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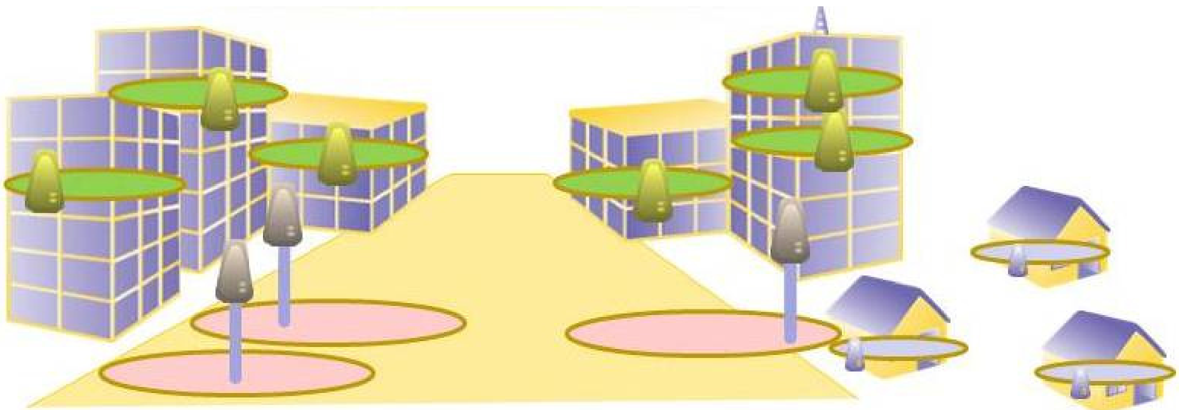
Final Report

Low-power shared access to spectrum for mobile broadband

Ofcom Project MC/073



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Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business. We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process. We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

We have specific experience in LTE, UMTS, HSPA, Wi-Fi, WiMAX, DAB, DTT, GSM, TETRA – and many more.

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1 Executive Summary

1.1 *UK spectrum at 2.6GHz is due to be auctioned shortly*

Ofcom is seeking to auction licences for the frequency band 2500 MHz – 2690 MHz (the “2.6 GHz” band) together with other bands, with the award of licences expected to take place in 2012. The band is arranged as 2500 – 2570 MHz (uplink) paired with 2620 – 2690 MHz (downlink), plus an unpaired portion 2570 – 2620 MHz. Although the award will be on a technology neutral basis, the expected technologies are LTE in frequency division duplex mode in the paired spectrum and WiMAX or TD-LTE in the unpaired spectrum.

This study is one element of analysis as input to Ofcom’s consultation on proposals for the award of the 800MHz and 2.6GHz bands. It relates to the potential to designate part of the spectrum for shared low-power use. In contrast to the remainder of the spectrum, this low-power shared access would involve multiple licensees operating in a concurrent, non-exclusive fashion across the same spectrum. The spectrum could be awarded on a reserved basis, where only low-power licensees would have access, or potentially on an underlay basis, where low-power shared access licensees use the same spectrum as a wide area (high-power) licence.

1.2 *Ofcom want to understand the technical issues associated with potentially introducing a low-power shared access channel in 2.6GHz spectrum*

Potential low-power shared access licences in the 2.6GHz band could exhibit particular interference challenges amongst licensees and to/from adjacent spectrum users for a number of reasons:

- Low-power applications may include femtocells and picocells, where deployment may be conducted by the end user or other untrained personnel, resulting in deployments of cells which may be suboptimum with regards to coverage or interference.
- The close proximity (in frequency and location) of high-power cells, which could cause substantial interference to the cells or user devices operating in the low-power spectrum.
- The presence of multiple concurrent operators in the same spectrum, who may or may not coordinate deployments amongst themselves.
- The presence of TDD systems adjacent (in frequency and location) to FDD systems in paired spectrum, and the presence of high-power radar systems adjacent to FDD systems in paired spectrum.

In order to limit these interference risks, the low-power licences will include appropriate technical conditions. The licensees might also enter into some form of technical agreement to further limit interference which may include, for example, additional technical restrictions, coordination procedures, shared databases, technical interfaces or roaming arrangements.

The aim of this study is to investigate the technical issues associated with low-power shared access in the 2.6 GHz spectrum, which could potentially open up the opportunity for more operators to compete for service provision to the benefit of citizens and consumers and for the spectrum to be used in a way which enhances the spectral efficiency and provides an opportunity for innovative business models.

1.3 Our approach and assumptions

While any award of low power shared access FDD licences in the 2.6GHz band are likely to be made on a technology neutral basis, we have assumed parameters associated with 3GPP specifications for FDD LTE Home eNode Bs (LTE femtocells) and Local Area Base Stations (LTE picocells) in the analysis presented in this study as these are the most likely devices to use a low power paired portion of the 2.6 GHz spectrum. However the findings are expected to apply broadly to other potential technologies.

The study results are structured around four sets of questions posed by Ofcom in the following areas:

- Power levels for providing suitable coverage for low power access points
- Co-channel interference both between low power access points and between low power access points and surrounding macrocells (in the case of underlay or hybrid access)
- Adjacent channel interference from the 2.6GHz TDD band and from S-band radar
- Trade-offs relating to spectrum quantity

Our approach has followed the following stages:

- Capturing LTE (both FDD and TDD)and S-band radar device parameters based on datasheets, 3GPP specifications and stakeholder discussions
- Modelling coverage for a range of indoor and outdoor deployments to determine maximum transmit power levels and define the likely worst case interference scenarios
- Modelling co-channel and adjacent-channel interference in the scenarios defined
- Based on the modelling results, forming conclusions on the trade-offs across different spectrum options for a low power shared access channel in terms of maximising capacity, restrictiveness of licence terms, limits on numbers of licensees and reliance on interference mitigation techniques and a common code of practice amongst licensees.

It should be noted that our study, being targeted at regulatory limits rather than typical service parameters, does not perform a full system level analysis of throughputs expected across low power cells. Instead it examines the worst case coverage and interference scenarios likely to be encountered and considers throughputs only for a single cell edge user to determine upper limits on likely licence parameters. Any potential operators bidding for a low power shared access licence should carry out a more detailed analysis to determine anticipated performance for their own target deployments and quality of service targets.

1.4 Our results support using a 2x20MHz dedicated channel or 2x20MHz hybrid channel for shared low power access at 2.6GHz

A low power shared access channel provides significant potential for making the most of capacity in the 2.6GHz band due to the improved spectrum efficiency density brought by:

- A higher cell density
- Improved signal quality (SINR) distribution in small cells relative to macrocells
- Being typically deployed in indoor environments where MIMO antenna technology works well

Our study has found that a low power shared access channel amongst multiple operators is feasible but will require appropriate restrictions to make best use of the capacity benefits of small cells in the areas of greatest demand.

The following approaches to spectrum allocation for a low power shared access channel were compared:

- A dedicated channel solely used by low power shared access networks. Here the options of a 2x10MHz or 2x20MHz channel are considered.
- An underlay channel where the entire low power channel allocation is shared with a wide area operator. Again the options of a 2x10MHz or 2x20MHz channel are considered.
- A 2x20MHz hybrid channel where 2x10MHz of the low power shared access channel is available on a dedicated basis and the remaining 2x10MHz is an underlay channel overlapping with a wide area operator.

We recommend that a dedicated 2 x 20MHz block at 2.6GHz would be the most attractive solution for a low power shared access channel. This is due to:

- 2 x 20MHz providing low power operators the opportunity to provide the best peak data rates and user quality of experience.
- The wider bandwidth improving the performance of dynamic scheduling as required to avoid interference from adjacent access points sharing the band.
- The larger spectrum allocation maximising the opportunity to gain the capacity and peak data rate benefits of small cells compared to wide area cells.

- Being the least complex option in terms of setting technical conditions on the licence compared to the underlay or hybrid spectrum allocation approaches which require a decision on the priority level between low power and wide area operators.

If a 2 x 20 MHz dedicated block cannot be provided, then a 2 x 20MHz hybrid band allocation with an overlap of 2 x 10 MHz with conventional high power use is also attractive as it allows three wide area 2 x 20MHz channels and a 2 x 20MHz low power shared access channel to be accommodated. However, more complex licence conditions would need to be applied to the low power shared access channel to minimise the impact on the overlapping wide area systems.

With either approach restrictions on transmit power, antenna height and a code of practice for sharing are recommended to ensure maximum benefit from this band.

Our headline conclusions are as follows:

- **A maximum EIRP of 30 dBm is recommended** – This will give adequate coverage in the majority of deployments likely to be targeted by low power networks, including outdoor cells providing indoor coverage. This level is in line with limits on Local Area Base Stations set by 3GPP and expected antenna gains of low power access points.

- **Interference amongst low power operators should be managed via a height limit on outdoor deployments and a code of practice ensuring cooperation on interference mitigation techniques and overlapping deployments** – Mitigating interference amongst small cell operators sharing spectrum via separation distances alone is not thought to be practical based on the results of our co-channel interference assessment. Instead cooperation on interference mitigation techniques amongst operators and a height limit on outdoor deployments are likely to be more effective as indicated by our findings as follows:

    - Interference mitigation techniques centred around dynamic scheduling and power control are central to LTE FDD small cell technologies and will likely need to be relied upon in a low power shared access channel. These have already been investigated by 3GPP and Femto Forum with promising results in both theory and practice. To ensure that capacity from this channel is optimised a code of practice amongst operators which aligns resource allocation sizes, scheduling approaches and avoidance of overlap on common control channels is recommended. Enforcing specific interference mitigation techniques within the licence terms is thought to be too restrictive and risks limiting technical innovation.
    - Technically, there is no specific limit on the number of operators that could be licensed to use the shared access channel. Interference mitigation techniques need to operate successfully given the limiting case of an adjacent cell from another operator and this will occur even with two operators in the band. From a technical viewpoint, we see no reason why 7 overlapping networks in a 2x10MHz channel and 14 overlapping networks in a 2x20MHz channel could not be accommodated assuming that overlap of common control channels is the limiting factor and frequency partitioning is applied. This does not necessarily translate to a limit on the number of licensees as not all operators will deploy in the same areas and operators may find other solutions such as conditional roaming. Therefore the

decision as to the number of licensees in the band is more of a policy decision based, for example, on the number of operators it would be practical to expect to work cooperatively to produce a code of practice.
  - A restriction on outdoor antenna height will help to reduce the range of interference from outdoor cells. Interference ranges rise more rapidly as the antenna heights become significantly above the heights of surrounding buildings. It is therefore recommended that the maximum height is set at or a little above the typical height of residential buildings. At around 12 metres this would be consistent with existing street furniture deployments by operators.

- **An underlay approach presents interference and coordination challenges, so we recommend a hybrid approach if dedicated 2x20 MHz spectrum is not feasible** – Setting the licence terms on an underlay channel for low power shared access networks will be challenging as this will need to offer adequate protection to the wide area operator but also ensure that low power shared access networks do not have prohibitively small service levels in areas with existing wide area networks or where a new wide area network is deployed. The hybrid option is considered a better choice as this maintains the opportunity to support three wide area operators with 2x20MHz allocations and also provides a dedicated portion of spectrum for low power networks to fall back on in areas where deployments with the wide area networks overlap. It also has benefits in terms of managing overlap on the common control channels between wide area and low power networks.

- **Positioning the shared channel at the upper end of the FDD block could assist high power macrocells in meeting radar protection requirements, although further study is needed on the impact of emissions from low power access points –** By positioning low power devices at the upper end of the paired 2.6 GHz spectrum, an additional frequency separation is introduced between high power macrocells and radar receivers above 2.7GHz. Although this study has not examined this case explicitly, this would seem helpful in providing an additional 'guard band' between high power transmissions and the radar systems. However, in some circumstances low power access points may have relaxed emission specifications, which could create noise rise to radar receivers and we recommend that this situation is examined explicitly. Our findings in terms of interference into the FDD band show:
  - Interference from S band radar to FDD low power network mobile devices is likely to be no worse than that for FDD macrocell mobile devices.
  - Interference from TDD macrocells to FDD low power access points may be less than interference to FDD macrocells due to the lower antenna gain likely in low power access points. However, some coordination between TDD and FDD low power operators will be needed in public areas with overlapping deployments to ensure separation distances and/or appropriate power limits are applied.
  - Widespread indoor usage of low power access points may provide some additional isolation from adjacent channel interference due to building penetration losses.
  - On balance, positioning the low-power shared channel at the top end of the FDD band seems a sensible choice, but the case is not overwhelming.

1.5 Answers to Ofcom's study questions

In response to the specific study questions posed by Ofcom the following subsections summarise our findings.

1.5.1 Trade-offs relating to spectrum quantity

Study Question	Summary answer
1.9 For both the designated spectrum approach and the underlay approach, assess the capabilities of the spectrum to support several concurrent low-power shared access operators if the quantity made available is: a) *2 × 10 MHz* b) *2 × 20 MHz* *1.10 In particular, the assessment should include:* • *what traffic capacity could be supported;* • *how many concurrent low-power operators could be accommodated (noting the working assumption of eight licensees); and* • *what is the impact of the spectrum quantity on an operator's frequency re-use within a geographic area.*	Smaller cells provide significant capacity improvements due to: • A higher density of cells • An improved SINR distribution across the cell • Improvements in performance of technologies such as MIMO in indoor environments where small cells are more prominent. 3GPP simulation results show a x2.3 improvement in cell spectrum efficiency and x54 improvement in cell spectrum efficiency density between indoor hotspots and urban macrocells. The uncoordinated nature of small cells will cause reductions in capacity due to interference. However, if power control and smart scheduling are applied the maximum capacity can be shared amongst the number of contending uncoordinated access points (which will increase with the number of operators). If operators of low power networks are willing to accept throughput degradations approximately proportionate to the number of contending access points there is no technical reason why 7 overlapping deployments for a 10MHz channel and 14 overlapping deployments for a 20MHz channel could not be accommodated assuming that frequency partitioning is applied. This does not translate to a limit on the number of low power operators as not all deployments will overlap. We recommend a 2x 20MHz dedicated band for low power shared access as this: • Maximises potential data rates and capacity gains from low power networks • Would give smart scheduling the maximum opportunity to work well due to the large number of resource blocks, minimising the

	associated overheads • Would be the least complex in terms of technical conditions on a shared access licence
1.11 What techniques are available for licensees to manage the spectrum sharing between low-power operators?	There are active discussions in 3GPP on interference mitigation techniques for low power access points. The main areas being standardised to facilitate interference mitigation include: • Radio environment monitoring (REM) by HeNBs • Use of UE measurements in combination with REM to schedule resources to avoid interference • Power control based on the above measurements • A power cap of 10dBm when an overlapping macrocell is detected. • Conditional roaming in cases of extreme interference

1.5.2 Power levels for providing suitable coverage for low power access points

Study question	Answer
1.13 What minimum power level would be needed in order to provide coverage in the following example scenarios: • *Indoor office environment* • *Indoor public area* • *Residential (home femtocell)* • *Campus / business park (including use of external base station antennas)*	***Indoor office environment**:* An EIRP of 27dBm (i.e. In line with 3GPP Local Area Base Station specification and a 3dBi antenna gain) easily provides maximum data rates at the range to cover a single floor medium sized office and could be backed off to 18dBm. ***Indoor public area:*** An EIRP of 27dBm l (i.e. In line with 3GPP Local Area Base Station specification and a 3dBi antenna gain) would provide maximum data rates at the range to cover a single floor medium sized shopping centre (8,000 m²). In practice operators are likely to deploy more than one access point for capacity reasons in the office and public areas and so the transmit power levels here could potentially be backed off even more. ***Residential (home femtocell):*** *A*n EIRP of 20dBm provides a range of 16.5m at a max data rate of 91Mbps downstairs and 6.66m upstairs. This is

	sufficient downstairs for most houses but may start to limit coverage at higher data rates upstairs in some larger properties. ***Campus / business park (outdoor access point):*** ***Outdoor users*** – An EIRP of 29dBm on the low power shared access channel (i.e. in line with the 3GPP Local Area Base Station transmit power specification) would provide maximum data rates to outdoor users at typical microcell ranges (i.e. 100m) ***Indoor users*** - *A*n EIRP of 29dBm would require the target cell edge data rate to be backed off to 20Mbps (in 10MHz) to achieve the target microcell range of 100m and good indoor penetration. Coverage is limited by the indoor penetration of outdoor base stations. Recommend the maximum EIRP is set at 29dBm in line with this.
1.14 What depth of in-building coverage would be provided by an outdoor base station operating at 20dBm e.i.r.p. in the campus scenario, assuming a mast height of 5m or below?	Both 20dBm EIRP and 29dBm EIRP were examined as a maximum transmit power of 24dBm and an antenna gain of 5dBi for outdoor local area base stations are discussed in 3GPP and were also highlighted by stakeholders. 29dBm is required to achieve maximum data rates into the building at ranges from the building of more than 20m. For direct angles of arrival, like a campus scenario, at 29dBm EIRP and a distance of 50m from the building an in building depth of 16m is achieved for peak data rates in 10MHz and 10m for peak data rates in 20MHz. At 100m from the building this is reduced to negligible levels of 1m. For an oblique angle of arrival, like a street scenario, the indoor penetration is worse. At a 50m perpendicular distance from the building and 45 degree angle of arrival the in building depth for maximum data rates at 10MHz is 6.5m. At 20MHz the range from the building needs to be reduced to 45m to get just 2m of indoor coverage

1.5.3 Co-channel interference both between low power access points and between low power access points and surrounding macrocells

Study question	**Answer**
1.17 What is the minimum separation distance between buildings where low-power networks can be deployed without operator coordination becoming necessary?	For the scenario analysed of two low power access points in adjacent houses, the minimum separation distances will be upwards of 23m assuming data rates of at least 10Mbps are targeted in interference free conditions and a throughput degradation of less than 50% is required at the cell edge. This will increase for more interference sources. With the use of a dynamic scheduler that identifies interference and targets un-contended resource blocks a zero separation distance can be achieved but the data rate will be degraded in proportion to the number of contending access points. In the example of 2 access points no separation distance would be needed if a degradation in throughput of 50% is acceptable at the cell edge.

1.18 What limits should placed on the maximum height of outdoor antennas, for the purpose of limiting interference to other low-power networks (our working assumption is 5m)?	Interference increases significantly once the antenna height is beyond the height of the surrounding buildings. Assuming a limiting case of a residential scenario this would suggest a limit of 10-12m.
1.19 In the case of underlay low-power networks, what restrictions on antenna placement would be needed in order to minimise interference to the co-channel wide-area network, e.g. minimum distance from macrocell antennas, restriction to indoor placement?	A much larger distance is required to mitigate uplink interference to the macrocell base station than to macrocell UEs. Also the impact of uplink interference is to desensitise the macrocell base station for all UEs and so the impact is more significant to the entire cell than the downlink interference case. The exception to this is in the “visitor problem” where a macrocell UE is in the same room as a low power access point. This may require conditional roaming in cases of extreme interference. In the analysed scenario of a single indoor UE from a low power network operating on the edge of coverage a separation distances in the range 800m-3.2km would be required if a less than 40% throughput degradation is required. This could be reduced to 400-1.5km if a 10dBm power cap is applied to the UE when an overlapping macrocell sharing the channel is detected. As previously described a zero separation distance is feasible if smart scheduling and a degradation in edge of cell throughput in proportion to the number of networks contending for resources is acceptable.
1.20 Based on an assumption that some low-power operators will deploy outdoor antennas on low-power networks, what is the minimum distance before the frequency (or resource blocks) can be re-used by indoor networks? What is the minimum separation distance for deployment of co-channel low-power indoor and outdoor networks without operator coordination becoming necessary?	The scenario analysed looks at interference between a single outdoor low power network and single indoor low power network. The separation distances required to minimise downlink interference are much larger than those on the uplink. In the scenario analysed, separation distances in the range 100m-600m are required to minimise interference on the downlink depending on the target throughput and acceptable degradation level if power control is applied at the aggressor. As previously described a zero separation distance is feasible if smart scheduling and a degradation in edge of cell throughput in proportion to the number of networks contending for resources is acceptable.

1.5.4 Adjacent channel interference from the 2.6GHz TDD and S-band Radar

Study Question	Summary answer	
1.23 What would be the impact of interference from adjacent WiMAX or TD-LTE networks in the unpaired band on the operation of a low-power network?	**10 MHz (16 Mbps) TDD –FDD (Indoor)**	**20 MHz (32 Mbps) TDD – FDD (Indoor)**
	For 20% throughput degradation 20-120m separation depending on transmit power (9 to 24dBm) For 50% throughput max degradation 10-50m separation depending on transmit power (9 to 24dBm) Some coordination between TDD and FDD low power operators will be needed in public areas.	For 20% throughput degradation 18-100m separation depending on transmit power (9 to 24dBm) For 50% throughput max degradation 8-43m separation depending on transmit power (9 to 24dBm) Some coordination between TDD and FDD low power operators will be needed in public areas.
	10 MHz (16 Mbps) TDD macro – FDD indoor low power	**20 MHz (32 Mbps) TDD macro – FDD indoor low power**
	For 20% throughput degradation 290-1600m separation depending on transmit power (28 to 43 dBm) For 50% throughput max degradation 100-590m separation depending on transmit power (28 to 43dBm) These are likely to be less than in the macrocell to macrocell case.	For 20% throughput degradation 235-1315m separation depending on transmit power (28 to 43 dBm) For 50% throughput max degradation 85-475m separation depending on transmit power (28 to 43dBm) These are likely to be less than in the macrocell to macrocell case.

1.24 What would be the impact of interference radar emissions in the 2700 to 2900 MHz band on the operation of a low-power network?	**Outdoor**	**Indoor**
	Main beam: 25 km separation distance for max throughput (91 Mps in 20MHz)	**Main beam**: 10 km separation distance for max throughput (91 Mps in 20MHz)
	Side lobes: 5 km separation distance for max throughput (91 Mps in 20MHz)	**Side lobes**: 2 km separation distance for max throughput (91 Mps in 20MHz)
1.25 What other technical conditions might be needed to manage any interference?	Some coordination between TDD and FDD low power operators will be needed in public areas with overlapping deployments to ensure separation distances and/or appropriate power limits are applied. As S band radar affects the UE rather than base station adjacent channel interference from S band radar to FDD low power network UEs is likely to be no worse than that for FDD macrocell UEs. Therefore no additional conditions to mitigate interference are recommended. The risk of interference may be less if a high proportion of low power access points are indoors.	

2 Introduction

2.1 UK spectrum at 2.6GHz is due to be auctioned shortly

Ofcom is seeking to auction licences for the frequency band 2500 MHz – 2690 MHz (the "2.6 GHz" band) together with other bands, with the award of licences expected to take place in 2012. The band is arranged as 2500 – 2570 MHz (uplink) paired with 2620 – 2690 MHz (downlink), plus an unpaired portion 2570 – 2620 MHz. Although the award will be on a technology neutral basis, the expected technologies are LTE in frequency division duplex mode in the paired spectrum and WiMAX or TD-LTE in the unpaired spectrum.

The 2.6GHz band is recognised as a highly desirable band for cellular operators and vendors, as its usage has been commonly defined for International Mobile Telecommunications by the International Telecommunications Union in all three of its regions [[1]]. This international harmonisation of the band allows vendors and operators to benefit from greater economies of scale. Sometimes known as the UMTS expansion band, it was originally anticipated that this band would be used by cellular operators to provide additional capacity to 3G networks [[1]]. However, more recently it has been associated with 4G networks and indeed is already being used in Sweden, Norway, Uzbekistan and Hong Kong to provide LTE services and in several places including the US to provide WiMAX services [[2]].

In Europe, Commission Decision 2008/477/EC outlined partitioning of this band between TDD and FDD services and Block Edge Mask (BEM) parameters for devices within this band. This band has already been auctioned in many European countries including Denmark, Finland, Germany, Norway, the Netherlands and Sweden [1].

This study relates to the potential to designate part of the spectrum for shared low-power use. In contrast to the remainder of the spectrum, this low-power shared access would involve multiple licensees operating in a concurrent, non-exclusive fashion across the same spectrum. The spectrum could be awarded on a reserved basis, where only low-power licensees would have access, or potentially on an underlay basis, where low-power shared access licensees use the same spectrum as a wide area (high-power) licence.

There is some precedent for such shared use of spectrum in Ofcom's previous award of low-power concurrent licences in the 1781.1-1785 MHz and 1876.7 MHz – 1880 bands, (often known as the DECT guard band [[3]]). The auction outcome was that 12 operators gained concurrent access to 2 x

3.3 MHz of spectrum. Although technology neutral, most use of this band to date has been for small area low-power GSM systems.

2.2 Potentially introducing a low power shared access channel to the 2.6GHz band is complicated by interference challenges

The low-power shared access licences exhibit particular potential interference challenges amongst licensees and from adjacent spectrum users for a number of reasons:

- Low-power applications may include femtocells and picocells, where deployment may be conducted by the end user or other untrained personnel, resulting in deployments of cells which may be suboptimum with regards to coverage or interference
- The close proximity (in frequency and location) of high-power cells, which could cause substantial interference to the cells or user devices operating in the low-power spectrum.
- The presence of multiple concurrent operators in the same spectrum, who may or may not coordinate deployments amongst themselves.
- The presence of TDD systems adjacent (in frequency and location) to FDD systems in paired spectrum, and the presence of high-power radar systems adjacent to FDD systems in paired spectrum.

In order to limit these interference sources, any low-power licences would include appropriate technical conditions to limit interference risks. The licensees might also enter into some form of technical agreement to further limit interference which may include, for example, additional technical restrictions, coordination procedures, shared databases, technical interfaces or roaming arrangements.

In the DECT guard band situation, the use of 200 kHz GSM channels in a 3.3 MHz band meant that some frequency planning amongst operators could avoid most potential cases of interference and issues would only be experienced at high deployment densities. Achieving the full data rate available from LTE requires a 2 x20 MHz band, so conventional frequency reuse planning is unlikely to be feasible.

2.3 Ofcom want to understand the technical issues associated with low-power shared access in 2.6GHz spectrum

The aim of this study is to investigate the technical issues associated with low-power shared access in the 2.6 GHz spectrum, which could potentially open up the opportunity for more operators to compete for service provision to the benefit of citizens and consumers and for the spectrum to be used in a way with specific properties in terms of spectral efficiency and via innovative business models. Ofcom seeks technical investigation to inform the nature of any such licensing:

- Should the low-power access be exclusive to a portion of the band, or on an ‘underlay’ basis, shared with a wide-area high-power licence?
- What are the implications of different sizes for the low-power block i.e. 2 x 20 MHz vs. 2 x 10 MHz? The investigation should account for the traffic capacity, number of concurrent operators, and frequency re-use characteristics of the resulting low-power uses.
- What techniques could be used to manage spectrum sharing between low-power operators?
- What power level would be needed to provide coverage in a variety of indoor locations, from both indoor antennas and from outdoors?
- At what separation distances between buildings does coordination between low-power operators become necessary?
- Is 5m outdoor antenna height an appropriate limit for the purpose of limiting interference between low-power networks?
- What restrictions would need to be placed on antennas to minimise interference in the case of an underlay network?
- What separation is needed between outdoor and indoor low-power antennas to allow frequency reuse and at what distance does operator coordination becomes necessary?
- What is the impact of adjacent channel interference from TDD WiMAX or TD-LTE systems and from radar systems to low-power operation and what associated technical conditions may be necessary?

2.4 Our approach and assumptions

Our work in this study was organised into four interdependent work packages, as illustrated in the study logic diagram shown in Figure 2-1.

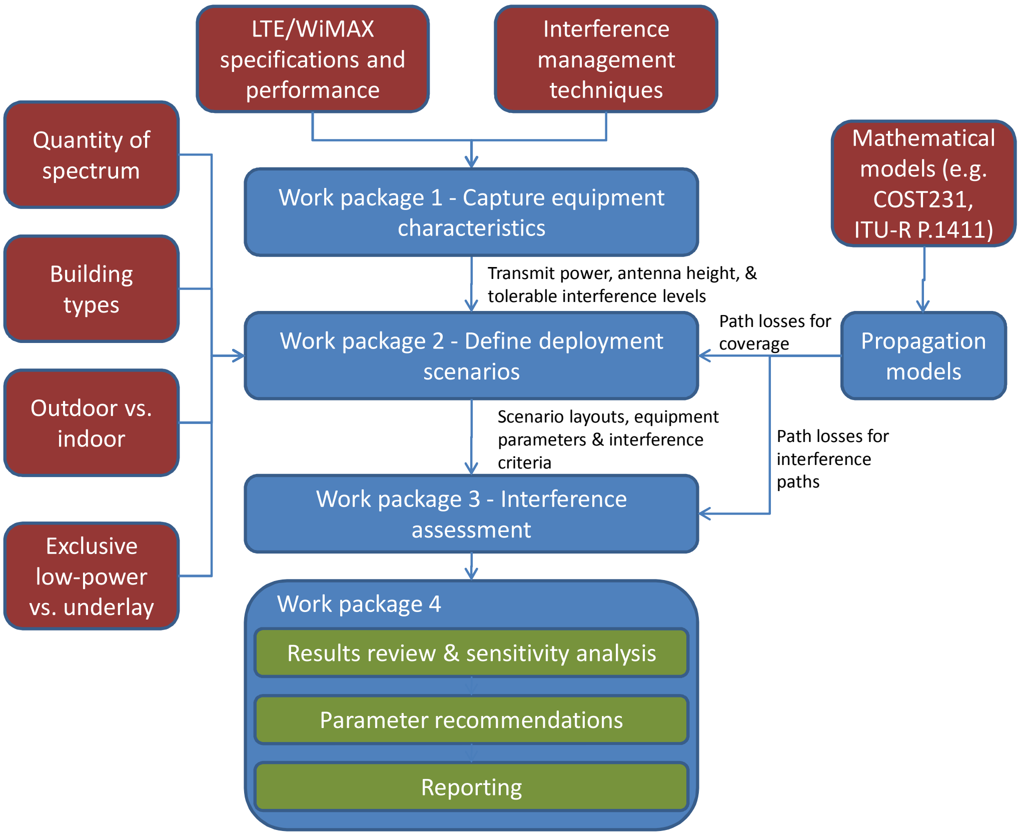


Figure 2-1: Study Logic

We have made some overall assumptions for the purpose of our study:

- Although the 2.6 GHz award will be on a technology neutral basis, we have assumed the use of FDD LTE technology in the low power band.
- We are not aiming to determine the typical overall performance of systems in the low-power band. Instead we seek to provide analysis relevant to the setting of technical licence conditions, which typically focus on relatively extreme parameter settings and challenging scenarios to set licence conditions and challenging cases as driven by interference issues. It is for operators seeking access to this band to conduct their own system simulations (and field trials where possible) to assess overall system performance according to their plans.
- We are generally using modelling techniques which are based on identifying the most important paths and static situations. It is not the target here to model fully the whole system performance or the finer details of the interference management techniques which could be applied.
- Interference from unpaired spectrum assumes the use of TD-LTE technology in the unpaired band, but this is intended also to be reasonably representative of interference from WiMAX systems.

2.5 The evolution of small cell technologies and the opportunity for more efficient spectrum usage

The concept of perhaps five to ten operators sharing the same spectrum for high data rate services, with cells deployed with limited or no planning, with potentially limited technical coordination between operators and possibly sharing with a high power network is undoubtedly ambitious, and a few years ago may have seemed infeasible. However, in recent years the development of femtocells, originally intended for deployment in homes, has opened up the possibility for a more flexible use of spectrum providing high-quality coverage and high capacity in limited areas. Femtocells are low-power access points, providing services in licensed spectrum which are essentially identical over the air to those delivered by a conventional base station, and therefore can be delivered to all standard mobile devices. They were originally designed for the home environment, where they connect into the mobile operator's network via the internet, over a standard domestic broadband connection. This connection allows the operator to remain in management control of the devices, but at the same time the devices include intelligence which permits, amongst other functions, dynamic management of interference between cells. Given this dynamic management, operators have increasingly adopted femtocells, predominantly for the 3G market today – in December 2010 there were 18 commercial services worldwide and a total of 30 operator commitments to deploy[4].

However the same technology is also targeted for application to LTE and WiMAX systems and to environments beyond the home. Our discussions with vendors and operators have highlighted that low power cells are likely to be a key part of 4G networks with many stakeholders identifying the 2.6GHz band as an excellent candidate for small cell deployments, leaving lower frequency bands primarily for providing wide area coverage. Similarly, Telefonica have said:

"[Telefonica is moving towards] street-level picocells and femtocells… based on this 2.6-GHz frequency"

- Jaime Lluch Ladron, Telefonica New Technology Executive October 2010[5]

Standards exist for LTE femtocells, known as Home eNodeBs (HeNBs) in the 3GPP specifications, finalised in 3GPP Release 9 in early 2010[6]. Likewise, the WiMAX Forum finalised femtocell specifications in June 2010[7]. Both standards support the 2.6 GHz band.

Due to the low power nature of small cells it may be wasteful to assign separate femtocell carriers to operators individually. An approach which is coordinated across operators to the minimum extent necessary to achieve acceptable performance may make a shared low power channel feasible and improve spectrum utilisation in this band in support of Ofcom's duty to *ensure the optimal use of the* *electro-magnetic spectrum* and also to *ensure that a wide range of electronic communications services – including high speed data services – is available throughout the UK*[8].

Such shared operation, however, relies on the successful operation of relevant interference management techniques and potentially additionally on operators cooperating to coordinate parameters and deployments such that each can achieve a viable service offering without excessive cost or complexity.

3 Our results indicate that a low power shared access channel is feasible if standard interference mitigation techniques are applied

A low power shared access channel provides significant potential for making the most of capacity in the 2.6GHz band due to the improved spectrum efficiency density brought about by:

- A higher cell density
- Improved SINR distribution in small cells
- Being typically deployed in indoor environments where MIMO works well

Estimates on the potential capacity improvements with small cells range up to x100[[34]].

As small cell access points are low power devices there is a greater opportunity for sharing spectrum amongst operators than for traditional wide area cellular networks. This is comparable to the way in which Wi-Fi systems dynamically share the capacity available, but with a greater degree of flexibility and assurances of quality of service arising from technical innovations developed for femtocells and the opportunity for centralised coordination by licensed operators. Also industry results have highlighted the 2.6GHz band as especially suitable for small cells compared to the low frequency (sub 1 GHz) bands which are best suited to providing wide area coverage [[9]].

Our study has found that a low power shared access channel amongst multiple operators is feasible but will require appropriate restrictions to make best use of the capacity benefits of small cells in the areas of greatest demand.

We recommend that a 2 x 20MHz channel would be the most attractive solution for a low power shared access channel at 2.6 GHz. This delivers the maximum user experience, best interference mitigation amongst operators and allows maximum benefit from capacity gains and spectrum efficiencies of small cells. If, however, dedicated low power access to this quantity of spectrum cannot be provided due to the impact on the quantity available to high power licensees, a hybrid approach where only part of the channel overlaps with a high power allocation will mitigate potential interference. Restrictions on transmit power, technology and a code of practice relating to coordination amongst operators are recommended to ensure maximum benefit from this band.

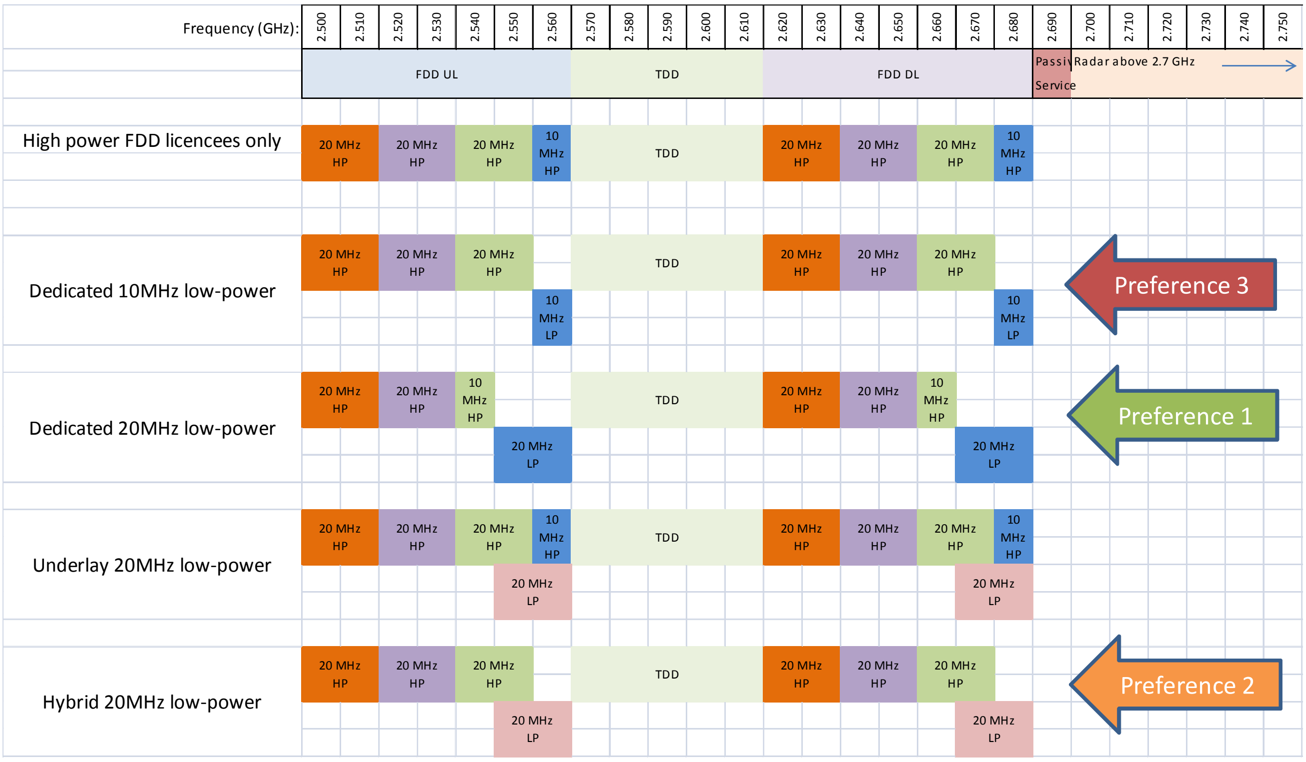


Figure 3-1: Spectrum options for the potential low power shared access channel (positioning is for illustration only)

Table 3-1 summarises the advantages and disadvantages across spectrum options for the potential low power shared access channel (illustrated in Figure 3-1). These are listed in order of our recommended preference.

Spectrum option	Advantages	Disadvantages
2 x 20MHz - dedicated	Improved user experience in low power networks compared to 10MHz. Data rate will typically be twice that of a 10MHz channel but in cases where frequency partitioning is less will benefit from a lower overhead so could achieve more than this (e.g. 11.3Mbps vs. 3.8Mbps for 7 sharing networks) Larger bandwidth allows for better	Reduces capacity available for wide area operators

	resource scheduling and less collisions on resource blocks between cells. Enhanced opportunity for fractional reuse schemes to improve isolation between concurrent operators.	
2 x 20MHz - hybrid	Low power networks guaranteed access to at least 10MHz even when close to macrocells. Avoiding collisions of control channels between macro and low power devices is made easier.	If a 2x20MHz hybrid channel is used, the capacity for wide area use in the overlapping 2x10MHz of spectrum is degraded by more than 40% in the case of two contending networks if separation distances of 400m -1.5km are not maintained (assuming a 10dBm power cap on low power networks in the region of macrocells) Setting licence conditions to ensure appropriate sharing with the overlapping wide area licensee will be challenging.
2 x 10MHz - dedicated	Allows three 2x20MHz wide area licences to be made available.	Restricts low power networks to half the peak data rates of wide area networks and less than half the capacity. Data rate will typically be half that of a 20MHz channel but in cases where frequency partitioning is less will suffer an increased overhead so could achieve less than this (i.e. 3.8Mbps vs. 11.3Mbps for 7 sharing networks) Reduced opportunity to use fractional frequency reuse schemes to avoid interference. For example in LTE with a minimum bandwidth of 1.4MHz 7 shared networks could be accommodated in a

		10MHz channel but 14 could be accommodated in a 20MHz channel.
2 x20MHz – underlay	Improved user experience in low power networks compared to 10MHz Larger bandwidth allows for better resource scheduling and less collisions on resource Having the underlay overlap two high power networks allows increased opportunity to avoid mutual interference between high power and low power networks	Extra interference from the macrocell as well as adjacent femtocells to consider If a 2x20MHz underlay channel is used, capacity for wide area use in the underlay spectrum is degraded by more than 40% in the case of two contending networks if separation distances of 500m -2km are not maintained (assuming a 10dBm power cap on low power networks in the region of macrocells) If low power network is a secondary user of the band they are not guaranteed access in all locations. This would reduce opportunities for low power networks in dense urban deployments to indoor scenarios and not spots. Setting licence conditions to ensure appropriate sharing with the overlapping wide area licensee will be challenging.

Table 3-1: Trade-offs in low power shared access channel spectrum options

3.1 A maximum EIRP of 30 dBm is recommended in a 2 x 20MHz or 2x10MHz scenario

Our results show that, for homes, +20 dBm EIRP gives more than adequate coverage in the majority of homes, in line with the 3GPP Home e-Node B (LTE femtocells) specification with a low-gain antenna. In offices and public environments (e.g. shopping centres) somewhat higher power at around +27 dBm EIRP may be required to provide good coverage at high-end data rates in some situations. This level is consistent with the 3GPP Local Area Base Station specification with a moderate gain antenna (i.e. 24dBm with 3dBi antenna gain).

However, in order to provide adequate in-building penetration from outdoor access points, this EIRP will be insufficient. An EIRP of +30 dBm gives improved performance and is still consistent with the Local Area Base Station specification with a higher gain (but still compact and omnidirectional) antenna.

As the maximum transmit power level of 3GPP LTE devices are specified independent of bandwidth this EIRP would be applicable for both a 2x10MHz or 2x20MHz low power shared access channel.

3.2 Interference amongst low power operators is manageable given a height limit on outdoor deployments and a code of practice ensuring cooperation on interference mitigation techniques and overlapping deployments

Imposing separation distances between uncoordinated low power access points is not seen as a practical solution for the co-channel interference scenarios examined in this study, since excessively large distances would be needed, limiting the utility of the spectrum. Instead intelligent interference mitigation techniques available in LTE such as power control and dynamic scheduling are thought to be more appropriate approaches for this band. Such techniques will allow most users to access the whole channel bandwidth in most situations and for a graceful degradation in bandwidth in limiting situations where the density of use and of cells is high. Technical conventions to ensure these techniques are compatible amongst operators may be necessary to maximise performance, but since the relevant technology is fast evolving and not standardised in detail, it is recommended that this is left to licensees to coordinate amongst themselves.

Such interference techniques often amount to dynamic portioning of the spectrum amongst neighbouring cells according to the signal conditions and demand. This partitioning will be more successful given a wider bandwidth, and the associated user experience and capacity will relate directly to bandwidth also, hence a 20 MHz channel is highly desirable.

A restriction on outdoor antenna height will help to reduce the range of interference from outdoor cells. Interference ranges rise more rapidly as the antenna heights become significantly above the heights of surrounding buildings. It is therefore recommended that the maximum height is set at or a little above the typical height of residential buildings. At around 12 metres this would be consistent with existing street furniture deployments by operators.

Technically, there is no specific limit on the number of operators licensed to use the shared access channel. Interference mitigation techniques need to operate successfully given the limiting case of an adjacent cell from another operator and this will occur even with two operators in the band. The decision as to the number of licensees in the band is more of a policy decision. From a technical viewpoint, we see no reason why 7 overlapping networks in a 2x10MHz channel and 14 overlapping networks in a 2x20MHz channel could not be accommodated assuming that overlap of common control channels is the limiting factor and frequency partitioning is applied.

This does not necessarily translate to a limit on the number of operators as not all operators will deploy in the same areas. Operators will however need to share the available capacity in overlapping deployments, typically in public areas, strengthening the case for 2 x 20 MHz. In practice, when the number of operators is high it is likely that operators will be incentivised to provide conditional roaming or share network equipment access points in areas where deployments overlap rather than suffering degraded throughput from interference. In cases where this did not happen, even using dynamic scheduling , operators would experience less than the total shared channel capacity split equally between the number of overlapping networks due to the higher overhead of their own common control channels in a reduced number of available resource blocks.

3.3 An underlay approach presents interference and coordination challenges, so we recommend a hybrid approach if dedicated 2x20 MHz spectrum is not feasible

If the low-power spectrum block is provided on an underlay basis with a high power licence, there are several scenarios where interference between the systems can be significant. There exist mitigation techniques to address all of these, but degradation of the performance may still be significant in the absence of inter-operator roaming. It may also be complex to include the required safeguards in the form of licence conditions. Even if priority is always given to the high power operator in an underlay scenario it is likely that there would still be significant opportunities to deploy low power shared access networks in indoor and not spot scenarios. However, these would obviously be much less than in the case where a dedicated low power channel was made available. A dedicated spectrum approach is therefore preferred, giving certainty to both forms of operator.

If however this option is not available with 2 x 20 MHz of spectrum, an intermediate solution would be to overlap just half of the low power channel with a high power channel and introduce licence conditions to ensure that interference is avoided. This “hybrid” spectrum approach may involve the high power systems always taking priority in the overlapping portion of the spectrum. This approach could provide a good balance between the opportunities for both high power and low power licensees if appropriate licence conditions can be arrived at. This approach always ensures that the low power shared access networks always have access to 2x10MHz of spectrum and in areas where interference with macrocells is not an issue in the overlapping portion of spectrum they will benefit from a boost in quality of service from a 2x20MHz channel.

3.4 Our recommendations rely on the use of interference mitigation techniques and other coordination measures, facilitated by a code of practice agreed amongst licensees

The separation distances to minimise interference at the proposed transmit power to ensure reasonable coverage are not thought to be practical for expected deployments. However, no separation distance is required if vendors implement intelligent scheduling and operators are prepared to accept throughput degradations proportional to the number of uncoordinated deployments in an area for the minority of users most affected by interference from neighbouring cells.

A code of practice amongst operators making use of the shared band is recommended to ensure capacity is maximised. This may include:

- Implementing intelligent scheduling schemes that back off target throughputs and share capacity where neighbouring low power access points and, in the underlay case, macrocells are detected.
- Implementing power control so that low power access points and associated UEs never transmit at higher powers than required for the target throughput and coverage.
- Although the licensees should be able to choose the technology which they deploy, efficient interference mitigation amongst operators is likely to require use of the same time and frequency resource block sizes amongst operators and compatible dynamic scheduling approaches and environment measurements by both the UE and low power access points. This may in practice lead to a convention on the use of a single technology, most likely FDD LTE.
- Mandating network listen functionality in low power access points for environment monitoring and interference mitigation.
- Sharing of deployment information such as cell locations, transmit powers, height and Cell IDs.
- Ensuring conventions on the frequency of scheduling to ensure resource allocations do not change too frequently with time and can be tracked by other adjacent uncoordinated access points attempting to share capacity.
- If separation distances are used to mitigate interference, the power spectral density (PSD) used on control channels should not exceed the PSD on the shared data channels. This is to ensure that the target SINR for control channels is achievable at the victim receiver if separation distances are set based on assumptions on the transmit power of the aggressor at a target throughput. This would only be required in cases where control channels overlapped.
- In the underlay or hybrid situation, giving priority to the macrocell network with the low power access point reducing its power and accepting throughput degradations when a macrocell is detected.

3.5 We recommend further study on positioning the shared channel within the FDD block

By positioning low power devices at the upper end of the paired 2.6 GHz spectrum, an additional frequency separation is introduced between high power macrocells and radar receivers above 2.7GHz. Although this study has not examined this case explicitly, this would seem helpful in providing an additional 'guard band' between high power transmissions and the radar systems. However, in some circumstances low power access points may have relaxed emission specifications, which could create noise rise to radar receivers and we recommend that this situation is examined explicitly.

Our findings in terms of interference into the FDD band show:

- Interference from S band radar to FDD low power network mobile devices is likely to be no worse than that for FDD macrocell mobile devices.
- Interference from TDD macrocells to FDD low power access points may be less than interference to FDD macrocells due to the lower antenna gain likely in low power access points. However, some coordination between TDD and FDD low power operators will be needed in public areas with overlapping deployments to ensure separation distances and/or appropriate power limits are applied.
- Widespread indoor usage of low power access points may provide some additional isolation from adjacent channel interference due to building penetration losses.

On balance, positioning the low-power shared channel at the top end of the FDD band seems a sensible choice, but the case is not overwhelming.

3.6 Lessons learnt from the DECT guard band study and Wi-Fi

There are few precedents for the concurrent low-power use of spectrum amongst multiple operators, and we are aware of none which relate directly to licensed use of a high speed mobile data technology.

However, there are two comparable cases which may provide some useful lessons: firstly the Ofcom award in 2006 of the 1781.1-1785 MHz and 1876.7 MHz – 1880 bands, commonly known as the "DECT guard band" or "low power GSM band" and the widespread use of Wi-Fi technology in the 2.4 GHz band.

3.6.1 The DECT Guard Band

In May 2006 Ofcom awarded licences to 12 operators on a concurrent low-power basis. Although the award was made on a technology neutral basis, the band is included in the definition of the DCS-1800 MHz band supported by GSM mobiles, so GSM remains the most likely technology and it is believed all commercial use of the spectrum has employed GSM technology. The technical conditions in the licence are included the following[10]:

- A maximum outdoor transmitter antenna height of 10 metres above ground level
- In the central 3 MHz of the band, a maximum EIRP of 0 dBm / kHz corresponding to 23 dBm in 200 kHz. In particular circumstances (e.g. where a cell is isolated and not likely to cause interference) licensees could mutually agree an increase to 7 dBm/kHz corresponding to 30 dBm in 200 kHz.
- Out of block emissions equivalent to those found in the GSM specification.
- Ofcom required licensees to enter into a Code of Practice on Engineering Coordination within six months of the award.

The technical conditions were informed by a technical study[11] conducted by Ofcom, some of the conclusions of which were:

- A low power system based on GSM pico cells operating at the 23dBm power level can provide coverage in an example multi-storey office scenario. Two pico cells per floor would meet the coverage requirements in the example 50m × 120m office building. For a population of 300 people per floor, the two pico cells would also meet the traffic demand.
- Analysis of interference between neighbouring office buildings with indoor GSM pico cells operating on the same radio frequency indicates that a 97% probability of call success inside each office could be achieved with 550m separation between buildings if there were no obstructions between them. For a building separation of 150m the probability of call success is achieved is better than 90%. We conclude that coordination is necessary.
- It is possible to serve users up to 40m within a building using an external base station with a power limit of 23dBm. However, to penetrate to users 50 meters within a building would require a higher power (30dBm would be needed to give a reasonable separation between the base station and building).
- An outdoor micro cell could cause interference to an in-building pico cell system. At 3km a 23dBm micro cell reduces the call success probability on the pico cell system below 90% while a separation of 10km would be required for 97% call success. These figures are reduced significantly if there is an obstruction in the path. Adding a building on a 730m path gives a call success rate of 97%. However, if the outdoor micro cell has a power of 30dBm it is not possible to achieve a call success of 97% even with an obstructing building in the path unless the distance between the cells is unreasonably long.
- We propose a maximum antenna height for outdoor installations of 10m as a means to reduce the occurrence of unobstructed interference paths. We also propose a maximum power level of 23dBm EIRP to prevent interference over a significant area.
- A probabilistic analysis of interference between co-frequency indoor GSM pico cells located within a row of terraced houses indicates that a 97% probability of call success inside each house could be achieved with a separation of two houses.

- A probabilistic analysis of interference between co-frequency indoor GSM pico cells located within houses in opposite terraces indicates that coordination will be required and that it will only be possible to assign frequencies from a total of 15 at random if the usage percentages are relatively low.

These act as a useful point of comparison with the conclusions from the present study. However in making such a comparison it should be noted that there are significant differences between the DECT guard band award and the potential 2.6 GHz low power award under consideration in this study:

- Using GSM technology, the DECT guard band award allowed for at least 15 GSM carrier frequencies. Thus there was considerable scope for using frequency separation to avoid interference until the density of cells and the required capacity exceeded a significant level. In the current case, achieving the highest peak data rates requires that all cells are capable of transmitting over the full bandwidth. Despite this, LTE and other next-generation mobile systems are capable of dynamically adjusting the bandwidth occupied according to the demand from users and the interference levels in different parts of the channel occupied, so that a form of dynamic frequency reuse can be applied, at the expense of a reduction in capacity and user throughput.
- The automated interference sensing and mitigation techniques which are now standard in femtocells had not been widely envisaged at the time of the award, so it was not possible to build in these capabilities as an assumption in setting the technical parameters in the DECT guard band award.
- The use of GSM technology suggested a mainly connection-oriented protocol, based particularly on voice services. In such systems, relatively short instances of interference can cause dropped calls to the major detriment of perceived quality. By contrast, LTE and similar systems are entirely packet-oriented and targeted mainly at data applications, where a temporary reduction in throughput may not be noticeable to a user and may be entirely overcome by appropriate prioritisation of packets according to the required quality of service.
- LTE and similar technologies achieve far higher spectrum efficiency than GSM, so they are capable of delivering a far higher level of traffic for equivalent signal conditions and bandwidth.
- The 2.6 GHz band produces higher propagation losses for a given distance than the 1.8 GHz band, so smaller distances should give equivalent protection levels.

These issues, taken together, suggest that the technical conditions applicable to the potential new award should be no more restrictive than those of the DECT guard band and that some of the conditions could potentially be relaxed to some extent, including potentially the transmit power levels, the antenna heights and the need for coordination.

3.6.2 Wi-Fi in the 2.4 GHz band

The use of Wi-Fi technology in the 2.4 GHz band is governed by a very different regime to that of the potential 2.6 GHz low power allocation. However there are some interesting similarities which may inform the current considerations.

Wi-Fi at 2.4 GHz is formally a system based on the IEEE 802.11b, g and n specifications. In the UK, the main band of operation is 2.4 – 2.4835 GHz, although there is increasing use of Wi-Fi in the 5 GHz range. Within this band the technical conditions are set out by a Radio Interface Requirement 2005[12]. The technical conditions are simple, being mainly a maximum transmit power of 20 dBm EIRP. Provided equipment complies with this Interface Requirement, it may be operated on a licence-exempt basis. Furthermore, since July 2002, commercial services have been permitted in this band[13]. A vast number of devices now operate in the band, including commercial services operated on a large scale by operators such as BT, who operate over 2 million UK Wi-Fi hotspots[14], and The Cloud who operate more than 22,000 access points across Europe[15]. In January 2011 O_2 announced plans to deliver a network which will be “at least double the number of premium hotspots offered by BT Openzone and The Cloud combined by 2012.”[16] This neglects the vast number of individual private deployments in homes and offices.

There are a number of technical factors which might be taken to suggest that services over Wi-Fi would yield poor performance:

- A complete lack of coordination amongst deployments.
- The presence of both outdoor and indoor deployments with no constraints on height.
- Many other devices which use the same spectrum band, including Bluetooth headsets, medical and scientific devices, baby alarms and even microwave ovens.
- A high likelihood of adjacent devices operating on the same radio frequency. Each Wi-Fi transmission is at least 22 MHz in bandwidth, so there are only three non-overlapping channels. Although newer Wi-Fi systems incorporate interference sensing and automated retuning, many existing devices do not. Indeed devices from the same manufacturer all typically come pre-configured with the same frequency channel.
- No power control in existing devices: although newer variants of Wi-Fi do include some power control, this is rare in existing devices, so both the access points and the client devices usually radiate at a fixed power of around 100 mW.

Indeed, in 1999, before Wi-Fi in its current form gained commercial acceptance, a study for Ofcom’s predecessor regulator the Radiocommunications Agency concluded that[17]:

> “Operation of high performance telecommunication networks in a very dense urban environment such as the City of London "square mile", which is also subject to a relatively high number of OBTV transmissions, is unlikely to be viable. Operation of a single such network in

other more typical urban areas should be viable in most instances, providing due account is taken of the projected future increase in interference levels. ”

Further, a study by Mass Consultants Ltd. on behalf of Ofcom[18] did identify real performance challenges with densely deployed Wi-Fi systems deployed in locations such as the centre of London. In such locations, the report found that it is rare for the user data frame rate to exceed 10% of the total frame rate, so that existing Wi-Fi protocols were using a substantial part of the 2.4 GHz band without carrying significant quantities of user-generated content. In addition this study found that in many situations where Wi-Fi performance was degraded, and originally attributed to congestion, the interference was due to other non Wi-Fi friendly devices such as baby alarms and CCTV cameras making use of the band.

Nevertheless, for most users, in most locations and for most of the time Wi-Fi delivers a useful service, with data rates which support a wide range of services. When Wi-Fi systems encounter interference on a particular packet, they retransmit it a random period of time later, so that the throughput is degraded but data still flows. Although there are various ways in which the original Wi-Fi protocols can be improved (and are being improved in newer versions), they still provide a satisfying service in most cases. Significant value has been ascribed to the use of Wi-Fi: for example, one study suggests that Wi-Fi usage in the home, for only the purpose of broadband extension, may be generating anywhere between $4.3 and $12.6 billion in annual economic value for consumers in the United States[19].

Comparing Wi-Fi with the use of LTE (or a similar technology) in the potential low-power concurrent allocations, there are several reasons to expect a service which is superior to Wi-Fi:

- A limited number of operators, with the potential to monitor and coordinate deployments via co-operation amongst themselves and by the deployed devices reporting their locations and parameters to a central controller for each operator and potentially amongst operators.
- A managed protocol in LTE which delivers assured quality-of-service streams which can be differentiated according to device and service to make best use of the available signal quality.
- A greater opportunity for operators to agree consistent technologies and interference mitigation conventions, avoiding the risk of interference from dissimilar devices.
- Uplink power control to minimise interference.
- A range of interference mitigation techniques, comprising the whole range of techniques which have already been tested in commercial operation for 3G femtocells and which are supported in LTE standards, including downlink transmit power control and both coordinated and distributed resource scheduling techniques.
- Support for full mobility amongst cells with seamless handovers even at high speed.

- Ability for the same devices to handover to wide area, high power macrocells given appropriate roaming arrangements amongst operators.

The only significant downside relative to Wi-Fi is the relatively small spectrum bandwidth available (20 MHz or 40 MHz in total compared with 83.5 MHz). On balance, then, it should be expected that low power concurrent licensed operation could provide a service which is beyond the level of performance of Wi-Fi. Given the proliferation of such systems, they could potentially act as a complement or even a replacement for Wi-Fi, such as in cases where a high level of service assurance is required for business-critical applications: a form of “first class Wi-Fi”.

4 Our assumptions on LTE devices, propagation models and interference mitigation techniques

This chapter sets out the modelling assumptions used throughout this study in the following areas:

- LTE equipment parameters
- Target quality of service levels used for coverage analysis and interference criteria used for co channel and adjacent interference analysis
- Propagation models used in the target deployments
- Assumptions on building sizes and types in the target deployments
- Interference mitigation techniques assumed to be available in small cell deployments

Our assumptions in each of these areas are based on our review of related work from 3GPP, the Femto Forum and previous Ofcom studies. We also summarise in this chapter our discussions with industry stakeholders as an additional check on the assumptions used in this study.

4.1 LTE device parameters

It is most likely that the award of any low power shared licence in the 2.6GHz FDD band will be made on a technology neutral basis. However, to answer the coverage and interference questions posed by Ofcom in this study we have made the assumption that LTE will be the main technology used in the 2.6GHz FDD band and that the devices used in the low power shared access portion of this band will be similar to LTE FDD Home eNodeB (HeNB) or Local area base stations as described by 3GPP. As most LTE FDD operators are targeting baseline deployments supporting 2x2 MIMO we have assumed that this configuration will also be used in low power networks.

Example throughputs given in this report are based on the spectrum efficiency achievable in a 3GPP EVA5 channel for 2x2 MIMO [[20]] and allowing for the overhead of control channels and an improvement in performance due to scheduler gain [[21]].

The following tables outline our modelling assumptions used for:

- LTE user equipment (UE)
- LTE local area base stations (i.e. outdoor low power shared access points)
- LTE home base stations (i.e. indoor low power shared access points)
- LTE macrocell base stations

These are based on parameters given in the LTE 3GPP standards, related 3GPP technical studies and previous work published by Ofcom. In particular we have aligned these parameters with those used by 3GPP for investigation of small cell interference techniques as given in 3GPP R4-092042 [[22]].

These parameter assumptions were agreed with Ofcom prior to carrying out the modelling work described in chapters 5 (coverage), 6 (co-channel interference) and 8 (adjacent channel interference).

It is worth noting that while LTE supports a number of bandwidths the technical specifications for both UEs and base stations specify transmit power levels that are independent of bandwidth. This results in a higher power spectral density for 10MHz devices compared to 20MHz devices. While licence terms tend to specify maximum EIRP levels for a given bandwidth, we have assumed that in the case of the low power shared access channel the same convention as in 3GPP of specifying a single maximum EIRP for all bandwidths will be used.

4.1.1 Parameter assumptions for LTE User Equipment

Table 4-1 gives our assumptions for LTE user equipment capabilities based on 3GPP TS 36.101 [[23]].

Parameter	Value	Units	Source
Maximum transmit power	23	dBm	In line with 3GPP UE maximum output power levels given on Table 6.2.2-1 of TS 36.101 [[23]]. Class 3 value used as no other power classes were specified at this time. Also matches with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [[22]].
Antenna gain	0	dBi	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [[24]]. Also matches with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [[22]] and baseline UE antenna assumption given in section 6.1 of TS 36.101 [[23]].
Antenna height	0.5	m	Assume handheld data device used away from head or unit placed on a desk.
Cable, combiner and connector losses	0	dB	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [[24]].
Receiver noise	9	dB	Assumption in line with 3GPP simulation assumptions for

figure			HeNB RF requirements given in R4-092042 [22]
Out of band selectivity	48 for 10MHz 41 for 20MHz	dB	Calculated based on out of band blocking requirements given in section 7.6.2 of TS 36.101 [23].
Body loss	0	dB	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [24].

Table 4-1: LTE Device Parameter Assumptions: User Equipment

4.1.2 Parameter assumptions for outdoor low power shared access points

Table 4-2 gives the parameters used for outdoor low power shared access points. We have assumed that these will be higher cost units than residential and indoor low power access points and will be similar in capability to 3GPP LTE "local area base stations" rather than HeNBs.

Parameter	Value	Units	Source
Maximum transmit power	24	dBm	In line with the maximum transmit power for a local area base station as given in table 6.2-1 of TS 36.104 [25]. This limit also matches with stakeholder comments.
Antenna gain	5	dBi	Assumption in line with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [22]. This document gives a range of antenna gains of 0, 3 and 5 dBi for HeNBs. We assume that the best antenna gain of 5dBi, which assumes a small directivity value is achieved by suppressing emissions in the vertical direction, will be most achievable in outdoor low power access points.
Antenna height	5 (default), up to 15	m	Assumes the outdoor access point is located on a lamp-post.
Cable, combiner and connector	0	dB	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [24] (i.e. a mast head amplifier is

losses			used).
Receiver noise figure	8	dB	Assumption in line with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [22] TS 36.104 section 7.2 [25] specifies the same receiver sensitivity for both HeNBs and local area base stations so we assume that the same noise figure applies to both.
Adjacent channel selectivity	49 for 10MHz 46 for 20MHz	dB	Calculated based on adjacent channel selectivity test cases for a local area base station given in table 7.5.1-4 of TS 36.104 [25].
Adjacent channel leakage ratio	45	dB	Assumption in line with section 6.6.2.1 of TS 36.104 [25]
Shadowing standard deviation	8	dB	Assumption in line with 3GPP simulation assumptions for modelling macrocell base stations to determine HeNB RF requirements given in R4-092042 [22]. We assume that an outdoor low power access point will be subject to a similar environment to a macrocell base station.

Table 4-2: LTE Local Area Base Station Parameter Assumptions

4.1.3 Parameter assumptions for indoor low power shared access points

Table 4-3 gives the parameters used for indoor low power shared access points. We have assumed that residential low power access points will be low cost units and will be similar in capability to 3GPP LTE HeNBs. We have assumed that indoor low power access points used in public areas and offices will be higher cost units and will have better performance than residential units.

Parameter	**Value**	**Units**	**Source**
Maximum transmit power	20 for residential 24 for public environments	dBm	For residential environments we assume a transmit power level in with a HeNB as given in table 6.2-1 of TS 36.104 [25]. For office environments and public areas we increase the maximum transmit power level

	and offices		to that of a Local Area Base Station. These assumptions also match with stakeholder comments.
Antenna gain	0 for residential 3 for public environments and offices	dBi	Assumption in line with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [[22]]. This document gives a range of antenna gains of 0, 3 and 5 dBi for HeNBs. We assume that the worst antenna gain will be achieved by low cost residential units whereas enterprise access points used in offices and public areas will achieve an antenna gain between the capabilities of residential and outdoor units.
Antenna height	0.5 for residential 2.5 for public environments and offices	m	Assume access point is on a desk or window ledge for residential scenarios. Assume access point is ceiling fitted or wall mounted in offices and public environments.
Cable, combiner and connector losses	0	dB	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [[24]] (i.e. a mast head amplifier is used).
Receiver noise figure	8	dB	Assumption in line with 3GPP simulation assumptions for HeNB RF requirements given in R4-092042 [[22]] TS 36.104 section 7.2 [[25]] specifies the same receiver sensitivity for both HeNBs and local area base stations so we assume that the same noise figure applies to both.
Adjacent channel selectivity	48 for 10MHz 45 for 20MHz	dB	Calculated based on adjacent channel selectivity test cases for a HeNB given in table 7.5.1-5 of TS 36.104 [[25]].
Adjacent channel	45	dB	Assumption in line with section 6.6.2.1 of TS 36.104

leakage ratio			[25]
Shadowing standard deviation	4 if walls modelled 10 if walls not modelled	dB	Assumption in line with 3GPP simulation assumptions for determining HeNB RF requirements given in R4-092042 [22].

Table 4-3: LTE Home e Node-B Parameter Assumptions

4.1.4 Parameter assumptions for LTE macrocell base stations

Table 4-4 gives the parameters used in this study for LTE macrocell base stations which are in line with 3GPP simulation guidelines and previous Ofcom studies.

Parameter	**Value**	**Units**	**Source**
Maximum transmit power	46	dBm	Assumption in line with 3GPP simulation assumptions for modelling macrocell base stations to determine HeNB RF requirements given in R4-092042 [22].
Antenna gain	14	dBi	Assumption in line with 3GPP simulation assumptions for modelling macrocell base stations to determine HeNB RF requirements given in R4-092042 [22].
Antenna height	25	m	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [24].
Cable, combiner and connector losses	0	dB	Matches assumptions used during the 900 and 1800MHZ liberalisation consultation [24] (i.e. a mast head amplifier is used).
Receiver noise figure	5	dB	Assumption in line with 3GPP simulation assumptions for modelling macrocell base stations to determine HeNB RF requirements given in R4-092042 [22].
Adjacent channel leakage ratio	45	dB	Assumption in line with section 6.6.2.1 of TS 36.104 [25]

Shadowing standard deviation	8	dB	Assumption in line with 3GPP simulation assumptions for modelling macrocell base stations to determine HeNB RF requirements given in R4-092042 [22].

Table 4-4: LTE Macrocell Base Station Parameter Assumptions

4.2 Quality of service and interference criteria assumptions

This study examines questions posed by Ofcom in the following areas related to low power shared access devices:

- Achievable coverage at various transmit power levels
- Separation distances required to minimise co channel interference
- Separation distances required to minimise adjacent channel interference

In modelling these issues we have had to make assumptions on the quality of service levels being targeted for coverage planning and reasonable levels of service degradation to be expected due to interference.

Due to the short timescales of this project, our coverage and interference models are based on a link budget calculation aimed at providing a target data rate to a single user at the cell edge rather than performing a complete system level simulation and determining the quality of service experienced across the cell. This provides a worst case scenario and an indication of the potential upper limits on licence parameters as required by Ofcom.

We have assumed that low power access points will be deployed in high densities to relieve capacity bottlenecks rather than to provide coverage. Our results therefore focus on providing the higher end data rates for bandwidths examined. These target data rates are translated to target cell edge SNR for coverage modelling or SINR for interference modelling based on the spectrum efficiency achievable in a 3GPP EVA5 channel for 2x2 MIMO [26] and allowing for the overhead of control channels and an improvement in performance due to scheduler gain [27].

In the case of coverage modelling, a fading margin is added to the target SNR which assumes that the target data rate is required across 90% of the cell area. This translates to a 78% confidence level at the cell edge given appropriate assumptions on cell geometry and shadowing statistics. In our interference analysis we apply a fading margin to the target SINR to ensure that the 78% confidence level for the target throughput at the cell edge is maintained. This fading margin is calculated from the expected SINR distribution at the victim which is based on a combination of the shadowing distribution at the aggressor and victim. The expected SINR distribution at the victim is calculated based on the average shadowing standard deviation expected between the two cases when the victim receiver is noise limited (and the SINR shadowing standard deviation is the same as the coverage case) and when it is interference limited (and the SINR shadowing standard deviation is based on the combined log normal shadowing distributions of the victim and aggressor assuming 0.5 cross correlation between the two).

When modelling the co channel and adjacent channel interference scenarios we have not set a hard limit on acceptable interference levels. Our discussions with stakeholders did not reflect a standard industry view on an acceptable performance degradation level due to interference. Our interference assessment therefore shows the different levels of throughput degradation as would be experienced by a single cell edge user at a 78% confidence level at various separation distances between the victim and aggressor. This gives the range of likely separation distances required rather than a single value.

4.3 Propagation models used

To select appropriate propagation models for this study, this section first identifies the propagation path types which occur in the scenarios identified for analysis. A survey of models used in other studies of interference amongst femtocells is then summarised. Finally models are assigned to each of the relevant path types by applying our judgement based on other studies and our experience in modelling similar systems. The individual scenario descriptions in chapters 5, 6 and 8 then identify the models used in each case.

While propagation models for specific scenarios can be highly accurate, we seek in this study to adopt a more generalised approach, which typically involves the use of models such as those provided by the ITU-R based on simple parameters such as distance, frequency and antenna heights. The wide variety of geometries and materials used in buildings make such generalisation especially difficult for the short range and indoor systems which are the subject of this study. In particular, such generalised models are unlikely to provide an accurate assessment of system performance. For our purposes this is acceptable since we seek to determine regulatory limits which protect against interference in relatively extreme scenarios. However, future operators of these systems are likely to need to adopt a more detailed approach to determine the level of service they will be able to offer to their customers in particular situations.

4.3.1 Path types to be modelled

Depending on the scenario, a wide variety of differing wanted and interfering signal paths need to be modelled. The propagation models assigned to each of these may need to be rather different, so we explicitly identify the path types here:

a) Outdoor, relatively short range for coverage, with rather low antenna heights, typically in the range of 5-10m and with relatively unobstructed paths.
b) Outdoor interference paths from cells mounted with higher antenna heights, often above the roofs of surrounding buildings.
c) Outdoor to indoor, where for example an outdoor cell is used to provide indoor coverage.
d) Indoor to indoor based on a low power cell providing coverage to an indoor user.
e) Indoor to outdoor interference, for example for an indoor low power cell creating interference to outdoor users.
f) Indoor to indoor between buildings, for example for a low power cell creating interference to an indoor user in another building.

4.3.2 Models used in other studies

The Ofcom technical study [[28]] in support of the award of the 1781.1-1785 MHz and 1876.7 MHz – 1880 bands ("DECT guard band" / "low power GSM band") makes extensive use of the propagation models in the ITU-R recommendation P.1238 [[29]] together with wall loss values as given in the COST 231[[30]] project report. It uses the free space loss plus appropriate wall losses for modelling interference between adjacent buildings. For calculating the loss between buildings with another building in between, a diffraction loss was added based on ITU-R recommendation P.526 [[31]].

The 3GPP document R4-092042 [[22]] contains common simulation assumptions specifically for modelling FDD HeNBs (LTE femtocells). This is applied within the main 3GPP technical report on interference mitigation techniques for HeNB, TR 36.921 [[32]]. The document recommends use of the following propagation models for the median path loss at a given separation distance:

- For UE to HeNB paths in the same house or apartment, two potential models are recommended. The main one corresponds to the COST231 Multi-Wall Model with parameters chosen as recommended in the original report (which focused on 1800 MHz) when predicting for the 2 GHz band, and with an assumed 4.9 m separation between walls. The other model does not model walls explicitly, but accounts for them via an increase path loss exponent relative to free space loss.
- For UE to macrocell paths, the following model is used:
  $$L\ (dB) = 15.3 + 37.6\log_{10}R + L_{ow}$$
  where L_{ow} is the loss associated with the outside wall of a building. The source for the model is not given but it follows the Okumura-Hata model for particular parameters.
- Shadowing is modelled via a lognormal distribution with a standard deviation (location variability) of 8dB for macrocell paths, 4 dB for HeNBs with explicit wall loss modelling (the COST231 Multi Wall Model) and 10 dB for HeNBs with the simplified path loss model.

- When paths between adjacent apartments are calculated, the same models are applied but an additional 5dB loss is applied to account for the loss associated with the wall separating the apartments.

The Femto Forum white paper on interference management in OFDMA femtocells [[33]] follows these 3GPP recommendations closely.

In the Femto Forum white paper on interference management for UMTS [[34]], the following models are used:

- ITU-R recommendation P.1238 [[29]] for indoor to indoor paths.
- ITU-R recommendation P.1411 [[35]] for femtocell UEs interfering with macrocells. An additional wall loss component is included for UEs which are inside buildings.
- Free space loss for calculation of 'dead zone' effects when UEs are very close to femtocells, with a minimum path loss limit applied corresponding to 1m separation.
- The COST 231 – Hata model [[30]] for macrocells, with an additional wall loss for paths to indoor UEs.
- A 3GPP micro urban model for an apartment block-to-outdoor scenario. The reference for this model is not given.

4.3.3 Selection of models according to path type

Table 4-5 provides our selection of propagation models according to the path type as used in our analysis of coverage (see chapter 5) and co channel interference (see chapter 6). In many cases existing published propagation models do not explicitly cover the 2.6 GHz band, necessitating corrections which we have been assigned based on the frequency trend of the model and other work previously published by Ofcom.

Path Type	Model
a) Outdoor, relatively short range for coverage, low height (5-10m).	The ITU-R P.1411 [[35]] model is applied for line-of-sight situations. The model provides lower bound and upper bound losses, so we use the average of these models (in decibels).
b) Outdoor interference range (diffraction over building rooftops)	We apply the version of the COST 231 Walfisch-Ikegami model [[30]] which is embodied in ITU-R P.1411 §4.2 [[35]], which covers non line-of-sight situations and base station heights 4-50m. Although this is only recommended up to 1km by ITU-R, the underlying model is valid up to 5km.

c) Outdoor to indoor (microcell providing indoor coverage)	The ITU-R P.1411 §4.2 [[35]] model is applied, with the addition of the penetration loss portion of the COST 231 LOS building penetration loss model in §4.6.3 of [[30]].
d) Indoor to indoor (femto coverage)	**For houses and indoor public areas:** The COST 231 Multi Wall Model in §4.7.2 of [[30]] is applied, with a wall separation appropriate to the environment. **For indoor office environments:** The ITU-R P.1238 model [[29]] is applied as this has been specifically developed for modelling office environments.
e) Indoor to outdoor interference (femto to outdoor interference)	The ITU-R P.1411 §4.2 [[35]] model is applied with the addition of a building penetration loss.
f) Indoor to indoor between buildings	The ITU-R P.1411 street canyon model[35] is used with two instances of penetration loss terms.

Table 4-5: Selection of propagation models according to path type

It should be noted that in the case of the adjacent channel interference scenarios presented in chapter 8 we have simplified the propagation models used as follows:

- **Impact of TDD interference from adjacent WiMAX or TD–LTE networks** – in this case we have assumed that there is a good line of sight and relatively short distance between the victim and aggressor and so it is applicable to use a free space path loss model with the addition of an external wall loss if the aggressor is outdoors and the victim is indoors.
- **Impact of S-band radar interference from radar emission in the 2.7-2.9GHz band** – in this case due to the high power of the radar the distances are too large to apply free space path loss as in the TDD interference case. Instead we have used the ITU-R P.1411 [[35]] line-of-sight model which is valid up to ranges of 5km. While interference from the radar main beam is expected to extend beyond this limit this is only present for short durations of time. The main source of interference from the radar side lobes is expected to be within this 5km range.

4.4 Typical building sizes and types in target deployments

Within this study we have examined coverage, co channel interference and adjacent channel interference in deployments environments likely to be used by low power shared access networks. These include:

- Residential deployments

- Offices
- Public areas
- Business park / campus

In addition to the device parameters described in section 4.1 the scenarios modelled make assumptions in the following areas based on the target deployments:

- Average sizes of the building
- Whether coverage is required on multiple floors
- Wall separations and penetration losses

4.4.1 Assumptions for residential deployments

When interpreting coverage results for residential deployments we have used the following benchmarks for residential building sizes in the UK:

- The average floor area of a new build house in the UK is 76 m² [[36]]
- A typical 4 bedroom detached house has a floor area of 200 m² (based on reviewing houses available on estate agents websites).
- High end properties could have floor areas up to 320 m² (based on reviewing houses available on estate agents websites).

We have assumed that in residential scenarios a single low power access point will be required to provide coverage both upstairs and downstairs. When using the COST 231 multi wall model to model indoor coverage in residential environments we have assumed the parameters shown in Table 4-6.

Parameter	**Value**	**Comment**
Distance between internal walls	4m for new build houses 6m for older houses	The average UK new build in 2009 had a room size of 15.9 m² [[36]] giving an average wall spacing of approximately 4m. For older houses we assume a larger wall spacing of 6m.
Loss for internal walls	4.2dB for new build houses 7dB for older houses	Calculated from the COST 231 wall losses at 900MHz and 1800MHz extended to 2.6GHz. The new build case assumes a wood and plaster wall whereas the older house assumes a concrete or brick wall.

Floor loss	20.2 dB	Calculated from the COST 231 floor loss at 900MHz and 1800MHz extended to 2.6GHz.
Floor spacing	3m	

Table 4-6: Parameters for indoor residential coverage modelling

4.4.2 Assumptions for offices

When interpreting coverage results for office deployments we have used the following benchmarks for office building sizes in the UK:

- An example medium sized office of a company of 60 people in a Cambridge science park has a single floor area of 840 m² [[37]]. Figure 4-1 shows that this number of employees covers the majority of office premises.
- Investment Property Databank (IPD) report that on average 12 m² of office space [[38]] is provided per private sector employee. For a large company of 500 employees this gives an office area of up to 6000 m².

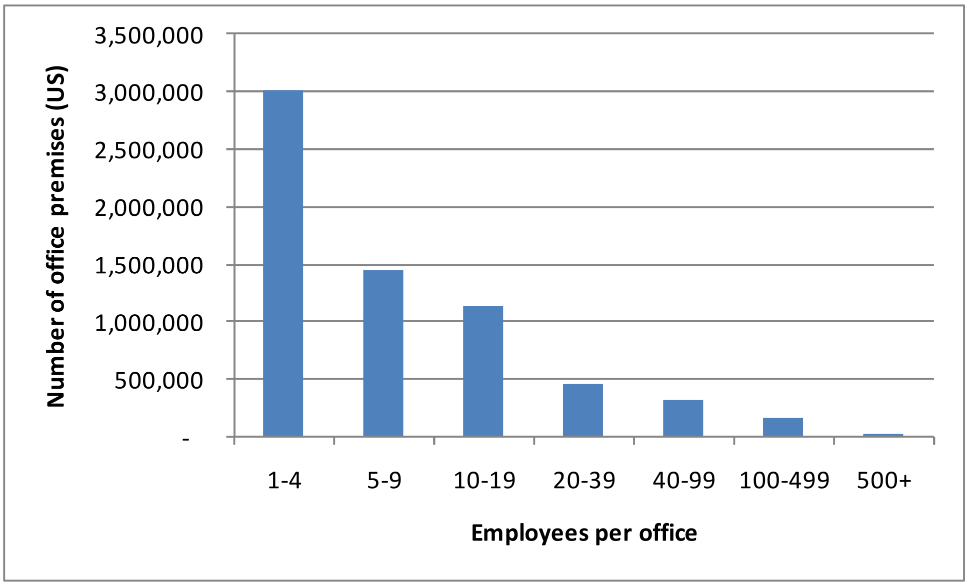


Figure 4-1: Typical numbers of employees per office in the US (provided courtesy of ip.Access based on US census data and ABI Research data)

We have assumed that in office environments coverage across multiple floors from a single access point is not crucial as access points are likely to be located on a per floor basis. When using the ITU-R P.1238 model (which has been specifically developed for a mixture of open plan and partitioned office environments) to model office coverage we have assumed the parameters shown in Table 4-7.

Parameter	Value	Comment
Distance power loss coefficient	30	Calculated based on the ITU-R P.1238 2GHz value
Floor loss	20.2 dB	This is kept the same as residential and public area deployments for consistency.
Floor spacing	3m	

Table 4-7: Parameters for indoor residential coverage modelling

4.4.3 Assumptions for public areas

For public area deployments we have focused on the example of a shopping centre as it is a challenging environment that covers a large area and includes a large number of wall losses compared to train stations or airports which tend to have large open areas.

When interpreting coverage results for public area deployments we have used the following benchmarks for shopping centre sizes in the UK:

- A very large shopping centre such as the Trafford centre in Manchester (6th largest in UK) has a floor area of 140,000 m² [[39]]
- An example medium sized shopping centre, the Sovereign shopping centre in Weston Super Mare, is approximately 7800 m² on a single floor with 40 shops [[40]]

We have assumed that in a shopping centre obtaining coverage across multiple floors from a single access point is not crucial as access points are likely to be located on a per floor basis. When using the COST 231 multi wall model to model indoor coverage in a shopping centre environment we have assumed the parameters shown in Table 4-8.

Parameter	Value	Comment
Distance between internal walls	13.5m	Based on an average shop size of 180 m² (based on retail units for rent at the Sovereign shopping centre in Weston Super Mare)
Loss for internal walls	4.2dB	Calculated from the COST 231 wall losses at 900MHz and 1800MHz extended to 2.6GHz. This assumes a wood and plaster wall.

Floor loss	20.2 dB	Calculated from the COST 231 floor loss at 900MHz and 1800MHz extended to 2.6GHz.
Floor spacing	3m	

Table 4-8: Parameters for indoor residential coverage modelling

4.4.4 Assumptions for a business park or campus

When interpreting coverage results for the business park or campus environment we have used the following benchmarks:

- A large business park, the Cambridge Science Park, of 90 companies has a land area of approximately 615,000 m² [[41]].
- We assume that multiple access points would be used to cover a science park and that a more reasonable coverage target would be the ITU microcell test environment case which assumes a 200m inter site distance (ISD).

For the business park or campus environment we examine coverage using the following models:

- Coverage from an outdoor access point achieving reasonable indoor coverage using ITU-R P.1411 with a "depth 2" building penetration loss appropriate for 2.6GHz. "Depth 2" here is shorthand for reasonable building penetration and indoor service as used in Ofcom's 900 and 1800MHZ liberalisation consultation [[24]].
- Indoor penetration by an outdoor access point using ITU-R P.1411 and a COST 231 line-of-sight building penetration loss for both a direct angle of arrival (where the access point is surrounded by buildings) and oblique angle of arrival (where the access point is providing coverage along a street).

In each of these we have assumed the parameters shown on Table 4-9

Parameter	**Value**	**Comment**
Outdoor low power access point height	5m	Assume low power access point is mounted on a lamp post.
Building penetration loss	14dB	This is a depth 2 building penetration loss appropriate for 2.6GHz.
Loss for internal walls	4.2dB	Calculated from the COST 231 wall losses at 900MHz and 1800MHz extended to 2.6GHz. This assumes a wood and plaster wall.

Internal wall separation	8m	Based on an example 60 employee office space of 840 m² at IQ science park split into 14 rooms [37].
External wall loss	7 dB at 90 ° 20 dB at 0°	Based on COST 231 values for a concrete wall with a normal size window.

Table 4-9: Parameters for indoor residential coverage modelling

4.5 Small cell interference mitigation techniques

In conventional mobile networks, cells are carefully planned and optimised by skilled engineers, using a variety of prediction, measurement and analysis tools. In a small cell deployment such an approach may not be viable, both because of the relatively higher number of cells involved and because some of the cells – especially femtocells for homes and small offices – may be deployed in locations which are not under the direct control of the operator.

To overcome this, manufacturers and standards bodies have investigated and implemented a wide range of techniques for determining the interference and coverage situation in which a small cell finds itself, and adjusting its parameters dynamically within ranges set by the operator to meet defined service quality targets. The parameters adjusted include the transmit powers of both the cells and the mobile devices which connect to them, the carrier frequencies and codes used by the cells, and the specific time and frequency resources used by adjacent cells for particular users. All of these parameters can be adjusted in response to a range of measurements, including location and performance data from the cells themselves (which may monitor both uplink and downlink frequencies), from mobiles and from the wider operator network and management system. In 3G systems, such techniques have been studied in depth by both Femto Forum and 3GPP [34,42], and are reported by operators to be effective in field operation, including when deployed co-channel with macrocells. For example, AT&T have said [43]:

> "We have deployed femtocells co-carrier with both the hopping channels for GSM macrocells and with UMTS macrocells. Interference isn't a problem. We have tested femtocells extensively in real customer deployments of many thousands of femtocells, and we find that the mitigation techniques implemented successfully minimise and avoid interference. The more femtocells you deploy, the more uplink interference is reduced"

However, the specific techniques used to mitigate interference and manage performance are not generally mandated by standards, but are left to the individual manufacturer and operator to determine. The specifications provide the 'hooks' to enable these techniques to operate successfully. For 3G, the following key dimensions were identified by the Femto Forum in [34]:

- "Femtocell downlink power – if femtocells transmit inappropriately loudly, then the cell may be large, but non-members of the closed user group will experience a loss of service close to the femtocell. On the other hand, if the femtocell transmits too softly, then non-group members will be unaffected, but the femtocell coverage area will be too small to give benefit to its users.
- Femtocell receiver gain – since UEs have a minimum transmit power below which they cannot operate, and since they can approach the femtocell far more closely than they can a normal macrocell, we must reduce the femtocell receiver gain, so that nearby UEs do not overload it. This must be done dynamically, so that distant UEs are not transmitting at high power, and contributing to macro network noise rise on a permanent basis.
- UE uplink power – since UEs transmitting widely at high power can generate unacceptable noise rise interference in the macro network, we signal a maximum power to the UE (a power cap) to ensure that it hands off to the macro network in good time, rather than transmit at too high a power in clinging to the femtocell."

When such mitigation techniques are applied, there is potential for very high capacity densities arising from intensive re-use of spectrum over a given area and in [[34]] simulations indicate the potential for air interface data capacity to increase by over a hundredfold by the introduction of femtocells co-channel with macrocells.

However, the scenario under investigation in this study is rather different from the one which is usually studied when evaluating such techniques. Differences occur in the following ways:

- Interfering cells may not be under the control of the same operator, so there is less opportunity for coordinated optimisation. This situation could be reduced by setting appropriate limits and conventions on cell behaviours, either via licence conditions or more likely via an agreement amongst operators.
- Users belonging to one operator may come close to the low-power cell of another and both suffer and cause interference as result (the so-called 'visitor problem'). This situation also arises in a single operator situation when closed subscriber groups are used, but may be more common when so many operators share the same channel and is exacerbated in the case of a potential underlay network. A possible remedy for this would be for operators to allow roaming of users amongst cells, potentially only in cases of extreme interference, similar to the hybrid access mode which is already envisaged for use by individual operators.
- If low-power operators wish to deliver the full potential throughput which the technologies can offer, they will need to occupy the full 10 MHz or 20 MHz channel bandwidth, giving no opportunity to shift carrier frequencies when extreme cases of interference are encountered. However, both LTE and WiMAX utilise OFDMA technology which allows subcarriers within the bandwidth to be allocated to particular users according to their interference conditions.

It is important to note that in likely small cell technologies such as LTE the common control channels will present a different set of interference mitigation challenges to the shared data channels due to their fixed locations in time and frequency. We next review potential interference mitigation techniques that might be applicable to low power shared access networks based on work from both 3GPP and the Femto Forum. We first outline typical environment measurements that are likely to be available in low power shared network devices based on typical capabilities of LTE UEs and femtocell access points (FAPs). Our discussion is then split between interference mitigation techniques applicable to data channels, which will limit throughput in the shared network, and techniques applicable to control channels, which may limit the number of allowable overlapping low power shared networks and introduce additional overheads.

4.5.1 Environment measurements likely to be available in LTE femtocells

3GPP technical report TR 36.921[[32]] summarises contributions to 3GPP on interference mitigation techniques for use in LTE small cells. This document includes a list of potential measurements which can be made by a HeNB (LTE femtocells) and is shown on Table 4-10. These measurements are all feasible based on standard reference channels and broadcast information used in LTE networks. For example measurements such as path loss are commonly carried out by LTE UEs as part of the uplink power control process. These measurements could also be exploited for interference mitigation.

It should be noted that where a measurement is collected by a HeNB DL receiver, this requires the HeNB to act as a UE rather than base station. This functionality known as “Network Listen” or “Remote Environment Monitoring” is a standard feature in commercial 3G FAPs and, while not mandated within the 3GPP standards, is an integral part of the initial FAP set up. It is likely that this feature could easily be incorporated in LTE FAPs also.

Measurements of	Measurement Type	Purpose	Measurement Source(s)
All cells	Received Interference Power	Calculation of UL interference towards HeNB (from MUE)	HeNB UL Receiver
Surrounding cell layers	Cell reselection priority information	Distinction between cell types based on frequency layer priority	HeNB DL Receiver
	CSG status and ID	Distinction between cell layers based on CSG, and self-construction of neighbour list,	HeNB DL Receiver
Macrocell layer	Co-channel RSRP	Calculation of co-channel DL interference towards macro UEs (from HeNB) Calculation of co-channel UL interference towards macro layer (from HUEs) Calculation of co-channel UL interference towards HeNB (from MUEs) based on estimated MUE Tx power Determine coverage of macro cell (for optimization of hybrid cell configuration)	HeNB DL Receiver HUE MUE (in case of hybrid cell)
	Co-channel RSRQ	Determine quality of macro cell (for optimization of hybrid cell configuration)	HeNB DL Receiver HUE MUE (in case of hybrid cell)
	Reference Signal Transmission Power	Estimation of path loss from HUE to MeNB	HeNB DL Receiver
	Physical + Global Cell ID	Allow HeNB to Instruct UEs to measure specific cells. Allow UE to report discovered cells to HeNB.	HeNB DL Receiver HUE
	Detection of UL RS	Detection of victim UE	HeNB UL Receiver
	Co-channel received CRS Êc (measured in dBm)	Measurement is used to determine whether HeNB is close to dominant Macro cell, or whether it is close to macro-cell-edge border.	HeNB DL Receiver
Adjacent HeNBs	Co-channel RSRP	Calculation of co-channel DL interference towards neighbour HUEs (from HeNB) Calculation of co-channel UL interference towards neighbour HeNBs (from HUEs)	HeNB DL Receiver HUE
	Reference Signal Transmission Power	Estimation of path loss from HUE to HeNB	HeNB DL Receiver
	Physical + Global Cell ID	Allow HeNB to Instruct UEs to measure specific cells Allow UE to report discovered cells to HeNB.	HeNB DL Receiver HUE

Table 4-10: Measurements available to LTE HeNBs from 3GPP technical report TR 36.921[[32]]

4.5.2 Mitigating data channel interference in LTE

Both the Femto Forum and 3GPP have carried out studies into interference mitigation in LTE femtocells. This section summarises their findings as appropriate to data channels.

Techniques from Femto Forum study of interference management for OFDMA femtocells

The Femto Forum published a study "Interference Management in OFDMA Femtocells" [[33]], focusing entirely on the case of closed user groups, which is comparable with the case of multiple operators with no roaming arrangements between them. The study focused on the 2GHz band, but the general findings are expected to be reasonably applicable to 2.6 GHz band. Ten key scenarios where identified where interference could be challenging. Only two of these related to interference amongst femtocells and the associated mobiles, while the others were related to interactions between femtocells and macrocells. The majority of the scenarios examined relate to interference and the consequent reduction in throughput on the data channels. Note that all femtocells in this study were deployed indoors.

Scenario	Outcome
Macrocell Downlink Interference to the Femtocell UE Receiver (A1)	Throughput degradation was limited to less than 1%
Macrocell Uplink Interference to the Femtocell Receiver (B1)	Interference power lower than thermal noise power: no detectable degradation of average throughput.
Femtocell Traffic Channel Downlink Interference to the Macrocell UE Receiver (C1)	Degradation can occur without mitigations, but mitigations are effective in reducing degradation – see below.
Femtocell Control Channel Downlink Interference to the Macrocell UE Receiver (C2)	Significant degradation of performance can be experienced for a visiting (same building) macrocell UE when within a 'deadzone' of tens of meters depending on the transmit power without mitigations. A 'passing' UE protected by a building wall experiences interference over several meters from the femtocells. Power control is expected to be effective in a similar way to the previous scenario but is not analysed in the report. Handover of the macrocell UE to another frequency is another mitigation suggested.

Femtocell Uplink Interference to the Macrocell NodeB Receiver (D2)	Potential interference is mitigated by placing a power cap on femtocells UEs as a function of pathloss to the macrocell, based on minimising noise rise below a specified level. If the target is less than 0.2 dB noise rise, macrocell average sector throughput is degraded by between 0 and around 20% and 5-percentile user throughput by up to 40% as the number of femtocells increases from 0 to 80 per sector. The throughput degradation of the femtocells users is significantly less. Although the total throughput of both systems combined is always increased by the addition of the femtocells, this is not so relevant in the case of different operators. A more advanced scheme signals the interference actually experienced at the macrocell via an interface between the two systems (the X2 interface defined by 3GPP) and significantly reduces the macrocell degradation, but would require close cooperation between the macrocell and low-power operators.
Femtocell Downlink Interference to Nearby Femtocell UE Receivers (E)	A distributed fractional frequency reuse system is proposed to mitigate interference in this situation. Each cell constructs a neighbour list through network listening and user reporting. This is used to establish a reuse pattern of the available bandwidth to maximise performance. Performance of the worst-affected is substantially improved relative to having no reuse scheme, with 20-30% of users achieving double the throughput depending on the penetration of femtocells. This would rely on the operators all adopting a similar scheme. A dynamic interference avoidance scheme is also studied, which can be achieved via over-the-air coordination to avoid a physical interface between operators. It is found to significantly improve performance over uncoordinated approaches, especially as regards the latency experienced in the presence of strong interference from loaded cells.

Femtocell Uplink Interference to Nearby Femtocell Receivers (F1)	Full mobile transmit power and two adaptive power control mitigation techniques (fractional and noise rise) are compared. At large deployment densities, fractional power control achieves better cell edge throughput than full power at the cost of lower average cell throughput. At low deployment densities, allowing full power operation is found to give higher system performance. The probability of large degradations is anyway found to be low such that overall system performance is acceptable.
Macrocell Downlink Interference to an adjacent channel Femtocell Receiver data channel (G3)	A 5 MHz adjacent channel frequency separation is examined. With 3GPP adjacent channel selectivity levels, 99% of locations experience SINR of 8dB or greater with 0dBm femtocell power. Overall performance degradation should therefore be small provided the femtocells power is set sufficiently high to provide good quality coverage in a given environment.
Macrocell Downlink Interference to the adjacent channel UE Femtocell Receiver (control channel) (G4)	Similar findings to the previous scenario – no major degradation.
Macrocell Uplink Interference to the adjacent channel Femtocell Receiver (H1)	Femtocell UEs are assumed to increase their power in response to the approach of a high power macrocell UE. 95% of locations are found to experience an SIR greater than 14dB, so the impact should be small.

Table 4-11: Summary findings from Femto Forum study of OFDMA femtocell interference mitigation techniques

In the case of potential downlink interference from femtocells to macrocell user equipments (UEs), performance degradation can be significant if unmitigated. Three potential interference mitigation techniques were studied:

a) *Distance based power control*, where the femtocell transmit power is reduced at close distances from a macrocell. This requires that the locations of the macrocells are previously known to the femtocell operator, which is unlikely in our scenario. The cell throughput was found to be largely unaffected at small numbers of femtocells but eventually to lead to significant throughput degradation at higher densities. The overall aggregate cell throughput was largely unaffected, but there are significant throughput degradations for a small number of particular users.

b) *Power control based on pathloss*. In this case a power limit is placed on femtocells to protect the macro downlink as a function of the measured pathloss to the neighbouring macrocells. The results indicated that interference was well controlled, with an increased average throughput and reduced outage probability even compared with the macrocell-only case, although clearly in this situation macrocell UEs are able to access the femtocells.

c) *Power control based on pathloss and detection of the presence of victim UEs*. This can be achieved without knowledge of the macrocell locations. Additionally the femtocell detects transmissions from the macrocell users and adjusts its power accordingly. The technique appeared effective and increased the throughput available to UEs.

In summary, interference mitigation techniques are important to achieve good performance. This is particularly acute when considering interference to co-channel macrocell users, where even with mitigation techniques, the macrocell operator's performance can be significantly affected, despite overall (macro+femto) capacity being increased. Amongst shared low power operators, good performance appears possible and can be enhanced via cooperation on the forms of interference mitigation technique which are implemented.

Techniques from 3GPP technical report TR 36.921

3GPP technical reports do not form mandatory specifications but are purely informative. Nevertheless technical report TR 36.921[[32]] provides details of the means by which various factors can be controlled to mitigate interference, particularly the transmit power but also including variable bandwidth and allocation of subcarriers. It also provides guidance to operators on techniques which may be used to set the appropriate values for these factors.

The report lists techniques for controlling interference for both the downlink and the uplink.

Downlink

Frequency partitioning to control downlink HeNB interference to macro eNB data channels

HeNBs operating in underlay mode could obtain frequency partitioning information from the overlayed eNBs if they have a downlink receiver. This does not require that the resource blocks used by the macrocell are completely avoided as this would cause a severe loss in capacity. Instead the macro eNB can preferentially use one set of resource blocks for users close to the macro and others for cell edge users. Based on a knowledge of its location or of the path loss to the macro, the HeNB can avoid resource blocks likely to be used by nearby macro UEs.

Control of HeNB downlink interference among neighbouring HeNBs

LTE supports sub-band fractional frequency reuse via channel quality information reporting. In a 10 MHz system with 6 resource blocks per sub-band, there are 8 regular sub-bands and one short sub-band that could be used to implement fractional frequency reuse.

The HeNBs can listen to neighbouring control channel and reference signal transmissions, determine the corresponding cell IDs and measure the associated path losses. UE measurement reports can also be used. Based on these measurements HeNBs can use a fractional frequency reuse scheme to avoid transmitting on the same resources as neighbouring HeNBs. This could be achieved via a centralised coordinator which uses the reports to form an 'adjacency graph' based on the measurement results and assigning resources to the HeNBs accordingly. This would require a specific interface between low power operators, or perhaps a third party which would operate the central controller on behalf of the operators. Alternatively each HeNB could construct its own 'jamming graph;' and one of a number of known distributed algorithms could be used to select resources. For example, an autonomous technique described in [[44]] concludes that:

> "Extensive simulation results provide evidence that the presented concept renders average cell throughput virtually insensitive to the density of neighboring femtocells, without compromising cell edge user throughput when compared to universal frequency reuse. Hence, it provides a fully distributed (scalable) and self-adjusting frequency reuse mechanism, which allows for uncoordinated eNB deployment without prior (expensive and manual) network planning."

This would rely on all low power operators adopting a similar technique, or at least operating in a 'fair' manner. The algorithms used on the HeNBs would not necessarily need to be identical, but they would need to be used in a manner which still led to fairness. This requires less technical coordination and is perhaps more likely for the low power concurrent operators than an approach involving a specific interface and a central controller.

Control of HeNB downlink interference by dynamically changing closed subscriber group IDs

When closed subscriber groups (CSG) are used, interference can occur to UEs close to a HeNB whose CSG it does not belong to. This would be the normal case for UEs of low-power operators. One approach to minimising this is for a special dedicated CSG to be assigned and for the CSG IDs for HeNBs to be assigned to the special CSG ID in a coordinated manner, reducing the number of mobiles experiencing interference. This is essentially a limited form of roaming arrangement, to be used only when interference is experienced or predicted. The report indicates that the control of this process would be conducted by a centralized controller, but it is possible to envisage distributed approaches to the same technique.

Victim UE aware downlink interference management

By explicitly detecting the presence of nearby UEs liable to be victims of interference, it is possible to ensure that mitigation techniques such as power control and resource allocation are only used when required, avoiding wasted capacity. This can be done on the basis of reported measurements from the UEs (which may require access to an appropriate interface between cells) or based on detected uplink transmission, which can be done without access to an interface. UEs likely to suffer interference are also likely to be transmitting at high power and close to the aggressor cell, so these transmissions should be detectable with high reliability.

Power control

Power control is an important interference mitigation technique, allowing a careful trade-off between coverage and interference on a dynamic basis. HeNBs will typically include a downlink receiver, allowing them to detect surrounding cells at their location. This alone may not, however, provide a good indication of interference conditions, since the victim UEs are in entirely different locations and could suffer significantly higher interference (Figure 4-2 provides an example). Measurements from UEs are therefore also useful in setting the power appropriately. The setting of the power based on these measurements depends on an appropriate trade-off between interference caused and the performance degradation in your own cell. Low-power operators may wish to agree on some of the relevant parameters in order to ensure a fair approach.

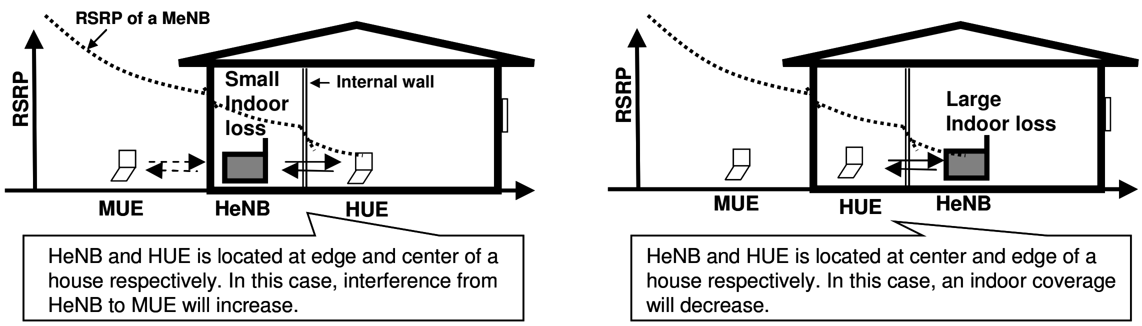


Figure 4-2: Scenarios where HeNB transmit power are not appropriately set by HeNB measurements alone (Source: 3GPP, from [42])

The quality of GPS signals can also be used as an input to the HeNB power control process. Poor GPS detection performance (based on the number of satellites detected and the reception quality) is correlated with scenarios where the HeNB is indoors or otherwise shielded and relatively unlikely to cause interference to macrocells. When GPS performance is good, the HeNB can set a lower power to protect the macrocells.

Uplink

Power control

To avoid creating uplink interference, HeNB-connected UEs (HUEs) should have their power set based on path loss from the HUE to its nearest neighbour macro eNode-B. The path loss can be estimated directly by the HUE from measurements of the macrocell Reference Signal Received Power and by decoding messages which provide the macrocell transmitted power. The maximum HUE transmit power can be set as a simple function of the estimated macrocell path loss or based on a combination of the macrocell path loss and the path loss to the serving HeNB to balance any loss in performance for both systems appropriately.

Approaches to the "visitor problem"

Additionally, the report discusses the concept of Hybrid Cells which are included in the 3GPP Release 9 specification. In a conventional Closed Subscriber Group cell, UEs which are not members of the CSG gain no access to the cell and can suffer and create interference as a result, particularly when they are at the edge of their serving cell (macro or HeNB) but close to the CSG HeNB. In hybrid access mode, CSG UEs still have priority access to the CSG cell, but other UEs may be granted admission on a conditional basis when the potential for interference is high. The result of a simulation of interference between macrocells and hybrid cells is shown in Table 4-12, where a significant reduction in outage probability and increase in cell-edge throughput results relative to conventional CSG HeNB even with adaptive transmit power.

This technique could be used in a slightly modified form as 'selective roaming' amongst low-power concurrent operators, or even between low-power and high-power operators in an underlay configuration.

	Outage Probability (SNR < -6 dB)	Worst 20% mobile throughput (kbps)	Median throughput (kbps)
No HeNB	12.7%	35	150
CSG HeNB with fixed Tx power of 8 dBm	18.9%	100	5600
CSG HeNB with adaptive Tx power	9.8 %	250	3300
Hybrid HeNB with fixed Tx power of 8 dBm	2%	900	5100
Hybrid HeNB with adaptive Tx power	3%	400	3400

Table 4-12: Improvement of performance using hybrid cells: results from simulation of interference between HeNB and macro eNB with conventional CSG HeNB (source: 3GPP [[32]])

4.5.3 Mitigating common control channel interference in LTE

The modelling of interference in section 6 focuses on the throughput performance of user data. However, LTE also requires successful decoding of common control channels such as the Physical Broadcast Channel (PBCH), primary and secondary synchronisation channels, Physical Downlink Common Control Channel (PDCCH) and Physical Uplink Control Channel (PUCCH). This section explains the additional interference issues associated with these channels compared to the shared data channels discussed in the previous section.

As described in the previous section, power control and dynamic scheduling are key elements of interference mitigation on the shared data channels for small cells. While power control can also be applied to reduce interference on the common control channels, dynamic resource scheduling is less transferrable. On the downlink shared data channel resources can be dynamically scheduled to be allocated around the interference as distributed scheduling is permitted. Scheduling is slightly less flexible on the uplink as resource blocks can only be assigned in contiguous assignments but the same general principles apply. However, common control channels both on the uplink and downlink are less flexible as they have fixed time and frequency resource locations. The locations of the common control channels for the downlink are illustrated in Figure 4-3 and Figure 4-4.

As the common channels occur at fixed intervals, if they do overlap with the common channels of a macrocell or another low power cell the interference will be continuously present on these channels. By contrast, if the interference was from an overlapping shared data channel the interference would come and go depending on scheduling. Also while the power of shared data channel resources causing interference can potentially be reduced, this is less feasible for overlapping common control channels as they need to be recoverable across the entire cell. For these reasons 3GPP TR36.921 [[32]] summarises techniques to avoid overlapping control channels between interfering small cells or between small cells and macrocells.

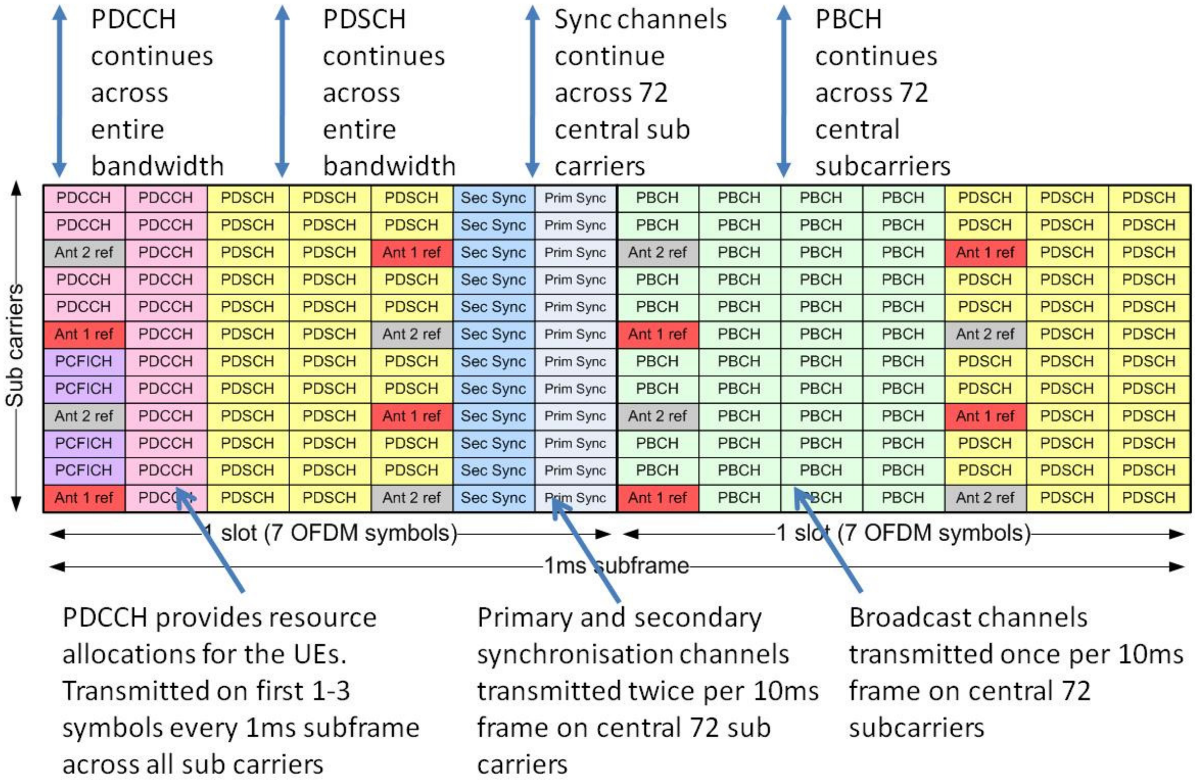


Figure 4-3: Control channel allocation in LTE downlink (note only first subframe and central 12 sub carriers shown)

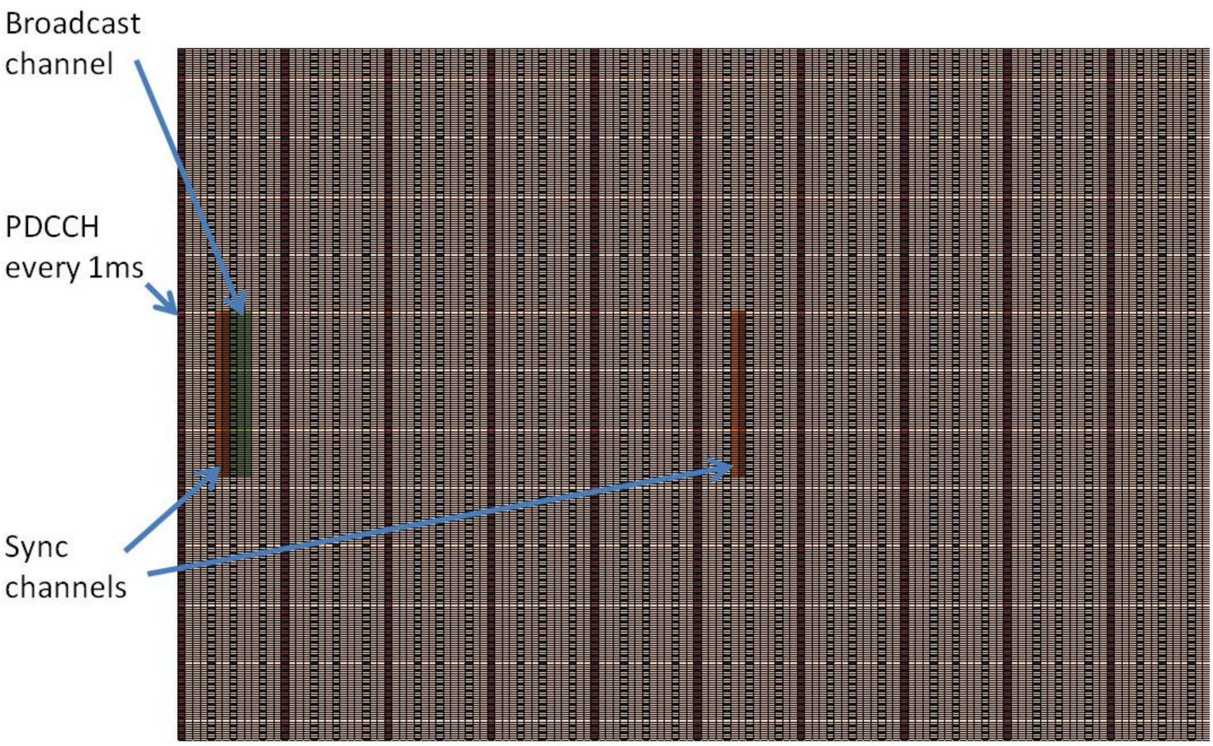


Figure 4-4: Downlink common control channel locations in a 5MHz bandwidth for a 10ms frame

While in the case of the low power shared network being examined in this study operators will most likely in practice work out amongst themselves the best approach to avoid the issue of interference on common control channels, it is useful to know if overlapping control channels could place a restrictive limit on the maximum number of overlapping low power networks and the impact on capacity as the number of operators and potential overlapping networks grows.

3GPP TR 36.921 suggests three approaches to avoid overlapping common control channels on the downlink:

- Time shifting
- Carrier offsetting
- Frequency partitioning

Time shifting

To avoid overlapping common control channels a timing offset could be applied between interfering networks as illustrated in Figure 4-5. Assuming that the low power networks will have a low number of users and only require 1 OFDM symbol for the PDCCH then 14 different time offsets could be applied to avoid overlapping PDCCH allocations between interfering networks. However, examining the position of the broadcast and synchronisation channels this would be reduced to 5 time offsets to avoid overlapping allocations on these. The main advanatage of this technique is that all operators still have the opportunity to schedule the shared data channel in resources across the entire shared channel bandwidth (unlike in frequency partitioning discussed later). However, this technique relies on timing synchronisation between networks which will be difficult to achieve across multiple operators. Also as the number of overlapping networks increases the opportunity to schedule the shared data channel will reduce as each network will need to avoid resource blocks containing their own control channels and at least transmit at a reduced power level in the resource blocks used by the common control channels of the overlapping cells. While the exact impact on the capacity of this technique is not straightforward to determine as resources may be reused in other parts of the cell or at lower transmit powers, in a worst case scenario where resource blocks being used for the common control channels of any of the overlapping low power networks must be avoided and assuming the capacity is shared equally across networks the capacity experienced by each network would be:

$$\frac{Shared\ channel\ total\ capacity}{No\ of\ contending\ networks} - (Control\ overhead\ in\ reduced\ no.of\ time\ slots)$$

Network 1

Network 2

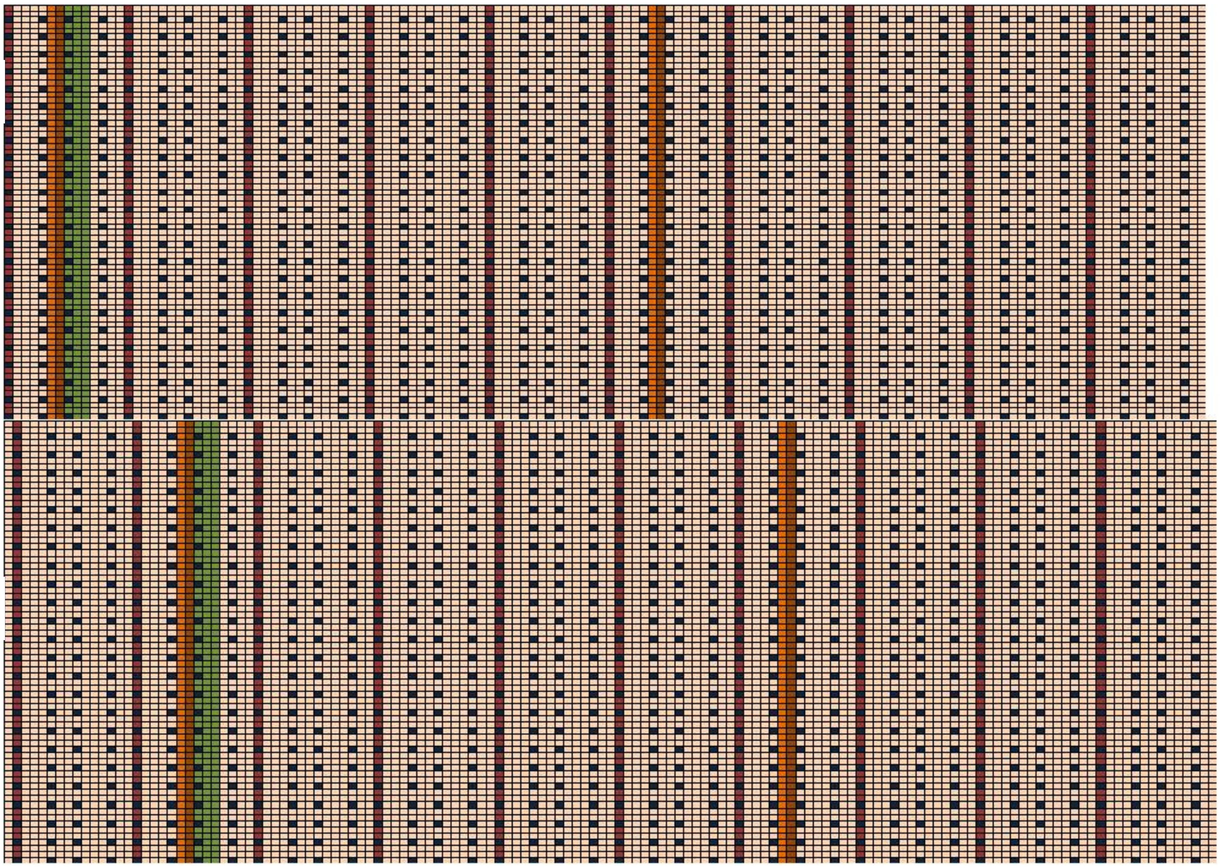


Figure 4-5: Time offsetting by 1 OFDM symbol on the downlink to avoid control channel interference (central 1.4MHz of the bandwidth only shown for each network)

Carrier shifting

To avoid an overlap on the synchronisation and broadcast channels a carrier offset of 72 sub carriers (1.08MHz) can be applied. However, we assume that in the spectrum options being assessed for the low power channel that offsetting the entire band by this amount is not feasible. Low power operators sharing the band would therefore need to partition the shared band into smaller channels and offset these smaller bands from one another which is similar to frequency partitioning as discussed next. This technique would also need to be used in conjunction with time offsetting to avoid interference on the PDCCH as this spans the entire bandwidth. It would also require coordination between operators to work out time synchronisation and agree band resizing and offsets.

Frequency partitioning

To avoid overlap on all common control channels both on the uplink and downlink, frequency partitioning can be applied. This is where each contending network would be assigned an equal share of the low power shared network channel in overlapping areas. As LTE supports variable system bandwidths this approach is already well supported by existing LTE equipment but may require some coordination or code of practice between operators to agree when low power networks should revert to a lower bandwidth. As LTE supports a minimum system bandwidth of 1.4MHz in a 2x10MHz band this would imply that in a worst case scenario 7 contending networks could be accommodated whereas in a 2x20MHz band this would be increased to 14.

It should be noted that with this technique as each contending network is now using a smaller bandwidth their capacity will be reduced due to two factors:

- The direct reduction in the number of resource blocks due to the reduction in system bandwidth
- The increase in overhead due to the common control channels occupying a higher proportion of the smaller bandwidth as illustrated in Figure 4-6.

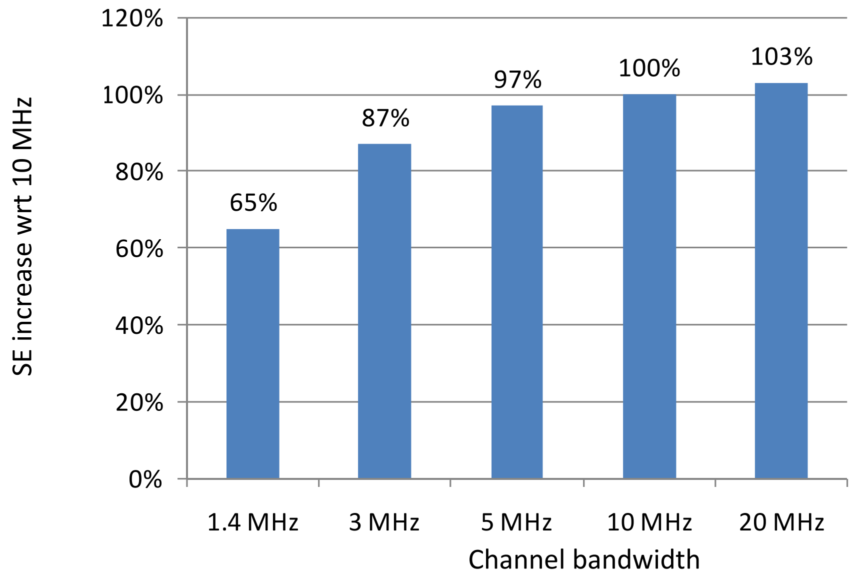


Figure 4-6: Spectral efficiency comparison for different bandwidths. The plotted values are relative to 10MHz. (Source: [[45]])

The capacity experienced by each contending network will therefore be:

$$\frac{Shared\ channel\ total\ capacity}{No\ of\ contending\ networks} - (Increase\ in\ control\ overhead\ in\ reduced\ bandwidth)$$

A further enhancement applicable to release 10 UEs is the hybrid frequency partitioning approach. This uses frequency partitioning to avoid control channel overlap but makes use of unused resource blocks in the frequency partition of contending networks spectrum aggregation. This approach can also be used to ensure that that the control channels of the two networks are kept when small cells are partially overlapped with macrocell networks.

On the uplink the main challenge is to avoid overlap on the PUCCH which is located at the edge of the system bandwidth as illustrated in Figure 4-7. One approach suggested in 3GPP TR 36.921 is for a HeNB to over allocate sub carriers to the PUCCH so that it and a contending network can use half of this allocation each. However, the disadvantage with this technique is that the size of the PUCCH increases with the number of contending networks which reduces the remaining resources in the centre of the system bandwidth for the shared data channel.

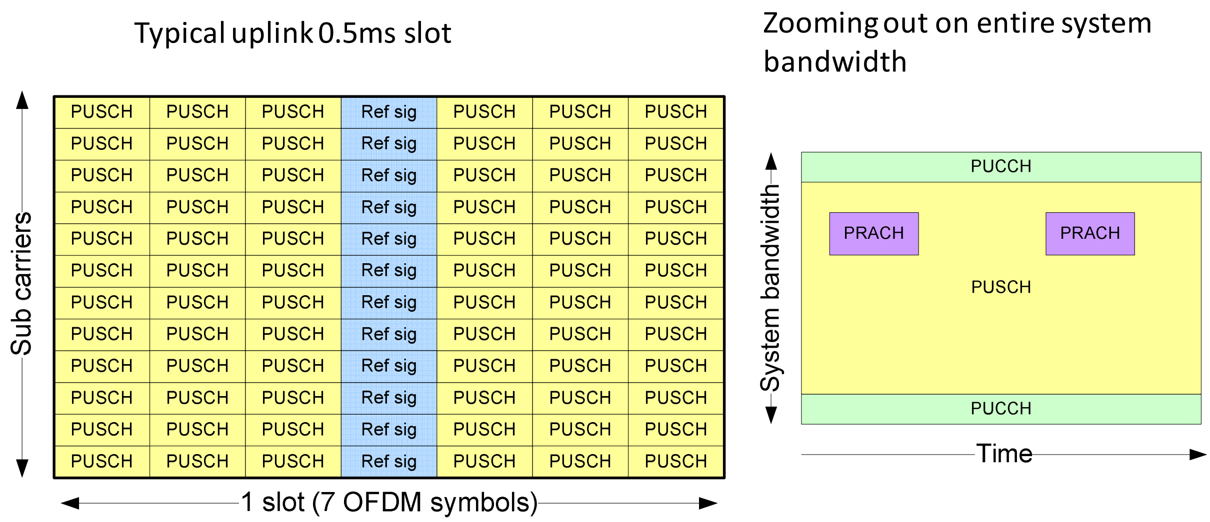


Figure 4-7: LTE uplink channels

Conclusions on control channel interference mitigation techniques applicable to a low power shared access network

In summary we can conclude the following from applying the 3GPP suggestions to the low power shared access network being examined in this study:

- In overlapping deployments frequency partitioning is the most practical approach to avoid interference on the control channels. This assumes that dividing capacity by the number of overlapping operators is acceptable
- For a 10MHz deployment this implies a limit of 7 overlapping networks each with a minimum bandwidth of 1.4MHz
- For a 20MHz deployment this implies a limit of 14 overlapping networks each with a minimum bandwidth of 1.4MHz
- The capacity experienced by each operator will be less than the shared channel capacity divided by the number of contending networks as the overhead of the common channels will occupy a larger portion of each contending network's now reduced bandwidth
- More contending networks could potentially be accommodated by applying time shifting on the downlink and PUCCH over allocation on the uplink in combination with frequency partitioning but this would be difficult to coordinate in practice and would likely lead to unacceptable waste of spectrum capacity due to increased overheads and difficulties guaranteeing a level of service for low power operators.

- These conclusions are based on LTE control channels and currently proposed interference mitigation techniques. Other approaches may be suggested as the technology matures.
- It should be noted that not all licenced low power operators will deploy in one area and so the limits on overlapping networks indicated here may be part of a code of practice amongst operators rather than a hard limit on the number of low power shared access licences available.

4.6 Stakeholder views

Although an extensive survey of stakeholders was not in scope for this study, we have made contact with a limited number of vendors of femtocells and other small cells in order to determine their views on the feasibility of concurrent operation, and on the likely capabilities of practical equipment for this band. Views on two particular issues were sought:

- Appropriate transmit power levels to provide adequate coverage in a range of scenarios
- The effectiveness of interference mitigation techniques in the specific scenario of concurrent operation in the same spectrum by different operators.

Only vendor stakeholders were consulted, namely:

- Ubiquisys, a femtocell vendor
- Picochip, a vendor of system-on-chips for femtocells
- A tier one mobile infrastructure equipment vendor

The main points of the feedback received were as follows:

Ubiquisys

- Much of the experience gained from deploying interference mitigation techniques in commercial 3G femtocell systems is also applicable, albeit in modified form, for LTE.
- For home deployments, in the vast majority of homes, considerably less than +20dBm is required to provide good coverage. However, for public spaces and large enterprises considerably more may be required to provide adequate service, particularly if it is desired to achieve reasonable indoor coverage from outdoor cells.
- In a concurrent operator scenario, notably in public places, some level of interference and associated performance degradation is inevitable if no coordination is applied, at least for dense deployments and where traffic levels are high. This degradation is not avoided by reducing the maximum transmit power, since cells will simply need to be closer together to avoid interference, so it would be better to give operators the freedom to deploy up to relatively high power levels, perhaps up to +30 dBm.
- The interference mitigation techniques used in LTE for single operator deployments should be applicable to concurrent access, although techniques which rely on technical interfaces between operators are less likely to be useful.
- The requirement to register low power networks on a central database could be linked to a certain power level threshold (e.g. 20dBm). Others factors such as height could also be used

to determine if registration on a central database and subsequent sharing obligations where necessary for a particular low power network.

- Generally it is the lack of isolation of low power networks rather than the maximum transmit power that causes the most interference concerns. Therefore the most challenging environments for sharing are likely to be public outdoor spaces where there is no natural isolation between networks.
- Allowing devices to roam to and from the macro network could be key in solving many of the interference issues associated with low power networks.

Picochip

- Transmit power should be higher than 20 dBm to provide useful coverage for applications beyond the home. The 3GPP local area base station specification of +24 dBm would be a useful starting point, combined with some moderate antenna gain.
- Several of the conventional techniques for interference mitigation within a single operator network are likely to be inapplicable or at least less favourable for the case of concurrent shared access, in particular those involving open/hybrid access (which corresponds to roaming in the concurrent case) or inter frequency handover.
- However, new techniques are continuously being developed and it is likely that existing techniques could be modified or enhanced to suit this scenario. No major specification or equipment changes would be needed to suit this case: essentially the same 'toolbox' of techniques would be used, but some additional optimisation might be needed potentially together with some additional agreements on approaches and caps of power levels in particular situations to be agreed amongst the relevant operators.

Infrastructure Equipment Vendor

It should be noted that the views expressed here are indicative by nature, derived from past experience and discussions; no conclusive research specifically on the topic was carried out.

- Felt that dedicated spectrum for concurrent low power access was the preferred situation, notably because it would be difficult to avoid the 'visiting problem' in this case without roaming arrangements amongst operators.
- If an underlay approach was adopted, however, it may be useful to offset the low power channel to overlap with two conventional channels, increasing the opportunity for frequency partitioning to avoid interference to the nearest macrocells in the overlay network.
- In 3GPP simulations it is common to assume 30 dBm EIRP for outdoor femtocells and 20 dBm EIRP for indoor femtocells. For outdoor cells covering outdoor mobiles, 27 to 30 dBm EIRP is sufficient for good coverage along 'street canyon' environments.
- However, providing good levels of coverage into buildings from outdoors is likely to require significantly higher powers, up to around 37 to 40 dBm EIRP. Such power levels are probably too high to justify a distinct low-power operation, and would certainly create excessive interference in an underlay situation.
- The main interference mitigation technique of relevance is simply to apply downlink power control based on a variety of uplink and downlink measurements and an appropriate algorithm to relate the measurements to the maximum transmitted power. Other techniques of relevance include cell selection based on path loss, time offsets to avoid

interference between control channels and the use of hybrid modes as specified in 3GPP TR 36.942.

- There is scope for standardising advanced interference mitigation techniques to be suitable specifically for this concurrent operator case. It may be important to ensure that differing techniques are compatible with each other and do not lead to damaging instabilities, where for example all cells decide to increase their power towards the maximum to establish dominance over surrounding interferers.
- In public spaces where multiple operators are deploying, coordination will be necessary to achieve good performance, although with some performance degradation uncoordinated deployment should be possible.
- In the case of private environments such as homes, or offices with a single operator, the most challenging interference situation is when the closest adjacent home/office has a low power cell from another operator. Such situations need to be considered and appropriately handled whether there are 2 operators or 10 in the same spectrum, so the selection of the appropriate number of operators is mostly not related to technical issues.

4.7 We have made reasonable simplifying assumptions regarding interference mitigation techniques based on the literature and stakeholder feedback

It is not the prime purpose of the study to examine the detailed algorithms available for LTE femtocells to mitigate and avoid interference. Nevertheless, our analysis of co-channel interference needs to make reasonable assumptions concerning the potential performance of such techniques (at least in the challenging conditions of main interest to this study) to avoid being overly pessimistic compared to the low power networks that are likely to be deployed in practice. Our co-channel interference analysis assumes the use of two interference mitigation techniques on the data channels:

- The application of power control so that the low power access point transmits no more than is required to achieve the target cell edge throughput in the deployment area.
- The use of dynamic resource scheduling to share capacity and avoid resource blocks experiencing interference where possible.

In the second of these techniques we have chosen to model two scheduling approaches; a *dynamic scheduler* and a *random scheduler*. The operation of these is illustrated in Figure 4-8 for the case of two cells adjacent to each other and contending for resources.

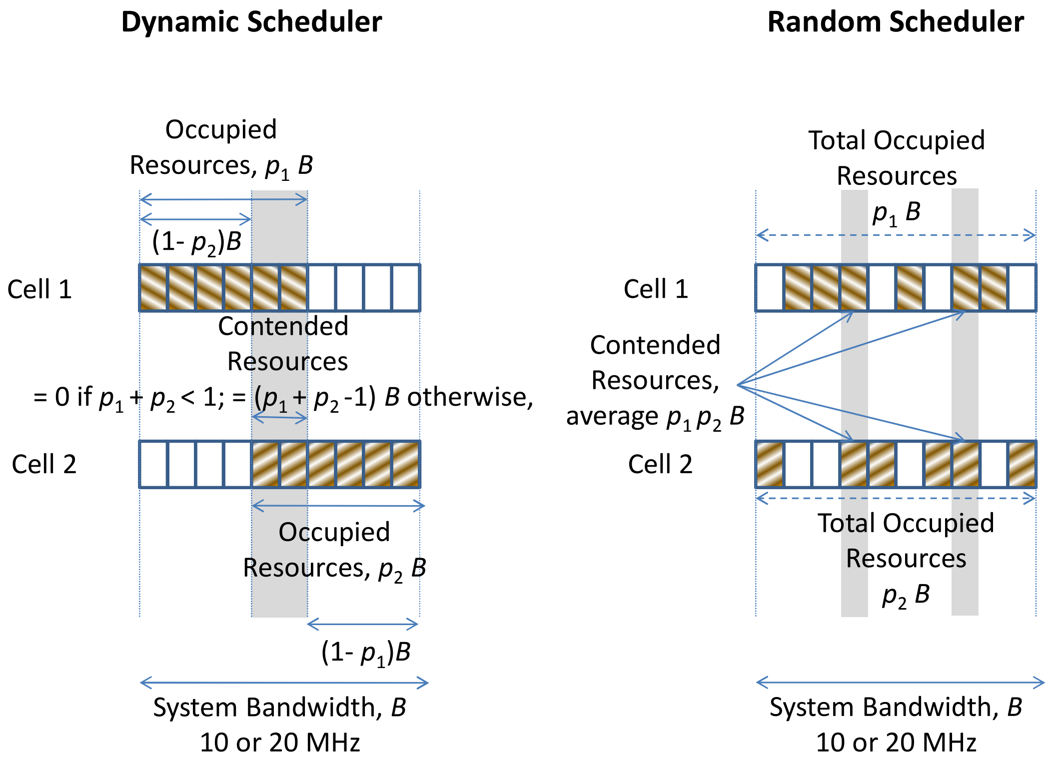


Figure 4-8: Illustration of the operation of two resource scheduling techniques for modelling purposes

In the case of the *dynamic scheduler*, the two cells are assumed to work cooperatively to minimise the overlap of resources. This may be achieved by central coordination, by conventions concerning which cells have priority over which resources, or via one of the distributed techniques described in section 4.4. If cell 1 transmits in resources occupying a proportion p_1 of the available bandwidth *B*[1], , while cell 2 transmits in a proportion p_2 of the available bandwidth and $(p_1 + p_2) < 1$ then the two cells have exclusive use of a bandwidth $p_1 B$ in the case of cell 1 and $p_2 B$ in the case of cell 2. These resources then suffer degradation only due to noise rather than interference. However, if $(p_1 + p_2) >$ 1 then there will be contended resources and interference between the cells. In this case a bandwidth $(p_1 + p_2 - 1) B$ is contended, and those resources have degraded performance due to interference.

The overall throughput for cell 1 is therefore given by:

[1] In practice some of the bandwidth is occupied by control channels. This overhead is accounted for in our calculations but not shown here for simplicity.

$$Tput_{dynamic} = \begin{cases} SE(SNR) \times (1 - p_2) \times B + SE(SINR) \times (p_1 + p_2 - 1) \times B & ;(p_1 + p_2) > 1 \\ SE(SNR) \times p_1 \times B & ;\text{otherwise} \end{cases}$$

where $SE(\cdot)$ is the spectrum efficiency as a function of SINR or SNR characteristic of a the low power network (in our case 2x2 MIMO LTE performance in an EVA5 channel as described in section 4.2). A similar expression applies for cell 2, although in our calculation we have assumed the same target throughput for both cells and hence the same loading. Our co channel interference model calculates the number of contended and un-contended resource blocks available to the victim cell for a range of cell loading levels, determines the target SINR and SNR in the contended and un-contended resources respectively to achieve the target throughput at the victim receiver and selects the cell loading level $p = p_1 = p_2$ that minimises the SINR requirement in contended resources. This minimises the separation distance required between the wanted (victim) and interfering (aggressor) cell to achieve a given target throughput.

In the case of the *random scheduler*, the resources are allocated by each cell without attempting to completely avoid interference. Each cell may schedule within any of the resources, and if we assume that the outcomes of those scheduling processes are statistically independent, then a mean bandwidth of $p_1 p_2 B$ is contended. The remaining ($p_1 B$ - $p_1 p_2 B$) resources (for cell 1) are un-contended on average.

The overall throughput for cell 1 is therefore given by:

$$Tput_{random} = SE(SNR) \times (p_1 - p_1 p_2) \times B + SE(SINR) \times p_1 p_2 \times B$$

Again the loading levels are adjusted to maximise the separation distance at which a given target throughput can be achieved.

In practice schedulers in low power networks are likely to perform somewhere between these two extremes of the ideal dynamic scheduler and blind random scheduler.

In terms of interference on the control channels we assume that as the co-channel interference cases analysed in chapter 6 only consist of two overlapping networks that the control channel interference mitigation techniques described in section 4.5 could be used to avoid overlap of control channels. To allow for the case where the victim control channels may coincide with contended resources used for the shared data channel of the aggressor system we have applied a minimum

SINR limit of -2dB when calculating separation distances in the co-channel interference model. This is the SINR level required to ensure successful recovery of the PDCCH[2].

[2] A SINR of -2dB is based on the SINR requirement of -1.7dB for a single port antenna [23] assuming an improvement in the scenario modelled due to the use of 2x2 MIMO.

5 Power levels in line with 3GPP recommendations will ensure good coverage for low-power shared access points

5.1 Study questions

Ofcom posed the study questions shown in Figure 5-1 to understand the technical conditions within licenses for low power shared access channels. This chapter investigates appropriate power levels to provide sufficient coverage for low power networks in their likely deployment scenarios, bearing in mind Ofcom's working assumption that the power limit in the licences would be no greater than 20dBm EIRP in line with 3GPP transmit power limits for Home eNodeBs. Following discussions with stakeholders it was highlighted that the 3GPP maximum transmit power level for local area base stations of 24dBm might be a more appropriate upper limit in some deployment scenarios and so has also been considered in our analysis.

Study questions

1.13 What minimum power level would be needed in order to provide coverage in the following example scenarios:

- *Indoor office environment*
- *Indoor public area*
- *Residential (home femtocell)*
- *Campus / business park (including use of external base station antennas)*

1.14 What depth of in-building coverage would be provided by an outdoor base station operating at 20dBm e.i.r.p. in the campus scenario, assuming a mast height of 5m or below?

Figure 5-1 Ofcom study questions addressed in Chapter 5

5.2 *Study approach*

The study approach is outlined in Figure 5-2 which defines the inputs to the coverage model outputs achieved. For each coverage scenario the main inputs are the transmit power range and selected propagation models applied to the different environments. The output cell area is then calculated for a fixed coverage confidence which for this analysis is 78% at the cell edge. This is equivalent to a 90% coverage confidence across the cell area given appropriate assumptions regarding cell geometry and shadowing statistics.

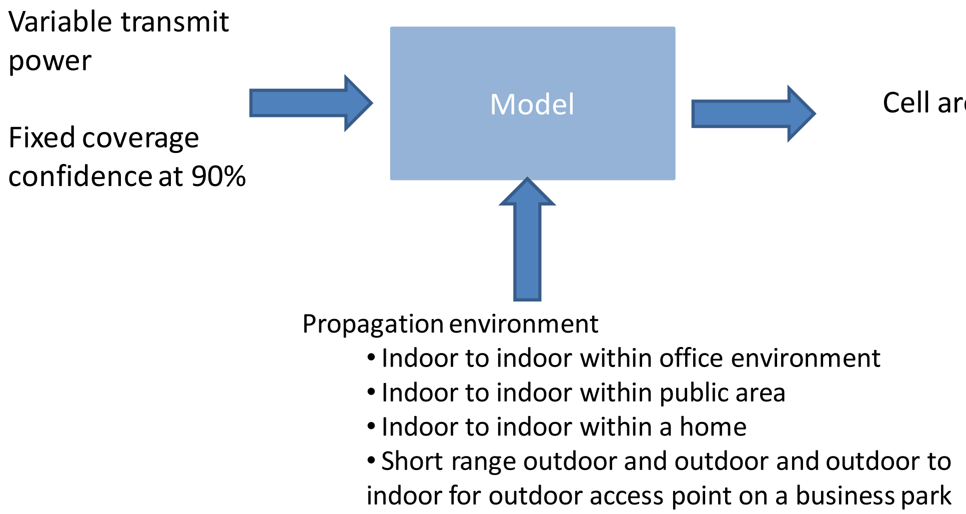


Figure 5-2 Approach to low-power shared access coverage modelling

The coverage model outputs show coverage area as a function of transmit power for a range of target throughputs for a single user located at the cell edge as shown in Figure 5-3. The target single user cell edge throughput sets the cell edge SNR requirement and thus range of the cell.

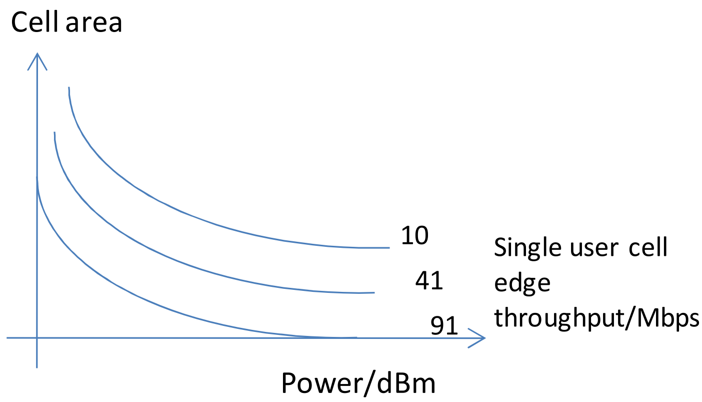


Figure 5-3 Output plots for coverage scenario analysis

5.3 Indoor office coverage – Study question 1.13

5.3.1 Scenario description and assumptions

Figure 5-4 illustrates the typical indoor office scenario across two floors that we have used for modelling for coverage. This environment is challenging to model due to a mixture of open plan and partitioned areas as well as a wide range of wall types. Our analysis uses ITU-R P.1238 as this has been developed specifically for modelling office environments and does not differentiate between open plan and partitioned offices.

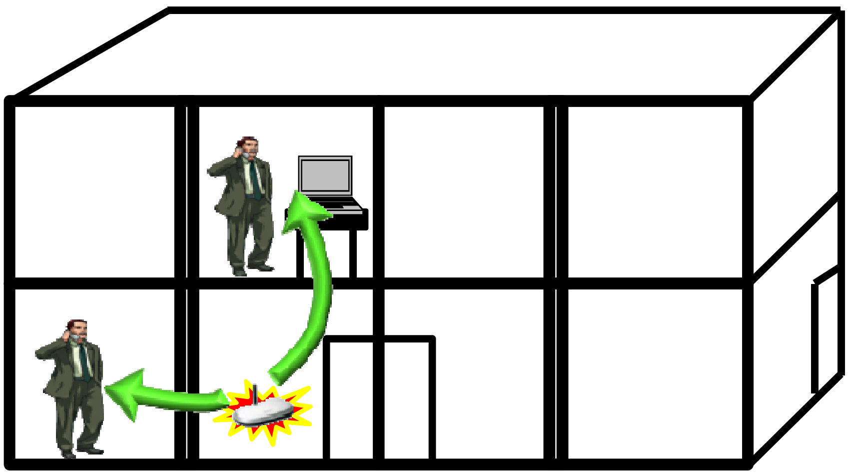


Figure 5-4 Indoor office coverage area with enterprise eNodeB as low-power device

Our assumptions when modelling this scenario include:

- A floor loss of 20.2dB, floor separation of 3m and distance path loss coefficient of 30dB (as described in section 4.4.2). Shadowing of 10dB is added based on 3GPP R4-092042 [[22]] as walls are not explicitly modelled in ITU-R P.1238.
- The office floor area of a medium size low rise office is 840m^2 on each floor (see section 4.4.2).
- Indoor low power access point parameters that are better than a residential low power access point with a transmit power up to 24dBm, device height of 2.5m and antenna gain of 3dBi (see section 4.1.3).
- A 10MHz channel is assumed. Results for both 10MHz and 20MHz were examined for a residential coverage case. This showed that doubling the bandwidth doesn't quite give double the data rate at the same cell range as the PSD is reduced in a 20MHz bandwidth compared to 10Mz as the maximum total transmit power is independent of bandwidth in the 3GPP specifications. However, as the difference is marginal all results shown are for the 10MHz case except where 20MHz is required to achieve the target throughput.

5.3.2 Results and conclusions

The results shown in Figure 5-5 are the total coverage area results for both upstairs and downstairs of the indoor office. Assuming an average office size of 840m^2 on a single floor our results suggests that the maximum EIRP is not necessary to provide coverage in this environment even at peak data rates. EIRPs in the range of 17 – 20 dBm are sufficient to cover 1000-1500m^2 for the higher throughputs and well over 4000m^2 for the lower throughputs.

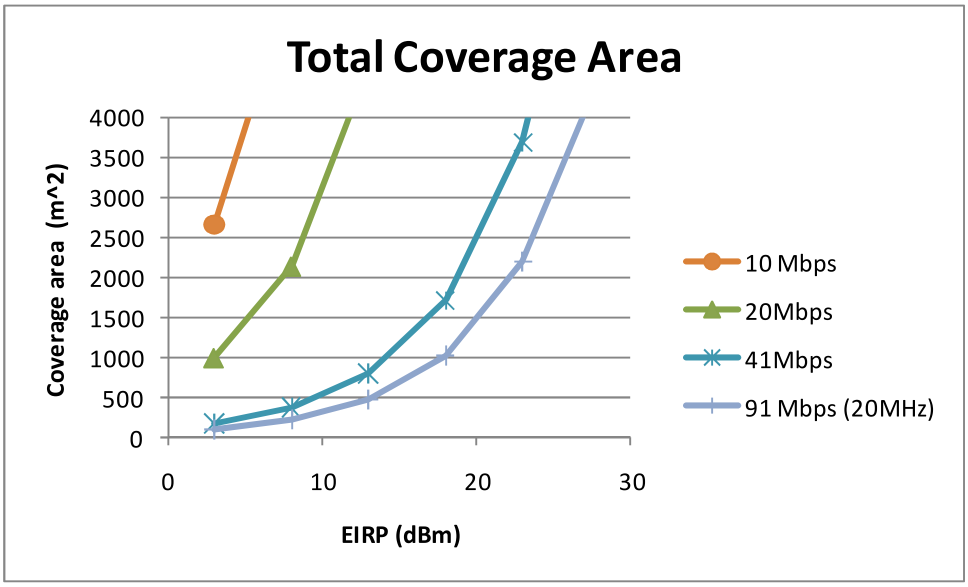
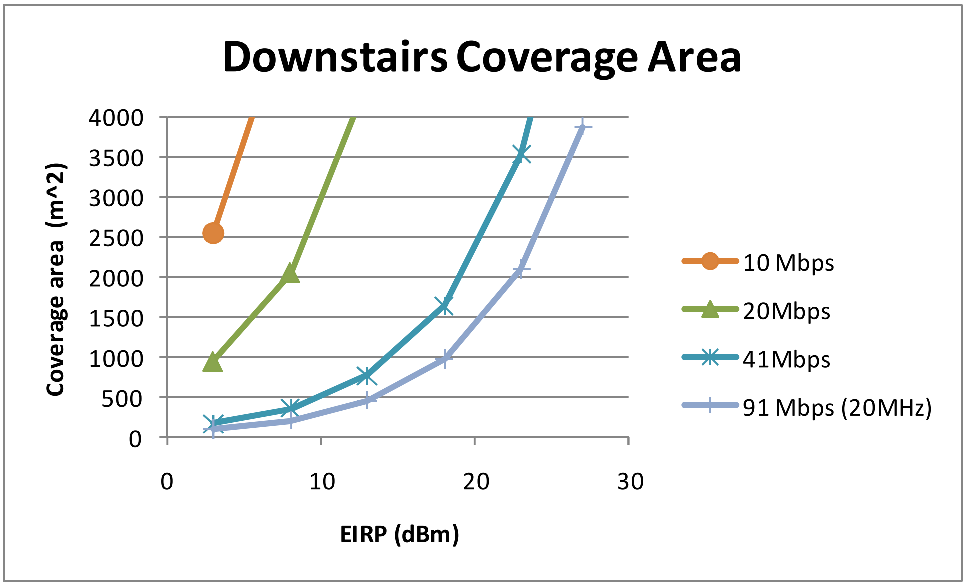


Figure 5-5 Indoor office total coverage area

We assume that in most offices at least one low power access point would be fitted per floor and so it is useful to examine how this total coverage area is split between floors in our 2 floor model. Figure 5-6 shows the coverage area and range for downstairs in the office scenario. At moderate EIRP levels (E.g. 10 dBm) the coverage area is 4000m^2 to achieve 20 Mbps. A comparable coverage area for higher throughputs (41/91 Mbps) requires higher EIRP levels in the order of 21 – 24 dBm in order to maintain the target SNR. Backing off the maximum EIRP to 18dBm would still provide adequate single floor coverage for our example medium sized office of 840 m^2 at maximum data rates.



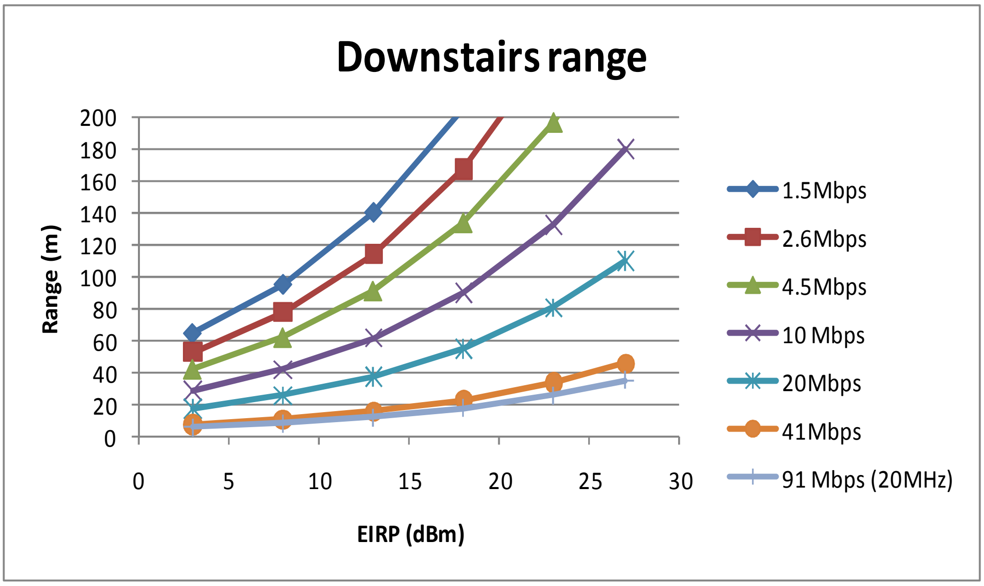
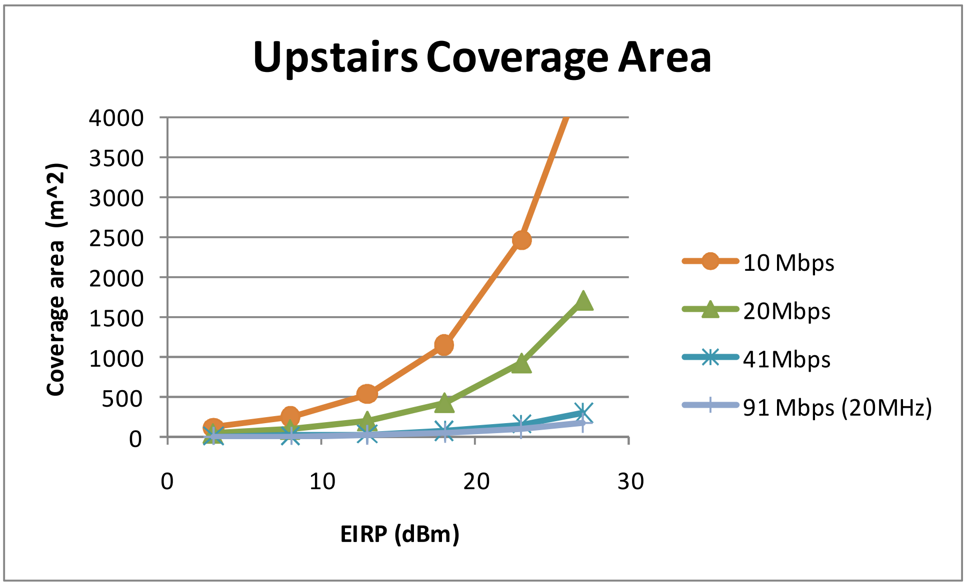


Figure 5-6 Indoor office downstairs coverage area and range

Figure 5-7 shows the coverage results for upstairs. There is a clear distinction between the upstairs and downstairs coverage area for an indoor office. The higher throughput levels do not exceed 250m^2 even for the highest EIRP which restricts upstairs throughputs to the lower values. Even at maximum EIRP the coverage area achieved is 1700m^2 for a 20 Mbps throughput which is less than half the downstairs coverage area.



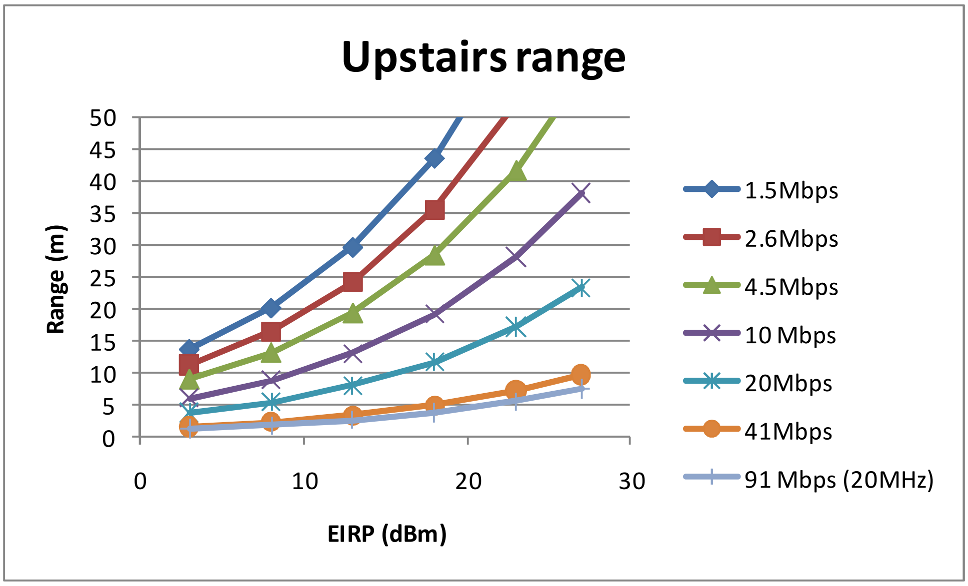


Figure 5-7 Indoor office upstairs coverage area and range

Conclusions

The following conclusions have been drawn based on the analysis of coverage area and coverage range for a medium sized low rise office building for the particular scenarios covered in this chapter.

- Setting a maximum EIRP of 27dBm on the low power shared access channel (i.e. in line with the 3GPP Local Area Base Station specification) would not limit operators in terms of achieving maximum data rates at the range needed to cover a single floor medium sized office.
- This assumes office femtocells will be higher performance enterprise units and have an antenna gain of 3dBi

- Coverage is more challenging on a second floor but it is assumed that most operators would deploy a FAP per floor in an office environment to provide adequate capacity for the number of users per floor.
- Backing off the maximum EIRP to 18dBm would still provide adequate single floor coverage for our example medium sized office of 840 m² at maximum data rates.
- It is assumed that for larger office areas the operator would deploy multiple access points.
- It is worth noting that most 3G enterprise femtocells solutions support 16 or 32 voice users. While the same limitations do not necessarily apply to LTE access points, as it is a packet switched rather than circuit switched system, it is likely that most operators would deploy more than one access point for our example medium sized office of 840 m² and 60 people for capacity rather than coverage reasons. Operators may also deploy multiple access points to ensure coverage in areas with larger losses than typical.

5.4 Residential coverage – Study question 1.13

5.4.1 Scenario description and assumptions

Figure 5-8 shows the transmit paths from a single home eNodeB for a residential area which are modelled in this study to capture:

- Downstairs range and coverage area
- Upstairs range and coverage area

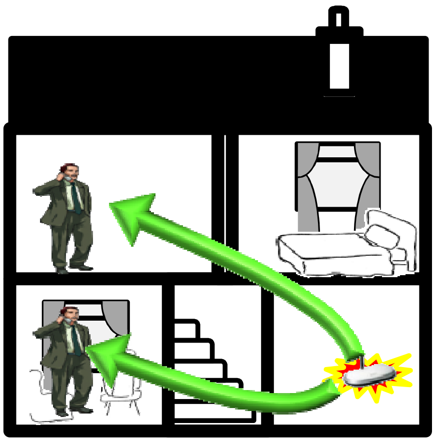


Figure 5-8 Residential coverage scenario with indoor Home eNodeB as low power device

The residential coverage scenario assumes a typical residential UK house in two particular types:

i) New build house
ii) Old style house

The differences between the two house types are the wall material and wall separation. The wall type typically found in a new build house will be a mixture of wood and plasterboard whereas the wall type within an older style house will be brick and plasterboard.

Our analysis uses the COST 231 multi wall model and assumes the following parameters as described in section 4.4.1 and section 4.1.3:

- A floor loss of 20.2dB and floor separation of 3m.
- Shadowing of 4dB is added based on 3GPP R4-092042 [[22]] as walls are explicitly modelled in the COST 231 multi wall model.
- A distance between walls of 4m for a new build and 6m for older houses based on average UK house sizes.
- A wall loss of 4.2dB and 7dB for new and old houses respectively
- Access point parameters in line with 3GPP HeNBs and a consumer grade product with a transmit power up to 20dBm, device height of 0.5m and antenna gain of 0dBi (see section 4.1.3). It should be noted that the transmit power of commercially available 3G FAPs are typically well below this i.e. 7dBm for ipAccess'[46] Oyster 3G FAP product.

5.4.2 Results and conclusions

Residential femtocell range results 10MHz vs. 20MHz in a new build house

Figure 5-9 and Figure 5-10 compares the coverage range achieved in a new build house for a 10MHz and 20MHz bandwidth. This shows that for a 10 MHz channel the range is marginally better than for twice the data rate in a 20 MHz channel. This is because the PSD is reduced in a 20MHz bandwidth compared to 10Mz as the maximum total transmit power is independent of bandwidth in the 3GPP specifications. However, as the difference is marginal all results shown in the remainder of this chapter are for the 10MHz case except where 20MHz is required to achieve the target throughput.

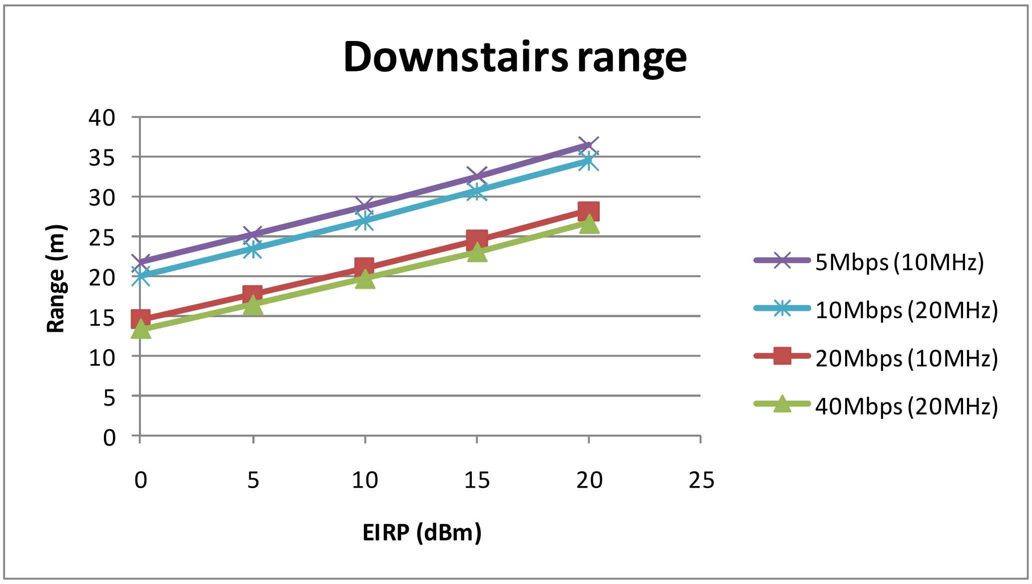


Figure 5-9 Residential coverage downstairs range in a new build house

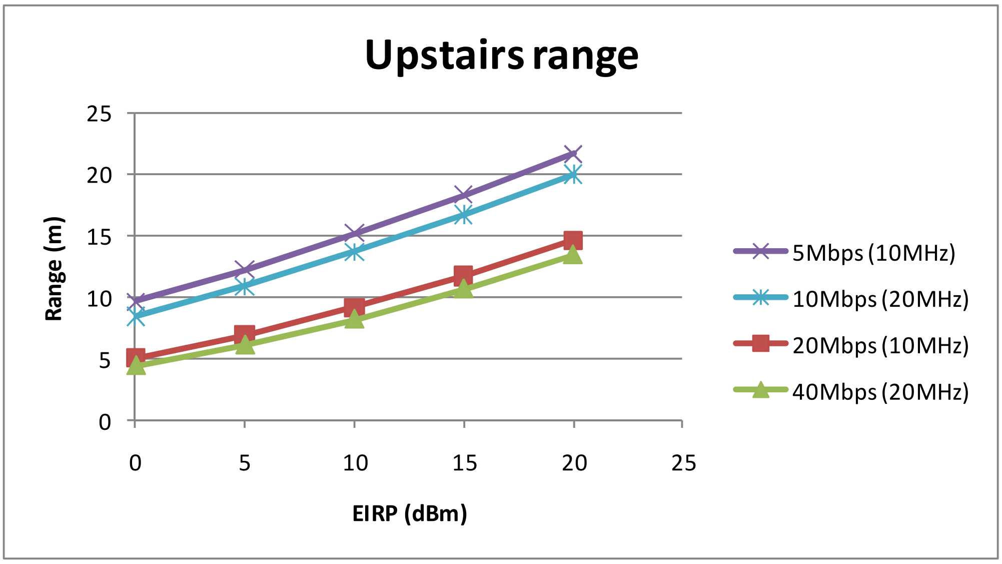


Figure 5-10 Residential coverage upstairs range in a new build house

Residential femtocell coverage area results in a new build house

The total coverage area results for our new build residential scenario based on achieving the SNR at the cell edge required for a single user achieving the range of data rates shown are given in Figure 5-11 (which includes upstairs and downstairs). This indicates that it is not necessary to transmit at maximum EIRP to provide coverage across an average new build house of 76m^2 even if maximum throughputs are targeted. Even for larger houses with total floor areas up to 320 m² the transmit power could be reduced significantly.

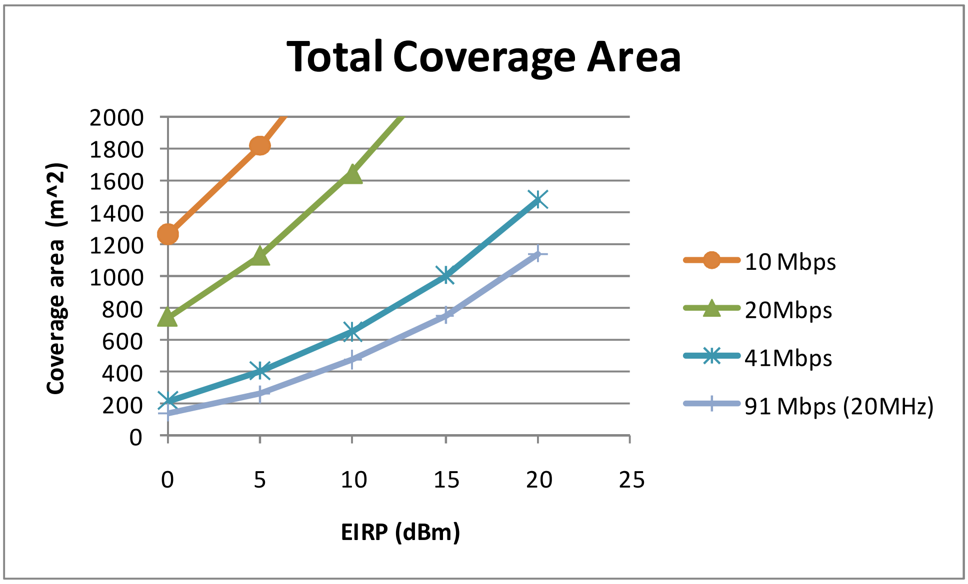


Figure 5-11 Residential total coverage area in a new build house

Figure 5-12 and Figure 5-13 shows the results for downstairs coverage area and range in a new build house. Here the highest throughput assuming a maximum EIRP can be achieved at a range of 17m compared to 41m for a 1.5 Mbps throughput. This shows the downstairs range required for high end properties could be easily be achieved at maximum target throughputs at much less than the maximum transmit power of 20dBm. As shown in Figure 5-14 and Figure 5-15 coverage is more challenging upstairs (assuming the access point is located downstairs). Here peak data rates could still be provided at the range needed in larger houses (6.5m assuming a downstairs centrally located access point) but the maximum transmit power of 20dBm would be needed .

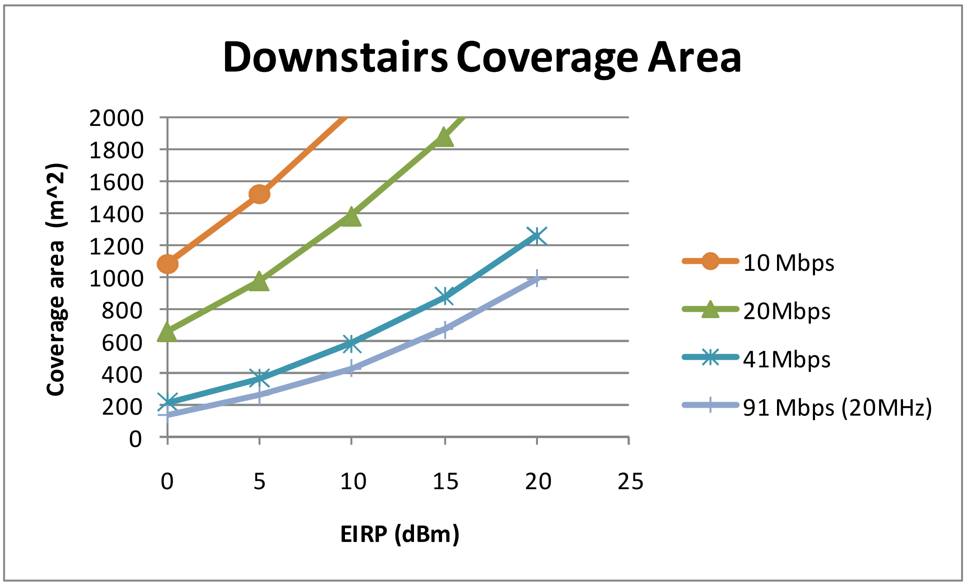


Figure 5-12: Residential downstairs coverage area in a new build house

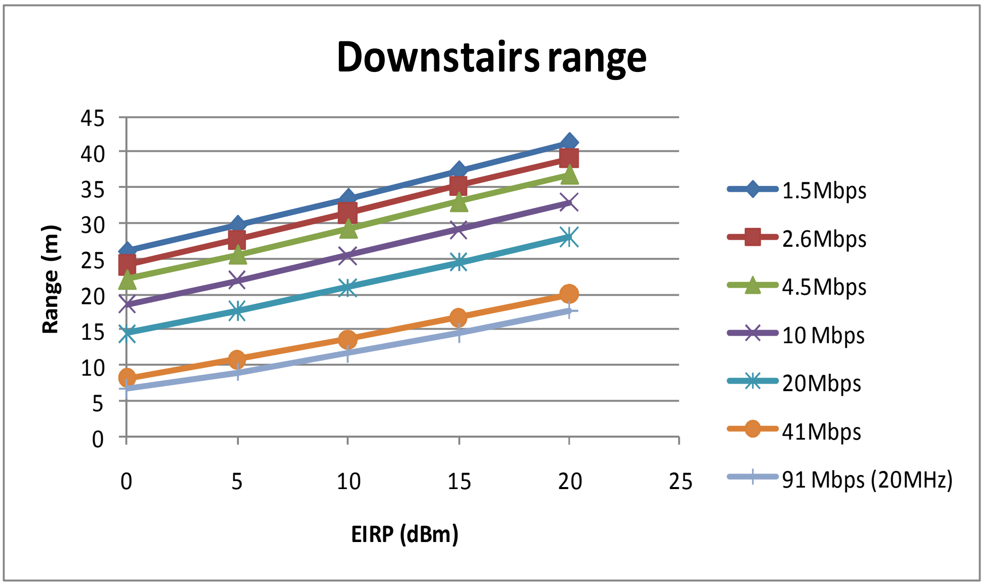


Figure 5-13 Residential downstairs coverage range in a new build house

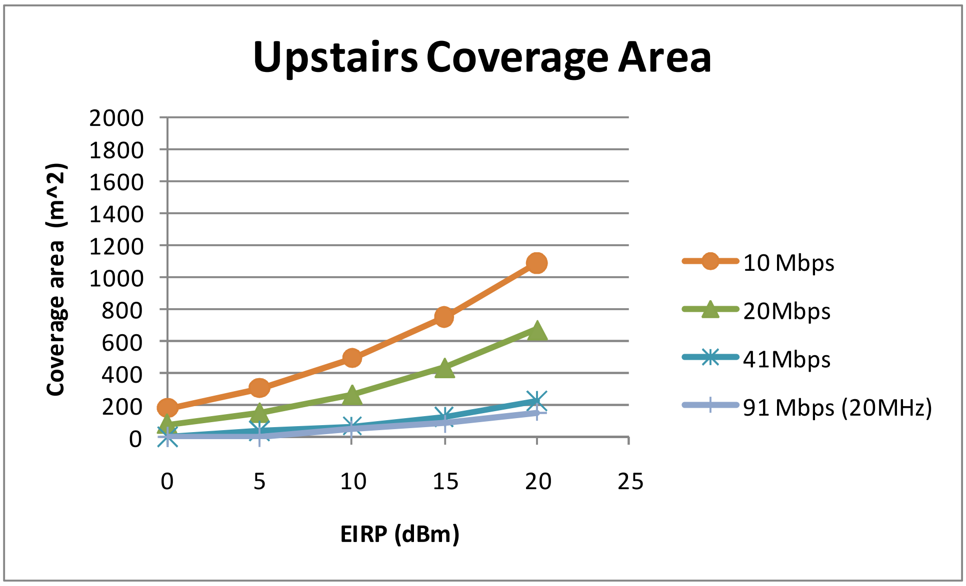


Figure 5-14 Residential upstairs coverage area in a new build house

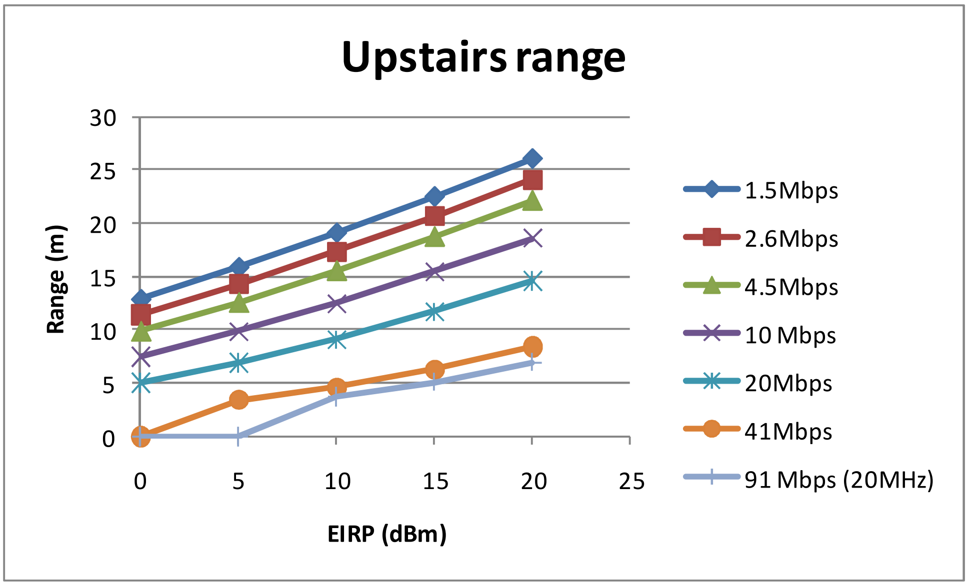


Figure 5-15 Residential femtocell upstairs range– New Build

Residential femtocell coverage area results – Old houses

Figure 5-16 presents the total coverage area results for an older style house. As expected the coverage area is less than in a new build house. However, there is not a significant difference in coverage area between the two as although the older style house assumes a higher internal wall loss, the room size and hence wall separation is likely to be higher than in a new build house.

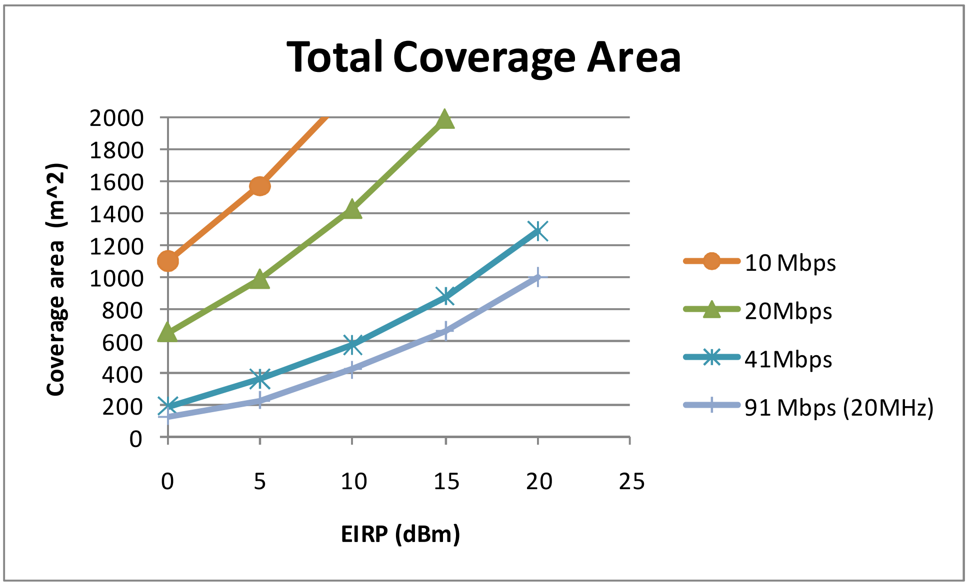


Figure 5-16 Residential total coverage area – Old house

The coverage results for an older house are split between downstairs and upstairs in Figure 5-17 to Figure 5-20. These show that at the maximum EIRP of 20dBm a range of 16.5m at a maximum data rate of 91Mbps can be achieved downstairs and 6.66m upstairs. This should be sufficient downstairs for most houses but may start to limit coverage at higher data rates upstairs in some larger properties.

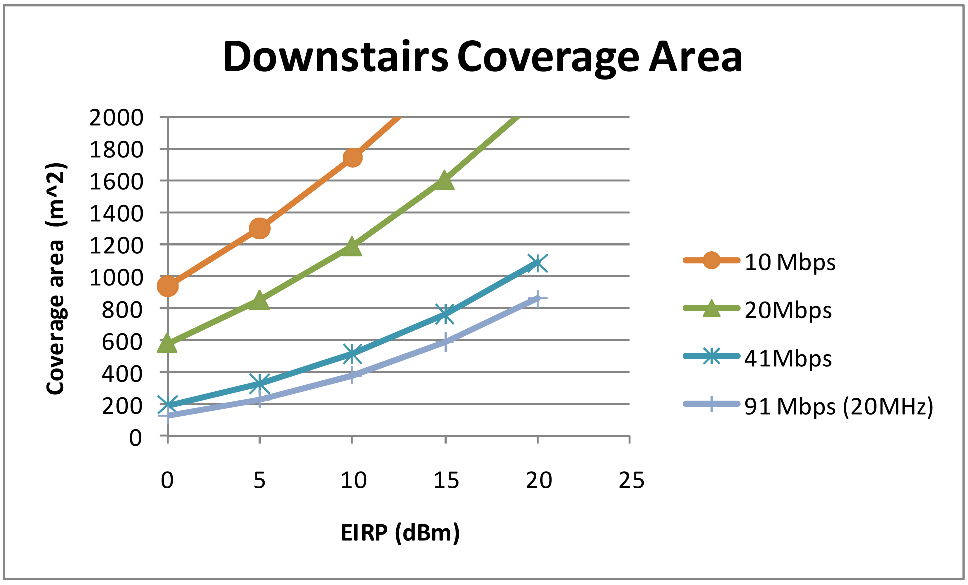


Figure 5-17 Residential downstairs coverage area - Old house

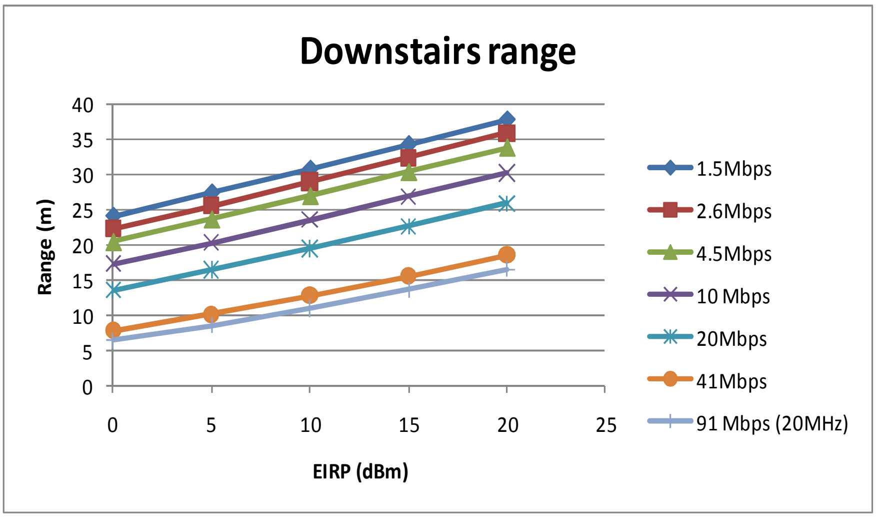


Figure 5-18 Residential downstairs coverage range – Old house

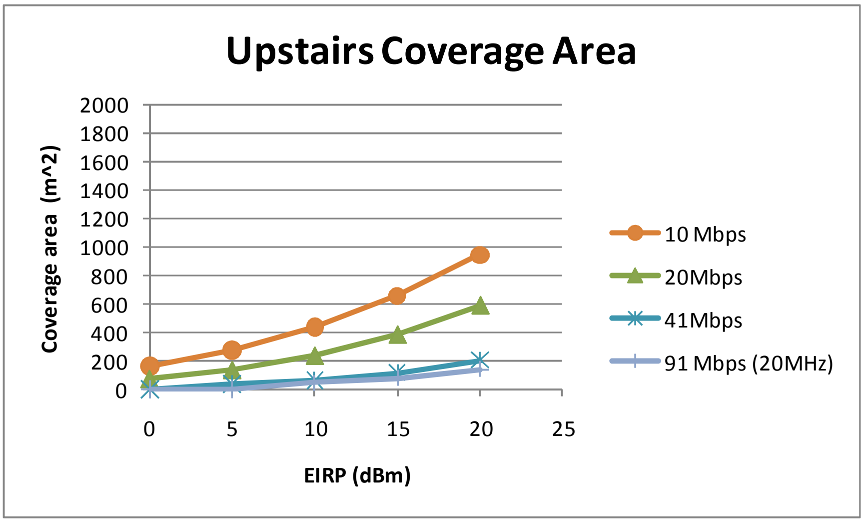


Figure 5-19 Residential upstairs coverage area - Old house

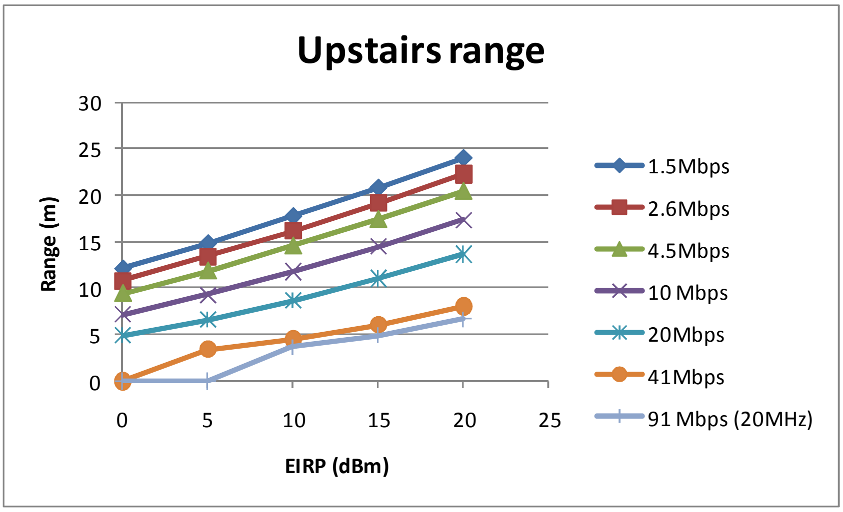


Figure 5-20 Residential upstairs coverage range – Old house

Conclusions – Residential Coverage Analysis

The following conclusions have been drawn based on the analysis of coverage area and coverage range for the various residential scenarios covered in this chapter.

- Setting a maximum EIRP of 20dBm on the low power shared access channel (i.e. In line with the 3GPP HeNB specification) would not limit operators in terms of achieving maximum data rates at the range needed for even large new build houses in the UK.
- This assumes residential femtocells will be low specification units with an antenna gain of 0dBi
- Coverage will be more challenging in older buildings compared to new builds. At EIRP 20dBm a range of 16.5m at a max data rate of 91Mbps could be achieved downstairs and 6.66m upstairs. This should be sufficient downstairs for most houses but may start to limit coverage at higher data rates upstairs in some larger properties.
- Therefore the residential coverage scenario is not the limiting case for setting the maximum transmit power and EIRP for the low power shared access channel, at least where interference levels are negligible. In practice operators are likely to need to allow some interference margin so greater power headroom may be required.
- Results show that the maximum transmit power level could be backed off significantly and still achieve maximum data rates at the range needed for typical residential scenarios
- If the maximum transmit power was backed off to 10dBm (as suggested in 3GPP if activity in an adjacent channel is detected) the downstairs range in older houses at a maximum data rate of 91Mbps would be 11m which is considered adequate for most houses.
- However, upstairs the range at this data rate and EIRP would be reduced to 3.7m so it is likely that data rates would need to be backed off to 10 or 20Mbps (depending on 10MHz or 20MHz BW allocation) to maintain reasonable upstairs coverage in larger houses.
- It is worth noting that in practice residential FAPs are highly cost sensitive and so the maximum transmit power tends to be driven by heat dissipation constraints in the product design. Typical 3G FAP products on the market today have a transmit power of 7dBm [[47]] for example. However, this may change over time to accommodate higher transmit powers and so any regulatory limits on a shared access channel will need to allow for this.

5.5 *Indoor public area coverage – Study question 1.13*

5.5.1 Scenario description and assumptions

Figure 5-21 represents an indoor public area which in the example below shows a shopping centre layout. This example provides a challenging radio propagation environment due to the mix of separate units, corridors and open spaces.

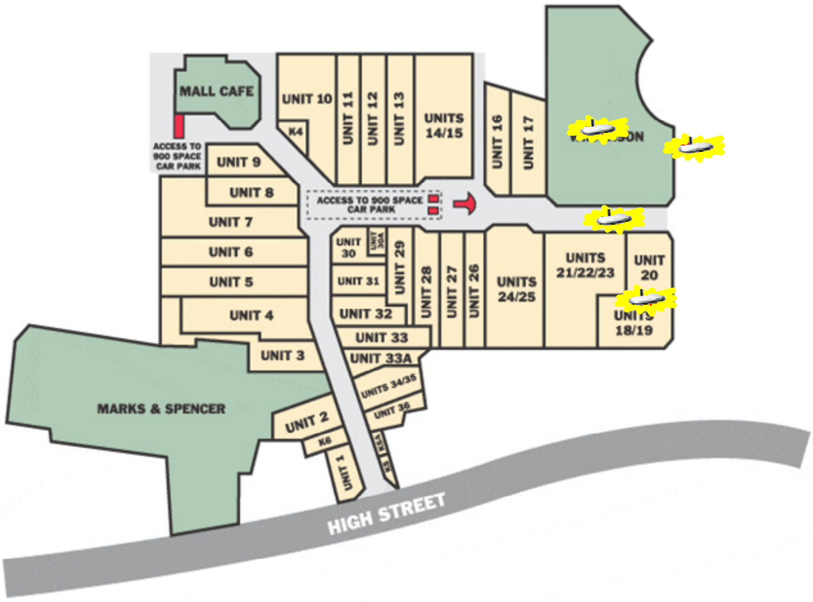


Figure 5-21 Indoor public area coverage – an example shopping centre (Source: Sovereign Centre, Weston Super Mare [[40]])

The COST 231 multiwall propagation model has been used for analysing coverage in this scenario. Within this we have made the following assumptions based on our example shopping centre building (see 4.4.3) and assumptions for indoor access points (see 4.1.3):

- A maximum EIRP of 27dBm has been used based on a transmit power limit of 24dBm and antenna gain of 3dBi.
- Wall loss of 4.2 dB
- Floor loss of 20.2 dB and floor separation of 3m
- Shadowing of 4dB is added based on 3GPP R4-092042 [22] as walls are explicitly modelled in the COST 231 multi wall model.
- Wall separation 13.5m

5.5.2 Results and conclusions

The results shown in Figure 5-22 are the total coverage area results for both upstairs and downstairs of the shopping centre. Figure 5-22 to Figure 5-26 splits this between upstairs and downstairs range. Our example shopping centre, the Sovereign Shopping Centre is approximately 7800 m² on a single floor with 40 shops. Our results show that this area could be covered at maximum throughputs if the maximum EIRP of 27dBm is used. If this shopping centre extended over two floors upstairs coverage would be limited but we assume that a low power access point would be deployed per floor. As a comparison a very large shopping centre such as the Trafford centre in Manchester (6^{th} largest in UK) is 140,000 m². However, we assume that an operator would deploy multiple access points to cover this size of area.

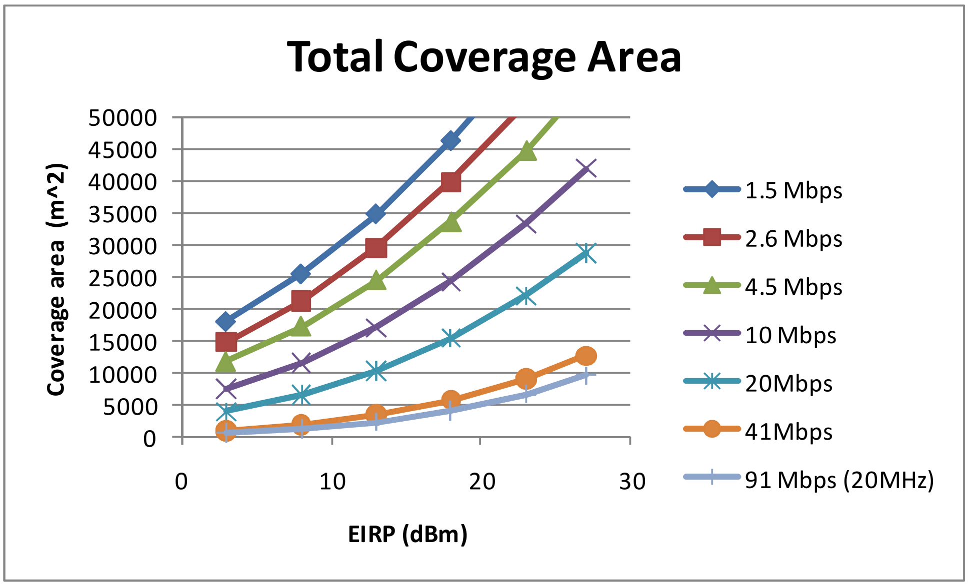


Figure 5-22 Indoor public area total coverage area

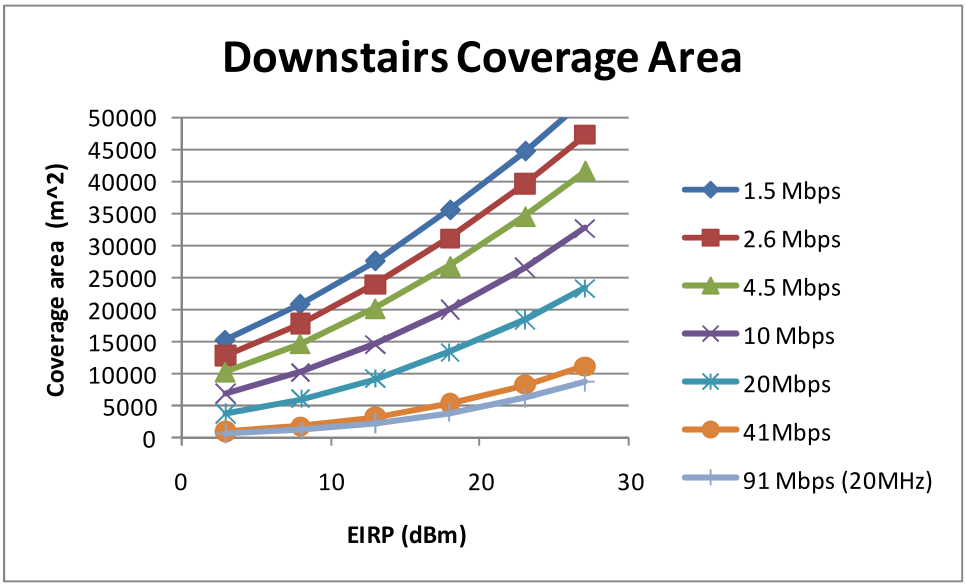


Figure 5-23 Indoor public area downstairs coverage area

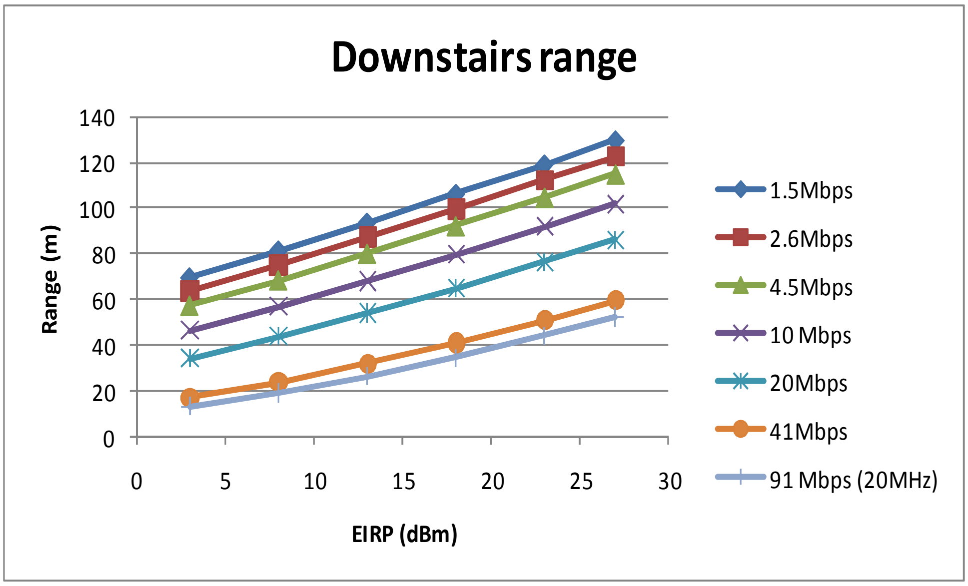


Figure 5-24 Indoor public area downstairs range

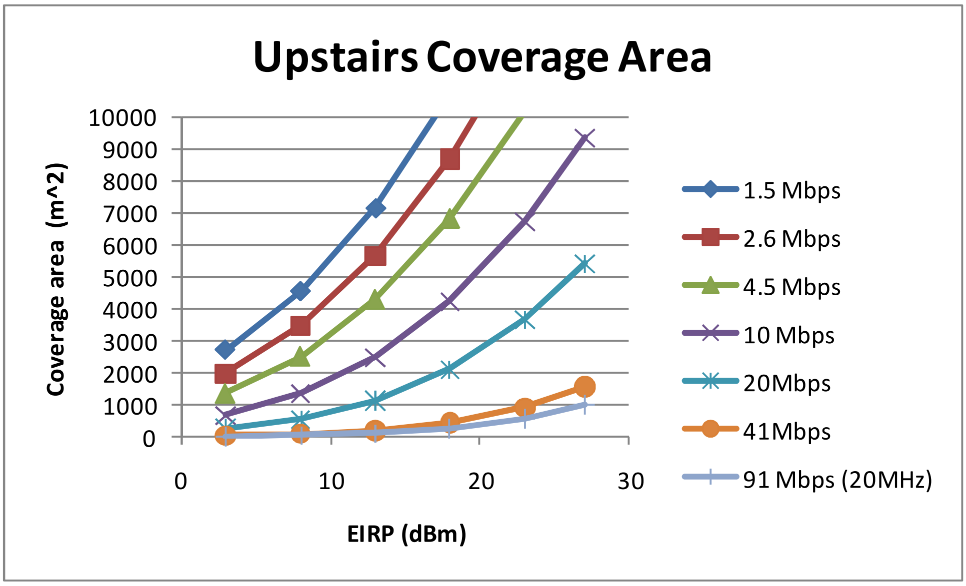


Figure 5-25 Indoor public area upstairs coverage area

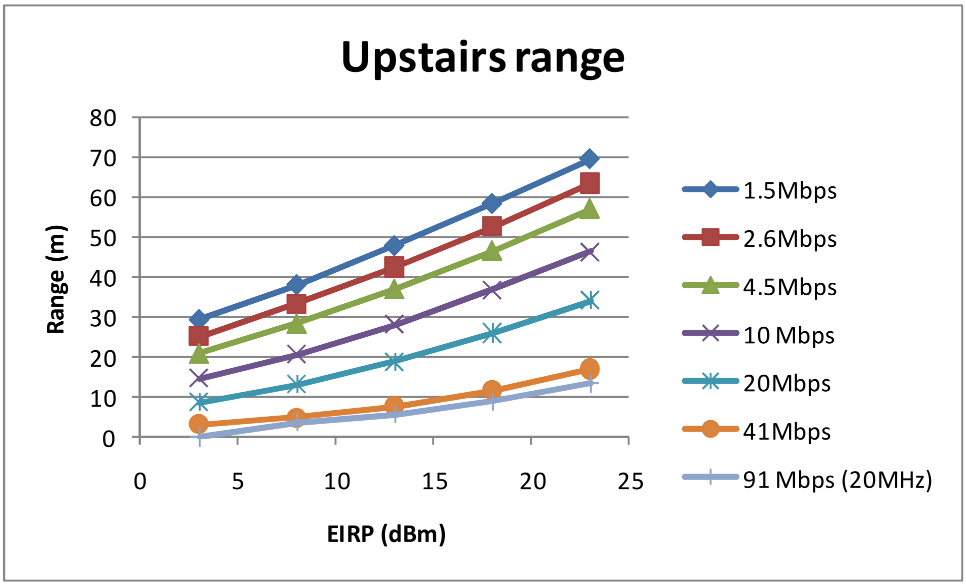


Figure 5-26 Indoor public area upstairs range

Conclusions – Public Area Coverage Analysis

The following conclusions have been drawn based on the analysis of the coverage area and coverage range for the shopping centre (indoor public area) scenarios covered in this chapter.

- Setting a maximum EIRP of 27dBm on the low power shared access channel (i.e. In line with the 3GPP Local Area Base Station transmit power specification) would not limit operators in terms of achieving maximum data rates at the range needed to cover a single floor medium sized shopping centre.
- This assumes public area femtocells will be higher specification units and have an antenna gain of 3dBi
- Coverage is more challenging on a second floor but it is assumed that most operators would deploy a femtocell per floor in a public area environment to provide adequate capacity for the number of users per floor.
- Backing off the maximum EIRP to 18dBm would still provide adequate single floor coverage for our example medium sized shopping centre if 2 access points were used to cover the example shopping centre.
- It is assumed that for larger shopping centres and public areas the operator would deploy multiple access points.

- It is worth noting that most 3G enterprise femtocells solutions support 16 or 32 voice users. While the same limitations do not necessarily apply to LTE access points as it is a packet switched rather than circuit switched system it is likely that most operators would deploy more than one access point in a shopping centre for capacity rather than coverage reasons. Operators may also deploy multiple access points to ensure coverage in areas with larger losses than typical.

5.6 Business park/Campus environment – Study question 1.13

5.6.1 Scenario description and assumptions

Figure 5-27 represents a business park which shows an outdoor low power eNodeB serving both outdoor and indoor users. For the purposes of this study our example shows low rise office buildings on a business park with an outdoor low power eNodeB in the car park serving both indoor and outdoor users.

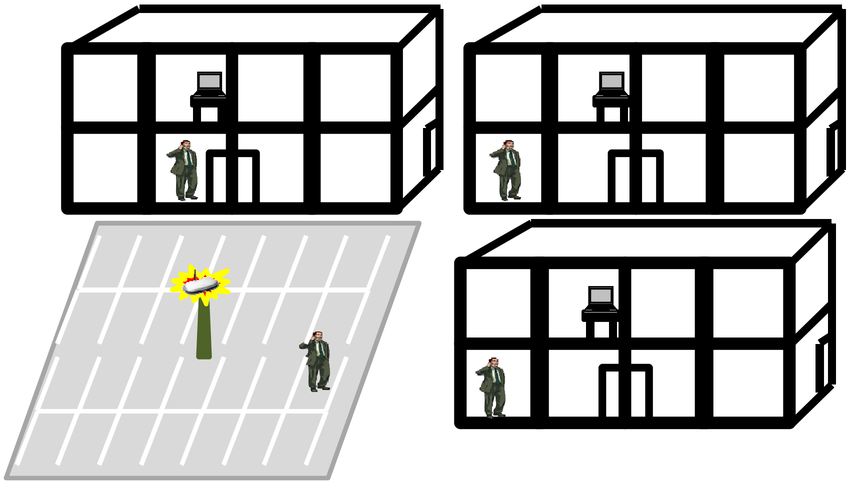


Figure 5-27 Business park environment scenario, low rise serving indoor and outdoor users from an outdoor eNodeB.

The propagation model for outdoor users assumes there is a short range LOS path between the access point and uses the ITU-R P.1411 LOS model in street canyons. We add a Depth 2 building penetration loss to this for indoor users as discussed in section 4.4.4.

Within this model we have made the following assumptions (as described in section 4.4.4):

- An upper EIRP of 29dBm based on the 3GPP Local Area Base Station maximum transmit power of 24dBm [[25]] and an antenna gain of 5dBi (based on a better unit being used in outdoor environments than indoors).
- Antenna height of 5m assuming the access point is mounted on a lamp post
- Depth 2 building penetration loss of 14dB

- We only model ground floor users as these will have the worst LOS path back to the access point at 5m.
- Shadowing of 8dB is applied which assumes the outdoor access point is in a similar environment to an outdoor macrocell

5.6.2 Results and conclusions

Outdoor users

The results shown in Figure 5-28 are the coverage area results for serving outdoor users. The coverage area is almost 120,000m^2 at an EIRP of 15 dBm for a 10 Mbps throughput. At the higher throughputs (41/91 Mbps) with a maximum EIRP the coverage area can reach 50,000m^2 to 80,000m^2 which is sufficient to cover 1/12 of a large business park such as the Cambridge Science park (which accommodates more than 90 companies and has a land area of approx 615,000 m^2).

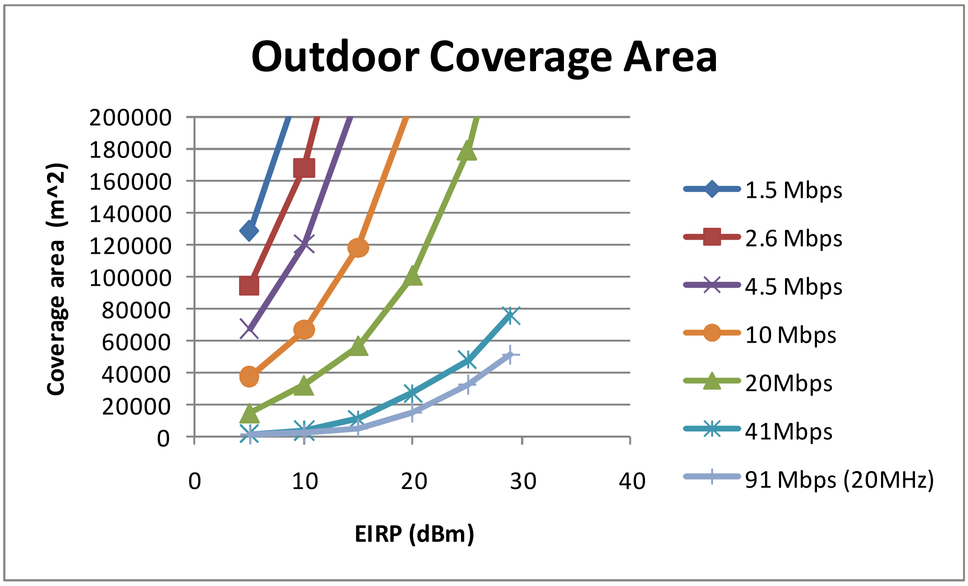


Figure 5-28 Business park outdoor coverage area – Outdoor users

The results shown in Figure 5-29 are the coverage range results for the outdoor business park scenario. The outdoor range can reach 800m at maximum EIRP for a 1.5 Mbps throughput down to 150m for the 41/91 Mbps throughputs. For the purposes of this study we assume a 100m range is adequate as this would match the ITU microcell test environment ISD. This range could be achieved for maximum throughputs provided the EIRP is at its maximum.

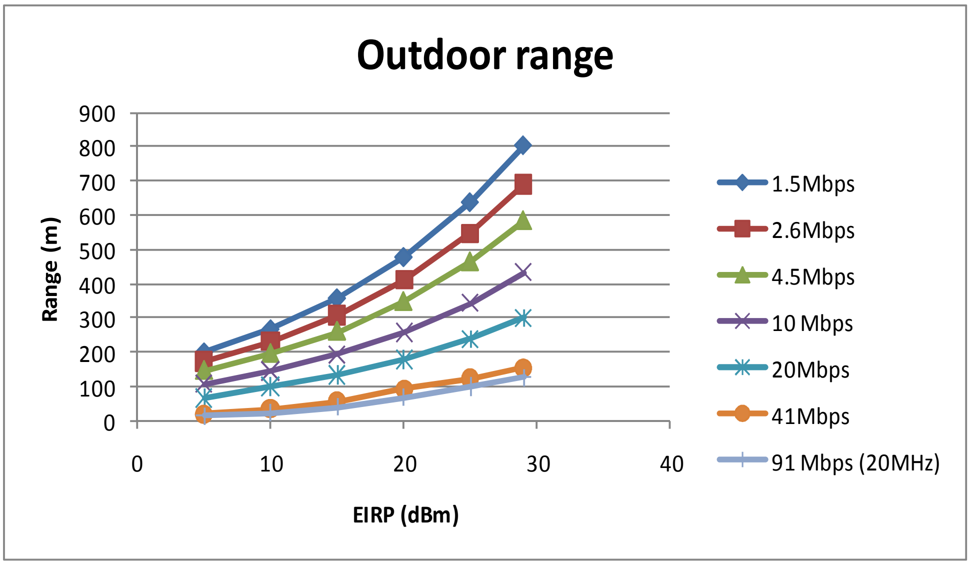


Figure 5-29 Business park outdoor coverage range – Outdoor users

Figure 5-30 and Figure 5-31 show the equivalent coverage results for indoor users. The indoor user range reaches 370m at maximum EIRP for a 1.5 Mbps throughput down to 40m for the 41/91 Mbps throughputs. The coverage range offered to indoor users is greatly reduced compared to the outdoor user range, as expected and therefore higher EIRP levels are required to match the coverage range to outdoor users.

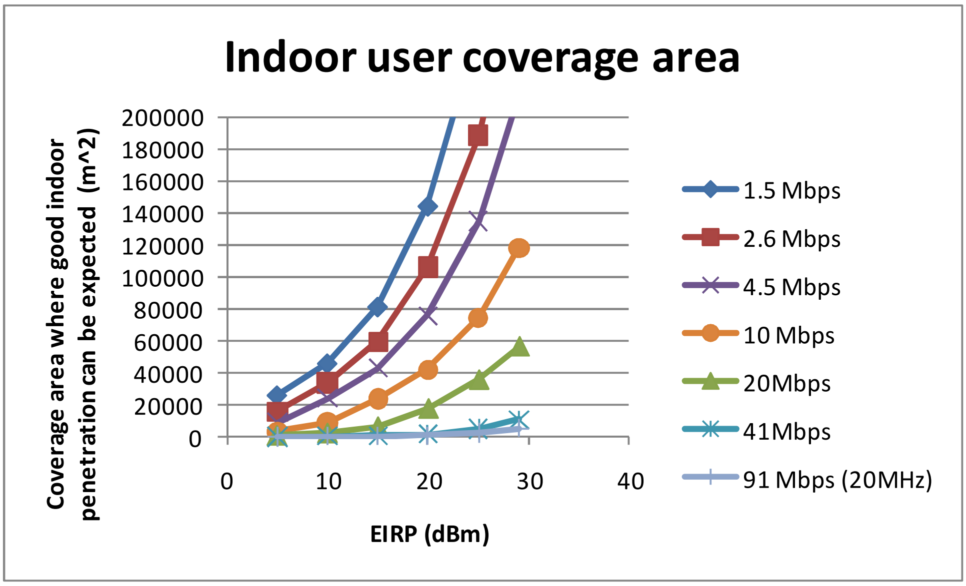


Figure 5-30 Business park indoor user coverage area

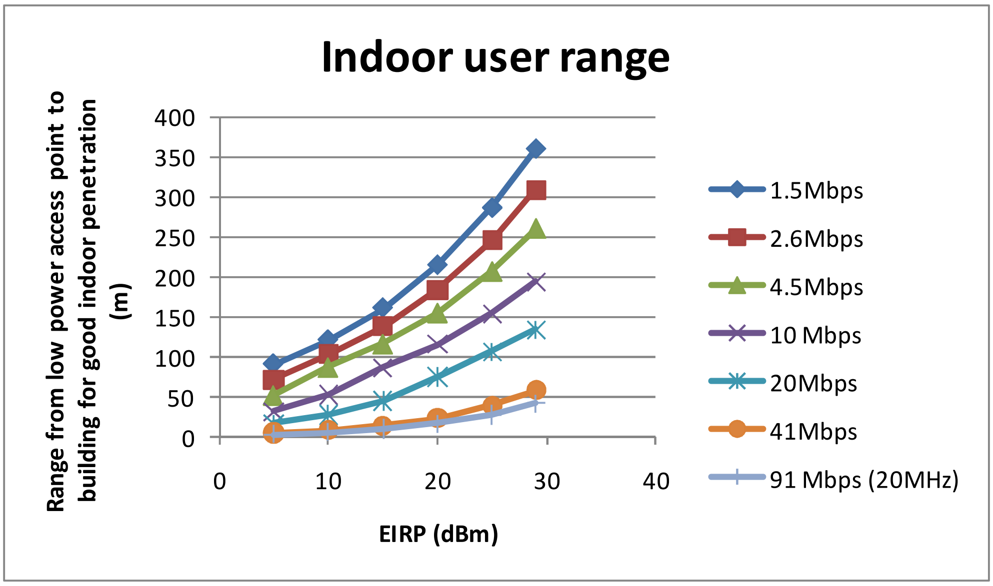


Figure 5-31 Business park indoor user coverage range

Conclusions – Coverage analysis for outdoor access points

- Setting a maximum EIRP of 29dBm on the low power shared access channel (i.e. in line with the 3GPP Local Area Base Station transmit power specification) would not limit operators in terms of achieving maximum data rates to outdoor users at typical microcell ranges (i.e. 100m)
- This assumes outdoor low power access points will be higher performance microcell-like units and have an antenna gain of 5dBi
- Coverage is more challenging for indoor users. At an EIRP of 29dBm the target cell edge data rate would need to be backed off to 20Mbps to achieve the target microcell range of 100m.

5.7 Depth of in-building coverage – Study question 1.14

5.7.1 Approach to depth of in-building coverage

Figure 5-32 shows our approach to modelling depth of in-building coverage from outdoor access points (which differs slightly to the generic coverage modelling approach in Figure 5-2). The modelling of depth of in-building coverage uses two particular scenarios to capture the effects of different angles of arrival to the wall of the building.

A. The campus scenario is used to derive the direct angle of arrival assuming 90°
B. The street scenario is used to derive the oblique angle of arrival assuming 45°

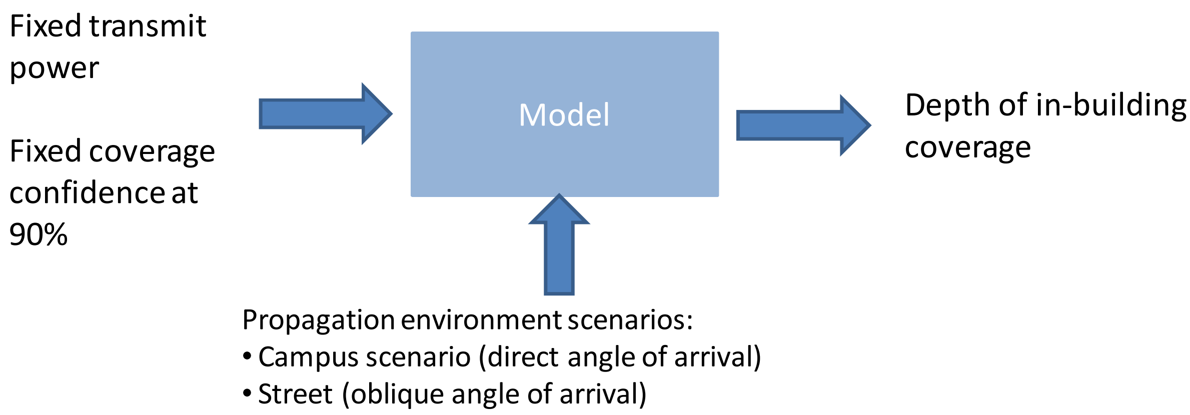


Figure 5-32 Approach to depth of in building coverage analysis

The output of this model is in the form shown in Figure 5-33 with the depth of coverage in metres shown for a given distance between the building and access point. As in the previous coverage results a target cell edge SNR is set based on achieving a target single cell edge user throughput. In building coverage is estimated at two EIRP two values as requested by Ofcom, 20dBm and 29dBm. The upper value is based on the 3GPP Local Area Base Station maximum transmit power of 24dBm [25] and an antenna gain of 5dBi (based on a better unit being used in outdoor environments than indoors).

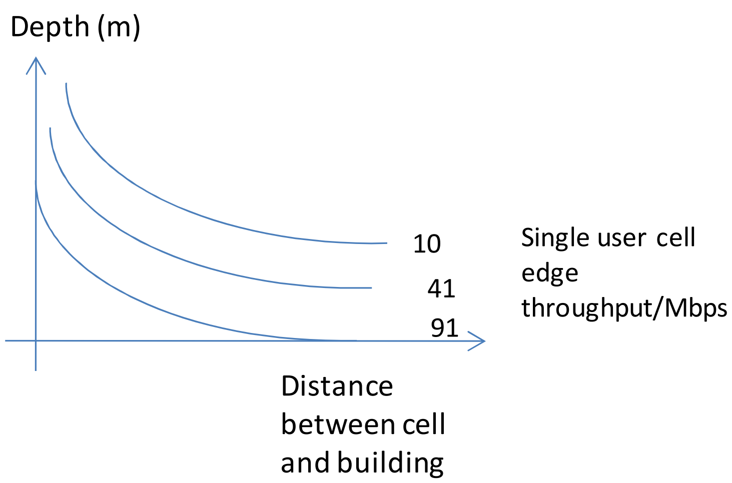


Figure 5-33 Expected results output

Figure 5-34 and Figure 5-35 show the example scenarios modelled for depth of in-building coverage. These scenarios represent two different angles of arrival that potentially would be encountered by outdoor low power access points. Scenario A shows the direct angle of arrival from the outdoor low-power eNodeB to the indoor users with little or no angle deviation from the base station and therefore the users are receiving the most direct signal possible. In contrast scenario B shows the oblique angle of arrival from the outdoor low-power eNodeB to the indoor users and the received signal arrives at a given angle to the users from eNodeB, this is due to the close proximity of the base station to the building resulting in potentially reduced in building coverage as shown in the diagram.

Scenario A – Direct angle of arrival

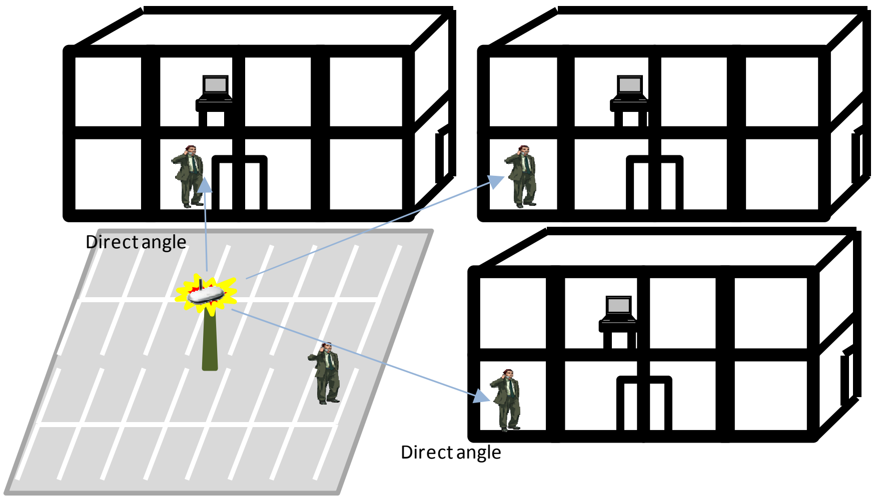


Figure 5-34 Depth of in-building coverage business park with direct angle of arrival 90° due to typical distance between building and access point

Scenario B – Oblique angle of arrival

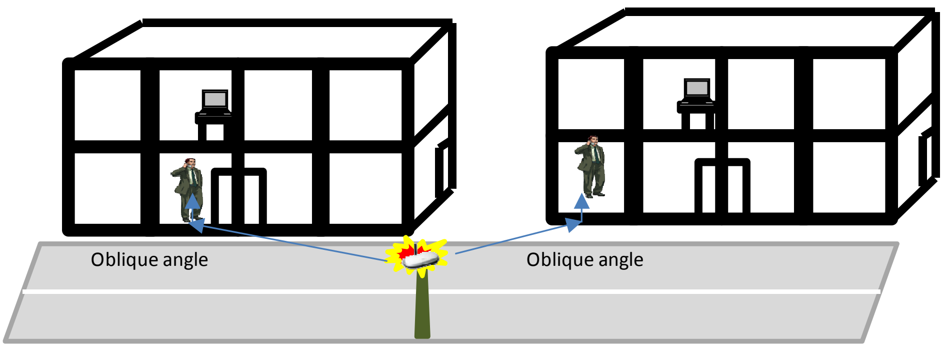


Figure 5-35 Depth of in-building coverage with oblique angle of arrival 45° due to close distance between buildings and access point

Both of these scenarios are modelled using ITU-R P.1411 for the external path loss with COST 231 LOS building penetration loss model added to this to estimate in building coverage as described in section 4.3.3. Within this model we have made the following assumptions as described in sections 4.4.4 and 4.1.2 :

- Antenna height of 5m assuming the access point is mounted on a lamp post

- External wall losses in line with COST 231 values for a concrete wall with a normal size window (7 dB at 90 ° and 20 dB at 0°)
- Internal wall losses of 4.2dB
- Wall separation 8m (see section 4.4.4)
- We only model ground floor users as these will have the worst LOS path back to the access point at 5m.
- Shadowing of 8dB is applied which assumes the outdoor access point is in a similar environment to an outdoor macrocell

5.7.2 Results and conclusions

Direct angle of arrival

The results shown in Figure 5-36 are the in-building depth for a direct angle of arrival at 20 dBm EIRP. The pattern shows decreasing depth of in-building coverage for increasing perpendicular distance between the building and access point. The depth of in-building coverage also decreases with increasing throughput. For example, at 20m distance between the building and access point the depth achieved is 10m for a 91 Mbps throughput compared to a 70m depth at the same distance for 1.5 Mbps throughput. Lower throughputs can achieve 20-40m depth of in-building coverage even at distances up to 100m but the closer to the access point is to the building the better depth of in-building coverage is achieved for all throughputs.

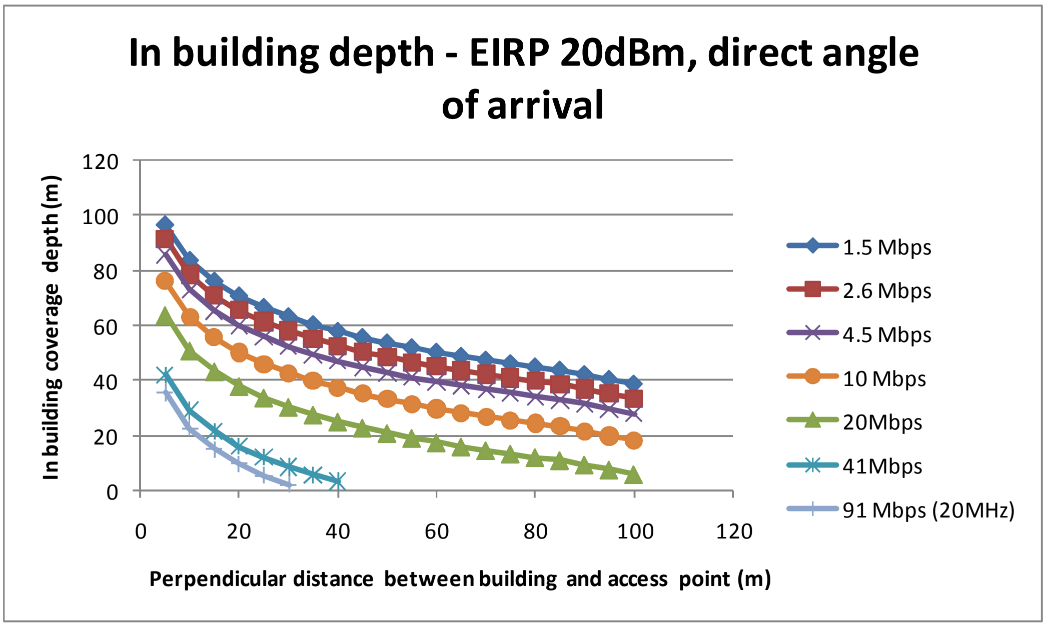


Figure 5-36 Depth of in-building coverage 20 dBm Direct angle of arrival

The results shown in Figure 5-37 are the in-building depth for a direct angle of arrival at 29 dBm EIRP. The difference compared to the 20 dBm scenario shows greater depth of in-building coverage for comparable distances between the building and access point. Using our same example, at 20m distance between the building and access point, the depth achieved is 27m for a 91 Mbps throughput compared to a 90m depth at the same distance for 1.5 Mbps throughput.

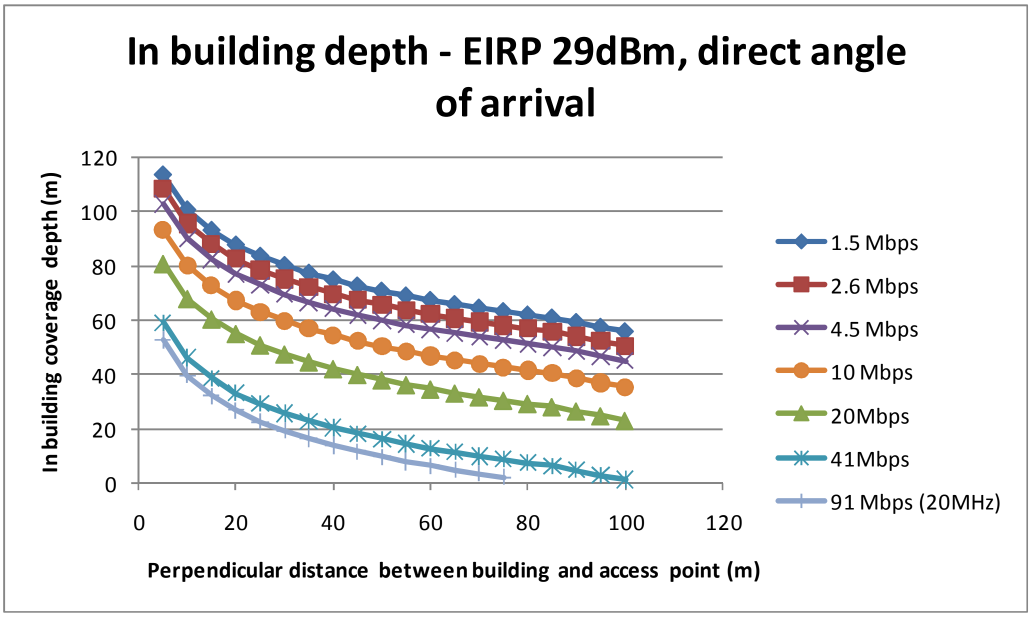


Figure 5-37 Depth of in-building coverage 29 dBm Direct angle of arrival

Oblique 45 degree angle of arrival

The results shown in Figure 5-38 are the in-building depth for an oblique angle of arrival at 20 dBm EIRP. Using the same example as the direct angle, at 20m distance between the building and access point there is no depth recorded for a 91 Mbps throughput. Using 41 Mbps at 20m distance between the building and access point achieves a 7m depth of in-building coverage compared to a 60m depth at the same distance for 1.5 Mbps throughput. As expected these are less than in the direct angle of arrival case.

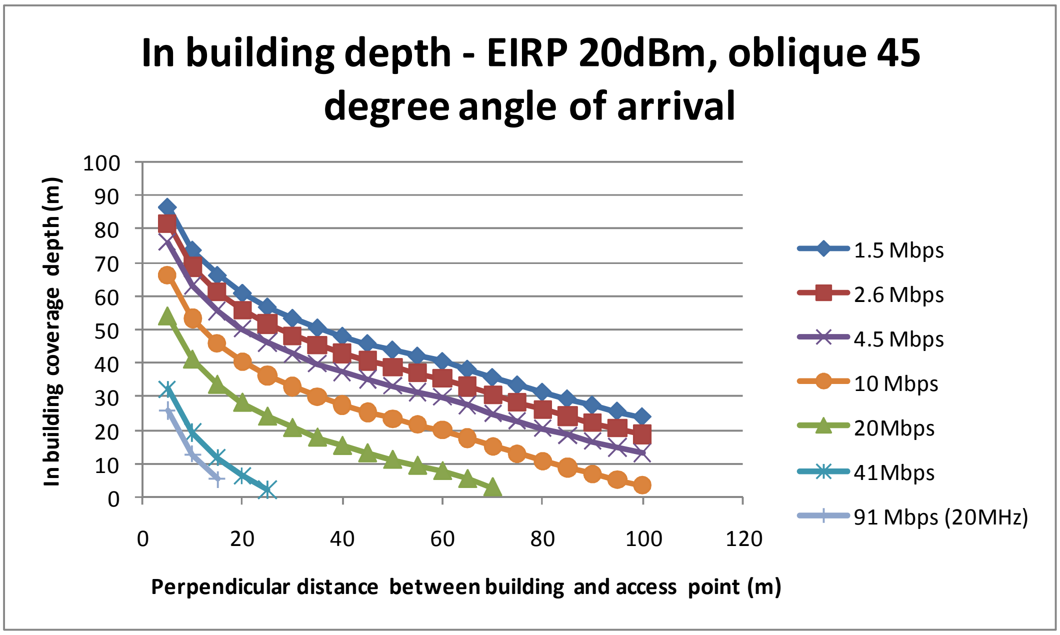


Figure 5-38 Depth of in-building coverage 20 dBm oblique 45 degree angle of arrival

The results shown in Figure 5-39 are of the in-building coverage depth for an oblique angle of arrival at 29 dBm EIRP. Using our same example, at 20m distance between the building and access point the depth achieved is 19m for a 91 Mbps throughput compared to a 79m depth at the same distance for 1.5 Mbps throughput.

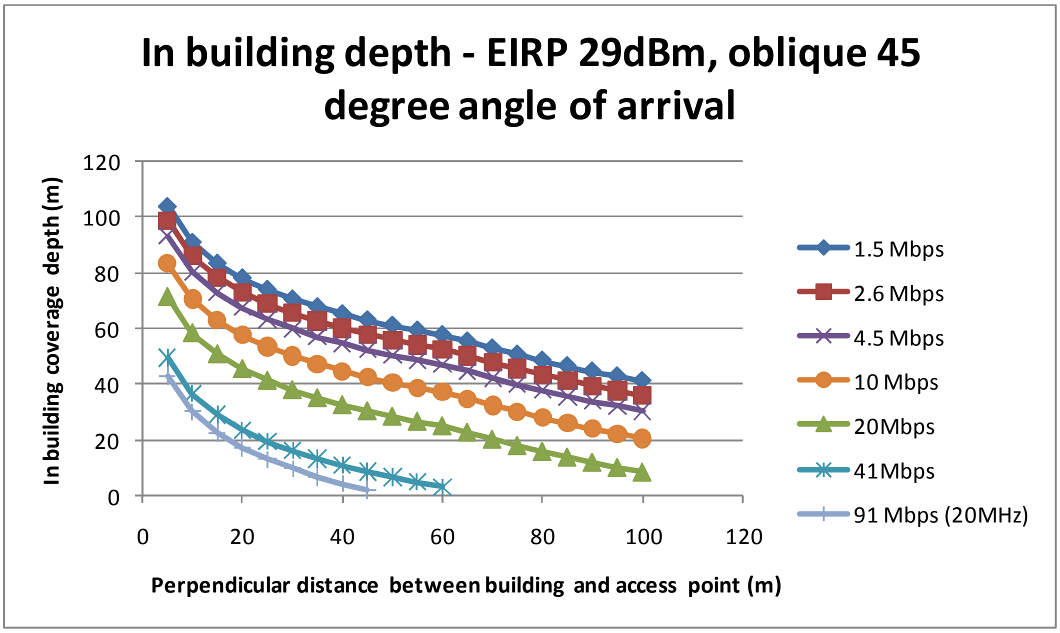


Figure 5-39 Depth of in-building coverage 29 dBm oblique 45 degree angle of arrival

Conclusions – In building depth analysis for outdoor access points

- Both 20dBm EIRP and 29dBm EIRP were examined as a maximum transmit power of 24dBm and an antenna gain of 5dBi for outdoor Local Area Base Stations are discussed in 3GPP and were also highlighted by stakeholders.
- 29dBm is required to achieve maximum data rates into the building at ranges from the building of more than 20m.
- For direct angles of arrival, like a campus scenario, at 29dBm EIRP and a distance of 50m from the building an in building depth of 16m is achieved for peak data rates in 10MHz and 10m for peak data rates in 20MHz. At 100m from the building this is reduced negligible levels of 1m.
- For an oblique angle of arrival, like a street scenario, the indoor penetration is worse. At a 50m perpendicular distance from the building and 45 degree angle of arrival the in building depth for maximum data rates at 10MHz is 6.5m. At 20MHz the range from the building needs to be reduced to 45m to get just 2m of indoor coverage
- These results support the findings of section 5.6, that in-building coverage provided by outdoor access points will be the limiting case for setting the maximum EIRP of low power network access points.

5.8 Summary

Study question	**Answer**
1.13 What minimum power level would be needed in order to provide coverage in the following example scenarios: • *Indoor office environment* • *Indoor public area* • *Residential (home femtocell)* • *Campus / business park (including use of external base station antennas)*	***Indoor office environment****:* An EIRP of 27dBm l (i.e. In line with 3GPP Local Area Base Station specification and a 3dBi antenna gain) easily provides maximum data rates at the range to cover a single floor medium sized office and could be backed off to 18dBm. ***Indoor public area:*** An EIRP of 27dBm l (i.e. In line with 3GPP Local Area Base Station specification and a 3dBi antenna gain) would provide maximum data rates at the range to cover a single floor medium sized shopping centre (8,000 m²). In practice operators are likely to deploy more than one access point for capacity reasons in the office and public areas and so the transmit power levels here could potentially be backed off even more. ***Residential (home femtocell):*** *A*n EIRP of 20dBm provides a range of 16.5m at a max data rate of 91Mbps downstairs and 6.66m upstairs. This is sufficient downstairs for most houses but may start to limit coverage at higher data rates upstairs in some larger properties.

	Campus / business park (outdoor access point): ***Outdoor users*** – An EIRP of 29dBm on the low power shared access channel (i.e. In line with the 3GPP Local Area Base Station transmit power specification) would provide maximum data rates to outdoor users at typical microcell ranges (i.e. 100m) ***Indoor users*** - *A*n EIRP of 29dBm would require the target cell edge data rate to be backed off to 20Mbps (in 10MHz) to achieve the target microcell range of 100m and good indoor penetration. Coverage is limited by the indoor penetration of outdoor base stations. Recommend the maximum EIRP is set at 29dBm in line with this.
1.14 What depth of in-building coverage would be provided by an outdoor base station operating at 20dBm e.i.r.p. in the campus scenario, assuming a mast height of 5m or below?	Both 20dBm EIRP and 29dBm EIRP were examined as a maximum transmit power of 24dBm and an antenna gain of 5dBi for outdoor Local Area Base Stations are discussed in 3GPP and were also highlighted by stakeholders. 29dBm is required to achieve maximum data rates into the building at ranges from the building of more than 20m. For direct angles of arrival, like a campus scenario, at 29dBm EIRP and a distance of 50m from the building an in building depth of 16m is achieved for peak data rates in 10MHz and 10m for peak data rates in 20MHz. At 100m from the building this is reduced to negligible levels of 1m. For an oblique angle of arrival, like a street scenario, the indoor penetration is worse. At a 50m perpendicular distance from the building and 45 degree angle of arrival the in building depth for maximum data rates at 10MHz is 6.5m. At 20MHz the range from the building needs to be reduced to 45m to get just 2m of indoor coverage

6 Co channel interference is manageable via appropriate antenna heights, dynamic scheduling and compromises in target throughputs

6.1 Study questions

Ofcom posed the study questions shown in Figure 5-1 to understand the impact of co-channel interference on devices in the proposed low power shared access channel.

Study questions

1.17 What is the minimum separation distance between buildings where low-power networks can be deployed without operator coordination becoming necessary.

1.18 What limits should placed on the maximum height of outdoor antennas, for the purpose of limiting interference to other low-power networks (our working assumption is 5m)?

1.19 In the case of underlay low-power networks, what restrictions on antenna placement would be needed in order to minimise interference to the co-channel wide-area network, e.g. minimum distance from macrocell antennas, restriction to indoor placement?

1.20 Based on an assumption that some low-power operators will deploy outdoor antennas on low-power networks, what is the minimum distance before the frequency (or resource blocks) can be re-used by indoor networks? What is the minimum separation distance for deployment of co-channel low-power indoor and outdoor networks without operator coordination becoming necessary.

Figure 6-1 Ofcom study questions addressed in Chapter 6

The following example scenarios shown in Table 6-1 have been analysed to answer these study questions.

Study Question	Deployment scenario	Aggressor	Victim	Requirement
1.17	Minimum separation distance between low power networks in shared spectrum	Single femto eNodeB (interfering)	Single femto UE in adjacent building (DL)	Separation distance in metres between buildings against throughput degradation.
		Single high power femto UE (interfering)	Single femto eNodeB in adjacent building (UL)	
1.18	Maximum height of outdoor antennas	Single outdoor femto eNode B with variable antenna height	Single outdoor femto UE on another low power outdoor network (DL) with 5m antenna	Antenna height in metres against separation distance between low power networks
1.19	Restrictions on (indoor) antenna placement for underlay approach due to interference to co-channel wide area network	Single indoor femto UE on limit of reception (interfering)	Single outdoor macro eNodeB (UL)	Separation distance between aggressor and victim against throughput degradation.
		Single indoor eNodeB	Single outdoor UE (DL)	
1.20	Minimum distance from outdoor low power antennas before frequency (or RB's) can be re-used by indoor networks	Single outdoor eNodeB	Single indoor UE (DL) served by indoor Low-Power eNodeB	Separation distance between aggressor and victim against throughput degradation.

		Single outdoor UE	Single indoor eNodeB (UL)	

Table 6-1: Co channel interference scenarios to address study questions

6.2 Study approach

The study approach is outlined in Figure 5-2. For each of the study questions we have defined an example scenario with an aggressor, the device causing the interference, and a victim, the device suffering interference. The following inputs are required to the model:

- Transmit power levels for the aggressor based on our earlier coverage results for target throughput in the scenario
- SNR at the victim receiver based on the target cell edge throughput in the absence of interference
- The allowable SINR at the victim receiver based on the allowable degraded cell edge throughput in the presence of interference
- Device parameters such as antenna gains at both the aggressor and victim and the victim receiver noise figure
- Channel conditions including the most appropriate propagation model for the scenario being modelled and values for the shadowing standard deviation

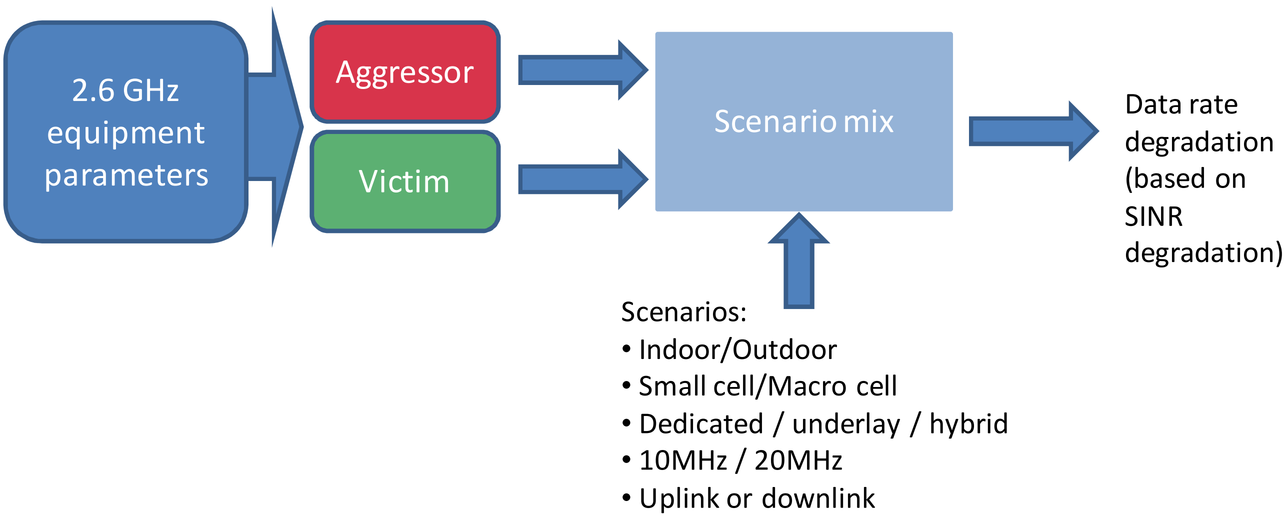


Figure 6-2 Approach to low-power shared access co-channel modelling

As LTE devices will only suffer interference on the resource blocks that overlap with the aggressor device it would be pessimistic to calculate the target throughput based on achieving the target SINR across all resource blocks. Instead we have modelled the two schedulers; a random scheduler and a dynamic scheduler, as described in section 4.7. Based on the two schedulers we estimate the number of contended and un-contended resource blocks available, determine how much of the target throughput would be carried on the un-contended resource blocks at the SNR and then calculate a target SINR for the remaining contended resource blocks to carry the remainder of the target throughput. A link budget between the aggressor and victim is then used to determine the separation distance necessary to achieve this SINR.

The target throughputs are based on the throughputs that would be achieved by a single cell edge user at 78% confidence to match the criteria applied in our coverage analysis. Our analysis reflects a very much worst case scenario of a user on the cell edge in the most challenging conditions. The actual degradation across the entire cell will depend on the resulting SINR distribution across the cell which was beyond the scope of this study.

The model output illustrates the expected degradation in throughput due to interference for different noise limited target throughputs at varying separation distances as shown in Figure 5-3.

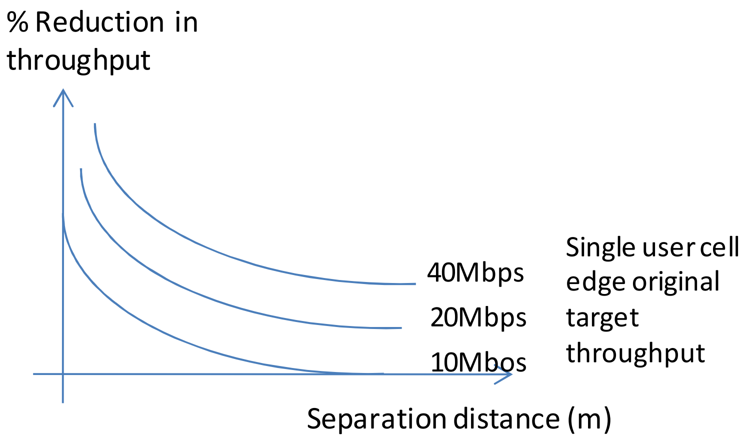


Figure 6-3 Output plots for coverage scenario analysis

6.3 Building separation – Study question 1.17

6.3.1 Scenario description and assumptions

Figure 6-4 illustrates the example scenario modelled to estimate the minimum building separation required to minimise interference between low power networks. We have selected a residential scenario of two neighbours both using low power access points. In the downlink scenario the UE is at the edge of coverage of its own low power network and suffers interference from the neighbouring access point. On the uplink the access point in the second house is desensitised by uplink interference from the UE in the first house which results in cell shrinkage in the second house.

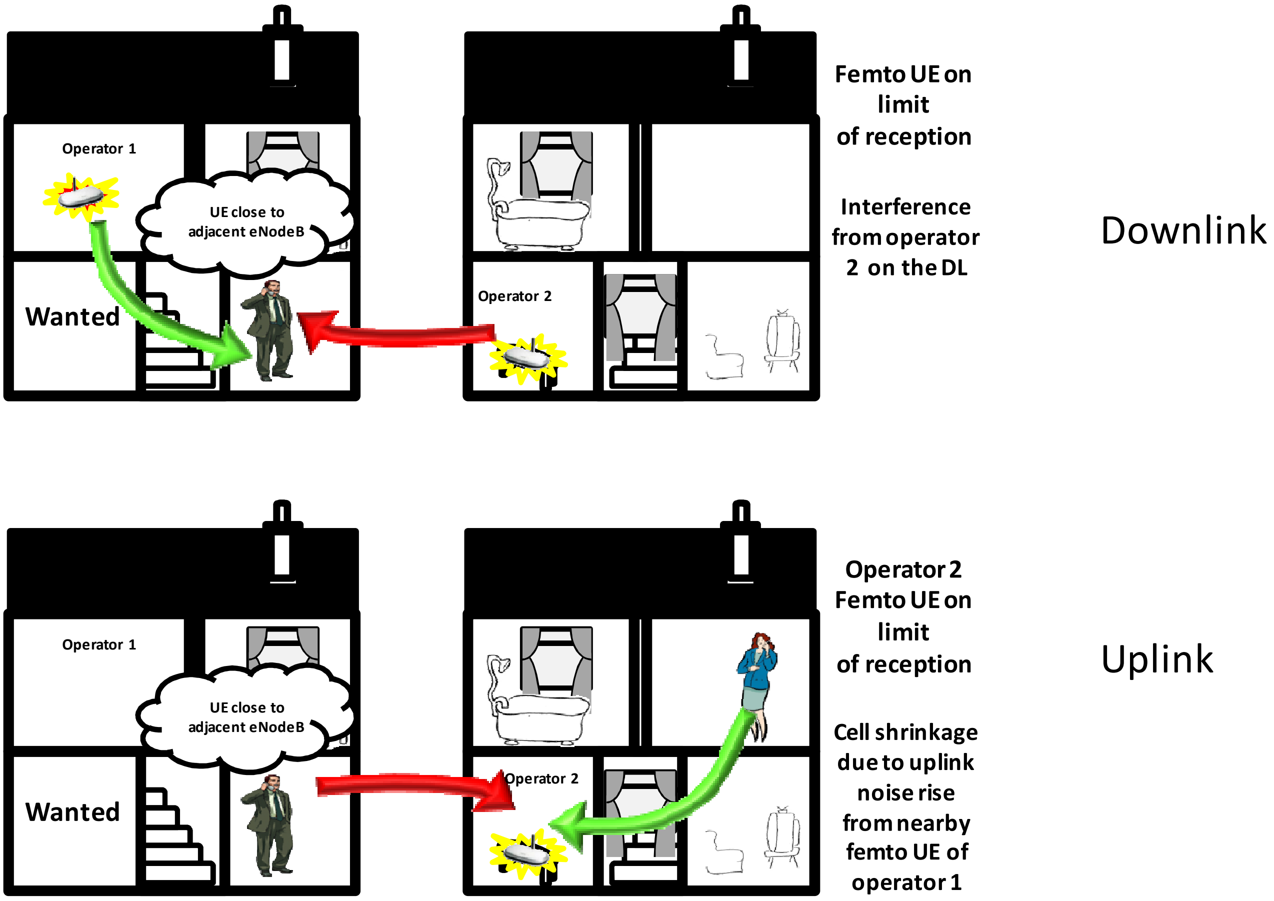


Figure 6-4: Example scenario used for estimating building separation to minimise interference between low power networks

We have modelled the downlink scenario to answer this study question as:

- The path loss and transmit power levels involved are the same in both cases
- Target throughputs will be more challenging on the downlink
- The victim receiver parameters are worse on the downlink scenario

In our model we have made the following assumptions:

- Power control is applied on the downlink so that the aggressor transmit power varies in line with our coverage results for a 10m upstairs range in a residential scenario. This range assumes a worst case that the victim UE and access point are on either side of a typical 4 bedroom detached house.
- A 10MHz bandwidth is modelled as this will have the maximum PSD
- Path loss is modelled using ITU P.1411 street canyon model
- Two external wall losses of 7dB each are applied. This represents a concrete external wall with a window.
- A 4 dB average shadowing standard deviation is applied to the target SINR based on 4dB shadowing standard deviation at both the victim and aggressor.
- A 0dBi antenna gain is applied at both the aggressor and victim. This assumes residential access points will be low end devices.

- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

6.3.2 Results and conclusions

Figure 6-5 shows the results for the separation distance that would be required between the two neighbouring houses in our example scenario to achieve different allowable levels in throughput degradation (shown on the y axis). The allowable throughput degradation is a proportion with respect to the original target throughput for a single cell edge user at the victim receiver in the absence of interference. Each throughput (shown by line colour) represents a different SNR starting assumption at the victim receiver. We assume that the aggressor is also targeting this rate and sets its transmit power to the higher levels required as the target throughput increases.

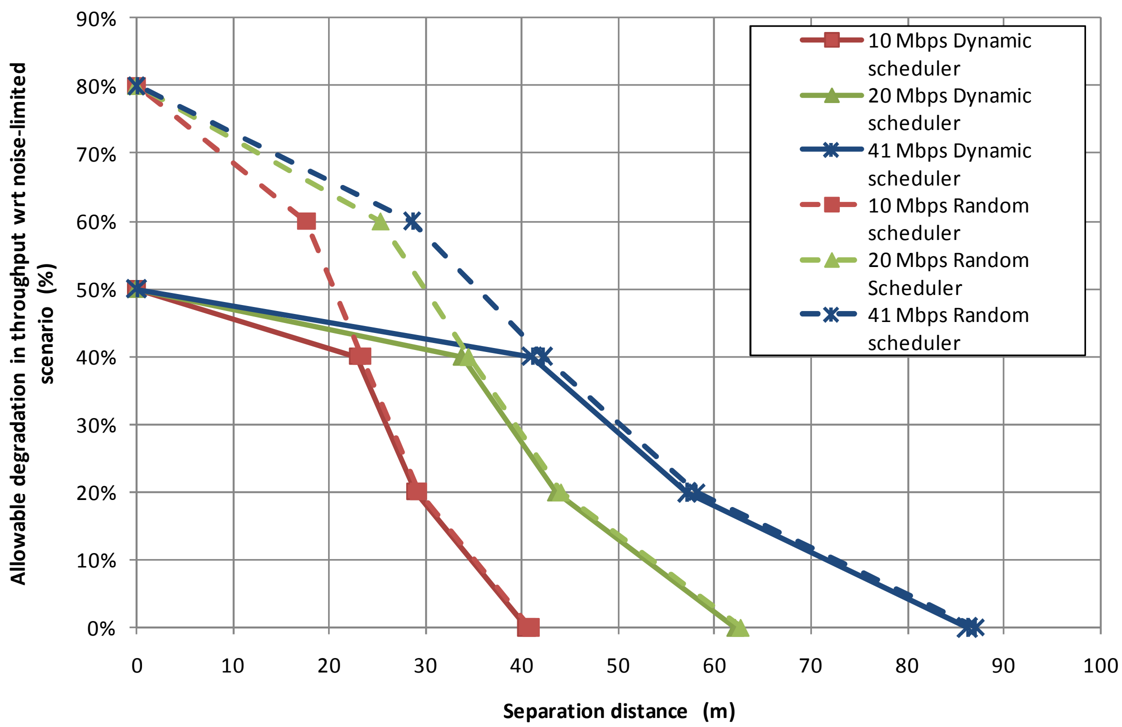


Figure 6-5: Separation distances required between two houses each containing a low power access point to achieve the target throughput degradation shown

The dashed lines on the graph show the results using the random scheduler. The solid lines show the performance of the dynamic scheduler which detects interference and schedules in un-contended resource blocks as much as possible to reach the target throughput. When the target degraded throughput allows for capacity to be shared equally amongst the contending networks, a zero separation distance can be achieved as both the aggressor and victim can use 50% of resource blocks un-contended to achieve the target throughput. This is better than a random scheduling approach which in this scenario must have an allowable degradation of up to 80% before the separation distance can be removed and the required degraded throughput is achieved on average by random scheduling.

As the allowable percentage degradation decreases and more contended resources need to be used to achieve the degraded throughput, the benefits of the dynamic scheduler diminish and its performance approaches that of the random scheduler. Therefore the dashed and solid lines converge on the graph.

If an allowable degradation in throughput of 50% is not acceptable to operators for this scenario then a separation distance between low power networks of greater than 23m is required.

Generally separation distance decreases as the original target throughput at the victim receiver decreases as the lower target SINR will be lower. However, there is a minimum limit on the target SINR of -2dBm to recover the PDCCH. When this limit is reached the separation distances for the higher original throughputs with higher victim SNRs start to approach those of lower target throughputs with lower SNRs.

Conclusions

The following conclusions can be drawn from the results for this scenario:

- With the use of a dynamic scheduler that identifies interference and targets un-contended resource blocks the data rate at the cell edge will be degraded by the number of interfering access points i.e. in this case 2 networks were modelled so the throughput can be expected to be halved.
- If the above degradations in throughput are acceptable no minimum separation distance is required between buildings provided this smart interference mitigation technique is applied.
- If the above degradations are not acceptable then the minimum separation distance is likely to be upwards of 23m depending on the signal level at the victim receiver. This will be difficult to enforce in practice.
- It should be noted that this scenario represents a worst case scenario of interference to a cell edge user from a nearby access point. The SINR across the victim cell will vary with distance, propagation environment conditions and wanted signal strength. These results only represent the degradation to a cell edge user and do not represent the degradation in throughput across the entire cell.

6.4 *Outdoor antenna height – study question 1.18*

6.4.1 Scenario description and assumptions

Figure 6-6 shows the example scenario analysed to determine the maximum recommended mast height for outdoor lower power access points. This represents two adjacent streets with two different low power operators providing service into each of the houses along the two streets. The aggressor is an outdoor access point whose downlink signal provides interference to a UE using the network in the adjacent street. In this scenario we have only modelled the impact of interference on an outdoor user. For indoor users the affect would be similar as although the interference signal is reduced by the building loss the wanted signal at the indoor victim UE would also be degraded by the same amount.

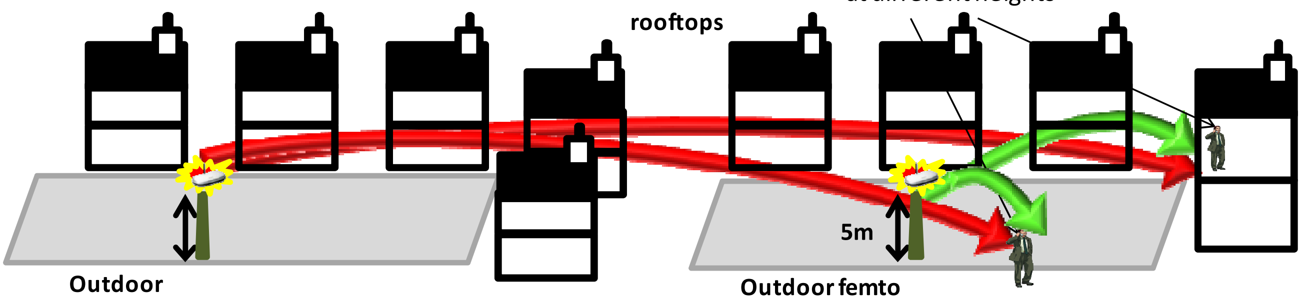


Figure 6-6: Example scenario analysed for determined maximum antenna heights for outdoor low power access points

In our model we have made the following assumptions:

- Power control is applied on the downlink so that the aggressor transmit power varies in line with our coverage results for a 50m range between the outdoor access point and building and achieving reasonable (depth 2) building penetration. This range assumes that a series of access points are regularly spaced on lamp posts to cover a street.
- A 10MHz bandwidth is modelled as this will have the maximum PSD
- Path loss is modelled using the ITU P.1411 non line of sight Walfisch-Ikegami model using a 9m roof top height and 14m street width.
- An 8dB average shadowing standard deviation is applied to the target SINR based on an 8dB shadowing standard deviation at both the victim and aggressor.
- A 5dBi antenna gain is applied at the aggressor and assumes outdoor access points will be high end devices compared to indoor equivalents. A 0dBi antenna gain is assumed at the UE.

- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

6.4.2 Results and conclusions

Figure 6-7 shows how the required separation distance between the outdoor low power access point aggressor and the victim UE varies with the mast height of the aggressor if a 50% degradation in throughput at the victim UE is allowed. As in the previous scenario the dynamic scheduler can provide the degraded throughput with no minimum separation distance if the system capacity is divided amongst the number of contending networks i.e. 50% in this scenario of two networks. As this is an over roof top scenario there is an assumption that there will always be at least a building and half a road between the victim and aggressor and so a separation distance of less than 19m cannot be reached.

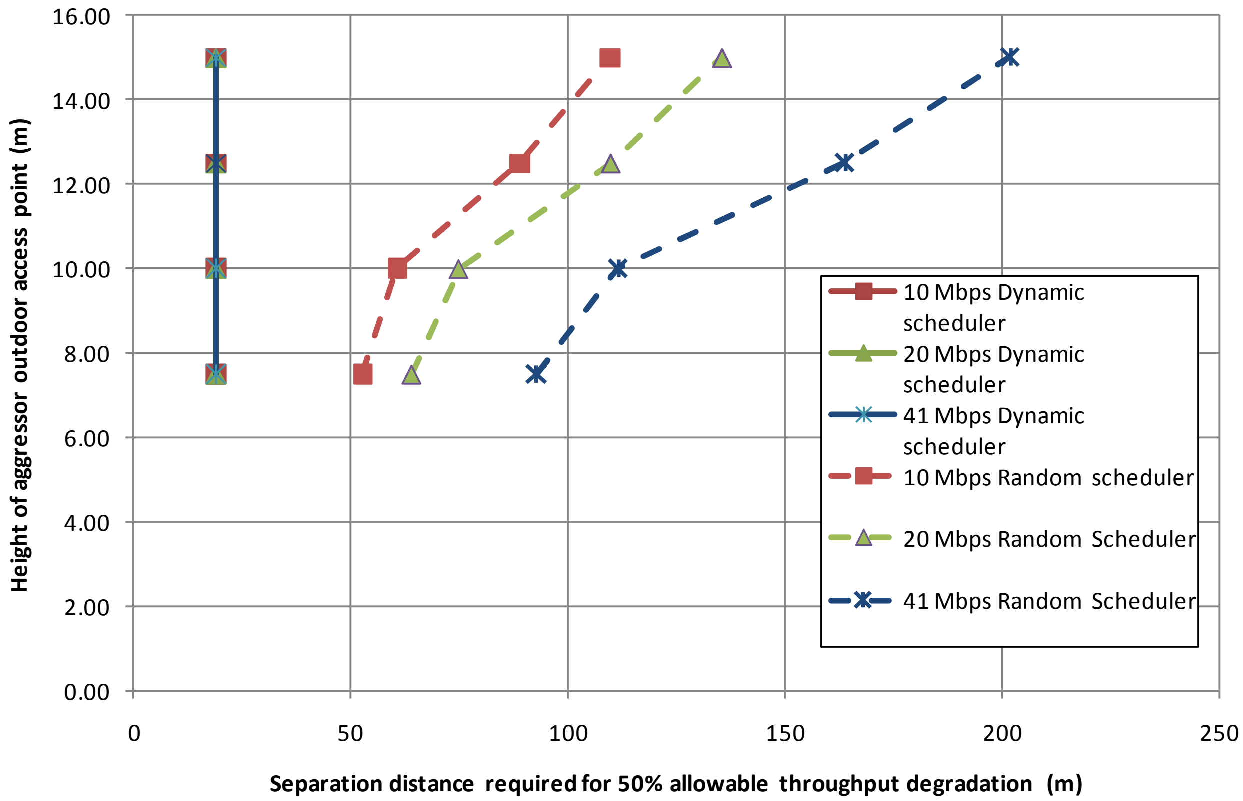


Figure 6-8: Separation distances required between an outdoor access point at different mast heights and a victim low power UE to achieve a to achieve a 50% degradation on the target throughput shown

In the case of the random scheduler we can see that separation distances and hence interference rises sharply beyond a 10m mast height. This is commensurate with the 9m building height used in the scenario.

Conclusions

The following conclusions can be drawn from the results for this scenario:

- As in the residential case, if a throughput degradation proportional to the number of interfering access points is acceptable then the outdoor antenna height does not impact separation distance as a dynamic intelligent scheduler can be used to avoid interference.
- The minimum separation distance of 19m is the minimum achievable in this scenario as this is a non line of sight over roof top scenario. This distance represents a building plus ½ a road.
- In the example scenario, the separation distance required increases steeply for heights beyond 10m which is commensurate with the rooftop height of 9m used in this scenario.
- Limits on outdoor antenna heights should be set in line with the height of surrounding buildings. The residential scenario will usually be the limiting case so we recommend a height of 10-12m.

6.5 Interference to macrocells in an underlay approach – study question 1.19

6.5.1 Scenario description and assumptions

Figure 6-9 shows the example scenario analysed to understand uplink interference to macrocell base stations from low power networks in an underlay spectrum approach where spectrum is shared between the two networks. In this scenario the UE of the low power network is at the edge of coverage and transmitting at maximum power. This desensitises a nearby macrocell base station and causes cell shrinkage. The impact of this interference will degrade the throughput of users across the entire macrocell.

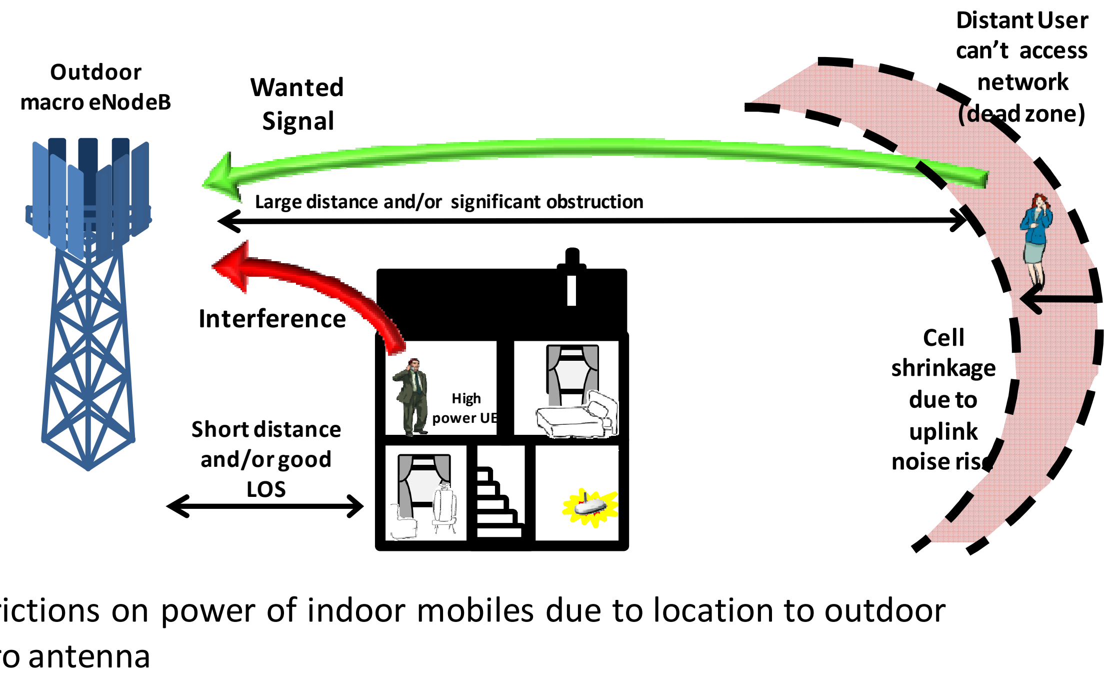


Figure 6-9: Uplink interference to a macrocell base station from a low power UE in an underlay scenario

In our model we have made the following assumptions for this scenario:

- The UE transmits at its maximum power of 23dBm. We have also allowed for the 3GPP interference mitigation approach where transmit power is dropped to 10dBm if the low power network detects a macrocell that it is sharing spectrum with.
- A 10MHz bandwidth is modelled as this will have the maximum PSD
- Path loss is modelled using the ITU P.1411 with a single external wall loss of 7dB representing a concrete external wall with a window
- A 5.5dB average shadowing standard deviation is applied to the target SINR based on a 4dB and 8dB shadowing standard deviation at the aggressor and victim respectively.
- A 0dBi antenna gain is applied at the aggressor. A 14dBi antenna gain is assumed at the victim.
- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

Figure 6-10 shows the downlink interference experienced by a macrocell network in an underlay spectrum approach. Here the low power access point is located close to a macrocell UE on the edge of coverage. In the worst case the macrocell UE will be a visitor to the house where the low power access point is being used but is not able to roam onto the low power network.

Restrictions on placement or power of low-power indoor antennas due to interference to co-channel wide area UE

Figure 6-10: Downlink interference to macrocell UE from a low power network

In our model we have made the following assumptions for this scenario:

- Power control is applied on the downlink so that the aggressor transmit power varies in line with our coverage results for a 10m upstairs range. This range assumes a worst case that the victim UE and access point are on either side of a typical 4 bedroom detached house.
- A 10MHz bandwidth is modelled as this will have the maximum PSD
- Path loss is modelled using the ITU P.1411 with a single external wall loss of 8dB representing a concrete external wall with a window
- A 5.5dB fade margin is applied to the target SINR based on a 4dB and 8dB shadowing standard deviation at the aggressor and victim respectively.
- A 0dBi antenna gain is applied at the aggressor and victim.
- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

6.5.2 Results and conclusions

Uplink results

Figure 6-11 and Figure 6-12 show the separation distances that would be required between the victim macrocell base station and aggressor low power network UE to achieve a range of allowable throughput degradations. It can be seen that the dynamic scheduler provides lower separation distances than the random scheduler, as was the case in earlier scenarios, and that a zero separation distance can be achieved if operators are willing to share capacity in proportion to the number of contending networks.

Figure 6-11 assumes that the aggressor UE is at the edge of coverage and transmitting at a maximum power level of 23dBm. Figure 6-12 shows the separation distances achieved if the UE transmit power is reduced to 10dBm. This is to illustrate the impact of a power cap on low power network devices if they detect that they are in the region of a macrocell that they are sharing spectrum with. This is an approach that has been suggested in 3GPP and is applied in the transmit power standards for HeNBs when other wide area networks are detected in adjacent channels.

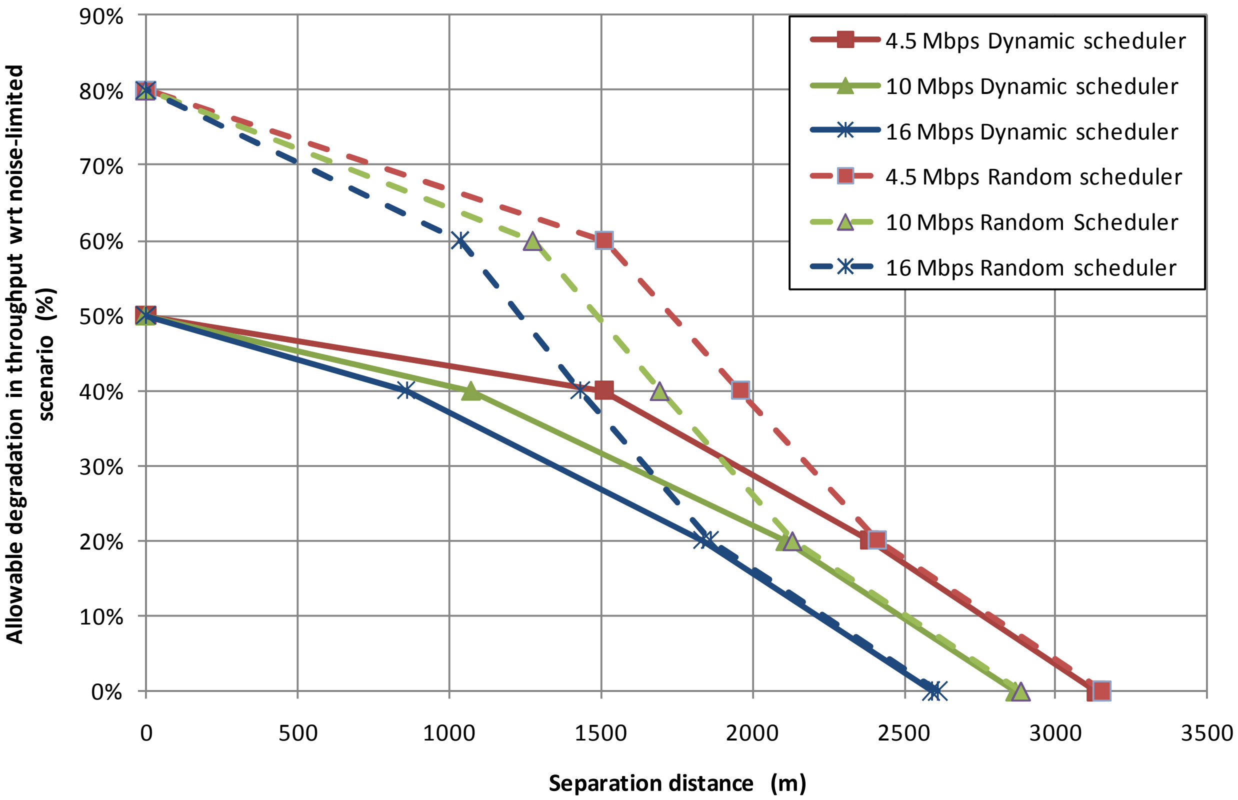


Figure 6-11: Separation distances required between victim macrocell base station and low power network UE aggressor to achieve the target throughput degradation shown for a 23dBm aggressor power

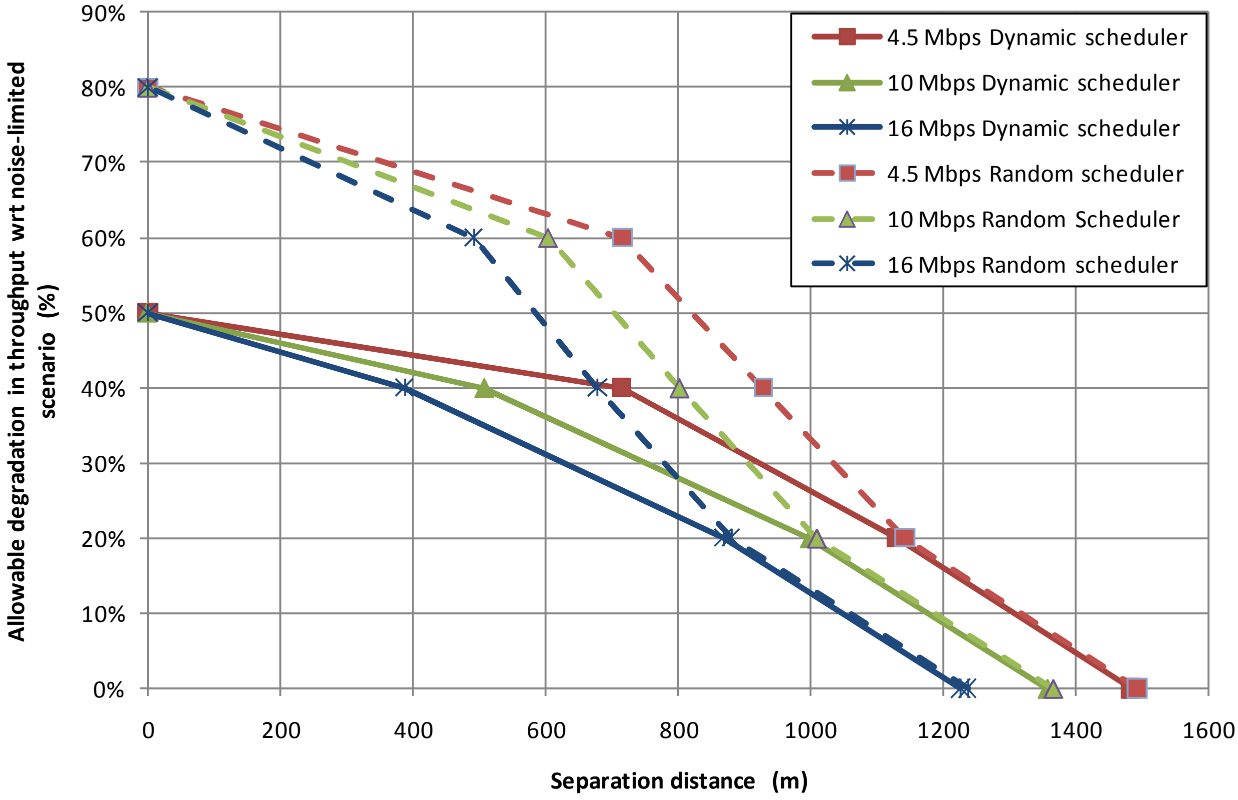


Figure 6-12: Separation distances required between victim macrocell base station and low power network UE aggressor to achieve the target throughput degradation shown for a 10dBm aggressor power

If throughput degradations of less than 50% are required in these scenarios then separation distances in the range of 400m to 1.5km and 800m –3.2km will need to be applied for the case with and without the 10dBm transmit power cap respectively. It is unlikely that distances in this region will be practical to enforce.

Downlink results

Figure 6-13 shows the resulting separation distances that would be required between the victim macrocell UE and aggressor low power network access point to achieve a range of allowable throughput degradations in the downlink interference case. This is for the scenario shown in Figure 6-10 where the macrocell UE is located outside the building where the low power access point is being used. Compared to the uplink results examined previously these separation distances are much smaller due to the reduced antenna gain and height of the victim receiver. The uplink interference results should therefore drive choices on the separation distances between low power access networks and macrocell networks.

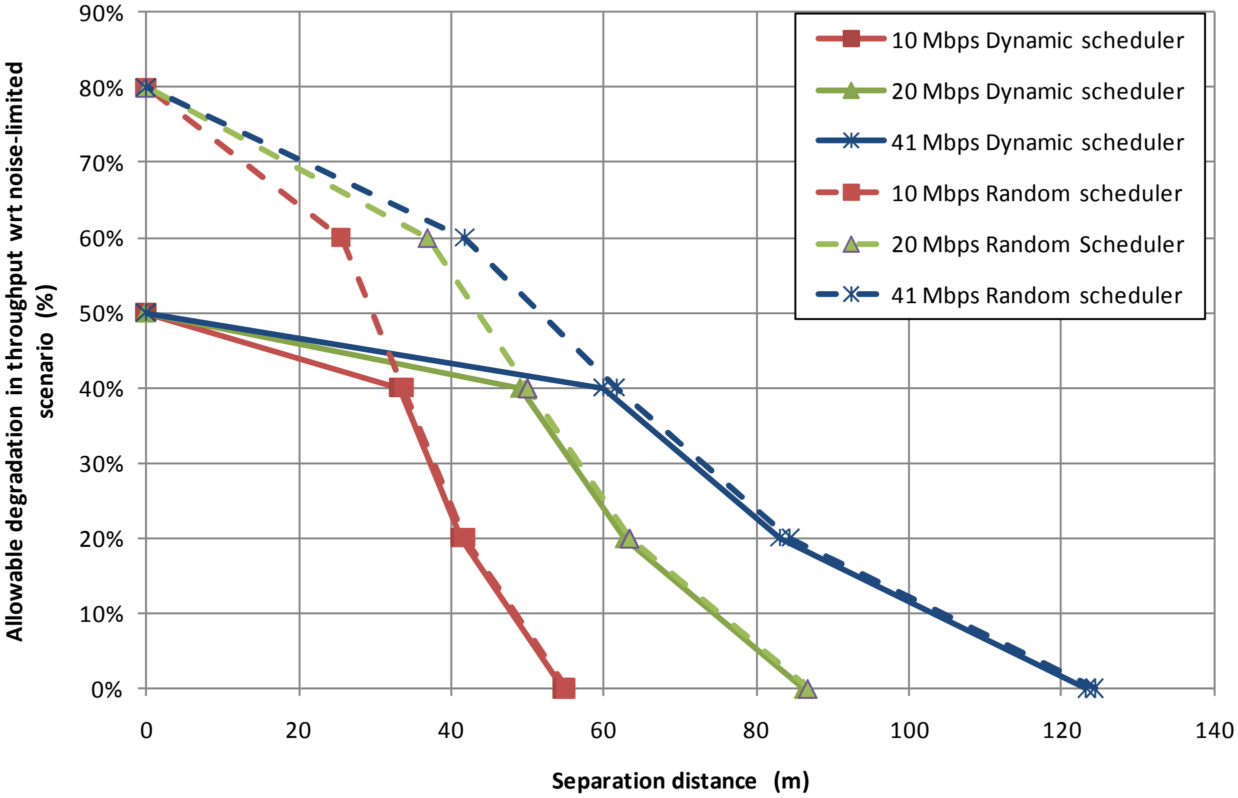


Figure 6-13: Separation distances required between victim macrocell UE and low power network access point aggressor to achieve the target throughput degradation shown

Figure 6-14 shows the exceptional case of downlink interference where a person visiting a home using a low power access point is not a member of the closed subscriber group of that access point and so is still attached to the wider are network but comes very close to the indoor access point. In this case there is no wall loss and a clear line of sight between the victim and aggressor. The model for this scenario assumes free space path loss which is clearly a worst case scenario and may not be valid at the high end separation distances. However, this does illustrate that the visitor problem is a significant issue for low power networks and may require conditional roaming of UEs onto the low power network in cases of extreme interference to avoid this situation.

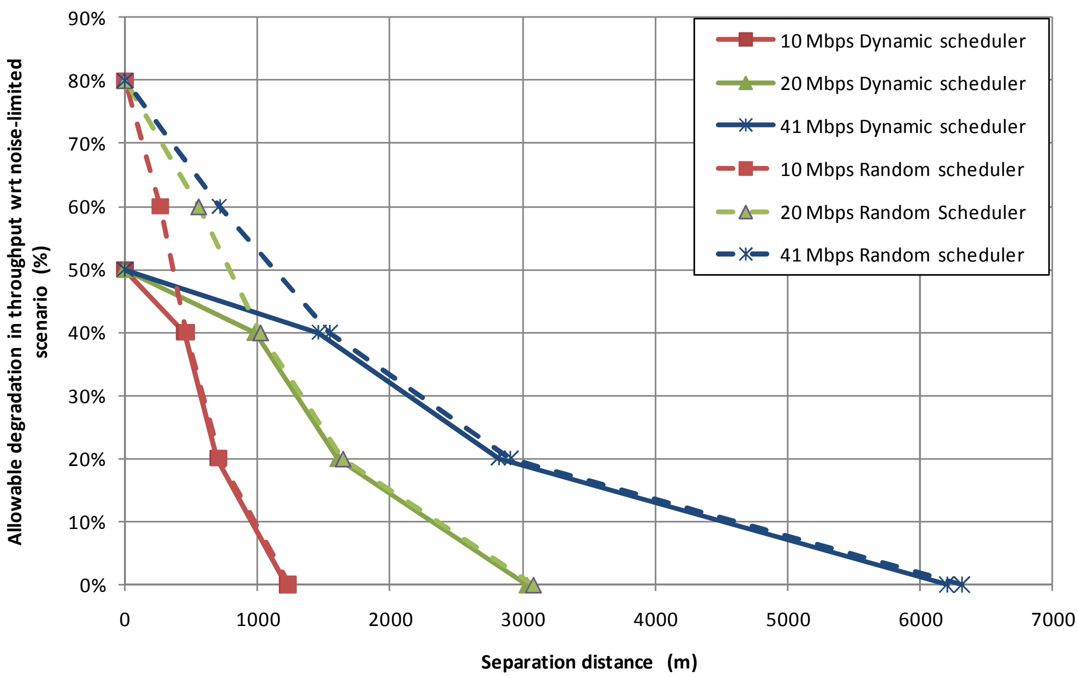


Figure 6-14: Separation distances required between victim macrocell UE and low power network access point aggressor to achieve the target throughput degradation shown in "visitor problem"

Conclusions

The following conclusions can be drawn from the results for these scenarios:

- The separation distances required in the uplink interference scenario are much larger than on the downlink. The impact of uplink interference is to desensitise the macrocell BS for all UEs and so the impact is more significant to the entire cell than the downlink interference case.
- Separation distances in the range 400m-1.5km would be required if less than a 40% throughput degradation is required in the example scenario. This relies on a 10dBm power cap being applied to the aggressor.
- If a throughput degradation proportionate to the number of contending networks sharing capacity is acceptable the interference can be managed by smart scheduling and a separation distance is not required. For example in this case a throughput degradation of 50% would need to be acceptable.
- It is unlikely that a wide area operator would be willing to accept such a degradation in throughput or that these separation distances would be practical. It is more likely that the low power access points would have to refrain from transmitting when in the area of a macrocell if an underlay approach was applied.

- Other interference mitigation in the underlay scenario could include a power cap on low power UEs detecting a macrocell network or to allow the low power UE causing uplink interferences to roam onto the macrocell network.
- On the downlink the extreme case of a visiting macrocell UE coming close to a low power access point may need to be accommodated by conditional roaming in the cases of extreme interference.

6.6 Separation distance between outdoor and indoor low power networks – study question 1.20

6.6.1 Scenario description and assumptions

Figure 6-15 shows the downlink interference experienced by an indoor low power network from an outdoor low power access point. Here the low power network UE is located at the edge of coverage with a weak signal and suffers interference from a nearby low power access point outdoors with which it is sharing spectrum.

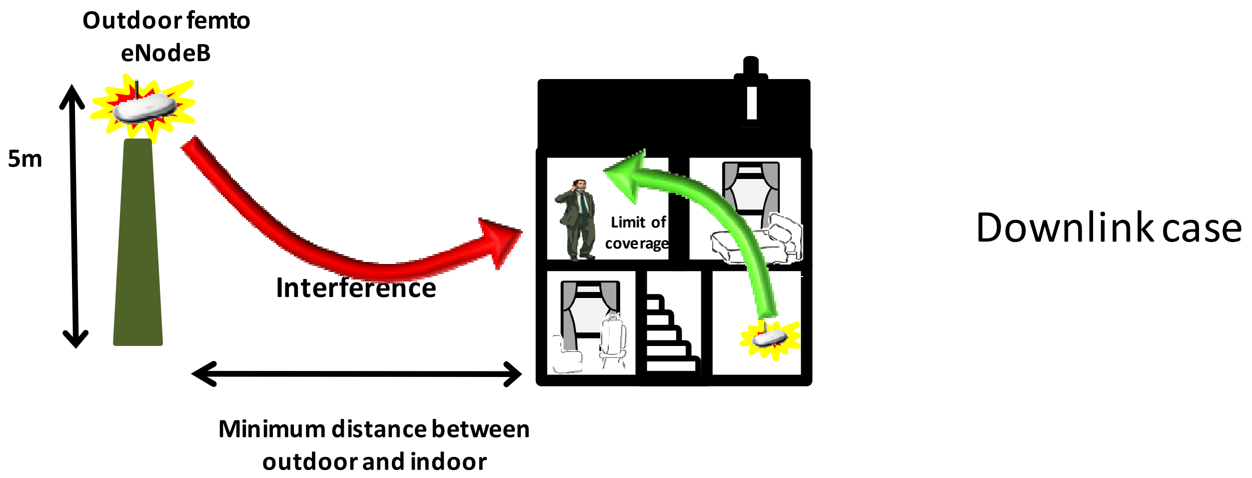


Figure 6-15: Example scenario for downlink interference from an outdoor low power network to an indoor low power network

In our model we have made the following assumptions for this scenario:

- We have modelled two levels of transmit power at the aggressor. The first assumes a fixed transmit power of 24dBm based on the 3GPP limit for local areas base stations. As an alternative we have also investigated the case when power control is applied at the aggressor to adjust transmit power levels to those required to reach target throughputs at a 50m range and with reasonable (depth 2) in building penetration as shown by our coverage results.
- A 10MHz bandwidth is modelled as this will have the maximum PSD

- Path loss is modelled using the ITU P.1411 with a single external wall loss of 7dB representing a concrete external wall with a window
- A 5.5dB shadowing standard deviation is applied to the target SINR based on a 4dB and 8dB shadowing standard deviation at the victim and aggressor respectively.
- A 0dBi antenna gain is applied at the victim. A 5dBi antenna gain is assumed at the aggressor.
- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

Figure 6-16 shows the example scenario analysed to understand uplink interference to an indoor low power network from an outdoor low power network that it is sharing spectrum with. In this scenario the UE of the outdoor low power network causes downlink interference to the access point of the indoor network resulting in cell shrinkage.

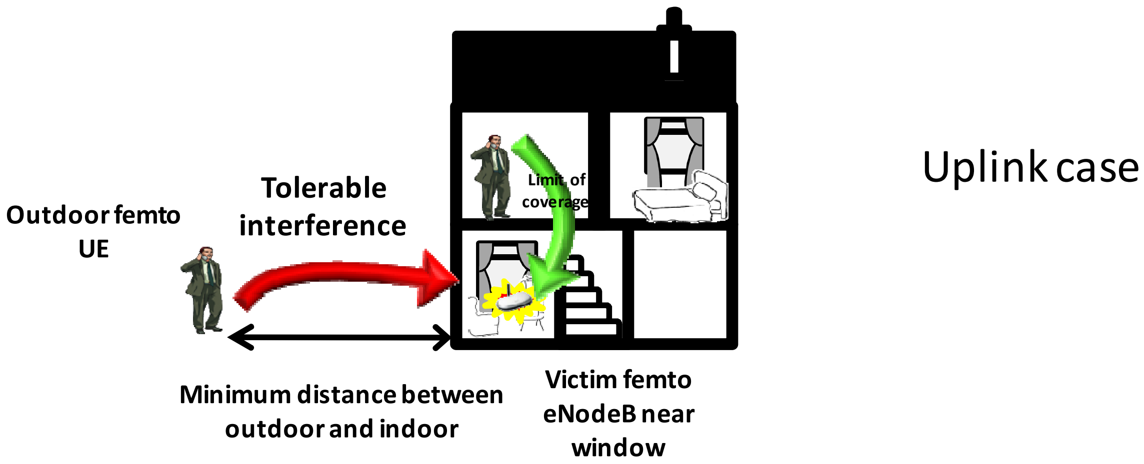


Figure 6-16: Example scenario for uplink interference from an outdoor low power network to an indoor low power network

In our model we have made the following assumptions for this scenario:

- We assume that the outdoor UE is at the edge of coverage and transmitting at a maximum power level.
- A 10MHz bandwidth is modelled as this will have the maximum PSD
- Path loss is modelled using the ITU P.1411 with a single external wall loss of 7dB representing a concrete external wall with a window
- A 5.5dB average shadowing standard deviation is applied to the target SINR based on a 4dB and 8dB shadowing standard deviation at the victim and aggressor respectively.
- A 0dBi antenna gain is applied at the victim and aggressor.
- The target SINR is set to receive the allowable degraded throughput at a 78% confidence limit for cell edge users. This is in line with the confidence limit used in our coverage analysis.

6.6.2 Results and conclusions

Downlink results

Figure 6-17 and Figure 6-18 show the separation distances required between an outdoor access point for a low power network causing interference to an indoor UE on a low power network that it is sharing spectrum with. Figure 6-17 shows the result when a constant maximum transmit power of 24dBm, in line with the maximum specified by 3GPP for LTE Local Area Base Stations, is assumed at the aggressor, the outdoor access point. Figure 6-18 shows the result when power control is applied at the aggressor and the transmit power is adjusted to provide the target throughputs at 50m range with reasonable (depth 2) in-building penetration in line with our coverage results for outdoor access points.

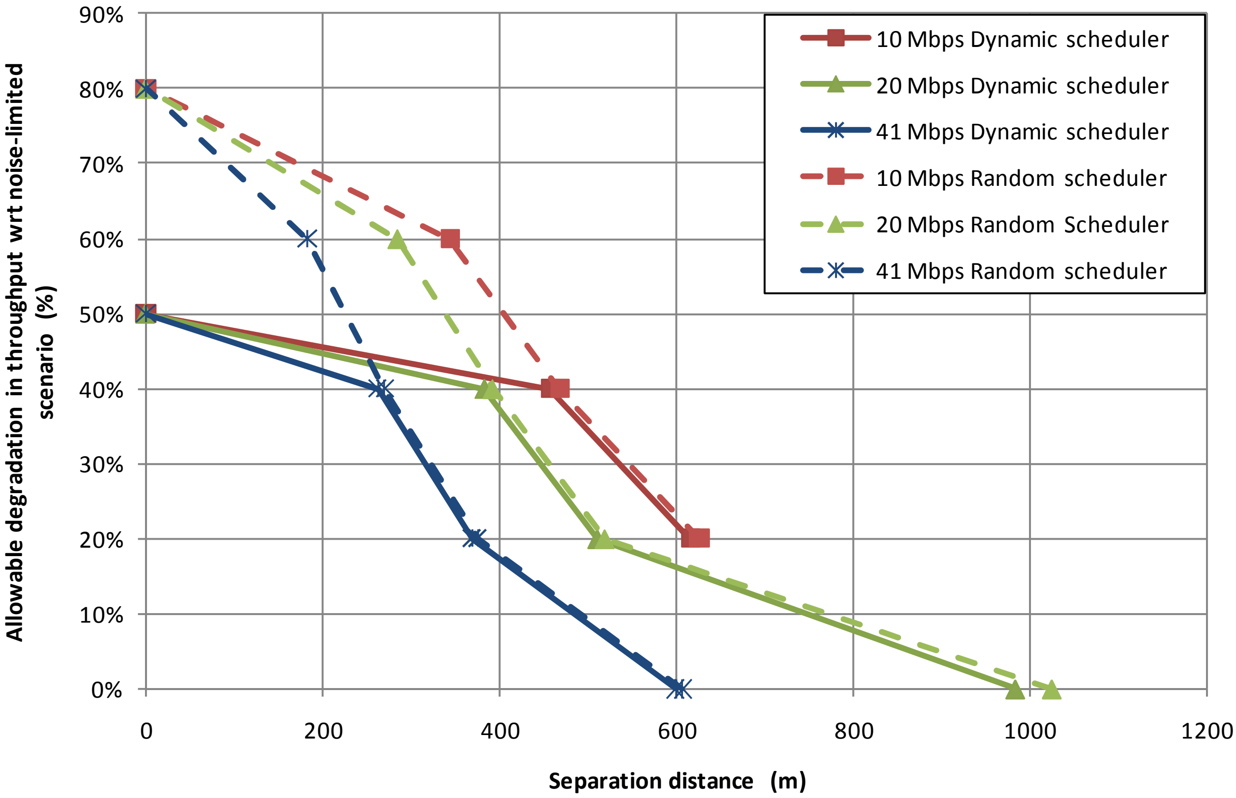


Figure 6-17: Separation distances required between victim indoor UE and outdoor access point aggressor to achieve the target throughput degradation shown a constant 24dBm transmit power is applied at the aggressor

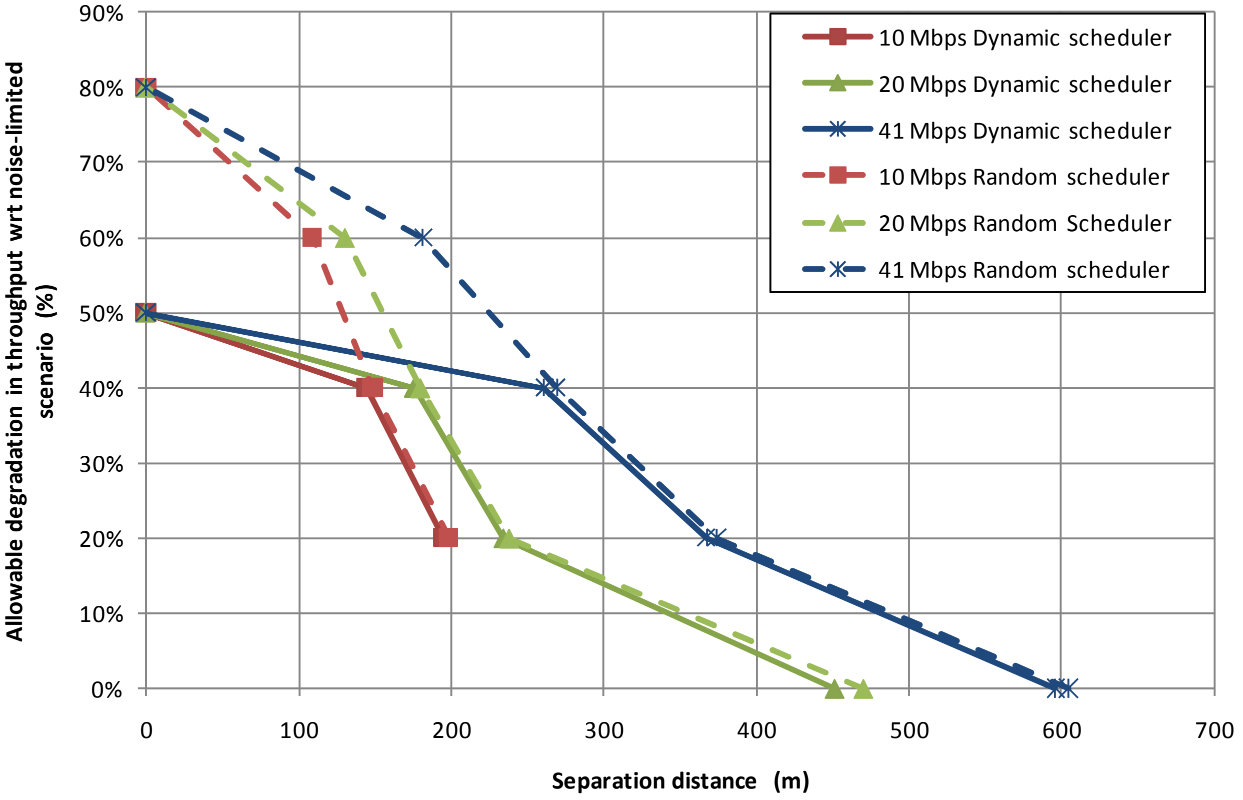


Figure 6-18: Separation distances required between victim indoor UE and outdoor access point aggressor to achieve the target throughput degradation shown when power control is applied at the aggressor

Uplink results

Figure 6-19 shows the resulting separation distances for the equivalent uplink interference scenario where the outdoor UE causes interference to the indoor access point. It can be seen that the separation distances in this case are lower than those required for the downlink interference scenario. Therefore the downlink interference results should be used to guide separation distances between indoor and outdoor access points.

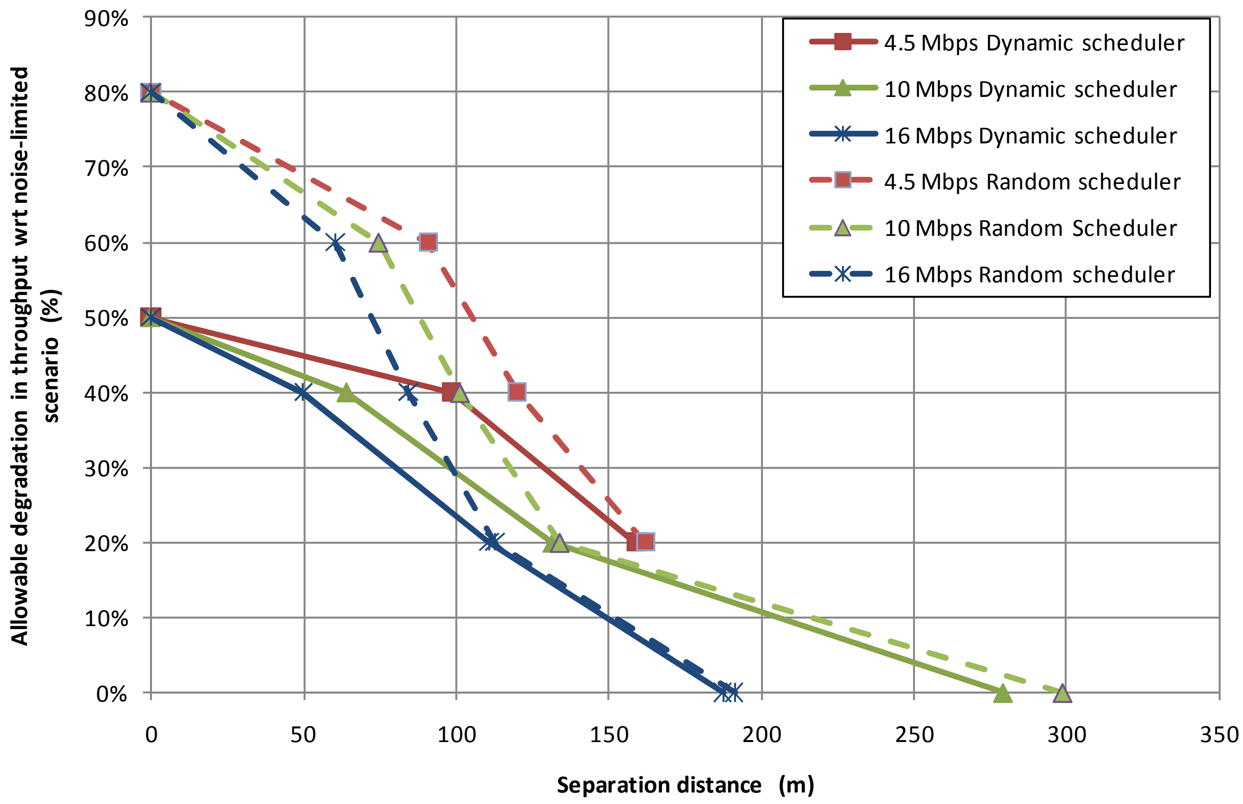


Figure 6-19: Separation distances required between victim indoor access point and outdoor UE aggressor to achieve the target throughput degradation shown

Conclusions

The following conclusions can be drawn from the results for these scenarios:

- The separation distances required in the downlink interference scenario is much larger than on the uplink.
- Separation distances in the range 100m-600m are required depending on the target throughput and acceptable degradation level. This relies on power control being applied at the aggressor.
- As in previous scenarios, if a degradation in throughput proportionate to the number of contending networks is acceptable then no separation distance is required and the interference can be managed via dynamic scheduling.

6.7 Summary

Study question	Answer
1.17 What is the minimum separation distance between buildings where low-power networks can be deployed without operator coordination becoming necessary?	For the scenario analysed of two low power access points in adjacent houses, the minimum separation distances will be upwards of 23m assuming data rates of at least 10Mbps are targeted in interference free conditions and a throughput degradation of less than 50% is required at the cell edge. This will increase for more interference sources. With the use of a dynamic scheduler that identifies interference and targets un-contended resource blocks a zero separation distance can be achieved but the data rate will be degraded in proportion to the number of contending access points. In the example of 2 access points no separation distance would be needed if a degradation in throughput of 50% is acceptable at the cell edge.
1.18 What limits should placed on the maximum height of outdoor antennas, for the purpose of limiting interference to other low-power networks (our working assumption is 5m)?	Interference increases significantly once the antenna height is beyond the height of the surrounding buildings. Assuming a limiting case of a residential scenario this would suggest a limit of 10-12m.
1.19 In the case of underlay low-power networks, what restrictions on antenna placement would be needed in order to minimise interference to the co-channel wide-area network, e.g. minimum distance from macrocell antennas, restriction to indoor placement?	A much larger distance is required to mitigate uplink interference to the macrocell base station than to macrocell UEs. Also the impact of uplink interference is to desensitise the macrocell base station for all UEs and so the impact is more significant to the entire cell than the downlink interference case. The exception to this is in the “visitor problem” where a macrocell UE is in the same room as a low power access point. This may require conditional roaming in cases of extreme interference. In the analysed scenario of a single indoor UE from a low power network operating on the edge of coverage a separation distances in the range 800m-3.2km would be required if a less than 40% throughput degradation is required. This could be reduced to 400-1.5km if a 10dBm power cap is applied to the UE when an overlapping macrocell sharing the channel is detected. As previously described a zero separation distance is feasible if smart scheduling and a degradation in edge of cell throughput in proportion to the number of networks contending for resources is acceptable.
1.20 Based on an assumption that some low-power operators will deploy outdoor antennas on low-power networks, what is the minimum distance before the frequency (or	The scenario analysed looks at interference between a single outdoor low power network and single indoor low power network. The separation distances required to minimise downlink interference are much larger than those on the uplink.

resource blocks) can be re-used by indoor networks? What is the minimum separation distance for deployment of co-channel low-power indoor and outdoor networks without operator coordination becoming necessary?	In the scenario analysed, separation distances in the range 100m-600m are required to minimise interference on the downlink depending on the target throughput and acceptable degradation level if power control is applied at the aggressor. As previously described a zero separation distance is feasible if smart scheduling and a degradation in edge of cell throughput in proportion to the number of networks contending for resources is acceptable.

7 Trade-offs relating to spectrum quantity

This chapter examines how the quantity of spectrum potentially made available to a low power shared access band impacts the potential capacity of that band in terms of maximising the number of operators and volume of traffic that could be supported. Our analysis so far has examined coverage and interference in specific low power shared access scenarios. This chapter draws on these results to illustrate how different sharing regimes and spectrum quantities will impact the overall capacity of a shared access channel.

7.1 Study questions

The FDD portion of the 2.6GHz band contains 2 x 70MHz of paired spectrum. If part of this is made available for a low power shared access channel the benefits of such a shared access channel need to be balanced against the reduction in spectrum potentially available for wide area deployments.

A low power shared access channel could be assigned as a completely separate "designated" channel from those used by wide area operators with macrocell networks. If 2x10MHz were allocated to the low power shared access band this would allow three channels of 2 x20MHz to be made available for wide area, high power use at 2.6 GHz, allowing the maximum number of wide area operators to benefit from peak LTE data rates (91Mbps downlink for 2x2 MIMO in a 3GPP EVA5 channel from our analysis). However, low power operators would be limited to the user experience offered in a 2x10MHz channel (41Mbps downlink for 2x2 MIMO in a 3GPP EVA5 channel from our analysis).

Alternatively the shared channel could be introduced as an "underlay" which shares spectrum with a macrocellular network either in a coordinated (such as via a geolocation database or direct connection) or autonomous (such as sensing spectrum gaps) manner. This would allow the shared access channel to be extended to 2 x 20MHz while preserving three 2 x 20MHz channels for wide area use but with the consequence of one of the wide area channels having potentially reduced capacity due to interference from the low power shared band.

A "hybrid" spectrum allocation which is made up of 10MHz of dedicated spectrum and 10MHz of underlay spectrum is also feasible as a third alternative.

The options for a low power shared access band examined by this study include:

- 2 x 10MHz Vs. 2 x 20MHz
- Underlay Vs. Hybrid Vs. Dedicated

In each option the SINR experienced both in the macrocell and low power cells will be degraded in different ways which will have a knock-on effect on capacity within these cells. The choice of bandwidth for the shared channel may also influence how readily resources can be shared amongst different low power network and macrocell users and again impact capacity.

Some example bandplans which could result from the introduction of the low power licences are shown in Figure 7-1 (position of the low-power blocks is for illustration only).

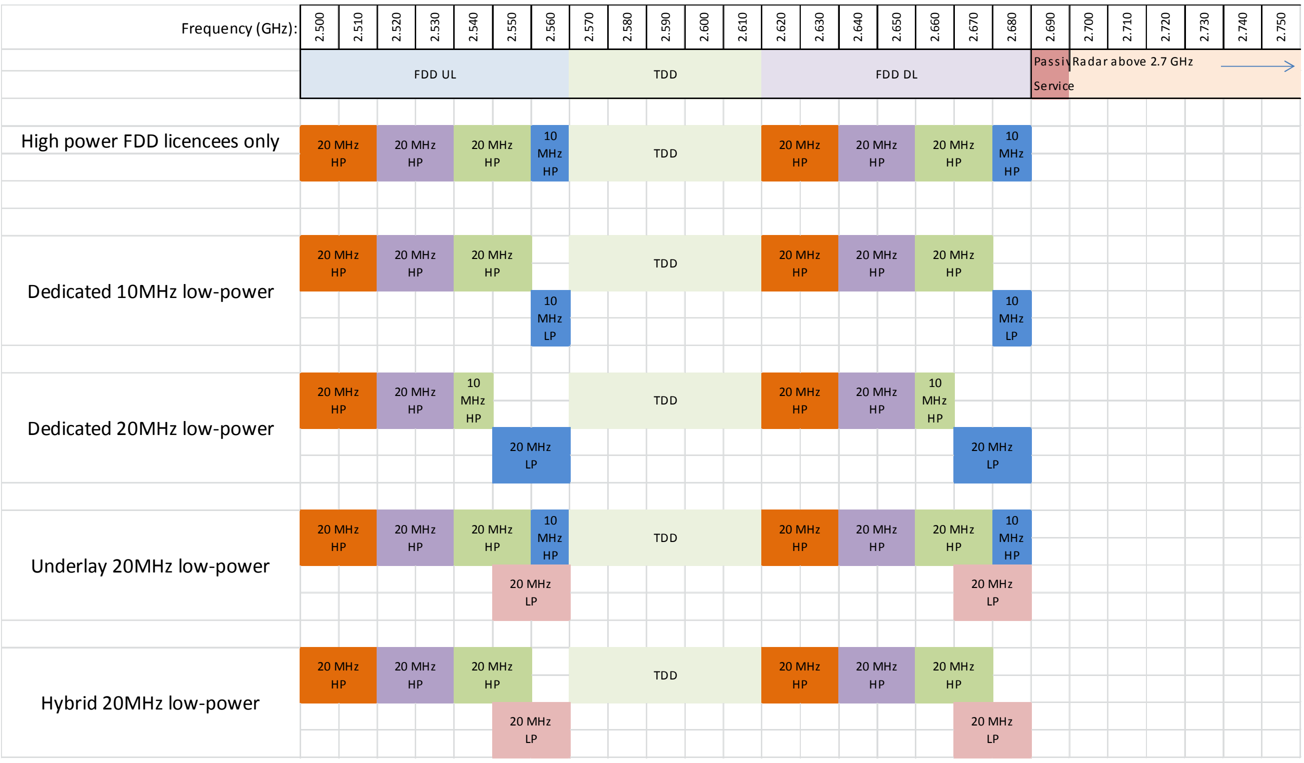


Figure 7-1: Example bandplans incorporating low-power concurrent allocation

Ofcom have posed the following questions in this area of determining the trade-offs relating to spectrum quantity:

Study questions

1.9 For both the designated spectrum approach and the underlay approach, assess the capabilities of the spectrum to support several concurrent low-power shared access operators if the quantity made available is:

a) 2 × 10 MHz

b) 2 × 20 MHz

1.10 In particular, the assessment should include:

> - *what traffic capacity could be supported;*
> - *how many concurrent low-power operators could be accommodated (noting the working assumption of eight licensees); and*
> - *what is the impact of the spectrum quantity on an operator's frequency re-use within a geographic area.*
>
> *1.11 What techniques are available for licensees to manage the spectrum sharing between low-power operators?*

7.2 *Factors impacting capacity in small cells*

The capacity that can be supported by small cells differs to that expected in traditional wide area networks in two key areas:

- Improvements in capacity due to improvements in the spectrum efficiency density achievable via:
  - A higher density of cells
  - An improved SINR distribution across the cell
  - Improvements in performance of technologies such as MIMO in indoor environments where small cells are more prominent.
  - Fewer users per cell giving lower contention rates and better user experience
- Reductions in capacity via interference due to the uncoordinated nature of small cells deployments which will vary with the:
  - Number of operators sharing the low power channel
  - Spectrum approach taken with interference from macrocells being an issue in the underlay and hybrid approaches.

The following two sections examine each of these areas.

7.2.1 Spectrum efficiency density in small cells

The capacity of a cellular network is a function of three key elements Figure 7-2:

- The *spectrum* used to deliver the service
- The *technology* which delivers bits over the air
- The *topology* of the cells which comprise the network

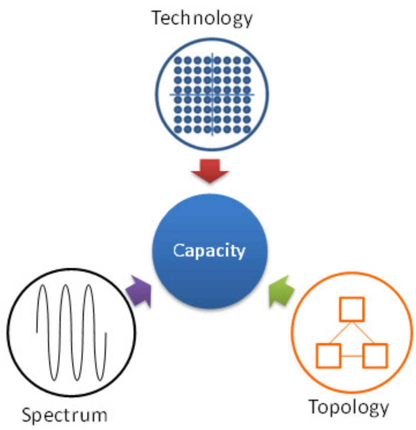


Figure 7-2: Capacity depends on a combination of spectrum, technology and topology of the network

Equation 1 shows how these three factors can be combined to represent capacity in a network. Here *spectrum efficiency* is an indicator of the network technology's ability to use the allocated spectrum to deliver services which meet the required quality criteria.

Capacity density [bits per second per km²]	*= Quantity of spectrum [hertz]*	*x Cell Spectrum Efficiency [bits per second per hertz per cell]*	*x Cell density [cells per km²]*
	Spectrum	**Technology**	**Topology**

Equation 1

The spectrum efficiency (i.e. throughput per Hertz of spectrum) achieved in practice in a cell depends highly on distribution of the signal quality across the cell, commonly known as the SINR distribution. Figure 7-3, Figure 7-4 and Table 7-1 below give an example of the difference in throughput and in turn spectrum efficiency due to the improved SINR distribution encountered in smaller cells.

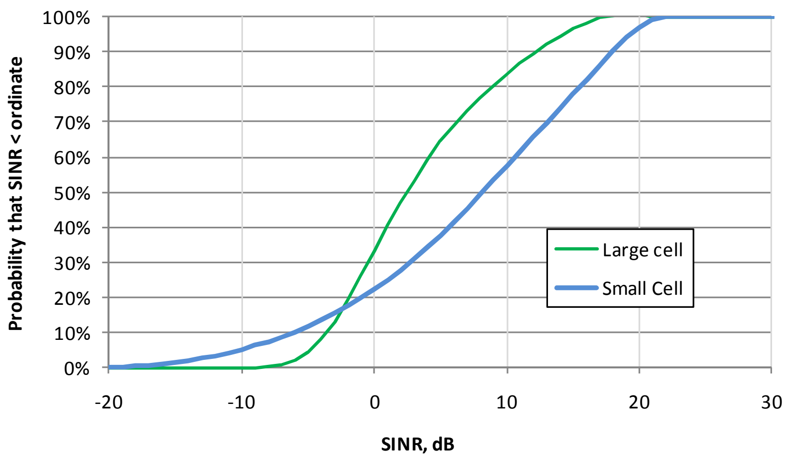


Figure 7-3 : SINR distributions for small and large cell topologies (Source: Ericsson[48], Qualcomm[49])

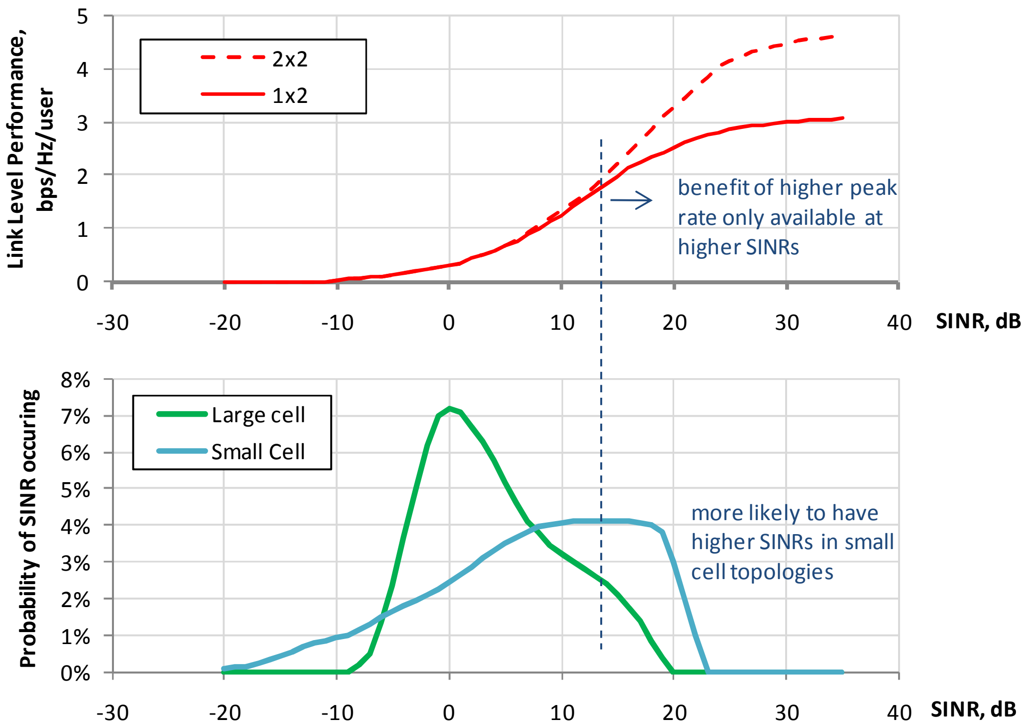


Figure 7-4: Analysing the benefit of higher peak rates: Comparison of SINR required for higher rates with the probability of achieving that SINR in a given deployment scenario. Sources: Rysavvy research[50], Ericsson[51], Qualcomm[52]

Cell Spectrum Efficiency			
b/s/Hz/cell	Technology		Benefit
Topology	1x2	2x2	
Large Cell	0.73	0.78	6%
Small Cell	1.18	1.34	14%
Benefit	61%	73%	

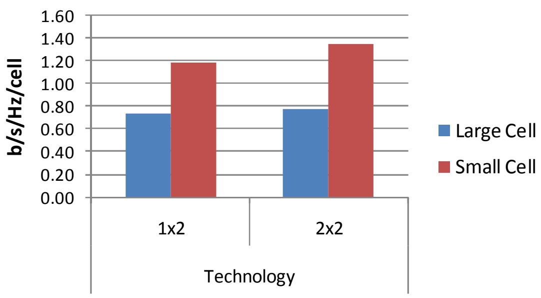


Table 7-1: Cell spectrum efficiency for normal and higher peak rate technologies, in large and small cell environments (Source: Real Wireless analysis)

In addition to these improvements in capacity due to an improved SINR distribution, we would expect technologies such as MIMO which rely on high amounts of multi path to operate better in indoor environments where small cells are more likely to be used.

As there is a strong link between the cell spectrum efficiency and the cell size, the spectrum efficiency density is therefore frequently used to show the combined effect of technology and topology between different cell sizes or deployment options.

Capacity density	= *Quantity of spectrum*	x *Spectrum Efficiency Density*
[bits per second per km²]	*[hertz]*	*[bits per second per hertz per km²]*
	Spectrum	***Technology* & *Topology***

Equation 2

Figure 7-5 illustrates the potential capacity gains from small cells and is based on simulations in three different test environments used in the ITU-R IMT-advanced evaluation [[53]]. This shows that smaller cell topologies have higher cell spectrum efficiencies resulting from the better SINR distribution, lower terminal device speeds and channel rank. The difference in spectrum efficiency density is even greater. It should be noted that the three options shown below are not comparable in cost. More sites and equipment would be needed for the small cell topologies, so the higher capacity of the microcell network comes at a higher cost.

It should be noted that the ITU indoor hotspot test environment is based on isolated cells at an office or hotspot. This may be a simplified environment compared to a large scale deployment of femtocells in an office block coexisting on the same carrier as outdoor macrocells.

These 3GPP simulation results show a x2.3 improvement in cell spectrum efficiency and x54 improvement in cell spectrum efficiency density between indoor hotspots and urban macrocells.

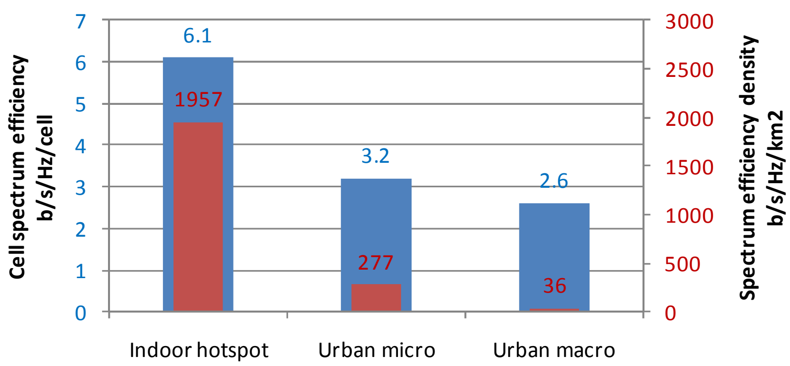


Figure 7-5 - Impact of network topology and environment on spectrum efficiency for a 4x2 MU-MIMO 20MHz LTE-A system (Source: 3GPP[[53]])

It is also worth noting that due to the improved SINR distribution in smaller cells that more users are likely to benefit from the peak data rates and enhanced user experience offered by a 20MHz channel than in a larger macrocell.

7.2.2 The impact of uncoordinated shared access on capacity

The downside of a low power shared access channel is that it will suffer capacity reductions from its potential peak levels (described in the previous section) due to interference if large volumes of uncoordinated low power networks are deployed in the same spectrum. Additional interference will be encountered from macrocells in the underlay and hybrid spectrum options. These potential reductions in capacity are examined in this section.

The impact of sharing amongst multiple low power networks

Wide area networks rely on an operator planning its network to coordinate interference and performance across sites in that network. This is partially automated by the X2 link in LTE which exchanges the overload indicator, neighbouring cell tables etc. However, in small cells coordination between access points or operators cannot be relied upon as it is not clear that an X2 link amongst the potentially large volume of low power access points would be feasible. Therefore more autonomous interference mitigation techniques are needed to minimise interference and maximise performance and capacity.

Section 4.5 has already examined interference mitigation techniques in small cells. These are mainly based around:

- power control to ensure low power devices do not transmit any further than necessary to maintain range and service for their users
- dynamic resource allocation to minimise collisions of resource blocks

As shown by our co channel interference assessment in chapter 6, if a dynamic scheduler which detects interference and targets un-contended resource blocks is applied in shared networks the capacity in interference limited situations will be shared equally amongst the number of adjacent access points causing interference. This approach relies on operators being willing to accept degradations in throughput in overlapping deployments proportional the number of contending networks and being willing to back off target data rates in a fair way when interference is detected.

As not all deployments from all low power operators will overlap the number of low power licensees does not place a direct cap on the capacity of small cells. However, obviously the likelihood of overlapping deployments will increase with the number of licensees and so this should be kept to a manageable level.

Assuming all operators did deploy in the same target area, the best case scenario would be where the operators coordinate and apply frequency partitioning. Here the capacity per operator would be the capacity divided by the number of operators as shown Figure 7-6. However, without coordination of access point placement between operators the capacity is likely to be degraded by a factor greater than the number of operators due to interference.

As discussed in section 4.5.3, to ensure overlapping deployments do not cause excessive interference on overlapping common control channels frequency partitioning amongst operators in overlapping deployments may be required. This will result in operators experiencing capacity at less than the total shared channel equally split amongst the number of operators as the overhead of each network's common control channels will increase in the reduced bandwidth resulting in a reduced spectrum efficiency. The impact of this increased overhead on throughput for a 2x10MHz and a 2x20MHz channel is shown in Table 7-2.

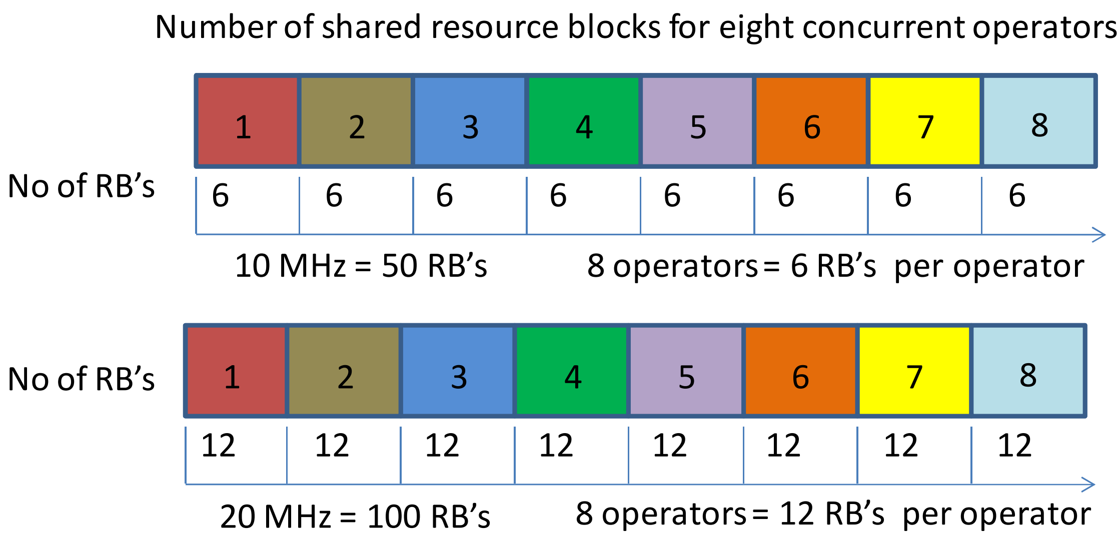


Figure 7-6: Illustration of capacity shared amongst operators

	Peak data rate in interference free case	Peak data rate in 7 overlapping deployments	Peak data rate in 14 overlapping deployments
2x10MHz	41Mbps	Assume frequency partitioning. 1.4MHz channel achieves 65% spectrum efficiency of a 10MHz channel (see section 4.5.3) 3.8Mbps	Time shifting may be needed in addition to frequency partitioning which is not proven for uncoordinated deployments. <1.9Mbps
2x20MHz	91Mbps	Assume frequency partitioning. 3MHz channel achieves 87% spectrum efficiency of a 10MHz channel (see section 4.5.3) 11.3Mbps	Assume frequency partitioning. 1.4MHz channel achieves 65% spectrum efficiency of a 10MHz channel (see section 4.5.3) 4.2Mbps

Table 7-2: Example throughputs for a 2x20MHz vs. 2x10MHz channel assuming 2x2 MIMO in an EVA5 channel

The impact of sharing with a wide area operator in the hybrid or underlay approach

In addition to interference from other low power access points, in the underlay and hybrid spectrum scenarios there will be additional interference from a macro network which will further reduce the capacity of the low power network and vice versa. Our co channel interference analysis has shown that separation distances of 400m to 1.5km are required between macrocells and indoor networks to achieve throughput degradations of less than 50% for the case of two contending networks. This is assuming that a 10dBm transmit power cap is placed on low power networks detecting macrocells in their area. These separation distances are likely to be difficult to enforce in practice. In the full underlay scenario it is more likely that the macrocell would be given priority and the low power access point would be expected to schedule resources to avoid the macrocell. The low power network therefore would not be guaranteed access to any spectrum in areas where coverage from macrocell networks is already at a reasonable level.

The hybrid spectrum approach is an improvement on the underlay situation as it at least guarantees access to half of the low power shared band and benefits from a boost in user experience in areas where macrocell coverage is poor. The hybrid approach also opens the way for better interference mitigation. One approach discussed in 3GPP involves scheduling the common channels for low power devices in the dedicated portion of the hybrid spectrum allocation and making use of spectrum aggregation features in LTE release 10 devices to schedule data in the overlapping portion of spectrum when no neighbouring wide area networks are detected. This avoids overlapping control channels between the wide area and low power networks and so there is no concern of the macrocell devices missing paging requests, call terminations etc. This approach requires that at least part of the low power channel does not overlap with the wide area channel so that the low power shared access control channels are scheduled in a different channel to the wide area network. However, the portion of spectrum overlapping with the wide area network could be part or the entire wide area network's channel provided that the low power network avoids scheduling in this channel when the wide area network is detected.

7.3 Licence requirements to maximise capacity

This section examines the potential licence requirements that may be needed in a low power shared access band to minimise interference and maximise capacity:

- Amongst low power networks sharing spectrum with other low power networks
- Amongst lower power networks sharing spectrum with wide area networks

7.3.1 Licence term requirements amongst low power shared access licensees

Amongst low-power operators, whether in shared or dedicated spectrum, measures are needed to minimise harmful interference and maximise user experience. Some measures may need to be in the form of licence conditions, especially if large-scale interference could be created or if interference could be created to systems in adjacent bands. Others may be in the form of a Code of Practice (CoP) amongst operators. Within this code of practice critical measures may need some oversight by Ofcom whereas others may emerge from voluntary agreements amongst operators.

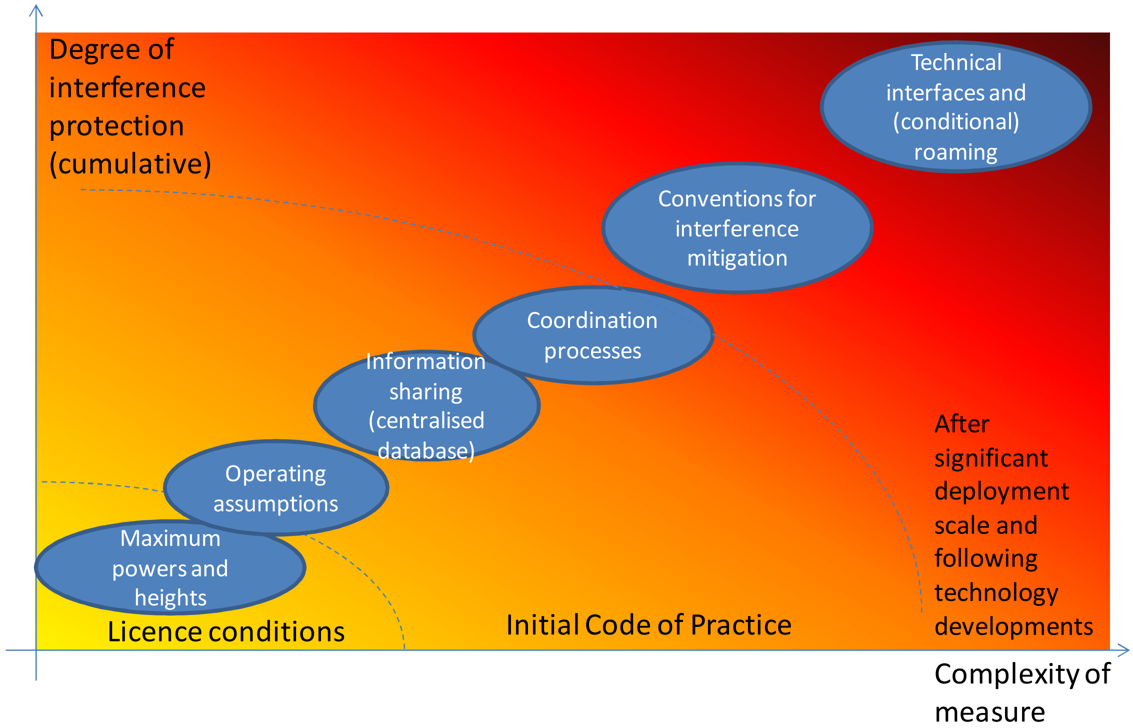


Figure 7-7: Different measures which may be applied to manage sharing amongst low power networks

Figure 7-7 illustrates the different levels of measures which may need to be applied amongst low power networks depending on the level of interference protection required. Only a small proportion of these may be included within the licence conditions. The following issues would typically be addressed within each of these categories:

1. Maximum power and heights – This would include limits on both transmit power levels and antenna heights to prevent excessive interference to other operators over wide areas. These limits would be intended as a 'backstop', not a routine standard value or as a prime means of mitigating interferences.

2. Operating assumptions – This includes assumptions that are not essential to preventing excessive interference over wide areas but will improve performance and channel capacity. Operators will be best placed to determine these based on the latest technology developments that they plan to deploy. For example, operators are expected to use interference mitigation techniques such as adaptive transmit power control to minimise the power required to provide coverage. They may wish to mandate this as part of a CoP for the shared access channel but it would not be essential to include this in the licence terms. Other operating assumptions that the CoP for the low power shared access channel might cover would include:

- Adopting conventions on the allocation of common control channels: potentially some randomisation of timing or a convention on frequency partitioning.
- Mandate use of ‘network listen’ downlink receivers in access points
- Specifying the use of a specific technology such as LTE or at least fixed time and frequency resource block sizes

3. Information sharing – This is likely to involve the use of a central database, potentially hosted by a third party, to capture key parameters to allow investigation of interference issues which arise, or to determine the need for coordination prior to deployment. Parameters stored may include location, height, maximum power, cell ID and any restrictions on bandwidth. This would assist planning of new deployments and investigation of interference situations in overlapping deployments as they arise. Such a database would be updated periodically, e.g. weekly as updating this in real time is not likely to be practical or necessary. In the case of very low power networks these *de minimis* cells may not need to be entered on the database depending on the agreed power threshold amongst operators.

4. Coordination process - When certain conditions are satisfied, a coordination process amongst low power deployments may be required. Conditions for coordination may include the density of cells (existing or planned) in an area, proximity amongst cells, or a plan to cover a common coverage area. The process itself would invoke a multilateral discussion amongst affected operators and would include some generic coordination procedures, similar to those used by existing operators for shared sites such as coordinating locations, maximum powers, capacity sharing, possible conditional roaming and possible infrastructure sharing.

5. Conventions for interference mitigation - When deployment densities are relatively low, each operator may use independent interference mitigation techniques without conflict. However, at higher densities there is a risk that very different algorithms can work against each other, or at least that they would not yield optimum capacity. This does not mean that all operators need to use the same mitigation techniques, but that certain conventions are observed for all algorithms. Conventions are likely to include ‘preferred’ channels for each operator when frequencies are segmented, threshold levels for detection and fractional reuse, and perhaps some limits on time constants for detecting and changing parameters.

6. Technical interfaces - Some reduction in performance is anticipated by the use of distributed coordination techniques, as implied by operator networks with no direct connection amongst them. Although some studies suggest the performance degradation can be small, specific interfaces may

provide greater confidence and flexibility. Technical interfaces to aid interference mitigation could for example include sharing management/monitoring data at relatively low intervals through to explicit coordination via X2 or similar interfaces.

7. (Conditional) roaming - Roaming amongst operator cells would remove many of the more challenging interference scenarios. If conventional roaming is too intrusive or commercially undesirable, this could be performed on a conditional basis, so only that it is only invoked when the alternative would be a higher level of performance degradation to both operators involved. This is similar to an inter-operator variant of the 'hybrid' access mode already envisaged in 3GPP standards

7.3.2 Licence term requirements between high power and low power licensees in the underlay or hybrid spectrum approach

In the case of underlay or hybrid underlay/dedicated spectrum, measures are needed to provide clarity and protection to both high power and low power licensees both for acquiring spectrum initially and in ongoing operation. These measures are most likely to need licence conditions since the nature of the interference is not reciprocal between the types of operators.

	10 MHz block A	10 MHz block B	10 MHz block C
High Power Overlay Operator			
Low Power Underlay Operators			

Figure 7-8: Illustration of the hybrid spectrum approach

Figure 7-8 illustrates the potential spectrum sharing scenario in a hybrid spectrum approach. In this case both the high power and low power operators can offer full 20 MHz peak-rate services for locations and users where there is little contention for resources in the shared block. However, in the shared block there is a risk of interference between the high power and low power operators, in addition to the existing risks amongst the low power operators. In the case of underlay spectrum the low power spectrum block would be completely shared with the high power operator.

There are a number of interference modes of concern between the high and low power licensees in this shared portion of spectrum which require appropriate licence measures to mitigate.

On the downlink these include:

1. **Visitor problem (DL)**: Here an edge of cell macro UE (MUE) comes in close proximity to low power access point (FAP) and suffers downlink interference. This will affect a relatively limited number of macro users per FAP as a FAP only covers a small region. However, the probability of this situation will increase as FAPs proliferate. Potential mitigations include reducing the FAP power when both a low macrocell downlink signal is detected and uplink measurement reports indicate that the MUE is in close proximity.

2. **FAP close to macro (DL):** Here an edge of cell low power network UE comes in close proximity to a macrocell base station. This is likely to affect a limited number of low power network UEs attached to limited number of FAPs. Potential mitigations include increasing the FAP power to compensate for the interference or accepting a reduced service level in proximity to macrocells. Increasing the FAP power will have a limited impact on MUEs due to existing strong macro signal. Alternatively the macrocell BS may reduce its power to reduce interference depending on the priority between the operators.

On the uplink these include:

3. **Visitor problem (UL):** Here a cell edge MUE at high power comes in close proximity to FAP and degrades the performance of whole FAP. This affects only users on a single FAP at a time. Potential mitigations include reducing the MUE power when close to FAP. Eventually avoid shared block altogether.

4. **FAP close to macro (UL):** Here a cell edge FUE at high power approaches close to macrocell causing interference to entire macrocell uplink. All MUEs near to the cell edge will be affected and overall capacity across the macrocell will be reduced. Potential mitigations include reducing the maximum FUE power when it is close to a macrocell and ultimately avoiding the shared block altogether.

Licence conditions may need to be applied to enforce the interference mitigation suggestions for each of these scenarios. The setting of these licence conditions will very much depend on the balance of priority between the high power and low power operators. We next examine how licence conditions in this shared portion of spectrum might be set for the two cases where:

- Priority is given to the high power operator
- Equal priority is given between the high power and low power operators

Case 1: where high-power operator has primary rights to the shared block

In this case the underlay operator (i.e. the low power network) would be required to monitor for path loss from the macrocell using broadcast information and power measurements made at both their access points and associated UEs. To avoid uplink interference to the macrocell when the FAP is in close proximity to the macrocell, these path loss measurements could be used to adjust the transmit power of the low power network UE in the following way (as illustrated in Figure 7-9):

- If the macro path loss L > threshold Th_1, then the UE can use the shared block to full extent of licence
- If the macro path loss $Th_2 < L <= Th_1$, then the UE must cap the maximum FUE transmit power to a linear function of L
- If $L <= Th_2$, then the UE must avoid the shared block altogether

Potentially additional minimum separation distances would be used to minimise the likelihood of this scenario occurring. The path loss thresholds would be set to limit interference to the macrocell to, for example, a 0.5dB noise rise in shared block. This threshold may need to be set differently depending on whether the path loss measurement came from the FAP and FUE measurements.

The exact setting of these thresholds will depend on the balance of priority between the low power and high power operators and their target quality of service levels and requires more detailed study.

To avoid the DL visitor problem the licence terms may require the FAP to reduce its transmit power when the FAP network listen mode observes low power from a macro BS and the FAP uplink receiver observes high interference indicating a nearby MUE on edge of coverage.

As noted in section 4.5.3, there will also be a need to protect the common control channels of the macrocell network being shared with. The hybrid spectrum approach offers a strong advantage in this area as the common control channels for the low power networks need only occupy the dedicated portion of the low power channel leaving the shared portion of spectrum free for the macrocell to avail of. In the full underlay spectrum scenario time shifting or frequency partitioning would need to be arranged between the low power and high power operators to avoid overlap of the common control channels which is likely to be complicated to enforce in practice.

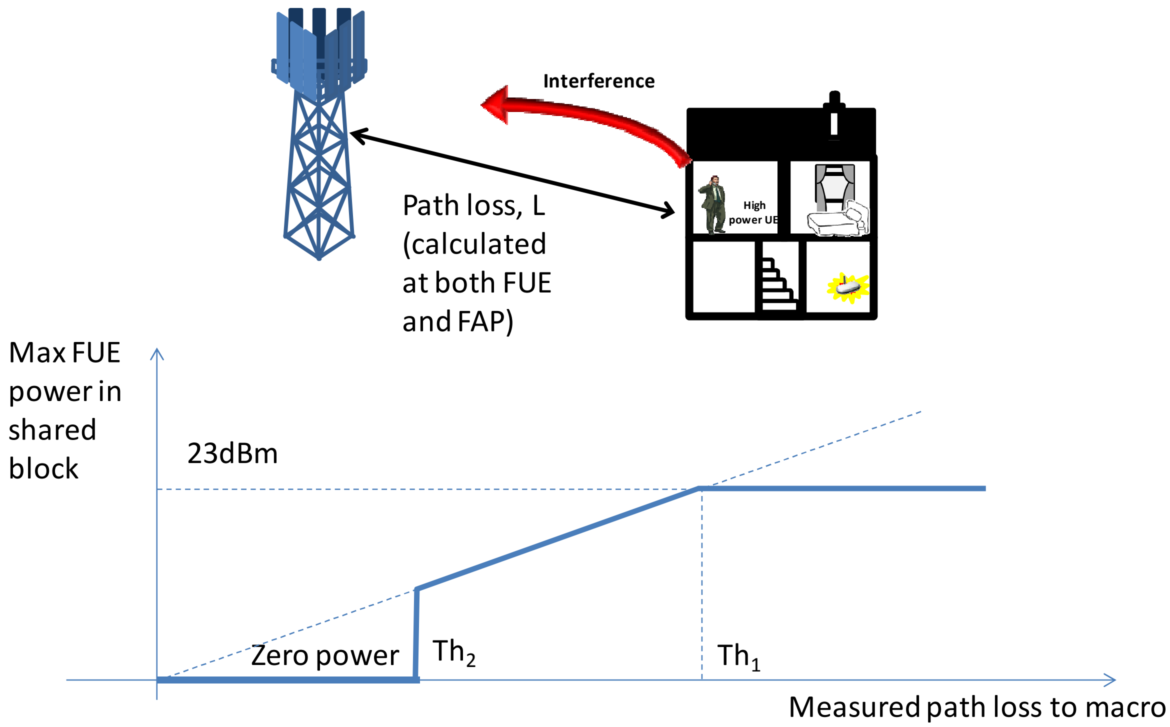


Figure 7-9: Illustration of low power network UE adjusting transmit power depending on path loss to the macrocell to mitigate interference in the underlay or hybrid spectrum scenarios

Other general measures which might need to be included in the licence conditions for this case include:

- Support for a shared database providing affected operators with location , power and ID of cells using shared block
- Possible conventions on the use of CellID and other broadcast information to distinguish cells between operators
- Applying different conditions when the overlay operator's cell is also low power
- Applying a protection time for low power networks deploying in not spot areas to prevent them being unfairly disadvantaged and evicted by new macrocell deployments.

It is worth noting that even when the high power network has priority as in this case there is still plenty of scope for low power networks to target high capacity hyper dense areas where wide area networks are already prominent without causing interference to the wide area network. For example low power networks could still be deployed in buildings provided access points are kept away from windows and antennas are directed towards the centre of the building rather than outdoors.

- ***Case 2: where underlay and overlay operators have concurrent rights to the shared block***

In this case the same conditions would apply as in case 1, but with the thresholds adjusted to balance performance degradation more evenly between operators. Dynamic resource scheduling is also more likely to be relied upon to share capacity in the underlay portion of spectrum (as in the case with multiple equal priority low power operators).

Additional measures may be applied to avoid downlink interference issues to the low power network when the FAP comes close to macrocell. These might include applying power reduction in the macrocell but this seems disproportionately harsh to the macrocell to protect a single FAP. Alternatively the FAP may be permitted to transmit at full EIRP in the shared block when macro path loss or signal strength < Th_4 .

Additional measures may be needed to avoid uplink interference to low power network FAPs from “visiting” MUEs in close proximity. This could potentially be mitigated by reducing the maximum MUE power when path loss to FAP < Th_5.

7.4 Summary of trade-offs across spectrum options

Table 7-3 summarises the advantages and disadvantages of the different spectrum approaches for the low power shared access channel taking into consideration the factors that impact capacity in small cells (discussed in sections 7.2.1 and 7.2.2), the implications in terms of the complexity of licence terms (discussed in section 0) and the impact on availability of spectrum for wide area licences. The spectrum options are listed in order of our preference, based on maximising the utility of the low power block.

Spectrum option	**Advantages**	**Disadvantages**
2 x 20MHz - dedicated	Improved user experience in low power networks compared to 10MHz. Data rate will typically be twice that of a 10MHz channel but in cases where frequency partitioning is less will benefit from a lower overhead so could achieve more than this (i.e. 11.3Mbps vs. 3.8Mbps for 7 sharing networks) Larger bandwidth allows for better resource scheduling and less collisions on resource blocks	Reduces capacity available for wide area operators

	between cells. Enhanced opportunity for fractional reuse schemes to improve isolation between concurrent operators.	
2 x 20MHz - hybrid	Low power networks guaranteed access to at least 10MHz even when close to macrocells. Avoiding collisions of control channels between macro and low power devices is made easier.	If a 2x20MHz hybrid channel is used, the capacity for wide area use in the overlapping 2x10MHz of spectrum is degraded by more than 40% in the case of two contending networks if separation distances of 400m -1.5km are not maintained (assuming a 10dBm power cap on low power networks in the region of macrocells) Setting licence conditions to ensure appropriate sharing with the overlapping wide area licensee will be challenging.
2 x 10MHz - dedicated	Allows three 2x20MHz wide area licences to be made available.	Restricts low power networks to half the peak data rates of wide area networks and less than half the capacity. Data rate will typically be half that of a 20MHz channel but in cases where frequency partitioning is less will suffer an increased overhead so could achieve less than this (i.e. 3.8Mbps vs. 11.3Mbps for 7 sharing networks) Reduced opportunity to use fractional frequency reuse schemes to avoid interference. For example in LTE with a minimum bandwidth of 1.4MHz 7 shared networks could be accommodated in a 10MHz channel but 14 could be

		accommodated in a 20MHz channel.
2 x20MHz – underlay	Improved user experience in low power networks compared to 10MHz Larger bandwidth allows for better resource scheduling and less collisions on resource Having the underlay overlap two high power networks allows increased opportunity to avoid mutual interference between high power and low power networks	Extra interference from the macrocell as well as adjacent femtocells to consider If a 2x20MHz underlay channel is used, capacity for wide area use in the underlay spectrum is degraded by more than 40% in the case of two contending networks if separation distances of 500m -2km are not maintained (assuming a 10dBm power cap on low power networks in the region of macrocells) If low power network is a secondary user of the band they are not guaranteed access in all locations. This would reduce opportunities for low power networks in dense urban deployments to indoor scenarios and not spots. Setting licence conditions to ensure appropriate sharing with the overlapping wide area licensee will be challenging.

Table 7-3: Summary of advantages and disadvantages of different spectrum choices for a low power shared access channel[3]

It is worth noting that our discussions with some stakeholders have indicated that operators with 20MHz allocations may benefit from trunking gains compared to those with 10MHz allocations if high user throughputs are considered. This is an area with few results to date but is worth monitoring in terms of the potential additional benefits of a 2x20MHz allocation over a 2x10MHz allocation for the low power shared access channel.

[3] Example throughputs given for a 2x2 MIMO EVA 5 channel

7.5 *Example scenarios of how capacity is impacted by spectrum choice*

In this section we give examples of how the improvements and degradations in capacity anticipated in a low power shared network and discussed earlier would manifest themselves in practice. Our two example scenarios include:

- A residential scenario
- A shopping centre scenario

In each case we examine how capacity would be influenced by:

- The number of operators sharing the spectrum
- The spectrum approach choice of hybrid, dedicated or underlay

7.5.1 Residential scenario

Figure 7-10 shows a typical residential deployment for low power access networks. In this scenario it is likely that each household will own one access point and that any contention for capacity will come from SINR degradation due to interference from neighbouring households.

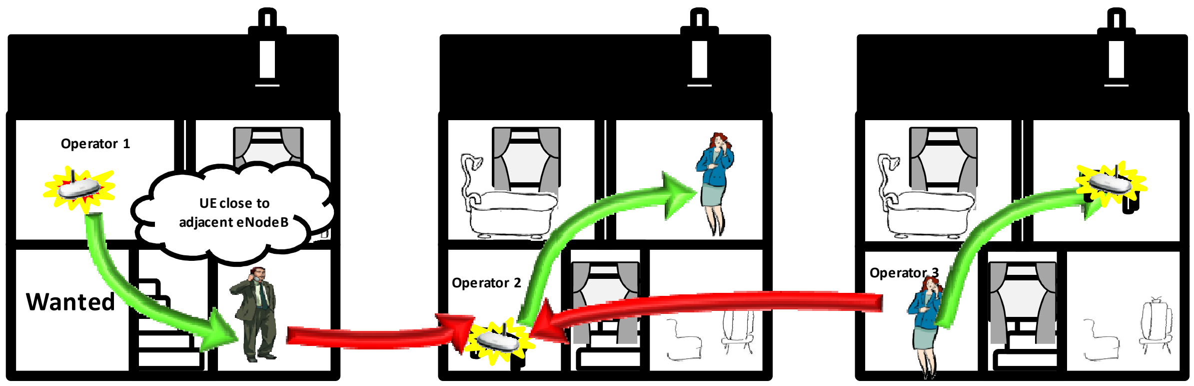


Figure 7-10: Example residential scenario for examining capacity reductions

As shown in our analysis of separation distances between low power access points in chapter 4, if an intelligent scheduler is used capacity gets shared amongst the number of contending low power networks. In this case capacity would therefore become a function of the number of houses qualifying as "dominant interferers" rather than the number of operators or licensees of the shared access channel.

Our co channel interference analysis also indicates that interference from outdoor low power networks to indoor low power networks will be an issue if separation distances of upwards of 100m are not maintained. In this example scenario it is feasible that a fourth operator is providing a broadband service to the street via outdoor cells within this separation distance which would further degrade the capacity of the indoor access points.

A third source of interference and capacity degradation would be from macrocell networks in the underlay scenario as most houses are likely to be within the large separation distances of 800m – 3.2km indicated by our co channel interference results. Even if a 10dBm power cap is applied to low power network UEs detecting overlapping macrocell networks the separation distances of 400m- 1.3km are still unlikely to be met.

7.5.2 Shopping centre scenario

Figure 7-11 shows an example scenario of a shopping centre where a large number of operators may potentially deploy contending low power networks. The best case scenario for overlapping deployments is shown first. This is where the operators all deploy access points at the same location and the capacity per operator would be the capacity divided by the number of operators. Below this is the worst case scenario of without coordination of access point placement between operators where access points are placed nearby to UEs at the edge of coverage. Our co channel analysis has examined a similar situation to this worst case scenario in form of separation distances required between buildings with residential access points. However, in this case the degradation in performance is likely to be worse as there will be no external walls separating the victim receiver and aggressor. However, our co channel interference results show that if a dynamic scheduler that detects interference and targets un-contended resources in a fair way that accepts throughput degradations in proportion to the number of contending networks, then separation distances aren't necessary. With this in mind, in our example shopping centre scenario, there would be an incentive for operators to apply roaming and network sharing in overlapping areas rather having the expense of rolling out their own access points without any additional benefits in capacity.

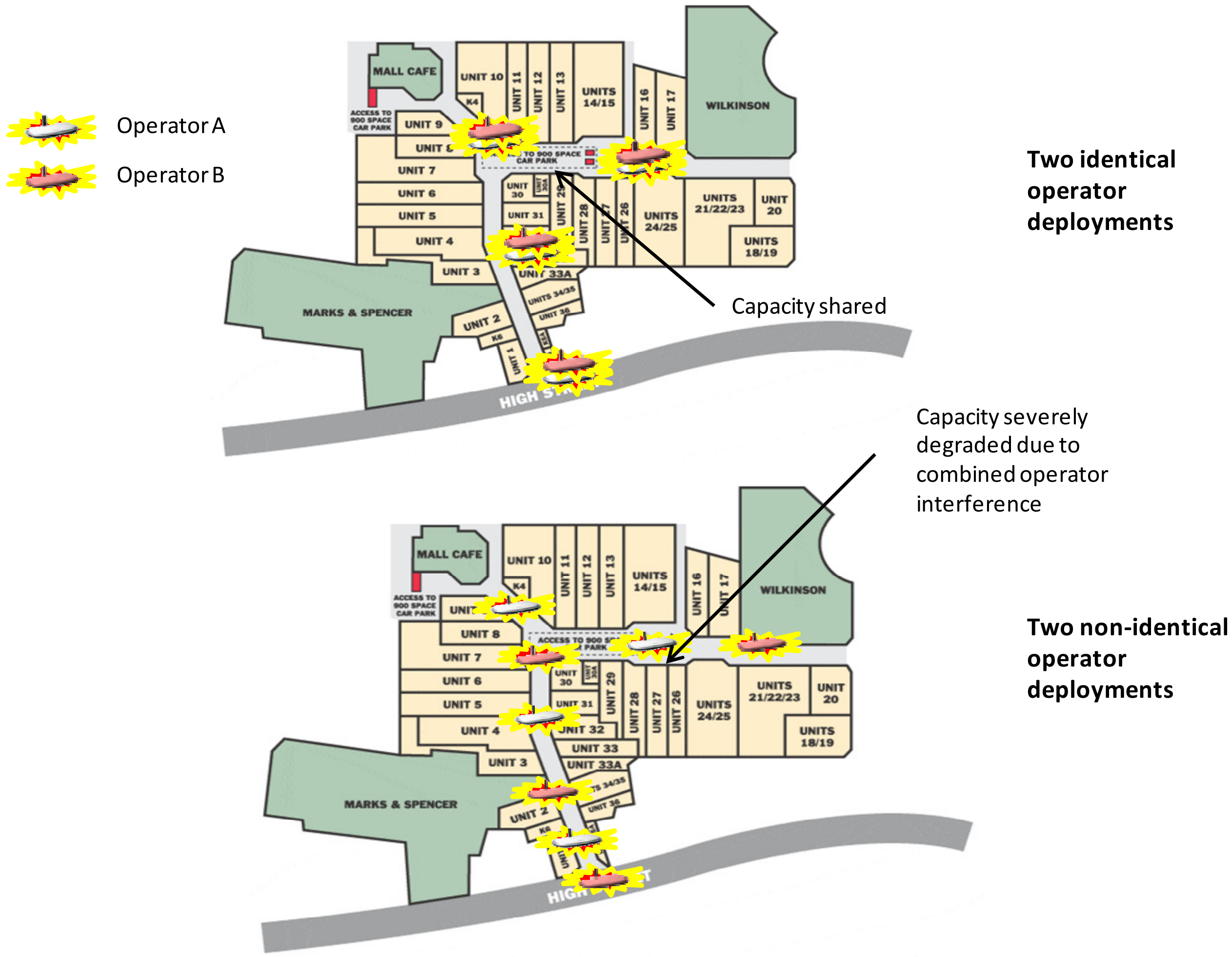


Figure 7-11: Example shopping centre scenario for multiple low power operator deployments

The same observations about degradations due to interference from outdoor low power networks and any overlaid macrocell networks as were discussed for the residential scenario above will also apply to this scenario.

7.6 Summary

Study Question	Summary answer
1.9 For both the designated spectrum approach and the underlay approach, assess the capabilities of the spectrum to support several concurrent low-power shared access operators if the quantity	Smaller cells provide significant capacity improvements due to: • A higher density of cells • An improved SINR distribution across the

made available is: c) *2 × 10 MHz* d) *2 × 20 MHz* *1.10 In particular, the assessment should include:* • *what traffic capacity could be supported;* • *how many concurrent low-power operators could be accommodated (noting the working assumption of eight licensees); and* • *what is the impact of the spectrum quantity on an operator's frequency re-use within a geographic area.*	cell • Improvements in performance of technologies such as MIMO in indoor environments where small cells are more prominent. 3GPP simulation results show a x2.3 improvement in cell spectrum efficiency and x54 improvement in cell spectrum efficiency density between indoor hotspots and urban macrocells. The uncoordinated nature of small cells will cause reductions in capacity due to interference. However, if power control and smart scheduling are applied the maximum capacity can be shared amongst the number of contending uncoordinated access points (which will increase with the number of operators). If operators of low power networks are willing to accept throughput degradations approximately proportionate to the number of contending access points there is no technical reason why 7 overlapping deployments for a 10MHz channel and 14 overlapping deployments for a 20MHz channel could not be accommodated assuming that frequency partitioning is applied. This does not translate to a limit on the number of low power operators as not all deployments will overlap. We recommend a 2x 20MHz dedicated band for low power shared access as this: • Maximises potential data rates and capacity gains from low power networks • Would give smart scheduling the maximum

	opportunity to work well due to the large number of resource blocks, minimising the associated overheads • Would be the least complex in terms of technical conditions on a shared access licence
1.11 What techniques are available for licensees to manage the spectrum sharing between low-power operators?	There are active discussions in 3GPP on interference mitigation techniques for low power access points. The main areas being standardised to facilitate interference mitigation include: • Radio environment monitoring (REM) by HeNBs • Use of UE measurements in combination with REM to schedule resources to avoid interference • Power control based on the above measurements • A power cap of 10dBm when an overlapping macrocell is detected. • Conditional roaming in cases of extreme interference Interference mitigation techniques are described in detail in chapter 4.

8 Adjacent channel interference from TDD and S-band radar is less significant than from FDD macros

8.1 Study questions

Ofcom posed the study questions shown in Figure 8-1 to understand the impact of adjacent channel interference into a low-power shared access block in the 2.6 GHz band. In particular, we were asked to consider interference into a block at the top end of the paired band, as can be seen in Figure 8-2. This configuration could bring benefits when considering the implications of interference from FDD 2.6 GHz systems to adjacent radar or TDD systems as the transmit power of the FDD devices will be less than in the case where the top end of the FDD paired spectrum is used for wide area networks.

Study questions

1.23 What would be the impact of interference from adjacent WiMAX or TD-LTE networks in the unpaired band on the operation of a low-power network?

1.24 What would be the impact of interference radar emissions in the 2700 to 2900 MHz band on the operation of a low-power network?

1.25 What other technical conditions might be needed to manage any interference?

Figure 8-1 Ofcom study questions for adjacent channel interference

Figure 8-2 shows the 2.6 GHz band with representative arrows indicating the direction of adjacent channel interference of interest to the study which also highlights the potential location of the low-power shared access blocks. There is a 10 MHz band allocated for radio astronomy services between the 2.7 GHz radar band and top of the downlink FDD band. This frequency separation provides further attenuation from radar emissions into the FDD UE receiver.

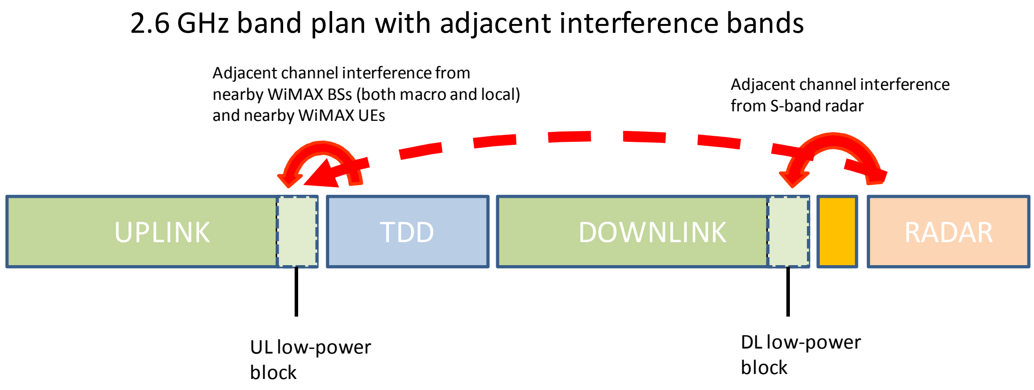


Figure 8-2 2.6 GHz spectrum band showing adjacent channel interference

The deployment scenarios that we have defined to analyse potential adjacent channel interference to low power shared access FDD devices are given in the table below. An aggressor and a victim and a brief description of the paths between these are defined in each case.

Study question number	Deployment scenario	Aggressor	Victim	Output assessment
1.23	**Impact of interference from adjacent WiMAX or TD-LTE networks**	WiMAX or TD-LTE UE/macro/indoor low power access point uplink/downlink path	Single femto UE (DL) indoor/outdoor We assume sufficient frequency separation between the TDD band and low power shared access FDD DL band so that this scenario doesn't need to be modelled.	Transmit power of aggressor against separation distance for different levels of acceptable throughput degradations
		WiMAX or TD-LTE device UE/macro/indoor low power access point uplink/downlink path	Single femto eNodeB (UL) indoor/outdoor	

1.24	**Impact of interference from radar emission in the 2.7-2.9 GHz band to operation of low power networks**	Radar downlink path	Single femto UE (DL) indoor/outdoor	Achievable throughput of UE against separation distance for main beam and sidelobes
		Radar downlink path	Single femto eNodeB (DL) indoor/outdoor We assume sufficient frequency separation between S band radar and FDD UL that this scenario is not modelled.	

Table 8-1 Description of adjacent channel interference scenarios

8.2 *Scenario parameters*

In our analysis of adjacent channel interference from TDD devices we have assumed that the aggressor system is an LTE TDD system and has the same parameters as those outlined for LTE devices in section 4.1. A free space path loss model is used as we assume a good line-of-sight between the victim and aggressor and that separation distances will be relatively short.

In our radar analysis we have assumed the parameters shown in Table 8-2 which were arrived at based on Radar B in ITU-R M.1464-1TTF [[54]] adjusted following discussions with the Ofcom S band radar team to align with typical commercially available ATC radars in the UK.

Parameters	**Value**	**Unit**
Radar Tx power	91.2 in a -40dB bandwidth of 37.6MHz 88.2 for 20MHz interference case 85.2 for 10MHz interference case	dBm
Antenna gain (main beam)	28	dBi
Antenna gain (side lobe)	-2	dBi

Radar effective vertical half power beamwidth	4.4	Deg
Radar effective horizontal half power beamwidth	1.5	Deg
Out of band suppression at 30MHz offset	50	dB
Radar uptilt	2	Deg
Short pulse width	1	µS
Short pulse repetition frequency	8.6	kHz
Long pulse width	75	µS
Long pulse repetition frequency	0.7 to 1.2	kHz
Pulse Repetition Frequency	1	kHz
Radar antenna height	12	m
Mobile height (assumes data terminal on a desk or held away from the head)	0.5	m

Table 8-2 Radar transmitter parameters for a typical ATC radar

In the S band radar scenario we have assumed that the aggressor S-band radar is at a carrier frequency of 2730MHz. In practice most radar systems are above this frequency and will cause less adjacent channel interference. Only one radar system in the UK uses the 2710MHz carrier frequency and so this has not been considered here.

In both the TDD and radar analysis, a 7dB external wall loss is applied for scenarios between indoor and outdoor systems. This is the COST 231 value for an external concrete wall with a window.

8.3 TDD interference

8.3.1 Impact of interference from adjacent WiMAX or TD-LTE network – study question 1.23

Figure 8-3 shows the scenario of an outdoor WiMAX or TD-LTE macrocell causing uplink adjacent channel interference to an indoor low power FDD eNodeB. The downlink case can be seen in Figure 8-4 and is not considered as critical as the uplink case due to the large frequency separation between the TDD band and FDD DL low power band and therefore not analysed further in this study.

The uplink scenario also impacts all users on the low-power cell compared to an arbitrary number of UEs who may happen to be on the limit of coverage in the downlink case.

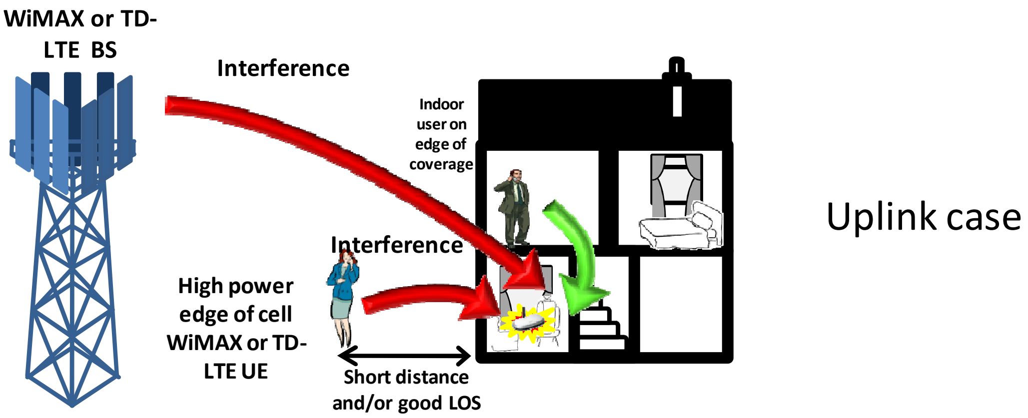


Figure 8-3 TDD interference in the uplink from outdoor macro to indoor low-power access point

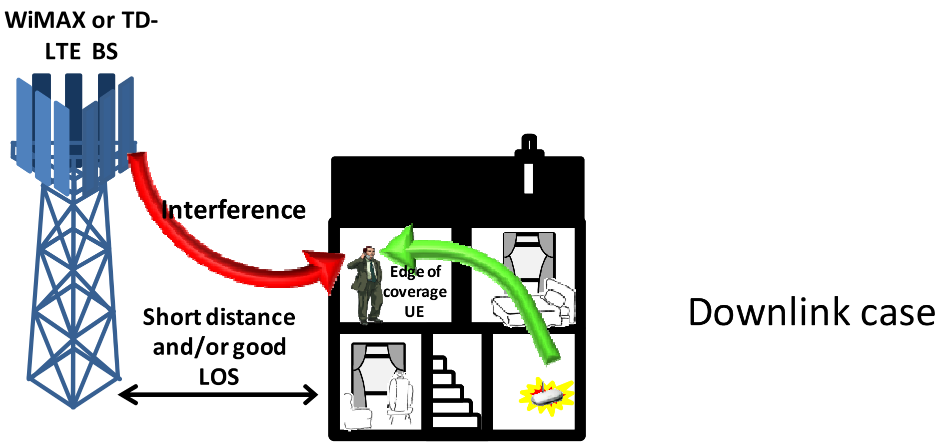


Figure 8-4 TDD interference in the downlink from outdoor macro to indoor low-power access point

Ofcom is particularly interested in the effects of closely located TDD and FDD low-power access points as this is quite different to the TDD macrocell to FDD macrocell interference cases covered in previous studies. This could occur in a public indoor environment such as the shopping centre example shown in Figure 8-5. Potentially TDD operators could deploy low power access points close enough to cause adjacent channel interference into the FDD low power access point. This study has investigated the impact of this interference scenario and the separation distance required to minimise such interference.

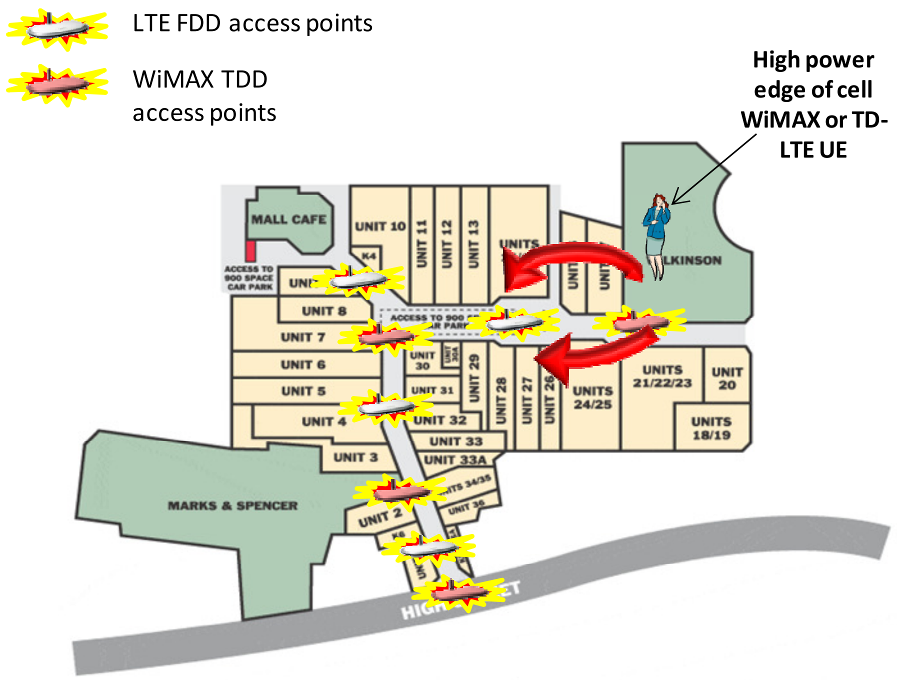


Figure 8-5 Indoor public area scenario TDD low-power access point into FDD low-power access point

8.3.2 Results from analysis of TDD ACI into FDD low power access point

Figure 8-6 shows the separation distances required between a TDD indoor access point and FDD indoor access point in for a 20 MHz channel in a public area environment. This assumes an original SNR at the victim receiver corresponding to a single cell edge user targeting a peak uplink throughput of 32Mbps. The separation distances required to ensure adjacent channel interference doesn't cause any more than a 20% or 50% degradation to this cell edge throughput is shown. As shown, if a 20% throughput degradation is acceptable separation distances in the range 18 to 100m are required depending on the transmit power level. This reduces to 8 to 43m for 50% throughput degradation. The upper range of our results correspond to a maximum transmit power level of 24dBm which is the maximum transmit power of a 3GPP LTE local area base station (see section 4.1).

Figure 8-7 shows the separation distances between a TDD indoor access point and FDD indoor access point in a 10 MHz channel in a public area environment. The required separation distance is slightly higher than the 20MHz case. This is due to the total transmit power of the aggressor being kept constant despite the narrower bandwidth which results in a higher interference power spectral density requiring a larger separation distance. As discussed in section 4.1, specifying a constant maximum transmit power level across all LTE bandwidths is a standard approach in 3GPP.

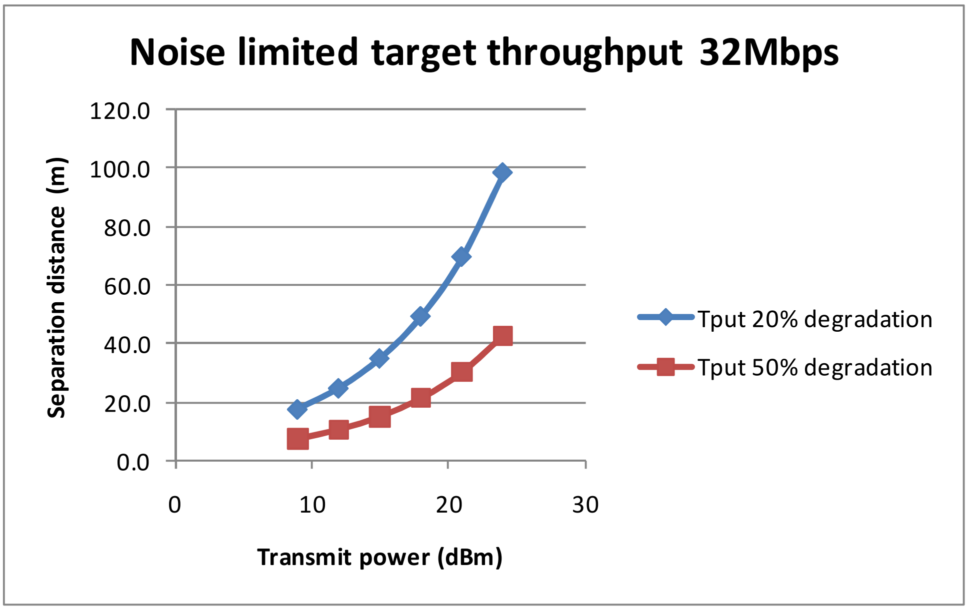


Figure 8-6 Separation distance between TDD low-power access points and FDD low-power access points in a 20 MHz channel

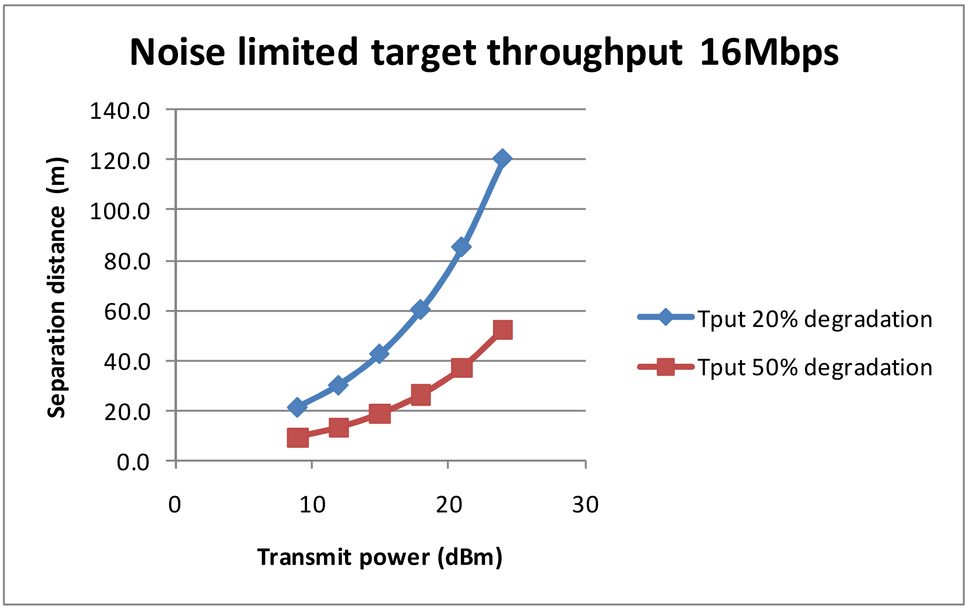


Figure 8-7 Separation distance between TDD low-power access points and FDD low-power access points in a 10 MHz channel

Figure 8-8 shows the separation distances between a TDD macro and FDD indoor residential access point in a 20 MHz channel. As shown, if a 20% throughput degradation is acceptable separation distances in the range 235 to 1315m are required depending on the transmit power level. This reduces to 85 to 475m for 50% throughput degradation. The upper range of our results correspond to a maximum transmit power level of 43dBm which is the maximum transmit power of used for modelling a macrocell base station in 3GPP performance simulations (see section 4.1).

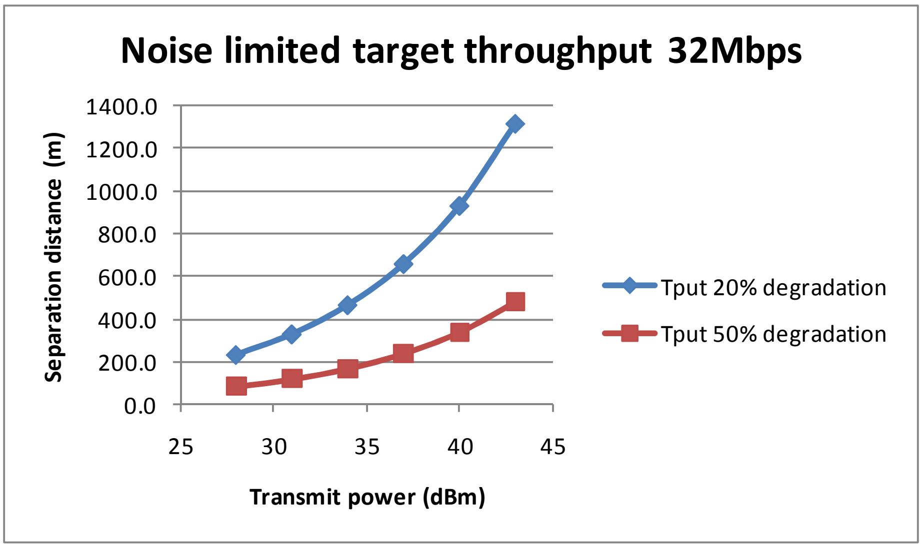


Figure 8-8 Separation distance between TDD macro and FDD low-power access points in a 20 MHz channel

Figure 8-9 shows the separation distances between a TDD macro and FDD indoor residential access point in a 10 MHz channel. As discussed earlier, the separation distances required at 10MHz are slightly higher than those required at 20MHz due to the increased power spectral density of the interference source.

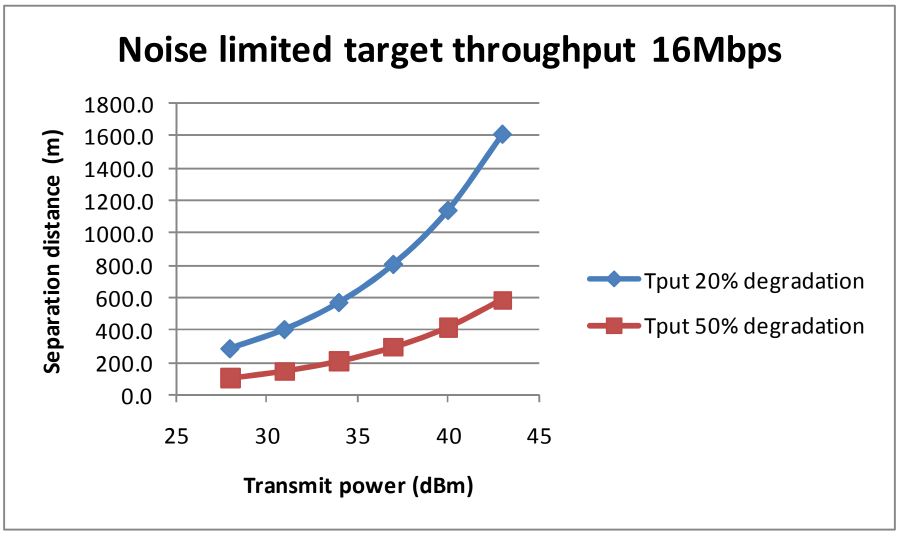


Figure 8-9 Separation distance between TDD macro and FDD low-power access points in a 10 MHz channel

8.3.3 Review of previous studies and conclusions

There have been many co-existence studies investigating interference between TDD systems and adjacent FDD systems in the 2.6 GHz band. A shortlist of these studies which are considered relevant to this work are given below:

- **CEPT Report 019 [[55]]** - Draft Report from CEPT to the European Commission in response to the Mandate to develop least restrictive technical conditions for frequency bands addressed in the context of WAPECS
- **CEPT Report 119 [[56]]** – Coexistence between mobile systems in the 2.6 GHz frequency band at the FDD/TDD boundary
- **ECC Report 045 [[57]]** - Sharing and adjacent band compatibility between UMTS/IMT-2000 in the band 2500-2690 MHz and other services
- **ECC Report 113 [[58]]** - derivation of a Block Edge Mask (BEM) for terminal stations in the 2.6 GHz frequency band (2500-2690 MHz)

The majority of these studies have been carried out by the CEPT European Conference of Postal and Telecommunications Administrations Electronic Communications Office (ECO formerly ERO) in the form of Electronic Communications Committee (ECC) reports and decisions. The reason for particular interest in establishing co-existence criteria was to satisfy the many possible combinations of systems that could use the TDD and FDD portions of the 2.6GHz band and understand the impact of adjacent channel interference amongst these.

CEPT Report 019 considers the use of Block Edge Masks to provide the necessary out-of-block protection to adjacent services. The main aim of this study was to establish the least restrictive technical conditions to remain independent of specific technology requirements. This particular study informed Ofcom’s spectrum award criteria which proposed a -45 dBm/MHz block edge mask for base stations to protect adjacent systems between the FDD and TDD blocks and also to protect the upper adjacent radar band.

We have used the approach described in CEPT Report 119 to derive the separation distances presented here (which is in turn based on ITU-R studies [59] [60], CEPT Report 019 and ETSI studies [61] [62] [63]). Report 119 includes analysis of a number of interference scenarios that are encountered between TDD and FDD systems such as:

- BS to BS
- BS to MS
- MS to BS
- MS to MS

The report also includes the methodology for calculating the component parts of the link budget to establish values such as the Adjacent Channel Interference Ratio (ACIR) and the Minimum Coupling Loss (MCL) which are used to calculate the path loss and thus separation distance.

The results from this report include those for BS to BS interference which found that separation distances of up to 1km were required with up to 10 MHz carrier separation without mitigation techniques applied. However, this study also quotes results from ITU-R M.2030 for rural TDD macro to FDD macro base station to base station interference cases using similar transmit power levels (40dBm) and effective antenna gain (30dB) to our analysis which results in separation distances of 4.3-4.7km. Our results for separation distances required between TDD macrocell base stations and indoor residential low power FDD access points are in the range 235 to 1315m for a 20% throughput degradation in a 20MHz channel with a target peak single user cell edge throughput of 32Mbps which corresponds to a 3dB decrease in SNR. For a 50% throughput degradation this is reduced to 85 to 475m. As expected our separation distances are lower than those in the macrocell to macrocell case as:

- The victim FDD low power access point has a lower antenna gain than its macrocell counterpart (0dBi for residential or 3dBi for public areas compared to 14dBi for macrocells)
- The victim FDD low power access point is assumed to be indoors and so is cushioned from the aggressor by an external wall loss

Conclusions

The following conclusions have been drawn based on the analysis adjacent channel interference between TDD systems and low power FDD networks

- A separation distance is required between indoor low- power TDD deployments and low power FDD deployments ranging between 18-100m for a 20% single cell edge user throughput degradation and 8-43m for a 50% single cell edge user throughput degradation for a range of increasing transmit powers up to 24dBm (assuming a 20MHz FDD system). This means TDD operators in the adjacent block to the low power uplink block will require some coordination when deploying in the same indoor public area.

- A wider separation distance is required for a 10 MHz channel compared to a 20 MHz channel if a bandwidth agnostic transmit power limit is applied to TDD systems.

- The separation distance between a TDD macro and an FDD low power access point can be up to 1.3km at maximum transmit power and 20% allowable single cell edge user throughput degradation.

- Compared to TDD macrocell base station to FDD macrocell base station results in previous studies our results show that TDD macrocell base station to FDD low power access points are likely to be less of an issue due to:
  - Smaller antenna gains at the FDD low power access point compared to macrocell base stations
  - FDD low power access points being more likely to be deployed indoors and so cushioned from interference from external TDD macrocells
- Our results are based on a basic analysis , however, more advanced calculations may take into account different antenna heights which may also vary the separation distance i.e. a larger TDD macro antenna height mast may cause interference to low-power access points at a greater distance (see study question 1.18) . Our analysis also uses a free space path loss model which might be improved upon in a more detailed analysis.

8.4 S-band radar interference

8.4.1 Impact of interference from radar emission in the 2.7-2.9 GHz band to operation of low power networks – study question 1.24

Figure 8-10 shows the scenario for the adjacent channel interference from S-band radar into an indoor UE on the limit of coverage. The downlink carrier frequency of the UE is adjacent to the radar emissions. The interference from radar emission takes two forms, a front (main) lobe which is intermittent in nature and the back lobes which are constant when not in the main lobe. The uplink carrier frequency of the FDD low power eNodeB is assumed to be sufficiently separated from the S-band radar that downlink rather than uplink adjacent channel interference is the main concern in this scenario.

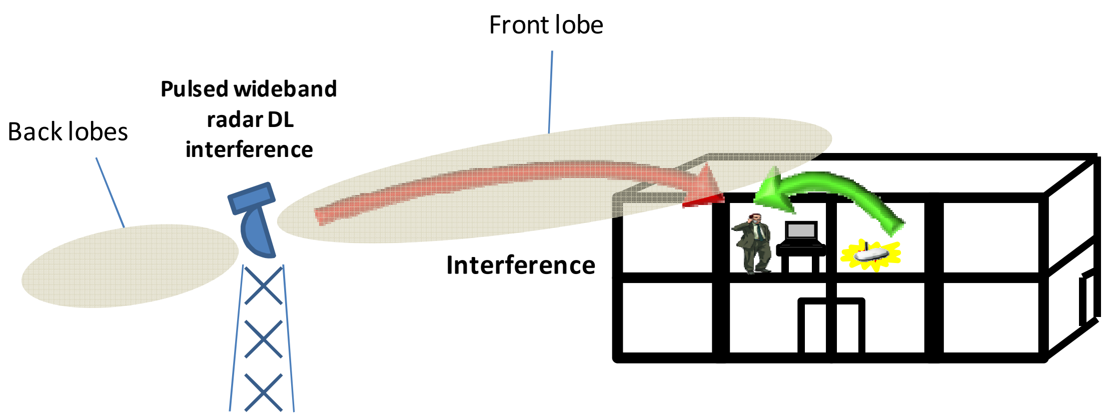


Figure 8-10 Adjacent channel interference from radar into FDD UE scenario indoor example

Figure 8-11 shows the scenario for the adjacent channel interference from S-band radar into an outdoor FDD UE on the limit of coverage. The interference from radar emissions to an outdoor UE are likely to be more severe compared to the interference to an indoor UE due to the penetration losses from the building walls. Furthermore the UE's can get closer to the radar when outdoors which would increase the interference.

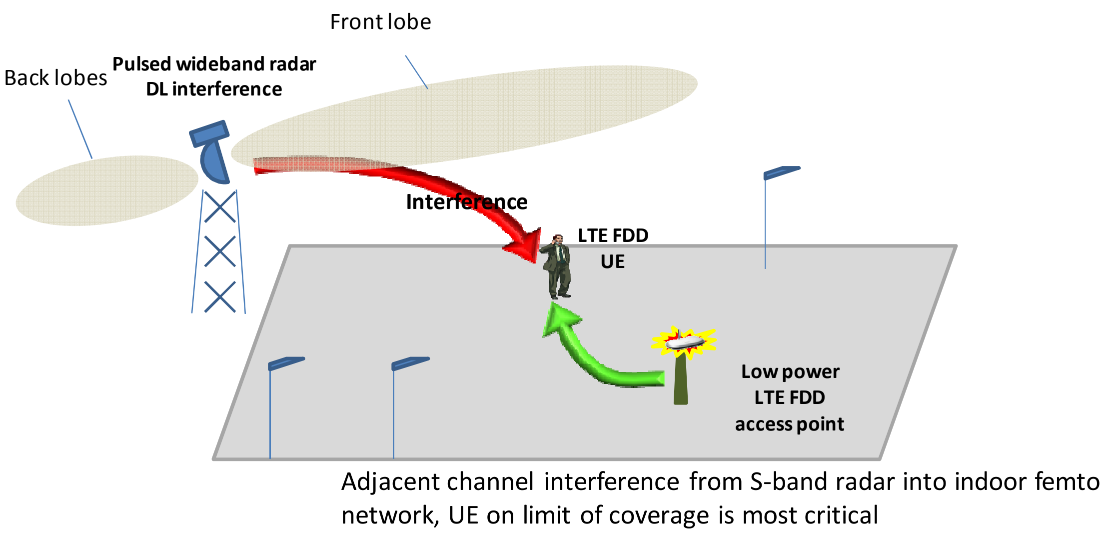


Figure 8-11 Adjacent channel interference scenario from radar into FDD UE outdoor example

8.4.2 Results from separation distance between an airport (ATC) radar and FDD UE

It should be noted that interference from radar emissions consist of peak power when the UE is in the main beam of the radar and the mean power when the UE is in the side/back lobes of the radar. The horizontal antenna pattern beamwidth is 1.5 degrees which means that the UE will only experience interference from the main beam for (1.5/360) 0.4% of the time. For 99.6% of the time the UE appears in the side lobes.

Figure 8-12 shows the required separation distance between a S-band radar and an LTE FDD UE when considering the main beam signal from the radar. This shows how the throughput of a single low power shared access UE at edge of coverage targeting a peak throughput of 91Mbps in a 20MHz channel will be affected by adjacent channel interference at different distances from the radar. This shows that a separation distance of 25km is required if no throughput degradation is permitted. Figure 8-13 shows the equivalent result considering interference from the side lobes of the radar. In this case throughput is unaffected at a separation distance of 5km.

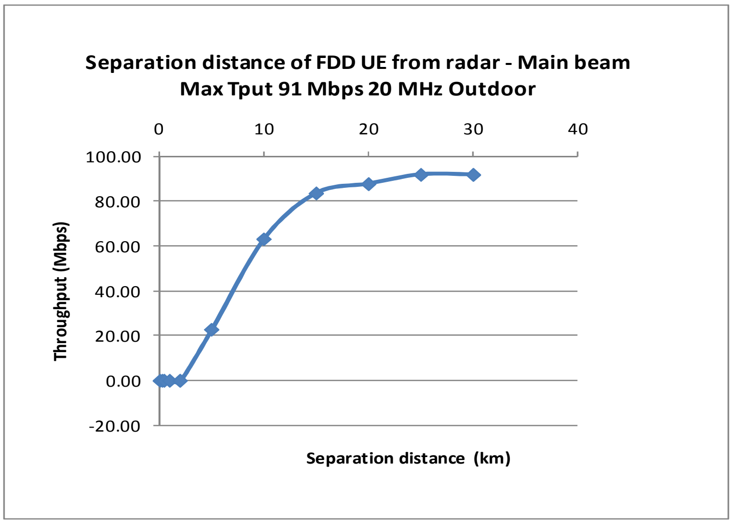


Figure 8-12 Separation distance required between a radar and FDD UE in the radar main beam (20 MHz channel)

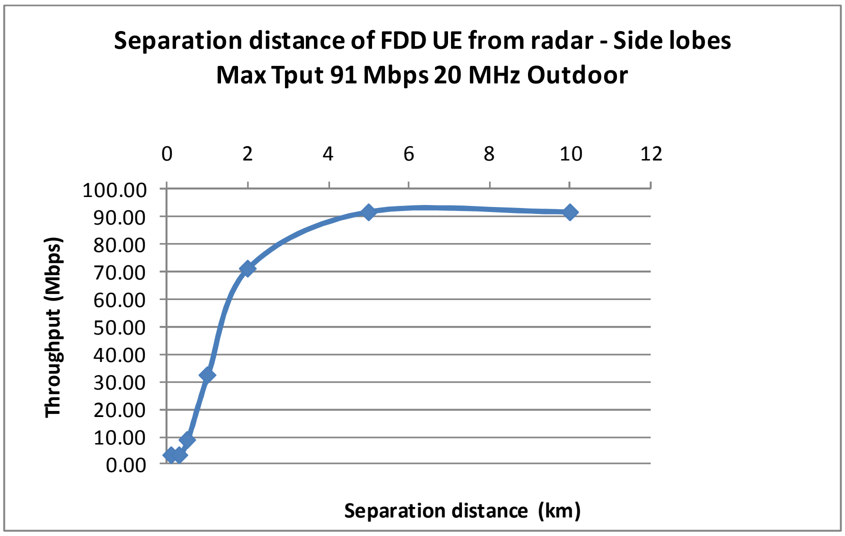


Figure 8-13 Separation distance required between a radar and FDD UE in the radar side lobes (20 MHz channel)

Figure 8-14 and Figure 8-15 show the results when the victim UE is located indoors and buffered from the interference source by an external wall. In this case separation distances of 10km and 2km are required for the main beam and side lobe interference respectively if no throughput degradation is tolerated at the victim receiver.

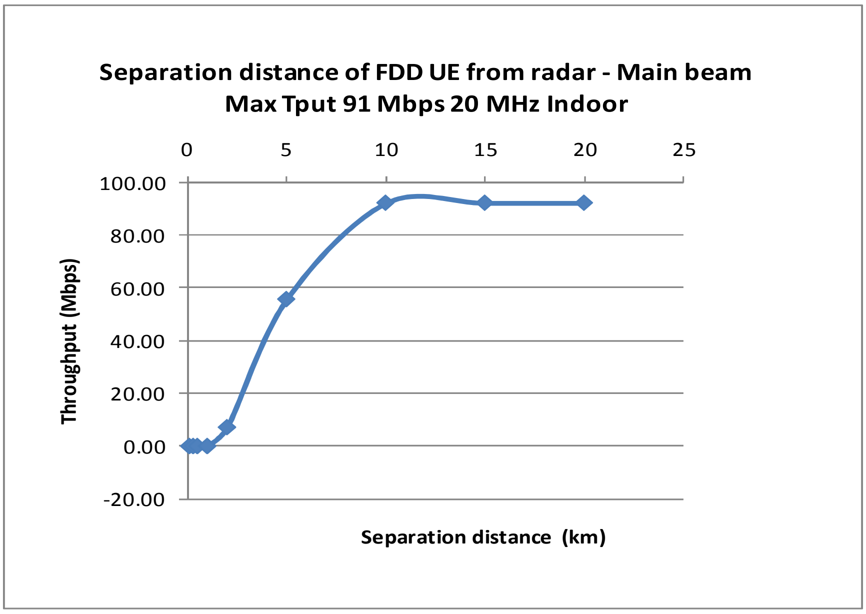


Figure 8-14 Separation distance required between a radar and an indoor FDD UE in the radar main beam (20 MHz channel)

Figure 8-15 shows the impact of interference from radars to indoor FDD UE's when in the sidelobes of the radar antenna pattern. The required separation distance is around 5km for a maximum achievable throughput. However, for a 50% throughput degradation the separation distance is reduced to 2-3 kilometres.

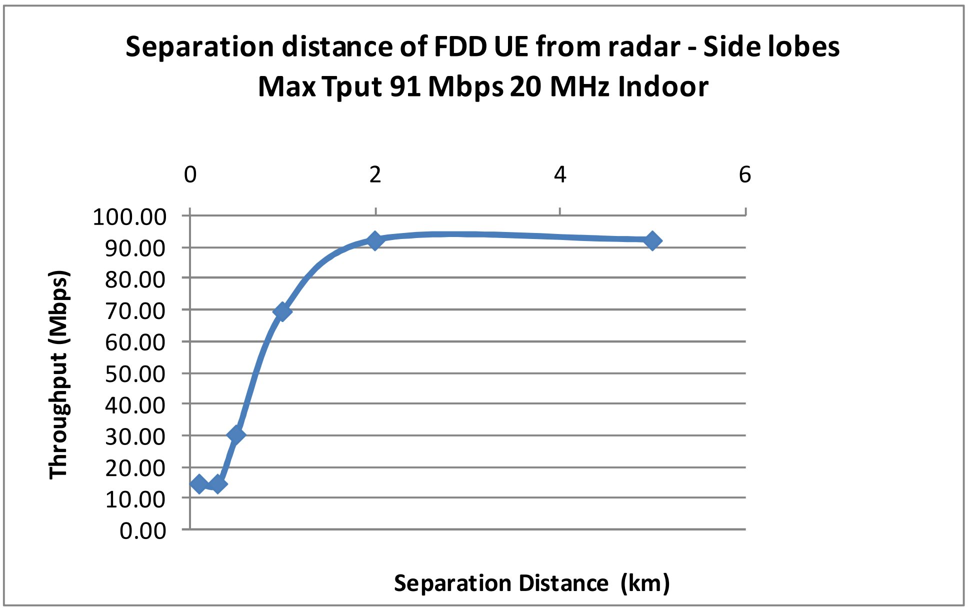


Figure 8-15 Separation distance required between a radar and an indoor FDD UE in the radar side lobes (20 MHz channel)

8.4.3 Review of previous studies and conclusions

This section discusses the other previous studies relevant to S-band radar interference into the 2.6 GHz FDD band. The two key studies are identified below with a description of the findings, methodology and how it is related to the present study.

1) ERA study on interference from airport radars into UMTS and WiMAX

- For the majority of ATC radars monitored the out of band emissions were below -40 dBm/MHz in the 2.6GHz band. Some radars higher up the S-band achieved out of band emissions of -70 dBm/MHz
- Between 600m and 800m from the radar no measurable interference was found during one full radar rotation to a UMTS handset.
- Radiated interference measurements were based on the BER of a reference UMTS channel with a data rate of 12.2 kbps. This is much lower than the peak throughputs of 91Mbps being targeted in our analysis which will have a much higher target SINR. Our study found that a 5km separation distance would be needed to maintain a downlink single cell edge user throughput at 91Mbps in a 20MHz low power access point suffering S band radar interference. As expected this is larger than the ERA measurements.
- The results of this study based on UMTS UEs may not be directly applicable to LTE UEs. It should be noted that some radars can have long pulse repetition frequencies in the region of 1kHz (see Table 8-2) which would align with the 1ms subframe timing used in LTE. This may potentially cause an increased interference impact to LTE compared to UMTS.

2) Roke Manor report for the WiMAX Forum on Radar WiMAX Technology compatibility study

- Link budget calculations were used to derive the required separation distance between an ATC radar and the WiMAX BS and MS
- A required separation distance between an ATC 2.7 GHz radar and WiMAX BS and WiMAX UE was found to be 104.8 km and 75.4 km in the main beam and 14.3km and 3.9km in the side lobes (outdoors) respectively
- These results are much larger than the separation distances calculated from our scenario and the previous ERA findings. Our results indicate a maximum separation for main beam interference of 25 km and 5km for side lobe interference when targeting a single cell edge user throughput of 91Mbps in a 20MHZ channel.

   - This study used free space path loss with exponent of 3 + 10 dB shadowing compared to ITU-R P 1411 for our scenario. This may account for some of the differences as ITU-R P.1411 allows for diffraction effects.

Conclusions

The following conclusions have been drawn based on the high level analysis of adjacent channel interference from radars into FDD UE's discussed in this chapter.

- The UE will only experience interference from the main beam for (1.5/360) 0.4% of the time. For 99.6% of the time the UE appears in the side lobes.
- The peak interference also occurs for a very short duration of time, in this case up to 75 µs for a long pulse with a pulse repetition frequency in the region of 1 kHz. This means a duty cycle of 7.5% which is considered negligible to the UE receiver as the signal appears as a short pulse and not continuous interference
- Therefore the side lobe separation distance results should be used from our analysis rather than the main beam results i.e. 5km for outdoor systems and 2km for indoor systems if no throughput degradation is permitted.
- It should be noted that some radars can have long pulse repetition frequencies in the region of 1kHz (see Table 8-2) which would align with the 1ms subframe timing used in LTE. This may potentially cause an increased interference impact to LTE compared to UMTS.
- Interference circumstances may be improved from this scenario based on the following variations in deployment characteristics:
   - Radar frequency higher up the S-band which will improve the adjacent channel Out of band suppression level
   - An increased radar height may improve the situation as the vertical pattern beamwidth reaches the horizon in shorter distance compared to decreased radar height
   - Lower peak power, this scenario used the highest possible licensed peak power which is not necessarily the case at every airport. Some airports will transmit at peak power's 3-10 dB lower that the peak used in this scenario
   - True behaviour for modelling a mobile is best reflected using Monte Carlo analysis which will be able to capture the dynamic effects of the moving random nature of the mobile

and the rotation of the radar antenna. This type of analysis will give a more accurate representation of the interference.

- As S band radar affects the UE rather than base station adjacent channel interference from S band radar to FDD low power network UEs is likely to be no worse than that for FDD macrocell UEs. Therefore no additional conditions to mitigate interference are recommended. The risk of interference may be less if a high proportion of low power access points are indoors.

8.5 Summary

This section analysed the adjacent channel interference scenarios that could impact performance of low power shared network FDD devices if the low power shared access channel is located at the top end of the 2.6GHz FDD band.

By positioning low power devices at the upper end of the paired 2.6 GHz spectrum, an additional frequency separation is introduced between high power macrocells and radar receivers above 2.7GHz. Although this study has not examined this case explicitly, this would seem helpful in providing an additional 'guard band' between high power transmissions and the radar systems. However, in some circumstances low power access points may have relaxed emission specifications, which could create noise rise to radar receivers and we recommend that this situation is examined explicitly.

The following table summarises the findings from the analysis.

Study Question	**Answers**	
1.23 What would be the impact of interference from adjacent WiMAX or TD-LTE networks in the unpaired band on the operation of a low-power network?	**10 MHz (16 Mbps) TDD – FDD (Indoor)**	**20 MHz (32 Mbps) TDD – FDD (Indoor)**
	For 20% throughput degradation 20-120m separation depending on transmit power (9 to 24dBm) For 50% throughput max degradation 10-50m separation depending on	For 20% throughput degradation 18-100m separation depending on transmit power (9 to 24dBm) For 50% throughput max degradation 8-43m separation

	transmit power (9 to 24dBm) Some coordination between TDD and FDD low power operators will be needed in public areas.	depending on transmit power (9 to 24dBm) Some coordination between TDD and FDD low power operators will be needed in public areas.
	10 MHz (16 Mbps) TDD macro –FDD indoor low power	**20 MHz (32 Mbps) TDD macro –FDD indoor low power**
	For 20% throughput degradation 290-1600m separation depending on transmit power (28 to 43 dBm) For 50% throughput max degradation 100-590m separation depending on transmit power (28 to 43dBm) These are likely to be less than in the macrocell to macrocell case.	For 20% throughput degradation 235-1315m separation depending on transmit power (28 to 43 dBm) For 50% throughput max degradation 85-475m separation depending on transmit power (28 to 43dBm) These are likely to be less than in the macrocell to macrocell case.
1.24 What would be the impact of interference radar emissions in the 2700 to 2900 MHz band on the operation of a low-power network?	**Outdoor**	**Indoor**
	Main beam: 25 km separation distance for max	**Main beam**: 10 km separation distance for

	throughput (91 Mps in 20MHz)	max throughput (91 Mps in 20MHz)
	Side lobes: 5 km separation distance for max throughput (91 Mps in 20MHz)	**Side lobes**: 2 km separation distance for max throughput (91 Mps in 20MHz)
1.25 What other technical conditions might be needed to manage any interference?	Some coordination between TDD and FDD low power operators will be needed in public areas with overlapping deployments to ensure separation distances and/or appropriate power limits are applied. As S band radar affects the UE rather than base station adjacent channel interference from S band radar to FDD low power network UEs is likely to be no worse than that for FDD macrocell UEs. Therefore no additional conditions to mitigate interference are recommended. The risk of interference may be less if a high proportion of low power access points are indoors.	

Table 8-3 Summary table of Adjacent Channel Interference

9 Conclusions and recommendations

9.1 Overall

The study investigates the technical issues associated with low-power shared access in the 2.6 GHz spectrum. We have assumed parameters associated with FDD LTE Home eNode Bs and Local Area Base Stations as these are the most likely devices to use a low power paired portion of the 2.6 GHz spectrum. However the findings are expected to apply broadly to other potential technologies.

Our study has found that a low power shared access channel amongst multiple operators is feasible but will require appropriate restrictions to make best use of the capacity benefits of small cells.

We recommend that a dedicated 2 x 20MHz block at 2.6GHz would be the most attractive solution for a low power shared access channel. This is due to:

- 2 x 20MHz providing low power operators the opportunity to provide the best peak data rates and user quality of experience.
- The wider bandwidth improving the performance of dynamic scheduling as required to avoid interference from adjacent access points sharing the band.
- The larger spectrum allocation maximising the opportunity to gain the capacity benefits of small cells compared to wide area cells.
- Being the least complex option in terms of setting technical conditions on the licence compared to the underlay or hybrid spectrum allocation approaches.

A 2 x 20MHz hybrid band allocation with an overlap of 2 x 10 MHz with conventional high power use is also attractive as it allows three wide area 2 x 20MHz channels and a 2 x 20MHz low power shared access channel to be accommodated. However, more complex licence conditions would need to be applied to the low power shared access channel to minimise the impact on the overlapping wide area frequencies.

With either approach restrictions on transmit power, antenna height and a code of practice for sharing are recommended to ensure maximum benefit from this band.

In this study Ofcom has asked us to examine the following four areas:

- Power levels for providing suitable coverage for low power access points
- Co-channel interference both between low power access points and between low power access points and surrounding macrocells
- Adjacent channel interference from the 2.6GHz TDD and S-band Radar
- Trade-offs relating to spectrum quantity

The conclusions in each of these are presented in the following subsections.

9.2 Coverage

Our analysis has examined transmit power levels required to provide coverage in the following four environments:

- Indoor office
- Indoor public area
- Residential
- Campus or business park using outdoor access points

Our results for each of these are as follows:

- *Indoor office environment:*
  An EIRP of 27 dBm easily provides maximum data rates at the range to cover a single floor medium sized office and could be backed off to 18 dBm.
- *Indoor public area:*
  An EIRP of 27dBm provides maximum data rates at the range to cover a single floor medium sized shopping centre (8,000 m^2).
- *Residential (home femtocell):*
  An EIRP of 20dBm provides a range of 16.5m at a max data rate of 91 Mbps downstairs and 6.66m upstairs. This is sufficient downstairs for most houses but may start to limit coverage at higher data rates upstairs in some larger properties, where 23 dBm would provide greater consistency.
- *Campus / business park (outdoor access point):*
  - *Outdoor users* – An EIRP of 29dBm on the low power shared access channel would provide maximum data rates to outdoor users at typical microcell ranges (i.e. 100m)
  - *Indoor users - A*n EIRP of 29dBm would require the target cell edge data rate to be backed off to 20Mbps (in 10MHz) to achieve the target microcell range of 100m and good indoor penetration.

In practice operators are likely to deploy more than one access point for capacity reasons in the office and public areas and so the transmit power levels here could potentially be backed off even more. Operators should adopt transmit power control techniques as a matter of course to limit interference.

Across these four environments, the indoor penetration of signals from outdoor base stations is the limiting case for setting the maximum EIRP of a low power shared access channel. We therefore recommend that the maximum EIRP is set at 30dBm. This is in line with a maximum transmit power of 24 dBm for local area access points as specified for 3GPP LTE Local Area Base Stations and an antenna gain of 6 dBi for outdoor access points.

9.3 Co-channel Interference

Our study has analysed co channel interference in the following four areas:

- Interference between low power networks
- Limits on mast height for outdoor access points based on interference to other low power networks
- Interference to macro cell networks from low power networks if an underlay or "hybrid" spectrum approach is applied
- Interference between outdoor and indoor low power networks

Our results in each of these are as follows:

- *Interference between low power access points:*
  For the scenario analysed of two low power access points in adjacent houses, the minimum separation distances will be upwards of 23m assuming data rates of at least 10Mbps are targeted in interference free conditions and a throughput degradation of less than 50% is required at the cell edge.
- *Limits on outdoor mast heights:* Interference increases significantly once mast heights exceed the height of surrounding buildings. Assuming a limiting case of a residential scenario this would suggest a limit of 10-12m.
- *Interference to macrocells:* A much larger separation distance is required to minimise uplink interference to the macrocell base station than downlink interference to macrocell UEs. Also the impact of uplink interference is to desensitise the macrocell base station for all UEs and so the impact is more significant to the entire cell than the downlink interference case. Therefore uplink interference is the dominant case for setting separation distances. In the analysed scenario of a single UE from a low power network operating on the edge of coverage a separation distances in the range 400m-1.5km would be required if a throughput degradation of less than 40% is required. This assumes a 10dBm power cap is applied to low power network UEs in the vicinity of overlapping macrocells sharing spectrum.
- *Interference between outdoor and indoor low power networks:* The scenario analysed examines interference between a single outdoor low power network and single indoor low power network. The separation distances required to minimise downlink interference in this scenario are much larger than those required for uplink interference. Based on the downlink interference in this scenario, separation distances in the range 100m-600m are required to minimise interference depending on the target throughput and acceptable degradation level.

The separation distances outlined here are unlikely to be enforceable in practice and are not recommended as a route for mitigating interference in a low power channel. Instead in all of the scenarios examined the separation distances can be reduced to zero if a dynamic scheduler that identifies interference and targets un-contended resource blocks is used as an interference mitigation technique. However, this does rely on operators being willing to share overall capacity and accept degraded throughputs in line with the number of adjacent networks causing interference. For example in the scenarios examined where there is one aggressor and one victim no separation distance would be needed if a degradation in throughput of 50% is acceptable at the cell edge.

9.4 Adjacent Channel Interference

Our study has examined adjacent channel interference from both TDD and S band radar for the case where the low power shared access channel is located at the upper end of the FDD band.

Our results in these two areas are as follows:

- *Interference from the TDD band:* We have examining uplink interference to a FDD low power access point from a TDD low power access point. For a 10MHz bandwidth and target cell throughput of 16Mbps in the absence of interference, a separation distance of 120m is required for a 20% throughput degradation. This decreases to 50m for a 50% degradation in throughput. This implies that there will be interference issues if a TDD and FDD operator both deployed low power access networks in the same public area such as a shopping centre. The equivalent separation distances for interference from a TDD macrocell base station to a low power access point would be 1.6km and 590m respectively.
- *Interference from S band radar:* We have examined downlink interference from both the main beam and side lobes of a radar signal at 2730 MHz towards a UE using a low power FDD network. Our results show a 25 km separation distance is required to achieve no throughput degradation in 20MHz when in the main beam and a 5km separation distance when in the side lobes of the radar. This is for outdoor users. For indoor users these distances reduce to 10km and 2km respectively. Higher radar frequencies will also reduce the extent of interference.

In the case of radar it should be noted the main beam points towards a given mobile for only around 0.4% of the time. It should also be noted that the impact of interference has been estimated by assuming radar interference affects the throughput in the same way as broadband noise. However the impact of the narrow pulses associated with radar may need further study, since the radar pulse repetition rate may be closely comparable to the duration of resource blocks in LTE.

By positioning low power devices at the upper end of the paired 2.6 GHz spectrum, an additional frequency separation is introduced between high power macrocells and radar receivers above 2.7GHz. Our findings have focused on interference into the FDD band and show that:

- Interference from S band radar to FDD low power network mobile devices is likely to be no worse than that for FDD macrocell mobile devices.
- Interference from TDD macrocells to FDD low power access points may be less than interference to FDD macrocells due to the lower antenna gain likely in low power access points. However, some coordination between TDD and FDD low power operators will be needed in public areas with overlapping deployments to ensure separation distances and/or appropriate power limits are applied.
- Widespread indoor usage of low power access points may provide some additional isolation from adjacent channel interference due to building penetration losses.

In terms of interference into the FDD band, positioning the low-power shared channel at the top end of the band seems a sensible choice, but the case is not overwhelming. However, in some circumstances low power access points may have relaxed emission specifications, which could create noise rise to radar receivers and we recommend that this situation is examined explicitly.

9.5 Trade-offs relating to spectrum quantity

Smaller cells provide significant capacity improvements due to:

- A higher density of cells
- An improved SINR distribution across the cell
- Improvements in performance of technologies such as MIMO in indoor environments where small cells are more prominent.

3GPP simulation results show a x2.3 improvement in cell spectrum efficiency between indoor hotspots and urban macrocells for their respective cell areas. The same results report a x54 improvement in cell spectrum efficiency density (which normalises cell spectrum efficiency to a uniform service area). However, to achieve these capacity improvements there are trade-offs in selecting the amount and type of spectrum used for a low power shared access channel. These include assessing:

- Whether 2x 10MHz or 2 x 20MHz of spectrum should be assigned
- The maximum number of operators sharing the low power band
- Whether a dedicated, underlay or hybrid spectrum allocation should be used.

9.5.1 10MHz Vs. 20MHz

Allocating 2x20 MHz rather than 2x10 MHz to low power systems complicates the award of the 2.6 GHz band, since (assuming dedicated low power spectrum) it will only allow two channels of high power 2 x 20 MHz spectrum. In other respects, however, it presents a number of significant advantages to low power licensees:

- It allows the licensees to offer services at the maximum peak data rates achievable by LTE. The signal quality distribution in isolated low power cells is more consistent than in large cells and contention ratios are lower, so this difference impacts on a greater proportion of users than in a macrocell system.

- The quantity of spectrum under discussion is not sufficient to allow a conventional frequency reuse scheme or to allow fixed allocations of frequencies between low-power operators. However there are several schemes for frequency segmentation and fractional frequency reuse which would allow essentially twice as many operators to deliver a given service quality to their users in the presence of interference from other operators in 2 x 20 MHz compared with 2 x 10 MHz.

- Examples of the throughput benefits between the 2x10MHz vs. 2x20MHz channel options in the cases where there is no interference and in the cases where capacity sharing is required are summarised below based on a 2x2 MIMO LTE system in an EVA5 channel.

	Peak data rate in interference free case	**Peak data rate in 7 overlapping deployments**	**Peak data rate in 14 overlapping deployments**
2x10MHz	41Mbps	Assume frequency partitioning. 1.4MHz channel achieves 65% spectrum efficiency of a 10MHz channel (see section 4.5.3) 3.8Mbps	Time shifting may be needed in addition to frequency partitioning which is not proven for uncoordinated deployments. <1.9Mbps
2x20MHz	91Mbps	Assume frequency partitioning. 3MHz channel achieves 87% spectrum efficiency of a 10MHz channel (see section 4.5.3) 11.3Mbps	Assume frequency partitioning. 1.4MHz channel achieves 65% spectrum efficiency of a 10MHz channel (see section 4.5.3) 4.2Mbps

9.5.2 Number of operators

- For non-overlapping deployments of low power cells, the limiting situation of interference between cells occurs when two cells from differing operators are deployed to cover adjoining areas. This situation will occur when as few as two operators have concurrent access to the spectrum. Such a situation may occur somewhat more often with more concurrent operators, but this does not affect the need to incorporate techniques which can address this situation.

- For overlapping deployments, such as in public areas where multiple operators wish to provide service, capacity is reduced by uncoordinated deployments, and the aggregate capacity of the spectrum can only be maintained via close coordination amongst operators, typically involving co-sited deployments. In such a case the maximum capacity is essentially shared equally amongst operators (given 'fair' interference mitigation techniques) if they are serving equal traffic volumes, or is shared in proportion to the traffic served if not. For a given demand level, then, the aggregate capacity of the spectrum is largely unaffected by the number of operators. In cases where sharing significantly reduces the bandwidth available to operators there will be an increase in overhead as the operator's common control channels will occupy a larger proportion of the reduced bandwidth and have a negative impact on capacity.

- There is little technical justification for assigning an 'optimum' number of concurrent operators in the low-power spectrum given that all operators are unlikely to deploy in the same areas. The costs of coordination may be somewhat higher given more operators, but the use of shared central databases and potentially the assistance of a neutral third party to assist in coordinating the band should reduce these increased costs to a one-off at the start of deployments. It should be emphasised also that such coordination measures only need be applied when the density of cells and of usage exceeds a certain level, so is in a sense a 'problem of success'.

- Overall, we believe that from a technical perspective it is entirely plausible for 7 overlapping low power shared access networks to coexist in a 2x10MHz channel. This increases to 14 for a 2x20MHz channel. The number of operators providing viable services in a concurrent low power shared access spectrum block may well exceeded these limits provided a code of practice is put in place between them to limit overlapping deployments. For greater bandwidths, the number of operators offering a given service quality rises essentially with the quantity of spectrum. For less than 2 x 10 MHz, overheads and peak user data rate experience may be reduced significantly. In the underlay case the benefits of the wider bandwidths will only be experienced in areas where wide area networks are not contending for spectrum (depending on the balance of priority between networks). In the hybrid spectrum approach low power networks would at least be guaranteed the benefits of a 2x10MHz bandwidth.

9.5.3 Dedicated vs. underlay vs. hybrid

Dedicated Spectrum

- If cells are deployed in adjacent houses or offices, the degradation in performance is moderate at ranges of 23m upwards, with less than 40% degradations expected for users at the edge of cell and close to the interfering cell. The degradation will be much lower on average for users distributed across the cell area. This requires that the cell transmit power is adjusted to close to the minimum required to provide coverage in a given building and that the cells use intelligent resource scheduling algorithms to minimise interference. It would also be advantageous in areas of dense deployment to implement some form of hybrid access (equivalent to a conditional roaming arrangement amongst operators) to avoid interference arising from high power mobiles close to cells from another operator.

- When cells are deployed outside, the interference range to indoor cells can be as large as 600 m depending on target throughputs and acceptable degradations in performance. This cannot be avoided by simply reducing power levels, because the number of cells to provide adequate coverage then increases to produce similar levels of interference. The more efficient approach is for operators to agree procedures for coordination - either manually or automatically - to ensure a fair sharing of resources. This also reduces the cost of delivering coverage. While the most efficient interference mitigation techniques would require technical interfaces between operators and centralised control of resource, several distributed techniques are available which can provide a comparable level of performance without interconnection. In this case some agreement amongst operators as to the principles and parameters of these algorithms may be necessary to ensure fair allocation of resources. Special arrangements may need to be made to avoid control channel interference (e.g. time offsetting).

- In public areas, it is likely that multiple operators may wish to provide service in overlapping areas. In such cases, uncoordinated deployments will cause a significant loss in capacity and performance for all operators. In the best case, deployments with cells at the same locations and powers will cause a simple sharing of available capacity amongst operators. In such cases operators may wish to adopt some closer coordination, including:

- Power control and resource scheduling algorithms which are compatible between operators
- Conditional roaming
- Full roaming with cell sharing (this would achieve the greatest aggregate capacity at the lowest infrastructure cost)

The situations in which such coordination is necessary could be identified by the sharing of a database amongst operators giving location and other basic data associated with deployed cells above a certain power limit.

Underlay and hybrid spectrum

- When a single operator deploys a layer of femtocells in the same spectrum as their macrocell network layer, a range of interference mitigation techniques, notably transmit power control, resource allocation and directed handover between layers, can reduce interference to the point that the overall system capacity and the overall user experience is greatly enhanced.

- However, in the case of different operators between the femtocell and macrocell layers, the performance of each system taken on its own may be significantly degraded. In particular, the interference to macrocell users who approach close to a femtocell but have weak macrocell signal can be significant ("the visitor problem") and this may affect many users when a large number of femtocells are deployed. The femtocell users cannot rely on switching to another frequency or cell to compensate in this case. The reciprocal problem, where high power femtocell users approach close to a macrocell, degrading the sensitivity of the macrocell, can also be significant since it can affect many users at the edge of macrocell coverage. This case can be mitigated by ensuring that the femtocells sense the power/path loss from the macrocell and reduce the maximum power of their users accordingly. In both these cases, however, clear limits and techniques would need to be set to avoid significant interference.

- One means of reducing this impact would be to adopt a hybrid underlay/dedicated approach, where perhaps half the low power spectrum allocation overlapped with one high power allocation and the other half is dedicated to low power use. In the case of a close approach of femtocells or their users to a macrocell, the femtocells could allocate resources only within the dedicated portion of the band. An intermediate approach would involve overlapping the low power channel across two high power allocations. A 'conditional roaming' approach would also be possible in this case. In any case a clear understanding of the limits of behaviour of the low power cells would be needed for high power licensees to evaluate the impact.

- Unlike interference mitigation techniques between low power networks, it is likely that in the underlay and hybrid spectrum approaches interference mitigation mechanisms would need to be prescribed in the licence terms to set the balance of priority between the wide area and low power networks in the overlapping portion of spectrum. These additional licence terms will most likely include a set of path loss thresholds and corresponding power caps which would be applied to the low power network and/or wide area network depending on the priority between the two. Other licence conditions may include:

- Support for a shared database providing affected operators with location , power and ID of cells using shared block
- Possible conventions on the use of CellID and other broadcast information to distinguish cells between operators
- Applying different conditions when the overlay operator’s cell is also low power
- Applying a protection time for low power networks deploying in not spot areas to prevent them being unfairly disadvantaged and evicted by new macrocell deployments.

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