audio could be made to stutter and mute with the LTE antenna placed at 0.05 m from the headset.

This effect was sudden and there did not seem to be any gradual worsening detectable before the muting was apparent.

3.2.4. DUT Mode Loopback Tests

The following tests were performed using the R&S CBT controlling the DUT using the Bluetooth SIG loopback mode. The CBT antenna is a loaded quarter wave monopole over a circular ground plane mounted vertically about 0.1 m away from the test connector on the CBT front panel, see Figure 3.1.

A standard loopback test was set up, running continuously with each device subjected to an Inquire then Connect and Test sequence.

For the in-ear headset the test was repeated in an RF quiet environment inside the anechoic chamber with the headset resting on a foam block.

The Bluetooth portable speaker could not be made to enter DUT mode.

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3.3. Test Results

3.3.1. CSR8510 Development Evaluation Board

Table 3.2 shows the bit error rate (BER) seen in a loopback test using a CSR8510 device on a development evaluation board.

The signal level seen by the Bluetooth receiver is at the Bluetooth SIG specification minimum receive level and the effect of increasing LTE signals is shown.

Test Parameters		LTE Level (dBm)	Received BER (%)	
			Recorded Signal	SMBV Sig gen
No 2.4GHz BPF on Bluetooth RF input	-	Off	0.8 - 1.4	0.8 - 1.4
	-	9	0.8 - 1.4	1.2 - 1.3
CBT RF level (dBm)	-30	11	0.9 - 1.5	1.4 - 1.5
Bluetooth link range (m)	1	13	0.9 - 1.8	1.6 - 1.8
2.38 GHz LTE interferer range (m)	0.5	15	1.4 - 2.2	1.8 - 2.0
LTE antenna gain (dBi)	0.55	17	1.6 - 2.5	3.1 - 3.2
Wanted signal level at Rx (dBm)	-70.0542	19	2.8 - 3.5	3.3 - 3.5
		21	4.5 - 5.5	3.5 - 3.8
		23	sync lost	sync lost

Table 3.2: CSR8510 Development Evaluation Board Test Results

In the open conference room environment the effect of the background ISM band Wi-Fi signals can be seen with a significant BER even with no LTE signal present.

It can also be seen that except at the highest LTE signal levels the fully resourced SMBV signal generator signal produced a greater BER than the recorded signal used. This indicates that the variation in average power has an effect on the Bluetooth link performance and that the change in BER is not always worse with higher LTE traffic loading.

This may be due to receiver AGC effects as the gain in each receiver circuit block changes with signal levels.

3.3.2. Mid-range In-ear Bluetooth Headset

Table 3.3 shows the performance of the in-ear headset in the anechoic chamber.

Test Parameters		LTE level (dBm)	Received BER (%)	
			LTE Vert.	LTE Horiz.
CBT RF level (dBm)	-37	off	0.06	0.06
Bluetooth link range (m)	1	3	0.11	0.07
2.38GHz LTE interferer range (m)	0.5	5	0.14	0.08
LTE antenna gain (dBi)	0.55	7	0.22	0.09
Wanted signal level at Rx (dBm)	-77.0542	9	0.34	0.10
		11	0.58	0.58
		13	1.15	0.19
		15	1.75	0.29
		17	2.80	0.56
		19	4.00	1.28
		21	3.50	1.73
		23	4.3*	3**
			* PER = 68%	** PER = 21%

Table 3.3: In-ear Headset Chamber BER Results

Table 3.4 shows the performance of the in-ear headset in the conference room.

Test Parameters		LTE Level (dBm)	Received BER (%)	
			LTE Vert.	LTE Horiz.
CBT RF level (dBm)	-20	off	0.08	0.08
Bluetooth link range (m)	1	3	0.09	sync lost
2.38GHz LTE interferer range (m)	0.5	5	0.15	-
LTE antenna gain (dBi)	0.55	7	0.35	-
Wanted signal level at Rx (dBm)	-77.0542	9	0.50	-
		11	0.50 - 1.00	-
		13	1.00 - 2.50	-
		15	sync lost	-

Table 3.4: In-ear Headset Conference Room BER Results

It is clear that when operating in a loopback test mode the ability to cope with the local RF environment is reduced, this is probably due to the Bluetooth channel selection being fixed. Whereas when streaming audio, the channels are controlled dynamically to minimise interference from Wi-Fi and other Bluetooth transmissions.

4. Conclusions

4.1. Overview

During the testing process it became clear that obtaining completely repeatable results are difficult because of the continually changing ISM band network traffic from the in-building APs.

In addition to this the use of recorded off-air signals for the LTE interferer did not guarantee worst case interference because during the 5 minute long repeating recording loop the LTE system recorded was carrying live traffic with a variable resourcing level of the LTE frame causing the average power to vary.

Note:

An attempt was made to show this effect by comparing the effect of a signal generator LTE source using PRBS modulation data and with a fully resourced LTE frame.

4.2. Loopback Testing

The devices tested showed significantly different behaviour to each other, which can be explained by the differences in the design of the circuitry around the Bluetooth chips.

The CSR8510 development evaluation board is designed to allow the performance of the packaged chip to be assessed and characterised, in particular it is not fitted with a band pass filter on the RF input and is therefore likely to be more affected despite the small frequency separation of the LTE signal.

The two products tested use fully functional chip firmware which is optimised for performance in the presence of RF interference in-band. The better performance seen during the heuristic tests is due to the ability of the link to adapt to the local RF environment and avoid excessive packet loss until the interferer level causes a large receiver gain reduction due to LTE signals blocking the receiver front end.

4.3. Heuristic Testing

Both the In-ear headset and the Bluetooth portable speaker tested exceeded the expected performance, continuing to function in the presence of very strong LTE interference with a UE signal at ranges down to 0.05 m.

While this suggests that devices in the field are resistant to LTE signals to a greater degree than expected, it does not mean that all devices will behave in this way.

Note:

This behaviour should not be extrapolated to other devices until more information can be gathered and results assessed.

4.4. Future Investigation

The safe distance is largely dependent upon product design; this test shows that it is in the region of 50 mm for the test configuration used. Appendix A shows further interference mitigation is possible using additional RF filtering.

Note:

An assumption made for this test is that few users expect to operate a Bluetooth link over a significant distance. Less than 2.5 m is the typical use case as Bluetooth was conceived as a Personal Area Network (PAN).

It is clear that there could be a considerable variation in performance of different products using Bluetooth radio links, a more complete view of this variation can only be obtained by further real-world testing of a range of products in typical environments with different use cases.

Tests performed by CSR have been made using features that are mandated by the Bluetooth SIG specification but that are not easily activated in devices using competitors' silicon (this would require unrestricted access to device firmware or modified firmware).

This means that the performance measured is based only on devices using CSR's own Bluetooth silicon. While the achievable radio performance of all Bluetooth devices will be similar, performance differences can be expected due to firmware and software behaviour that is not predictable as software development beyond the functions needed for

Bluetooth SIG compliance testing is dependent on customer requirements and on the approaches taken by different engineering teams.

Bluetooth Smart devices have not been included in this test, should the implementation of the receivers in these devices result in poorer blocking or intermodulation performance then the effect of local LTE interferers is likely to be more significant. Loopback testing is not possible as the Bluetooth SIG does not require it for Bluetooth Smart devices.

Adoption of LTE devices in the UK market place is currently early in the purchase cycle, as time goes on the number of devices is likely to increase significantly presenting an increasing density of Bluetooth and LTE devices sharing both spectrum and physical proximity.

In particular, reports of interoperability problems in markets where 2.3 GHz LTE is already deployed warn of the real probability of interference severe enough to encourage end user complaints.

This testing does not consider the effect of LTE-LAA (Licensed Assisted Access). In future this may involve LTE devices using the ISM band directly and therefore would defeat the use of FBAR type filters to remove a blocking signal at high level.

Note:

> There is some potential for this to be a more severe environment than the current situation where the spectrum is already shared by Wi-Fi devices.

4.5. Summary

From these results it can be concluded that Ofcom's proposal to limit the LTE node power to +65 dBm is overshadowed by the presence of LTE UE transmitters within mobile handsets able to come into much closer proximity to unsynchronised Bluetooth devices.

Determining a safe separation distance is not straightforward. This test demonstrated Bluetooth links over a ~1 m range, operating at 0.05 m separation from an LTE device. Tests were carried out with a 10MHz guard band above 2390MHz.

It would not necessarily be possible to achieve a similar result with a different test geometry where the Bluetooth link was operating over a longer range and had less signal-to-interferer margin in the receiver.

Existing Bluetooth devices cannot be modified to improve their resistance to LTE transmissions at small frequency offsets.

New products can have additional or improved RF filtering to drastically reduce their susceptibility to nearby LTE devices but doing this results in a BoM and assembly cost penalty and potentially a design or styling penalty due to the additional volume required to contain the filter.

Bluetooth Smart devices may be more susceptible to LTE interference if their receivers have traded strong-signal performance for reduced current drain. Lack of 10MHz guard band is likely to make this improved filtering less effective.

Note:

> Existing products use first generation Bluetooth Smart chips, future generations are not yet available to test at all.

4.6. Key Findings

This section itemising the key findings of the testing carried out.

- LTE UE devices cause greater interference levels to Bluetooth than LTE nodes at +65 dBm EIRP
- Only tested Bluetooth links over 1 m range
- 'Safe' distance for UE is >50 mm from Bluetooth receiver with 1m Bluetooth link range under these conditions
- Larger Bluetooth link ranges will require more separation from a UE interferer
- Bluetooth link budget reduced by 20 dB in the presence of UE interference (by analysis)

- LTE interference could be mitigated by inclusion of RF filtering adding cost and size to the Bluetooth device

Appendix A FBAR Filters

Because of the very small frequency offsets in use, a band pass filter that can pass ISM band signals while giving significant attenuation of signals immediately below the 2.4 GHz ISM band is not possible with conventional filter technology. Bulk Acoustic Wave filters are able to provide better performance but the Film Bulk Acoustic Resonator (FBAR) filter has less insertion loss and higher stop band attenuation.

One product in a very small package of 1.4 x 1.1 mm that could be used to improve the rejection of LTE signals in the 2.3 GHz range is the Avago ACPF-7124. It has an insertion loss below 2 dB for ISM band signals and can provide >45 dB attenuation in the LTE band 40 frequency range. It may be possible to fit such a filter into very small devices although the cost penalty needs to be considered.

Full technical specifications are not available from Avago as this product is not yet in production but it does offer an opportunity to resolve ISM band interference problems by preventing blocking signals from entering the receiver. It is still incumbent on the LTE device to ensure that ISM band noise sidebands are low enough to avoid de-sense of ISM band receivers.

Document References

Document	Reference
2.3 and 3.4 GHz spectrum award: Consultation on a 3.4 GHz band plan, varying UK Broadband Limited's licence and a call for inputs on other aspects of the award	http://stakeholders.ofcom.org.uk
LTE/Bluetooth Coexistence – Where the Shadows Lie	CS-324402-TC

Terms and Definitions

AAC	Advanced Audio Coding
AGC	Automatic Gain Control
AP	Access Point
BER	Bit Error Rate
BLE	Bluetooth Smart (formerly Bluetooth Low Energy)
BlueCore®	Group term for CSR's range of Bluetooth wireless technology chips
Bluetooth®	Set of technologies providing audio and data transfer over short-range radio connections
BoM	Bill of Materials
CSR	Cambridge Silicon Radio
dBi	Decibel isotropic
DUT	Device Under Test
EIRP	Effective Isotropically Radiated Power
FBAR	Film Bulk Acoustic Resonator
FDMA	Frequency Division Multiple Access
HSPA	High Speed Downlink Access
ISM	Industrial, Scientific and Medical licence exempt bands
LTE	Long Term Evolution
PAN	Personal Area Network
PAPR	Peak to Average Power Ratio
PCB	Printed Circuit Board
R&S	Rohde and Schwarz
RF	Radio Frequency
Rx	Receive or Receiver
SC-FDMA	Single-carrier Frequency Division Multiple Access
SIG	Special Interest Group
SNR	Signal to Noise Ratio
Tx	Transmit or Transmitter
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
Wi-Fi®	Wireless Fidelity (IEEE 802.11 wireless networking)