MC192 Assessment of Capacity Impacts with Various TD-LTE Block Configurations_v3 1.docx

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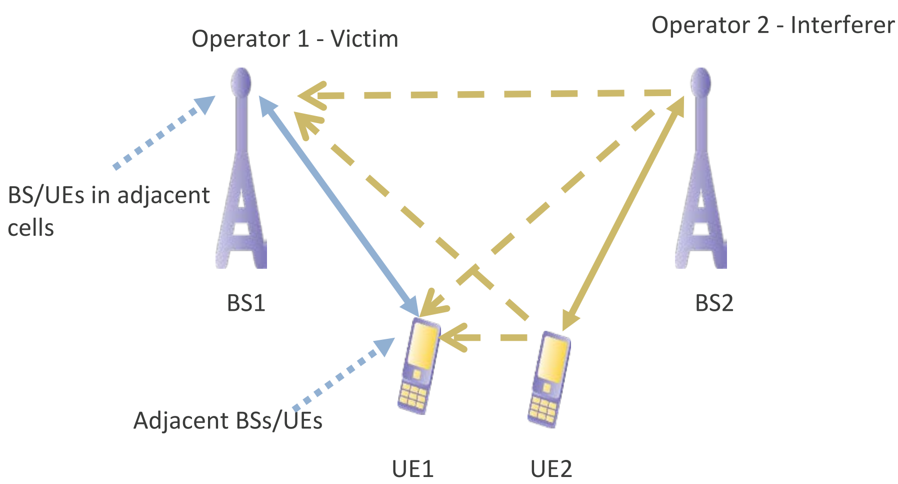

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Executive summary

To facilitate economic growth the UK government plans to release 500 MHz of public sector spectrum by 2020 [1]. An important element of this initiative is the UK Ministry of Defence intention to release spectrum for new civil use within the 2.3 GHz and 3.4 GHz bands. 40 MHz (2350 – 2390 MHz) is to be released in the 2.3GHz band and 150MHz in the 3.4 GHz band (3410-3480 MHz and 3500-3580 MHz).

The spectrum to be released in the 3.4 GHz band is adjacent to two blocks of 20 MHz licensed to UK Broadband. UK Broadband's 2007 application to vary its license was granted to allow communication to non-fixed terminals and to use BS (base station) transmit EIRPs (equivalent isotropic radiated power) up to 59dBm/MHz [3] (the 2007 mask). As part of the process of releasing public sector spectrum, Ofcom published a statement in December 2010 identifying technical conditions that would apply to future uses in the 3400 – 3480 MHz and 3500 – 3580 MHz frequency ranges [4] with maximum BS EIRPs of up to 53dBm/MHz (the 2010 mask). It was decided that UK Broadband could align its license conditions to these technical conditions, should it choose to do so.

3GPP has identified the frequency ranges 2300-2400MHz and 3400-3600 MHz as 3GPP bands 40 and 42 respectively, meaning that they are standardised bands for LTE. CEPT's European Communications Committee (ECC) PT1 working group are currently investigating appropriate technical conditions that could be used as the basis of an ECC Decision to allow harmonised use of these bands [5] for any MFCN (Mobile/Fixed Communication Networks) system, including those variants which use unpaired spectrum and Time Division Duplex (TDD) methods to separate uplink and downlink communications. TDD systems have the potential to suffer from additional Adjacent Channel Interference (ACI) compared to the more conventional Frequency Division Duplex (FDD) methods because the uplink (user equipment to basestation) and downlink (basestation to user equipment) communication directions use the same frequency.

Adjacent channel interference can be reduced by a variety of measures. The number of ACI interference modes can usually be reduced if operators using adjacent frequency blocks synchronise their networks so that uplink and downlink transmissions are synchronised. Other methods of reducing ACI are to limit the maximum power that is transmitted outwith the intended channel and by improved rejection of adjacent (and nearby) channel power in the receiver. CEPT's PT1 group have proposed Block Edge Masks (BEMs) at 3.4GHz which constrain the maximum power of out of band emissions, with a lower limit proposed for unsynchronised TDD systems than synchronised systems. This additional suppression is intended to reduce interference between unsynchronised operators in adjacent frequency blocks. Interference to an adjacent operator can also be reduced if the channels used are separated in frequency (using gaps or restricted power blocks adjacent to different operators' frequency blocks). However such frequency separation means that some spectrum may be underutilised, which would be inefficient unless the additional isolation provides an overall benefit. Other methods exist to reduce ACI where operators can co-ordinate their network deployment and parameters in order to reduce inter-system interference.

Ofcom have a duty to encourage efficient use of spectrum. Licence conditions can be imposed that could reduce the interference impact on an adjacent operator. Typically Ofcom can regulate the characteristics of transmissions. Many methods to support efficient use of spectrum are more difficult to stipulate including those related to receiver characteristics or network deployment topologies. Mobile operators should normally be motivated to use their spectrum efficiently and any license conditions imposed could restrict operators' freedom to innovate in future.

This report examines the impact on spectrum capacity when adjacent blocks of unpaired spectrum have different BEMs, levels of synchronisation (phase aligned and unsynchronised timeframes), frequency gaps between frequency blocks, restricted power blocks and different channel bandwidths. We examine the particular case of the incumbent operator, UK Broadband, who, owing to legacy issues, could use a range of different BEMs and maximum transmit powers and both mobile and nomadic UEs (User Equipment or mobile devices).

Over the course of this study and by examining some challenging interference environments via simulation and calculation, we have established:

- **Effect of network synchronisation**: It is technically feasible for operators to phase align their networks if desired. This would impose an additional constraint on network co-ordination but is likely to be a small marginal impact since fine phase synchronisation across modern networks is becoming the norm. Maintaining phase synchronisation and use of a common time frame configuration as an adjacent operator removes 2 ACI interference modes and, in general, improves the capacity attainable. Mandating phase alignment may however preclude operators from using different time frame configurations which would constrain the balance of uplink/downlink capacity available for use by an operator. Imposing a regulatory requirement for synchronisation across the entire network could also impose unnecessary constraints in environments where such measures are not needed, for example for isolated cells. Given that the operators would have a mutual incentive to synchronise to the extent that their performance was enhanced, it may be unnecessary to require this of them via direct regulatory intervention.
- **Effect of geometry**: The level of interference varies across the cell. Some locations (typically remote from the desired transmitter and/or close to an interfering transmitter) exist where blocking (i.e. no communication would be possible) can occur. In some low signal quality (SINR) locations, more channel throughput may be possible with unsynchronised networks than with synchronised networks. This typically occurs when the interference due to a non-serving base station causes less interference to a victim UE than a nearby (unsynchronised) interferer UE transmitting to its own serving cell. Results are given for 3 different types of geometry (geometry 1 and 3 are different low SINR topologies), geometry 2 is for good SINR conditions.
- **Effect of a frequency gap between operator blocks:** In some high interference environments a frequency gap (sometimes a gap combined with assumed ACS improvements) were able to prevent receiver blocking. However in nearly all the simulations the increased spectrum occupancy of the frequency gap reduced overall spectrum efficiency.
- **Effect of Narrower Channel Bandwidths:** Using narrower bandwidths allows increased rejection of ACI at the receiver which improves the achievable capacity, although adjacent narrowband channels can result in increased Out of Band leakage. Improvements in ACS at the UE and the BS reduce the opportunity for narrower channels to benefit from this improved isolation. For good SINR

environments with improved ACS, the narrower channel bandwidths offer a small performance advantage (slightly less than 1%).

- **Effect of restricted power blocks:** By analysis, we have established that the effect of using a restricted block of 5MHz bandwidth is likely to have little reduction in interference caused to an adjacent operator using a wide bandwidth channel than a full power block. Modest technical improvements (ACS and ACLR) will have a much greater impact. It is unlikely that using higher bandwidth restricted blocks would be acceptable.
- **Effect of BEM:** For synchronised networks, PT1 recommended values of Out of Band limits [11] that are less restrictive for synchronised networks than for unsynchronised networks (which can simplify the transmitter). We found that restricting the synchronised baseline limit to the value of the unsynchronised limit has a small impact on capacity (less than 1%) when systems are synchronised.
- **UK Broadband:**
  - Where UK Broadband is considered to be a source of interference, there are potential small negative impacts on the victim spectral efficiency. This is due to modelling an increased EIRP from either the base station or the CPE. The impairments are typically small (in the order of 0.01bps/Hz) and have a large relative change (approximately 25%) in poor (geometry 3) SINR environments. Some protection is provided by imposing a frequency gap, but this has a large negative impact in other environments owing to increased spectrum occupancy.
  - Where UK Broadband is considered to be the victim, the results for geometries 1 and 2 are identical to the PT1 baseline case. In the poor SINR geometry 3 case the differences from the PT1 baseline are marginal (less than 0.05bps/Hz). When combined with a 5 or 10MHz gap, the higher EIRP allows the SE to increase above zero – but to a very low value. However, this spectrum gap reduces overall capacity in other environments owing to increase spectrum occupancy.

There is a range of options available for mobile operators to reduce the impact of the additional potential ACI environment with TDD networks. Improving the ACS beyond the values assumed by PT1 has the opportunity to reduce interference and removes any benefit of a frequency gap.

There is opportunity for operators to avoid the performance degradations identified above, such as co-locating base stations, synchronising appropriate network layers (such as macrocells) and improved filtering. Mandating such measures could prevent operators from deploying network nodes in some areas that may benefit from a different configuration from the rest of the network, or where establishing the same configuration could be problematic, but where any additional interference may have little impact. With the default assumed ACS levels, some frequency gaps can reduce interference in some environments. Establishing these gaps as part of technical conditions could however have the effect of reducing the incentive for ACS improvements and would leave some spectrum underutilised should technical conditions improve.

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Tables

Figures

1. Introduction

This report represents the final deliverable from a study conducted by Real Wireless on behalf of Ofcom, assessing the impact of various TD-LTE block configurations on the capacity and performance of networks operating in spectrum within the 2.3 GHz and 3.4 GHz bands.

1.1 Background

To facilitate economic growth the UK government plans to release 500MHz of public sector spectrum by 2020 [1]. An important element of this initiative is the UK Ministry of Defence intention to release spectrum for new civil use within the 2.3 GHz and 3.4 GHz bands. The 40MHz (2350 – 2390MHz) to be released in the 2.3GHz band and the 150MHz in the 3.4GHz band (3410-3480 MHz and 3500-3580MHz) are shown in Figure 1 and Figure 2 respectively [2].

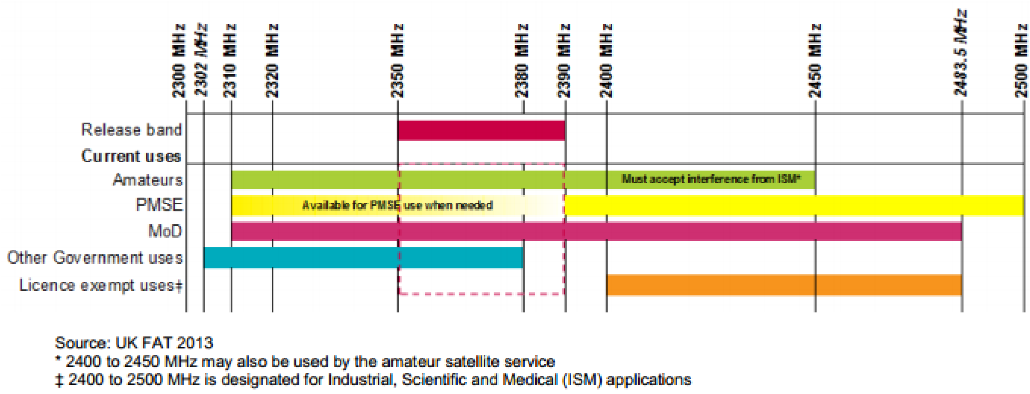

Figure 1: Spectrum in the 2.3GHz band showing alternative uses (from Figure 3 from [2])

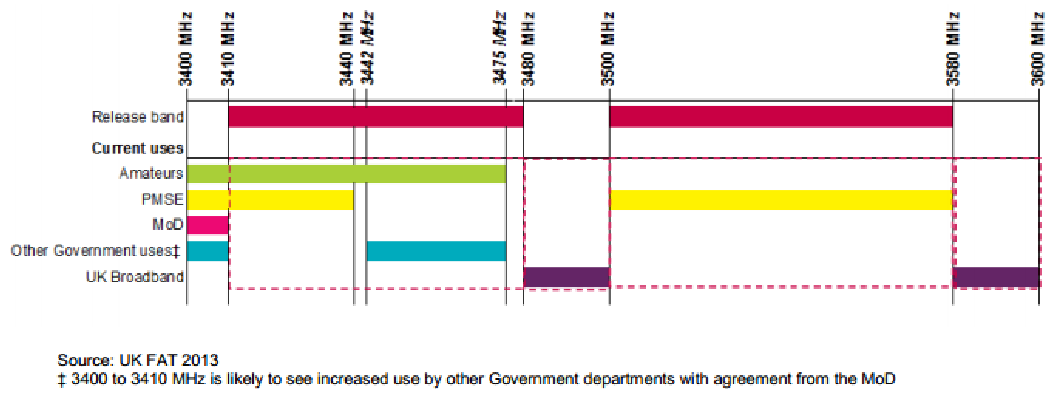

Figure 2: Spectrum in the 3.4GHz band showing alternative uses (from Figure 4 from [2])

Also shown in Figure 2 are the two blocks of 20 MHz licensed to UK Broadband. Originally licensed for Fixed Wireless Access (FWA) use, UK Broadband's 2007 application to vary its license was granted to allow communication to non-fixed terminals and to use higher transmit powers [3]. As part of the process of releasing public sector spectrum, Ofcom published a statement in December 2010 identifying technical conditions that would apply to future uses in the 3400 – 3480 MHz and 3500 – 3580 MHz frequency ranges [4]. It was decided that Ofcom would permit UK Broadband to align its license conditions to these technical conditions, should it choose to do so.

3GPP has identified the frequency range 2300-2400MHz and 3400-3600 MHz as 3GPP bands 40 and 42 respectively, meaning that they are standardised bands for LTE (and potentially for 3G too, although this is less likely in practice). CEPT's European Communications Committee (ECC) PT1 working group are currently investigating appropriate technical conditions that could be used as the basis of an ECC Decision to allow harmonised use of these bands [5] for any MFCN (Mobile/Fixed Communication Networks) system (including mobile and fixed variants of the WiMAX standard). Whilst any new licences will be issued on a technology neutral basis, ongoing moves towards pan-European harmonisation of spectrum use means it is likely that the released MoD spectrum will be used for Long Term Evolution (LTE) technology or LTE advanced. A key technology variant that could be deployed in these bands is the unpaired Time Division Duplex (TDD) variant of LTE, termed TD-LTE, but co-existence with other MFCN and legacy standards should be considered.

1.2 Interference effects in TDD

TDD uses the same frequency channel for each duplex direction, with different periods of time used for uplink or downlink communication. This has the potential to allow the proportion of the uplink and downlink channel capacity to be matched to the traffic demand. Conventionally, with Frequency Division Duplex (FDD), different frequency channels are used for uplink and downlink directions, with transmit and receive bands typically separated by several 10's of MHz, reducing the opportunity for interference from the other duplex direction. Using the same frequency channel for both transmit and receive means that TDD technology has two additional adjacent channel interference modes than FDD. These are the base station (user equipment, UE) transmitting in the adjacent channel of another UE (base station). These additional interference modes can be removed if operators using adjacent channels adopt a common and time-synchronised frame structure[1] which will prevent uplink (or downlink) receivers being subject to interference from the adjacent channel simultaneously using downlink (uplink) transmission. This however reduces the ability of the TDD frame structure to dynamically adjust the uplink and downlink capacity to match traffic demand. Note that, phase alignment of a common frame structure does not remove all ACI.

Adjacent channel interference can be reduced by limiting the maximum power that is transmitted (leaked) out of the intended band, and improved rejection of adjacent (and nearby) channel power at the receiver. CEPT's PT1 group have proposed Block Edge Masks at 3.4GHz which constrain the maximum power of out of band emissions, with a lower limit proposed for unsynchronised TDD systems than synchronised systems. This additional suppression is intended to reduce interference between unsynchronised operators in

[1] Time synchronisation at the physical layer time-frame structure is termed phase alignment. Phase alignment, or phase synchronisation, will be used in the remainder of this report.

adjacent frequency blocks. Interference to an adjacent operator can also be reduced if the channels used are separated in frequency (using gaps between frequency blocks) – but this means that some spectrum is left unused. In any given spectrum allocation, use of restricted blocks or frequency gaps reduces the spectrum availability for other uses. If the capacity benefit allowed by reducing interference, by use of restricted blocks or frequency gaps, is less than the capacity in the allocation without gaps, despite interference, then any allocation with gaps or restricted blocks would be less efficient. It should also be noted that any ACI tends to be determined for instances of high interference – but any assignment which uses restricted blocks or gaps by license conditions constrain that spectrum use over the extent of the license area – even in areas where such high interference may not be prevalent.

Operators can also reduce the opportunity for interference by a range of other means, including co-ordinating their location and network configuration parameters, improved filtering and power restrictions.

1.3 Ofcom's requirements

The purpose of this study is to examine the spectrum capacity when adjacent blocks of unpaired spectrum have different BEMs, synchronisation methods, frequency gap or restricted block between frequency blocks or different channel bandwidths. We examine the particular case of the incumbent operator UK Broadband who, owing to legacy issues, could use a range of different BEM and maximum transmit powers and both mobile and nomadic UEs.

Phase alignment between operators of TDD systems could reduce the opportunity for interference, and we assess the practicality of different operators being able to synchronise their networks to the accuracy required.

Lastly, we comment on alternative methods of mitigating interference between different operator's methods and the range of policy instruments that could be used by Ofcom to facilitate efficient use of spectrum by operators.

1.4 Structure of this report

This report is broken into the following sections:

- Section 2 identifies the different ACI modes that can exist in a mobile TDD network environment and determines suitable geometries to model problematic ACI modes;
- Section 3 describes the frame structures of the main TDD technologies, examines the statistics of different ACI modes that can occur in TD-LTE systems and between TD-LTE and WiMAX systems, before examining the feasibility of phase aligning different operator networks. Lastly this section examines the statistics of different ACI modes between different unsynchronised TD-LTE frame structures;
- Section 4 describes the 3.5GHz BS BEM currently being developed by PT1, intended to establish a harmonised BEM for use of MFCN in 3.5GHz (and 2.3GHz) bands, the UE BEM and the different BEMs that apply to UK Broadband;
- Section 5 describes the method used to emulate the different ACI modes in order to determine the impact upon the capacity with changes to the synchronisation

between networks, different BEMs, different gaps between frequency blocks, the impact of ACS and different channel BW;

- Section 6 presents the results for the above cases;
- Section 7 discusses mitigation measures that could be taken by operators to reduce the effects of TDD ACI;
- Section 8 summarises the findings of this report.

2. Adjacent Channel Interference (ACI) modes

Adjacent channel interference (ACI) is a potential source of interference in all wireless communication systems. Typically transmitters need to ensure that they limit their emissions outside of the intended band, and receivers seek to reduce the impact of adjacent channel energy contributing to in-band noise. Improved rejection of adjacent channel interference can add to equipment costs, such as additional filtering at the base station. ACI can be more problematic in TDD systems since the transmitter and receiver use the same frequency channel, resulting in two additional ACI interference modes compared with FDD systems.

Four different interference modes are shown in Figure 3.

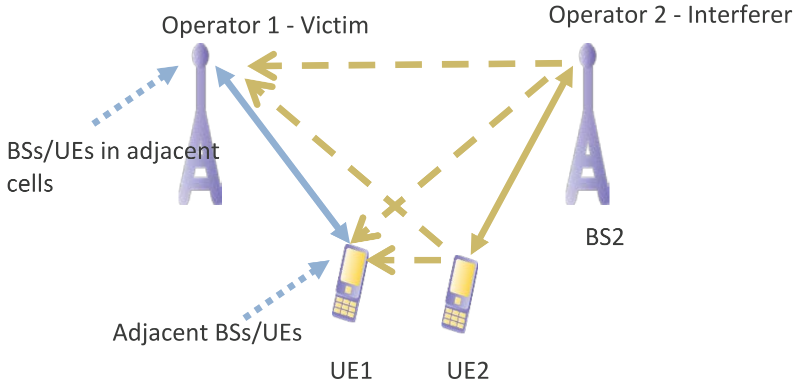

Figure 3: Communication network interference modes – dotted arrows indicate interference signals

Without loss of generality we can consider Operator 1 to be the victim in all cases. This environment can be replicated for macrocell, femtocell and microcell environments.

- Uplink victim cases:
  - BS2 → BS1 (DL→UL): This occurs when BS2 is transmitting whilst BS1 is receiving data. This would occur only in TDD mode, when the victim has an uplink slot and the interferer has a downlink slot. This mode can be severe (since it has the potential to prevent BS1 receiving data from many UEs simultaneously) and prolonged (the base stations do not change location), and is therefore potentially very serious. The worst case is when BS1 and BS2 are close together with UE1 near the cell edge.
  - UE2 → BS1 (UL→UL): This happens when UE2 is transmitting to BS2, at the same time that BS1 is receiving data from its serving mobile(s). The worst case is when UE2 is far from BS2, but close to BS1 and BS1 is receiving from a cell-edge UE1. This occurs in both FDD and TDD duplex methods. This mode of interference can be severe – but is relatively unlikely (since it would only occur when UE2 is close to BS1).
- Downlink victim cases:
  - BS2 → UE1 (DL→DL): This occurs when BS2 is transmitting to UE2, at the same time that UE1 is receiving data from BS1. The worst case is when UE1 is close to BS2 but at the cell edge of BS1. This can happen in both FDD and

TDD duplex methods. This mode of interference can be problematic (only UEs close to the BS2 would be impacted) but is relatively unlikely.

- o UE2 → UE1 (UL → DL): This occurs when UE2 is transmitting whilst UE1 is receiving data. This would only occur in TDD mode, when the victim has a downlink slot and the interferer has an uplink slot and UE2 is close to UE1. This mode can therefore be problematic but is unlikely.

Using synchronised frame and slot structures precludes DL→UL and UL→DL time slot clashes and means that TDD would only suffer from the interference modes normally experienced in FDD networks.

2.1 Interference mode geometries

Normally, ACI is determined for some worst case environments. The four interference modes identified above would occur to different extents depending upon the relative positions of UE1, UE2, BS1 and BS2. However, not all possible combinations are likely or possible (e.g. UE1 cannot be simultaneously close to UE2 and BS1, when BS1 is distant from UE2). We are therefore interested in examining feasible poor interference environments to establish reasonable though still problematic cases.

We can identify six key cases of interest, as shown in Figure 4.

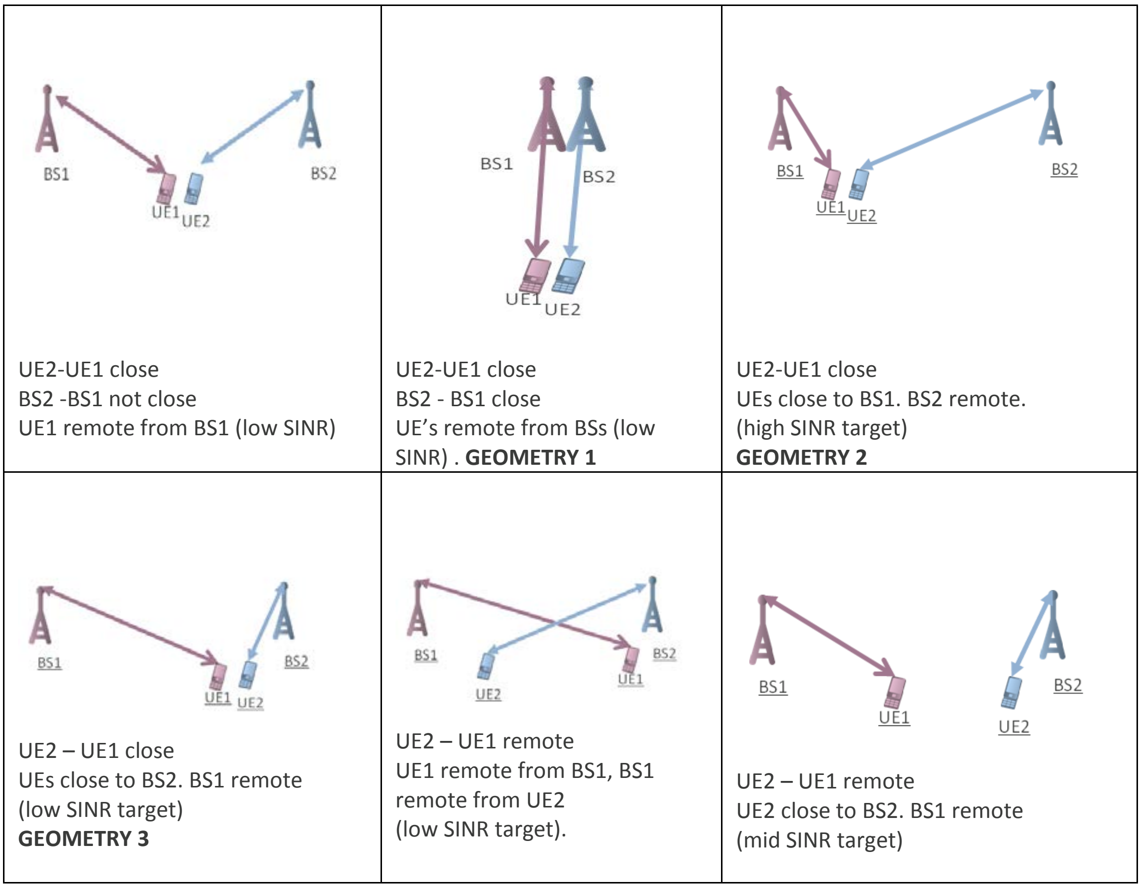

Figure 4: Different interference mode link geometries of interest

Interference scenarios corresponding to Minimum Coupling Loss paths between interferer and victim can be so severe to result in receiver blocking, meaning that no communication is possible. If we examine the above interference environments, we can determine additional path loss values (additional to the minimum coupling loss) that we can add on to suitable links to determine more realistic path loss values for each of the different link geometries. The middle and right case on the second row are of less interest, since the interference environment is relatively benign. The first cases on the first row default to one case, since the BS-BS path loss does not vary significantly with modest increases in distance. We can therefore consider 3 generic geometries, and these are denoted Geometry 1, Geometry 2 and Geometry 3 in Figure 4. The values of the RF parameters and associated coupling losses for each of the four links for the three geometry types is described in Section 9.

2.2 RF Parameters needed to model these interference modes

We have selected to model the interference in macrocell, femtocell and microcell environments. The RF parameters that have been used by PT1 in their modelling have been used as the baseline RF parameters [22]. These reflect typical industry practice, network deployment, equipment parameters, antenna gains, etc. There is some uncertainty about reasonable values for BS ACS and UE ACS. We have therefore used the baseline values as used by PT1 and performed some sensitivity analysis on these values to model situations where the ACS can be improved upon this baseline. The baseline RF parameters for the interference modelling, and sources for the values are listed in Section 9.The parameter values vary depending upon the channel bandwidth.

The interference mode geometries identified 3 key different geometries that are of interest to study. These would be characteristic of areas of a cell with either low or high SINR. The target macrocell SINR values for realistic high and low SINR environments have been chosen from the SINR distribution that would be found in an LTE macrocell environment using a simulation with hexagonal geometry and 3 sector sites[2].The low (high) SINR has been selected as the 5% (95%) of the cumulative SINR distribution across the cell and are shown in

femtocell and microcell values are derived by applying the differences between macrocells and microcells (femtocells) at the cell edge and cell centre reported in [6]. Geometries 1 and 3 correspond to low SINR environments and geometry 2 to a high SINR environment.

[2] This value is derived from an in-house simulation (Real Wireless unpublished internal research) based upon macro environment simulation with hexagonal geometry and 3 sector sites.

Table 1: SINR values used for low and high SINR environments in macrocell, femtocell and microcell environments, using the percentile of typical SINR cdf values for different cell types

Name	Percentile	Direction	Macrocell	Femtocell	Microcell
Low SINR	5th	DL	-3 dB[2]	2 dB[3]	-3 dB
		UL	-3 dB	2 dB	-3 dB
High SINR	95th	DL	11 dB	42.6 dB	11.1 dB
		UL	4 dB	35.6 dB	4.1 dB

3. TDD frame structures and Network Synchronisation

One of the benefits ascribed to systems using the TDD method is that the channel capacity in uplink or downlink directions can be adjusted to better reflect the instantaneous traffic demand than is possible with FDD methods. TDD frame structures are able to adjust the ratio of downlink to uplink capacity by adapting the number of time slots allocated in each duplex direction. The degree to which this is possible depends upon the technology-specific frame structure. TDD frame structures of particular interest are TD-LTE and WiMAX.

3.1 TD-LTE frame structures

The TD-LTE frame structure has been designed to be compatible with the FDD LTE frame structure and also to permit different amounts of time to be used for uplink and downlink directions. TD-LTE has a frame length of 10ms. The 10ms frame comprises two half frames, each 5 ms long. These half-frames are further split into five subframes, each 1ms long, as shown in Figure 5.

[3] Femtocell and microcell values are based on differences between macro and micro/femto wideband SINR in simulation results from 3GPP R1-092019.

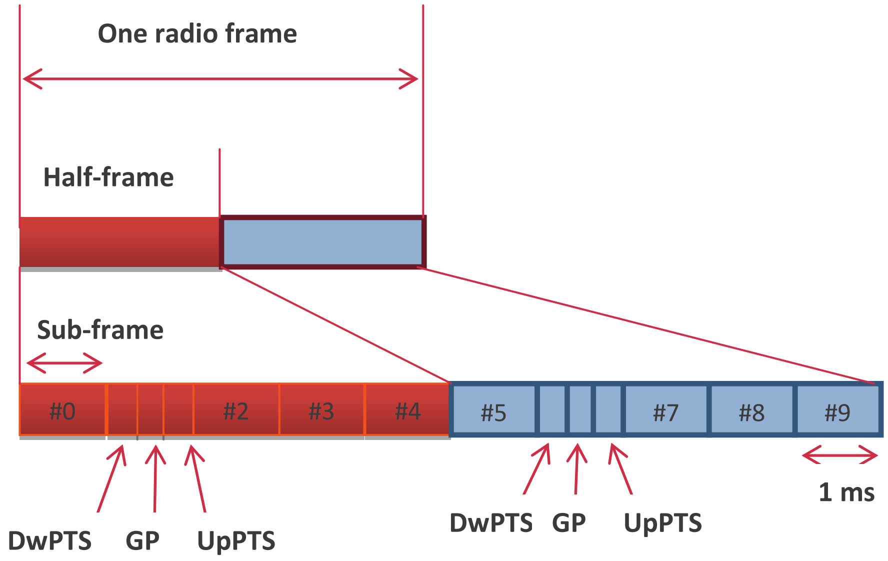

Figure 5: The TD-LTE frame structure format (see 3GPP 36.211 [7])

Subframes can be designated to carry uplink traffic (U), downlink traffic (D) or to allow switching (S) between U and D. The different configurations that are possible are shown in Table 2. These different configurations allow the proportion of dedicated DL/UL slots to range between downlink:uplink time ratios of 8:1 and 1:3. In practice, the S-slot contributes to some additional downlink capacity as will be explained below.

Subframes 0 and 5 are always reserved for downlink data and the subframe that follows the S subframe is always reserved for UL data.

Table 2: Configurations of uplink and downlink slots of the TD-LTE frame structures

UPLINK-DOWNLINK CONFIGURATION	SWITCH PERIODICITY	SUBFRAME NUMBER										DL : UL: GUARD	DL/UL
		0	1	2	3	4	5	6	7	8	9		
0	5 ms	D	S	U	U	U	D	S	U	U	U	2:6:2	0.33
1	5 ms	D	S	U	U	D	D	S	U	U	D	4:4:2	1.00
2	5 ms	D	S	U	D	D	D	S	U	D	D	6:2:2	3.00
3	10 ms	D	S	U	U	U	D	D	D	D	D	6:3:1	2.00
4	10 ms	D	S	U	U	D	D	D	D	D	D	7:2:1	3.50
5	10 ms	D	S	U	D	D	D	D	D	D	D	8:1:1	8.00
6	5 ms	D	S	U	U	U	D	S	U	U	D	3:5:2	0.60

As well as switching between U and D slots and supporting system control information, the rest of the S slot capacity is intended to carry as much DL user information as possible. The S subframe contains three main system control elements [8]: downlink pilot time slot (DwPTS), guard period (GP) and uplink pilot time slot (UpPTS). The guard period is a time gap which allows the base station to switch between transmitting and receiving. The DwPTS is a shortened downlink subframe which can contain downlink traffic like normal D slots. The control and signalling information in the S subframe can also be supported in other parts of the LTE frame structure. Averaging the number of DL symbols that can be used in different S subframe configurations, and removing the 3 symbols for RS/Control and Primary Synchronisation Signal leaves 5.6 symbols (out of the 14 possible in a normal subframe) that can be used for Downlink data (i.e. it has 40% of the normal DL slot capacity).

In a previous study by Ericsson [9] on DL throughput capacity the S subframe was treated as a DL slot, since the intent is to use as much of its capacity for DL data after the requirements for Guard time and UpPTS have been addressed. For the purposes of determining capacity impact, it therefore seems reasonable to model the S subframe as a reduced capacity downlink slot, where the slot capacity is 40% of a normal DL slot. Ericsson's paper [9] also demonstrated that, owing to higher level protocol effects, the impact on the overall channel throughput can be impacted more significantly than the proportional impact on the physical layer. Whilst this is an important consideration, modelling physical layer impact upon the higher layer protocols is out of the scope of this study, and we will restrict our analysis to comparing only physical layer capacity impacts.

3.2 Slot clash cases in TD-LTE

As an example, we can examine the nature of the interference mode in more detail by selecting 2 of the 7 different TD-LTE configurations, with a 1 slot time synchronisation phase shift, as shown in Figure 6.

Figure 6: Examination of slot clash between TD-LTE configuration 1 and configuration 4.

There are 9 different cases of slot clash possible, as shown in columns 1-3 of Table 3.

Table 3: Different cases of slot clash possible in TD-LTE

Case	Interferer	Victim	Interference Mode
1 (BS → BS)	Downlink	Uplink	D → U
2 (UE → BS)	Uplink	Uplink	U → U
3	Switch Subframe	Uplink	S →U (model as 60% U→U and 40% D→ U)
4 (BS → UE)	Downlink	Downlink	D → D
5 (UE →UE)	Uplink	Downlink	U → D
6	Switch Subframe	Downlink	S → D (model as D→ D)
7	Downlink	Switch Subframe	D → S(model as 40% D→D)
8	Uplink	Switch Subframe	U → S(model as 40% U→D)
9	Switch Subframe	Switch Subframe	S → S(model as 40% D→D)

Maintaining the logical consistency that S is a 40% downlink slot, we can replace 5 of the 9 possible slot clash cases with equivalent cases scaled to reflect the capacity impact, as shown in column 4 of Table 3. The assumptions made in Table 3 are slightly pessimistic in cases 3 and 6. Since U→U is normally more benign than D→U we have treated S→U as 60% U→U and 40% D→U (though this is more pessimistic than would occur in practice where much of the uplink would not be subject to any interference in practice). Similarly we have treated S→D as a D→D whereas some of the D slot would be unlikely to receive any interference in practice. This simplification allows the victim slot capacity to be estimated using only the 4 interference modes identified above.

3.3 WiMAX frame structures

The LTE standard is being backed by a host of operators and equipment vendors and it is likely that any short term future deployment in the UK would follow this route. However, it is of interest to consider the WiMAX standard since variants of this standard have already been deployed and it offers many of the spectral efficiency advantages of modern communications systems. The WiMAX frame structure [10] is split into a downlink portion and an uplink portion separated by a gap as shown in Figure 7.

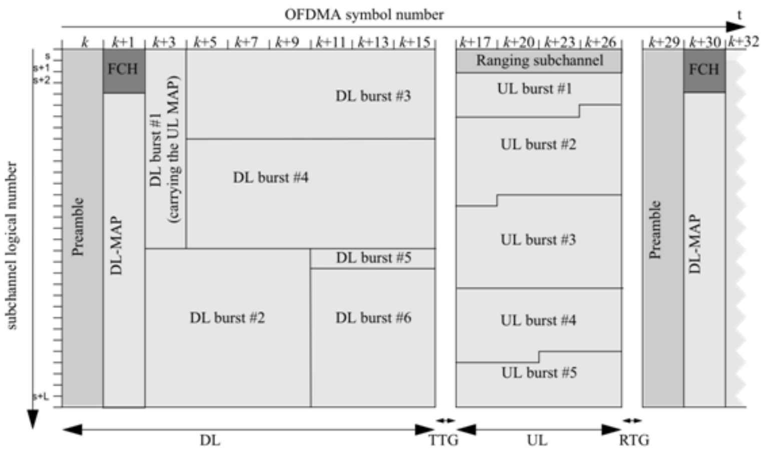

Figure 7: WiMAX802.16e TDD Frame structure (reproduction of Figure 9 from [12])

The WiMAX standard [10] only includes a TDD profile. Each frame is configured to be 5ms long and is time division duplexed into downlink (DL) and uplink (UL) subframes. In order for interference to be avoided between downlink and uplink signals, these signals are separated by small time gaps called transmit time gaps (TTG) for the transition from downlink to uplink sub-frame and receive time gaps (RTG) for the transition from an uplink subframe to a downlink subframe. The channel bandwidths can be 3.5, 5, 7, 8.75 or 10MHz. The 5MHz and 10MHz cases have similar transmit time gaps (TTG) and receive time gaps (RTG) and would be compatible with the 3400-3800MHz band 5MHz channel raster for use across Europe[11].

At the beginning of each subframe, downlink control information is transmitted which has a preamble, a frame control header (FCH), and a media access protocol (MAP) message. The physical channels defined for this WiMAX frame structure as well as their function are described below:

- Preamble: The preamble is broadcast in the first OFDM multiplexed symbol of the frame in the DL. It is used by the UE for BS identification, timing synchronisation and channel estimation.
- Frame Control header (FCH): This follows the preamble and provides the frame configuration information. Such information could be MAP message length, coding schemes and usable sub-channels.
- The DL-MAP and UL-MAP provide resource allocation and other control information for the downlink and uplink frames respectively.

ECC PT1[12]has examined whether it is possible to select particular TD-LTE and WiMAX frame structures which would avoid times where one system transmits UL data when the other transmits DL data (and vice versa). They have concluded that compatible frame structures exist which allow ‘synchronised’ operation between all frame structures in TD-LTE and WiMAX.

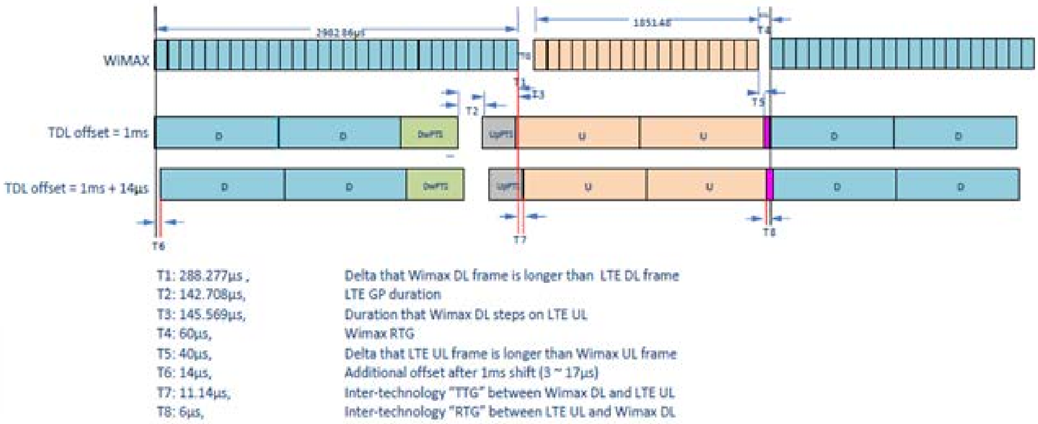

Figure 8: Frame alignment mechanisms between WiMAX and TD-LTE (reproduction of Figure 6 from [12])

By delaying the beginning of the TD-LTE frame, and puncturing particular slots where DL-UL and UL-DL clashes would occur, it is possible to avoid all such clashes with some reduction in capacity (PT1 contributors estimated that the maximum capacity impact is 10%). In particular, “This solution has been successfully implemented by Clearwire US as part of their WiMAX to LTE-TDD transition, which shows it is technically effective”. PT1 have demonstrated that with LTE as the victim, compatible frame structures with WiMAX exist that would not significantly impact on any control information, since they can be inserted into different subframes which would not suffer an incompatible clash.

3.4 Synchronisation between networks

Given that compatible frame structures can exist, it is of interest to determine the practicality of synchronising two different operators’ networks, assuming that they are motivated to do so.

PT1 [12] have undertaken a study item to address this specific question. In addition, Real Wireless have also consulted with industry experts, Chronos [13], on the practicalities of synchronising networks. The rest of this section is based on these two sources.

According to 3GPP TS36.133 TD-LTE requires phase synchronisation to an accuracy of 3µs (small cells) upto 10µs (large cells). This is based upon ensuring that the combination of synchronisation error, propagation delay, and multipath delay spread remains less than the smallest Cyclic Prefix (CP) length defined for the physical layer. Hence, irrespective of other operators' networks, all operators need to be able to maintain synchronisation between their base stations across their network to accuracy in the order of 1µs.

The favoured approach by operators to achieve this is to use a master clock, or usually multiple master clocks, for their network and distribute that timing through the network. Typically, operators would use GNSS (Global Navigation Satellite System) as the primary input to the master clock. As this is a steered source of UTC time, use of this input ensures high stability and accuracy at the master clock (typically +- 100ns to UTC).

Operators prefer to distribute timing rather than have multiple equipment-specific GNSS references as this is a lower cost option and mitigates local vulnerabilities such as jamming or poor GNSS reception. These vulnerabilities can, however, be mitigated at a master clock protected at a central site or using multiple, distributed master clocks. Note however that GNSS receivers are subject to potential space weather outages, environmental changes or physical degradation of hardware or infrastructure so alternatives may be necessary in the case of critical communications applications according to the recommendations in[14].

Timing is distributed throughout the network using a variety of techniques, notably SDH[4], PTP[5] and Sync-E[6]. Whilst this can be complex, given the delay variability of the transport network, the operators need to address delay variability anyway. In addition, operators are likely to be motivated to maintain tight phase synchronisation across their networks to support emerging capabilities in LTE (such as eMBMS (evolved Multimedia Broadcast Multicast Services (MBMS) and eICIC (Enhanced inter-cell interference coordination).

In the event of the master clock reference being lost (holdover), network operators would typically be able to maintain phase synchronisation for a limited time using a variety of solutions: caesium clocks (hold 1µs for a minimum of 28 hours, upto 10+ days), rubidium (hold 1µs for at least 3-4 hours up to 24 hours) or oven-controlled crystals (several hours). Caesium is usually considered too expensive for practical deployment at more than 1 or 2 master clock sites. When in holdover all sync transport protocols have a feature to alert base stations of the holdover condition. This would allow base stations to be configured to stop transmitting data when holdover occurs. For a single network, drift between adjacent base stations is likely to take longer to be noticeable as network segments can 'all drift together' since adjacent base stations are likely to be referenced by the same master clock.

If two operators seek to synchronise their networks they have the following options:

[4] Synchronous Digital Hierarchy – a transport protocol standard for transferring digital data from multiple sources within a single (synchronised) framing protocol, using the most reliable timing reference available.
[5] IEEE 1588 Precision Timing Protocol – a standard for distributing time over IP/Ethernet using the best available timing master clock.
[6] Synchronous Ethernet – a method of synchronising the physical layer of Ethernet networks to the most reliable available clock source, in the same manner as SDH/SONET.

- Have both networks synchronised to a common masterclock time reference;
- Have the two networks independently synchronised to their own master clocks, with the masters delivering a common absolute time (ultimately referenced to UTC via GNSS), which is used as a phase timing phase reference in each network.

Approach 1 raises the question as to which operator would run the master clock and what interfaces would be used to keep the two networks in synchronisation. The second approach would require the two operators to agree their frame timing relative to the absolute time and have an agreed level of network synchronisation to ensure base stations in their network are aligned within agreed limits. Whilst operators would need to be able to monitor and maintain inter-network synchronisation, no other technical interface between the networks would be required (though agreements on establishing new compatible timeslot configurations may be needed from time to time).

Hence, we can summarise this section as follows:

- Network synchronisation: in principal, though technically challenging, it is possible for different network operators to maintain phase synchronisation between their networks. Solutions do exist to make this possible (and has already been demonstrated by Clearwire). Operators are likely to be motivated to try to achieve high levels of intra-network phase synchronisation to benefit from emerging LTE capability – so the overhead in synchronising with another network may be less daunting than it would be otherwise.
- Frame Synchronisation: Different frame structures exist which allow variation in the balance between UL and DL capacity. It is possible to select the same configurations or to have compatible configurations between TD-LTE and WiMAX, with a capacity loss impact of less than 10% of the physical layer capacity. Selecting compatible frame structures may involve a further compromise since the balance of UL/DL may not be what would be selected without the constraint of needing a compatible match.

3.5 Statistical properties of UL-DL clashes given TD-LTE frame structures

In order to gain insight into the nature of the UL-DL and DL-UL clashes we have taken different TD-LTE frame configurations and identified what clashes would occur[7].

3.5.1 Configurations with phase aligned time frames

3GPP and PT1 consider timeframes to be synchronised only when operators use the same configurations and their timeframes are phase aligned. The time frames are structured so that there is a lot of commonality between many of the slots in phase aligned time frames. The maximum number of UL→DL or DL→UL clashes is 5 between any pair of configurations that are phase aligned. Over the 49 (7^2) possible configuration pairs the distribution of UL→DL and DL→UL clashes for different pairs of configurations is shown in Figure 9. Owing to symmetry, the distribution of UL→DL and DL→UL clashes is the same.

[7] For this exercise, the S subframe was treated as a D slot.

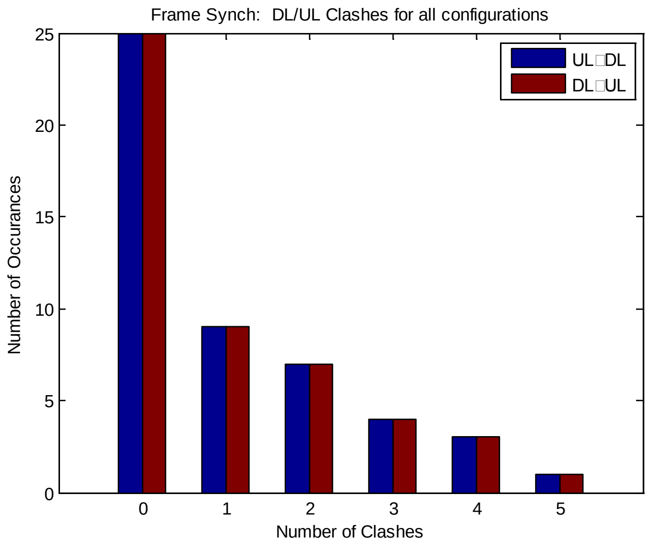

Figure 9: Distribution of UL→ DL and DL→UL clashes for phase aligned time configurations

This figure shows that one combination of configuration and phase offset has five clashes out of 10 possible timeslots, the remainder of potential configurations have less than five clashes. Approximately 50% (25 out of the 49) configuration combinations have no clashes in one direction, and the remainder have a total of 52 slot clashes in each direction (10.6% of the number of slots) as shown above. Hence, although using different configurations in adjacent frequency blocks is not considered 'synchronised' by PT1, this method of phase aligning timeframe structures could provide a simple method of avoiding time slots clashes for a large number of the available timeslots. However, any impact on one or other operator is unlikely to be symmetrical, and may depend upon the details of the configurations selected.

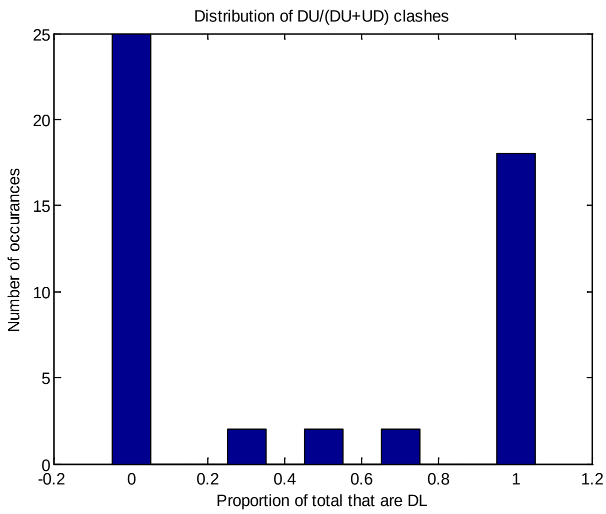

Figure 10: Distribution of the proportion of DL→UL clashes of total clashes

Figure 10 is a particular example that demonstrates a trend that when clashes do occur, they are predominantly in one direction or the other. The extent to which any one operator would experience clash (in one direction, or another) is therefore highly dependent upon the configuration pair used and the phase offset between the operators. The impact of these clash events is unlikely to impact operators symmetrically.

3.5.2 Configurations with non-aligned time frames

When operators are not synchronised, the time difference between the beginning of one frame structure and the other can be random. However, section 3.4, showed that the time drift of each operator's network relative to another operator's network is likely to be small given the phase stability required in a TDD network for the operator's own purposes.

Figure 11 shows the distribution of symbol clashes for all time slot phase differences using configuration pairs 1 with 4 and 1 with 5 as examples. The number of clashes and the nature of the clash (UL-DL or DL-UL) are highly variable and depend on the precise configurations used and the time-offset between the time frames. The number of clashes that any user session would experience would not be an average of the clash probability over the distribution of possible clashes, but would depend upon the particular clashes that would occur with the configurations and frame time offset at the time of a given communications session.

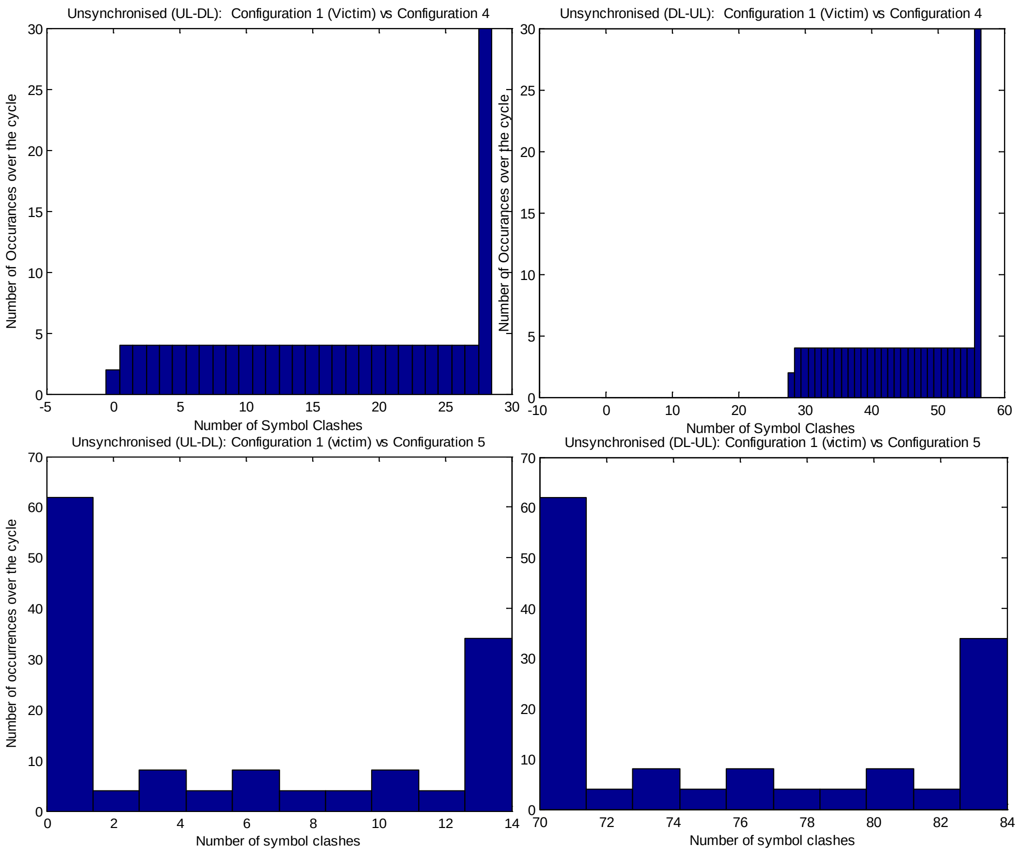

Figure 11: Distribution of UL-DL and DL-UL clashes between different configurations over all phase offsets between the configuration pairs

We also note that the clash probabilities are not independent. A high probability of UL→DL clash is likely to have a correspondingly low probability of DL→UL clash for a given configuration pair and vice versa.

We have used the particular probabilities of different clash events for all different configuration pairs, in the subsequent analysis, since the clash incidence probabilities are correlated.

4. BEMs applicable to the 2.3 GHz and 3.5 GHz bands

A block edge mask (BEM) is a regulatory emission mask that defines the maximum power that can be radiated either within the frequency block of a licensed operator or their Out of Band (OOB) emissions. The out of block components of the BEM itself consists of a baseline level which can extend far from the licensed block and where applicable intermediate (transition) levels which describe the maximum signal component of the transition from the in-block level to the baseline level as a function of frequency.

Any spurious emissions must be maintained below the BEM – and so it is very unlikely that any real transmitter would emit energy close to the defined mask across a wide range of frequencies. Using this BEM as an estimate of the emitted power from any transmitter is therefore a conservative measure of the adjacent channel interference. In this section, BEMs applicable to base-stations and UEs considered by PT1, and the BEMs used by UK Broadband are described.

4.1.1 Base Station BEMs

ECC PT1 has developed a proposed Block Edge Mask (BEM) for the 3.5 GHz band [15]. This mask has different parameters which are used to alter the mask values for use with FDD and TDD systems and which vary according to the synchronisation level and the EIRP power spectral density. These mask definitions can have 4 different levels:

- In-band power limits, with a maximum value of 68 dBm/5MHz allowed;
- Two transition levels extending from the edge of the mask for 0 to 5 MHz, and from 5MHz to 10MHz. These transition regions can be left out resulting in a BEM requiring a much sharper frequency roll-off response;
- A baseline level – this is the maximum power that can be transmitted in any other frequency outside of the transition limits.

The parameters which define the mask are listed in Table 4:

Table 4: Mask parameters for 3.5 GHz, proposed by PT1

Parameter	Synchronized (dBm/5MHz)	Unsynchronised (dBm/5MHz)
In-band limit	min (EIRP/5MHz, 68)	min (EIRP/5MHz, 68)
First transition level limit	min (Inband limit – 40, 21)	min (Inband limit – 40,21)
Second transition level limit	min (Inband limit – 43, 15)	min (Inband limit – 43,15)
Baseline limit	min (Inband limit – 43, 13)	-34

PT1 recommend that where TDD networks are unsynchronised, or where different TDD frame structures are used, the mask for unsynchronised systems should apply. These mask definitions establish limits based upon the minimum achieved by suppressing the inband channel power spectral density or an absolute value - and so the limit depends upon the base station inband transmit power. We can translate these masks into the suppression that is required for different carriers. For a typical macrocell base station with a channel bandwidth of 20 MHz and an EIRP of 63 dBm the required suppression relative to the carrier power is shown in Figure 12.

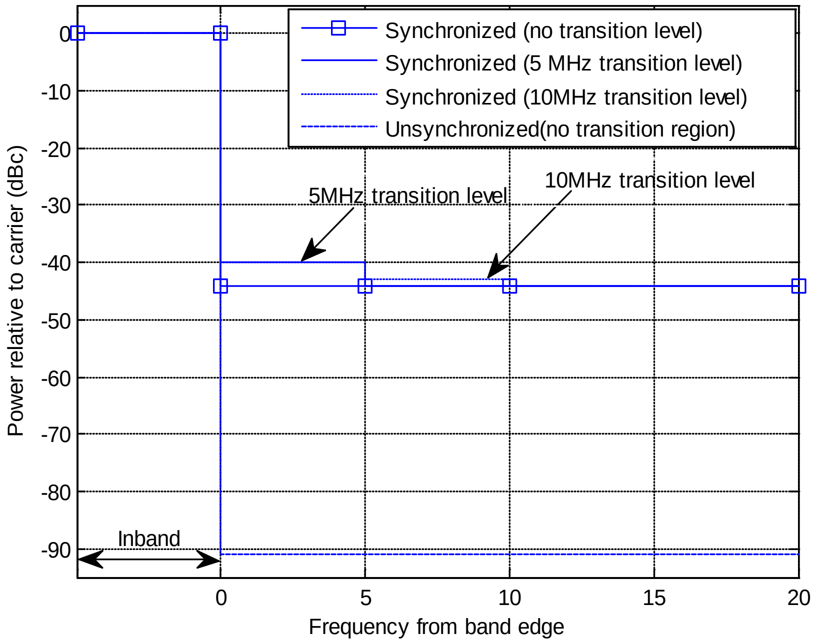

Figure 12: Suppression relative to carrier versus offset from channel edge with a 63dBm EIRP 20MHz channel bandwidth carrier showing different transition levels, synchronised and unsynchronised baseline suppression limits.

ECC PT1 suggest that for synchronised systems the transition levels may be allowed to overlap with adjacent channels of another operator, but that the baseline limit must not be exceeded in another operator's spectrum for unsynchronised systems. When using unsynchronised systems, PT1 recommend that transition regions should not overlap adjacent operator blocks, requiring a gap between frequency blocks or a sharp roll-off from the in-band limit to the unsynchronised baseline limit. Gaps between frequency blocks of different operators can be used to reduce any interference power leakage into an adjacent channel – at the cost of occupying more spectrum. As can be observed from Figure 12 a key difference between the mask definitions for synchronised and unsynchronised TDD systems is the difference in the baseline level. Though these masks have been developed for the 3.5GHz band, it is likely that this same mask will also apply in the 2.3GHz band [16].

The in-band powers identified in section 9 for different channel bandwidths have been used in the simulations in this report, except for the UK Broadband cases were the maximum EIRP for the 2007 and 2010 mask for a 20MHz bandwidth channel have been used. For clarity, the EIRPs used in the modelling for this report for the baseline PT1 case, and different UK Broadband masks for different channel bandwidths are shown in Table 5.

Table 5: BS EIRPs used in this report – these values define the OOB limits as defined by the mask parameters

	Basestation EIRP (dBm (dBm / 5MHz))				
DL	Macrocell			femtocell	microcell
Bandwidth (MHz)	PT1	2010 Mask	2007 Mask	PT1	PT1
20	63 (57)	66 (60)	72 (66)	20 (14)	41 (35)
10	63(60)			20 (17)	41 (38)
5	60 (60)			20 (20)	41 (41)

4.1.2 UE BEMs

In this section, we describe the masks defined by PTI for 3.5GHz UE's [1]. The UE Out of Band emissions that have been used by PT1 are the same values used by 3GPP TS 36 101, with a maximum in-band power of 25dBm.These are also assumed to apply to the 2.3GHz band.

For the case of UE's, the same mask is applied regardless of the level of synchronisation. The UE mask definition has 8 different levels which depend on the frequency offset from the channel edge. The parameters which define this mask are summarized in Table 6.

Table 6: Parameters used by PT1 to define UE BEM

Offset from channel edge	Value (dBm/MHz)
0→1MHz from channel edge	-5.8
1→5MHz from channel edge	-10.0
5→10MHz from channel edge	-13.0
10→15MHz from channel edge	-13.0
15→20MHz from channel edge	-13.0
20→25MHz from channel edge	-25.0
>25MHz from channel edge	-30.0
Out of band	-50.0

By subtracting the EIRP/MHz from these values the suppression caused by the presence of the BEM mask can be readily obtained. The equivalent suppression for a typical UE with a channel bandwidth of 5MHz and an EIRP of 23dBm is shown in Figure 13.

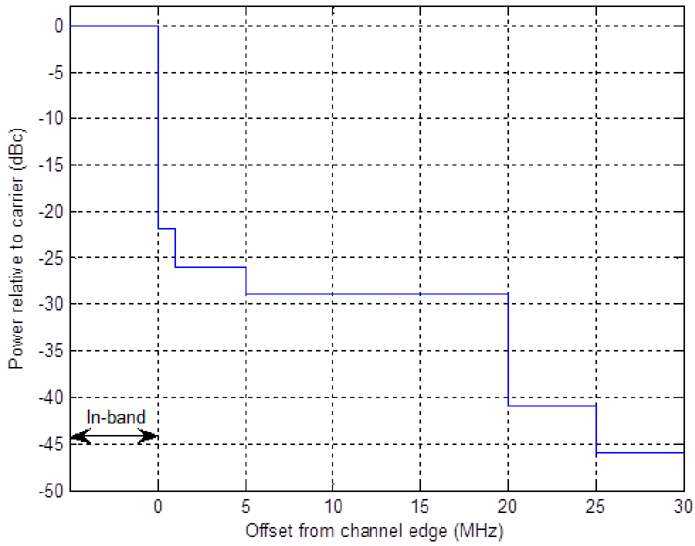

Figure 13: Suppression relative to carrier versus offset from channel edge for a UE with an EIRP of 23dBm and a channel bandwidth of 5MHz

4.1.3 UK Broadband BEM Masks

In this study, two UK Broadband masks are considered. In particular, the existing UK Broadband mask (2007)[17] as well as an alternative defined by Ofcom (see the 2010 consultation)[18] are used. These masks differ in having different rates of roll-off in the Out of Band (OoB) emissions and in the maximum in-band power limits. The 2007 limits allow UK Broadband to have a maximum EIRP of 59dBm/MHz, compared to the 2010 limit of 53dBm/MHz. A summary of the parameters used to define the existing UK Broadband mask is given in Table 7.

Table 7: Parameters that define the 2007 UK Broadband mask

Offset from channel edge	Value (dBm/MHz)
In-band limit	59
(0→3.5MHz from channel edge)	-13
Baseline limit	-26

Table 8: Parameters that define the 2010 UK Broadband mask

Offset from channel edge	Value (dBm/MHz)
In-band Limit	53
(0→4MHz from channel edge)	$10 - (41 * f)/4$
(4→7MHz from channel edge)	$31 - 4 * (f - 4)$
Baseline Limit	-42

In Table 8 the mask identifies the minimum suppression, relative to the carrier, from the band edge. The UK Broadband masks defined in 2007 and 2010 for a typical macrocell base station with a channel bandwidth of 20MHz and maximum licensed transmit EIRPs of 59dBm/MHz and 53dBm/MHz, respectively, are shown in Figure 14. UK Broadband currently use the mask agreed in 2007, and the Ofcom 2010 consultation stated that they will allow UK Broadband to adopt the 2010 definition if they choose to do so.

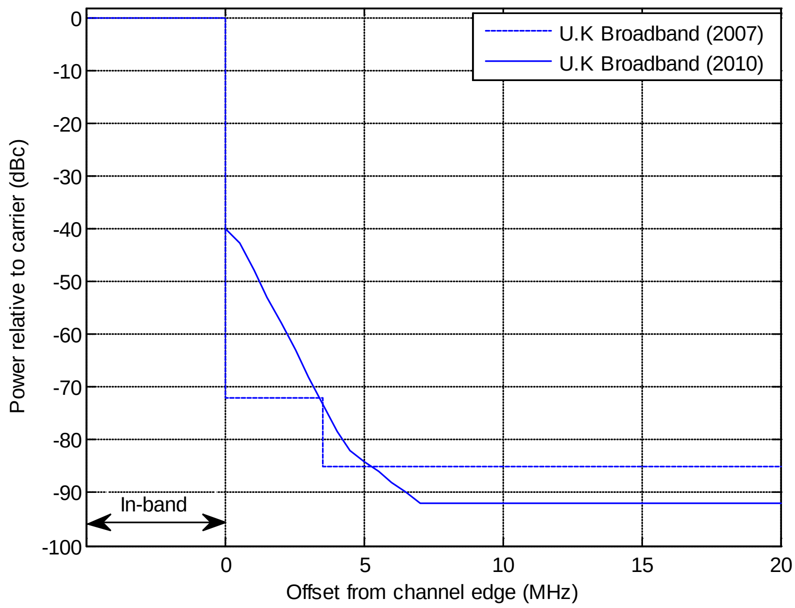

Figure 14: Suppression relative to carrier versus offset from edge of channel for UK Broadband masks using the maximum licensed EIRP permitted

4.1.4 Restricted (power) blocks

Gaps or restricted (power) blocks can be used to limit the interference between (unsynchronised) TDD blocks or between TDD and FDD blocks. The motivation for restricting the power is to protect the adjacent block from interference whilst making more use of the spectrum than leaving an unused gap. The restricted block is not conferred any interference protection from the adjacent full power block. This section examines the limits that would apply to a restricted block and considers the types of application that could utilise the spectrum given the power and interference constraints that would apply.

The effect of interference into any adjacent channel is composed of the ACLR and ACS components. The ACLR component depends upon the power emitted from the interferer into the adjacent channel (a product of the in-band power and the transmitter ACLR). The ACS component depends upon the response of the victim receiver in (not) selecting the interferer's in-band power within the victim receiver (a product of the interferer in-band power and the victim ACS). Hence any consideration of the effect of interference must consider these two components, and not just the restricted power limits.

Potential uses of the restricted block

Whilst the primary objective of the restricted block is to protect the adjacent block it is useful to examine the utility of any restricted block. CEPT Report 31 [19] noted that possible uses of a restricted block could include:

- Low power applications, such as PMSE, in particular radio microphones
- Low power IMT applications, including a femtocell layer
- Other national defence applications

In addition, developments in R8 and R10 of the LTE specifications (InterCell Interference Cancellation (ICIC) and enhanced ICIC (eICIC), respectively) use reduced power. Both of these methods, as noted in Section 3.4, assume phase synchronisation between low power and high power carriers in an operator's network. Using restricted blocks to reduce interference would not be required between synchronised networks. If operators can synchronise to benefit from ICIC techniques, they would not need to introduce restricted blocks solely for the purpose of reducing interference. They could use full power adjacent channels that are synchronised.

Other than the ICIC variants, the most likely use of a restricted block of the above options would be a femtocell layer which may not be synchronised and use a different frame structure from a higher power adjacent carrier in order to use a different balance of uplink and downlink traffic.

Restricted Block Limits

In 2007, CEPT Report 19 [20] advocated the BEM concept as part of its recommendation on developing least restrictive conditions for WAPECs (Wireless Access Policy for Electronic Communications Services) and when considering a 5MHz channel bandwidth in the 2.6GHz band. It recommended:

- A 5MHz guard between FDD DL and TDD (to protect TDD BS), or,
- Restricted block between adjacent unsynchronised TDD blocks (the upper block is restricted to protect the lower block from BS-BS interference)
- Restricted block between adjacent TDD and FDD UL (upper TDD restricted to protect TDD BS->FDD BS))

The restricted block EIRP of 25dBm/5MHz was suggested since it would be equivalent to the power radiated by a UE and could be used to support femtocell use in the restricted block.

ECC Report 119 [21] also refers to reducing interference in an adjacent block by "decrease[ing] the output power down to 25 dBm EIRP (a "restricted channel")". Based on the CEPT Report 19 work, this report translated the restricted block limits of power emitted in adjacent bands. Based on assumed power and ACLR limits, table I1 derived that a restricted block TDD Transmitter should not emit more than -6.5dBm / 5MHz into an adjacent block. It should be noted that the unsynchronised baseline limit discussed in section 4.1.1 has an unsynchronised baseline limit of -34dBm/5MHz. Based on a MCL interference analysis [21] noted that the TDD ACLR may need to be increased to reduce interference into the adjacent block. If the more conservative limit of -34dBm /5MHz is achievable, as assumed in section 4.1.1, we can assume it could be applied to any restricted block baseline limit.

Given an unsynchronised baseline limit of -34dBm/5MHz, the energy emitted into the victim receiver bandwidth would not exceed -34dBm/5MHz – irrespective of the restricted block EIRP limits. The effect of the ACS component in the victim receiver depends upon the power in the adjacent frequencies. If a 5MHz restricted block is adjacent to a victim block using a 20MHz channel bandwidth, the full 20MHz bandwidth adjacent to the victim is assumed to be an adjacent channel. The ACS response in the 1st adjacent channel would integrate over this 20MHz bandwidth. Hence restricting the power in ¼ of this first adjacent channel is unlikely to significantly reduce the ACS interference component (a 5MHz gap adjacent to a full power 15MHz would reduce the interference effect across the 20MHz by only 1.25dB). It is likely that improvements in the receiver ACS could be at least as beneficial.

The overall effectiveness of any restricted power block would need to consider the ACS of the victim receiver and the channel bandwidth of the victim compared to the restricted block size. The CEPT 19 report was developed assuming 5MHz channel bandwidths. A 5MHz gap or restriction between block used for FDD or TDD may reduce the utility of a relatively small fraction of the total spectrum allocation. However providing sufficient protection for the higher channel bandwidths anticipated in future is likely to require wider restricted blocks which can reduce the utility of a large fraction of available spectrum and thus is unlikely to be acceptable. Other methods of protecting receivers are likely to be preferable, including improvements in receiver ACS.

5. Calculating the capacity impact

A model has been developed to establish the capacity impact in a victim frequency block using different arrangements (such as different BEMs, synchronisation methods, frequency gap or different channel bandwidths). This section explains the simulation methodology.

5.1 Simulation overview

The approach we have taken to computing the capacity and performance impact of adjacent channel TDD interference is illustrated in Figure 15.

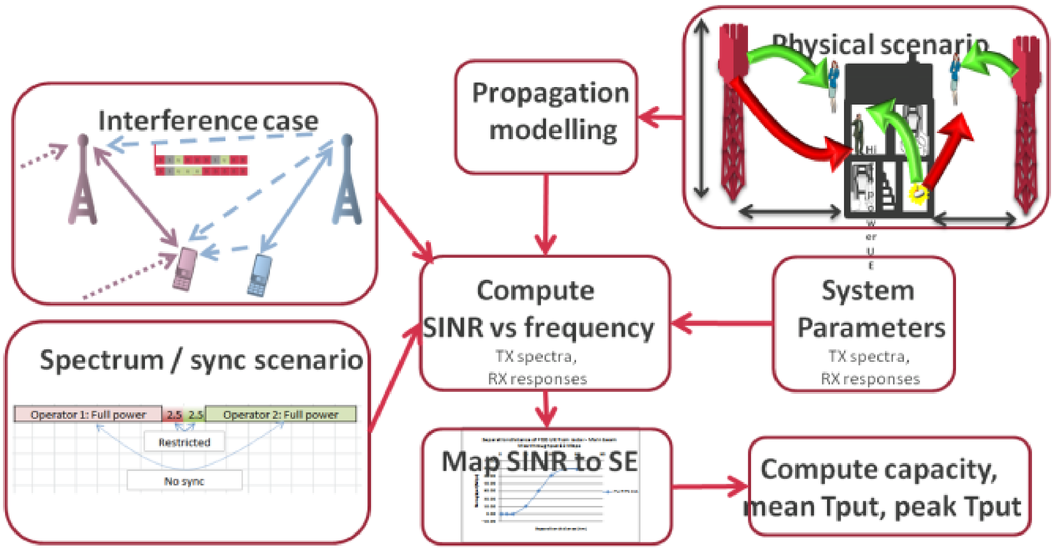

Figure 15: Key elements used to simulate capacity impact effects

In this analysis we are interested in assessing the capacity impact owing to issues associated with synchronisation between operators in adjacent blocks of spectrum and interference mitigation at the receiver. We have therefore chosen in discussion with Ofcom to adopt a Minimum Coupling Loss approach, selecting minimum coupling losses for geometries of interest and to examine the effect of changing mask parameters, phase alignment, ACS, channel bandwidth and gap between frequency blocks.

Each of the key blocks used in the simulation are outlined below:

- The **Spectrum block arrangements** and the BEMs are described in section 4;
- **Spectrum / Sync scenario**: This section selects different configurations of two 20MHz blocks (one the victim, one the interferer), with different channel widths, and BEMs, as described in Sections 5.2 and 5.3;
- The **Interference cases**: The different ACI interference modes identified in section 2 are simulated to determine the SINR across the victim operator 20MHz block;
- The **Method of computing the capacity** based upon computation of the SINR versus frequency and mapping to spectral efficiency is described in Section 5.2.1.

5.2 Spectrum arrangements

The capacity for different scenarios is calculated across a 20MHz victim frequency block with an assumed interferer frequency block separated with different width guard bands, as shown in Figure 16.

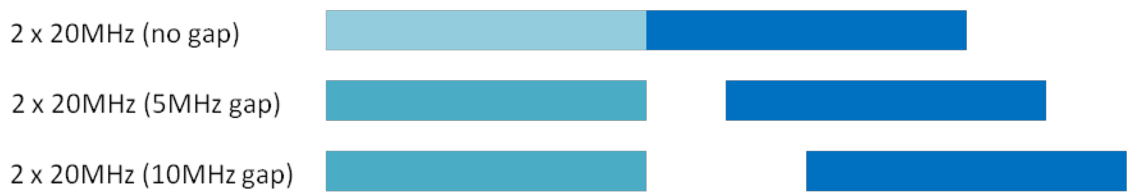

Figure 16: Spectrum arrangements of the victim and receiver frequency blocks

The above spectrum arrangements are combined with the different BEM to derive combined spectrum/ BEM mask scenarios. These are identified in Table 9 below, and the associated RF parameters for the different channel bandwidths, and base station type are identified in Section 9. It should be noted that when a spectrum arrangement is used that has a gap between 'used' 20MHz frequency blocks, then each operator can potentially gain by the isolation. In order to make comparison of capacity in the 20MHz victim received bandwidth fair, we scale the simulated capacity by the total spectrum occupancy assuming that each operator 'uses' ½ of the gap (so in the case of a 10MHz gap, the capacity in the 20MHz victim bandwidth is scaled by a factor of 20/25 to allow fair comparison with the capacity in a 20MHz block with no gap).

Table 9: Mask definitions used to identify Spectrum Arrangements and BEMs used in the simulations

Mask Scenario	Description
Mask 1	2x20MHz, No Gap. PT1 3.5GHz proposed mask (synchronised baseline, with no transition). Victim and receiver have 2x20MHz channels.
Mask 2	2x20MHz, No Gap. PT1 3.5GHz proposed mask (synchronised baseline, with 5MHz transition overlapping into adjacent frequency block). 2x20MHz channels.
Mask 3	2x20MHz, No Gap. PT1 3.5GHz proposed mask (synchronised baseline, with 10MHz transition overlapping into adjacent frequency block). 2x20MHz channels.
Mask 4	2x20MHz, No Gap. PT1 3.5GHz proposed mask (unsynchronised baseline, with no transition overlapping into adjacent frequency block). 2x20MHz channels.
Mask 6	2x20MHz, 5MHz Gap. PT1 3.5GHz proposed mask (unsynchronised baseline, with 5MHz transition but not overlapping into adjacent frequency block). 2x20MHz channels.
Mask 8	2x20MHz, 10MHz Gap. PT1 3.5GHz proposed mask (unsynchronised baseline, with 10MHz transition but not overlapping into adjacent frequency block). 2x20MHz channels.

Mask 9	2x20MHz, No Gap. UK Broadband mask 2007 definition (transition leaking into adjacent operator frequency block). 2x20MHz channels.
Mask 10	2x20MHz, No Gap. UK Broadband mask 2010 definition (transition leaking into adjacent operator frequency block). 2x20MHz channels.
Mask 11 -14	Spectrum arrangements and masks as per Mask 1 – 4, but with victim and receiver assumed to have 2x10MHz channel bandwidths.
Mask 15-18	Spectrum arrangements and masks as per Mask 1 – 4, but with victim and receiver assumed to have 4x5MHz channel bandwidths.

The exact BEM response for each of these masks varies depending upon the base station EIRP (i.e. different for macrocell, femtocell and microcell environments) and channel bandwidth. When narrower bandwidth channels are used, the mask defines the maximum power each transmitter is permitted to 'leak' out of band. This power leakage aggregates from all the assumed channels – resulting in a higher effective ACLR for narrower bandwidth channels. Conversely ACS of narrower bandwidth channel is able to reduce the in-band interference from an interferer that can be deemed to be separated in frequency by more than one bandwidth.

5.3 Modelling victim SINR

In the absence of ACI, a target SINR is assumed to be available at the victim receiver. This allows for a wide range of locations throughout the cell to be examined. The SINR target is:

$$SINR_{Target} = \frac{Signal_{Desired}}{Noise_{Thermal} + Noise_{OwnNetwork}}$$

Where $Noise_{thermal}$ is the thermal noise and $Noise_{own\_network}$ is the self interference of the network. The self-interference will vary depending on the radio environment being considered.

The value of the actual SINR (SINR including external interference) is given by the following formula:

$$SINR_{Actual} = \frac{Signal_{Desired}}{(Noise_{Thermal} + Noise_{OwnNetwork} + ACI)}$$

where ACI is the Adjacent Channel Interference. The power of the interference at the front end of the victim receiver in the adjacent channel is simply the transmit EIRP minus the interferer-victim path loss. Owing to the OOB emissions from the adjacent channel, interference will be present in-band at the victim receiver, and, owing to imperfections in the victim receiver's discrimination, some of the interferer adjacent channel power will be selected by the victim. The Adjacent Channel Interference Ratio is the ratio of the adjacent channel power at the front end of the victim receiver to the adjacent channel interference from each of these two sources of interference.

$$\frac{1}{ACIR} = \frac{1}{ACS} + \frac{1}{BEM}$$

The value of ACIR will vary across the victim receive band, depending upon the value of the ACS and BEM in that particular frequency segment. The ACI in the victim receiver can therefore be calculated (in dB) as:

$$ACI\ (dB) = EIRP_{IF}(dB) - Pathloss\ (dB) - ACIR\ (dB)$$

where *Pathloss* refers to the pathloss between the interference source and victim receiver. Hence $SINR_{actual}$ can be determined.

It should be noted from the definition of ACIR, that the total interference power affecting a victim receiver, is dominated by the lesser of the ACS or BEM values.

The SINR at the victim receiver for the four interference modes are calculated in each 500 kHz 'chunk' across the 20MHz victim band. A 'chunk' size of 500 kHz was chosen since it is the largest frequency bandwidth that can be chosen to accurately reflect the block edges of the BEMs that have a 'step function' change in value and small enough to represent the sloping BEMs of the UK Broadband 2010 mask with little error. The SINR varies across the victim band owing to changes in out of band emissions from the transmitter or adjacent channel selectivity (ACS) by the victim receiver. The out of band emissions are assumed to be suppressed by the limits given by the BEMs in Section 4.

The ACS values from [22] have been used as the baseline values for each receiver type and are noted in Section 9. This value is constant across the band of the adjacent channel. In consultation with Ofcom, we have assumed that the next adjacent channel has additional 10dB selectivity, and subsequent channels have negligible impact (selectivity level set to 200dB). We also add additional ACS to the BS and UE to determine the sensitivity of the results to this parameter.

For each ACI interference mode, the SINR for each 500 kHz frequency segment of the victim receiver can be converted into a corresponding spectrum efficiency, SE. Consistent with a previous Ofcom study by Real Wireless [23], but revising the SINR cutoff according to more recent industry sources, we can translate the SINR into SE taking into account the characteristics of the LTE data, signalling and synchronisation overheads on the physical layer, as:

- Resource Blocks occupy 90% of channel bandwidth;
- Data occupies 80% of RBs;
  - Hence data occupies 72% of system bandwidth;
- Using implementation margin parameters taken from 3GPP 36.942, we assume that DL data (2x2 MIMO) can achieve 60% (UL (1x2 MIMO) 40%) of the Shannon Limit. Receivers cannot decode successfully at SINRs below -8.1dB (DL) and -7.5dB (UL). The spectrum efficiency is capped at 8.8b/s/Hz in the DL (2 b/s/Hz in the UL).

5.4 Computing capacity

The uplink (downlink) capacity depends upon the number of uplink (downlink) slots, and whether these slots are subject to interference from either other uplink (downlink) slots in the adjacent channel, or from downlink (uplink) slots in the adjacent channel.

The uplink and downlink capacity can then be calculated as:

$$Capacity_{uplink} = \sum_{frequency} (P_{UN}.SE_{UN} + P_{UC}.SE_{UC})$$

$$Capacity_{downlink} = \sum_{frequency} (P_{DN}.SE_{DN} + P_{DC}.SE_{DC})$$

where:

- P_{UN} represents the probability of uplink slot ***not*** being clashed (i.e. probability of victim system transmitting an uplink slot at the same time that the interferer transmits an uplink slot);
- P_{DN} represents the probability of downlink slot ***not*** being clashed;
- P_{UC} represents the probability of uplink slot being clashed;
- P_{DC} represents the probability of downlink slot being clashed;
- SE_i represents the Spectrum Efficiency resulting from the $SINR_{actual}$ obtained by simulating the interference environments for each ACI mode, corresponding to clash incidences UN, DN, UC and DC (defined above); and,
- the summation adds up the frequency dependent spectrum efficiencies across the 20MHz of the victim operator frequency block assumed in this study.

Section 3.5 demonstrated that the different TD-LTE configurations, as well as offering different ratios of UL:DL traffic, would have different amounts of each interference mode depending upon the configurations used for the victim and interfering operator and the time phase offset between their time frames. In the simulation we account for the correlated slot clash by using the actual probability of slot clash for every combination of configuration pairs and time-slot phase offsets. Phase offsets that are less than one time slot produce intermediate values between adjacent slot phase offsets. Different combinations of configurations and phase offset result in different sets of probabilities for uplink and downlink clash. These different probabilities are combined with the frequency-dependent spectrum efficiencies across the victim receiver bandwidth for the four interference mode cases, as described in the equations above.

5.5 Geometry dependent synchronisation effects

It is of interest to examine the terms used for uplink (downlink) capacity to examine the impact of the geometry of the particular scenario being evaluated. We can consider the uplink only, as an example. The uplink capacity depends upon the choice of configuration used by the victim (and interferer), the phase offset between the two and the interference environment geometry. The configuration combination pairs and timing offset will define the values of P_{UN} and P_{UC}. Synchronised networks will always have $P_{UC} = 0$.

If we now consider the uplink interference case as shown in Figure 17.

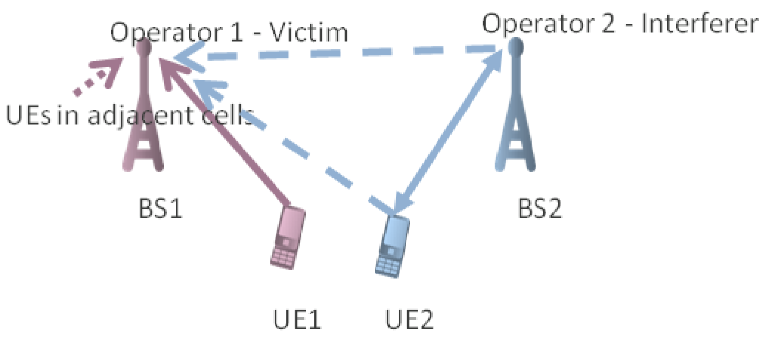

Figure 17: Example of uplink geometry-dependent ACI

Uplink Interference occurs at the victim BS when slots are not clashed (UE2 → BS1) or when slots are clashed (BS2→BS1).

When the interference is much less than the total noise already present at the receiver, from own network and thermal noise, then this ACI does not contribute significantly to the link or system performance[8].

The approximate ACI power at the victim BS can be determined for clashed and non-clashed cases as:

$$ACI_{UN} \approx UE2_{eirp} - CL_{UE2\_BS1} - \min\left(ACLR_{UE2}, ACS_{BS1}\right)$$

(where the simplification that $\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS} \approx \frac{1}{\min\left(ACLR,\ ACS\right)}$ has been made[9], and CL_{x_y} is the coupling loss between equipment x and y), and,

$$ACI_{UC} \approx BS2_{eirp} - CL_{BS2\_BS1} - \min\left(ACLR_{BS2}, ACS_{BS1}\right)$$

ACI_{UN} would only occur when UE2 is transmitting (on a subset of U slots), whereas ACI_{UC} would occur in all clash cases where we assume the BS2 is transmitting at all times. Given the baseline values of ACLR and ACS, for the synchronised case, improvements in BS ACS (nominally 45dB) are unlikely to be helpful unless the BS ACLR (with a macro site suppression of 43dBc) also improves.

Hence in the uplink, the uplink clash will result in reduced ACI, compared to the non-clashed case, when,

$$BS2_{eirp} - CL_{BS2\_BS1} - \min\left(ACLR_{BS2}, ACS_{BS1}\right) < UE2_{eirp} - CL_{UE2\_BS1} - \min\left(ACLR_{UE2}, ACS_{BS1}\right)$$

[8] Note that if the ACI noise contribution is 6dB less than the other sources of noise, then the total noise including ACI is raised by ~1dB (which is often considered acceptable).
[9] The approximation error here is less than 3dB. When ACS=ACLR the approximation will underestimate by a maximum of 3dB. When the difference between them is more than 6dB, the approximation will underestimate by less than 1dB.

Using baseline parameter values we would therefore expect the uplink clashed case to outperform the uplink non-clashed case where:

$$CL_{BS2\_BS1} - CL_{UE2\_BS1} > \ \sim 20dB$$

This is unlikely to apply to geometries 1-3 and so we should expect synchronised systems to outperform unsynchronised systems in the uplink direction.

We can perform a similar analysis for the downlink, as shown in Figure 18.

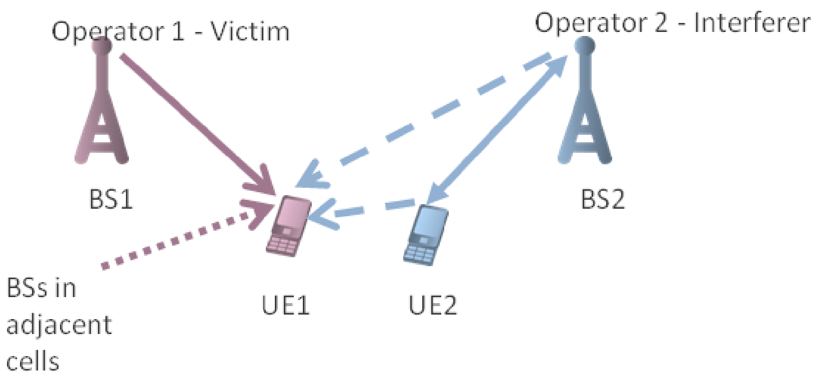

Figure 18: Example of downlink geometry-dependent ACI

Analogously to the above, we can determine that,

$$ACI_{DN} \approx BS2_{eirp} - CL_{BS2\_UE1} - \min(ACLR_{BS2}, ACS_{UE1})$$

and,

$$ACI_{DC} \approx UE2_{eirp} - CL_{UE2\_UE1} - \min(ACLR_{UE2}, ACS_{UE1})$$

ACI_{DN} is likely to occur on all UE1 D slots, and so could be problematic whenever the victim UE is close to the BS. Since the UE ACS is much lower than the BS ACLR, any change to the ACLR is unlikely to help with this synchronised case. ACI_{DC} is unlikely to affect every D slot since UE2 is unlikely to transmit in every slot in which UE1 is to receive DL data.

Hence in the downlink, the downlink clash will result in reduced ACI, compared to the non-clashed case, when,

$$BS2_{eirp} - CL_{BS2\_UE1} - \min(ACLR_{BS2}, ACS_{UE1}) \ \sim < UE2_{eirp} - CL_{UE2\_UE1} - \min(ACLR_{UE2}, ACS_{UE1})$$

Using baseline parameter values we would therefore expect the uplink clashed case to outperform the uplink non-clashed case where:

$$CL_{UE2\_UE1} - CL_{BS2\_UE1} > \ \sim 35dB$$

Based on the baseline parameters, this is unlikely to apply to geometries 1 and 2, but is more likely to apply to geometry 3.

We can therefore expect synchronised systems to outperform unsynchronised systems with the exception of geometry 3 type environments. We further note that for synchronised systems the ACLR could become the limiting case if UE ACS is improved, but is unlikely otherwise.

6. Results

This section contains the results for all simulations performed in this study. Since the spectrum efficiency is different in the uplink and the downlink, and the number of U and D slots varies between configurations, it is difficult to meaningfully present the results as an overall capacity measure. We have chosen radio environments which are considered to be challenging and divided these into 3 different geometry types. The geometry dependent and RF parameters for the different cases are listed in Section 9.

The capacity achievable would vary by geometry type and by configuration used, irrespective of whether synchronised frame structures, different BEMs or gaps between different operator blocks are used. We have set target SINRs (in uplink and downlink directions, consistent with the three different geometries). From this it is possible to determine the capacity that would result at the target SINR in the absence of ACI (which has been termed the 'uncontended' capacity) for each geometry. We can then assess the 'impact' when different factors are modified and compare this to the baseline case. Whenever percentage changes are used, we have expressed these as the percentage gain relative to the same victim configuration timeframe structure.

The results in the rest of this section are as follows:

- Section 6.1 examines the impact of different sized gaps between adjacent frequency blocks;
- Section 6.2 examines the impact of different BEMs with synchronised time frames;
- Section 6.3 examines the impact of using synchronised frames with synchronised baseline BEM limits (mask 1) compared to unsynchronised configurations with unsynchronised baseline limits (mask 4);
- Section 6.4 examines the impact of different victim and receiver channel bandwidths;
- Section 6.5 examines the case of a frequency block adjacent to UK Broadband by considering various scenarios where UK Broadband can be the victim or interferer.

6.1 Effect of gap size

In the following, gap sizes of 0, 5 and 10MHz are simulated between the two 20MHz frequency blocks. It should be noted that the capacity values are scaled to reflect the total spectrum occupancy in order to make a fair comparison with the case where there is zero frequency gap. The legend of Figure 19

shows the symbols used to denote the capacities achievable for geometry 1, macrocell environment, with gaps of 0, 5 and 10MHz for unsynchronised time frame configurations. The solid horizontal lines show the uncontended capacity available at the target SINR (i.e. without any ACI) with time slot configurations 0 to 6 (see Table 2). Different capacities are achievable for each configuration since different numbers of uplink and downlink slots and the spectrum efficiency differs in each direction. The multiple markers show the different capacities available for different phase offsets for all 490 different combinations[10] of time frame configuration pairs and time offsets, including the effects of ACI.

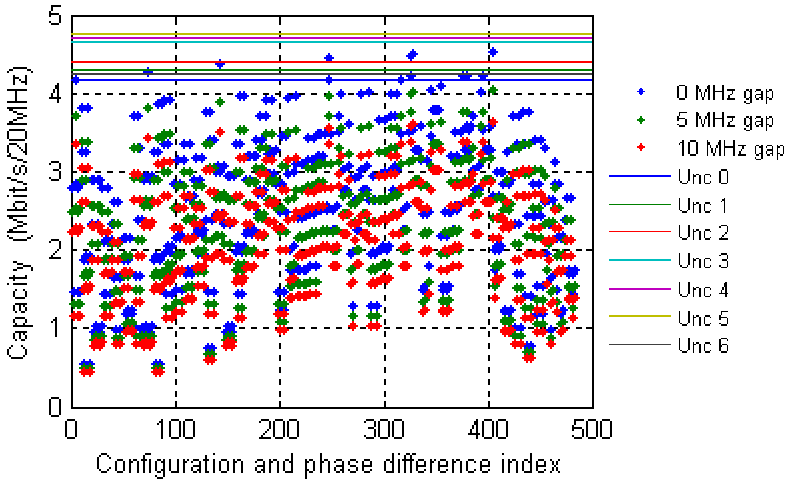

Figure 19: Capacity of unsynchronised cases with variable gap, cell edge, geometry 1, macrocell

The large variation amongst different configuration pairs and phase offsets is typical and demonstrates the difficulty in comparing 'capacity' for different scenarios. In general inserting a gap in this environment reduces the capacity since any reduction in interference does not compensate for the increased spectrum occupied.

Figure 20 uses the same data as Figure 21, but shows the percentage gain of 5MHz and 10MHz gaps compared to the zero gap case. We have ascribed ½ of the gap to each operator, and therefore the 5MHz gap implies that each operator 'occupies' 22.5MHz. If the same spectrum efficiency in the 20MHz channel was achievable the increased occupancy would result in an apparent capacity reduction of 11.1%. The 10MHz gap would similarly result in a 20% reduction. Figure 21 demonstrates that any additional isolation provided by having a gap therefore has little benefit in this case. Figure 21 shows the results in the same format as Figure 22 for the three different geometry cases. The uncontended capacity for different configurations for cell edge (low SINR, geometries 1 and 3) and cell centre (high SINR, geometry 2) are shown. This demonstrates that the gap has little impact on reducing the interference from the adjacent channel, and that the additional occupancy reduces overall spectrum efficiency in all three geometry types considered.

[10] These 490 combinations result from 7 different victim and interferer timeframe configurations, and each pair can be shifted by 10 different time slots, resulting in 490 combinations. 7 of these combinations will be the 7 different configurations paired with an identical configuration with zero offset (i.e. the same configurations that are possible with synchronised networks).

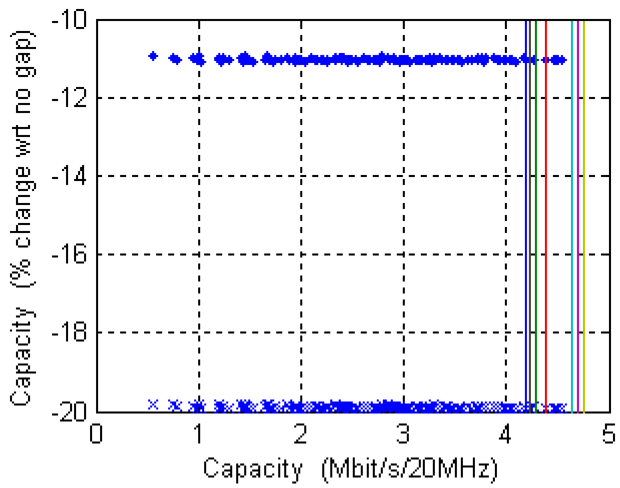

Figure 20: Effect of gap of masks used in unsynchronised cases, cell edge, geometry 1, macrocell

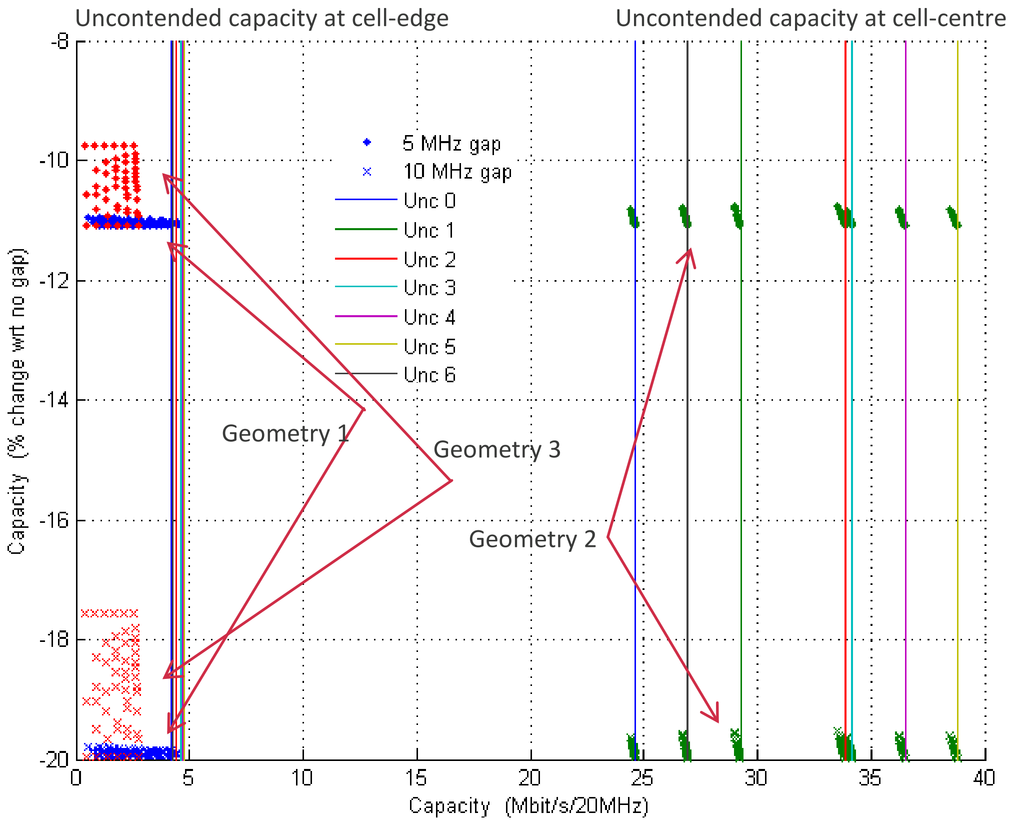

Figure 21: Effect of gaps used in unsynchronised cases, macrocell

We can extract the SE values in the channel bandwidths[11] for the different interference mode links, as shown in Table 10, Table 11 and Table 12 for geometries 1, 2 and 3

[11] The Spectrum Efficiency values quoted in tables are the average of the SEs in each 0.5MHz frequency chunk in the 20MHz victim bandwidth. When different gaps are used between the frequency blocks the effective SE will be less (since more spectrum is occupied). This is taken into account in the plots of capacity, but the raw SE in the 20MHz is tabulated in this report.

respectively. Example capacity values for a configuration pair and time slot offset are also shown, but the SE values are functions of the interference mode for this scenario, irrespective of the configuration pair and phase offset used.

Table 10: Spectrum efficiency values: geometry 1, different gap sizes

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.26	0	2.78	(0,0)1
5	0	0.23	0.26	0	2.48	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1

Table 11: Spectrum efficiency values: geometry 2, different gap sizes

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.2	24.44	(0,0)2
5	1	1	2.2	2.2	21.79	(0,0)2
10	1	1	2.2	2.2	19.64	(0,0)2

Table 12: Spectrum efficiency values: geometry 3, different gap sizes

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbit/s/20MHz)	Cfg and phase
0	0.21	0.23	0	0	2.75	(0,0)5
5	0.22	0.23	0	0	2.44	(0,0)5
10	0.22	0.23	0	0	2.2	(0,0)5

For Geometry 1 environments, the 'clashed' ACI modes have SE=0 – and would result in receiver blocking, whereas the non-clashed ACI modes (which would occur with synchronised networks) have some throughput – though not as much as the higher SINR geometry 2 case. In the high SINR geometry 2 environment, the SE does not vary between clashed and non-clashed ACI modes, nor with a gap. In geometry 3 environments, the downlink for both clashed and non-clashed ACI modes result in SE=0 bps/Hz, and receiver blocking would occur. Inserting a gap does not mitigate this interference, in this case. In geometry 3, for the uplink, the clashed ACI mode has a marginally worse SE than the non-clashed ACI mode, and though the SE increases slightly with a frequency gap, the gain is small and would not compensate for the increased spectrum occupancy.

To examine the impact of ACS with different sized gaps between the frequency blocks, we simulated an improvement of 20dB ACS at the base station and 10dB at the UE. These results are shown in Figure 22. The capacity gain uses all combinations of configuration pairs comparing the relative performance of ACS improvements of (20/10) dB (at BS/UE) at 5MHz and 10MHz gaps with the zero gap case (with the same assumed ACS improvements).

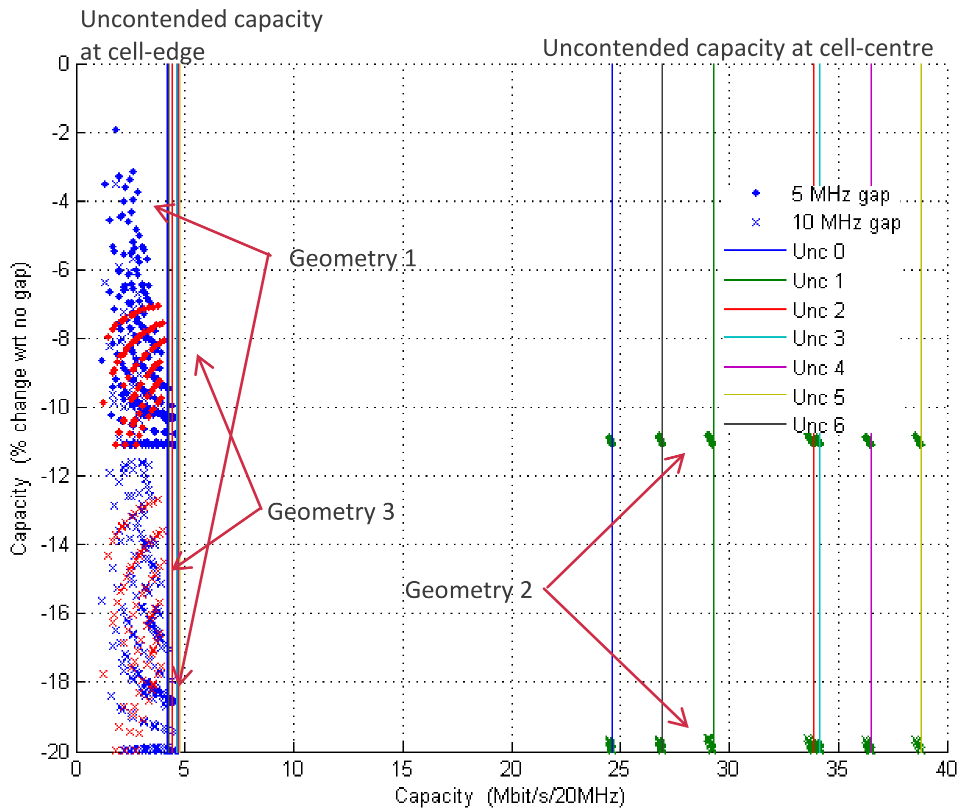

Figure 22: Relative capacity of 5 and 10MHz gaps (compared to zero gap case) with BS/UE improvements of 20/10dB.

The spectrum efficiency values with assumed ACS improvements of 20/10dB at the BS/UE for geometries 1,2 and 3 are shown in Table 13, Table 14 and Table 15.

Table 13: Spectrum efficiency values: geometry 1, different gap sizes with ACS improvements of 20/10dB at the BS/UE

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0.13	0.23	0.26	0	4.17	(0,0)5
5	0.15	0.23	0.26	0	3.71	(0,0)5
10	0.17	0.23	0.26	0	3.34	(0,0)5

Table 14: Spectrum efficiency values: geometry 2, different gap sizes with ACS improvements of 20/10dB at the BS/UE

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.2	24.47	(0,0)2
5	1	1	2.2	2.2	21.81	(0,0)2
10	1	1	2.2	2.2	19.66	(0,0)2

Table 15: Spectrum efficiency values: geometry 3, different gap sizes with ACS improvements of 20/10dB at the BS/UE

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbit/s/20MHz)	Cfg and phase
0	0.23	0.23	0.21	0	4.02	(3,5)0
5	0.23	0.23	0.22	0	3.7	(3,5)0
10	0.23	0.23	0.23	0	3.44	(3,5)0

Improving ACS coupled with a frequency gap allows the SE to be more than zero for the downlink non-clashed geometry 3 case, and the uplink clashed case for geometry 1 with some minor improvements in the uplink clashed case for geometry 3. Increasing the gap marginally improves the spectrum efficiency (but not sufficiently to compensate for increased spectrum occupancy). Further improvements in ACS, or movement of the UE away from the source of interference would be needed to allow the spectrum efficiency to improve. Clearly, in severe interference conditions the use of a gap can allow a communications link to be established that may not be possible without a gap – though this gap has previously reduced average capacity owing to increased spectrum occupancy in other cases.

Figure 23 and Figure 24 show the same results for femtocell and microcell environments respectively. Note that the capacity per 20MHz is higher with the femtocell. These allow the micro and femto environments to have significantly improved capacity values than the macro-cell environment. In the low SINR environments (Geometry 1 and 3), it can be seen that inserting a gap can result in capacity improvements for some of the configuration combinations compared to the zero gap case. These capacity improvements are, however, modest improvements from a low baseline value.

In summary, in some poor SINR environments, a gap can help to provide isolation that can mitigate against ACI. However, the increased spectrum occupancy resulting from use of a gap reduces the average capacity in the majority of cases considered. Improvements in ACS had little impact in the majority of cases considered but, coupled with a 10MHz gap, were able to prevent downlink receiver blocking in low SINR geometry 3 environment. The ACI modes associated with unsynchronised networks (clashed modes) suffered from reduced SE compared to the unclashed modes.

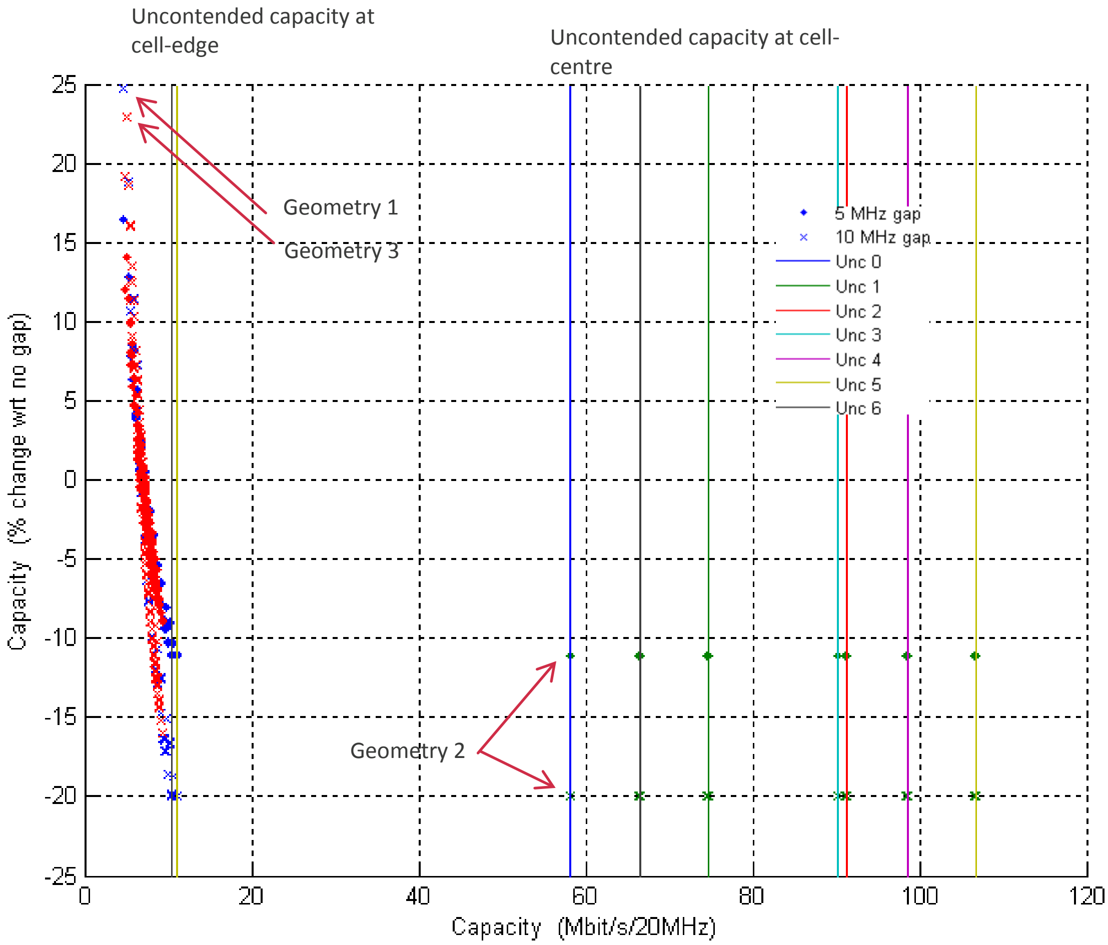

Figure 23: Relative impact of 5MHz and 10MHz gaps used in unsynchronised cases, femtocell

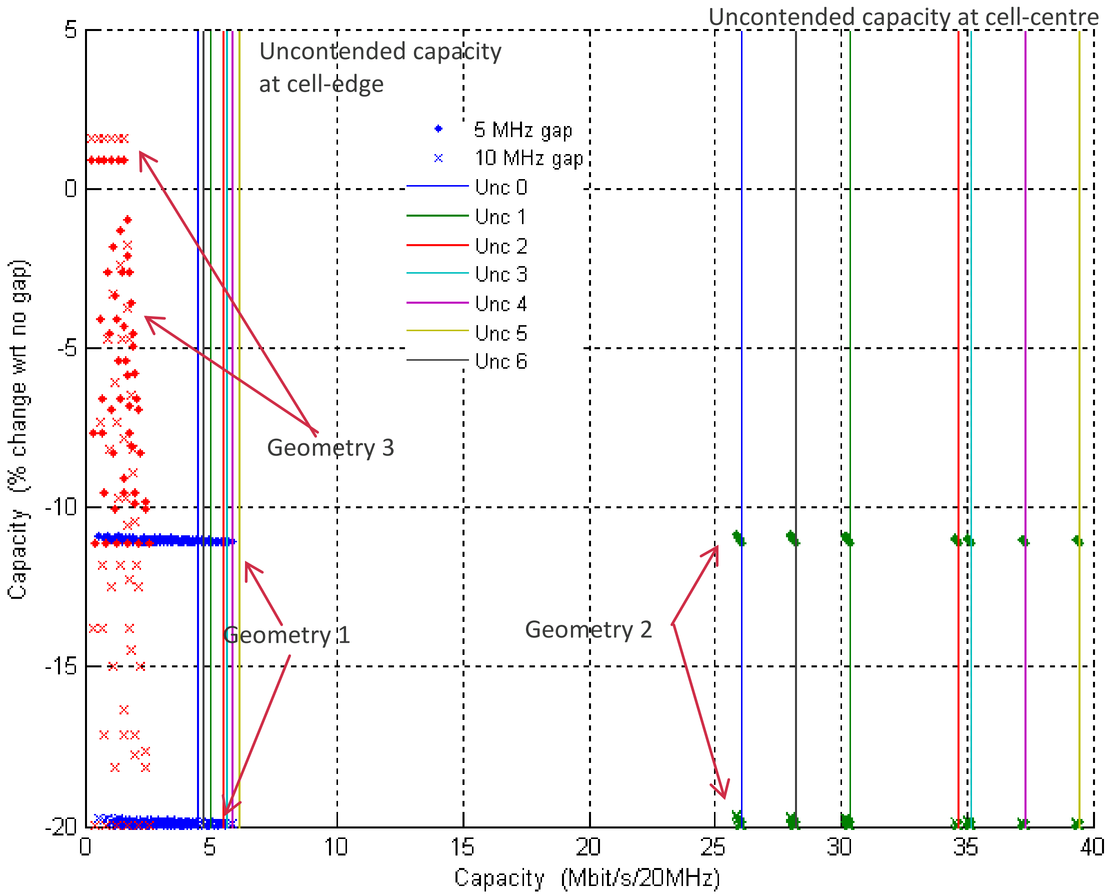

Figure 24: Relative impact of 5MHz and 10MHz gaps for unsynchronised cases, microcell

6.2 Effect of BEM with phase aligned (synchronised) timeslots

The effect of different block edge masks (see section 5.2 for the mask definitions) that have different baseline levels and transition bandwidths (allowing more energy to leak into adjacent operator blocks) for synchronised frame structures is shown in Figure 25.

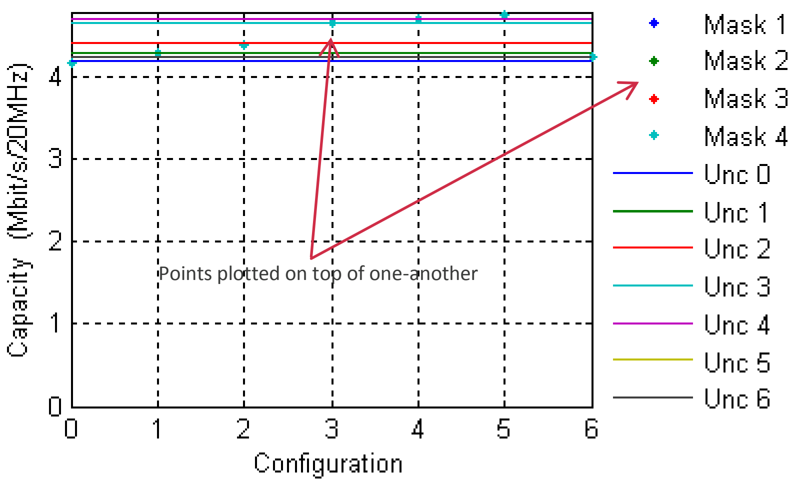

Figure 25: Capacity of synchronised cases with variable mask, cell edge, geometry 1, macrocell (Note all masks yield essentially the same results). The solid horizontal lines correspond to the uncontended (i.e. zero ACI case) capacities for timeframe configurations 0 to 6.

The results for different masks in the presence of ACI corresponding to the victim configuration time frame are plotted (masks 1 to 3 allow different leakage into adjacent operator block with synchronised baseline limit, mask 4 uses unsynchronised baseline limits from the edge of the operator block with no transition zone leakage into adjacent (victim) block).

The capacity values for the different BEMs (masks 1 – 4) are plotted virtually on top of each other – indicating that the ACI is insensitive to the masks used if the networks are synchronised. The relative impact on capacity for all three geometries (macrocell, synchronised configurations, masks 1-4) is shown in Figure 26. These values are normalised against the mask 1 case which uses the synchronised baseline limit with no transition zone. There is a small improvement in geometry 1 environments by having the more restrictive masks – but the impact is small. In this environment the desired and interfering signals will have similar power and the additional suppression has some marginal benefit.

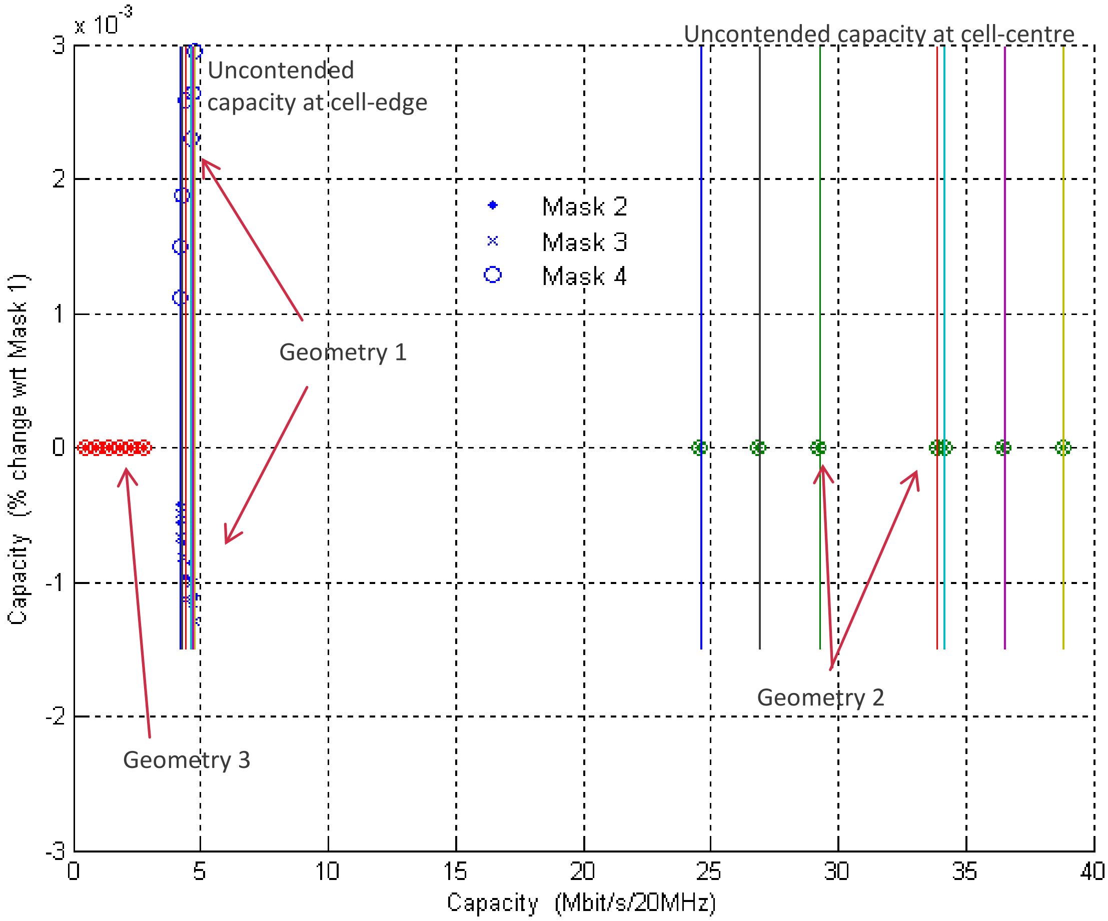

Figure 26: Capacity of synchronised cases with variable mask, macrocell (using the same colours to denote the uncontended configuration capacities as before)

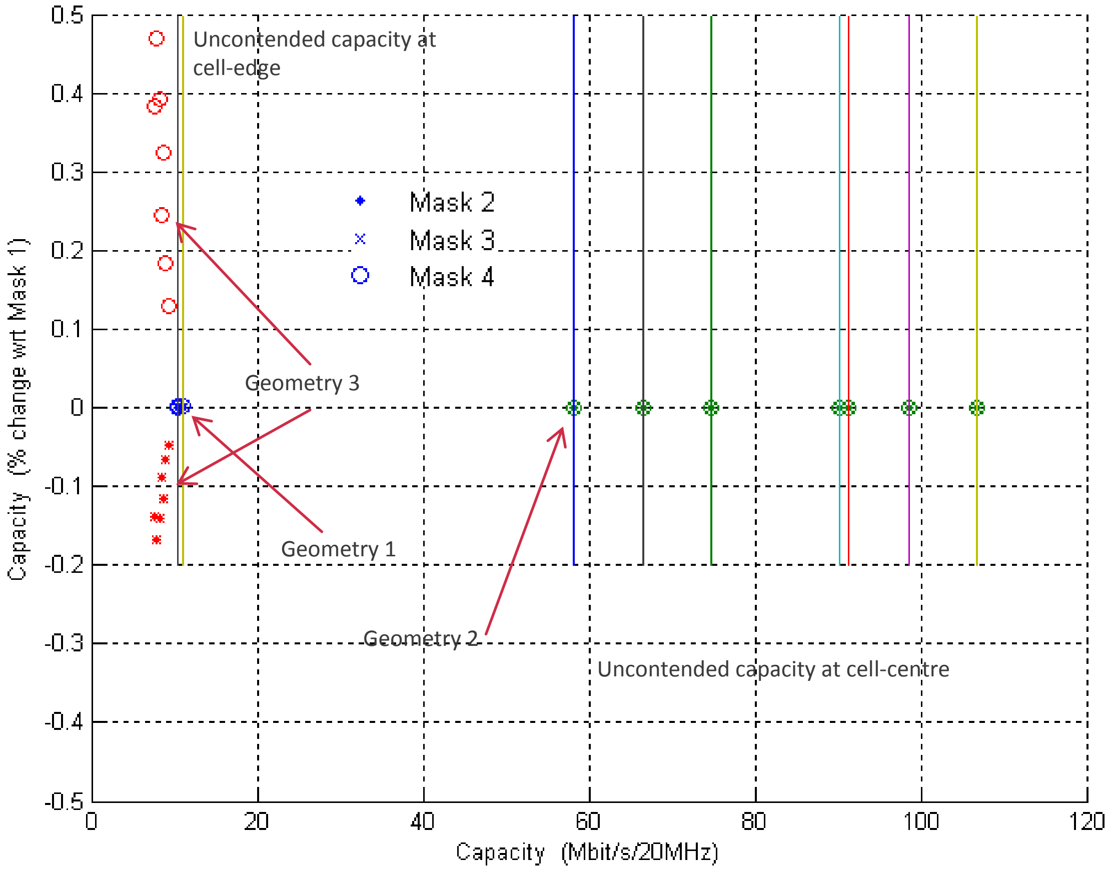

Figure 27: Capacity of synchronised cases with variable mask, femtocell case (using the same colours to denote the uncontended configuration capacities as before)

Figure 27 and Figure 28 show the results for synchronised configuration and different BEMs for femtocell and microcell cases respectively. Whilst the cell capacities vary for the different environments and geometries considered, the effect of the BEM is limited, and reduced baseline limits would have little impact on the capacity achievable for synchronised networks.

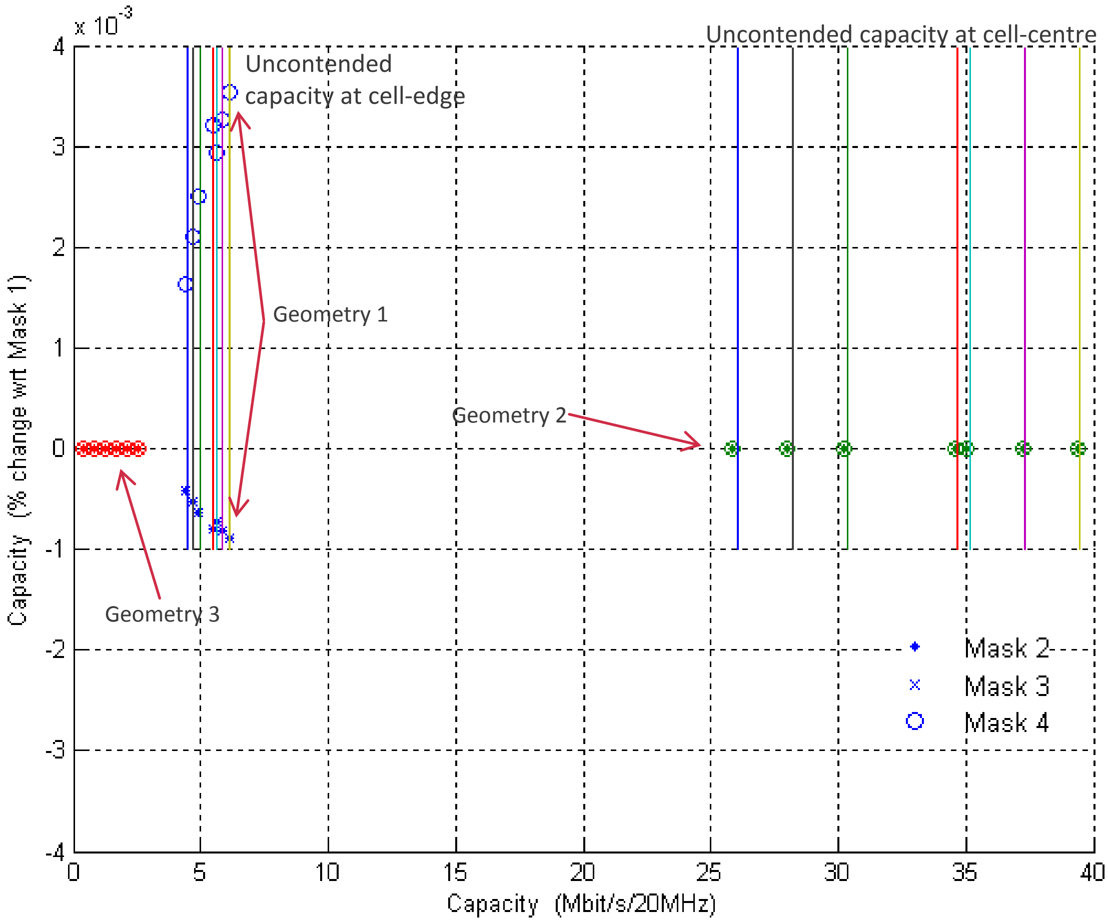

Figure 28: Capacity of synchronised cases with variable mask, microcell case (using the same colours to denote the uncontended configuration capacities as before)

In summary, and as predicted in Section 5.5, the effect of the baseline limit is limited for synchronised networks (<1%) using the default ACS. Since the baseline limit for macrocells with 63dBm EIRP (43dBc) is much better than the UE ACS there would be little need to adjust baseline BEM limits; improvement in UE ACS may mean that the baseline limit becomes important to review.

6.3 Effect of synchronisation

In this section, we compare the capacity of synchronised timeframes versus unsynchronised timeframes for different configurations. The synchronised timeframes use mask 1 with the synchronised baseline limits (NB: results in section 6.2 demonstrate that the impact of different BEMS for synchronised configurations is small), and all combinations of different configuration pairs (unsynchronised) use the unsynchronised baseline limits (mask 4).

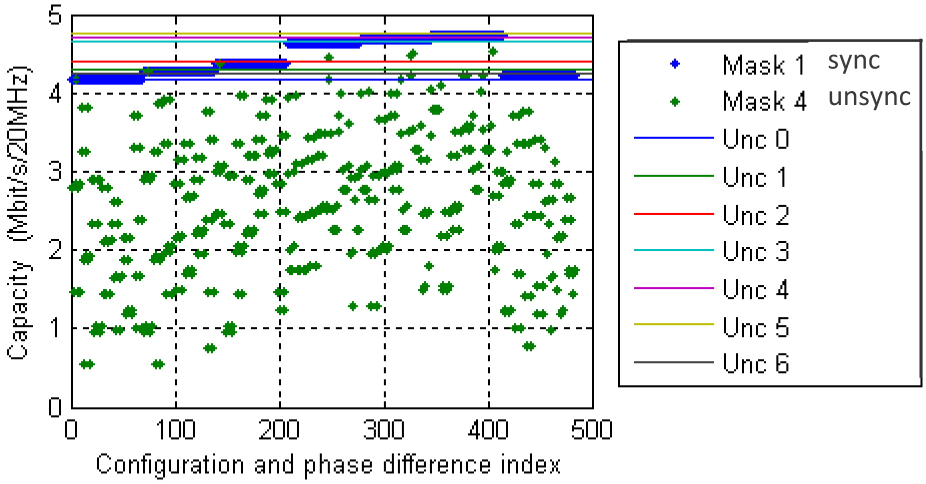

Figure 29: Capacity of synchronized and unsynchronized cases, cell edge, geometry 1, macrocell case

From Figure 29 it can be observed that, the unsynchronised configurations have lower capacity than synchronised cases. The additional protection of the unsynchronised mask does not mitigate the ACI associated with unsynchronised ACI modes. The precise capacity for unsynchronised configurations depends on the phase offset and on the configuration pair as shown by the different capacity for different combinations of timeframe configuration. Some configurations can have more capacity reduction than others.

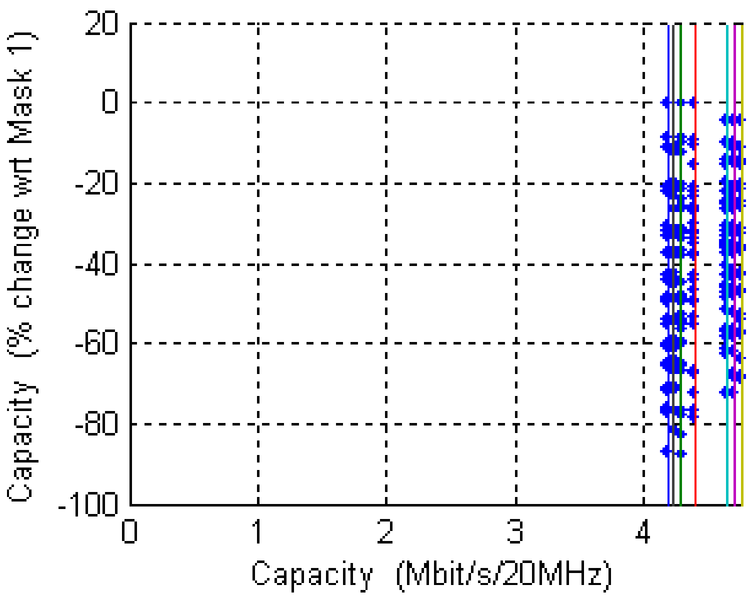

Figure 30: Effect of synchronisation, cell edge, geometry 1, macrocell (using the same colours to denote the uncontended configuration capacities as before).

Figure 30 shows the unsynchronised capacity (using mask 4) compared to the same configuration when synchronised (using mask 1). Configurations with different phase offsets have a variable capacity reduction compared to the same (synchronised) victim configuration. This is the same data as Figure 29, but shows the % capacity achieved compared to the capacity attained with the case of synchronised time frames for the same victim time frame configuration. Figure 31 shows % capacity relative to the synchronised timeframe case – for geometries 1, 2 and 3.

From Figure 31 it can be observed that the impact of losing synchronisation on capacity depends on the geometry as well as the timeframe configuration combination. In general unsynchronised timeframe capacities are less than the synchronised case. There is little capacity impact on the high SINR geometry 2 environments between synchronised and non-synchronised cases. Any small capacity improvement that is evident is owing to the higher ACLR possible using mask 4 compared to the synchronised case using mask 1.

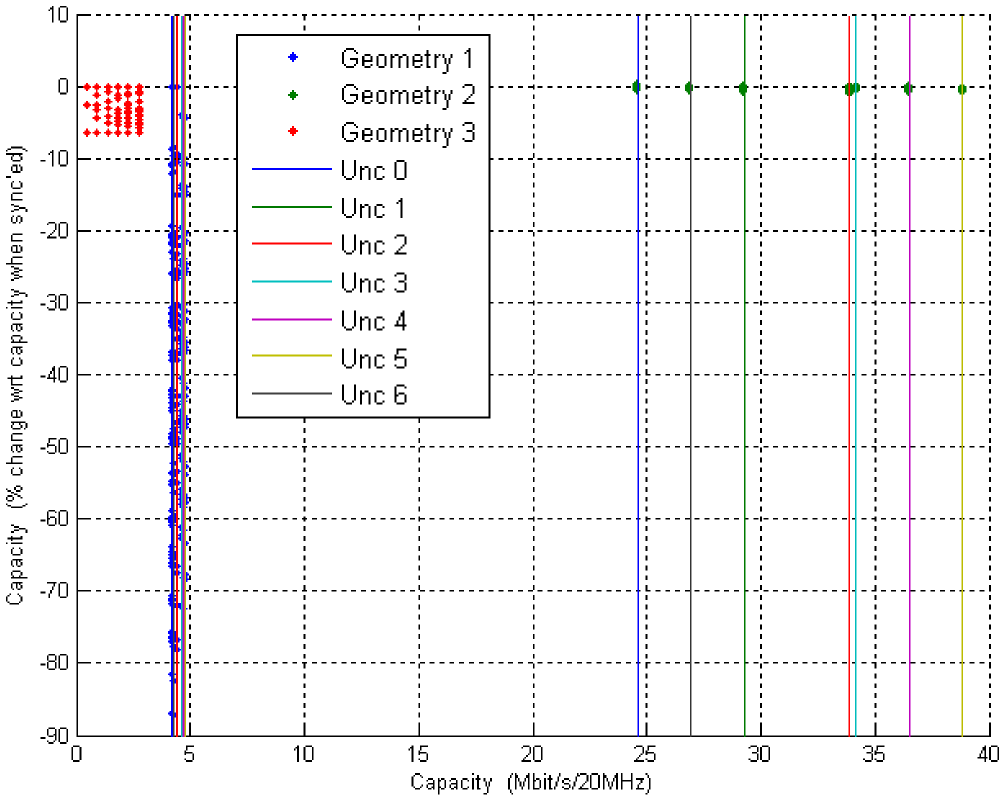

Figure 31: Effect of synchronisation compared to the same victim timeframe for the synchronised case, various geometries, macrocell. Geometries 1-3 are denoted with the same colours as previous figures, and noted in the legend.

Figure 32 and Figure 33 shows the effect of synchronisation for different geometries for femtocell and microcell environments respectively and demonstrate similar behaviour to the macrocell case.

In summary, in high SINR environments, the unsynchronised ACI modes have little performance degradation compared to the synchronised modes. However the SE is, in general less in the unsynchronised ACI modes and leads to lower available capacity, particularly in low SINR environments.

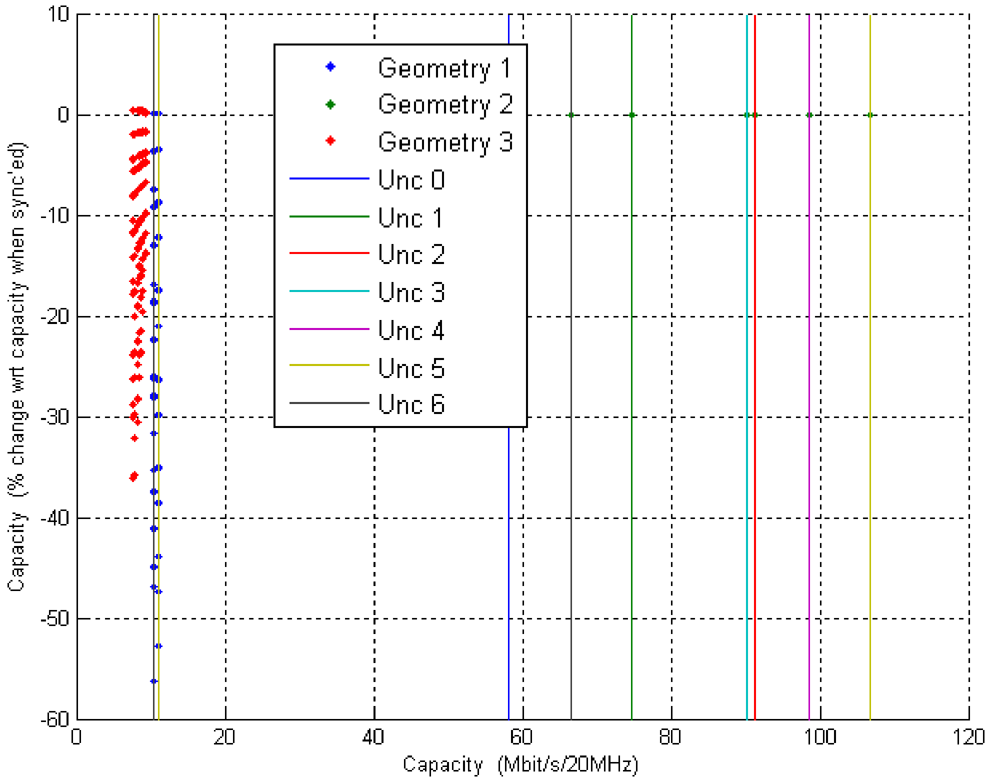

Figure 32: Effect of synchronisation, various geometries, femtocell

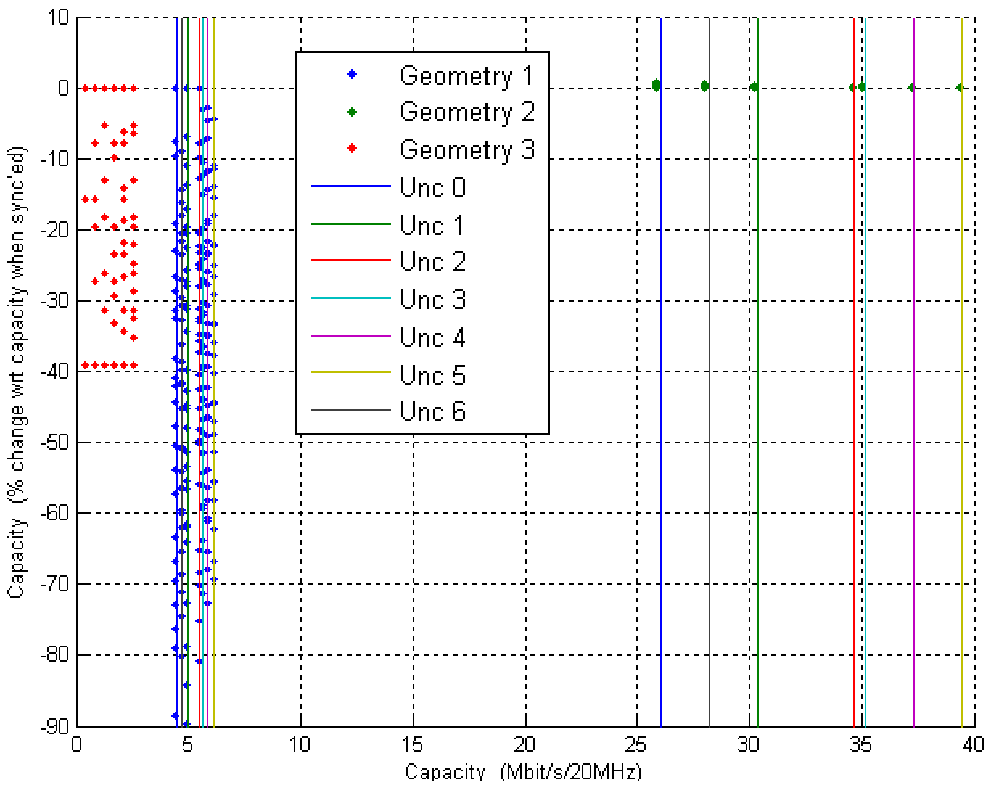

Figure 33: Effect of synchronisation, various geometries, microcell.

6.4 Impact of different channel bandwidths

Results in previous sections have been based upon both victim and interferer having channel bandwidths of 20MHz. In this section we determine the capacity impact when channel bandwidths of 5, 10 and 20MHz are used in both victim and receiver 20MHz blocks.

The 2nd adjacent channel uses the baseline ACS+10dB, and the 3rd adjacent channel is assumed to have an ACS of +200dB (i.e. essentially isolated). Hence this has the impact of rejecting any interference that is more than two channel bandwidths away from the victim. Own network adjacent channel interference would, in reality, contribute to part of the victim receive channel. In this study we have not considered the ACI caused by users on the same network, but restricted the interference analysis to the interference emanating from the other operator frequency block. For the purposes of this study, this means that with 5MHz channels any energy from a channel separated by more 10MHz is considered negligible. As was noted earlier, the values of baseline ACS values are thought to be conservative, and so this analysis is likely to indicate higher benefits of narrower channels than are likely to be achievable in practice.

Using the BEMs as defined in section 4, the transition or baseline limits overlap with more than one of the channels from the interferer's band. Energy leaking from interferers in nearby channels would accumulate in the victim channel. In narrower bandwidth channels, more of these would accumulate so as to increase the effective leakage into the victim band, and is modelled in this analysis. In reality, the BEM would define the maximum emission out of band and the total energy that would leak into the victim band would be less than the BEM would suggest. Using narrower channels will therefore have the effect of improving ACS, but increasing the ACLR.

6.4.1 Synchronised configurations

The absolute capacity of macrocells using masks with synchronised (upper part) and unsynchronised baseline limits (lower part) is shown in Figure 34. There is little difference between using synchronised or unsynchronised baseline limits, and the improved isolation of the narrower channels has only a marginal improvement.

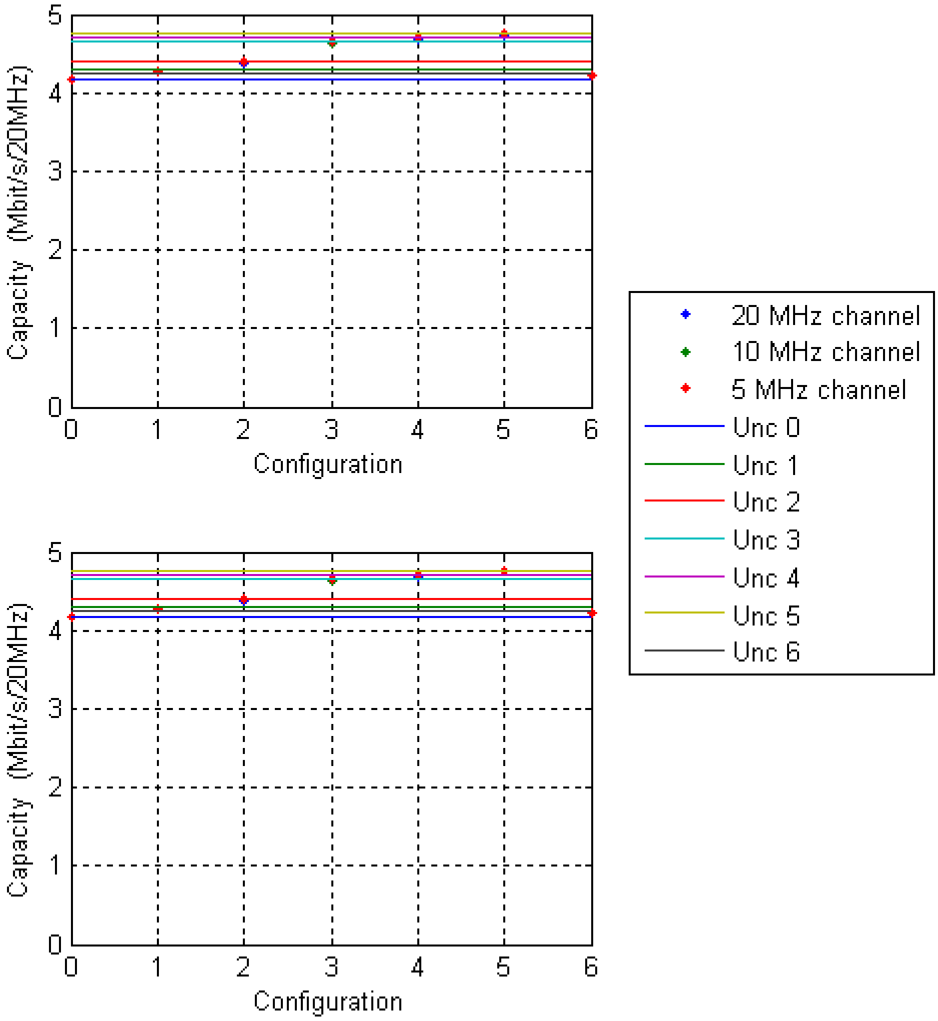

Figure 34: Capacity of 5, 10, 20MHz channels with synchronised configurations using synchronised baseline limits (upper graph) and unsynchronised baseline limits (lower graph), for geometry 1

The spectrum efficiency values for the three different geometries for the different channel bandwidths with unsynchronised baseline limits are shown in Table 16, Table 17 and Table 18 and show little variation with channel bandwidth. A key difference is where narrower channels permit SE to increase above 0, though still at a low value.

Table 16: Spectrum efficiency values for synchronised baseline levels for geometry 1 with different bandwidth channels

B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	0	0.23	0.26	0	4.17	(0,0)0
10	0	0.23	0.26	0	4.17	(0,0)0
5	0.11	0.23	0.26	0	4.18	(0,0)0

Table 17: Spectrum efficiency values for synchronised baseline levels for geometry 2 with different bandwidth channels

B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	1	1	2.2	2.2	24.55	(0,0)0
10	1	1	2.2	2.2	24.57	(0,0)0
5	1	1	2.2	2.2	24.58	(0,0)0

Table 18: Spectrum efficiency values for synchronised baseline levels for geometry 3 with different bandwidth channels

B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	0.21	0.23	0	0	2.75	(0,0)0
10	0.22	0.23	0.06	0	3.1	(0,0)0
5	0.23	0.23	0.09	0	3.26	(0,0)0

As can be seen with the geometry 3 case for the downlink non-clashed ACI mode, the narrowband channels have improved selectivity which improves the SINR sufficiently well to prevent receiver blocking in this poor SINR environment. A similar result occurs in the geometry 1 environment for the uplink clashed ACI mode – although the SE obtained is still less than half of the uplink non-clashed ACI mode.

The capacities for different timeframe configurations for each of the different geometry environments is shown in Figure 35. This demonstrates that the improved isolation of narrower channels can result in some capacity improvements in some low SINR environments – though these improvements are from a low baseline value.

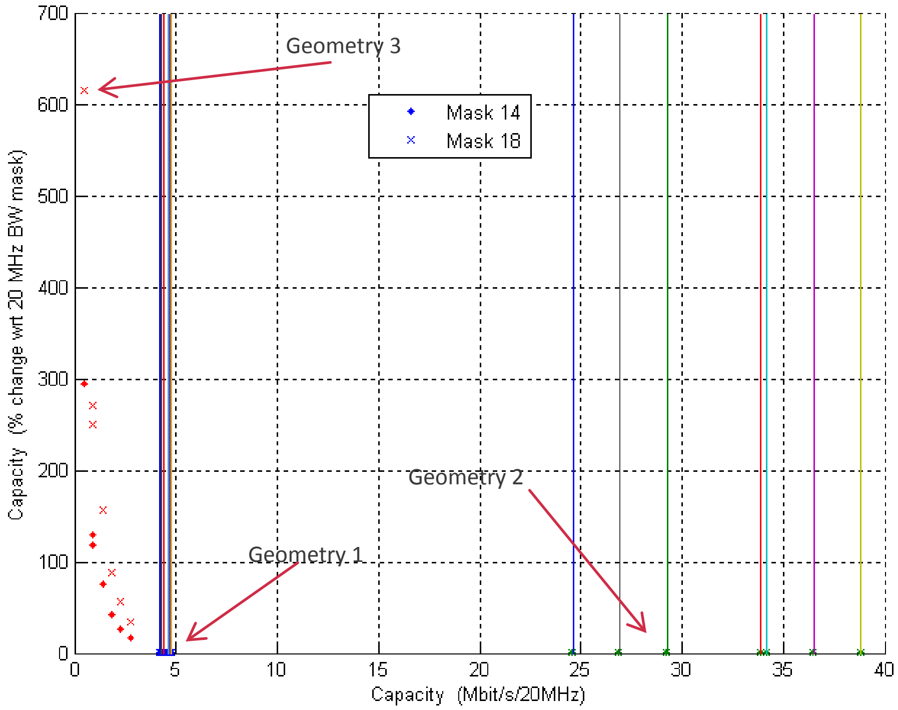

Figure 35: Relative capacity with 5MHz (mask14) and 10MHz (mask 18) channel bandwidths compared to 20MHz channel bandwidth for geometries 1, 2 and 3 for synchronised configurations (with unsynchronised baseline limits)

6.4.2 Unsynchronised configurations

The absolute capacities for unsynchronised configurations with unsynchronised baseline levels for geometry 1 are shown in Figure 36.

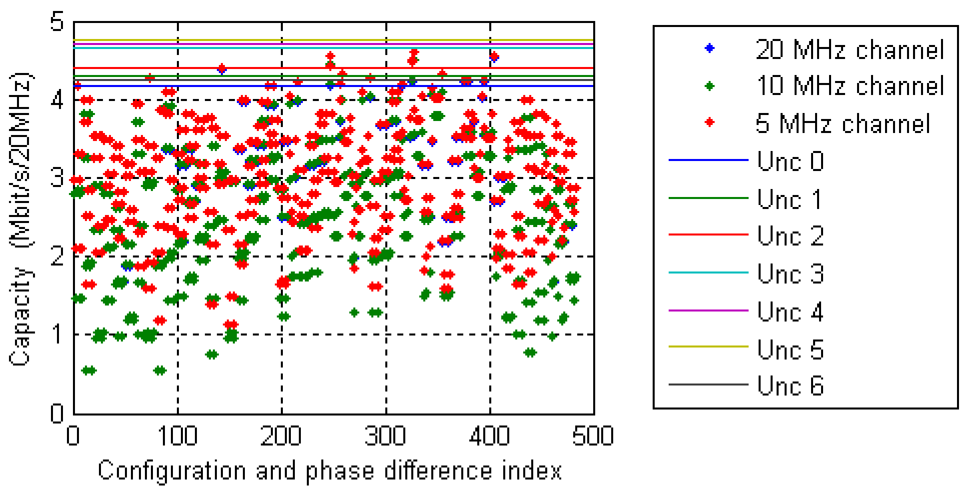

Figure 36: Capacity for unsynchronised configurations using channel bandwidths of 5, 10 and 20MHz bandwidths, using unsynchronised baseline limits from the band edge, geometry 1

The improved isolation of the narrowband channels results in higher throughput compared to the 20MHz channels. The results for the three different environment geometries is shown in Figure 37.

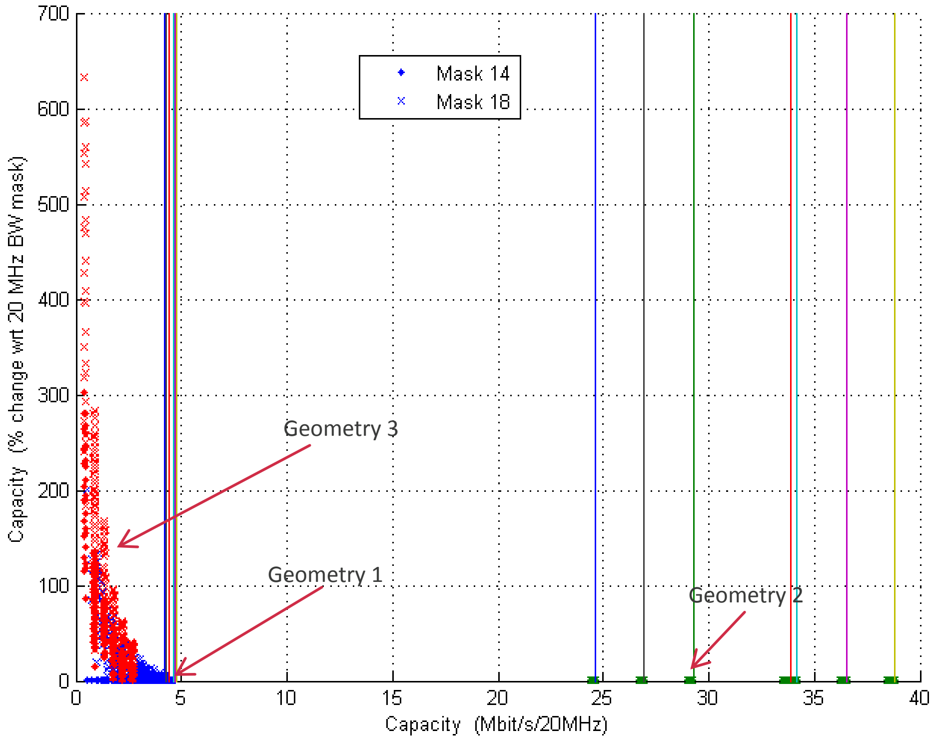

Figure 37: Relative capacity with 5MHz (mask14) and 10MHz (mask 18) channel bandwidths compared to 20MHz channel bandwidth for geometries 1, 2 and 3 for unsynchronised configurations (with unsynchronised baseline limits)

As before, the high relative gains occur in low SINR environments where any improved isolation is sufficient to increase capacity from a low baseline level. The improved selectivity with these narrower bandwidth channels is again evident – and has the biggest advantage in the low SINR environments.

It is therefore of interest to understand if the benefits of narrower channels persist if assumed ACS improvements of both UE and BS can be attained. These are plotted in Figure 38 with an assumed ACS improvement of 20dB at the base station and 10dB at the UE.

The SE values for the three different geometries corresponding to Figure 38 are shown in Table 19. These demonstrate that the improved selectivity of narrower channel bandwidths becomes much less important when the assumed ACS improvements are made, and that the greatest improvements are for the high interference environments, where the capacity % improvement is high (but from a low initial throughput). A particular benefit is to prevent the receiver blocking in the geometry 3 downlink non-clashed mode. Comparing Table 19 with Table 15 we can note that improvements in UE ACS coupled with the higher BEM suppression of the unsynchronised baseline limits work together to prevent downlink blocking without a gap between the frequency blocks.

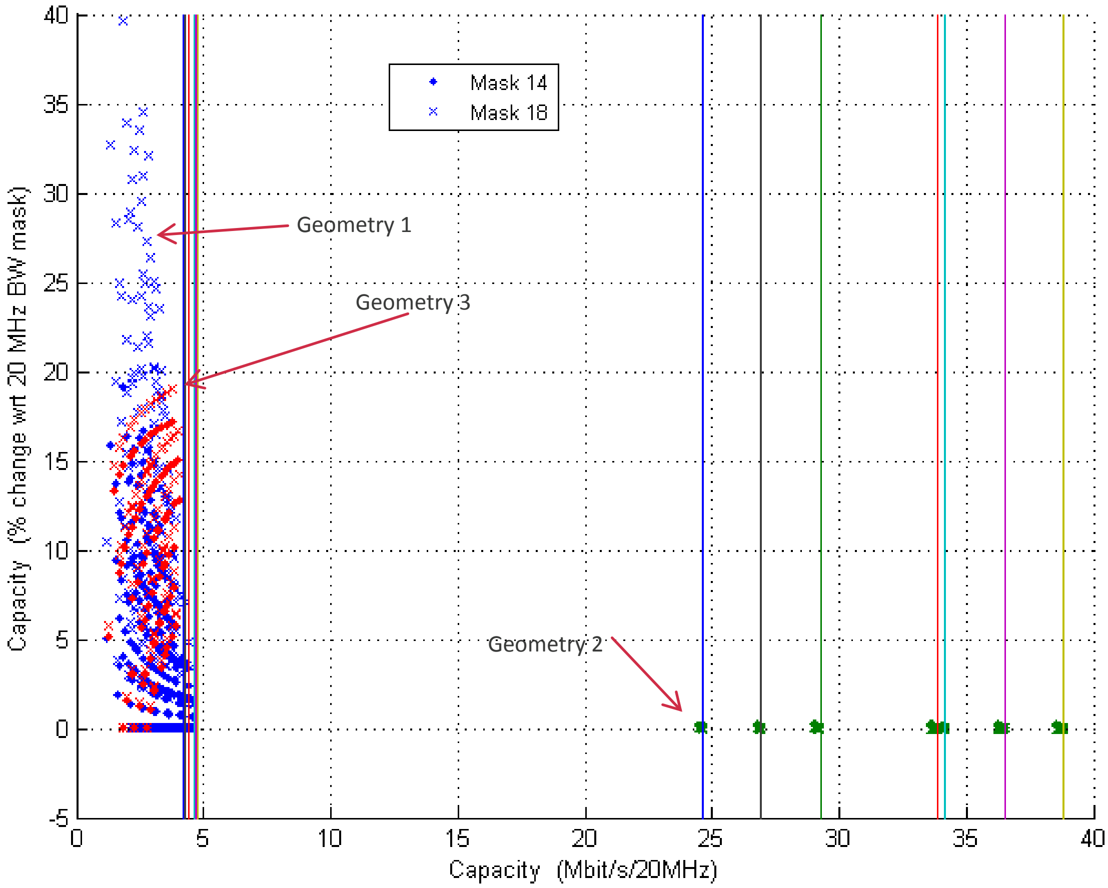

Figure 38: Capacity benefits of using 5 and 10MHz channels (compared to 20MHz channels) assuming ACS improvements of 20/10dB at the BS/UE.

Table 19: efficiency values for unsynchronised baseline levels for geometry 1 (top) to 3 (bottom) with different bandwidth channels and assumed ACS improvements of 20dB/10dB at the BS/UE

B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	0.13	0.23	0.26	0	4.17	(0,0)5
10	0.17	0.23	0.26	0	4.17	(0,0)5
5	0.21	0.23	0.26	0	4.18	(0,0)5
B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	1	1	2.2	2.2	24.47	(0,0)2
10	1	1	2.2	2.2	24.52	(0,0)2
5	1	1	2.2	2.2	24.48	(0,0)2
B/W (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
20	0.23	0.23	0.21	0	4.02	(3,5)0
10	0.23	0.23	0.25	0	4.54	(3,5)0
5	0.23	0.23	0.25	0	4.59	(3,5)0

In summary, using narrower bandwidths allows increased rejection of ACI at the receiver which improves the achievable capacity, although adjacent narrowband channels can result in increased OOB leakage. Improvements in ACS at the UE and the BS reduce the opportunity for narrower channels to benefit from this improved isolation. Based on the assumptions for the ACS and baseline limits, for good SINR environments the narrower channel bandwidths offer a small performance advantage.

6.5 UK Broadband (synchronised and unsynchronised) cases

UK Broadband has the opportunity of using 3 different masks:

- The 2007 mask with BS EIRP[12] of up to 59dBm/MHz
- The 2010 mask with BS EIRP of up to 53dBm/MHz
- The proposed PT1 masks for use in the 3.4 GHz band – this will be similar to the cases considered above – and referred to as the baseline case in the following.

Increased liberalisation could result in fixed, nomadic or mobile terminals being used. Therefore, it is of interest to explore differences on whether UK Broadband was to use a mobile TD-LTE handset or a CPE window ledge device to support broadband provision.

We have therefore established the following scenarios to analyse, based upon combinations of the above:

[12] In practice UK Broadband may not transmit at the maximum limit of their permitted EIRP and may adopt EIRP values similar to the PT1 baseline. This analysis assumes that they transmit at maximum permitted EIRP in order to compare the performance at their permitted maximum against PT1's assumed nominal baseline.

- UK Broadband as a victim system:
  - UKBB_V1: UK Broadband with an adjacent channel using the unsynchronised baseline masks (as proposed by PT1 and used in previous results), but with UK Broadband using window-ledge CPE equipment with an antenna gain of 5dBi[13];
  - UKBB_V2: UK Broadband with an adjacent system using the masks and base station transmit powers defined in the 2010 consultation, UK Broadband with standard TD-LTE UEs;
  - UKBB_V3: As UKBB_V2, but with window-ledge CPE user equipment;
  - UKBB_V4: As V1 but using standard UEs. This would be identical to the cases considered for the PT1 defined parameters in sections 6.1 to 6.4 above and so are not considered in this section.
- UK Broadband as an interfering system:
  - UKBB_I1: UK Broadband using the 2007 mask and BS transmit power levels using window-ledge CPE, victim system is a baseline TD-LTE system;
  - UKBB_I2: As UKBB_I1, but with standard TD-LTE UE's.
  - UKBB_I3: As UKBB_I1, but using 2010 mask and BS transmit power levels;
  - UKBB_I4: As UKBB_I2, but using 2010 mask and BS transmit power levels.

We will assess the impact if these systems are synchronised or unsynchronised by examining the spectrum efficiencies that would exist for each of the different ACI interference modes described in sections 2.1 and 5.4. Note that the spectrum efficiencies of only 2 of these modes are relevant for synchronised networks (SE_{UN} and SE_{DN}) but that all 4 ACI modes can occur with unsynchronised networks (with associated spectrum efficiencies SE_{UN}, SE_{UC}, SE_{DN}, SE_{DC}) and that the capacity achievable will depend upon the number of slot clashes of different types and other factors such as geometry, gap between frequency blocks, channel BW and assumed level of ACS.

6.5.1 UK Broadband as a victim

V1 case: UK Broadband using 2007 mask with window ledge CPEs and adjacent system using PT1 (baseline) parameters

The interference assessment method includes the receiver gain to increase the path loss (effectively increasing the cell range) when establishing the coupling loss for the scenario definition, and so the effect of increased CPE gain will not increase the sensitivity of CPE equipment to downlink interference, in this analysis.

The results comparing V1 case with different gaps compared to the zero gap case are shown in Figure 39 and Table 20. These results can be compared to the baseline parameter case of Table 10 to Table 12.

Compared to the SE values for the PT1 baseline case we can note:

- In geometry 1 and 2, the SE values are identical to 2 decimal places

[13] Ofcom has provided Real Wireless with a value to be assumed as the CPE antenna gain for any CPE equipment for the purposes of this analysis.

- In geometry 3, the SE_{UC} increases by 0.01bps/Hz for the zero gap case and reduces by the same amount for the 10MHz gap
- In geometry 3 the SE_{DN} reduces slightly and the SE_{DC} increases for gap sizes of 5 and 10MHz.

The small changes for geometry 3 in the downlink performance are owing to a result of the combination of increased desired BS EIRP. The CPE equipment additional gain contribution must be small since it doesn't result in a gain in case V2.

For the non-clashed ACI mode, this increased downlink throughput is less than the benefit achieved in the same geometry environment with improvements in ACS of 20/10dB for the BS/UE noted in Table 15.

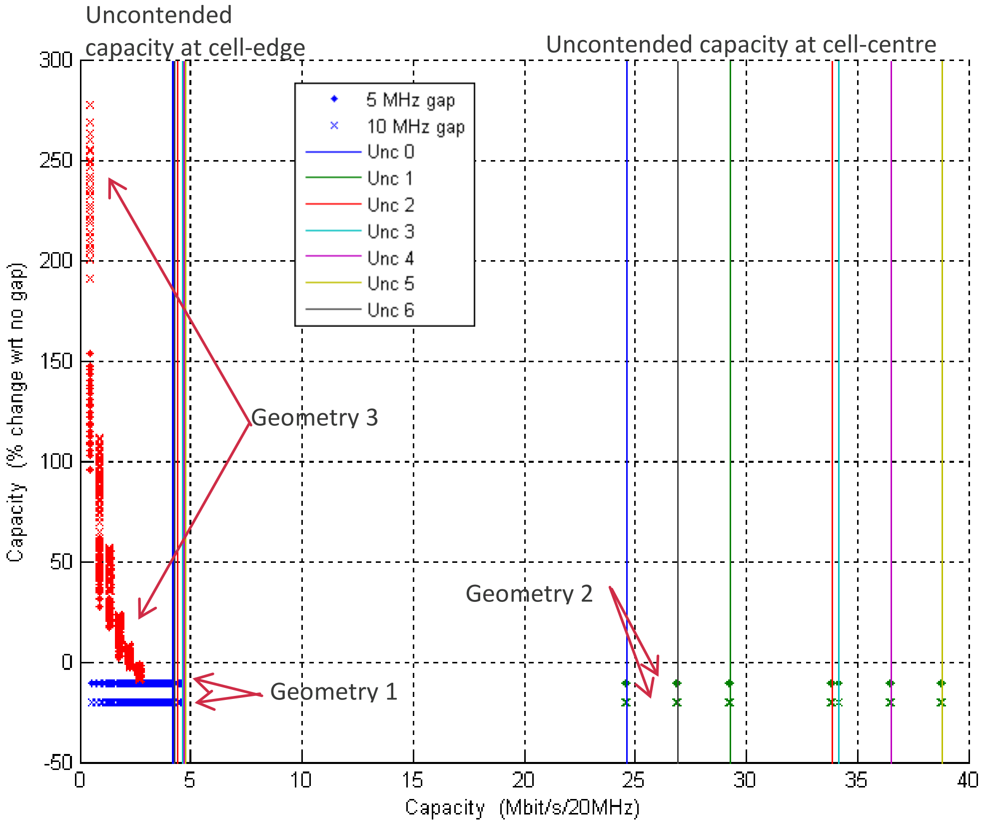

Figure 39: UK Broadband with gaps V1 (UK Broadband as the victim system with higher gain antenna windowledge CPEs). Synchronised and unsynchronised performance of 5MHz and 10MHz gaps compared to the zero gap case.

Table 20: Spectrum Efficiency values for different interference modes: UK Broadband, V1 case, geometry 1 (top), 2 and 3 (bottom).

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.26	0	2.79	(0,0)1
5	0	0.23	0.26	0	2.48	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.2	24.56	(0,0)1
5	1	1	2.2	2.2	21.86	(0,0)1
10	1	1	2.2	2.2	19.68	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0.22	0.23	0	0	2.75	(0,0)5
5	0.22	0.23	0.049	0.025	2.69	(0,0)5
10	0.22	0.23	0.098	0.059	2.64	(0,0)5

V2: UK Broadband using 2007 mask and TD-LTE UEs and adjacent system using 2010 masks

For this case, the victim UE has a gain of 0dBi, but the interfering base station has additional EIRP compared to the (PT1) baseline cases considered previously. The results are shown in Figure 40 and Table 21.

Compared to the SE values for the PT1 baseline case we can note:

- The spectrum efficiency values are identical to 2 decimal places for geometries 1 and 2.
- For geometry 3 there is a small increase in the downlink SE for both clashed and unclashed ACI modes with 5 or 10MHz gaps.

For geometry 3, the downlink improvements are due to the higher desired BS EIRP (2007 mask). The gain for the downlink non-clashed case is less than the V1 case owing to the increased EIRP of the interfering BS with the 2010 mask.

Table 21: Spectrum efficiency values: geometry 1, 2 and 3, UK BB V2

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.26	0	2.78	(0,0)1
5	0	0.23	0.26	0	2.48	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.2	24.55	(0,0)1
5	1	1	2.2	2.2	21.85	(0,0)1
10	1	1	2.2	2.2	19.68	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0.20	0.23	0	0	2.75	(0,0)5
5	0.21	0.23	0.04	0.025	2.64	(0,0)5
10	0.21	0.23	0.08	0.059	2.56	(0,0)5

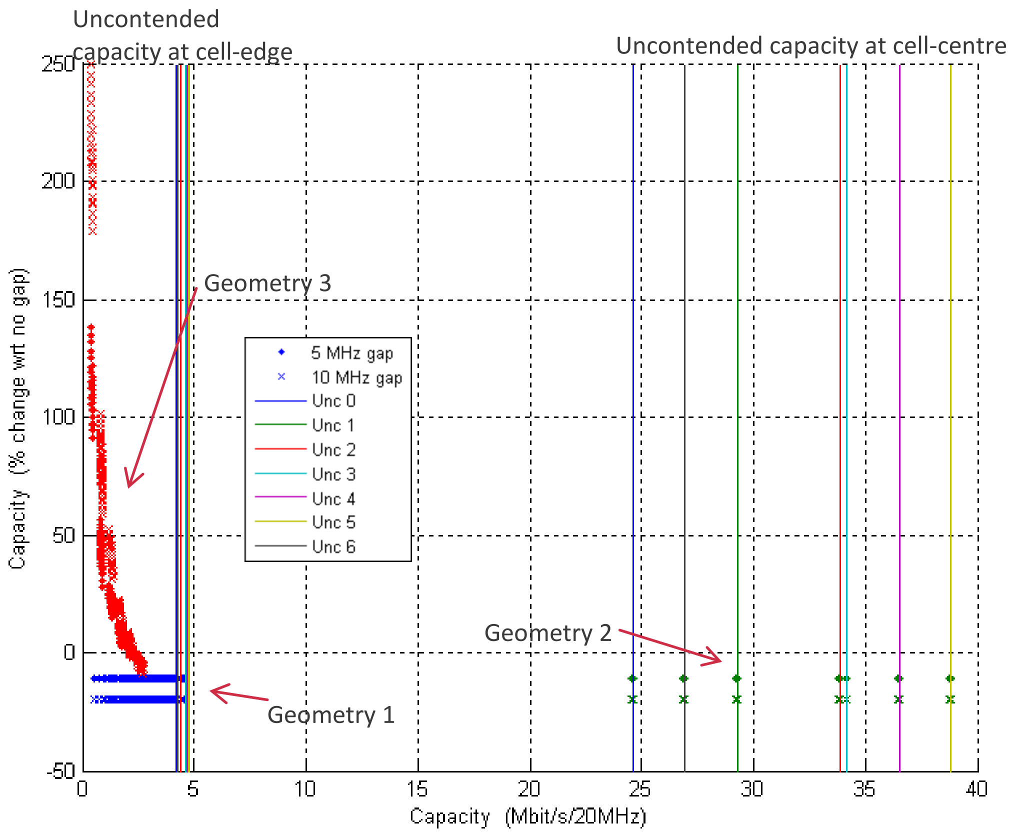

Figure 40: UK Broadband and the effect of mask gap, V2 (Adjacent system with 2010 mask adjacent- UK Broadband and standard TD-LTE UEs)

V3: UK Broadband with 2007 mask and window-ledge CPEs, and adjacent system using 2010 mask
This case combines the higher gain antenna of case V1, with the higher interferer EIRP of case V2 and the results are shown in Figure 41 and Table 22.

Compared to the SE values for the PT1 baseline case we can note:

- The spectrum efficiency values are identical to 2 decimal places for geometries 1 and 2.
- In geometry 3, the downlink SEs are greater than zero for gaps of 5 and 10MHz. and are identical to the V1 case with the same interferer BS mask.

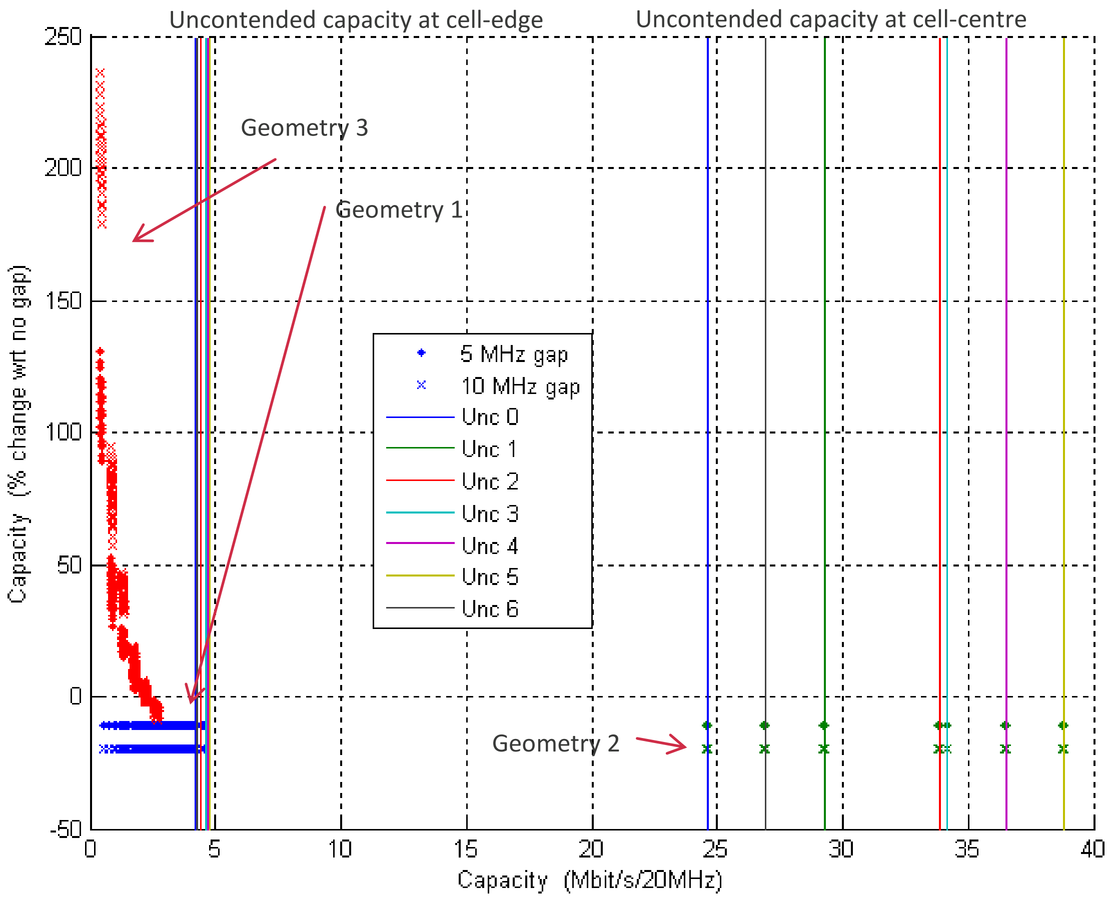

Figure 41: UK Broadband and the effect of frequency gap, V3 (adjacent system with 2010 mask - UK Broadband with window ledge CPEs)

Table 22: Spectrum efficiency values: geometry 1, 2 and 3, UK BB V3

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.26	0	2.79	(0,0)1
5	0	0.23	0.26	0	2.48	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	1	1	2.2	2.2	24.56	(0,0)1
5	1	1	2.2	2.2	21.86	(0,0)1
10	1	1	2.2	2.2	19.68	(0,0)1
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	0.21	0.23	0	0	2.75	(0,0)5
5	0.22	0.23	0.04	0.025	2.64	(0,0)5
10	0.22	0.23	0.08	0.059	2.56	(0,0)5

In summary, where UK Broadband is considered to be the victim, the results for geometries 1 and 2 are identical to the PT1 baseline case.

In the poor SINR geometry 3 case the differences from the PT1 baseline are marginal (less than 0.05bps/Hz). When combined with a 5 or 10MHz gap, the higher desired basestation EIRP allows the SE to increase above zero – but to a very low value. However, this spectrum gap reduces overall capacity in other environments owing to increase spectrum occupancy.

6.5.2 UK Broadband as a source of interference

This section looks at different options where UK Broadband's system is a source of interference to an adjacent operator.

I1: UK Broadband using the 2007 mask, window-ledge CPE, victim is a baseline TD-LTE system

The results of the I1 case comparing different gaps to the zero gap case are shown in Figure 42 and the spectrum efficiencies are shown in Table 23 (again this can be compared to the previous PT1 parameter simulations shown in Figure 21).

The SE values are again generally similar to the PT1 baseline case with the following exceptions:

- In geometry 1 the downlink non-clashed SE reduces by 0.01bps/Hz.
- In geometry 2 the downlink clashed SE reduces by 0.01bps/Hz for the zero gap case

- In geometry 3, the uplink clashed SE are reduced by approximately 0.05bps/Hz.

The downlink non-clashed and uplink clashed capacity reductions are due to modelling with the assumed higher interferer BS EIRP. The geometry 2 downlink clashed SE reduction is likely to be due to the increased interferer CPE EIRP.

The overall capacity changes are small.

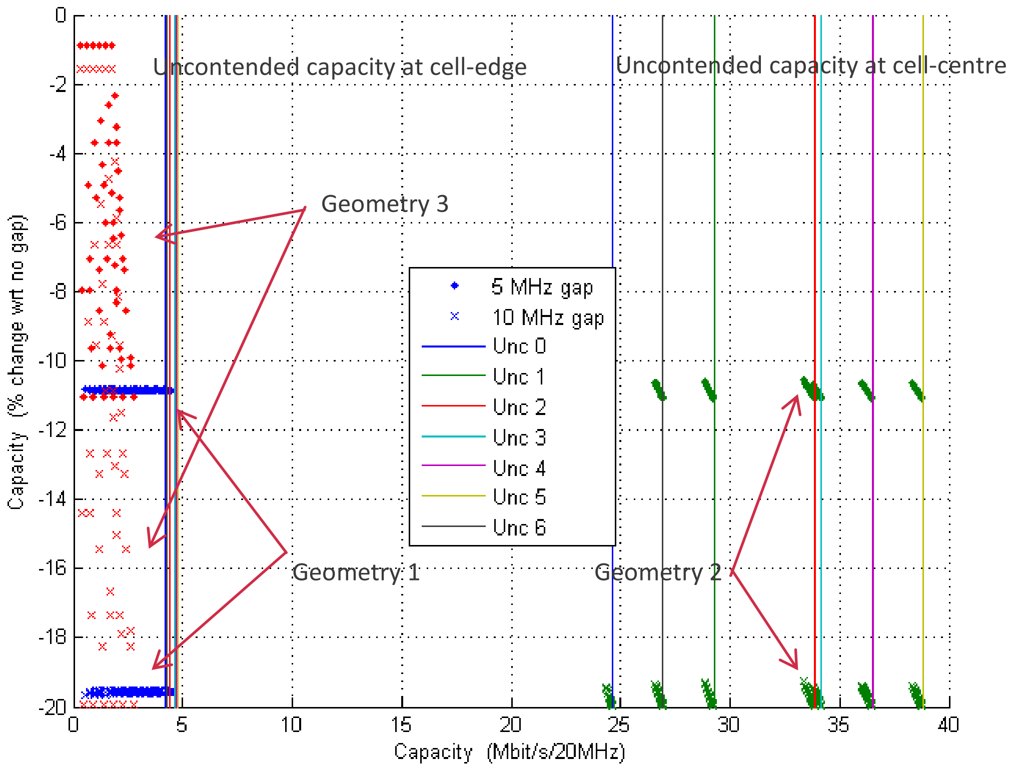

Figure 42: UK Broadband and the effect of mask gap, I1 (UK Broadband with 2007 mask and window ledge CPEs)

Table 23: Spectrum efficiency values - UK BB I1

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.25	0	2.77	(0,0)1
5	0	0.23	0.25	0	2.47	(0,0)1
10	0	0.23	0.25	0	2.23	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.1	24.33	(0,0)2
5	1	1	2.2	2.2	21.73	(0,0)2
10	1	1	2.2	2.2	19.61	(0,0)2
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0.15	0.23	0	0	2.75	(0,0)5
5	0.17	0.23	0	0	2.44	(0,0)5
10	0.18	0.23	0	0	2.2	(0,0)5

I2: UK Broadband with 2007 mask, standard UEs, and victim is a baseline TD-LTE system
The results of the I2 case are shown in Figure 43 and Table 24.

The SE values are again generally similar to the PT1 baseline case with the following exceptions:

- In geometry 1 the downlink non-clashed SE reduces by 0.01bps/Hz.
- In geometry 3, the uplink clashed SE reduces for all gaps by approximately 0.05bps/Hz.

Like the I1 case, these differences can be explained by the assumed increased interfering BS EIRP used in the simulation model.

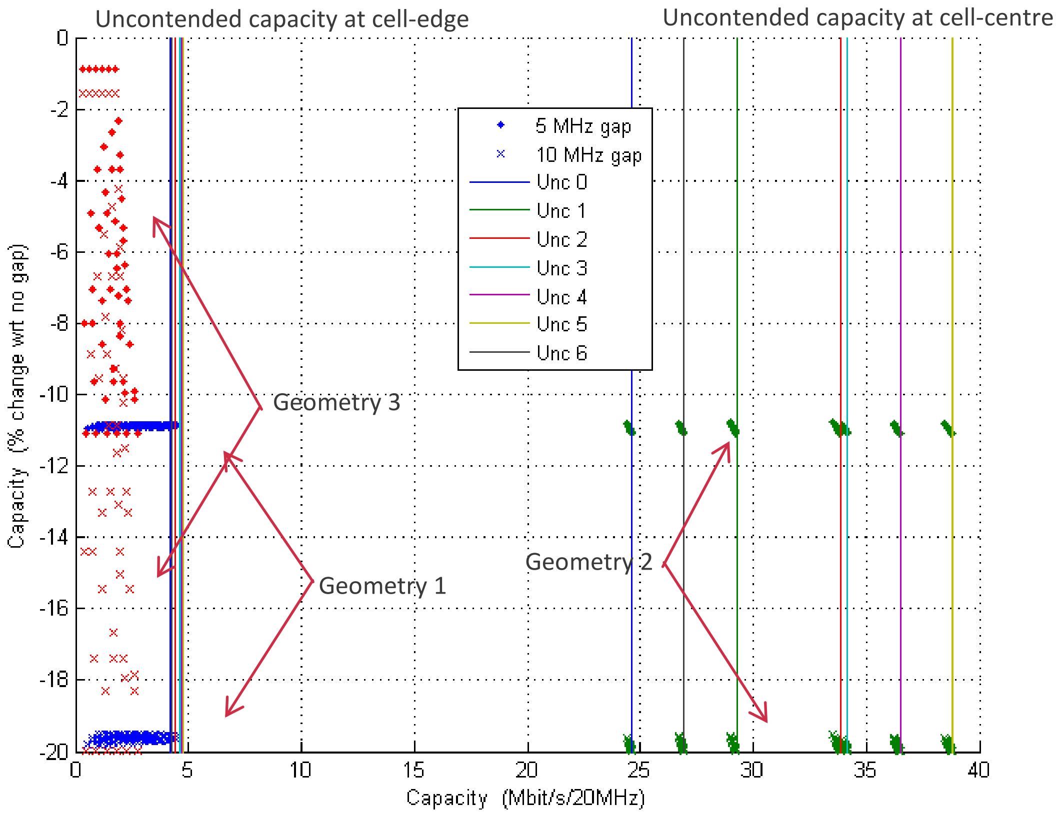

Figure 43: UK Broadband and the effect of mask gap, I2 (UK Broadband with 2007 mask and standard UEs)

Table 24: Spectrum efficiency values - UK BB I2

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.25	0	2.78	(0,0)1
5	0	0.23	0.25	0	2.47	(0,0)1
10	0	0.23	0.25	0	2.23	(0,0)1
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	1	1	2.2	2.2	24.44	(0,0)2
5	1	1	2.2	2.2	21.79	(0,0)2
10	1	1	2.2	2.2	19.64	(0,0)2
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	0.15	0.23	0	0	2.75	(0,0)5
5	0.17	0.23	0	0	2.44	(0,0)5
10	0.18	0.23	0	0	2.2	(0,0)5

I3: UK Broadband using 2010 mask with window ledge CPEs, and victim is a baseline TD-LTE system

This case combines the interferer using the 2010 EIRP (higher than the PT1 reference case, but less than the 2007 mask EIRP) with the higher gain CPE, where the victim uses the PT1 baseline parameters. The results of the I3 case are shown in Figure 44 and Table 25.

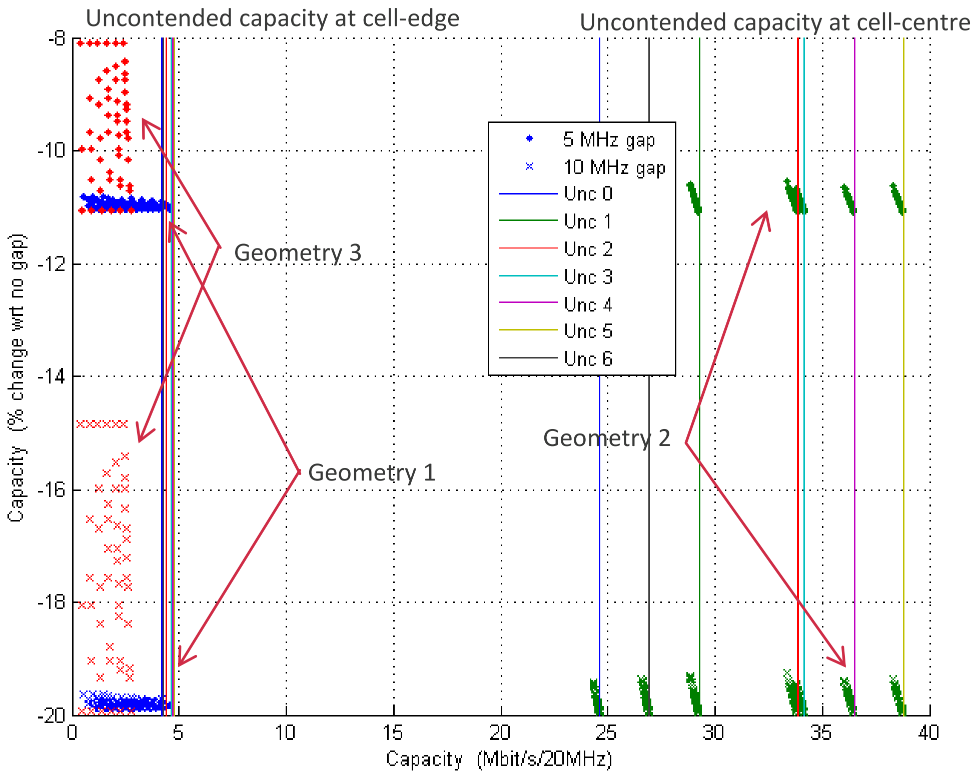

Figure 44: UK Broadband and the effect of mask gap, I3 (UK Broadband with 2010 mask and window ledge CPEs)

The SE values are again generally similar to the PT1 baseline case with the following exceptions:

- In geometry 1 the downlink non-clashed SE reduces by 0.01bps/Hz for no gap
- In geometry 2 the downlink clashed SE reduces by 0.1bps/Hz for no gap
- In geometry 3, the uplink clashed SE reduces for all gaps by approximately 0.01bps/Hz.

The geometry 1 and 3 capacity reductions can be explained by the increased interfering BS EIPR compared to the PT1 case. The impairments in the uplink clashed case are less than the higher interference EIPR used for I1 and I2 cases but more than the baseline PT1 case owing to the assumed higher BS EIRP with the 2010 mask. The downlink clashed impairment is because of the increased interfering CPE EIRP.

Table 25: Spectrum efficiency values: UK BB I3

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.25	0	2.77	(0,0)1
5	0	0.23	0.26	0	2.47	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	1	1	2.2	2.1	24.33	(0,0)2
5	1	1	2.2	2.2	21.74	(0,0)2
10	1	1	2.2	2.2	19.61	(0,0)2
Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0.2	0.23	0	0	2.75	(0,0)5
5	0.21	0.23	0	0	2.44	(0,0)5
10	0.21	0.23	0	0	2.2	(0,0)5

I4: UK Broadband using 2010 mask and standard UEs, and victim is a baseline TD-LTE system

The results of the I4 case are shown in Figure 45 and Table 26.

The SE values are again generally similar to the PT1 baseline case with the following exceptions:

- In geometry 1 the downlink non-clashed SE reduces by 0.01bps/Hz for no gap
- In geometry 3, the uplink clashed SE reduces for all gaps by approximately 0.01bps/Hz.

The geometry 1 and 3 capacity reductions are identical to the I3 case owing to the interfering BS using the 2010 mask. Using the standard UE bring the geometry 2 downlink clashed into line with the I2 case.

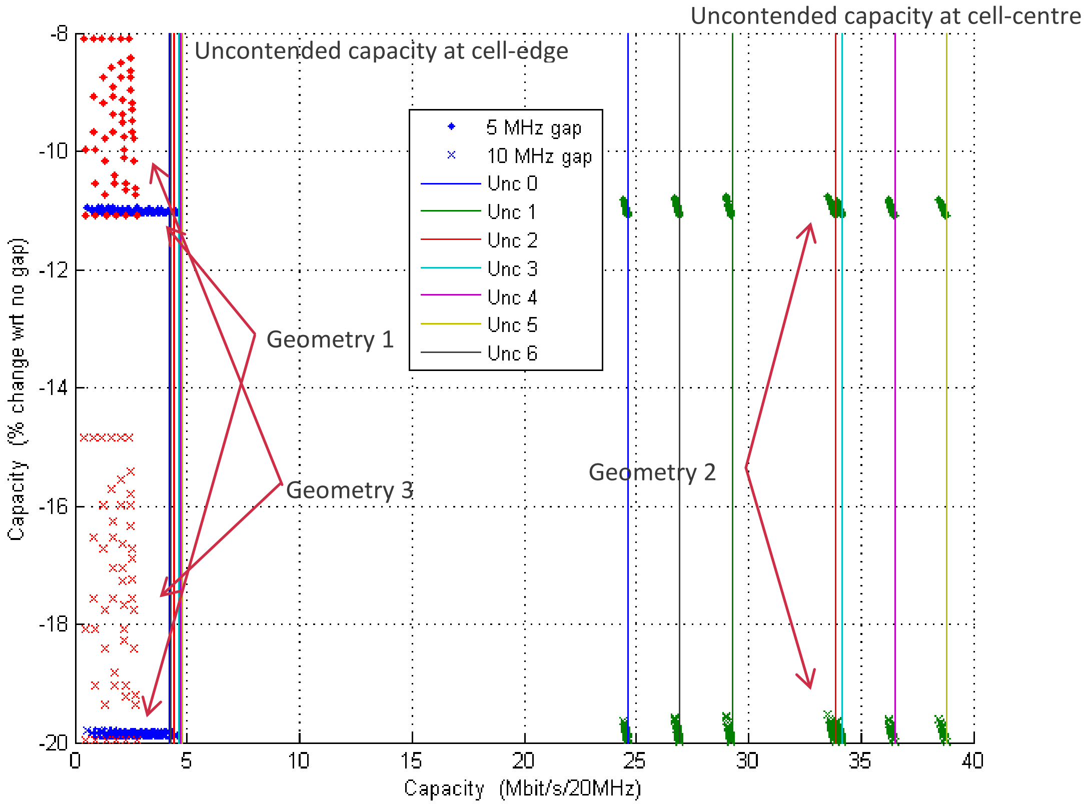

Figure 45: UK Broadband and the effect of mask gap, I4 (UK Broadband with 2007 mask and standard UEs)

Table 26: Spectrum efficiency values - UK BB I4

Gap (MHz)	SE_{UC} (bps/Hz)	SE_{UN} (bps/Hz)	SE_{DN} (bps/Hz)	SE_{DC} (bps/Hz)	Capacity (Mbps/20MHz)	Cfg and phase
0	0	0.23	0.25	0	2.78	(0,0)1
5	0	0.23	0.26	0	2.48	(0,0)1
10	0	0.23	0.26	0	2.23	(0,0)1
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	1	1	2.2	2.2	24.44	(0,0)2
5	1	1	2.2	2.2	21.79	(0,0)2
10	1	1	2.2	2.2	19.64	(0,0)2
Gap (MHz)	**SE_{UC} (bps/Hz)**	**SE_{UN} (bps/Hz)**	**SE_{DN} (bps/Hz)**	**SE_{DC} (bps/Hz)**	**Capacity (Mbps/20MHz)**	**Cfg and phase**
0	0.2	0.23	0	0	2.75	(0,0)5
5	0.21	0.23	0	0	2.44	(0,0)5
10	0.21	0.23	0	0	2.2	(0,0)5

In summary, where UK Broadband is considered to be the interferer, there are small negative impacts on the victim spectral efficiency. This is due to modelling with an assumed increased EIRP from either the base station or the CPE. The impairments are typically small and have a large relative change (approximately 25%) in poor (geometry 3) SINR environments. Some protection is provided by imposing a frequency gap, but this has a large negative impact in other environments owing to increased spectrum occupancy.

7. Options for mitigation

A range of options to avoid excessive ACI exist. A previous report by Real Wireless for Ofcom [24] noted these options as a series of increasing integration / co-ordination between operators, as shown in Figure 46, resulting in increased protection from interference.

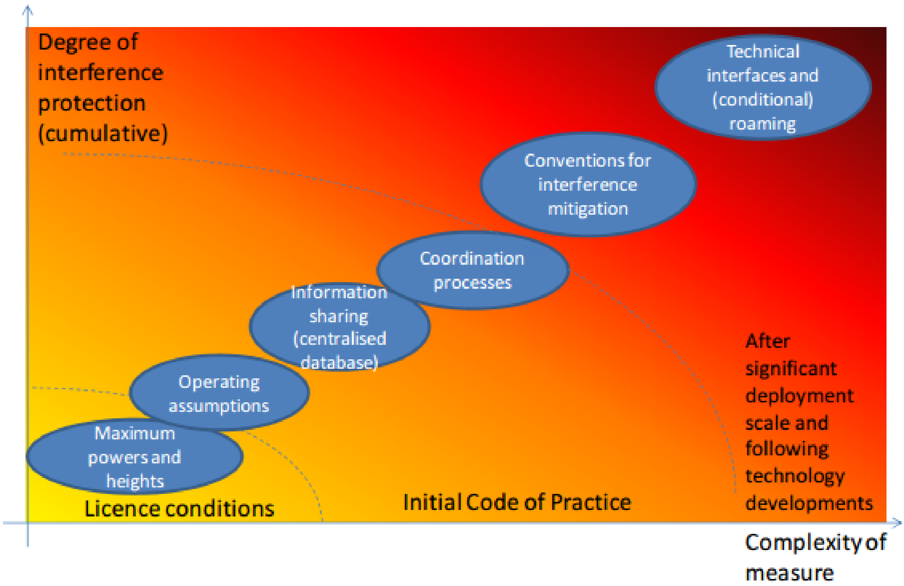

Figure 46: Degrees of interference protection measures to protect operators from ACI (taken from [24]).

Regulators can minimise the opportunity for any interference by introducing restrictive power limits and/or frequency gaps. Introducing these to protect against worst case interference scenarios results in inefficient spectrum use where the interference environment is less severe. Regulators, in general, can restrict the RF emissions of operators but cannot mandate that operators avoid ACI by their receiver design, site placement, or other inter-operator co-ordination measures.

Clearly operators can share information on their own networks, and increasingly mobile operators in the UK have done so to a great extent as part of site sharing arrangements. In addition, it is in the interests of operators to use best practice methods to maximise the performance of their own networks. Operators in the UK are able to establish suitable co-ordination processes where it is in their own best interests. The co-ordination processes identified in this report are within operators' capability to ensure efficient operation of their networks.

Several key issues have emerged in this report:

- In general, phase aligned time frames have superior performance in almost all of the interference scenarios studied – however for some particular cell locations (low SINR) unsynchronised frame configurations could increase capacity – though the impact in other parts of the cell would be negative;
- Phase alignment of different networks does not appear to present any great technical difficulty to modern networks, and is perhaps only a marginal addition

to what operators would seek to do for their own network performance management – however imposing this as a regulatory obligation could be seen as dictating network management methods to operators whose key task this is;

- Much of the mitigation to avoid ACI in synchronised networks is addressed by improving the receiver characteristics or attenuating sources of ACI. Benefits resulting from improving BS/UE ACS depends upon the interference geometry.
- The maximum EIRP of the 2007 and 2010 masks available for use by UK Broadband have a negative impact on ACI compared to the default EIRPs used elsewhere in this report.

The above factors suggest that operators who would seek to use unpaired spectrum in 2.3GHz and 3.5GHz would be motivated to achieve sufficient protection of their own networks to agree methods of co-ordinating themselves.

Dominant modes of interference identified in this report were the BS-UE and UE-BS interference cases. Co-locating base stations with similar EIRP, would mean that any downlink ACI would be suppressed by the UE ACS, and that ACI in the receiver would be significantly below the desired SINR. In addition, the interfering UE power control when it is close to the serving cell would also reduce interference into a co-located victim BS. Such mitigation actions may require operators to perform site engineering to avoid BS-BS interference, but this is an issue that is within the control of the operators, whereas UE geometry is not. This could involve additional filtering and aspects related to controlling intermodulation effects.

Another method which would reduce interference would be for operators to share RANs, though this may have non-radio related issues (including competition issues) that may preclude this mode of operation. Again, operators have demonstrated an ability to do this, it would reduce costs and ACI. This mode of operation may also simplify the need for each operators' network to be phase synchronised throughout the Core network – since by definition shared RANs would be phase aligned. Difficulty at boundaries between different geographical areas using different RANs may need improved co-ordination but this could provide a migration path until any difficulties in more complete phase alignment are addressed.

8. Summary

This report examines the impact on spectrum capacity when adjacent blocks of unpaired spectrum have different BEMs, synchronisation methods, frequency gaps between frequency blocks and different channel bandwidths. We examine the particular case of the incumbent operator, UK Broadband, who, owing to legacy issues, could use a range of different BEM and maximum transmit powers and both mobile and nomadic UEs.

By examining some challenging interference environments, we have established:

- **Effect of network synchronisation**: It is technically feasible for operators to phase align their networks if desired. This would impose an additional constraint on network co-ordination but is likely to be a small marginal impact since fine phase synchronisation across modern networks is becoming the norm. Maintaining phase synchronisation and use of a common time frame configuration as an adjacent operator removes 2 ACI interference modes and, in general, improves the capacity attainable. Mandating phase alignment may however preclude operators from using different time frame configurations which would constrain the balance of uplink/downlink capacity available for use by an operator. Imposing a regulatory requirement for synchronisation across the entire network could also impose unnecessary constraints in environments where such measures are not needed, for example for isolated cells. Given that the operators would have a mutual incentive to synchronise to the extent that their performance was enhanced, it may be unnecessary to require this of them via direct regulatory intervention.
- **Effect of geometry:** The level of interference varies across the cell. Some locations (typically remote from the desired transmitter and/or close to an interfering transmitter) exist where blocking (i.e. no communication would be possible) can occur. In some low signal quality (SINR) locations, more channel throughput may be possible with unsynchronised networks than with synchronised networks. This could occur when the interference due to a non-serving base station causes less interference to a victim UE than a nearby (unsynchronised) interferer UE transmitting to its own serving cell.
- **Effect of a frequency gap between operator blocks:** In some high interference environments a frequency gap (sometimes a gap combined with assumed ACS improvements) were able to prevent receiver blocking. However in nearly all the simulations the increased spectrum occupancy of the frequency gap reduced overall spectrum efficiency.
- **Effect of Narrower Channel Bandwidths:** Using narrower bandwidths allows increased rejection of ACI at the receiver which improves the achievable capacity, although adjacent narrowband channels can result in increased Out of Band leakage. Improvements in ACS at the UE and the BS reduce the opportunity for narrower channels to benefit from this improved isolation. For good SINR environments with improved ACS, the narrower channel bandwidths offer a small performance advantage (slightly less than 1%).
- **Effect of restricted power blocks:** By analysis, we have established that the effect of using a restricted block of 5MHz bandwidth is likely to have little reduction in interference caused to an adjacent operator using a wide bandwidth channel than a full power block. Modest technical improvements (ACS and ACLR) will have

a much greater impact. It is unlikely that using higher bandwidth restricted blocks would be acceptable.

- **Effect of BEM:** For synchronised networks, the PT1 recommended values of Out of Band limits [11] that are less restrictive for synchronised networks than for unsynchronised networks (which can simplify the transmitter). We found that restricting the synchronised baseline limit to the value of the unsynchronised limit has a small impact on capacity (less than 1%) when systems are synchronised.
- **UK Broadband:**
    - Where UK Broadband is considered to be a source of interference, there are small negative impacts on the victim spectral efficiency. This is due to increased EIRP from either the base station or the CPE. The impairments are typically small (in the order of 0.01bps/Hz) and have a large relative change (approximately 25%) in poor (geometry 3) SINR environments. Some protection is provided by imposing a frequency gap, but this has a large negative impact in other environments owing to increased spectrum occupancy.
    - Where UK Broadband is considered to be the victim, the results for geometries 1 and 2 are identical to the PT1 baseline case. In the poor SINR geometry 3 case the differences from the PT1 baseline are marginal (less than 0.05bps/Hz). When combined with a 5 or 10MHz gap, the higher EIRP allows the SE to increase above zero – but to a very low value. However, this spectrum gap reduces overall capacity in other environments owing to increase spectrum occupancy.

There is opportunity for operators to avoid the performance degradations identified above, such as co-locating base stations, synchronising appropriate network layers (such as macrocells) and improved filtering. Mandating such measures could prevent operators from deploying network nodes in some areas that may benefit from a different configuration from the rest of the network, or where establishing the same configuration could be problematic, but where any additional interference may have little impact.

9. Appendix 1: RF and related geometry parameters used in the simulation

In the main body of this report we identified three geometries of interest. This section discusses the parameters that have been used to characterise each of these geometries. Table 27 summarises the SINR values at cell-edge and at cell centre for each radio environment, geometry, and link.

Geometries 1 and 3 correspond to edge of cell conditions, and geometry 2 to the cell centre. The target SINR (i.e. the SINR without any ACI) was set according to the conditions expected to be experienced in the assumed radio environment. The cell-edge was selected to correspond to the 5th SINR percentile, for macro and femto radio environments, and to the 10th percentile, for micro radio environment. This selection was so that there is basic connectivity at the cell-edge. The coupling gain and SINR CDF curves from [25] for downlink, and from [26] for uplink have been used. The centre cell case uses the 95% SINR percentile value.

Table 27: SINR and coupling gain assumptions for the studied geometries

Radio environment	Cell-edge to cell centre coupling gain difference (dB)	Target SINR (dB)			
		DL	DL	UL	UL
		Cell-edge (Geometries 1 and 3)	Cell centre location (geometry 2)	Cell-edge	Cell centre location
Macro	41.6	-2.9	15.1	-1.3	10.4
Femto	25.9	2.0	42.6	5.1	23.3
Micro	53.4	-1.4	15.3	-1.8	11.6

The received signal strength, PRx, is calculated by:

PRx = PTx + Gt + Gr – PL, where PTx is the transmit power, Gt the transmitter antenna gain, Gr the receiver antenna gain, and PL the median path loss (all in dB)

The minimum coupling loss, MCL, is by definition:

MCL = PL - Gt - Gr

Thus the path loss value, PL, required in the simulation, so that minimum coupling loss occurs when the transmitter and receiver are in close proximity is given by:

PL = MCL + Gt + Gr, which is dependent upon the antenna gains. Table 28 summarises the antenna gain and other RF parameters for the baseline case (based on PT1 simulation parameters) and Table 29 summarises the UK Broadband specific parameters.

Table 28: Simulation parameters for simulations

Parameter	Macrocell Parameters	Femtocell Parameters	Microcell Parameters	Comment
EIRP Interferer	63dBm per 20MHz or 10MHz. 60dBm per 5MHz	20 dBm per 20MHz or 10MHz or 5MHz	41 dBm per 20MHz or 10MHz or 5MHz	TD02 Annex1rev1_Draft ECC report 3.5 GHz" - BEM definition draft for 3.5GHz, output from PT1 May 2nd Berlin Meeting
Antenna Gain (Victim)	17dBi	0dBi	6dBi	As above
Noise Figure	5dB (Macrocell noise figure)	13dB (femtocell noise figure)	8dB (microcell noise figure)	As above
ACS	Adjacent channel: 45dB Next Adjacent: Adjancent +10dB Next Next Adjacent: 200dB	Adjacent channel: 45dB Next Adjacent: Adjancent +10dB Next Next Adjacent: 200dB	Adjacent channel: 45dB Next Adjacent: Adjancent +10dB Next Next Adjacent: 200dB	Adjacent channel as Above. Next adjacent – input from Ofcom. Next Next total isolation assumed.
Own interference (rise above thermal)	2dB (H.Holma & A.Toskala, "WCDMA for UMTS: HSPA Evolution and LTE", John Wiley & Sons, 2010)	0.5dB (Femtocell indoors – only serving one user. RW assumption.)	1dB (Outdoor Microcell – below roof height. Interference reduced compared to Macrocell. RW Assumption.)	

Table 29 UK Broadband simulation parameters

Parameter	Value	Comment
BS tx EIRP	59dBm/MHz (2007 Mask) 53dBm/MHz (2010 Mask)	See [3] See [4]
BS Antenna Gain	17dBi	TD02 Annex1rev1_Draft ECC report 3.5 GHz" - BEM definition draft for 3.5GHz, output from PT1 May 2nd Berlin Meeting
Mobile Noise Figure	9dB	As PT1 (above)
CPE Noise Figure	9dB	Uses LTE chipset – similar to mobile UE
CPE Antenna Gain	5dBi	Input from UK Broadband on equipment parameters.
CPE EIRP	30dBm / 20MHz	This assumes 25dBm EIRP and the CPE antenna gain

The path loss between UEs was determined to be:

PL_UE1_UE2 = 40 + RX_ant_UE1 + RX_ant_UE2 + a

where 40 dB corresponds to 0.9 metres separation distance at 2.6 GHz, and a is a frequency adjustment factor for 2.6 GHz, given by:

a = 10*log10(2600/1800)

The path loss between base stations is summarised in Table 30. Note that the frequency adjustment factor, a, is used in some equations.

Table 30: Path loss between base stations (dB)

	Geometry 1	Note:	Geometry 2	Geometry 3
Macro BS to macro BS	30 + 2*RX_ant_mac + a + 2*20	1,3	90 + 2*RX_ant_mac + 6 + 7	
Femto BS to femto BS	40 + 2*RX_ant_fem + a + 4.8	2,4	40 + 2*RX_ant_fem + a + GainDiff	
Micro BS to micro BS	30 + 2*RX_ant_mic + a	1,5	22.7*log10(180) + 41.0 + 20*log10(2.6/5.0)	

1. 30 dB coupling loss is typical for co-located base stations, as reported by several operators [28], at 1800 MHz. 20 dB corresponds to the typical isolation provided by a single antenna pattern [29] and we have assumed that operators will take the necessary measures to provide this level of isolation for co-sited antennas from different operators.
2. 40 dB corresponds to 0.9 metres separation distance at 2.6 GHz
3. The methodology is similar to that of Section 10.2.1 of [28]. 90dB corresponds to 288 metres line of sight free space loss at 2.6 GHz, as in [28]. 6 dB corresponds to the reduction in effective antenna gain due to antenna tilt. From [28] an increase in loss of 7 dB is also assumed.
4. 40 dB corresponds to 0.9 metres separation distance at 2.6 GHz. GainDiff is the cell-edge to centre path gain difference, see Table 27.**Error! Reference source not found.**
5. Estimation using the LOS typical urban microcell Scenario B1 of [27] for a distance of 180 m, based on the maximum displacement between micro sites in the Manhattan grid, see [28].

Table 31: Path loss between base stations and user equipment

Radio environment	BS1: Victim, BS2: Interferer	UE1: Victim, UE2: Interferer		Path loss value	Comment in list below
Macro	BS1	UE1	Geometry 1	70 + RX_ant_mac + RX_ant_UE1 + a + GainDiff	1
			Geometry 2	70 + RX_ant_mac + RX_ant_UE1 + a	1
			Geometry 3	70 + RX_ant_mac + RX_ant_UE1 + a + GainDiff	1
		UE2	Geometry 1	70 + RX_ant_mac + RX_ant_UE2 + a + GainDiff	1
			Geometry 2	70 + RX_ant_mac + RX_ant_UE2 + a	1
			Geometry 3	70 + RX_ant_mac + RX_ant_UE2 + a + GainDiff	1
	BS2	UE1	Geometry 1	70 + RX_ant_mac + RX_ant_UE1 + a + GainDiff	1
			Geometry 2	70 + RX_ant_mac + RX_ant_UE1 + a + GainDiff	1
			Geometry 3	70 + RX_ant_mac + RX_ant_UE1 + a	1

Radio environment	BS1: Victim, BS2: Interferer	UE1: Victim, UE2: Interferer		Path loss value	Comment in list below
		UE2	Geometry 1	70 + RX_ant_mac + RX_ant_UE2 + a + GainDiff	1
			Geometry 2	70 + RX_ant_mac + RX_ant_UE2 + a + GainDiff	1
			Geometry 3	70 + RX_ant_mac + RX_ant_UE2 + a	1
Femto	BS1	UE1	Geometry 1	40 + RX_ant_fem + RX_ant_UE1 + a + GainDiff	2
			Geometry 2	40 + RX_ant_fem + RX_ant_UE1 + a	2
			Geometry 3	40 + RX_ant_fem + RX_ant_UE1 + a + GainDiff	2
		UE2	Geometry 1	40 + RX_ant_fem + RX_ant_UE2 + a + GainDiff	2
			Geometry 2	40 + RX_ant_fem + RX_ant_UE2 + a	2
			Geometry 3	40 + RX_ant_fem + RX_ant_UE2 + a + GainDiff	2
	BS2	UE1	Geometry 1	40 + RX_ant_fem + RX_ant_UE1 + a + GainDiff	2
			Geometry 2	40 + RX_ant_fem + RX_ant_UE1 + a + GainDiff	2
			Geometry 3	40 + RX_ant_fem + RX_ant_UE1 + a	2
		UE2	Geometry 1	40 + RX_ant_fem + RX_ant_UE2 + a + GainDiff	2
			Geometry 2	40 + RX_ant_fem + RX_ant_UE2 + a + GainDiff	2
			Geometry 3	40 + RX_ant_fem + RX_ant_UE2 + a	2
Micro	BS1	UE1	Geometry 1	53 + RX_ant_mic + RX_ant_UE1 + a + GainDiff	3
			Geometry 2	53 + RX_ant_mic + RX_ant_UE1 + a	3
			Geometry 3	53 + RX_ant_mic + RX_ant_UE1 + a + GainDiff	3
		UE2	Geometry 1	53 + RX_ant_mic + RX_ant_UE2 + a + GainDiff	3
			Geometry 2	53 + RX_ant_mic + RX_ant_UE2 + a	3
			Geometry 3	53 + RX_ant_mic + RX_ant_UE2 + a + GainDiff	3
	BS2	UE1	Geometry 1	53 + RX_ant_mic + RX_ant_UE1 + a + GainDiff	3
			Geometry 2	53 + RX_ant_mic + RX_ant_UE1 + a + GainDiff	3
			Geometry 3	53 + RX_ant_mic + RX_ant_UE1 + a	3
		UE2	Geometry 1	53 + RX_ant_mic + RX_ant_UE2 + a + GainDiff	3
			Geometry 2	53 + RX_ant_mic + RX_ant_UE2 + a + GainDiff	3
			Geometry 3	53 RX_ant_mic + RX_ant_UE2 + a	3

1. 70 dB is the minimum coupling loss for the macrocellular radio environment [28]
2. 40 dB corresponds to free space loss for 0.9 metres separation distance at 2.6 GHz
3. 53 dB is the minimum coupling loss for the microcellular radio environment [28]

In the simulation we assume that the user equipment have a power controlled EIRP value. The methodology for the power control is adopted from [29], Parameter set 1. The variable CLx-ile was adjusted for each radio environment so that the UEs transmit at full power at cell edge.

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